PETROLEUM GEOLOGY OF THE PERSIAN GULF

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In the Name of God

PREFACE

The intention of this book is to provide a detailed synthesis of the available information published on the petroleum geology of the Persian Gulf. Despite the intensive petroleum exploration which has taken place in the Persian Gulf over the past seventy years, relatively little has been published in the petroleum geology literature. One of the main reasons for this is that many of the studies are undertaken either for or by oil companies, who, for competitive reasons, impose restrictions on publication to maintain confidentiality. This information will aid in estimating oil and gas reserves as well as improving field development technology.

Much work remains to be done regarding the geology of the Persian Gulf. The need for a book on the geology of the Persian Gulf is therefore clear, and it is hoped that it will continue to provide a useful reference manual and resource of ideas for students as well as professionals.

As it is almost always the case with a book of such nature, it is impossible to provide a comprehensive and thorough coverage of geologic and sedimentologic studies in the Persian Gulf. Although this book is not intended to give an impression of the breadth of studies being carried out and the variety of approaches implemented, it should hopefully begin to rectify this, and to provide information on some of the key points.

Progress in the oil and gas producing industry is related closely to the improvement in exploration techniques and increase in discovery rates. Indeed, exploration and production of hydrocarbon resources must be based on reliable scientific information. Considerable amount of geological, geophysical, petrophysical, geochemical, and engineering information has been gathered over more than decades of oil and natural gas exploration and production in the Persian Gulf. The geological history of this economically important region has become increasingly better-investigated in recent years and this trend will undoubtedly continue.

This book takes the reader through the most fundamental description of geological history in the Persian Gulf region. Geoscientific knowledge concerning the Persian Gulf region has been widely scattered in many published works and attempt has been made to survey these materials. The present book also has an important academic purpose. The compilation and editing of this book required the assistance and cooperation of many people. A number of reviewers also dedicated their time to significantly improve the technical merit of each contribution.

It is hoped that the present contribution to the geology of the Persian Gulf will be of interest to stratigraphers and sedimentologists as a general background reference book, to those involved in geophysical exploration, and to environmental geoscientists who are interested in protecting the natural environment of the Persian Gulf as one of the most valuable and magnificent parts of the world.

This book on the Petroleum Geology of the Persian Gulf contains eleven chapters. It provides a broad, but not superficial, introduction to various aspects of the geology of the Persian Gulf.

Chapter one provides a general introduction including a brief historical background on the Persian Gulf and its magnificent history, and also some remarks about the history of oil exploration.

Chapter two is concerned with the physical oceanography of the Persian Gulf including the description of water circulation and hydrological aspects, water chemistry and movements of water. In general the Persian Gulf has been the subject of extraordinary neglect by modern oceanographers, remarkably so in view of the economic and political importance of the area, and the vast amount of marine trade carried on, principally in tanker traffic. This chapter emphasizes the need for better oceanographic knowledge of the Persian Gulf.

Chapter three mainly addresses the stratigraphy of the rock sequences in the Persian Gulf region with description of the Precambrian to Recent rocks. The paleogeography, paleontology and facies of the Persian Gulf are also reviewed.

Many stratigraphic columns have been studied by various workers from both subcrops (well logs) and outcrops (measured) sections in various parts of the Zagros Belt and the northern Persian Gulf. Based on this database and available published stratigraphic, sedimentological, and petrographic information, a description for each stratigraphic unit has been presented in this chapter. Such work forms the basis for a synthesis of the uppermost Neoproterozoic through Phanerozoic successions, and provides a framework upon which a scheme for Persian Gulf region geologic evolution can be established.

Chapter four is on the source rocks. The petroleum charge system requires source rocks, which must be capable of generating and expelling petroleum, and have a migration pathway into the reservoir unit. Possible source rocks within the Persian Gulf and surrounding region and their potential have been presented in this chapter. In different parts of the Persian Gulf, sediments of quiet different types and age have been suggested as the source rocks, and evidently quite different organic materials are candidates as source. The quantities of organic sediments have been regarded as inadequate for the production of the oil and gas and would probably be seen to be much more inadequate still, if one allowed for the large natural seepage rate of the region observed since ancient times.

Chapter five is confined to a selection of representative, relatively well-documented accounts of carbonate and clastic reservoirs in the Persian Gulf and surrounding region. One of the objectives of this chapter is to focus on the geology of a select number of reservoirs and to present geologic case studies. The cases also demonstrate the depositional settings and facies, diagenesis and the resulting petrophysical modification of these facies, and the reservoir properties that resulted from all these interrelated factors.

The small number of reservoirs cited in this chapter provided a reasonable representation of known reservoirs in the Persian Gulf, since carbonates are the principal reservoirs in majority of the oil fields. The chapter also focuses on the lithology and depositional settings of the producing formations of the Persian Gulf, and describes the habitat of the hydrocarbons (sources, reservoirs, and seals) for the region. Non-producing formations are also described to give the reader a general sense of local stratigraphy.

Included in this book (i.e., **Chapter six**), is a chapter on caprocks. Petroleum generation remains the rate-limiting factor in the formation of a petroleum system but competent caprocks are vital for commercial accumulations of petroleum in the sedimentary basin. The characters of efficient seals, including the regionally extensive evaporites and shales, especially in Upper Jurassic, Cretaceous and most importantly Miocene have been described.

Chapter seven is on the structural history of the Persian Gulf. Many authors have noted that the occurrence of petroleum seems to be more closely related to large-scale tectonic features of the crust than the magnitude of organic sedimentary deposits. Within the petroliferous province of the Persian Gulf, it is indeed common to find many different stratigraphic levels that are productive. The tectonic framework and evolution of the Persian Gulf is the focus of this section, with a review of the structural significance of the Zagros zone. The present tectonic picture of the Persian Gulf region is described in this book. This chapter is completely written by Dr. Shahrum Sherkati from National Iranian Oil Company.

Salt Diapirism is dealt with in **chapter eight**. The subject of how structures are evolved is very important to understand because they are associated with major hydrocarbon reserves in the Persian Gulf. In this regard salt diapirism plays a very important role. Dr. Abbas Bahroudi is the main author of this part of the book and he has extensive experience in salt tectonic of the Persian Gulf region.

Chapter nine is concerned with some of the oil fields located in mostly Iranian waters of the Persian Gulf. This includes development, exploration and production history of the field and a summary of stratigraphy and reservoir characteristics. In the Persian Gulf, similar to the onshore region surrounding it, a close association of suitable source rocks and high quality reservoirs appears to be the most significant factor in the development of the great productivity of the Persian Gulf region. The main idea for organizing this chapter comes from Mr. Homayoun Motiei.

Chapter ten is a review of the geophysical activities during the past few decades and the main draft was contributed by Mr. Changeez Amir Behboodi and revised by Mr. Abdolhamid Memarzia. The chapter also provides some of the results of 3D seismic interpretation performed by geophysical consultants on some of the oil fields.

Chapter eleven is on the environmental geology of the Persian Gulf. This chapter focuses on, the quaternary geology, environmental aspects, oil and industrial pollutions, and some climatic aspects of the region.

I am deeply appreciative of the help given by others to make this book a reality. I am very grateful to Homayoun Motiei who provided some of the background materials used in this book. Mr. Hassan Nazari significantly improved the illustrations appeared in the book. Mr. Arta Sharifi as always helped to make a respectable cover design.

Special recognition and appreciation is due to my family, who provided me with many years of patient, understanding and encouragement while this edition was in preparation.

For the shortcomings that remain in the book, I alone feel responsible. Preparing this book was a major task and there is a lot of material used, probably too much to be error-free. I welcome all comments, pro and con, as well as suggested revisions. I hope that readers will actually enjoy reading most of this book.

This book is dedicated to the geoscientists who contributed to the knowledge and our understanding of the geology of southern Iran and the Persian Gulf.

Fereydoun Ghazban
August, 2007
Tehran University, Iran

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Mrs. Arengo of the University of Zurich sincerely provided assistance with locating some of the key references in the library of the Swiss Technical University, geology department. Staff of the library of the exploration division of the NIOC in Tehran was also of considerable help.

The quality of the book was significantly improved by the insights provided by comments from the reviewers. The main text benefited greatly from critical and constructive reviews and suggestions by Homayoun Motiei, Mohammad Reza Kamali, Mahmood Bargrizan and Reza Nouri. Mrs. S. Arya of the NIOC Research and development department also provided much needed encouragement and financial assistance throughout the work. The author thanks Ali Pourmand (Tulane University, Louisiana) for constructive editing of the manuscript.

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CHAPTER-1

INTRODUCTION

Persian Gulf is the location of phenomenal hydrocarbon reserves and is an area of the world where the oil industry is engaged in intense hydrocarbon exploration and production. Petroleum geology has been an integral part of this from the beginning of the Persian Gulf oil industry. Many talented geologists have worked in the region during this time; some have made important contributions to our present geoscientific understanding of the region through their publications.

Past decade has seen increased petroleum activity in the Persian Gulf. Through various initiatives in the economic as well as technological sphere, countries surrounding the Persian Gulf are trying to preserve their high levels of production and reserves. High reward and low risk are the key words in this region. One of the major areas of increased activity is the Persian Gulf.

A solid understanding of the petroleum geology forms the foundation of successful exploration and production investment programs. Considering the limits, there is a wealth of publications available on the petroleum geology and sedimentology of the Persian Gulf. The availability of hard data is, however, a major problem. The situation of the offshore Iran has improved recently with a few commercial data packages becoming publicly available.

This book on petroleum geology of the Persian Gulf is an attempt to provide a comprehensive, accessible and up-to-date review of the current status of geology in this region. It concentrates on the geology of the best known and most important part of the Persian Gulf. Among Iran's various contributions to the miscellany of the oil industry is the Iranian or Persian word for oil, "naft", the root of the familiar word "naphtha".

Sedimentary geology in the Persian Gulf region has been the subject of intense investigation during at least the past 50 years (for example Bramkamp and Powers 1955; Emery 1956; Mina et al., 1967; Uchupi et al., 1999; Swift and Ross, 2002). The first significant study of the sediments of the Persian Gulf was published by Emery in 1956. Evans (1966) also published a general description of the Persian Gulf, its oceanographic characteristics and generalized sedimentary facies.

The sedimentology of the Persian Gulf was first studied by Emery (1956) and Houbolt (1957) and was further extended in the 1960s through the benchmark work by Pursur and others. A better understanding sediment generation processes and the pattern of sediment accumulation was achieved with publication of The Persian Gulf (Purser, 1973). Recent works by Uchupi and coworkers (1999) and Swift and Ross, 2002 have resulted in the current state of the art sedimentology of the Persian Gulf basin.

In addition to comprehensive reports on the general geologic, structural and geomorphic, and sedimentological setting of the Persian Gulf, a particularly detailed account of the Holocene sediment types and their distribution in the Persian Gulf have been provided.

The Persian Gulf is cited in most key literature (e.g., Wilson, 1975; Wilson and Jordan, 1983) as an ideal example of a recent ramp. Reviews of carbonate facies models and their dynamic, including those of Read (1985) Scoffin (1987) and Burchette and Wright (1992) perpetuated the view that the floor of the Persian Gulf is a definitive modern example of a ramp.

The present Persian Gulf region was once on the edge of the Tethys Seaway, where tropical reef were abundant and later on through its geologic history, the region gained significant importance for hosting hydrocarbon occurrences. The Tethys Sea was a particularly anoxic ocean locally and as a result, facilitated the deposition of sediments with source rock potential. The closure of the Tethys produced numerous traps for hydrocarbon accumulation.

There are several reviews of the geology and stratigraphy of the Persian Gulf region, in particular those of Mina et al. (1967), Saint-Marc (1978), Murris (1980; 1981) Koop and Stoneley (1982), Motiei (1995) and most recently by Alavi (2004). The reasons for this prolific abundance of hydrocarbons lie in the fact that the region has repeatedly been the site of the extensive deposition of source rocks in the right juxtaposition with permeable and extensive reservoirs that are overlain by regionally effective seals. The source rocks have charged large traps formed at optimum hydrocarbon maturation and migration times.

Sediment facies, facies belts and stratigraphic models of carbonates have been described in detail in many publications. They are largely based on outcrop and core studies. A major problem is the use of a variety of, though often confusing, lithostratigraphic nomenclatures and a general lack of supporting biostratigraphic data. Some of the zonations and regional correlations cannot easily be verified and lateral facies variations are difficult to understand from a chronostratigraphic perspective.

Recent application and integration of conventional and innovative analysis and interpretation techniques have made it possible to identify important stratigraphic horizons in the Persian Gulf. These bounding surfaces, showing a distinct hierarchy, are considered to be the result of regional (latitude-related) climatic changes. These stratigraphic bounding surfaces are near-synchronous and allow time-related well-to-well correlations on regional and local scale, across facies belt boundaries.

The correlations show the large-scale cyclostratigraphic architecture of the carbonate platform and its climate-controlled depositional facies. It also enables to define intra-shelf basins, and to recognize onlap patterns and hiatuses. Cyclic depositional patterns and lateral lithofacies variations have also been recognized in some of the important carbonate reservoirs.

HISTORY OF THE PERSIAN GULF

The Persian Gulf is a unique geographical phenomenon whose role in human affairs began in remote antiquity and has continued to date. Traditionally, this role was due to the place it occupies as an avenue of cultures and trade; today, as the site of a resource vital not only for the inhabitants of the countries along its shores but for much of the modern world. The Persian Gulf's unique geostrategic position further enhances its present importance.

The earliest recorded civilizations appeared near its shores approximately five millennia ago, when the kingdoms of Elam and Sumer blossomed at the head of the Persian Gulf in today's southwestern Iran. There is evidence that they and their successors, the Assyrians and Babylonians, had relations with maritime principalities along the southern coast of the Persian Gulf, and that trade in precious commodities grew.

By the time the Roman Empire became the consumer of Oriental luxuries such as spices, gems and pearls, the Sinus Persicus functioned as one of the principal routes by which this commerce moved. The spices and gems came from India and the Orient; the pearls chiefly from the Persian Gulf. In fact, pearls were the famous luxury item exported from there ever since antiquity until they were replaced by oil in the first half of the 20th century.

The Persian Gulf has been a valuable waterway since the beginning of known human history and as the place of the collision of civilizations with a background of several millennia. Since centuries ago, the Ilamites used the Port of Boushehr and the Kharg Island in Iran for dwelling, shipping and ruling over the coasts of the Persian Gulf as well as transaction with the West Indies and the Nile Valley.

Even before the flow of Roman, a political transformation had occurred in the entire area. The last Mesopotamian kingdom of Babylon had been conquered by the Persians, whose earliest historical kingdom that of the Achaemenids spread its rule over much of the Middle East. They and the Seleucids, Parthians and Sasanians, created an empire that intermittently controlled the Persian Gulf. They sent expeditions and acquired coastal regions, a process that, in turn, stimulated mutual interest and movement of populations and occasional settlement. This Arabo-Persian maritime community asserted itself to an almost legendary degree after the foundation of the Abbasid Caliphate in the middle of the 8th Century A.D.

The Caliphs and their prosperous elites became consumers of Oriental luxuries. The Persians and the Arabs were the merchants and mariners who now brought a growing range of commodities from India and even China. The romantic story of this maritime trade fired the curiosity and imagination of the public, and the adventures of Sindbad the Sailor became the main part of the thousand and One Nights cycle. The texts of this tale, also known as "The Arabian Nights," are in Arabic, but of a kind that reveals the Arabo-Persian community from which they had sprung. Sindbad is a Persian name, as are

many basic terms adopted by Arabs, e.g., "nakhuda" for captain, "rahnama" for sailing direction, etc. Moreover, ongoing archaeological research suggests that the port of Siraf on the Persian coast was among the principal termini of the seagoing traffic during the 9th and 10th Centuries A.D.

The decline and fall of the Abbasid Caliphate reduced the prosperity and importance of this core in the Islamic Middle East and decreased the long-distance trade with the Orient. A revival, however, came with the rise of Europe as an avid consumer of Oriental luxuries, especially spices. Until the end of the middle Ages, the shippers and traders were the same Arabs and Persians, but a fierce contest for this lucrative traffic opened with the irruption of the Portuguese into the Indian Ocean and the Persian Gulf at the turn of the 16th century A.D.

The Portuguese seized several ports in the Persian Gulf, of which Hormoz was the most important. In addition, the Ottoman Empire made its entry into the arena with the conquest of Iraq and attempts to challenge the Portuguese in the Persian Gulf. Significantly, the Turks failed where the Persians succeeded a century later. By then, in 1622 A.D. the East India Company had sown the seeds of the British empire of India, and in subsequent centuries the Persian Gulf functioned as one of the two arteries of Britain's trade with its major colony. Britain found it necessary to control the Persian Gulf for this reason, and successfully strove to establish dominant position there during the 18th and 19th centuries. In the first decade of the 20th century Britain added a new dimension to her efforts: search for oil. This in turn brings the latest and most dramatic stage in the history of the Persian Gulf.

The Persian Gulf, while important as an international trade route, has its own distinct cultural identity. The Persian Gulf has historically been an integrated region characterized by constant interchange of people, commerce and religious movements. Before the modern era, peoples of the region shared a maritime culture based on pearling, fishing and long-distance trade, and many tribes moved freely. The Persian Gulf's seamen maintained close ties with the Indian subcontinent and East Africa. The society in the Arabian Peninsula was tribally organized and tribes were the key in forming modern states. Until the 20th century, tribes also played an important role in Persia and Ottoman Iraq.

The modern strategic importance of the Persian Gulf dates as far back as the mid-19th century, when the British, Tsarist Russia and Ottoman Turkey empires confronted each other there. The British established political control over much of the Persian Gulf in the early 1800s and kept it for 150 years, establishing a tradition of outside involvement.

After World War I, the political map of much of the Middle East was redrawn as the Ottoman Empire was replaced by modern states, including Turkey, Iraq and Saudi Arabia. The small Arab Sheikhdoms on the western shore of the Persian Gulf were under British protection until 1971 (in the case of Kuwait, 1961).

The present importance of the Persian Gulf stems from its massive energy deposits. Sixty-five percent of the world's known oil reserves are located in the Persian Gulf countries, which produce over a third of the world's daily output. (By comparison, North America holds 8.5 percent of the world's reserves.) Saudi Arabia ranks first in reserves, with 261 billion barrels, followed by Iraq (100 billion), the U.A.E. (98 billion), Kuwait (96.5 billion), and Iran (89 billion). The Persian Gulf is also rich in natural gas, with Iran and Qatar holding the world's second and third-largest reserves, respectively.

OIL DISCOVERY IN THE PERSIAN GULF REGION

All the countries surrounding the Persian Gulf, in varying degrees, are blessed with vast oil reserves lying along the coasts both on land and below the Persian Gulf sea bottom. It is this vital resource that has propelled the Persian Gulf into the limelight of world events and the story of its discovery, development and struggle over its exploitation makes for fascinating reading.

It all began almost more than a century ago, when in 1908 British prospectors struck oil at the Persian site of Masjid-e-Suleyman. Although oil was discovered in the southwestern Iran in 1908, it was not until the 1930s, when major discoveries were made, reviving international interest in the Persian Gulf region. The Persian Gulf oil fields, among the most productive in the world, have been extensively developed since World War II.

Although the Persian Gulf region is a relatively new oil-producing region, indigenous hydrocarbon in various forms, particularly as bitumen, have been used in the region throughout history. Among the notable early historical reports on the use of hydrocarbons are those in the Bible, which refers to the infamous Towers of Babel, been cemented by "Tar out of the rock"? Human workings for petroleum in Iran, in particular, date back to antiquity.

Well digging was highly important to the peoples of region and as a result Kanat water system was developed in Iran with some of the early Kanats are still in use. Herodotus states that wells or holes were dug in Iran 500-450 BC for the recovery of asphalt or"slime". Strabo, Discordies, Pliny and Plutarch all wrote about the use of oil in the first century A.D., suggesting digging of hole or wells for its production.

In the 13th century, Marco Polo while traveling across Asia Minor into China passed Baku which belonged to Persia and found the fire temples of the followers of Zoroaster, the Persian philosopher who founded the religion of the fire worshipers. These fires, above what are now the Baku oil fields, are supposed to have burned from ancient times until the development of the oil fields decreased the pressure on the reservoir and consequently shut off the flow of gas to the surface. Oil from this same area had been used by the Persian many centuries before the Russians acquired the area, and here were the "Eternal Fires of Surakhani".

Shortly after modern commercial oil possibility was understood in the middle of the 19th century, enterprising oil prospectors turned toward Iran, which was known as Persia at the time. This was due to the invention of the combustion engine, which promoted early exploration efforts around the oil and gas seeps in the Zagros Mountains of Iran. Liquid oil and solid and semi-solid bitumen have been obtained from southwestern Iran since antiquity. The first prospectors arrived as early as 1855 while the first oil exploitation concession was granted in Iran as long ago as 1872.

In 1884 a British commercial firm obtained a concession for oil exploration in Daleki, near Bushehr on the Persian Gulf. In the course of the following twenty years wells were dug in Deleki and Qeshm Island. The results were negative and it was not until the beginning of the 20th century that oil was struck.

William Knox D'Arcy with an interest in Persian archeology first learned of oil seeps at Chiah Surkh in Khuzestan. In 1903, D'Arcy created a company and, by Mid-1904 was drilling near the oil seeps at Chiah Surkh. Only non-commercial oil shows were found there.

It was, however, not until May the 26th, 1908 that the first major commercial oil accumulation was discovered at Masjed-e-Suleiman in the Zagros fold belt of Northern Persian Gulf in Iran located in Oligocene-Miocene Asmari carbonate reservoir. Nearly one hundred years later this super-giant oil field is still on production.

In the early days at Masjid-e-Sulayman, many people believed that the oil was being produced from the Gachsaran Formation rather than the underlying Asmari formation because most of the producing wells were shallow. However, geologic studies of cable tool cuttings and correlation with Asmari outcrops about 60 km from the filed proved that the Asmari carbonate was the prolific producing formation.

The oil was struck at 1,109 feet proving for the first time large commercial oil in Iran. This successful well flowed at more the 1000 barrels of oil per day. This discovery brought about the formation of the Anglo-Persian Oil Company in 1909 (later renamed the Angelo-Iranian Oil Company (AIOC) in 1935 and eventually British Petroleum).

Therefore, the first oilfield in modern times to be discovered in the now prolific oil-producing of the Persian Gulf was in the shadow of the Masjed-e-Suleiman fire temple; one of a dozen of such fire temples scattered around Iran. Thus, the first modern oil industries in the Persian Gulf region was built in an area of Iran where oil and gas has been utilized, in one or another application, for thousands of years. By 1911 the Anglo-Persian Oil Company (APOC), a British concern, was producing oil in Iran.

In 1914, the British government purchased the Anglo-Persian Oil Company to better safeguard a supply of oil for its navy. The British found oil in Iraq after World War I. The war and the quickened pace of consumption in

the industrial world, especially in the United States, led to further development of the petroleum sources.

World War II delayed development of whatever fields had been discovered in the 1930s. Until the early 1950s, the province of Khuzestan was the center of production, processing and exporting oil. After the war the world-wide search for new oil sources shifted into high gear and the industrial nations of Western Europe and the Far East began to replace war-damaged and obsolete plants and to plan new industry and the need for increased energy. By 1948, industrial expansion had gathered the momentum that would shortly revolutionize world energy consumption. Coal was still king, and the traditional basic fuel supplied 80% of total energy consumption. Oil, on the other hand, supplied only 10% or a daily volume of 830,000 barrels.

More and more industries were designed around energy systems that utilized oil. In 1949, the same year that offshore exploration in the Persian Gulf was started, the first slight change showed up in the pattern of fuel consumption. Coal dropped to 79% of total energy consumed in Western Europe and fuel oil increased to 12%, or 972,000 barrels a day.

By 1951, coal fell to 76%, and oil climbed to 14%, or 1,301,000 barrels a day. Techniques, some of which had been invented earlier, were rapidly developed to allow exploration to extend in bays, gulfs and territorial seas. As part of this "offshore" trend, oil companies turned their attention to the land that lay beneath the Persian Gulf.

During 1949, an exploration party initiated the pioneer seismograph program in northwestern Persian Gulf and in Saudi Arabian coastal and offshore waters. On August 15, 1951, the first offshore oil field discovered in Persian Gulf. Far beneath the floor of the Persian Gulf lied the Safaniya Field, one of the largest offshore oil reservoirs ever discovered.

The following years came with a windfall for the companies exploiting the oil fields on the southern side of the Persian Gulf and their prospectors discovered still more deposits. Safaniya oil field in the Persian Gulf started production on schedule in mid-April 1957. By the early 1970s, the region accounted for a large portion of world oil production.

Proved oil reserves in the Persian Gulf is estimated to total 685 billion barrels representing approximately 65% of oil reserves in the world (Oil and Gas Journal Data Book, 2002; BO Statistical Review of Energy, 2003). Daily production in 2002 for the Persian Gulf region stood at almost 21 million barrels, representing over 28% of global production. Saudi Arabia held the largest production capacity and produced 8.7 million bbl/day (mmstb/d) throughout 2002.

These unique and significant volumes of hydrocarbons in a single sedimentary basin in the world indicate that hydrocarbon generation occurred on an extraordinary scale and reflects the formation and rapid development of giant petroleum foci.

HISTORICAL PERSPECTIVE IN THE PERSIAN GULF

Geologists have rightly suspected that hydrocarbon accumulations might exist in many parts of the Persian Gulf region. During the 1920s and 1930s, AIOC and the Iraq Petroleum Company (IPC), a consortium, which had interests covering Iraq, the Near East and most of the coastal states of the Arabian Peninsula, were active in oil exploration and production over much of the Middle East.

The Turkish and later Iraq Petroleum Company did not discover commercial oil until 1927 in the northwest prolongation of the Zagros fold belt. In the 1930s exploration moved from the mountains of the Zagros to the Arabian plains and a number of discoveries were made on the southern side of the Persian Gulf from Iraq all the way to Oman. Thus, a flurry of oil exploration activity occurred in the Persian Gulf in these years and oil was discovered outside the Tertiary Zagros belt.

In 1932 Standard Oil Company of California (SOCAL) discovered a super-giant oil field in Awali of Bahrain in Cretaceous sandstones and subordinate carbonate reservoirs. SOCAL then obtained a concession in Saudi Arabia in 1933 and discovered oil in commercial quantities in 1938. The discovery of very large oil fields in Kuwait (1937) and Saudi Arabia (1938) set the stage for substantial production enhancement as the world demand for oil grew during the following years.

Resumption of exploration after II World War resulted in the discovery of additional super giant oil fields such as Ghawar, the largest oil field yet discovered on the earth in 1948. Other discoveries include Dukhan in Qatar in 1950, Rumaila in Iraq in 1952, and Bab in Abu Dhabi in 1958. It was, therefore, not until the 1950s that countries that still technically depended on Britain for their security began to earn large incomes.

The oil fields in Kuwait were developed the fastest, and by 1953 Kuwait had become the largest oil producer in the Persian Gulf. Considerably smaller fields in Qatar came on-stream in commercial quantities in the 1950s and Abu Dhabi began to export offshore oil in 1962.

OFFSHORE OIL DISCOVERY IN THE PERSIAN GULF

The search for hydrocarbon and exploration activities in the Persian Gulf dates back to 1950s. In 1957, National Iranian Oil Company signed an agreement for oil exploration covering the Iranian continental shelf of the Persian Gulf with an Italian company (AGIP) and Pan American Oil Company and two companies SIRIP and IPAC were established.

The first oil well on the Iranian continental shelf of the Persian Gulf was drilled by SIRIP at Bahregansar in 1961; IPAC struck oil on the Iranian continental shelf, discovering the Dorood (formerly Darius) oilfield. However, the first commercial hydrocarbon discovery was made in southern Persian Gulf,

i.e., Abu Dhabi (Bab field) in 1959 and since then a series of discoveries has been made. The main production units are from Asmari and Sarvak Formations. Gas and oil are present in the Ahwaz Sand Member, and Ghar sandstone reservoir at the top of the Asmari and gas is also present in Jahrum limestone. Other fields discovered later include Nowrooz, Doroud (1962) and Hendijan (1968).

According to stratigraphic, structural, reservoir, source and cap rock characteristics, the continental offshore of Iran in the Persian Gulf has been divided into five different zones (e.g., Najabadi, 1987; Javadian, 1996 and many others, see Figure-1) described as follows:

The first zone is located in northwestern Persian Gulf and concerning the hydrocarbon resources, is the richest part. The reservoirs are mostly clastics in nature including Ahwaz Sand Member of the Asmari Formation, Azadegan sandstone of Kazhdumi and Zubair. Carbonate reservoirs are also producing oil including Dariyan and Fahliyan. In most of the oil fields such as Nowrooz and Doroud the anticline structures have north-south trend matching the structures in the Saudi Arabian part of the region. Some other anticlines have different structural trends (i.e., Abouzar and Soroosh).

In the second zone, the structures are different from those discovered in the Saudi Arabia and Zagros regions. The reservoirs in this zone consist mainly of carbonates. They have been subjected to old tectonic activity and movements and most of the structures have continued their activities from Jurassic up to the end of Mesozoic era. Their movements have been postulated to be related to the Hormoz salt. The constant movements of the anticlines have been accompanied by decrease in thickness of the sediments forming the anticline structures and weakening of the cap rock causing the hydrocarbon migration to the sea floor. Oil traces on the samples taken from the Farsi oilfield in the Persian Gulf is the prime evidence for such phenomena and secondary oil migration.

The third zone is located on the north and northeast of the Qatar Arch and contains one of the largest gas fields in the world.

The fourth zone is located between the Qatar-Gavbandi Arch and the Strait of Hormoz at the eastern end of the Persian Gulf. This zone is very different from the western areas and the sedimentary strata attain their highest thickness in this zone. This is due to the higher depth compared to the rest of the Persian Gulf. Extensive distribution of the evaporites, formed from Oligocene until Early Miocene, is one of the main sedimentological characteristics of this zone. Carbonate platform rocks such as Sarvak, Dariyan, Fahliyan and upper part of the Surmeh Formation (equivalent of the Arab Formation) form the most important reservoir rocks in this zone.

The last and the fifth zone include the Strait of the Hormoz area. This zone is highly influenced and affected by the Zagros structure in the north and Oman Mountains in the south. The Sarvak and Dariyan Formations in this zone contain hydrocarbon reserves.

HYDROCARBON IN THE PERSIAN GULF

There are many factors which make the Persian Gulf region one of the richest locations of the world in terms of hydrocarbon accumulations. Some of the most important factors responsible for such richness in hydrocarbons in the Persian Gulf and surrounding areas have been discussed by many researchers in the past quarter of a century (e.g., Dunnington, 1974; Grunau, 1977; Murris, 1980; Beydoun, 1988). These factors include the presence of repeated and extensive source rock beds, excellent carbonate and some sandstone reservoirs in good juxtaposition, excellent regional seals, huge anticlinal traps and uninterrupted sedimentation. However, the critical factor is the areal extent of the northeastern margin of the shelf.

Of the prime importance is the availability of large areas of high-quality source rocks preserved throughout the geological history of the region, especially during the Mesozoic era. At this time, the Persian Gulf region as a part of the Arabian Plate was situated in warm latitudes with high organic productivity.

Arabian shelf margins in general and its northeastern margin including the Persian Gulf had a long and almost continuous and uninterrupted history of sedimentation since the close of the Proterozoic (Late Precambrian) some 570 Ma ago.

The development of juxtaposed source and reservoir facies belts facilitated hydrocarbon expulsion and migration over long distance. Tectonic fracturing of the younger sedimentary units and stratigraphically higher carbonates reservoirs during the overprinting of the Zagros foreland basin in the Neogene permitted vertical migration into large anticlines under efficient evaporitic seals.

It is highly important to mention that Murris (1980) identified the most outstanding factor which contributed to the ground preparation for formation of petroleum systems that was the extraordinarily extensive horizontal scale of the northeastern Arabian margin shelf and especially its width, reaching some 2000 kilometers.

EXPLORATION POTENTIAL

The Persian Gulf region contains major reserves of the world and its share is certain to increase in the future. Despite the large numbers, the Persian Gulf area is likely to yield significant additional reserves and further petroleum discoveries, as witnessed by the 1999 Iranian announcement of the Azadegan and Tabnak discoveries, of some 25 billion barrels and 16 trillion cubic feet in-place, respectively. Thus, the knowledge of the petroleum systems and subsurface architecture of the Arabian plate and Persian Gulf is of paramount importance to the future of not only Iran and the neighboring counties but also the world oil industry.

Early exploration began at the site of surface seeps and expanded to mapped prominent surface anticline folds. Surface exploration continued until the 1930's when the seismic data aided in subsurface interpretations. Even with seismic data, the true configuration of some structures had to be revealed by drilling. Modern seismic data acquisition and processing and structural interpretation models will undoubtedly improve future exploration efforts in both offshore and onshore in the Persian Gulf region.

Despite decades of exploration, the potential for new discoveries is still considered to be great. Many surface structures have yet to be explored or are under exploration. This effort includes investigation of major impressive structures tens of kilometers long. In some cases, those structures were drilled in the early days without seismic data or adequate mud-logging equipments to detect hydrocarbons. Known surface structures need to be considered in the exploration prospects.

To evaluate the onshore and offshore exploration prospects, the industry has some useful newer technology available, including 3-D seismic, satellite imagery, software application, and horizontal and multilateral completions, workover rigs, and logging tools. Satellite imagery provides excellent interpretation of surface structures and tectonics, with good resolution. This imagery can also detect previously unknown surface seeps.

Offshore seeps of oil and gas can be detected with satellite radar, ultraviolet imagery, and airborne laser fluorosensor surveys. Special processing of satellite imagery onshore can show hydrocarbon indicators caused by shifts in redox conditions, associated secondary mineralization and spectral brightness of surface geology. Landsat multispectral scanner (MSS), thematic mapper (TM), infrared bands and SPOT imagery can show surface anomalies caused by subsurface hydrocarbon accumulations. These changes are known to be caused by ascending microseeps of oil and gas.

New offshore techniques can also assist in exploration in the Persian Gulf. Surface-imagery analysis of the Persian Gulf water surface can be processed to reveal oil and, in some cases gas seeps that may lead to identification of prospective plays. Satellite radar altimetry and gravity data can be processed to reveal water surface topographic highs and lows associated with sea floor topographic features that may also aid enhanced exploration.

Several such anomalies appear to be structural features offshore, including intrusive salt bodies that may be prospective for gas. Some offshore prospective trends can be projected from onshore productive structural trend with seismic data and may lead to development of viable prospects.

As an example of the remaining exploration potential in the Zagros fold belt, in September 1999, the national Iranian Oil Company (NIOC) announced discovery of a giant field Azadegan, with 26-billion bbl oil in place (5-6 billion bbl recoverable), west of Ahwaz. Another recent success has been achieved offshore in the Persian Gulf, where NIOC has had 20 large gas discoveries in the south Pars region. The South Pars gas field alone has proven

reserves of about 280 tcf. In addition, Sirri C and D oil fields offshore near Abu Dhabi have total reserves of 1.2 billion bbl oil in place.

THE PERSIAN GULF FOREVER

The historical name of the Persian Gulf is a familiar name for all the countries in the world. For thousands of years, the people of ancient Persia and their descendants in modern Iran and settlers in the region have called it the Persian Gulf. Historical facts are known and self-evident and require no proof. Throughout the years, a few of Iran's neighbors have claimed many of Iran's men and women of sciences and letters as their own. Sadly enough, now there is yet a new vain attempt to re-name the body of water that has been universally known as the "Persian Gulf' for several millennia to the "Arabian Gulf'.

There are those who are unaware of the historical truths and unintentionally contribute to this psychological warfare against the Iranian people with their lack on interest in studying the history of the region. Although using the "Arabian Gulf" instead of the "Persian Gulf" has no historical basis and will ultimately be rejected in any culture or language, as Persians and the oldest inhabitants of this region, it is still our responsibility to clearly point out the historical facts and eliminate any ambiguities in this respect.

In Latin geography books the Persian Gulf has been referred to as More Persicum or the Sea of Pars. The Latin term "Sinus Persicus" is equivalent to "Persicher golf" in French, "Persico qof" in Italian, "Persidskizalir" in Russian and "Perusha Wan" that all mean "Pars".

Prior to the stationing of the Aryan Iranians on Iran's Plateau, the Assyrians named the sea in their inscriptions as the "bitter sea" and this is by far the oldest known name that was used for the Persian Gulf. An inscription of Darius found in the Suez Canal, used a phrase with a mention of river Pars, which points to the Persian Gulf.

The great Greek historian Herodotus in his book, History of Herodotus (485-425 BCE), has repeatedly referred to the Red Sea as the "Arab Gulf". Straben, the Greek historian of the second half of the first century BC and the first half of the first century AD wrote: “Arabs are living between the Arabian Gulf and the Persian Gulf’.

The ancient Greek geographers and historians called this body of water "Sinus Persicus". It is interesting that prior to the time of Jesus Christ until as late as the 17th century, the world’s greatest historians and cartographers from Strabon and Ptolemy to famous Flemish geographer, Mercator, along with Arab historians referred to the Gulf south of Iran as either "Sinus Persicus" or " Mare Persicum" and clearly distinguished it from "Arabicus Sinus", the name they used to refer to what is known as the Red Sea today.

Ptolemy, another renowned Greek geographer of the 2nd century has referred to the Red Sea as the "Arabicus Sinus", i.e. the Arabian Gulf. In the

book "the world boundaries from the East to the West", written in the 4th century Hegira, the Red Sea was also referred to as the Arabian Gulf.

There are undeniable legal evidences and documents in confirmation of the genuineness of the term Persian Gulf. From 1507 to 1560 in all the agreements that Portuguese, Spanish, British, Dutch, French and Germans concluded with the Iranian government or in any other political event elsewhere in the region, there is a mention of the name "Persian Gulf", rather than any other alternative name.

For the last two millennia the term "Persian Gulf' has been used universally by historians, geographers, scholars, strategists and politicians. Also Arab historians and geographers from Ibn al-Mujawir to Yusuf Kamal, the author of "Monumenta Cartographica", used "AlKhalij al-Fars", or the Persian Gulf. The late president Sadat of Egypt, in his book, "Revolt on the Nile", correctly identified the "Persian Gulf" by its historical and original name. Even the British cartographers adopted the name Persian Gulf at the turn of the last century when the Anglo-Persian Oil Company was formed to tap Iranian oil.

Anyone who has troubled himself to look at antique maps some of which are presented at the end of this chapter, contemporary writings and research documents, historical accounts of the region and encyclopedias written either by western or eastern observers and scholars will conclude that there is but one single name recognized for the Persian Gulf.

Experts agree that the name Persian Gulf, or Khalij-e Pars, predates Arabian Gulf by a long shot. "The earliest references stemmed from the time of the Sumerian rulers in the third century B.C. That ought to be old enough to establish it," says James Bill, an Iranian specialist at the College of William and Mary. Even in agreements with the participation of Arabs there is a mention of "Al-Khalij al-Farsi" in the Arabic texts and "Persian Gulf" in English texts, such as the document for the independence of Kuwait signed between the Amir of Kuwait and the British government in the Persian Gulf.

Professor Ernie Haernick from Belgium who is a world-renowned expert on Iranian archaeology believes the name Persian Gulf has been known since 2,000 years ago from the time of the Roman Empire. Also, Professor Ahmed Hasan Dani from Pakistan confirms that the Persian Gulf region in ancient times included the "eastern part of the Hormuz Strait extending to the western and northeastern parts of the Indian sub-continent."

Since the beginning of the 20th century, the name "Persian Gulf" has been used in geography and history books with less reference to the "Fars Sea". Such a change has suggested the idea that the "Fars Sea" had been an old name substituted by a new term "Persian Gulf".

It is the practice of the White House, the State Department, the U.S. government agencies and also the United Nations Secretariat, and National Geographic Society, to use in the document and maps the term "Persian Gulf" to indicate the body of water between Iran to the north and east and a number of other states to the south and west. It is a long established usage that is fol-

lowed by publishers of world atlases and geographical dictionaries. It has been established that the "Arabian Gulf' was the ancient name of the Red Sea, actually a gulf prior to being connected with the Mediterranean via the opening of the Suez Canal.

The beginning of 1930s was a turning point in the history of efforts for changing the name of Persian Gulf when Sir Charles Bellgrave, the British diplomatic envoy in Bahrain opened a file for the change in the name of the Persian Gulf and proposed the issue to the British Foreign Office. Even before the response of the British Foreign Office he used the fake name.

Some of the states of the Persian Gulf region, have during the past few years tried to gain an identity and expand their cultural and political domain by altering the names of the areas belonging to other countries. Changing the historic name of Persian Gulf into Arab Gulf is one of their selected maneuvers used in the region's petroleum related studies.

Today, the most common Arabic works refer to the sea in south Iran as the "Persian Gulf", including the world famous Arabic encyclopedia `Al-Monjad', which is the most reliable source in this respect.

Besides all the disputes that have been made over the name of the Persian Gulf, the United Nations has on two occasions officially declared the unalterable name of the sea between Iran and the Arabian Peninsula as the Persian Gulf. The first announcement was made through the document UNAD, 311/Qen on March 5, 1971 and the second was UNLA 45.8.2 (C) on August 10, 1984. Moreover, the annual U.N. conference for coordination on the geographical names has emphatically repeated the name "Persian Gulf" each year.

Considering all this, it seems improper that some news and official circles favor prejudice to wisdom and use a false name for the Persian Gulf. The Persian Gulf was called by this name even before the advent of Islam. If there was any need to change the real and historical name of the Persian Gulf, the Prophet Mohammad would definitely have changed it. Even the prophet Mohammad spoke of the Persian Gulf.

In issue No. 6, Vol. 13, of Nasher-e-Danesh journal there was a praiseworthy article by Dr Majid Zadeh called "The Name of Persian Gulf and Foreign Archeology." The efforts of this researcher should undoubtedly be complimented and praised. The article is addressed to all those involved in scientific and research activities. The article covers two main issues: first, the increasing inclination of foreign scientists to cooperate with some Arab States in changing the name of the Persian Gulf; and secondly the weakness of the Iranian archaeologists to confront this rising trend. It should unfortunately be added that the battle for changing the name has started to spread into some areas of science and technology. One of the important of such sciences is geology, especially in its subdivisions such as sedimentology, geomorphology, petroleum geology, marine geology and environmental geology.

The states in the Persian Gulf region in fact build the heart of the Middle East. During the past two centuries, foreign geoscientists and researchers have become highly interested in this area as one the most attractive regions of the world because of its vast petroleum resources.

Some researchers in the field of geology are publishing their articles where the name "Arab Gulf" or "The Gulf" or the "Persian-Arab Gulf" is constantly repeated. Some politicians whom, by hiding under the cover of science and technology, are trying to inject the "Arab Gulf" virus into the writers who will use the name in their research articles.

Throughout history, educators, historians, travelers and geographers have always referred to this region as the "Persian Gulf" not only because of the vast coastal lines of various Persian Empire or the number of its Persian/Iranian inhabitants, but simply, and in their own words, to recognize the noble notion that, "The Persians were the first to have developed and greatly improved this part of the earth". Although it is not surprising that certain prejudiced or misinformed individuals would change the authentic and historical name of the Persian Gulf, it is not expected from intellectuals who should be clarifying public opinion with historical truths to fall for such mischief. Thus, it is our responsibility in expressing the reality and by contemporary writings and performing research documents, clarifying and emphasizing that there is but one single name that is applicable to the Persian Gulf.

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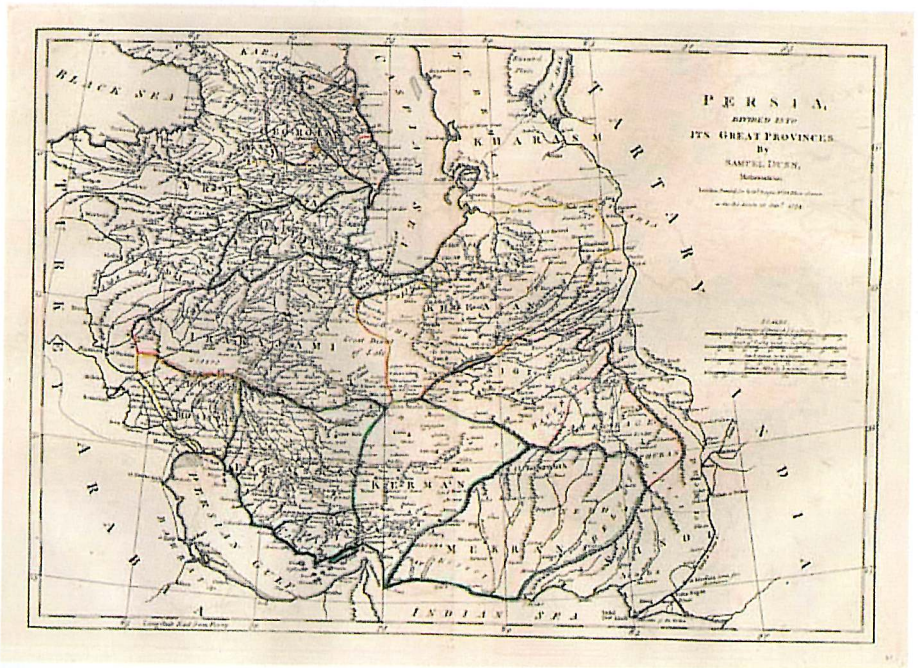
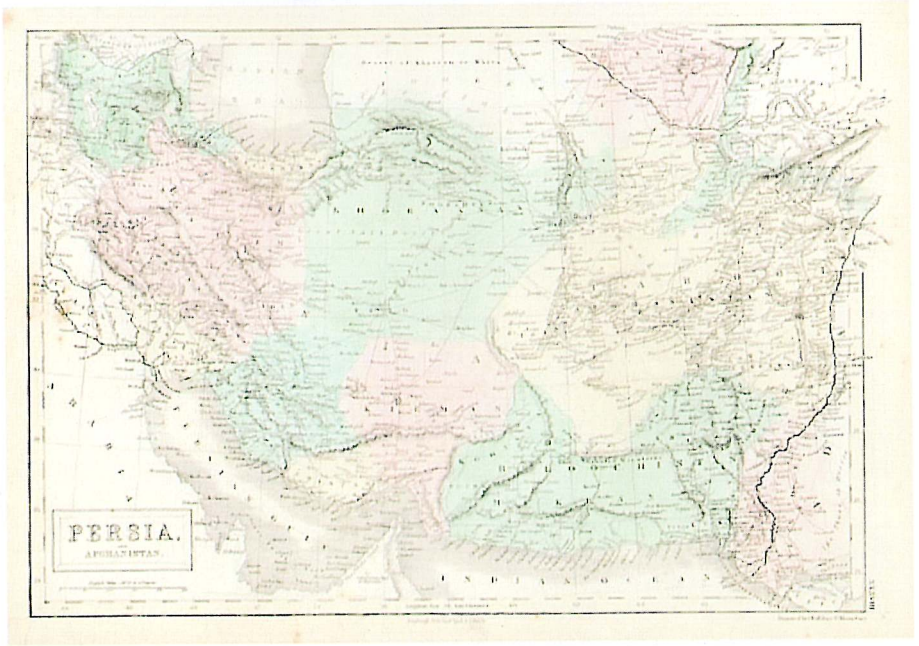
Some of the old Persian Gulf maps from different periods

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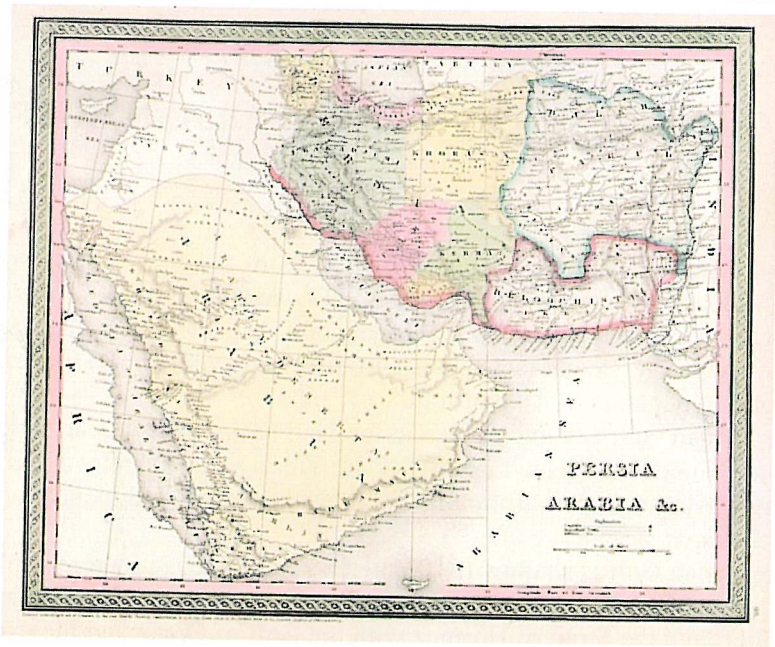
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Strait of Hormuz, but the average depth is only 35 meters. The Persian Gulf is separated from the Gulf of Oman by the Strait of Hormuz, which is only 56 kilometers wide at its narrowest point. There is no sill in the Strait of Hormuz; the trough simply deepens more than 100 meters through the Strait and drops quickly more than 2000 meters within 200 kilometers far from the Strait. The maximum width of The Persian Gulf is 338 km, and the length to its northern coast is nominally 1000 kilometers. The surface area of the Persian Gulf is approximately 2.4 $x10^5 km^2$, and the mean depth of 36 m implies an average volume of 8.7 x 10^3 km^3. Its shallow depth has made the Persian Gulf extremely susceptible to the effect of sea level changes. The turnover and residence time is estimated to be around 2.5 years (Brewer and Dyrssen, 1985).

The bathymetry of the Persian Gulf (Figure 2-1) shallows to the northwest and to the west coasts. An isolated trough extends northward from the Strait of Hormuz along the Iranian coast approximately 100 kilometers. This trough collects denser bottom water and impedes the existing bottom flow. The possibility exists that a weak bottom circulation into these depressions could lead to a build-up of pollutant. Fine-grained muds are found in this area, which supports the theory (Hunter, 1983; Reynolds, 1993).

The longitudinal axis of the Persian Gulf is a southeasterly extension of the Tigris-Euphrates valley, the whole being a Zagros feature of Plio-Pleistocene age (Kassler, 1973). The deepest water is found near the Iranian shore and it is separated into an eastern and western area connected by a shoal region about 110 kilometers inside the Strait of Hormuz. Where the deeper water is separated from the Iranian coast by a narrow shoal area, a broad area, less than 20 fanthoms in depth, occupies the southwestern side of the Persian Gulf, being best developed in the south and narrowing toward the head of the Persian Gulf.

BATHYMETRIC FORM OF THE PERSIAN GULF

The basin is characterized by a marked asymmetry across its axis; its floor on the tectonically unstable Iranian side of the basin is relatively steep (175 cm/km), while that on the more stable Arabian side slopes gently (35 cm/km) towards the bathymetric axis. The axis is thus situated relatively close to the Iranian coast, especially in the eastern half of the basin, its position and orientation being determined by underlying Iranian tectonic trends. Tilting of the Arabian Peninsula during the opening of the Red Sea in the Neogene has accentuated the asymmetry of the Persian Gulf.

The Persian Gulf has been subdivided into a series of bathymetric provinces by Seibold and Vollbrecht (1969), illustrated in Figure 2.1. A clearly defined ridge, the "Central Swell", either related to the underlying Iranian fold system, or possibly of sedimentary origin, subdivides the Iranian half of the basin into two secondary depressions, the "Western basin" and the "Central

Basin". The Arabian side of the Persian Gulf has been termed the "Arabian Shallow shelf" by Seibold and Volbrecht (1969).

Tectonic-driven subsidence in the Persian Gulf has locally deepened the seafloor in the Strait of Hormuz to 200-300 meters and produced a 70-95 meters deep trough along the Iranian side of the southern half of the Persian Gulf (see Figure-2-1). The Strait of Hormuz and the basin trough are separated by a broad sill at about 86 m near 55°30'E in the western approaches to the Strait. A southward widening channel leads from the Strait south across a series of sills (water depth of ~110 m) and shallow basins to the shelf edge (Seibold and Ulrich, 1970). Although water is deeper in the channel than in the Persian Gulf, the narrow Strait of Hormuz restricts water exchange and isolates the Persian Gulf from well-mixed water masses of the Oman Sea.

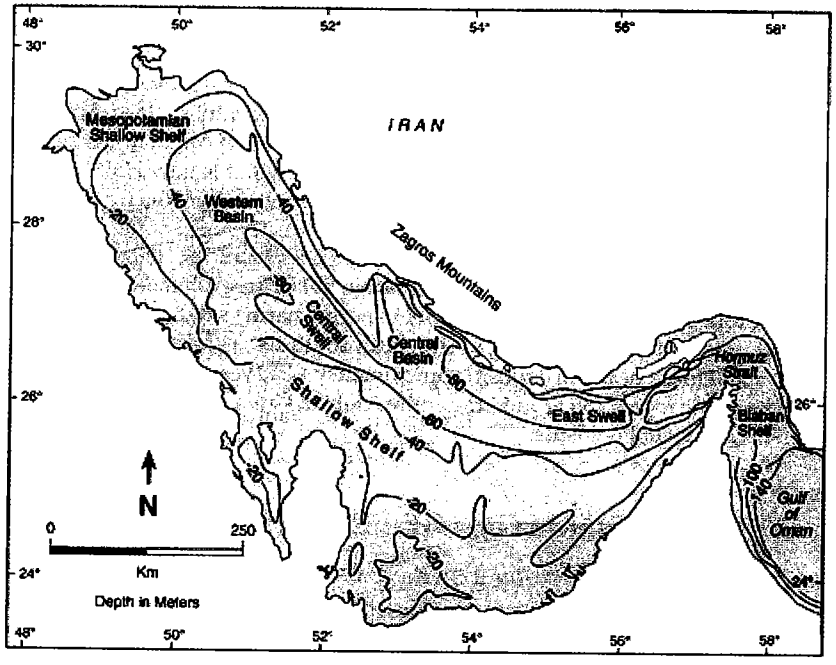

Figure 2-1 Principal bathymetry of the Persian Gulf (Modified from Kassler, 1973).

The broad region of shallow water off the southern coasts of the Persian Gulf features many small islands and lagoons where it is extremely difficult to operate oceanographic vessels. This area is a region of intense evaporation, and a significant contribution to the deep circulation of the Persian Gulf is made here.

Except for the irregular topography atop diapiric structures the terrains are or were the creation of external processes, i.e., wave action and/or tidal or non-tidal currents. Nevertheless all the microtopography is believed to be the result of a combination of internal and external processes (Uchupi et al.,

1996). High resolution echo sounding profiles recorded in the Persian Gulf indicated that the most unique topographic feature are near circular depressions with reliefs of several meters. They occur throughout the Persian Gulf and are superimposed on the late Holocene south-east trending sediment lobes off Iran. Uchupi et al. (1996) inferred that these features are predominantly pockmarks formed by seepages of thermogenic gas.

PERSIAN GULF AND THE STRAIT OF HORMUZ

The basic features of the Persian Gulf can be divided into a northern and southern or eastern regime. The northern regime is dominated by wind forcing to the south along the axis of the Persian Gulf and the riverine input at the Persian Gulf's head. The wind-driven response of the Persian Gulf appears to be the typical adjustment of the pressure field producing a down-wind flow, i.e., there is down welling on the western coast and upwelling on the coast of Iran (figure 2-2), and evidence for a southeastward flowing coastal current along both northern and southern coasts (Reynolds, 1993). The flow along the southern coasts of the Persian Gulf is augmented by the freshwater input from the north which forms a riverine plume.

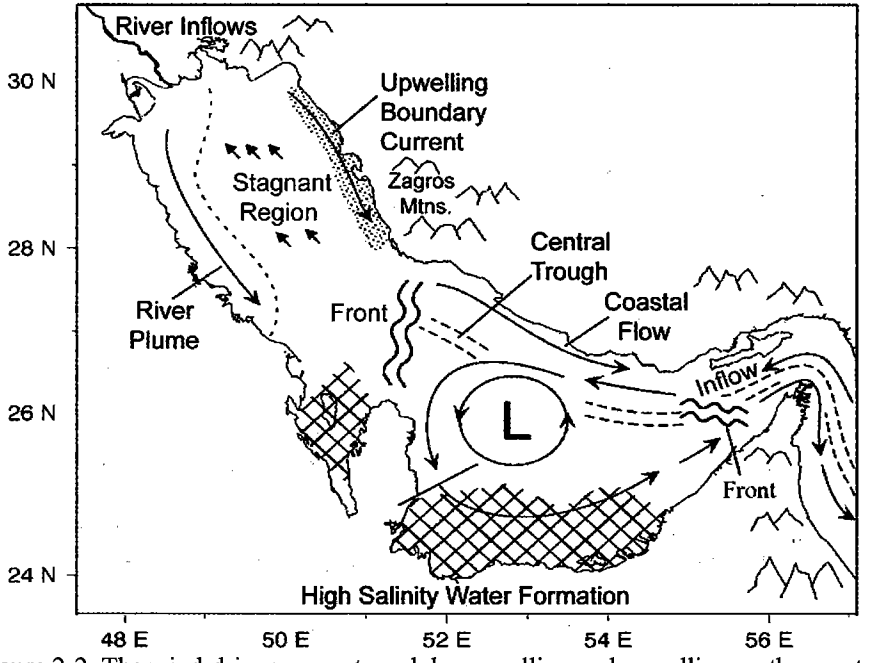

Figure 2-2. The wind-driven currents and down welling and upwelling on the coast of Iran and different fronts and high salinity regions in the Persian Gulf (Reynolds, 1993).

The river inflows are approximately split between the flow out of the Tigris and Euphrates Rivers and Hendijan, Hilleh, and Mand Rivers flowing out of the highland of Iran. It is not clear what kind of changes this decline of freshwater input has made. According to Figure 2-2 the central part of the northern Persian Gulf appears to be fairly stagnant (Reynolds, 1993). The southern end of this regime corresponds roughly to the longitude of Qatar and Bahrain.

The flow along the Iranian coast seems to continue into the southeastern basin as a tightly trapped coastal current extending perhaps as far as the Strait of Hormuz. This flow becomes very complex in proximity to the Island of Jazareh in the northern portion of the Strait.

The northern Persian Gulf is separated from the southern regime by a front that typically is found off Qatar (see Figure 2-2). This front is most intense in summer and weakest, at least in sea surface temperature, in late winter and spring. The available data suggests that much of this inflow may terminate in a counter-clockwise, cyclonic flow to the east of the mid- Persian Gulf front. This cyclone appears in circulation climatology and appears as a coherent Sea Surface Temperature (SST) anomaly in satellite imagery. At the eastern part of this front the available data suggest a flow out of the Persian Gulf around the tip of the Musandem peninsula and into the northern Gulf of Oman.

Due to its shallow nature the Persian Gulf appears to be influenced by both wind driven and thermohaline forces. The persistent southward wind stress, at least in the northern half of the Persian Gulf, appears to set up coastal current regimes along both Saudi (downwelling) and Iranian (upwelling) coasts. A persistent thermal front across the Persian Gulf about the latitude of Qatar appears to be related to the thermohaline exchange through the Strait of Hormuz.

CLIMATE

The Persian Gulf is arid by any definition, and, being largely landlocked, it is subjected to a continental climate with marked seasonality. Regional winds are westerly at the head of the Persian Gulf, swinging to north-northwest in the southeastern Persian Gulf. Gales but not hurricanes are experienced in the Persian Gulf region and as a result storm deposits are poorly developed.

In the north, the local climate is influenced by orography. The Taurus and Pontic Mountains of Turkey, the Zagros Mountains of Iran, and the Hejaz Mountains of the southern region of the Persian Gulf all together with the Tigris-Euphrates Valley, from a northwest-southeast axis that strongly influences the tracks of extra-tropical storms to the southeast direction.

The climate in the Persian Gulf is markedly different from the Oman Gulf. While the Persian Gulf is mainly affected by the extra-tropical weather systems from the northwest, the Gulf of Oman is at the northern edge of the tropical weather systems in the Arabian Sea and Indian Ocean. The monsoon

circulation produces southerly winds at summer and strong northerlies at winter. The Strait of Hormuz approximates a boundary between the two systems.

The constancy of the regional wind and wave direction is responsible for the formation of extensive sand bodies at the southeast of islands and shoals throughout much of the Persian Gulf (Pursur, 1973). Orientation of lagoon barriers and many other sedimentary features along the southern Persian Gulf shore are related to the wave approach direction (Pursur, 1973). Sand dunes orientation, source areas for sand, and sand movement directions are also controlled by the regional wind direction.

Temperatures are high, but winters are quite cool particularly at the head of the Persian Gulf. Air temperature reaches 45 to 50°C in summer and fall to 10°C or even lower in winter; sea water temperatures are less extreme, 20 to 32°C in the open waters, but in near shore areas ranging from 15°C or even less to values in excess of 35°C. The low winter temperatures are probably ecologically limiting reef corals in many places.

The rainfall is very slight and infrequent and also slightly higher in the northeast. It falls mainly as a few brief downpours from November to April. The relative humidity is high. Cloud cover is small but greater in winter than summer. The occasional flash floods may also transport vast amount of unstablized surface materials. Relative humidity in the Persian Gulf and along the shoreline areas is generally rather high (>60%) but may fall inland to very low values. Night time dew is often heavy and is the main source of water for many desert plants. Thunderstorms and fogs are rare in the region. Dust storms and haze occur frequently during summers.

WINDS

The Persian Gulf is situated between latitudes 24-30°N in which most of the Earth's deserts located. This region marks the boundary between tropical circulations (Hadley Cell) and the synoptic weather systems of mid-latitude. Descending dry air in these latitudes produces clear skies and arid conditions.

The most well-known, common and notorious, weather phenomenon in the Persian Gulf is the Shamal wind, a northwesterly wind (Figure 2-3) (Perrone, 1979). The "Shamal" winds flow from Iraq and Kuwait down the axis of the Persian Gulf to the Arabian Sea. These winds are strongest from late May to early July and are a result of the semi-permanent high pressure zone over Saudi Arabia and the same continental low pressure centre that initiates the SW summer monsoon winds (Membery, 1983). The topography of Saudi Arabia with higher elevations to the west, and a wind trough formed by the Zagros Mountains in southern Iran accentuate the Shamal wind (Membery, 1983) that commonly reach wind speeds of 15-20 m/s (30-40 knots) between surface and 300 meters (Sirocko et al., 1989). Today the Shamal winds veer to the south before reaching the sea and flow parallel to the Arabian coastline

where they merge with northwesterly winds that flow though the Red Sea region (Glennie et al., 2002).

The Shamal wind seldom reaches strength of Beaufort force 6 and rarely Beaufort force 8. Squalls with waterspouts are common particularly in autumn. The wind has been recorded to attain speeds of 95 mph in five minutes. The winter Shamal is a wind that sets in with great abruptness and force, and is related to synoptic weather system to the northwest. It seldom exceeds 10 m/s (<5% frequency) but lasts several days. The summer shamal is practically continuous from early June through July. It is associated with the relative strengths of the Indian and Arabian thermal lows.

The extension of these dry winds raises above the SW monsoon winds and transports large amounts of sediment from the semi-arid regions of the Arabian Peninsula to the Oman Sea. Though dust storms on the Arabian Peninsula begin in the spring, satellite imagery indicates that this dust is spread to the Oman Sea during the summer monsoon season (Sirocko et al., 1989). Between June and August, 1979, about 105 x 10^6 metric tons of sediment was transported as dust by the Shamal winds (Sirocko et al., 1989).

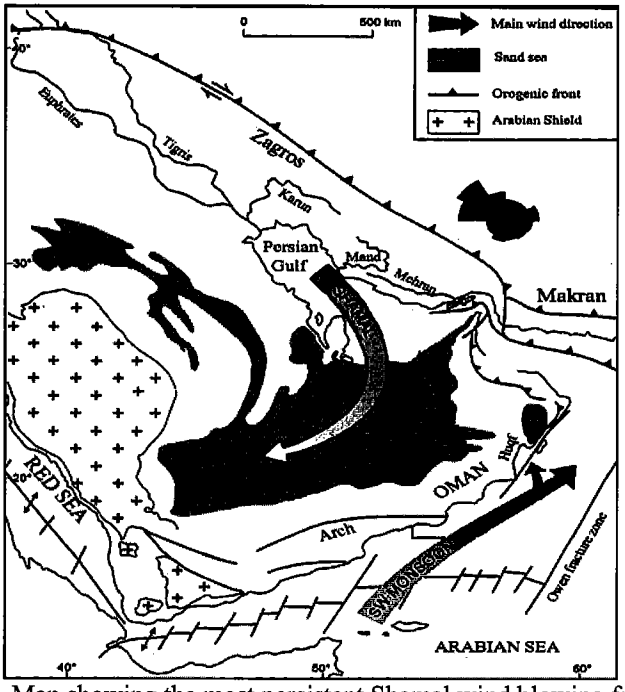

Figure 2-3. Map showing the most persistent Shamal wind blowing from north-northwest and west-northwest and the location of the desert affected (Teller et al, 2003).

While a relatively rare event, occurring only once or twice each winter, the Shamal brings some of the strongest winds and highest sea level of the season

to the Persian Gulf. Before the onset of the winter Shamal, winds in the area ahead of an approaching cold front blow from the southeast. These winds called "Kaus" in Arabic or shakki in Farsi, and slowly increase in intensity as the front approaches. They may reach gale force before the passage of the front and the onset of the Shamal.

Due to the channeling of the low-level airflow by the Zagros Mountains of southwestern Iran, the strongest of the southerly winds occur on the eastern seaboard. The Shamal usually occurs firstly at the northwest and then spreads to the south.

A strong sea breeze occurs along the entire coastline, especially along the southern coasts of the Persian Gulf. Driven by the intense temperature difference between the land and water surfaces, the "sea breeze" circulation adds a landward component to all winds. The effect of these winds is to drive surface pollutants (oil and others) to the beach much faster than they would move otherwise. Examples of on or offshore winds as high as 15m/s are evident in coastal meteorological stations.

EVAPORATION

The arid climate in the Persian Gulf region results in excess evaporation over precipitation plus river run-off. Estimation of evaporation varies from 144 to 500 cm/yr (Privett, 1959). The lower figure from Privett (1959) is in agreement with Meshal and Hassan (1986) who estimated 200 cm/yr, and his latter term is probably closer to the actual amount.

Measurements indicate that even though the water temperature is significantly higher in the summer, most of the evaporation occurs in the winter, mainly due to the high wind speed. The highest evaporation in the Persian Gulf occurs in the southern part on either side of the Qatar peninsula.

The following published values give a sense of balance: river run-off 0.15-0.46 m/yr, and precipitation 0.07-0.1 m/yr (Hartmann et al., 1971; Chao et al., 1992; Reynolds, 1993). Therefore, the water balance inside the Persian Gulf is negative. Evaporation which is being several times the sum of precipitation and run-off acts as the dominant control (Brewer and Dyrssen, 1985). Since evaporation in the Persian Gulf is much higher than both river inflow and precipitation, the net loss of water creates a Mediterranean-like, reverse-flow, estuarine circulation. In summary the evaporation is replaced by river inflow, precipitation and surface inflow through the Strait of Hormuz.

Owing to excess evaporation, the Persian Gulf exhibits a reverse estuarine circulation in which, due to geostrophy, the dense bottom outflow follows the coastline of UAE, whereas inflow of Indian Ocean Surface Water (IOSW) moving along the Iranian coastlines.

FRESH WATER EXCHANGE

Six rivers including Mand, Hilleh, Hendijan, Karun, Tigris and Euphrates, flow into the Persian Gulf with individual annual average flows ranging from 203 m^3s^{-1} to 1387 m^3s^{-1}. The total-river flow and precipitation are 37 km^3yr^{-1} and 34 km^3yr^{-1}, respectively. This seems to be far less than that given by Reynolds (1993) (see Table 2-1 and 2-2).

Table 2-1 River input into the Persian Gulf (Reynolds, 1993)

Name of the River	Rate of inflow
Mand	1387 m^3s^{-1}
Karun	748 m^3s^{-1}
Hilleh	444 m^3s^{-1}
Tigris and Euphrates	708 m^3s^{-1}
Hendijan	203 m^3s^{-1}
Total	3490 m^3s^{-1} =110 km^3 yr^{-1}

Most river inflow into the Persian Gulf occurs in the northern end, primarily on the Iranian side (see Figure 2-3). The Arvand Rood is a nexus of three rivers: the Tigris and Euphrates rivers together provide an annual average of 708 m^3s^{-1} and the Karun adds 748 m^3s^{-1}. Thus, the total average outflow of the Arvand Rood is 1456 m^3s^{-1}. Other major rivers are Hendijan (203 m^3s^{-1}), Hilleh (444 m^3s^{-1}) and Mand (1387 m^3s^{-1}).

Table 2-2. Water budget for the Persian Gulf (Reynolds, 1993)

Evaporation in the Persian Gulf	326 km^3 yr^{-1}
Rainfall + rivers	71 km^3 yr^{-1}
Inflow from Gulf of Oman	3365 km^3 yr^{-1}
Outflow from Persian Gulf	3110 km^3 yr^{-1}
Net inflow from Gulf on Oman	255 km^3 yr^{-1}

The total river run-off is 110 km^3yr^{-1}. This estimate, from the Iranian rivers is considerably greater than earlier published and needs further verification. Industrial and agricultural developments are having a pronounced effect on the outflow from the Arvand Rood, where annual runoff has decreased substantially over the past three decades.

Annual rainfall in the arid climate of the Persian Gulf is small, of the order of 7cm/yr. Rainfall makes a negligible contribution to the fresh-water budget of the Persian Gulf.

River discharge from the Arvand Rood and other Iranian rivers are diverted into currents flowing southward along southern and northern coasts of the Persian Gulf (Brewer et al., 1978; Lardner et al., 1993; Reynolds, 1993) reducing their immediate impact on water mass formation in the central portions of the Persian Gulf.

When a water body such as the Persian Gulf is semi-enclosed and where evaporation is in excess of fresh water supply a typical circulation pattern results. Higher evaporation in the Persian Gulf leads to the formation of high saline and highly dense waters that sink and fill up the deeper parts the silled depth. Once the high-density water rises above the sill depth it spills into the adjacent water body. To compensate this outflow there should be an inflow similar to what is shown in Figure 2-4. This results in a continuous exchange of water between the two adjacent water bodies affecting their physical and chemical characteristics by way of the Mediterranean type water exchange.

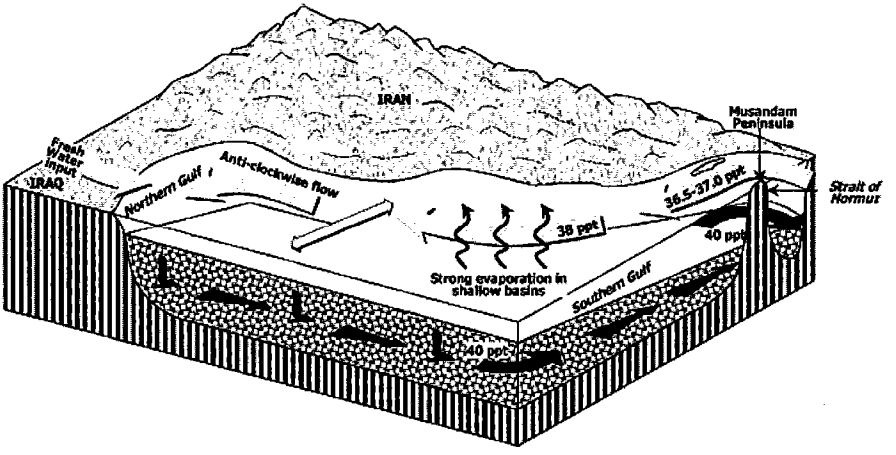

Figure 2-4. Schematic diagram showing the "Mediterranean" type water exchange in the Persian Gulf. Counter-clockwise circulation pattern of the Persian Gulf is evident. Note that salinities are slightly higher than the incoming water from the Oman Sea.

The surface water gains salt as it moves from mouth inwards. Sinking of saltier and denser water starts in the northwestern part of the Persian Gulf. Dense saline water migrates down the shallows from the semi-enclosed lagoons in the south and increases the salinity of this deeper water (Linden et al., 1990). This water flows out below the surface inflowing water from the Oman Sea (see figure 2-4).

The Persian Gulf is a negative water body with evaporation rate (326 km^3 yr^{-1}) roughly five times more than the sum of river discharge and precipitation. Evaporation in the Persian Gulf is relatively more in the south. ROPME expedition recorded salinities greater than 40 and 43 to the east of Qatar peninsula during summer and winter respectively. Shamal wind enhances the rate of evaporation in winter. The evaporation leads to the high density bottom water in the basin that eventually flows into the Gulf of Oman and subsequently to the Arabian Sea. The Persian Gulf water is found to flow along the 26.6 sigma-theta density layers in the Arabian Sea (figure 2-5).

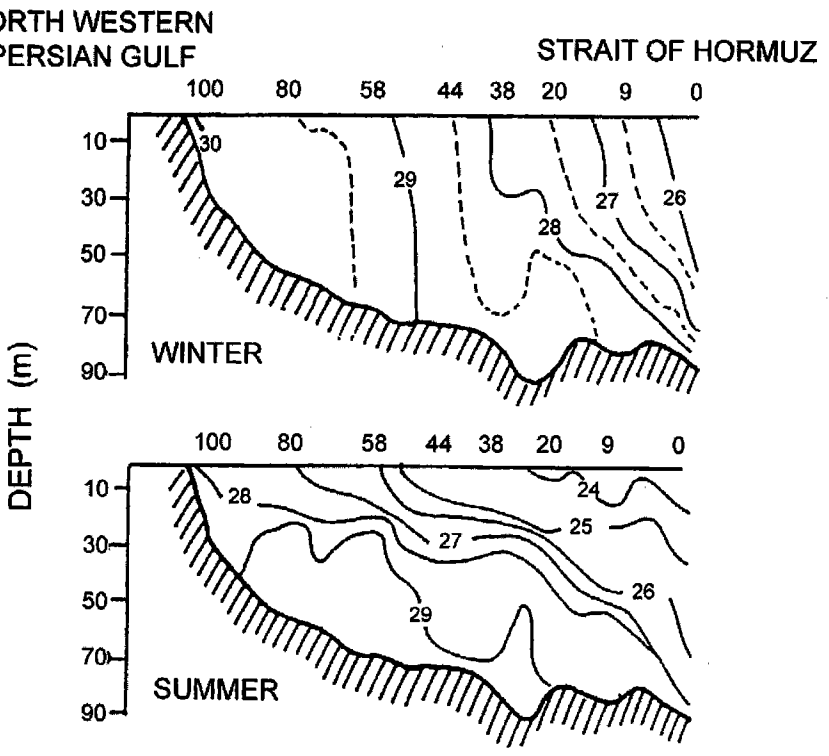

Figure 2-5. Seasonal variability in longitudinal density (σ_t, kg m^{-3}) distribution in the Persian Gulf (modified from Brewer and Dyressen, 1985).

Thus, the outflowing water sinks to its own density level of 26.6 sigma-theta surface in the Arabian Sea, flows mainly east of 63°E longitude at 200-350 meters depth and could be traced by weak salinity maximum up to 12°N latitude (Wyrtki, 1971).

TIDES AND CURRENTS

Tidal ranges are large throughout the Persian Gulf: over 3 meters at the head of the Persian Gulf, and over one meter anywhere else (Lehr, 1993). Off Qatar the tidal range is 0.4 to 0.7 meters (Emery, 1956). Off Abu Dhabi on the open shelf the range at springs is 2.1 meters. Tides are very important for stirring and mixing waters vertically and on a horizontal scale of 10 kilometers, but they do not make an important contribution to the residual circulation of the Persian Gulf.

Tidal energy enters the Persian Gulf through the Strait of Hormuz and progresses up the Iranian coast and down the Arabian side as a Kelvin wave. The result of these two opposite Kelvin waves forms a set of amphidromic points. Co-tidal charts of the four major tidal constituents (the diurnal O_1 and

K_1 components and the semi-diurnal M_2 and S_2 components) all show these points.

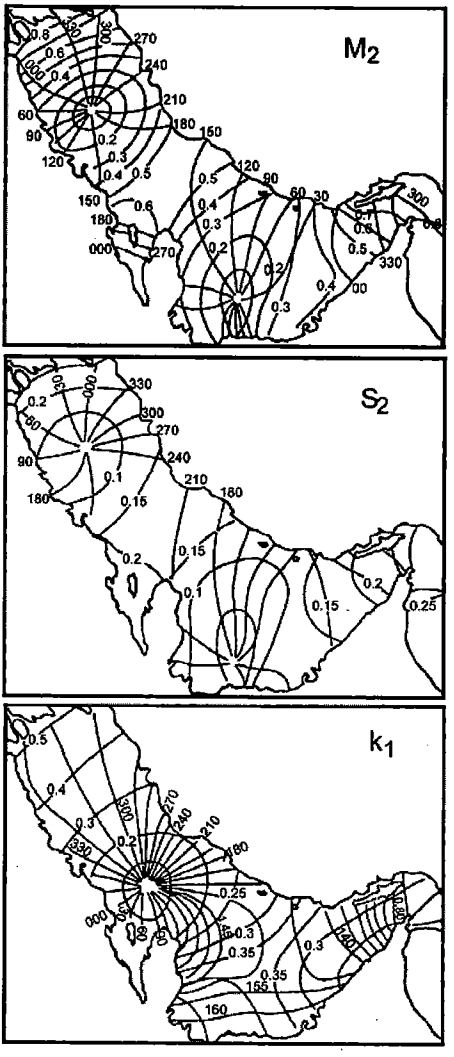

Figure 2-6. The M_2, S_2, and K_1 tidal constituents in the Persian Gulf.). Tide heights are shown in meters *(Lardner et al., 1983)*

The tides in the Persian Gulf co-oscillate with those in the narrow Strait of Hormuz, which opens into the deep Gulf of Oman (Figure 2-6). The tides in the Gulf of Oman co-oscillate with those in the Arabian Sea.

The tides in the Persian Gulf are complex standing waves and the dominant pattern varies from being primarily semi-diurnal to diurnal (Reynolds, 1993). The tidal range is large, with values greater than 1 meter (Lehr, 1993). The dimensions of the Persian Gulf are such that resonance amplification of

the tides can occur and the result is that the semi-diurnal constituents have two amphidromic points, in the northwest and southeast ends, and the diurnal constituents have a single amphidromic point in the center near Bahrain.

Major semi-diurnal and diurnal tidal constituents in the Persian Gulf are M_2, S_2, K_1, and O_1 (Najafi, 1997). Semi-diurnal constituents have two amphidromic points that are located in the north-western and southern ends of the Persian Gulf, respectively. The diurnal constituents have a single amphidromic point in the centre of the Persian Gulf near Bahrain (Hunter, 1982). Tidal hydrodyphidromic hydrodynamic simulations (e.g. Najafi, 1997) predict tidal flows of about 0.9 m/s near the Strait of Hurmoz and at the head of the Persian Gulf, and 0.3–0.6 m/s elsewhere in the Persian Gulf.

The Persian Gulf's tidal regime is very complicated. M_2, S_2 and K_1 constituents with two (M_2, S_2) and one (K_2) amphidromal points interfere, producing tidal amplitudes extremely varying in locality and time. The tidal amplitude is 4 meters in the northern Persian Gulf which is almost double in the south with current speeds of 1-2 meters per second near islands and also in narrow passages.

Khowr-e Mussa seems to exhibit the highest amplitudes, attaining five meters or more. A general impact on biological features results from the interference of diurnal and semi-diurnal tides, so the upper intertidal areas are occasionally dry over several days, exposed to insulation, heat, evaporation and high salinity and salt crystallization.

While the highest high water line (HWL) is almost everywhere clearly marked by a trash line, a mean HWL is hard to be defined. The same holds for a mean low water line (LWL), while the lowest LWL is a sharp biological boundary between the lowest intertidal (occasionally exposed to the harsh climatic conditions) and the highest subtidal biocoenoses (permanently protected by the overlying seawater). This does not mean that high-lying areas are poor in organisms and there are enough well adapted algae and animals. It is typical that cyanobacterial mats, characteristic for extreme conditions, are frequent in the upper eulittoral and the lower supratidal zone.

Tidal flows near the islands are likely to be as accelerated as they are adjacent to the tip of the Musandam Peninsula by narrowing of the channel. Bower et al. (1992) suggested that the accelerations are accompanied by formation of eddies and higher rates of vertical mixing reaching the seafloor. The only significant occurrence of gravel in the Persian Gulf occurs in these channels and those that bend around the tip of the Musandam Peninsula (Emery, 1956; Hartmann et al., 1971), indicating that scour driven by turbulent eddies is most effective there. West of the islands, fewer topographic constrictions occur and the rate of vertical mixing may decrease.

As mentioned previously, an important, secondary current in the Persian Gulf is a coastal reverse circulation along the Iranian coast. Density currents are important in the distribution and removal of pollutants from the Persian Gulf region because of their consistent direction. Driven by the density differ-

ences resulting from river run-off, the coastal currents along the Iranian coast are southerly, against the inflow water. The reverse currents are evident in shuttle photographs and AVHRR images.

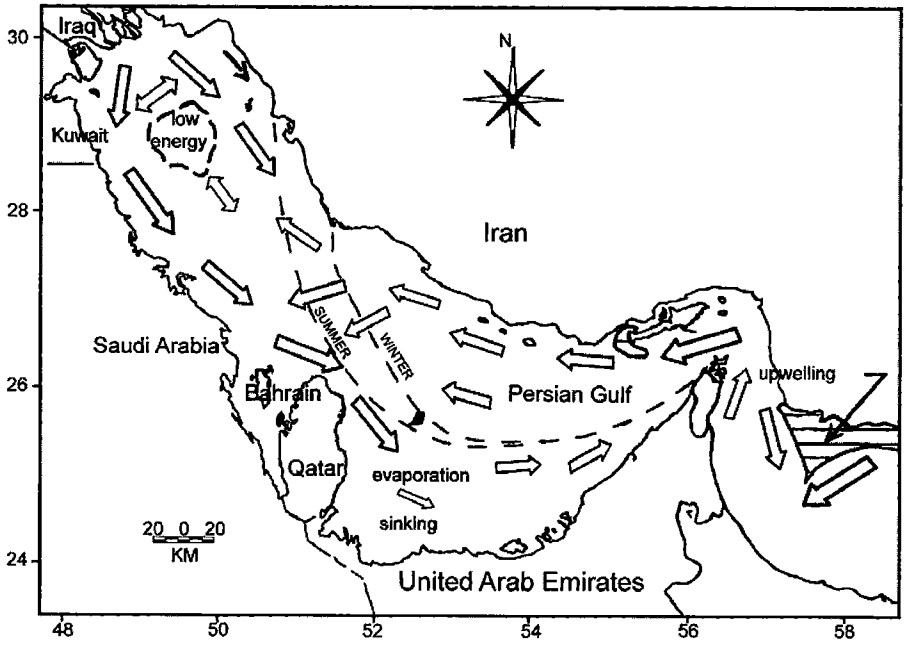

Figure 2-7 Surface currents and circulation processes in the Persian Gulf with northern Persian Gulf circulation largely wind-driven (cited from Reynolds, 1993).

Along the northern coast of the Persian Gulf the surface currents are somewhat opposing since the inflow occurs at Strait of Hormuz as well as near extreme northwest (river flow). The inflow current along the Iranian coasts is weakened by shamal winds in the winter, but in the summer it strengthens and exceeds almost to the head of the Persian Gulf.

Modeling suggests that strong, northwest winds in the winter and spring producing southeast-flowing surface currents along both coasts in the northern region of the Persian Gulf (Chao et al., 1992; Lardner et al., 1993). The mean winter time surface current pattern in the southern Persian Gulf is the most widely known current pattern. The flow is density driven with surface flow inward from the Strait of Hormuz and adjacent to the Iranian coast. A southward coastal flow is present along the entire southern coast of the Persian Gulf. The flow stagnates east of Qatar, where high evaporation and sinking forms a dense, bottom flow to the northwest and out of the Strait of Hormuz.

Johns and Olson (1998) found relatively little seasonal change in the current speed and thickness of the outflow along the Strait of Hormuz. Speeds averaged 20-30 cm/s from about 45 meters depth to the bottom boundary layer (Johns and Zantopp, 1999). While flow elsewhere in the Strait may vary

seasonally, it seems reasonable to assume that the total flux also remains relatively constant.

MIXING PROCESS

Potential density distribution suggests that high-density water of the northwestern Persian Gulf is found much deeper in the Arabian Sea. Salinity, oxygen and nutrients distributions reveal that the outflowing water undergoes intense mixing process at the entrance of the Persian Gulf thereby higher levels of oxygen, occurring in the Persian Gulf are immediately lost. The Persian Gulf outflow penetrates the intense oxygen minimum layer in the northern Arabian Sea (Sen Gupta and Naqvi, 1984). Thus, the outgoing water moves through the oxygen minimum layer in the Arabian Sea.

Detailed studies during winter and summer revealed that the water column in the Persian Gulf is stratified in the latter period while it is well mixed in winter. Higher winds and evaporation set in the convection resulting in well-mixed water column in winter. However, in the Strait of Hormuz and the Gulf of Oman stratification occurs even in winter (Bower et al., 1992).

During winter two distinct oceanographic regimes exist in the Persian Gulf: a vertically-mixed region in the northwest and a two-layered structure with a strong halocline in the southeast. In summer, intense solar heat creates a surface-mixed layer and a thermocline which separates the surface layers from bottom mixing.

The Persian Gulf is probably the warmest sea in the world, the temperature at its surface, in the open sea, varying from about 20°C in February to 34°C in August (Emery, 1956). Warming of the sea surface affects the Persian Gulf throughout the spring and summer. Emery's (1956) August temperature data shows high temperatures extending to 45-55 meters deeper water depths in this region than the central Persian Gulf. Johns and Olson (1998) found that vertical temperature profile observed west of the Strait becomes much warmer in summer.

Sea surface temperature increase of 3 to 6°C occurs throughout the Persian Gulf during the spring. By summer months the sea surface in the Persian Gulf has a nearly uniform temperature of 30 to 32°C. Higher water temperatures reported in 50 meters depth in the western approaches to the Strait may be due to higher rates of vertical mixing there than elsewhere. As the surface water warms up during the spring and summer, the higher temperatures are mixed downwards to near-bottom depths. The difference in temperature between the surface and 50 m depth is 5-6°C in both May-June and July-August periods indicating that the mixing rate is constant through time (Bower et al., 1992).

Compared to the Persian Gulf as a whole, the rate of vertical mixing in the Strait of Hormuz channel around the Musandam Peninsula has the highest range. This distinction seems to be unrelated to meteorological forcing. Swift and Bower (1992) attributed the high rate to numerous topographic features

that constrict the channel, accelerating tidal flows and generating large eddies capable of scouring the seafloor.

In summary, it appears that there are three dominant mixing processes in the Persian Gulf: 1) strong tidal current which induces mechanical turbulence at the bottom, 2) winds created waves and mechanical turbulence at the surface, and 3) high evaporation, enhanced by winter time cooling which generates vertical mixing near the surface. Internal waves at density interfaces, and topographic features such as islands, also contribute to mixing but their influence is probably small. Mixing forces are countered by stabilizing effects of surface warming in the summertime and, along the coastline, by river run-off.

RESIDENCE TIMES

The Persian Gulf is a shallow embayment with no sill or saddle or barrier which could restrict the circulation and water exchange through the Strait of Hormuz with the open ocean waters. Because of such a physical feature, the exchange process is quite rapid and the estimated "turn over-residence time" of water in the Persian Gulf is 2.5 to 4 years.

The estuarine circulation exchanges water between the Persian Gulf and the Gulf of Oman via the Strait of Hormuz. Simple box models have been used to predict the residence time for a water parcel in the Persian Gulf. Assuming a long term steady state and instantaneous, perfect mixing, the residence time is the ratio of volume of water to the volume exchange rate (in or out) of the Persian Gulf. It is a measure of the mean amount of time a parcel of water will remain in the volume (see Reynolds, 1993).

It is assumed the same measurement applies to passive pollutants. Up to present, the circulation in and out of the Strait of Hormuz has been poorly defined, and as a result, estimates of residence times vary in the approximate range of 2-5 years (Hunter, 1983). However, knowledge of the circulation in the Strait of Hormuz plays a key role in understanding the basin-wide behavior of the Persian Gulf.

A parcel of water in the northern end of the Persian Gulf may have a much larger residence time than the one in the southern end. As noted by Reynolds (1993), there is a distinct difference between the northern and southern ends. The north is shallow and dominated by wind friction. River outflow at the northern end plays a role in the local circulation. At approximately the longitude of the Qatar peninsula, density-driven, negative-estuary conditions prevail. High evaporation in the broad coastal areas on the coast of the UAE provides much of the saline bottom water that feeds the bottom outflow through the Strait of Hormuz.

WATER CIRCULATION IN THE PERSIAN GULF

Major portion of the information regarding the circulation in the Persian Gulf is based on three surveys conducted to map the water masses. The first one was by Emery (1956) which covered summer conditions, while the second one in 1983 surveyed the well-mixed winter conditions (Brewer and Dryssen, 1985). An extensive survey in 1992 immediately after the Gulf war covered the spring transition conditions (Reynolds, 1994).

One of the well documented surveys was the Atlantis II survey of the Persian Gulf in February of 1977 (Brewer et al., 1978; Brewer and Dyrssen, 1985). The Mt Mitchell surveys in winter and spring of 1992 included comprehensive CTD sampling that covered many regions of the Persian Gulf that were poorly sampled by other expeditions, including the Strait of Hormuz and the shallow southern banks (Reynolds, 1993). Follow-up CTD surveys were done in April of 1994 and March-April of 1996, but the area investigated by these cruises is not as wide as the one covered by the Mt Mitchell.

The overall circulation process inside the Persian Gulf is cyclonic. Water flows westwards form Indian Ocean into the Persian Gulf along the northern side of the Strait of Hormuz. It continues flowing northward along the Iranian coast (Emery, 1956; Brewer et al., 1979; Reynolds, 1993). The inflowing Ocean water becomes denser as it moves to the northwest due to increased evaporation, while the return flow is in the south. Thus, the overall circulation process inside the Persian Gulf is counter-clockwise (see Figure 2-7). This is also confirmed by satellite tracking of drift buoys (MEPA, 1984).

A major part of the circulation in the Persian Gulf is due to the relatively less saline (36-37 psu) water flowing in from the Gulf of Oman on the eastern side along the Iranian coast to replace the dense high salinity waters (typically 40-41 psu) formed in the broad shallows on the Arabian side. The regions adjacent to Bahrain and UAE are also quite shallow, often as shallow as a few meters deep and it is in these regions that the salinity can reach values as high as 50 psu. Consequently, dense water is formed in shallow regions of the Persian Gulf, with high salinities and exits into the Gulf of Oman through the Straits of Hormuz.

The relatively high evaporation combined with restricted exchange with the ocean leads to formation of saline, dense water mass and a "reverse estuary circulation" through the Strait of Hormuz. Within the Strait, water flow out of the Persian Gulf is mostly confined to the southern side of the channel by geostrophy (Emery, 1956; Chao et al., 1992), although the opposite was true in late February, 1992 (Reynolds, 1993).

The saline bottom waters that flow out through the Strait may originate from several locations in the Persian Gulf. Historical salinity data and SST data implicate a broad region of high salinity waters extending from Qatar eastward along the UAE coast. Waters in this shallow region can reach very high salinities (>42 psu) and appear to form a warm and saline Persian Gulf

outflow. The temperature salinity relationship of the observed outflowing waters implies a fairly complicated set of water mass modifications in the Persian Gulf (figure 2-8).

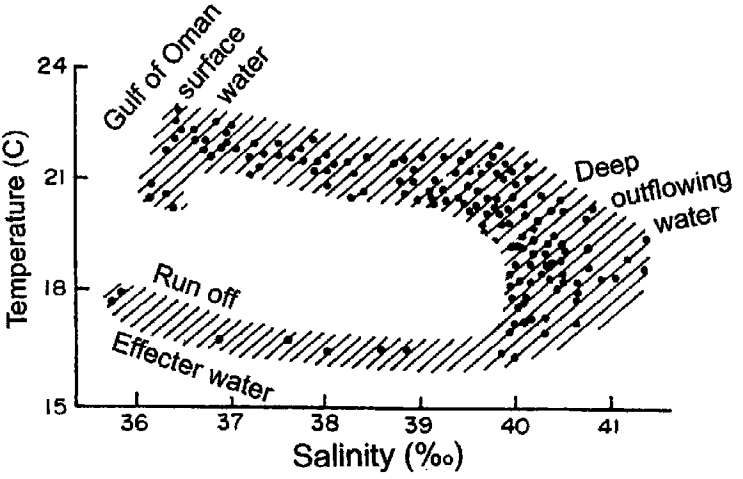

Figure 2-8. Diagram showing the temperature-Salinity relationship with respect to source of water in the Persian Gulf (Brewer and Dyrseen, 1985).

Sinking of more saline and denser water starts in the northwestern part of the Persian Gulf. Dense saline water migrates down the shallow and semi-enclosed lagoons along the southern coast of the Persian Gulf. This water flows out below the surface inflowing water to the Persian Gulf from the Gulf of Oman through the Strait of Hormuz. Such exchange of water is known as "Mediterranean-type". Unlike the Mediterranean Sea and the Red Sea, there are no constrictions or sills limiting the exchanges with the adjoining seas. Consequently, there is essentially unrestricted exchange between the Persian Gulf and the Gulf of Oman.

Outflow from Arvand Rood is carried by the counter clockwise-circulation in a westerly direction down to the southern coasts. Inflow from the Arabian Sea occurs with a low velocity of 0.1-0.2 m/s, due to opposing winds. Runoff from Arvand Rood in the northwest of the Persian Gulf maintains a cyclonic circulation that would otherwise be anticyclonic.

The annual mean outflow of the deep waters and compensating fresh surface inflow is estimated to be approximately 0.2 Sv, assuming a mean evaporation rate of approximately 1.5 m/yr (Privett, 1959; Hastenrath and Lamb, 1979) and net freshwater input from rivers of ~0.2 m/yr (Wright, 1974). Estimates of the exchange rate by available models span a range from 0.1 Sv to nearly 0.4 Sv (Chao et al., 1992). Seasonal variability of the deep outflow and surface inflow is not clearly established, although recent measurements (Johns and Olson, 1998) suggest that the deep outflow may be fairly constant throughout the year.

While the density-driven circulation dominates the central and southern part of the Persian Gulf, the wind-induced circulation dominates the northwestern parts, with the surface flow along both coasts in a southerly direction. Along Iranian coasts, the flow is intensified by baroclinic forcing produced by low-density, river outflow.

In the northcentral part of the Persian Gulf a northerly return flow completes the wind-induced secondary circulation. This secondary circulation balances wind-drift in the surface water and forms a region of very low net drift. Circulation north and south of this low-energy region is variable and sensitive to winds. Flow at the northern Persian Gulf could be easterly or westerly, clockwise or counter-clockwise circulation, moving northerly or southerly to the south of the low-energy area.

Much of the dense water that sinks covers subsurface depths or flow into the neighboring sea. Thus, the circulation in the Persian Gulf is density driven where the longitudinal gradient in surface density, between Gulf of Oman and the northern Persian Gulf is ~ 3.5 kg m^{-3}. High salinity water forms along the western and southern Persian Gulf coastlines, but the lowest densities are not reached because winter temperatures are milder than those in the north and considerable dilution occurs before high salinity water formed in shallow bays reaches the main Persian Gulf basin. On the other hand, the surface density difference across from north to south of the Persian Gulf is also of the same magnitude. Consequently, high-density waters sink in northern and southern parts-outflow from the shallow high salinity (~70) lagoons at the southern coast of the Persian Gulf that together form the outflow water. Thus, deep flow out of the Persian Gulf is likely driven by the density difference between deep water at the head of the Persian Gulf and near-bottom water on the Oman-Iranian shelf

Based on estimates of evaporation/ precipitation and the bulk temperature-salinity properties of the inflow and dense outflow, the annual mean exchange flow through the Strait of Hormuz is 0.1-0.2 Sv (see Hartmann et al., 1971; Ahmad and Sultan, 1991; Johns and Olson, 1998).

Chao et al. (1992) studied the circulation of the Persian Gulf with a three-dimensional hydrodynamic model under realistic meteorologic forcing. Model predictions indicate that inflow through the Strait peaks at 0.17 Sv in March and decrease to 0.03 Sv in August-September, the latter being far too weak as compared with ADCP data (Johns et al., 2003). Chao et al. (2002) were able to simulate the cyclonic overturning circulation in the Persian Gulf, but their simulations had some shortcomings.

Chao et al. (1992) claimed that the prevailing northwest wind is stronger in winter than in summer and suggests that the summer influx of Indian Ocean Surface water is due to relaxation of surface wind stress. Data presented by Swift and Bower (2002) suggests revisions in these interpretations are warranted.

The nature and circulation of water masses in the Persian Gulf have been recently investigated by examination of a historic data base of hydrographic observations (Swift and Bower, 2003). According to the available data the densest water forms in winter at the northern end of the Persian Gulf rather than along the warmer southern and western coasts.

A principal feature of the long time circulation in the Persian Gulf is the cyclonic gyre driven by the Gulf of Oman waters entering the Straits of Hormuz and flowing along the Iranian coast before turning around north of the central basin and forming a cyclonic gyre. Another feature is the wind driven circulation in the shallow regions northwest adjacent to the southern coasts. The prevailing winds are along the axis of the Persian Gulf to the southeast (about 5m/s) and drive a southeastward coastal current along the southern coasts. However the winds are variable, particularly in winter, when strong frontal passages cause strong evaporation from the Persian Gulf. Thus, the exchange through the Straits is also high during this period.

Colder and somewhat fresher waters are also found in the deep outflow from the Persian Gulf and suggest another source, probably from the northern Persian Gulf. Modeling results (Horton et al., 1994 cited in Swift and Ross, 2002) suggest that some of the outflow arises from sinking in the shallow high salinity area off the Emirates, but further sinking occurs in the vicinity of the variable mid- Persian Gulf front.

The lack of significant seasonal variability in the flux through the Strait reported by Johns and Olson (1998) can be attributed to relatively small seasonal changes of density contrast between Persian Gulf Deep Water and water at comparable depths on the Persian Gulf continental shelf outside the Strait of Hormuz.

With the exception of small amounts of water directly above the seafloor, most water flowing out of the Persian Gulf mixes across a density front that separates Persian Gulf Deep Water within the Persian Gulf from the Indian Ocean surface water.

Contrary to previous inferences, the seasonally-variable incursion of Indian Ocean surface water into the Persian Gulf peaks in late spring. This timing may be due to seasonal changes in sea surface slope driven by variations in evaporation rate. High-salinity water flows out of the Persian Gulf into the Gulf of Oman and spreads at 200-350 meters depth within the Gulf of Oman (Rochford, 1964; Wyrtki, 1971; Qasim, 1982; Premchand et al., 1986; Bower et al., 1992; Prasad et al., 2001).

DENSE WATER IN PERSIAN GULF

Formation of dense water in the Persian Gulf is commonly associated with processes that increase salinity (Emery, 1956; Chao et al., 1992). This viewpoint follows from the understanding of the Persian Gulf as a shallow reverse-estuary system in an arid, subtropical setting.

The densest water in the main Persian Gulf basin forms in winter. Most of this water has salinity less than 41 psu. The densest water is formed from surface water by cooling of warm mixed layer water by up to 13°C and evaporative salinity increases of up to 3 psu. This densest water mixes with relatively fresh, warmer inflow from the Gulf of Oman to form Persian Gulf deepwater. Most of the dense water forms above shallow seafloor at the northwest end of the Persian Gulf with lesser amounts forming along the lagoons and shallow banks off the southwest and southern coastlines.

Dense water also forms along the Bahrain-Qatar shelf and behind the shallow banks off the southern Persian Gulf along the south coast. High salinity values (41.6±0.9 psu) compared to the high-density samples in the north (40.5±0.3 psu), in general, are more common along the southern coast.

A density front separates cool, saline deep water in the Persian Gulf from warmer, fresher surface water in the Gulf of Oman. The nature and dynamics of the front reflect and, to some extent, control exchange processes in and out of the Persian Gulf.

In the Strait of Hormuz the front appears to be a near-vertical feature oriented north-south across the Strait. Long density sections down the Persian Gulf axis, collected during February by Brewer and Dyrsson (1985) and Reynolds (1993) indicate that isopycnals in the front intercept the seafloor in the region of the Strait. Isopycnals appear to be near-vertical. A prominent density front separates modified Indian Ocean Surface water at the surface from the Persian Gulf Deep Water. The front intercepts the seafloor in the Strait and the sea surface in the interior of the basin.

Summarizing the limited available data, density surfaces in the Strait during winter appear to be planar features that are vertical at the bend in the Strait north of the tip of the Musandam Peninsula but dip towards the west within the Persian Gulf. The densest water forms during winter in shallow water at the northern end of the Persian Gulf. The densest isopycnals crop out there from January to April.

Relatively fresh surface water from the Oman-Iran shelf flows into the Persian Gulf to replace water lost due to evaporation. Input from river discharge and precipitation is much lower than estimates of evaporative flux (Hartmann et al., 1971; Reynolds, 1993). For a long time, it was inferred that the surface water of the Persian Gulf is more saline in winter than in summer. Schott (1908 cited in Swift and Bower, 2002) attributed the difference to changing river fluxes, whereas Emery (1956) attributed the difference to changing the rate of evaporation.

SALINITY DISTRIBUTION

The surface salinity of the Persian Gulf water is presented in Figure 2-9.

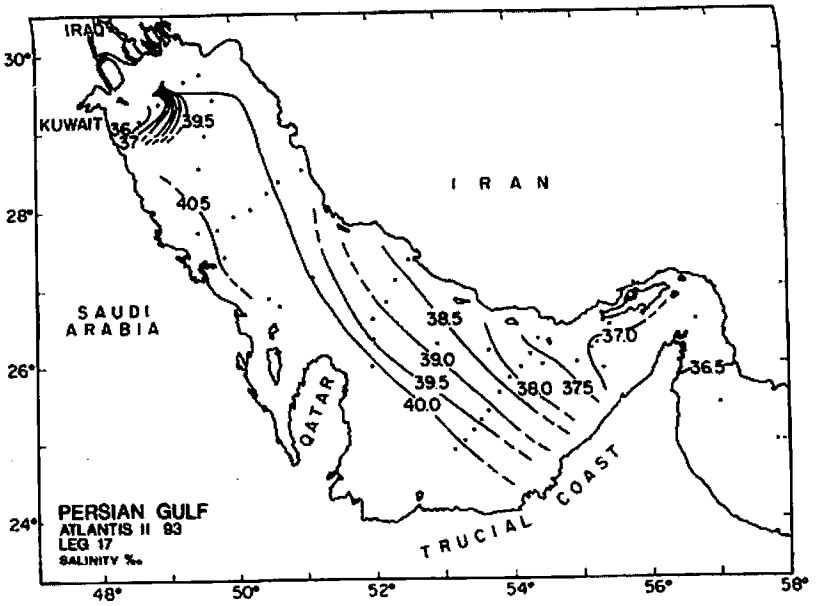

Figure 2-9. Map of the surface salinity in the Persian Gulf (modified from Brewer and Dyrsen, 1985).

The Persian Gulf surface water gains salt as it moves inwards from the mouth because of increasing rate of evaporation inside the Persian Gulf. Schott and Sugden documented the distribution of salinity before the systematic studies were undertaken by RV Meteor (1964-65) and RV AtlantisII (1978). An excellent summary was provided by Brewer and Dyrsen (1985) on the earlier works. Warm surface water enters the Persian Gulf while the subsurface higher salinity water flows out. Signatures of cold but high salinity waters were presented in Figure 2-8.

Neither the salinity nor the density of water below 30-35 meters depth in parts of the Persian Gulf changes significantly from winter to summer (see figure 2-5) and that outflow seems to be driven by a density contrast. Therefore, the salinity of water below the surface layer in parts of the Persian Gulf changes little during the year. Salinity values of 39.5-41 psu remains nearly the same from January to August in the northwest half of the Persian Gulf. Salinity decreases from 40-41 psu in January-February to 39.5-40.5 psu in March-June and to 39-40 psu in July-August.

Assuming that the evaporation rate increases when the air temperature dropped below that of the sea surface, Emery (1956) argued the evaporation rate for the Persian Gulf would be higher in winter and would produce higher sea surface salinity.

Modeling performed by Kampf and Sadrinasab (2005) showed that the densest water in the Persian Gulf on the shallow southern coast off UAE from December through August. They indicated that their model contradicts the

observed data gathered during this period and published by Brewer and Dyressen (1985), Reynolds (1993) and Swift and Bower (2003), which indicates that the densest water in the Persian Gulf occurs northwest of Bahrain.

Deep-water density, however, changes significantly only from May-June to July-August, and this change is due to a warming of ~2°C of deep water, in the Persian Gulf west of 54.5°E, and a warming of ~4°C in the Strait and its western approaches. The salinity at 50 meters depth indicates only minor changes during the year (Swift and Bower, 2002).

Seasonal changes in contrast with density between the interior of the Persian Gulf and the Gulf of Oman are too small to produce changes in outflow and temporal and spatial patterns for deeper depth intervals. The longitudinal-axis salinity distribution remains nearly constant during the year.

The temperature distribution remains constant from January to June but warms up in July-August. This temperature increase is greatest close to the Strait, and, as a result, the density distribution flattens. There is, however, only a small change in the density difference between the central Persian Gulf and the Gulf of Oman through the year.

Swift and Bower (2002) have suggested that the presence of low-salinity surface water increases from January to June and then decreases in July and August. Maps of surface salinity show that salinity less than 37 psu spreads westward into the Persian Gulf from January-February into March-April. In May-June most contours spread 20-40 km further northwestward into the Persian Gulf. Low saline water remains within the Iranian half of the Persian Gulf despite a wide-spread, well developed thermocline at this time. By summer, low salinity water (<38.5 psu) has retracted almost 100 kilometers southeastward along the coast and covers an area smaller than it does in winter.

Extremely high salinity values (>50 psu) have been observed in shallow bays west of Qatar (Sugden, 1963; Chandy et al., 1990) and probably are common in lagoons elsewhere along the south coast. Such high salinity values do not appear in Swift and Bower (2002) data indicating considerable dilution before reaching the shallow southern banks and the main Persian Gulf basin where their samples were taken. High salinity water formed along the coast appears to be trapped there by the same topographic and oceanographic restrictions that allow salinity to increase to high levels.

The sea surface salinity distribution in the summer may vary dramatically from year to year. Despite high variability in salinity during the summer months, less saline water reaches farther into the Persian Gulf during the spring than in winter and summer. In Iranian coastal region of the Persian Gulf, rainfall peaks in mid-winter (Kappus et al., 1978), but river run-off from the Zagros Mountain peaks during March-May when most of the snow melts (Beaumont, 1973).

The section of Iranian coastline where low salinities are observed, however, does not have significant river discharge due to low annual precipitation in the mountain watersheds (Beaumont, 1973). Thus, it could be inferred that

the salinity change is unlikely to arise from changes in fresh water runoff. Additionally, in surface water samples (0-10 meters depth) southeast of the Tigris-Euphrates-Karoun coastline, no salinity values lower than Indian Ocean Surface water on the Iran-Oman shelf at any time of the year are observed, indicating that the discharge from other Iranian rivers has little effect on water properties beyond the coastal zone.

Since the prevailing surface winds blow from the northwest against inflow, the increase in low salinity surface water in the Persian Gulf during the spring can not result from a decrease in surface wind stress, and the apparent recession of Indian Ocean Surface water from the Persian Gulf does not correlate with an increase in wind stress. The broader extension of low salinity values at the sea surface up the Iranian side of the Persian Gulf indicates greater transport of Indian Ocean Surface water through the Strait in late winter and spring.

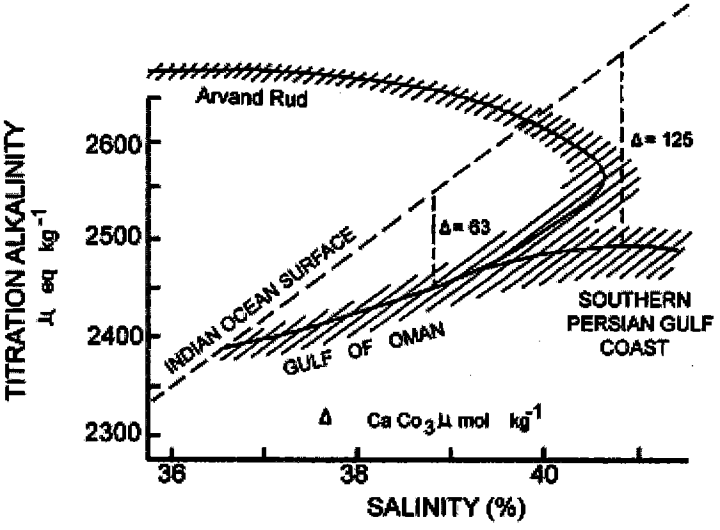

Figure 2-10. Salinity relationship with titration alkalinity in the Persian Gulf (Brewer and Dyressen, 1985).

BOTTOM SEDIMENTS

The Persian Gulf is very rich in carbonate sediments where inorganic precipitation is favored. The carbonates have higher values (>50%) towards northwestern Persian Gulf adjacent to Arabia and also in shallow areas. Shallow-water carbonates are accumulating on topographic highs caused by salt diapirism in the Persian Gulf (Pursur, 1973). Off the southern coasts of the Persian Gulf, topographic highs with coralgal reefs rise above the deep and muddy ramp are a few square kilometers in area.

Brewer and Dyressen (1985) found decreased alkalinity level in the Persian Gulf waters with respect to those in the Indian Ocean (figure 2-10). In-

creased removal of carbonates from seawater is obvious with increasing salinity which is even more significant towards the southern Persian Gulf particularly in the Trucial Coast. On average about 63 μmoles/kg of carbonate precipitation was estimated in the Persian Gulf (Brewer and Dyressen, 1985).

Skeletal sandy muds of the deeper, outer ramp give way to carbonate sands and reefs in the shallow subtidal to intertidal zones of the inner ramp along the Trucial coast. The outer-ramp skeletal sandy mud lithofacies consists largely of bivalve and foraminiferal debris, often unbroken and unbraided, with mud which has come largely from the Tigris and Euphrates Rivers at the head of the Persian Gulf.

Sediment texture indicates the prevalence of muds in the Iranian and most of the northwest oriented sides of the Persian Gulf (Figure 2-11). Sands are dominant in the southern regions of the Persian Gulf region, particularly near Qatar, whereas muddy sand occurs in the southeastern parts. This pattern of sediment distribution could be related to low energy conditions in the north of the Persian Gulf to high-energy conditions towards Arabia. Increased skeletal production on the Arabian side of the Persian Gulf also leads to the larger grain size. Accordingly, the non-carbonate contribution in muds is higher (>20%) in the Iranian side while it is 0-10% on the southern side of the Persian Gulf.

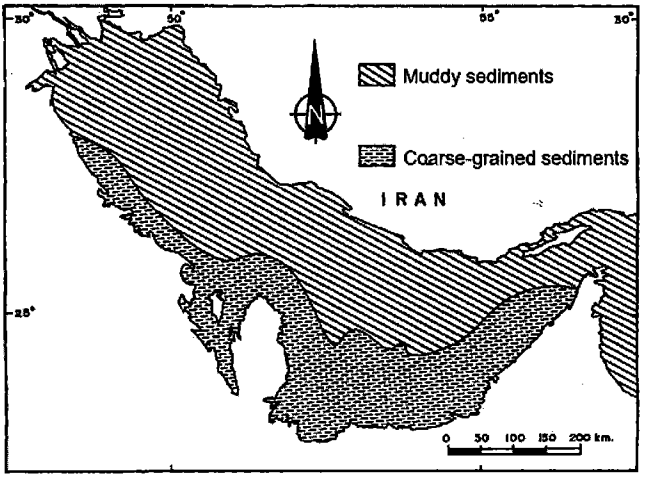

Figure 2-11. Regional distribution of sediments in the Persian Gulf (modified from Baltzer and Purser, 1990)

There seems to be an excellent positive correlation between the carbonate abundance and grain size, suggesting the organisms are primary source along the Iranian coast which is relatively poor in carbonate content. Otherwise, benthic organisms seem to be the chief contributors to carbonates dominance in sediments. The dominant groups in the Persian Gulf sediments are calcare-

ous foraminifera and benthic molluscs, whereas those in the slope region of the Gulf of Oman are dominated by planktonic foraminifera.

High fine-grained sedimentation rates appear to be concentrated along the Iranian coasts where there is a low degree of bioturbation. The southern strip of the Persian Gulf is mainly occupied by coarse-grained rock fragments (see figure 2-12).

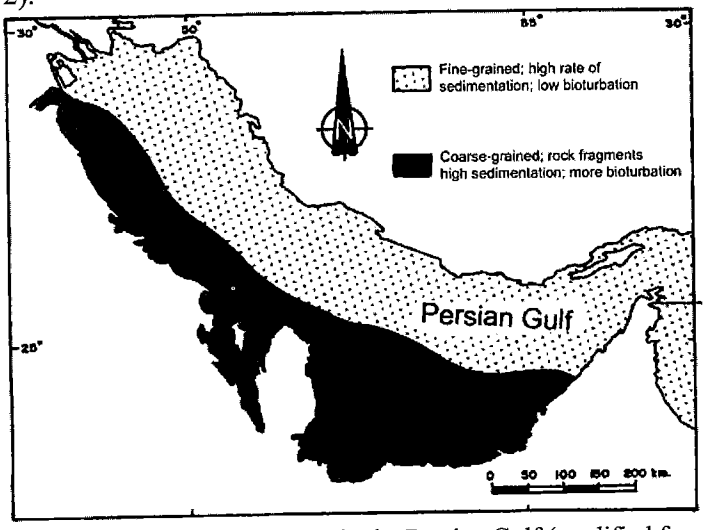

Figure 2-12. Inferred bioturbation area in the Persian Gulf (modified from Baltzer and Purser, 1990).

PRODUCTIVITY

The Persian Gulf is a sedimentary basin with extreme environmental conditions and hence not conductive for survival of great number of species of plants and organisms. In view of the shallow nature of the Persian Gulf, benthic production is expected to dominate over that in water column. However, the neighboring areas of the Persian Gulf (i.e., Arabian Sea) are productive regions with a rich diversity in flora and fauna. Although, the Gulf of Oman Sea water flows into the Persian Gulf, the transported fauna and flora do not survive in higher salinities and therefore the biological diversity in the Persian Gulf is limited.

This gradual reduction in biological diversity in the Persian Gulf is termed as "bottleneck effect" (Sen Guptha, 2001). The nutrients in the Persian Gulf waters seem to be supplied by the inflow of the Gulf of Oman and the Iranian rivers in which the productivity is higher. In general, the northwestern parts are oligotrophic while the eastern region is relatively more productive.

High productivity, in general, should reflect the benthic production rather than pelagic one since this body exist in shallow depth, although it is well illuminated. Phytoplankton density is higher in winter (250 x $10^6 l^{-1}$) than in the summer (100-150 x $10^6 l^{-1}$) to the north of Saudi Arabia. In summer phyto-

plankton are dominated by diatoms while in winter dinoflagellates are more abundant.

Biologically the Iranian coastal regions of the Persian Gulf seem to be the least explored. This region is prevailed by soft substrate ecosystems in the coastal waters which are less than 10 meters deep which is conductive to the growth of sea grasses and algal beds. The hard substrate systems, in deep waters, comprises of coral reefs and carbonate platforms.

In the subtidal ecosystems the coral reefs are highly productive and diverse but cover only a small area in the Persian Gulf whereas sea grasses are important and dominant. Coral reef distribution in the Persian Gulf is very patchy having poor diversity with about fifty to sixty zooxanthellae species. The extreme temperature and salinity variations are the main reasons for the low diversity of the coral species. The massive form of *Porities*, known in the Caribbean for its high tolerance, in the Persian Gulf withstands salinities as great as 48% (figure 2-13).

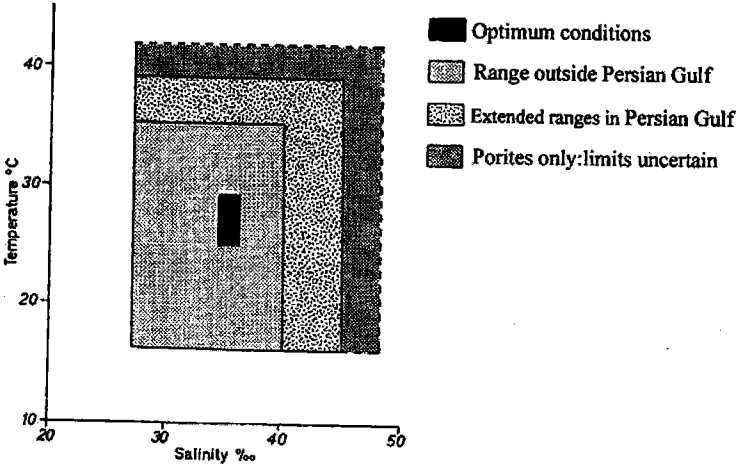

Figure 2-13. Temperature and salinity tolerances of reef corals (from Bathurst, 1975).

The inhospitable nature of the Persian Gulf environment generally is apparent from the small number of genera, 15 compared with 80 in the Indo-Pacific fauna (Kinsman, 1964). Therefore, prolific coral growth is inhibited by the slight hypersalinity of the Persian Gulf waters and occasional low (<20°C) water temperatures. Three coral types are common: the branching *Acropora,* the massive *Poritis* and the brain coral *Platygyra.*

The inflow of nutrient-rich fresh water from the Euphrates and Tigris Rivers through the *Arvand Rood* waterway deposits its silt load in the extensive mudflats and salt marshes at the head of the Persian Gulf. The clear warm waters, good penetration of sun light and shallow depth encourage the growth of

coral reefs, the most productive marine habitat, which contribute to the production of plankton that in turn support the food chain of fish and birds.

Net primary production in the Persian Gulf is thought to be provided almost entirely from subtidal communities (Sheppard and Price, 1991; MEPA, 1992). According to MEPA (1992), gross phytoplankton productivity (57.9 x 10^{11}grams of carbon per year) in the Persian Gulf exceeds that of subtidal communities (42.4 x 10^{11}grams of carbon per year); however, net phytoplankton productive is thought to be zero while some subtidal communities contribute excess organic carbon.

Oxygen consumption in the Persian Gulf is not significant although the oxygen decrease by 150 μM within the upper 50 meters depth in the Gulf of Oman, where the secondary nitrite (that indicates the occurrence of nitrate reduction) was also observed. This could be attributed to the short residence time of water in the Persian Gulf. Well oxygenated water with ~190 μM concentration outflows into the Arabian Sea (see Figure 2-14).

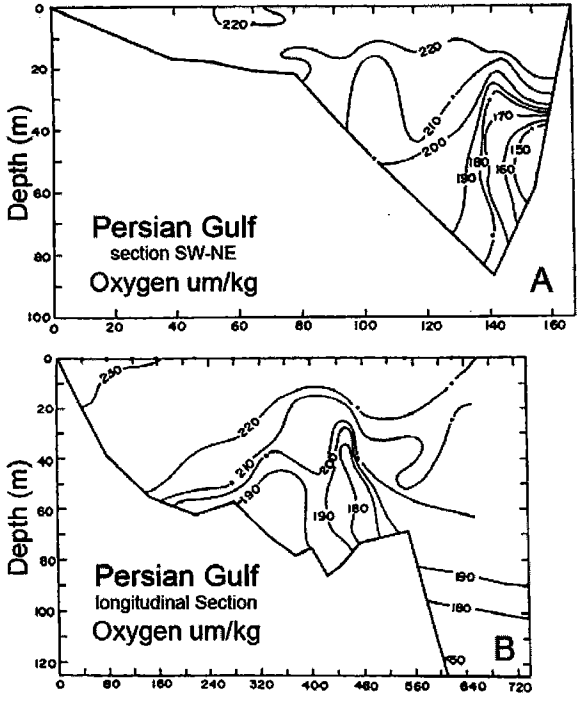

Figure 2-14. Oxygen distribution (A) across and (B) longitudinally in the Persian Gulf.

Phosphate is present in the surface layers of the entire Persian Gulf which imply that it is not a limiting nutrient for biological production (see figure 2-15). However, surface nitrate is largely below the detection limits in large parts of the Persian Gulf and hence the nitrogenous nutrients seemed to be limiting the productivity.

Significantly, the regeneration in the Persian Gulf does not seem to be appreciable so as to supply nutrients to sustain productivity within the Persian Gulf that demands an external source. Nevertheless, oxygen-minimum cell occurs on the slope off Iranian coast indicating the continuous oxidation of particulate organic carbon in the sediments.

As mentioned earlier upwelling occur along the Iranian coasts of the Persian Gulf during the northeast monsoon. This upwelled nutrient-rich water flows into the Persian Gulf largely supporting the biological production. In addition to upwelling, winter convection, inflows from rivers and the Arabian Sea, as well as an atmospheric deposition provide great nutrient inputs to the surface waters of the Persian Gulf.

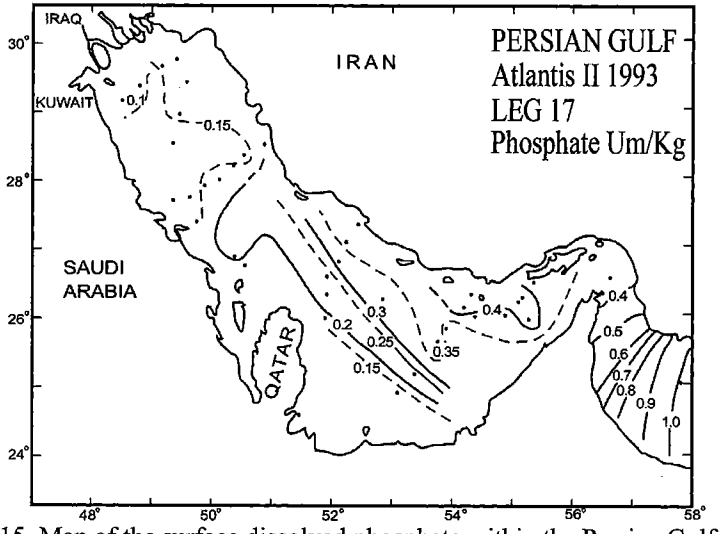

Figure 2-15. Map of the surface dissolved phosphate within the Persian Gulf (Brewer and Dyressen, 1985)

CONCLUDING REMARKS

Water exchange with the Gulf of Oman dominates the circulation of the southern Persian Gulf. The net freshwater loss to the atmosphere is replaced by a surface inflow in the Strait of Hormuz. Throughout the year and against prevailing Shamal winds, relatively low-salinity water enters through the Strait of Hormuz to freshen the hypersaline water. High salinity water forms along the western and southern Arabian coastlines, but the lowest densities are not reached because winter temperatures are milder than those in the north and considerable dilution occurs before high salinity water formed in shallow bays reaches the main Persian Gulf basin.

High evaporation increases the density of the surface water so it sinks to exit as a high-density undercurrent through the deeper portion of the Strait of Hormuz. This reverse estuary flow is similar to the circulation of the Mediterranean Sea.

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CHAPTER-3

STRATIGRAPHY OF THE PERSIAN GULF

INTRODUCTION

This chapter of the Petroleum Geology of the Persian Gulf reviews the generalized stratigraphic evolution of the Persian Gulf and adjacent areas. However, in view of the facies variations seen throughout the Persian Gulf region, it is impossible to do more than a general summary indicating some of the more important regional references on the area.

Lithostratigraphic units of the Arabian plate have been described in outcrop and subsurface from the Mediterranean to the Gulf of Oman and from Red Sea to the Zagros Mountains. It is of prime importance to mention that serious variations in nomenclature exist regionally between the surface and subsurface.

Various authors (e.g., Beydoun, 1988; Christian, 1997) have published regional lithostratigraphic reviews in attempt to comprehend the vast amount of stratigraphic information. Lees (1950) was among the first in describing the fundamental depositional history and structure of the greater Persian Gulf area, and thus, to outline the geologic background of its huge hydrocarbon reserves. The authors who followed Lees provided valuable additional information. Among these are especially Mina et al. (1967), Dunnington (1967) and Stocklin (1968), whose broad reviews brought to a close nearly two decades of publication of technical literatures. Mina et al. (1967) published valuable information dealing specifically with the stratigraphy and petroleum system of the present Persian Gulf area and set the cornerstone for future geological work on the Persian Gulf.

Sharland et al. (2001) published the first chronostratigraphic interpretation of the rock units of the Arabian plates. Through the stratigraphy, they identified, dated, and correlated Maximum Flooding Surfaces (MFS) across the Arabian plate and provided time lines for chronostratigraphic interpretations. These sequence stratigraphic interpretations of the Arabian plate place source, reservoir, and seal lithologies in a chronostratigraphic framework and allow identification, characterization, and construction of each petroleum system element within specific time intervals.

Recently, Alavi (2004) in a comprehensive work revised the stratigraphy of the Zagros Fold-Thrust Belt of Iran and its proforeland basinal evolution. The revised stratigraphy consists of four groups of rocks, each composed of a number of unconformity-bounded megasequences representing various tectonosedimentary settings.

A striking feature of sedimentation in the Arabian Platform and also Persian Gulf region is the very extensive lateral persistence of many formations

over distances of up to several thousands of kilometers. The lateral continuity of these blanket lithologies, such as the Dalan Formation (see Edgell 1977, 1992), is noticeable in a NW-SE direction paralleling the Persian Gulf, but across the Persian Gulf, as seen in Iran, some of these units are replaced by different lithostratigraphic units (James and Wynd 1965). Many unconformities, or disconformities, occur within the stratigraphic succession of the Persian Gulf oil fields. Thus, based on the drilled wells in the Persian Gulf proper almost identical lithofacies of the same age from late Precambrian through Early Tertiary are present on both sides of the present Persian Gulf.

It is important to emphasize that interest in Persian Gulf stratigraphic petroleum plays is demanding a better understanding of a regional correlation and depositional architectures. This understanding is necessary to resolve the vertical and lateral facies variations that are required for stratigraphic traps.

Recent detailed investigations concerning sedimentological aspects of the Iranian segment of the Zagros Basin in the context of a better-constrained tectonic framework, and the aerial distributions and interrelationships of rock units in light of new developments in sequence stratigraphy and deformation/ sedimentation relationships, as well as geodynamic concepts, have resulted in a more comprehensive stratigraphy.

This chapter reviews the generalized stratigraphic evolution of the Persian Gulf and surrounding regions. A vast amount of literature exist dealing with parts of the stratigraphy and these often define informal local subdivisions which are not traceable regionally. Furthermore a huge amount of stratigraphic information exists, often overwhelming in terms of volume and is incomprehensible to all but the specialists.

INFRACAMBRIAN

Introduction

The oldest and first unmetamorphosed sedimentary rocks covering the southern region of the Persian Gulf and Arabian Shield are the carbonates, clastics, and evaporites of Infra-Cambrian age deposited within the rift salt basins. These rocks resting on Precambrian basement are the InfraCambrian to Early Cambrian evaporite sequences. In the northern regions of the Persian Gulf, it appears that no in-situ basement outcrops are known in Zagros region.

Motiei (1995) suggests that the Zagros basement should be the northeast continuation of Arabian-Nubian shield, which exposed southwest of Arabian plate. The oldest sediments here are of late Proterozoic age consisting of evaporites, carbonates, and varicolored sandstones and shales. In Zagros and some of the Islands in Persian Gulf such as Hormoz and Larak, these sediments correspond to the mobile Hormoz complex. Their deposition followed the consolidation and immobilization of the shield-like basement complex which is believed to underlie the entire Middle East, being exposed in the Za-

gros Basin north of the Persian Gulf (Ala et al., 1980). These evaporites include the infamous Hormoz Formation of the Persian Gulf and Zagros Mountain and the Ara Formation of south Oman, the Ravar Formation of Kerman in central Iran and Salt Range Formation northern Pakistan.

The evaporite sequence was very important in generation of geologic structures, and some of the oil fields in the Persian Gulf region are salt-related structures produced by the upward salt mobilization. In addition, throughout much of the southern Persian Gulf region and Oman, the Hormoz strata and its stratigraphic equivalent are proposed to have some source potentials (Shuster, 2003).

Massive evaporites with thickness of greater than one kilometer in the Persian Gulf (Kent, 1970) not only form the salt core of the many of hydrocarbon rich structures but also surround major basement-controlled, hydrocarbon-bearing structures of Infra-Cambrian origin. These evaporites manifest themselves as piercement domes throughout the Persian Gulf region and much of the southern Iran, where they have also provided the detachment level for the late Neogene compressional folding (Kent, 1979; Stocklin, 1986).

In Oman, the equivalent of Hormoz is found in isolated salt basins in southern Oman Mountains (i.e., Ara Formation) but seemingly not in the northern Oman Mountains (see Clarke, 1988). Thus, in the southern regions of the Persian Gulf, the oldest exposed sedimentary rocks underlie the entire UAE except the Oman Mountains and immediate flank areas are dome-shaped at the surface and are cored by Hormoz Salt (named after similar salt on Hormoz Island in the Straits of Hormoz).

The salt was deposited almost about 600 million years ago on the floor of an almost enclosed basin when evaporation resulted in its water becoming super-saturated with respect to halite. About 20 million years ago, it appears that the Red Sea was also floored by salt in a similar way (Glennie, 1987).

Much of the eastern part of the Phanerozoic sequence of the Arabian Platform is underlain by the Infra-Cambrian Hormoz salt (Beydoun, 1991). The salt surfaces in the form of salt glaciers emanates from the breached cores of anticlines in the Fars Platform south of the Zagros Main Fault (Koyi, 1988; Jackson et al., 1990) and the islands of the Persian Gulf. Hormoz salt beneath the Fars Platform seems to have been initially overlain by competent and stable overburden rocks. Salt movement did not commence there until Jurassic, with Infra-Cambrian salt first surfacing in Cretaceous (Kent, 1990). The tilting of Miocene, Pliocene and Holocene beach deposits at many of the islands including Qeshm, Hormoz and Larak, indicate that structural salt growth has been continuous up to the present time in the Persian Gulf region.

INFRA-CAMBRIAN SEDIMENTARY SEQUENCES

During the Infra-Cambrian (from about 600 to 540 Ma) the Persian Gulf and Zagros Mountains occupied by great basins where massive evaporites

were deposited. Much of the region was covered by shallow epeiric seas bordering lowlands whose aerial extent altered in response to succeeding transgression and regressions which periodically gave rise to extensive intrashelf basins. The width of this epeiric shelf was at least 2000 kilometers and may have reached 3000 kilometers, and its setting was principally in temperate latitudes of the southern hemisphere with occasional incursions into tropical regions.

During Late Precambrian and Paleozoic time the whole area on either sides of the future site of Zagros Suture line was an extension of the Afro-Arabian continental shelf and was the location of extensive platform marine sedimentation flanking a continental block (Gondwana). Distinct intrashelf salt basins lay on both sides of the Zagros Suture (Stocklin, 1974; Murris, 1980).

Thick evaporites were deposited throughout most of the Persian Gulf forming the Infarcambrian Hormoz complex, which is up to 2.5 kilometers thick and the equivalent Ara Formation of Oman, where thickness of salt reaches 4 kilometers. In northeastern Saudi Arabia, the deposition of salt took place at the same time between uplifted, north-south trending, basement horsts. Initial Infra-Cambrian carbonate-evaporite deposition was followed by a predominantly clastic regime that prevailed until Permian time.

Almost all the major salt diapirs in the Persian Gulf region originated from these very thick and deep evaporites. These rocks are seen only in small, scattered, emergent salt plugs associated with thrust faults in Zagros and more abundantly in the Fars region in northern Persian Gulf. Some of the salt plugs contain an assemblage of intrusive rocks. Radiometric dating of these rocks show ages from Precambrian to Tertiary which correspond to different periods of magmatism (Motiei, 2003). One sample dated as Precambrian by Player (1969) provided the only indication of possible basement composition.

Major subsiding rift basins of the Persian Gulf region formed during Infra-Cambrian and early Cambrian time while the Arabian plate was close to the equator (Kornet et al., 2001), and massive salt deposited in these restricted basins early in their history (Gorin et al., 1982; Al-Husseini, 2000). Oterdoom et al. (1999) reported that in Oman, this rifting period, which was between 570 and 530 Ma, is represented by deposition of the Infra-Cambrian Huqf Supergroup.

The north Persian Gulf basin extends northwards into Iraq, Kuwait and eastwards into eastern Saudi Arabia, Bahrain and Qatar. The lack of Infra-Cambrian salt along the NE-SW trending Qatar-Gavbandi Arch, which separates the two Persian Gulf basins, suggests that the Persian Gulf includes NW-SE trending structural elements (Figure 3-1).

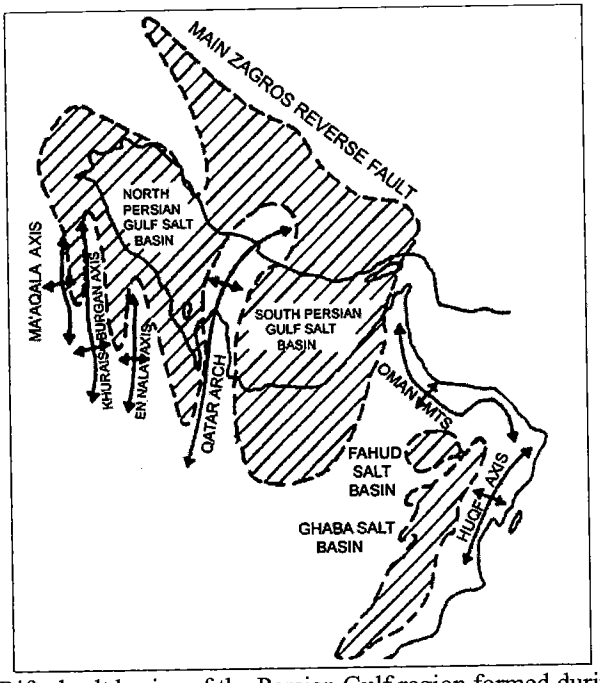

Figure 3-1. Rifted salt basins of the Persian Gulf region formed during the Infra-Cambrian (Modified from Edgell, 1992).

Basically, the Persian Gulf basin has developed along the northern edge of the Arabian plate where it was subducting beneath the Iranian Plates. Its development had taken place since Late Proterozoic when a number of evaporite basins developed, interfingering between N-S Arabian trend extensional uplifts, and bordered to the northeast by the line of Main Zagros Reverse Faults.

The marked isopach low southeast of Kuh-e-Mund on the northern shores of Persian Gulf is well controlled on land, and it is generally assumed to be the north end of an important positive area (figure 3-1), crossing the Persian Gulf from the Qatar Peninsula, which swings northwest at its northern end.

FORMATION OF PERSIAN GULF SALT BASIN

Following Late Proterozoic extensional rifting of the Arabian plate along the north-south Arabian trend, dextral faulting occurred along the line of the present-day Main Zagros Reverse Fault. As a result, narrow graben-type troughs were formed within the current southeastern and northwestern parts of the basins. This led to the development of a number of evaporite basins in the latest Proterozoic, extending through southwestern Iran, southern Iraq, Kuwait, northeastern Saudi Arabia, and all the Persian Gulf, except for the Qatar-Gavbandi Arch. In addition, Neoproterozoic evaporite basins were developed in southern and southeastern Iran, the UAE, part of northeastern Saudi Arabia

and Oman. During this period, rift basins formed in the present Persian Gulf and also the western and southern regions of it where thick salt deposits are found (Hormoz complex of Iran and Ara Formation of southern Persian Gulf). Al-Husseini (2000) provides a recent review of this early stage of Plate evolution. Infra-Cambrian subsidence as a result of pre-Tethys rifting led to development of the proto-Tethys realm and continental-rift basins in which thick deposits of Hormoz salt accumulated (Figure 3-2).

Figure 3-2. Diagram showing possible basin geometry of a failed rift system in which the Hormoz salt was deposited (Talbot and Alavi, 1996).

Because these rift basins contain thick salt deposits and multiple stacked petroleum systems of Infra-Cambrian through Tertiary age, they play an important role in the occurrence and migration of hydrocarbons, and also in hydrocarbon trap formation throughout the southwestern Persian Gulf region.

These basins formed by extension from left-lateral, strike-slip (rifting and wrenching) movement of the Najd transform fault system, which ultimately moved the Arabian plate with a cumulative strike-slip component some 300 km eastward (Schmidt et al., 1979; Loosveld et al., 1996). Therefore, evaporite sequences in the salt basins were deposited in a tectonically active basin and, consequently, an important role for tectonic can be inferred.

It is tempting to suggest that the extension, which led to the subsidence of the salt basins predates transcurrent motion along the Najd faults, was caused by intra-plate tensional stresses and crustal thinning directly related to the final phase of the Pan-African Orogeny. It is possible, particularly in the Hormoz Salt Basin that these linear, evaporitic grabens may have developed into incipient rift basin (Husseini, 1988) before the stress regime change and extension ceased, some time close to the start of the Cambrian. Nevertheless direct lithologic evidence for such a geodynamic model is sparse at present.

In the Zagros Mountains, the syn-rift Hormoz complex is composed of evaporites, carbonates, clastics and volcanic rocks which are probably syn-sedimentary (Kent, 1970). Kent deduced that the saline units might be two or more in number and overlain and underlain by more that one kilometer of non-evaporitic beds cropping out as salt plugs and salt glaciers (Wolfart, 1981).

Continued basinal subsidence was required for salt accumulation. As mentioned previously, the NW-SE trending Hormoz complex is considered to be

syn-rift, while the NE-SW south Oman Salt Basin is a rift, bounded by extensional faults (Husseini and Husseini, 1990).

Much of the Hormoz complex in coastal areas of southern Persian Gulf has been shown to have formed in NS trending extensional rifts on the older crystalline Precambrian basement (Edgell, 1992). However, the main NW-SE control is by early dextral faulting along the Zagros Line, as suggested by Stocklin, (1968b) and Husseini (1988), with the Zagros Fault Line forming a northeastern border to the Hormoz complex. Exception is the evaporites of Proterozoic Desu Formation near Kerman and the salt of Ravar Formation in eastern Iran. The evaporites of Hormoz complex can be correlated with the Desu Series and Ravar Formation of eastern Iran (Stocklin, 1962; Huchriede et al., 1962). The Soltanieh Formation in the northern Iran is also possible time-equivalent deposits. In general, Soltanieh Formation is considered to be broadly correlative to the Hormoz complex of the Persian Gulf and Zagros Mountains which contains only stromatolite, mostly *Collenia.*

To the east of the Zagros Suture, Late Precambrian is represented by Soltanieh Formation consisting of massive to well bedded stromatolitic dolostones, interbedded with dark shales, siltstones and black chert bands. Within this formation, the Chapoglou shale, which consists of slaty-shale is interbedded with thin limestone and calcareous shale and may be interpreted as maximum transgression phase between the two overlying and underlying shallow marine dolostones of the Soltanieh Formation and the two evaporites cycles of the Hormoz salt.

The Soltanieh dolostones overlies the Precambrian Kahar and Morad metamorphics. Kahar Formation of latest Proterozoic age is a monotonous sequence of more than one kilometer of argillaceous and siliceous slate with intercalation of quartzite, dolostones and tuff. The Kahar Formation of northern Iran and its equivalents in high Zagros have much in common with the Morad series in central Iran.

In the Alborz Mountains of northern Iran, the Soltanieh Formation overlies the Bayandor Formation consisting of nearly 500 meters of clastics intercalated with dolostones stringers (Stocklin et al., 1964; Wolfart, 1983). Husseini (1988) interpreted the Hormoz complex as a syn-rift sequence and the Soltanieh and Bayandor as the time-equivalent platform sequence deposited on the Paleo-Tethys side of the Zagros Suture. Such an interpretation implies that the Hormoz complex and associated evaporite deposits were intra-continental.

There is evidence suggesting that the basement has been already faulted along the Arabian Trend in the Late Precambrian. Therefore, the sediments of the Hormoz complex were deposited in a series of NS troughs, between uplifts or headlands. Repeated rejuvenation of these uplifts, or basement horsts, particularly along the N-S Arabian Trend, is reflected in the pattern of deposition throughout the Phanerozoic. Furthermore, the basement of the Persian Gulf basins appears to have been a checkerboard of positive and negative blocks. Even the oil-bearing anticlines in the southern Persian Gulf region and

in Arabia are thought to have resulted from movement of basement blocks rather than the compression (Weeks, 1957).

In Iran, the Hormoz Salt Basin was linked towards the north with an open marine trough or re-entrant in the region of what is now the Caspian Sea. Kent (1979, 1987) suggested that the Hormoz Salt Basin was isolated from the open ocean in the north by a system of NW-SE trending Precambrian structural elements which were later reactivated into structural belts such as the Zagros Mountains.

The salt domes mushrooming in the northern Persian Gulf appears to be sharply limited on the northeast by the main thrust line of the Zagros; the line means certainly more than a mere Tertiary thrust front, and it may have acted as an important facies divider since Early Mesozoic time. Furthermore, the Zagros Fault line seems to have acted as an ancient uplifted border to the Neoproterozoic Hormoz evaporite basin (Stocklin, 1968b), or as a major, right-lateral strike-slip fault line (Husseini and Husseini, 1990).

As far as the dating will allow, it appears that the period of most rapid subsidence in the Infra-Cambrian Rifted Salt Basins coincided with the last pulse of the Pan-African Orogeny and final pulse of collision produced an N-S trending suture and had a median age of about 590 Ma.

SALT BASINS

The salt basins of the Persian Gulf region are numerous. The salt of the South Persian Gulf basin probably extends into parts of the Rub al Khali in Saudi Arabia and is separated from the north Persian Gulf salt basins by a NE-SW basement high, which extends from the Qatar-Gavbandi Arch (see Figure 3-1) acting as a divide to the Zagros Mountain range.

From their inception, about 650Ma ago, the evaporite basins have been followed by continuous Phanerozoic sedimentation. Recent sedimentation is still taking place throughout more than 900 kilometer long Persian Gulf, which is the present day expression of the 2600 kilometer Persian Gulf Basin. Thus, the sedimentary sequences deposited within these rift salt basins include rocks ranging from Proterozoic to Recent age.

The Qatar-Gavbandi Arch served as a divide in the Basin possibly from Precambrian, when two salt basins existed on either side (Murris, 1980). West of the Arch, some of the structures seem to be related to the movement of the Infra-Cambrian Hormoz complex. In the southern Persian Gulf region, the central Oman high, which separates the Ghaba-South Oman Salt Basin from the Fahud Basin to the north, may play the same role as the Qatar-Gavbandi Arch in separating the Northern and Southern Persian Gulf Salt Basin.

The rift salt basins are approximately perpendicular to the Najd Fault Zone and the orogenic collision front and are related to escape tectonism (Molnar and Tapponier, 1975; Stern, 1994). In the Persian Gulf region, the Infra-Cambrian rifted salt basins include, but are not restricted to, the North and

South Hormoz Salt Basins and the Ghaba, Fahud, and South Oman (Ara) Salt Basins of Oman. Smaller-scale Infra-Cambrian rift basins of similar origin and sedimentary fill, recently have been recognized on seismic profiles in the central and eastern portion of the Rub 'al Khali Basin and along the main Najd fault trend (see figure 3-3) (Kornet et al., 2001; Sharland et al., 2001; Ziegler, 2001).

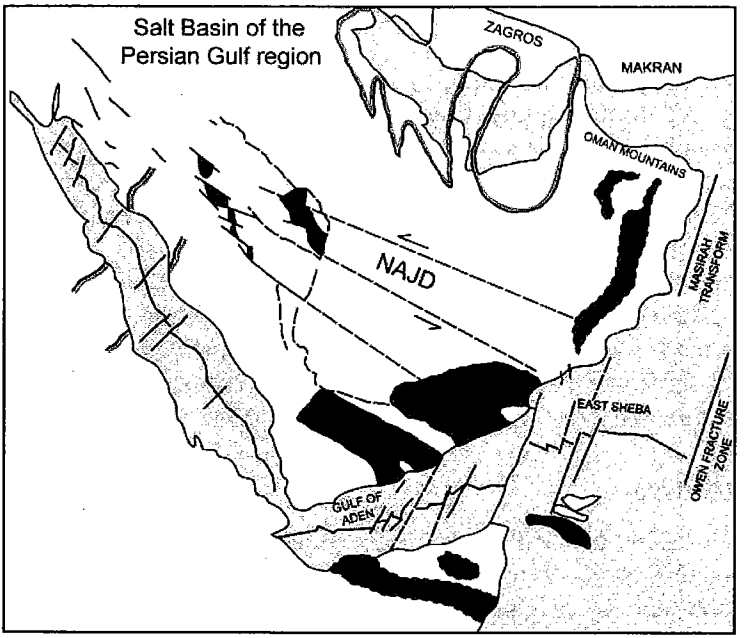

Figure 3-3 Major fault system and rift basins of the Persian Gulf and Arabian Peninsula formed during the Infra-Cambrian Najd tectonic Event (Modified from Loosveld et al., 1996)

In Oman, clastic rocks compose most of the lower Paleozoic part of the section, whereas Permian through Tertiary rocks are predominantly carbonate and reflect climatic variations due to the changing paleolatitude of the Arabian plate through geologic time (Beydoun, 1991). The subsurface extents of these clastic-carbonate-evaporitic deposits presently can only be conjectural. Gorin et al. (1982) extended them under much of Arabia and the adjacent portions on India and central Iran where the Paleo-Tethyan border of Gondwana was located.

The Zagros and Dibba faults sharply define the eastern side of the Hormoz Salt Basin. The extent of the Hormoz Salt to the north and west is less well-defined. According to Al-Husseini (2000) the salt is believed to be absent along the Qatar-Gavbandi Arch and its northeast trending extension towards the Zagros Suture. To the west it thins out toward the Rub'Al Khali embayment. The extent of the Hormoz salt in the Arabian plate is not fully mapped.

Certain large-scale basement irregularities are recognized by facies variations of the oldest, Infra-Cambrian covering sediments show that the fundamental framework of the present Alpine structure of Iran was inherited from Baikalian basement trends. Thus, Hormoz Salt Basin of south Iran and Arabia was sharply limited in the east by a north-trending basement swell, the "Oman High". A straight northern extension of this seems to appear in the western margin of the Lut Block of eastern part of Iran, which forms the eastern limit of the small Infra-Cambrian salt basin north of Kerman (Stocklin, 1968a), and of a lower Cambrian gypsum facies north of Tabas (Ruttner et al., 1968). Therefore, continuity is suggested with the late Precambrian carbonate platform of central Iran, which is the lateral extension and equivalent of the Hormoz complex. The Kerman salt occurs on the eastern side of this carbonate platform.

HORMOZ COMPLEX

Tavernier (1642) were one of the first pioneers reported the Hormoz Formation in his memoirs while traveling from Turkey through Iran on expedition to India. Prior to that Sillva Figueroa (1617) reported salt in the Persian Gulf region while visiting Hormoz Island. More than two centuries later, based on geological observations, Blanford (1872) introduced the name Hormoz salt Formation for the complex salt and associated sedimentary and igneous rocks that crop out on Hormoz Island in the Persian Gulf (cited in Motiei, 1993).

Geologically, the Hormoz complex was first described by Pilgrim (1908, 1922, 1924), and Busk and Mayo (1918). Pilgrim (1908) introduced the term "Hormoz series" for a unit of evaporite sediments, which essentially form the diapirs of Zagros Mountains and the Persian Gulf. To some degree, he related all the rock types brought to the surface by salt movement stratigraphically to the Hormoz salt. However, diapiric nature of the Hormoz rocks was first pointed out by Holland in 1915 (cited in Ala, 1974). The plugs still were regarded generally as representing the outcrops of a normally folded sequence, but Pilgrim (1924) stressed his idea in the intrusive nature of the domes.

The works of Richardson (1926, 1928) and Lees (1927, 1931) marked the beginnings of modern studies of the Hormoz salt plugs, and subsequently 63 of them were mapped and described briefly by de Bockh et al. (1929). According to Motiei (2003), several unpublished descriptive investigations regarding the age and stratigraphy of the Hormoz series had been produced for oil companies by the mid 1920's.

Useful contributions were made by Gansser (1960) and Ala (1974) who reviewed the geology of salt domes in various parts of Iran, including the Persian Gulf, and summarized the current ideas of their origin. Player (1969), N.I.O.C (1977), Esfandiyari and Barzegar (1979), Stocklin and Nabavi (1975), Ahmadzadeh-Heravi et al. (1990), Farhoudi (1984), Farhoudi and

Ghazizadeh (1993) and most recently Bahroudi (2005) have published works on the south Iranian and Persian Gulf salt domes.

The first systematic study of these plugs was Harrison's great contribution, the results of which were published in 1930, 1931, and 1956. Later, the diapiric islands and salt structures of the Persian Gulf were studied by O'Brien (1957; 1968) Stocklin (1968) and Halbouty (1979).

Kent (1958) investigated nine plugs and later published the results of some of the most recent work on the south Iranian salt dome province (1970, 1979). These two articles are particularly significant, as they contain information on the age of the salt and the structural setting of the plugs in relation to regional tectonics in the Persian Gulf Basin.

Characteristics of Hormoz Complex

In the Iranian offshore of the Persian Gulf the oldest sediments encountered in the wells is mostly the Permian Dalan carbonate to pre-Dalan Formation. The pre-Dalan Faraghan clastic Formation has been only encountered in the deep well drilled on the Salman oil Field in the Persian Gulf. Therefore, the lithostratigraphy and thickness of the sediments between Hormoz salt and Dalan have not been recognized beneath the Persian Gulf. Nevertheless, the Hormoz evaporitic complex is known from outcrops along the southern border of the Zagros thrust, Fars region, some of the Islands and also from seismic data in the Persian Gulf (Edgel, 1996; Letouzey and Sherkati, 2003).

The Hormoz complex of the Persian Gulf is composed of massive rock salt, anhydrite, fetid limestone, dark cherty dolomite, red sandstone, shales and volcanic rocks. The thickness of the Hormoz complex is estimated to exceed one kilometer in Zagros Range to an estimated 2.3 kilometers beneath certain anticlines in southern Iran. Therefore, the thicknesses of the Hormoz complex vary considerably with the maximum thickness of the Formation occurring near Bandar Abbas in the northern coast of the Persian Gulf (Motiei, 1993).

The sediments of the Hormoz complex and its type section in the Hormoz Island typically comprise carbonates, gypsum, halite, variegated shales, and siltstones often displaying the characteristics of sabkha cycles (Ala, 1974). There are also interlayers of red iron oxide associated with other rocks units. The bulk of the iron ore is red hematite and limonite, with blocks of lamellar hematite commonly occurring. Hematite iron ore is mined on the south side of the Hormoz Island. Igneous and metamorphic fragments are also commonly reported in the Hormoz diapirs.

A wide range of igneous rock types occurs within the Hormoz complex and both intrusive and extrusive strata are recorded. The presence of pillow lavas suggests a subaqueous origin for some of the sequence. The volcanics tend to be predominantly acidic (quartz porphyries and rhyolite), although intermediate and basic igneous rocks are also found. Contact metamorphic

effects are described and it is suggested that the igneous phase was largely penecontemporaneous with the sedimentation of the complex (Alavi, 2004). Not only rock salt is present but also potassium later is incorporated into the salt as demonstrated by the water analysis reported by Furst (1976). In addition, Huber (1977) noted that brine analyzed from associated salt springs shows the presence of a certain amount of potash salts and sulfate.

Hormoz complex also includes exotic blocks of gabbro, granitoids, and metamorphic rocks (slate, phyllite, schist) presumably derived from underlying basement; grades laterally toward the northeast into interbedded dolostones and fissile shale (termed Soltanieh in the Zagros imbricate zone) (Alavi, 2004).

The late Precambrian orogeny (around 850-570 Ma) and its associated magmatism represent an earlier compressional phase before the Hormoz complex deposition. The Upper Precambrian acid and basic alkali-volcanics are subsequent to the Late Precambrian orogeny and presumably developed during the rifting that formed the sedimentary basins in which the Hormoz Salt and the Upper Precambrian-Lower Cambrian sediments were deposited, and might be associated with this rifting (Berberian and King, 1981).

Debate has also centered on the significance of the igneous and metamorphic rocks in the Hormoz complex. The metamorphic suite appears to be derived from the underlying basement, although the precise process (s) of incorporation is still uncertain. In an overview of the Hormoz salt development (Kent, 1979); various theories regarding the incorporation are described.

One of the original suggestions was that the salt, moving towards the diapiric center, acted in a manner similar to a glacier by plucking blocks from irregularities in the basement floor, carrying them upwards during its rise to the surface. A later interpretation suggested that they represent olistostromic deposits that developed within the sedimentary pile at the base of the salt layer. A third alternative suggested that the blocks were detached from loose fault-scarp surfaces and attributed the distribution of the diapirs largely to basement dislocations.

According to Talbot and Alavi (1996) there has been little attempt to discern details in the Hormoz complex geologic history. However, their work on Zagros salt extrusions suggests that Hormoz lithofacies can be divided into the older and younger sequence.

Although generally strongly disturbed, some sequence can be recognized in the Hormoz complex. Schroeder (1946) and Huber (1977) have recognized a Lower Hormoz, mainly evaporitic deposit, consisting of 'white and light red, coarse crystalline rock salt with, probably condesary, flow induced banding of impure salt and anhydrite with crushed dolomite, basic igneous rocks and red siltstones.

In the early 1960's the discovery of non-diapiric equivalents of Hormoz strata enabled the establishment of an internal stratigraphy within the sequence. The succession contained a basal sabkha sequence (i.e., the Lower

Evaporites), overlain by a lower Cambrian clastic fluvial to marine sequence (i.e., Lalun Formation) capped by another evaporitic package of lower to middle Cambrian age (the Upper Evaporites) (Bahroudi, 2003).

The portion of rock salt decreases towards the top of the member, whereas the number of gypsum beds increases. An evaporitic cycle generally begins with carbonates and sulfates succeeded by rock salt and, sometimes, by potassium precipitation; therefore, it could be concluded that the lower Hormoz member represent such an evaporitic cycle with rock salt domination in thickness.

The lower Hormoz conformably underlying the Lalun sandstone and corresponds to the widespread "Infra-Cambrian" sedimentary succession of Iranian plateau (Stocklin, 1972). In its non-evaporitic member, this group consists characteristically of thick cherty and stromatolitic dolomites (Soltanieh dolomite) associated with dark, fetid limestone, red sandstone and silty shales, exposed in many areas including the High Zagros and the Soltanieh Mountain (Stocklin, 1974). Thus, in southern Iran, the Hormoz complex laterally grades into the gypsum bearing dolostones and limestones of the Soltanieh Formation, deposited on the carbonate platform separating the evaporite basin from the open ocean (Zharkov, 1984).

The upper Hormoz member that crops out on the rim of the Hormoz Island salt piercement was investigated in detail at the type locality and particularly on many diapirs of the mainland (Wolf, 1959; Gansser, 1960); however, it is difficult to present complete profile. On the salt of the lower member, lies a unit of purple silty shale, especially with micaceous siltstone and fine-grained sandstone of the same color. White and pink gypsum beds and gypsum stringers are intercalated. An alteration of these clastic sediments with gypsum layers can often be observed. Beds of tuff breccia, agglomerate and conglomerate are also found.

The sedimentary sequences, which include the Hormoz, Rizu and Desu Formations, were laid down in subsiding basins in which laminated dolomites, evaporites and occasional iron sulfides accumulated. These areas were bounded in central and northwestern Iran by carbonate shelves, which in turn interfingers northward with more clastic sequences that include the older sediments, as well as those of the younger Soltanieh and Barout Formations.

The siltstone and shale of the Zaigun Formation in northern, central and southwestern Iran mark the terminal, regressive phase of the Infra-Cambrian and indicate partly subaerial, arid conditions. Evidence of the northwestern part of Iran suggests the presence of an erosional unconformity above the Zaigun Formation, separating Infra-Cambrian succession from Lalun Formation.

The succession in Oman provides a clear parallel with the Infra-Cambrian better known Infra-Cambrian of Iran, despite the differences in the stratigraphy recorded. In both sides of the respected areas in the Persian Gulf, there is a repetition of the clastic-carbonate succession which both, ends with the deposition of evaporites. The Ara Formation of the Huqf Group parallels the

Kahar, Bayandor and Morad of Iran; while the three-fold division of the Soltanieh Formation, into lower and upper dolostone separated by the Chapoghlu Shale, matches the Khufai, Shuram and Buah Formations of the Huqf Group. The Ara salt then may be paralleled with the Barout Formation (Edgell, 1996).

Berberian and King (1981) in their correlation of the InfraCambrian units of the region, show a preference for including the Hormoz evaporitic unit and its lateral non-evaporitic equivalent, the Soltanieh and the shallow water arkosic Rizu group of Stocklin mainly in the lower Cambrian rather than the Infra-Cambrian.

DISTRIBUTION OF EVAPORITES

The distribution of the sedimentary facies and the system of Infra-Cambrian basins suggests that during this time, central Iran and Zagros together with the Salt Range of Pakistan, Arabia and possibly beyond were all part of the same landmass, probably covered by a common shallow sea. This implies that the Persian Gulf region was also covered by a shallow restricted sea, in which the Hormoz salt accumulated. The Hormoz salt depositional cycle occurs mostly in the offshore Persian Gulf area, is as much as 2.5 kilometers thick, and has produced numerous halokinetic structures (Edgell, 1996).

The eastern boundary of the Arabian plate, the Zagros fault, coincides with the eastern margin of Hormoz evaporites. The Hormoz Formation extends regionally beneath the Persian Gulf and the Zagros Mountains (Stockin, 1968) and correlates with Ara evaporites in southern Oman and Ghaba Basin (Figure 3-4).

The stratigraphic section varies in the onshore and offshore areas, as the Hormoz complex is geographically limited to the Infra-Cambrian rift basins that mostly underlie the offshore Persian Gulf. The Hormoz salt beds are found in coastal Saudi Arabia and offshore in northwestern Persian Gulf, but do not occur in major onshore fields (Greig, 1958). In Ghawar field, mostly the Infra-Cambrian clastics that have not yet been shown to contain hydrocarbons rest directly on Precambrian basement (Wender et al., 1998). Hormoz evaporites are also the oldest rocks recorded in UAE and a number of Islands at the western part of the U.A.E.

Salt basins in southern part of the Persian Gulf contain a well-preserved sedimentary sequence. More specifically, the evaporite-carbonate sequence provides a complete record of sedimentary, biological and geochemical event at the boundary. The salt-bearing part of the stratigraphic section is best represented by the Huqf Group of Oman, the oldest sediments in Oman. Throughout the entire southern Persian Gulf region the Hormoz sequence is referred to as the Huqf Group.

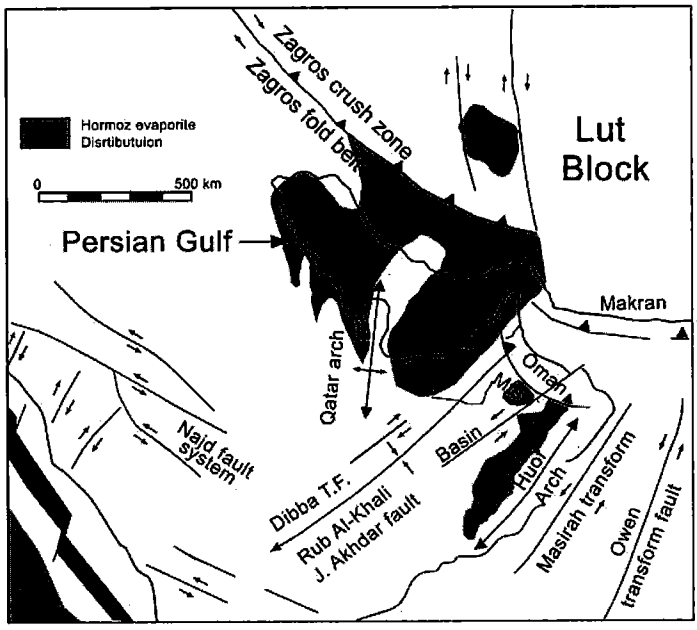

Figure 3-4. The distribution of the Hormoz evaporite and the current plate tectonic setting around the Persian Gulf region (modified from Marzouk and El-Sattar, 1994)

The massive salt of the Ara Formation is continuous under northern Oman and is laterally equivalent to the Hormoz complex of the Persian Gulf and Iran, and was probably its genetic continuation before major strike-slip faulting reshaped the margins of the rift basins. In Oman, the Huqf section has been partly exposed in two surface outcrops, and has been penetrated by deep drill cores.

The Huqf Supergroup consists of a lower group (i.e., Abu Mahara) of marine; diamictite-bearing sediments in structurally confined extensional basin, well imaged on seismic and excellently exposed in the central Oman Mountains. The middle group comprises an extensive carbonate dominated succession (i.e., Nafun) that onlaps the basin margin in the east and deepens down dip into the Oman Salt Basins. The upper group (Ara) records a phase of structural partitioning of the Huqf basin, volcanism, evaporite deposition and eventually the eastward shedding of coarse siliciclastics. Well-developed ignimbritic ashes yield dates around the Precambrian-Cambrian boundary. This group is up to 7 kilometers thick in the Ghaba Salt Basin (Visser, 1991), consisting of basal sands and shales followed by interbedded carbonates and sandstones, capped by the evaporites of the Ara Formation.

Apart from a number of southern Oman salt domes, in which blocks of Ara Formation dolomite have been rafted to the surface, the Ara is entirely missing on surface exposures. In outcrops associated with the salt plugs, the carbonates, mostly in the form of dolomites, are dark and fetid, locally silty or

sandy with chert nodules, and possibly stromatolites. These are similar to fetid dolomites encountered in Hormoz complex (Edgell, 1991).

The Ara Group contains a cyclic sequence of carbonates, evaporites, siliciclastic and organic-rich dolomite. In each cycle, evaporites represent a period of important basinwide restriction. Subsequent flooding by waters of normal salinity led to carbonate deposition, followed by slowly increasing restriction which ultimately terminated carbonate deposition. Ara Formation evaporites were deposited in geographically restricted basins during periods of low relative sea level where stratified, anoxic conditions periodically prevailed and organic-rich sediments and salt were deposited (Mattes and Morris, 1990; Edgell, 1991).

Fossils from the Ara Formation include typical Neoproterozoic (Late Riphaean to Vendian) acritarchs, such as *Protosphaerium* spp., and *Sticto-sphaeridium*.spp., as well as the cynobacterial genus *Angulocelaria Vologdin* and the primitive shelly fossil *Cloudina*, observed elsewhere in the latest Precambrian (Mattes and Morris, 1990).

Based on strontium isotope analyses of microscopic clay fraction of Ara Formation carbonates, the presence of shelly faunas and bioherms, very high sulfur isotope values the base of the Ara Formation appears to have an age of about 550-50 Ma. Very high sulfur isotope values characterized the Ara sulfates correlates with a sulfur isotope peak in Iran and Pakistan (see Holser, 1977). The age of Ara Formation is determined to be between 620 Ma and 570 Ma (Hughes-Clarke, 1988), which also supports the Infra-Cambrian (Riphaean) age of the more extensive Hormoz complex.

The carbonates contain algal mats and stromatolites and are rich in organic matter, which was deposited during periods when normal marine conditions prevailed in a basin setting varying from marginal to deep basinal. Thick halites and potash salts were deposited from which hypersalinity is inferred (Mattes and Morris, 1990).

The Ara Formation contains both direct and indirect evidence which show that it was deposited in association with a flourishing late Precambrian to early Cambrian biota. The main indirect evidence is the abundance of kerogenous organic matter that was deposited in Ara sediments throughout the basin. Direct indications include the abundance of stromatolite in many forms, microbial framestones and boundstones, and the presence of microfossils.

The occurrence of the Marine fossil *Cloudina* in Ara Group reefs indicates a connection to the open ocean during carbonate deposition (Mattes and Conway Morris, 1990). Seawater was progressively evaporated during final stages of carbonate deposition. This process eventually led to massive evaporite precipitation once sulfate super saturation was reached.

A paleolatitudinal position close to the equator favored an arid climate and evaporite deposits were originally widespread in the late Neo-Proterozoic-early Cambrian (Husseini and Husseini, 1990).

AGE OF THE HORMOZ COMPLEX

The precise age and stratigraphy of the Hormoz complex has been the subject of extensive debate since 1908. The earliest attempt to assign an age to the Hormoz complex was that of Pilgrim (1908), who considered it to be post Cretaceous. Richardson (1926) considered the age of Hormoz to be pre-Cretaceous but this was proved by the discovery of pre-Cretaceous trilobites in carbonate-shale sequence brought to the surface by the salt movement (Lees, 1927).

It has long been recognized that stromatolite mostly *Collenia* and *Trilobites* in different parts of the Hormoz sequence indicates ages ranging from late Neo-Proterozic to mid-Cambrian. The black shale marker ("Chapoghlou Shale") in the lower part of the Soltanieh dolomite found in many outcrops contain small discs of *Chuaria circularis* (also described as *Fermoria*), a characteristic fossil of the Vendian stage. In summary a late Proterozoic to middle Cambrian age can be assigned to Hormoz complex.

Since Lees discovered Mid-Cambrian trilobites in a Hormoz salt plug (de Boech et al., 1929, cited in Stocklin, 1968), most geologists have assigned a Cambrian age to the Hormoz salt. According to Stocklin (1968), the trilobites were actually found in limestone blocks included in the salt mass, but it was never proved whether these limestones were originally overlying or intercalated with salt. Gansser (1960) stressed the striking similarity of many Hormoz plugs with certain Olistortrome formations and questioned whether some of the Hormoz materials might not even be older than the salt.

After this finding, an early Cambrian age for the sequence was accepted. However, later radiometric data show that the sequence is, for the most part, of the late Proterozoic age, and algal stromatolitic material comparable with other Proterozoic regions has also been frequently recorded (Edgell, 1996).

Early work on the Hormoz complex indicate that due to the absence of fauna, the Hormoz complex of the diapiric Islands in the Persian Gulf was dated as Infra-Cambrian to early Cambrian. The age of the Hormoz complex is considered to be late Proterozoic, since it was found beneath thick lower Cambrian red sandstones of the Lalun Formation. However, radiometric dating of the igneous rocks produced values of 1040 to 540Ma (National Iranian Oil Company, 1978). This is partially in accordance with the U-Pb zircon dating of granitoids indicating age of 547±6 Ma (Alavi, 2004). The Lalun sandstone distributed over vast areas of Iran has apparent similarities with clastics of the upper Hormoz Member and holds the same stratigraphic position underneath the fossiliferous lower Cambrian (Stocklin, 1968).

The Infra-Cambrian age of the lower evaporite group is also confirmed by paleontological as well as radiometric evidence. The Soltanieh Dolomite (probably correlating with the main salt mass) lies some one kilometer below the oldest Paleozoic fossils recognized. These are the late lower Cambrian trilobite (Anomocare, etc.) initially recognized by King (1930) from beds im-

mediately overlying the Lalun sandstone in the Kerman area, and trilobite footprints attributable to the early Cambrian *Redlichia* zone in the upper part of the Lalun sandstone itself (Ruttner et al., 1968).

Motiei and Zahedinezhad (cited in Motiei, 1993) identified Middle Cambrian trilobites in the Hormoz complex, however, Zhakov (1984) based on time equivalency with Soltanieh dolomite advocated Infra-Cambrian age. This is in spit of the fact that Hamdi (1984) assigned a late Cambrian age for Soltanieh dolomite. Ghavidel Syooki (cited in Motiei, 2003) has also reported several species of achritaches in the upper part of the Hormoz complex in Darang Well No#1 at 2107 to 2110 meters depths indicating the lower to Middle Cambrian age for the complex.

Such an age determination is in agreement with the strontium isotope determination (Sr^{87}/Sr^{86}) of the Hormoz complex (Salah, 1996). In addition, Hurford et al (1984) dated the Hormoz complex as late Precambrian based on the dating of Hormoz apatites associated with red iron oxides, salt and other sedimentary and Igneous rocks of this complex.

ENVIRONMENT OF EVAPORITE DEPOSITION

The occurrence of shallow marine carbonates, supratidal evaporites and thick salts implies that the entire Persian Gulf region and a significant portion of the Arabian plate were near sea level. The enormous volume of evaporites deposited in large evaporitic/carbonate environment precludes the possibility that these evaporite deposits formed by simple evaporation within a closed body of ocean waters.

Most probably the exotic Hormoz sedimentary rocks were initially a multicyclic, dominantly evaporitic series with several very thick salt units interbedded between dolomites of different dates and with thick clastic rocks also interbedded (Kent, 1979).

In large basins such as Hormoz Basin with some degree of connection to the open sea, evaporation alone, in the absence of a tectonic or eustatic drive, can only raise salinity slightly before it is limited by either atmospheric humidity or by oceanic influx. During low stand of relative sea level, when oceanic influx is reduced or stopped altogether, brine concentrations can rise to the level of sulfate, halite or potassium salt saturation throughout large areas of the basin.

To form very thick Hormoz evaporite accumulation, some influx to the basin must be maintained. For precipitation of such a large evaporite deposits, the source of this influx was probably a restricted supply of sea water. More importantly, meteoric, hydrothermal and volcanogenic waters may also contribute significantly to evaporitic brine, particularly in fault-bonded basins such as the Hormoz system.

Deposition of the sequence was determined by generally restricted and evaporitic conditions (sulfate and halite) with intervening freshening phases

represented by carbonates. The repetition of similar evaporite-carbonate sequence demonstrated relatively stable arid conditions during deposition.

Carbonate and evaporite members of the Hormoz Formation formed during different phases of the basin's history. Within a single basin, carbonates and salt do not form synchronously on a basinwide scale. When salinity levels are high enough for halite precipitation in large volumes in the deeper parts of a basin, they are probably too high throughout the basin to allow carbonate-secreting organisms to flourish to the point where they can contribute significantly to sedimentation.

The Hormoz Formation in southern region of the Persian Gulf consists basically of a sequence of tectono-eustatically controlled lithologic cycles. The carbonate intervals were deposited during periods of relatively high sea level, when the basin was connected to an open ocean and must have had a positive water balance. The evaporites precipitated during low stands, when restricted inflow and net precipitation drew down the water level in the basin, eventually to the point where the basin floor consisted of large saline lakes surrounded by sandy desert with playas and sabkhas.

Sedimentary sequences formed in response to rapid subsidence, renewed tectonics and basin restriction (Loosveld et al., 1996). All sequences have a similar stratigraphic organization with a lower evaporitic part and an upper carbonate unit. Owing to their high sedimentation rates evaporites represent much shorter time intervals than the carbonates (Schreiber and Hsu, 1980).

LATE PRECAMBRIAN TO EARLY CAMBRIAN

In the Persian Gulf region, the Precambrian to lower Cambrian basement rocks are steeply dipping, fractured metasediments. Because the basement complex was subjected to N-S compression, subsequent rejuvenation of the dominant N-S structural elements also controlled the structural development of the sedimentary cover, and thus influenced the distribution of hydrocarbons. The N-S orientation of major basement involved structures, such as at Ghawar field, are easily identified on gravity maps where structural highs are generally associated with positive gravity anomalies (Wender et al., 1998).

The late Precambrian and Cambrian sequences of the Persian Gulf area began with partly cherty, grey and black dolomites with stromatolites, red shales, evaporites and some intrusive rocks. The sequence was followed by up to 700 meters of micaceous sandstones and sandy shales of early Precambrian age, which are overlain by up to 500 meters of dolomite, limestones and shales, containing a fauna with *Irania pisiformis* and *Redlichia chinensis*, indicative late early and mid-Cambrian age.

PALEOZOIC

Introduction

The limited Paleozoic outcrops in the Zagros are insufficient to determine the precise geological evolution of the region during this period. To overcome this problem, the Paleozoic stratigraphy of the Persian Gulf region has been based mostly on the outcrop investigations along the margins of the Arabian shield and within the Zagros region and exploration wells drilled generally over structural highs. Paleozoic sedimentary sequences ranging in age from Cambrian to Permian crop out and subcrop in an offlap manner away from the Arabian shelf.

In the Persian Gulf early Paleozoic sequences are located at great depths and drillings, except over structural highs do not penetrate them. The situation is different in Iranian territories where, the early Paleozoic rocks are cropping out at the surface. In addition, there are some drilled wells such as 0-4BIS located 44 km south of the Lavan Island in the Persian Gulf which penetrate through the entire sedimentary sequence down to the lower Paleozoic sequence. In fact Well # G3 and G4 in Golshan field penetrated through the Silurian shales in the Persian Gulf and provide valuable geologic information.

Most of the Paleozoic sequence is made up of epicontinental silisiclastics deposited in an intracratonic setting. Tethyan rifting (Permian and Triassic in age) was succeeded by essentially carbonate sediments along the entire paleomargin of the expanding Neo-Tethys Ocean. In general, the stable and shelf conditions indicated for the Cambrian seem to have persisted throughout the Paleozoic and early Mesozoic.

In the interior part of Iran the available data is essentially derived from outcrops and large areas, especially in the deeper parts of the basin, contain only sparse or no well data. In addition, most of the basin is covered by older vintages of seismic data that do not adequately image the Paleozoic section. All these considerations limit our understanding of the Paleozoic sequences. In the Persian Gulf region, thickness of the Paleozoic sediments as well as their lateral facies variations combined with tectonic activity is fundamental for the evolution of these sediments as potential hydrocarbon reservoirs.

Continued subsidence and marine sedimentations were interrupted by cyclic epeirogenic uplift movements allowing the marine organic-rich shales to alternate with the non-marine potential reservoir rocks. Wedge-out in these clastic sediments play a significant role in forming stratigraphic traps. These clastic sequences are significant targets where they overlie the shales and other potential source rocks.

GEOLOGIC SETTING OF PERSIAN GULF REGION

During the Paleozoic, the Persian Gulf region experienced a series of major uplifts and subsequent erosion marked by pronounced unconformities and

incised paleovalleys and subside the succession into depositional cycles of Middle Cambrian to Early Ordovician, Late Ordovician to Early Silurian, Middle Devonian and Middle Carboniferous to Late Permian. The great thickness of shallow water deposits and nature of the lithologic successions of the Early Paleozoic sediments represent deep trough sequence, which was tectonically active (see Alavi, 2004).

The geologic history of the Persian Gulf region and adjacent area during the Late Carboniferous-Permian is framed by two main tectonic events: the Mid-Devonian to Early Carboniferous Hercynian orogeny and the Zagros rifting which began during Late Permian and continued until Triassic time (Husseini, 1992). The evidence for major Hercynian tectonic in general is derived from marginal zones. The effects of the Late Paleozoic Hercynian Orogeny are reflected by uplift which is accompanied by erosion and diversification of topography.

There seems to be a reasonable ground for assuming some form of the Devonian-Carboniferous event (s), for which subduction or alternatively obduction have been proposed. In the Talesh Mountains of Iran (i.e. southwest of the Caspian Sea) and in Turkey, there are records of metamorphism, deformation and radiometric dates spanning from the late Devonian and early Carboniferous. In the Talesh Mountains, there are high-grade gneisses and ophiolitic rocks dated at 382±47, and 375±12 Ma. Also in the Sanandaj-Sirjan Belt, greenshist grade rocks have been dated as Devonian (Berberian and King, 1981) consistent with dates of 362 ±7 and 404±8 Ma from rocks in the mountains west of Sirjan (see Berberian and King, 1981).

Over the greater part of the Arabian region, contemporaneous with this event, major uplift was accompanied by erosion which stripped off hundred to few thousands of meters of sediments. The erosion was greater in the west. The sediments in those areas were eroded down to the Precambrian basement, although a fraction of those eroded sediments seems to have been preserved in the region.

The Paleozoic of the region consists of relatively uniform sedimentary sequences with prevailing continental to epicontinental conditions. Two main facies zones can be distinguished;

1) Zone of the Arabian facies on the west characterized by detrital clastic sediments generally unmetamorphosed, becoming slightly altered towards the east.

2) Zone of the Iranian facies characterized by sand and shale deposits laterally changing eastwards into the massive sequence of carbonates being in some cases metamorphosed.

The Zagros area throughout Paleozoic time was mainly affected by vertical movements (Stocklin, 1968b), as indicated by typical platform conditions and sedimentation ranging from terrigenous clastic in the Early Paleozoic time to dominating carbonate at the end of the Paleozoic; from Carboniferous to Late

Cretaceous time, carbonate deposits dominated the sedimentation (Kashfi, 1980).

Following stabilization of the Arabian shield, the maturely peneplaned surface of the igneous and metamorphic rocks supplied the foreland shelf with an influx of clastics that reflected continental to shallow-marine depositional environments. A primary supplier of these sedimentary rocks is believed to have been the igneous and metamorphic terrain of the Arabian shield. Paleozoic sandstones, which are almost lacking or very poor in non-quartz minerals, represent long-distance transportation or reworking of older sediments.

The igneous and metamorphics of the neighboring low-lying shield may have been important but were not the sole provenance of these sediments. The postulated eastward highlands and distance low-lying basement to the south also may have been important source of feldspar-free clastics. The limit to which the Paleozoic rocks extended over the shield can not be extrapolated because much of the sediments must have been eroded.

A predominantly clastic sedimentary regime prevailed during the Paleozoic. The sedimentary source areas generally laid to the south, while more open-marine conditions to the north. Within the sequence, there are marked unconformity and considerable lateral facies changes. Terrestrial to shallow-marine clastics with minor limestones comprise the lower Paleozoic record, but the upper Paleozoic is relatively poorly represented by sediments.

From Cambrian through Devonian, thick sequences of Paleozoic clastics with some minor carbonates were deposited regionally. However, the Hercynian uplift and erosion, removed an increasing amount of section to the northwest. Finally a thin veneer of Late Cretaceous and Tertiary clastics and carbonate sediments overlaid the Paleozoic sequence (see, Ziegler, 2001).

Glaciations during Ordovician affected much of western Arabia, and a great deal of the Ordovician sediments in central Arabia deposited by glacial-fluvial melt water from retreating ice (McGillivray and Husseini, 1992). The glacial influences decrease northwards, and in Iran and also eastern Turkey coastal deposits correspond in age to the glacial beds (Szabo and Kheradpir, 1978). During the advance and later retreat of these glacial systems, the Zarqa and the Sarah Formations in greater Ghawar area were deposited representing a complex of glacial and periglacial sequences (Vaslet, 1987).

The Zarqa Formation is dominated by glacial features and a continental environment succeeded by sub-aquatic deposits, except in the uppermost part, where laminated sandstone is interpreted as interglacial to marine. Glaciogenic sandstones of the Sarah Formation lying on top of the Zarqa Formation represent a low stand deposit associated with Gondwanaland glaciations in southern Persian Gulf (Senalp and Al-Laboun, 1996). The lower part of the Sarah was interpreted as glacial paleo-valley deposits, followed by fluvial-marine sediments and terminating in the upper part with subaquatic sedimentation in which terraces of a periglacial lacustraine environment persist locally but have become increasingly marine in character.

Lower Paleozoic strata throughout Iran, in much of Middle East and in parts of Pakistan and even Afghanistan have a similar stratigraphy consisting of upper Precambrian to lower Cambrian rhyolite and basalt overlain by lower Cambrian salt; dolostone and arkosic to quartzitic sandstones, and Middle Cambrian to Silurian carbonates and shales (see Berberian and King, 1981). This stratigraphic sequence records the development of a extensive Gondowanian passive continental margin following Late Precambrian orogenesis (Stocklin, 1974).

Lees (1950, 1953) noted an absence of angular unconformity in the geologic record, and concluded that the Early Paleozoic was a time of mild tectonic activities. Stocklin (1968) agreed with this view and pointed out that tectonic calm continued through succeeding periods until the middle Triassic, at which time areas of central Iran east of the Persian Gulf became tectonically active.

Throughout Paleozoic to Early Permian time the Middle East including the Persian Gulf region, with the exception of northeastern Iran, lay on a stable continental shelf formed by the Afro-Arabian Massif. The Zagros sedimentary Basin was also part of the main Tethys Ocean system (Kashfi, 1976). Thus, the Paleozoic deposits of the Zagros Basin are possibly underlain by an eastward continuation of the granitic and metamorphosed Precambrian Arabian shield. The geologic evolution of the Zagros Mountain Belt of Iran and the Arabian platform bordering the Persian Gulf during the Paleozoic and early Mesozoic was characterized by platform-type and continental-margin type sedimentation (Berberian and King, 1981).

The Paleozoic sediments reflect transgression with progressively younger strata overstepping the basement sequence onto the Arabian Massif. The massif remained stable and was subjected to only epeirogenic movement. For much of its evolution, it was an uplifted area, which provided a source for intermittent clastic detritus. The platform, a relatively simple and undisturbed broad shelf bordering the positive massive, was the site of siliciclastic-dominant continental to shallow marine deposition, in lower Permian time, subordinate mixed clastic-carbonate shallow marine conditions (Berberian and King, 1981).

PALEOCLIMATC SYNOPSIS

The Persian Gulf and surrounding region as part of the *Gondwana* super continent lay about midway between the South Pole and the equator throughout the Paleozoic Era when the glacial and other cold climate systems were active. Initially it was geometrically 'up-side-down' (figure 3-5) relative to the poles as Gondwana moved south across the South Pole (and came up the other side the 'right-way up') under the influence of plate-tectonic processes. Because Arabia's southern traverse was undertaken largely in temperate latitudes, most of the Paleozoic rocks comprise sandstones and shales.

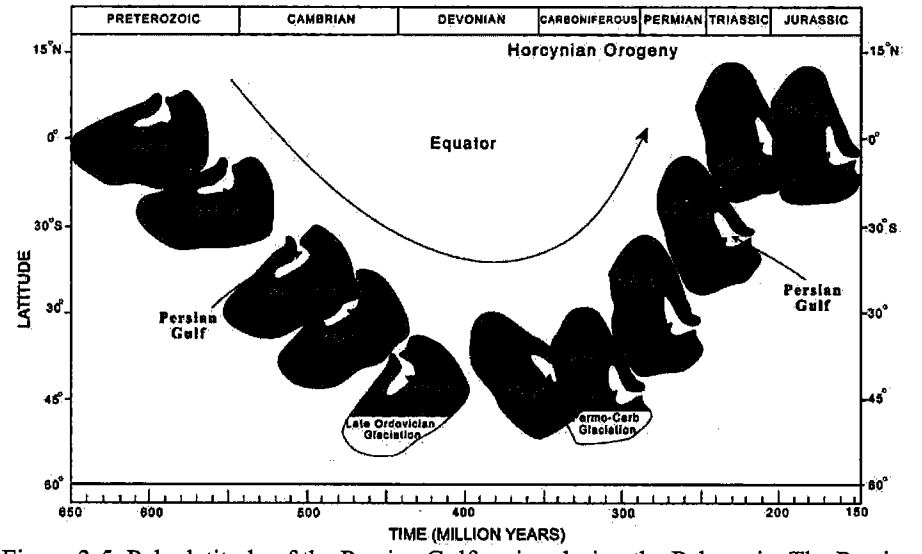

Figure 3-5. Paleolatitude of the Persian Gulf region during the Paleozoic. The Persian Gulf region reached its most southerly position in the Late Ordovician to Permian-Carboniferous where this position coincides with two periods of glaciations.

Two climatic events occurred in the southern Persian Gulf region during Paleozoic time. The first is the discovery of evidence for the early Paleozoic glaciations in central Arabia. Proglacially-deposited sandstones interfingure laterally with the tillites, and paleovalleys cut into earlier Ordovician strata of the lower part of Ordovician sequence (McClure, 1978). Ice movement seems to have been towards the northeast, in the direction of a shallow shelf. Thus, the northern Afro-Arabian part of Gondwana marked a margin of the southern polar glacial epicenter.

Evidence of Permo-Carboniferous glaciation in Arabian continent has been accumulating for a number of years and has now built into a cohesive picture (Kornet et al., 2000). At the end of the Paleozoic Era, there was a relatively rapid change in climatic conditions required for a late Carboniferous to early Permian glaciation to warm waters of late Permian coral reefs and carbonate environments.

GONDWANA AND PERSIAN GULF

During the Paleozoic, Iran, Turkey and the Arabian plate (which now has the Zagros belt situated along its northeastern border) collectively with Afghanistan and India, made up the long, very wide and stable passive margin of Gondwana bordering the Paleo-Tethys Ocean to the north. For much of the Paleozoic Era, a major ocean known as Tethys separated Gondwana from Asia. The passive margin remained remarkably stable throughout much of its history with only slow but steady, probably thermally driven, subsidence in

response to initial late Precambrian-Cambrian rifting that allowed wide-spread sheet-like deposition of shallow marine sediments. As a result the Early Paleozoic deposits which stretch from the Zagros to central and northern Iran show a compatible depositional history.

Structural, lithologic, paleontologic, and paleoclimatic evidences indicate that, during the late Paleozoic, the platform of Iran had a geographic position at the northern passive margin of Gondwana, being separated from Laurasia by Paleo-Tethys Ocean (Stocklin, 1974; Stampfli and Pillevuit, 1993). However, geologic information indicates that interior Iran started to follow its own tectonomagnetic evolution separated from Gondwana at least since Early Silurian (Berberian and King, 1981; Stocklin, 1974; Takin, 1972).

In the late Permian a continental block comprising Anatolia, Central Iran, Helmand (south Afghanistan) and perhaps Tibet, separated from the Arabian-Indian margin of Gondwana to form a microcontinent (Glennie, 1995). The Paleo-Tethys, a triangular-shaped Paleozoic ocean between Gondwana and Eurasia, was largely subducted before the northernmost Gondwana fragment collided with Eurasia. The new ocean was referred to as the Neo-Tethys by Stocklin (1974) (see figure 3-6). Thus, fragmentation of Gondwana started in Permian when the northernmost fragments (central Iran, Lut Block, and Afghanistan) began moving toward the Eurasian landmass. Northward movements of the Indo-Pakistan subcontinent and the Afro-Arabian continent in the late Cretaceous followed this northward flight.

The tectonic history of the Persian Gulf in the Mesozoic onward is connected with Permian opening and the late Cretaceous-Paleogene closure of the southern Neo-Tethys Ocean (Metour et al., 1995). During the late Permian continental rifting and spreading occurred along present-day Zagros Suture and Gulf of Oman as the Neo-Tethys Ocean started to develop. The deposition of extensive carbonates and anhydrites occurred over the entire Arabian shelf in shallow marine to tidal flat environments. The depositional environments were predominantly intertidal and sabkha together with subtidal carbonate sand shoals, lagoons and sandbars.

CAMBRIAN IN NORTHERN PERSIAN GULF

Marine transgression characterized by clastic and shallow water deposits took place during Cambrian time, and similar sedimentation continued to early Carboniferous. After deposition of the Hormoz complex, and deposition of initial Infra-Cambrian carbonate-evaporite sequences, clastic regime prevailed throughout the Persian Gulf region. This includes shallow water red arkosic sandstones and shales of Cambrian age. Thus, early Cambrian was a period with widespread clastic sedimentation in shallow environments.

Figure 3-6. The Palegeographic reconstruction of the Persian Gulf at the end of Paleozoic Era and opening of the NeoTethys Ocean (modified from Hughes, 2000).

On the Iranian mainland a pre-Permian unconformity eliminates most of the lower Paleozoic sediments. Up to one kilometer of argillaceous and arenaceous sediments with subordinates limestones characterize the Cambrian deposits of the Zagros area. In southern Iran great thicknesses of salt deposited during the Cambrian later resulting in diapiric extrusions and intrusion in an extensive area including parts of the southern Persian Gulf.

The stratigraphy of the lower Paleozoic is not well known in the Persian Gulf area. In Bahrain however, a deep test penetrated a sequence of micaceous sandstones below the Permian that are believed to be Ordovician, Silurian and Carboniferous in age (Mina et al., 1967).

Lalun, Barout and Zaigun Formations

In the Iranian mainland, the basal Cambrian is the Lalun sandstone, consisting of purple red, cross bedded, arkosic, quartzitic sandstone, with thickness of up to one kilometer. Lalun sandstone is very uniform and persistent throughout Iran. It contains the same Cambrian fossils as the purple sandstones of Pakistan (Assereto, 1963; Wolfart 1981). Early Cambrian red beds and evaporites followed by the Middle Cambrian fossiliferous shales and Late Cambrian quartzite. This is a recurrent pattern in many regions throughout the world, indicative of Early Cambrian arid conditions, followed by a eustatic

rise of sea level, and a global equable climate. Marine transgression was universal in the middle Cambrian and indicates a general rise of sea level.

East of the Zagros Main fault, the Lalun sandstone is conformably underlain by a sequence of purple and variegated micaceous shale, sandstone, thick cherty dolomite and stromatolitic limestone with fossils such as *Cruziana*. Near the top of the Lalun Formation, the presence of *Redlichia Trilobite* (cf. Stocklin, 1972) provides evidence not only of an early to middle Cambrian age, but of the beginning of the late early Cambrian transgression.

Barout Formation of the Lower Cambrian consists of thin-bedded stromatolitic dolomite interbedded with locally tuffaceous shale. Above the final stromatolitic limestone, the Barout Formation passes gradually into the Zaigun Formation. The uppermost portion of the Barout Formation is exposed in Kuh-e-Dinar where some dolostones interbedded shales exposed at the base. The dolostones are strongly crystallized, thin bedded and laminated with stromatolites (Setudehnia, 1975). According to Setudehnia (1975) two main dolostone units are present in the lowermost and uppermost portion of the Formation with pronounced middle shale. The thickness of Barout Formation is more than 150 m.

Zaigun Formation of the Lower Cambrian age consists of variegated nonmarine micaceous shale becoming silty and sandy near the top. Lalun Formation is cross-bedded fluvial sandstones, siltstone, and shale with polymict conglomerate near top. Zaigun Formation is overlain by the sandy quartzite of the Lalun Sandstone.

Red clastic units, the Zaigun and Lalun, both of continental origin, reflect the terrain configuration after the epeirogenic uplifting and emergence. Outcrops of the Lalun sandstone is very persistent throughout southwest Zagros area and exposed along the Zard Kuh frontal thrust and the sequence correlated perfectly with the Lalun sandstones of the northern Iran. The lower contact of the Lalun sandstone with the underlying Zaigun Formation is rather transitional. The upper boundary is always sharp and is placed at the top of the pinkish weathering, friable, white sandstone. Near the top of the Lalun sandstone Cruziana-like tracks of middle to late Lower Cambrian have been identified (Gansser and Huber, 1962; Allenbach, 1966). The Lalun sandstone passes into the middle Cambrian limestones of Mila Formation (485 meters).

Lalun sandstone and the slightly older Hormoz complex are present both northeast and southwest of the alleged Zagros Suture Zone (Kashfi, 1992). These units or part of them are extended over a wide area from Arabia in the south to the Alborz Mountains in the north. According to Kashfi (1992) the correlation of the Lalun sandstone is so clear and decisive that there is no doubt concerning the tectonic unity of this region.

The Zaigun Formation in the Zagros is exposed in Kuh-e-Dinar, Kuh-e-Sabzu, Kuh-e-Lajin and Kuh-e-Gereh, where nearly 122 meters of this formation is measured without reaching the base. The Zaigun Formation is comparable in much detail with the Zaigun of the Central Alborz and Soltanieh

Mountains (Assereto, 1963; Setudehnia, 1975). This formation is mainly composed of varicolored shales which are generally micaceous and fissile becoming sandier upwards. The upper portion is coarser and is composed of intercalations of red fine-grained sandstones and shales. Both lower and upper contacts are apparently conformable and transitional.

Lalun and Zaigun sandstones are very widespread in Iran with no obvious sedimentary break between the two Formations. They were deposited over a wide area from Saudi Arabia and the Persian Gulf and also in the Alborz Mountains. These deposits also occur in Pakistan (i.e., purple sandstone of the salt Range), Afghanistan, and Turkey. They were followed by carbonates and marl/shale shallow marine deposition, and then by fully-fledged marine carbonates in middle and late Cambrian time. Stratigraphically, the lower Hamia group (Karim and Haradh Formations) is approximately equivalent to part of the Saq and Lalun Formations of Saudi Arabia and Iran respectively.

The sandstone sedimentation was followed by the deposition of dolomite, marl, and shale (with salt pseudomorphs) in shallow water conditions. The first fully marine carbonates deposited in mid to late Cambrian Epochs, and in Ordovician or the Silurian the marine transgression was terminated with the deposition of sandstone. The late early Cambrian transgression, which persisted into the late Cambrian, is marked by carbonates of the Mila Formation. Terrestrial to very shallow marine depositional environments are consistent with a passive and continuously connected continental margin at least between 600 and 400 Ma (Setudenia, 1975).

Following the extensional Najd rift phase, massive post-rift, and continental clastic of late early Cambrian age were deposited over most of the Arabian plate and major parts of Persian Gulf (see figure 3-7). These were sourced from interior Gondowana to the south and west, and are bounded below by a regional unconformity that represents a stable platform.

The Cambrian-Ordovician sequence of the northeastern shelf margin was principally clastic although there were short episodes of warmer-water carbonate deposition during the middle to late Cambrian. Cambrian to late Permian sediments western Persian Gulf are composed of a massive sequence of siliciclastics (i.e., >2.4 km) in the basinal areas to about 600 m on the crest of the Ghawar structure where significant erosion has occurred (Kornet et al., 2001).

In southwest Iran, the post rift Zaigun and Lalun Formations appear, on the basis of sedimentary structures (e.g., cross-bedding), to be non-marine. However, some parts of the Formations may have been deposited under marine conditions. The Lalun Formation consists of cross-bedded arkosic sandstones, and Cruziana trace fossils deposited under shallow water conditions. Due to the lack of age-diagnostic fossils, however, the formal Lalun Formation of northeast Iran has been dated as Early Cambrian.

By the late Early Cambrian, siliciclastic tidal flats were established in marginal settings, which grade basinwards into low-energy carbonate and

mixed clastics and carbonate tidal flats followed by subtidal carbonates. During this time, widespread dolomite, marl, and shale with salt pseudomorphs were deposited in a shallow, shelf sea (Member 1 of the Mila Formation) in the Alborz Mountains (Stocklin et al., 1964; Kushan 1973, 1978), in Central Iran (Ruttner et al., 1968), and in the Zagros Mountains (Harrison, 1930; King 1937; Setudehnia, 1975).

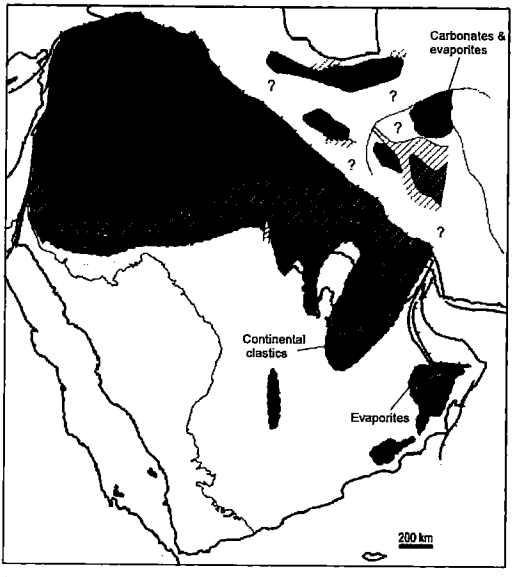

Figure 3-7. Middle Cambrian depositional environments in the Persian Gulf and neighboring region (adopted from Kornet et al., 2001).

In summary, the early Cambrian in the Zagros Basin consists of detritus sandstone, shale and conglomerate with limestone intercalations. The middle Cambrian, however, comprises of limestone, shale, and trilobite-bearing marlstone (Setudehnia, 1972), the late Cambrian is poorly preserved.

Mila Formation

Marine transgression was a global event in the middle Cambrian indicating a general rise in sea level. During this period, a vast shallow carbonate platform covered most of the northern Arabia and interior Iran. The carbonates of Mila Formation represent platform depositional conditions.

Mila Formation of middle to lower upper Cambrian is considered as transgressive sandstone resting disconformably on Lalun and overlain gradationally by shallow-marine trilobite-bearing, partly stromatolitic limestone and dolomitic limestone with thin shale intercalations near the top (Alavi, 2004).

In the eastern part of Iran and the Alborz Mountains in the north, Mila Formation is represented by sedimentary facies deposited in shallow marine environments. Stocklin (1972) divided the Mila Formation into five different

members. The lowest member (i.e., M-1) consists of alternating dolostones and marlstones while M-2 is mainly composed of limestone with subordinate marlestone and siltstone. Member-3 is made up of glauconitic limestone whereas M-4 consists of siltstone, sandstone, glauconitic limestone and marlstones. The last member, i.e., M-5 consists of well-bedded sandstone and shales of possible Ordovician age.

In interior Iran, carbonate deposition persisted into the late Cambrian. By the beginning of the late Cambrian Epoch, a fully marine environment with the deposition of fossiliferous limestones prevailed (Member 2 to 4 of the Mila Formation, middle to upper Cambrian). The Mila Formation, in northern Iran includes Cambrian strata equivalent in age, and of similar facies to the Andam Formation in Oman (Kushan, 1973; Wittke, 1984).

Mila Formation was introduced for the first time in southwest Zagros as a sequence of mainly dolostones, limestones and shales exposed north of Bazuft valley along Zard Kuh, Kuh-e-Gereh, Kuh-e-Lajin and Kuh-e-Sabzu. It has also been exposed along Kuh-e-Dinar where its thickness is greatly reduced and the upper portion is missing (Setudehnia, 1975).

In the southeastern Iran, equivalents of Mila Formation are represented by Zard Kuh Formation with average thickness of more than one kilometer, but thins from depocenters in Zard-Kuh (80 km southwest of Golpaygan) to the southeast (Kuh-e-Dinar) and northwest (Oshtoran-Kuh) (Setudehnia, 1975). The greater amount of detrital mica points to the metamorphic basement high on the pre-Zagros swell as a source.

Setudehnia (1975) divided the Mila Formation in the Zagros Basin into three distinctive members namely A, B and C. Member A with a thickness of 71.6 m, deposited during early middle Cambrian, consists of silty shale grading up into an alternation of silty shale with limestone and dolostones followed by massive coarse crystalline sucrosic dolostone. This member terminates with fine to coarse crystalline dolostones interbedded with red shales. Member A was measured at Kuh-e-Gereh where it has a thickness of 70 meters but in Zard Kuh this member is not exposed. No fossil was found in this member, but the regional correlation of this unit with the lower part of Mila Formation and the presence of middle Cambrian trilobites higher up in member C of the formation suggest an early middle Cambrian age for this unit.

The middle member (B) possibly middle Cambrian age has variable thickness ranging from 30 meters in Kuh-e-Dinar and reaching a maximum thickness of 138 meters in Zard Kuh. This unit is well exposed at Kuh-e-Gereh where it measures about 102 meters. This member consists of silty fractured shale containing salt pseudomorphs. The lower contact with member A is generally sharp whereas the upper contact with C member is transitional. No fossils have been reported from this unit, but the presence of middle Cambrian fauna in the overlying beds suggests a Middle Cambrian age for this member.

Member (C) which forms the uppermost member of the Mila Formation has been assigned middle to late Cambrian, posses the maximum thickness of

about 350 meters and mainly consists of interbedded and well-bedded limestones and shale with minor sandstones. The best exposure and most complete section were measured in Tang-e-Ilebeyk, Zard Kuh (Setudehnia, 1975) where more than 320 meters of this member is present. Abundant fossils in this member made it possible to determine the age of this unit. In addition the lower 240 meters of this member contain several fauna including: *Dorypygella, Solenoparia, Nisusia sp., Circotheca, Paradoxides sp., Oblus sp., Lingulell sp.,* indicating middle to late Cambrian age for the host rock.

The upper 83 meters of this member contains the following upper Cambrian fauna: *Billingsella* sp., *Billingsella* cf. *Rhomba, Circotheca* sp., aff. Jamesella, *Eurudagnostus, Agnostus, Coosina, Laganellus, Labiostria.* Thus, the age of this member is considered to be middle-upper Cambrian (Setudehnia, 1975).

The member C of the Mila Formation in Zard Kuh area is overlain conformably by the shale and sandstone of Ilebeybek Formation. The upper part of this formation is truncated by the disconformities in Kuh-e-Dinar where it measures only 42.7 meters in Tang-e-Putak and reduces in thickness southeastwards. Occurrence of trilobite species such as *aff. Polliellina* identified in this member, indicate a Middle Cambrian age.

Ilebeyk Formation

The name Ilebeyk was introduced for the first time inferring to a sequence of predominantly shales and sandstones exposed only along the Zard Kuh Mountain range (Setudehnia, 1975). According to this author, the regional disconformity at the base of the Permo-Carboniferous sequence truncates this formation towards the southeast. As a result, this unit disappears towards the southeast and is not present in Kuh-e-Gereh and Kuh-e-Dinar.

Ilebeyk Formation consists of trilobite-bearing, micaceous marine shale interbedded with thin-bedded siltstone and fine-grained sandstone, with rare thin intercalations of brachiopod-bearing limestone (Alavi, 2004). The following faunas have been identified in Ilebeyk Formation: *Saukia iranicus, Plectotrophia sp., Saratogia latefrons, Idahoia sp., Calvinella sp., Billingsella aff. Tonkiniana, Baltagnostus., Coosia sp., Meeria sp., Circotheca sp., Hyolithes sp., Lotagnostus, Pseudagnostus sp., Chuangia sp., Labiostria sp.*

The lower contact of this formation is equivalent to Mila Formation whereas the upper boundary corresponds to the Zard Kuh Formation. In Chaleesheh area, northwest of Zard Kuh, the upper contact is identified by the Faraghan Formation which is resting unconformably on the Ilebeyk Formation. The presence of this unconformity in the southeast is the main evidence that the Ilebeyk Formation is completely missing (Motiei, 2003).

Based on paleontological evidence, Setudehnia (1975) assigned a Middle Cambrian age for the Ilebeyk Formation which consists of sequence of nearly 280 meters of mainly shale and sandstones exposed along the Zard Kuh range.

The shale is fissile and micaceous, enclosing minor, thin fossiliferous limestone. The sandstone is micaceous, laminated and slightly cross-bedded.

Trilobite fossils identified in this formation, at approximately 33.5 meters below the top of the formation indicate an upper Cambrian age for the sedimentary sequence. Furthermore, the lowermost layer which contains the lower Ordovician trilobites lies at about 12.2 meters above the top of the formation. It is worth mentioning that the boundary of upper Cambrian-lower Ordovician has been taken arbitrarily at the lithological change that corresponds to the formational boundaries.

Berberian and King (1981) considered Ilebeyk as equivalent to the top part of the Mila Formation, but showed the Zard Kuh Formation as post Mila, occupying nearly all of the Ordovician and extending into early Silurian. However, based on the palynological investigation by Ghavidel-Seyooki (1990) the entire Ilebeyk Formation with exclusion of its 12.5 meters of upper part belongs to lower to upper Tromadocian of the early Ordovician age. The achritarchs reported for Ilbeyek Formation are *Volcanispheara.* Sp, *Acantodiacordium Sp. Moracanium* Sp and *Arbusclulidium.*Sp.

CAMBRIAN IN SOUTHERN PERSIAN GULF

The early Cambrian, lower Haima Group of Oman which includes Karim and Haradh of Oman Formations consist of lithic and quartzose, often micaceous sandstone, considered to have been deposited in a variety of environments ranging from scree fans to mature fluviatile or even aeolian conditions. It has been suggested that the range of environment and lithology may relate to a variety of synsedimentary structures resulting from deformation of the underlying evaporites of the Ara Formation (Hughes-Clarke, 1988).

Regionally, the Andam Formation and its equivalents extend into Oman and the marine sandstone and carbonate from Iran, where the Andam Formation is similar to the Mila in age and facies. Sandstones dominate the Andam Formation in Oman, with subordinate carbonate in the middle part. The lower part of the formation includes red beds with no fossils. Carbonates, including oolites, dolomites and stromatolites, appear in the middle member. The trilobite faunas from the Andam formation are of the Upper Cambrian in age. These faunas compare closely with those described from localities in Iran. Trilobites such as *Paracoosia*, *Torifera*, *Prochuangia, Dipyrgtes, Eosaukia and Changshania* are typical. Some of the trilobite tracks have been identified as *Cruziana semiplicata*, a species characteristic of upper Cambrian (Pollastro et al., 1999).

Wolfart (1981) showed the entire southern Persian Gulf region was dominated either by land in the west, or by continental to littoral clastics extending from NW to SE of the present Persian Gulf (figure 3-8). It can be established that a marine sandstone and carbonate belt extended southwards from Iran into the Persian Gulf and Arabian Peninsula. In Oman Salt Basins a marine-

influenced environment of deposition became established in the Late Cambrian.

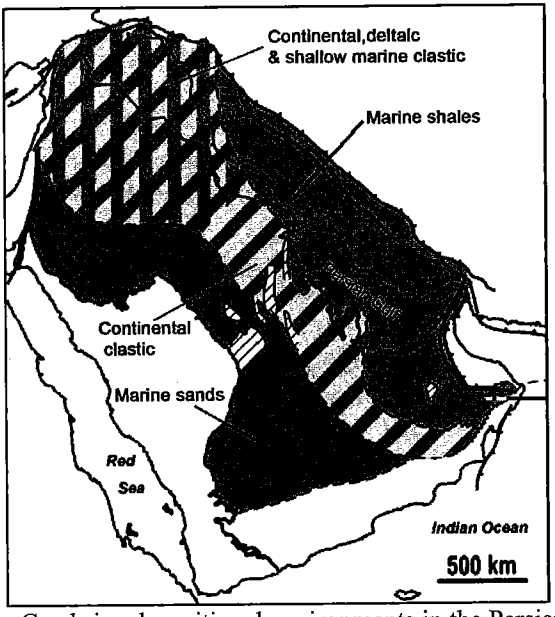

Figure 3-8. Late Cambrian depositional environments in the Persian Gulf and surrounding region (modified from Kornet et al., 2001)

The pre-Middle Permian clastics were deposited in terrestrial to shallow-marine environments on the stable passive margin of Gondwana. Four erosional events have been recognized in the Paleozoic section of the Greater Ghawar area in the southern Persian Gulf (Wender et al., 1998); however, the greatest amount of erosion was the result of uplift of the Arabian Plate associated with the Hercynian Orogeny. Variations in thickness of the pre-mid Permian section are due to broad epeirogenic uplifts of the Arabian plate, creating intracratonic sag basins with intervening broad arches.

ORDOVICIAN

The Cambrian-Ordovician boundary in the Persian Gulf region is weakly defined in the stratigraphic records. During Early Ordovician, the Arabian Platform was once more inundated, and deeper marine environment became established basinward in the north and interior Iran. By Ordovician-Silurian time, regression gave rise to the deposition of sandstones of shallow-water to terrestrial environment with widespread epicontinental deposition. There are vital sedimentary gaps in the sequence, as well as thickness and some facies variations, which are, indicative of either periodic epeirogenetic movements or eustatic sea-level fluctuations. No proper evidence of orogenesis is present (Berberain and King, 1981).

Marine sedimentary rocks of Ordovician and Silurian age, although absent in some parts of Iran, however they are widespread in southern Persian Gulf region between the Arabian shield and the Oman region. Furthermore, widely scattered occurrences are known from northern Persian Gulf (see figure 3-9).

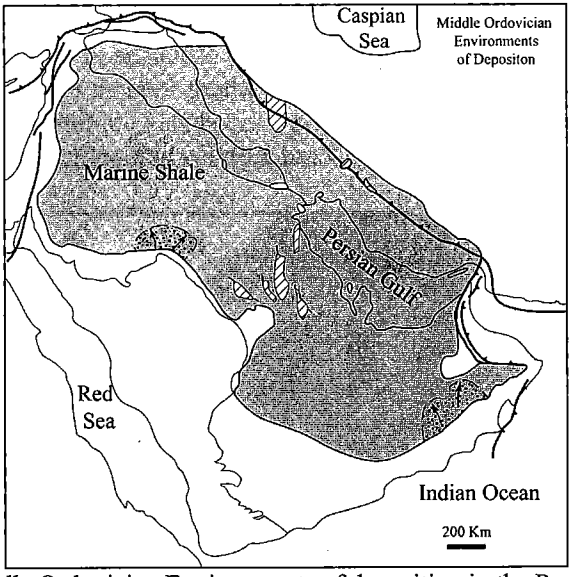

Figure 3-9. Middle Ordovician Environments of deposition in the Persian Gulf region and surrounding area (adopted from Konert et al., 2001).

Commencing the Early Ordovician time in Iran, the nature of the sediments changed from marine carbonates to quartzitic sandstone, indicating period of marine regression. Carbonates are rare in both the Ordovician and Silurian sequences. The lower Paleozoic sedimentary section of Iran, and probably to lesser extent, Iraq, is somewhat different from the rest of the Persian Gulf region and it contains a higher proportion of carbonates and has several small unconformities.

Mixed clastics and carbonate settings are found on the central Iran microplates (Rickards et al., 1994). Along the basin margin, braid-plain to braid-delta environments were formed and followed by coastal plain to inner-neritic clastic environment (Saq Formation in southern Persian Gulf). Over most of the southern Persian Gulf the upper part of the Saq Formation is characterized by late Cambrian and early Ordovician palynomorphs (Al-Hairi and Owen, 2000; Sharland et al., 2001).

In general, the upper Cambrian to lower Ordovician strata of the southern Persian Gulf comprises fluvial, alluvial and lacustrine sandstones with occasional shales. These strata rest unconformably on eroded Huqf sediments which change upwards to brackish and shallow marine shales and micaceous sandstones of upper Ordovician to Silurian age.

A clastic sequence crops out in southern Persian Gulf (i.e., Tabuk Formation in Saudi Arabia, Powers, 1968). In Iran, Zard Kuh Formation in the Zagros was deposited, signifying that the entire region was covered by marine graptolite-bearing shales during the Early Ordovician time (Setudehnia, 1975). During the middle Ordovician time, the Persian Gulf region was covered by a major marine prograding clastic sequence (Figure 3-10). These sediments were deposited in inner-neritic to estuarine or deltaic environments. Point source can be recognized in the southern Persian Gulf region. Basin inwards deposition of middle to outer-neritic shales continued during the Middle Ordovician and ended up with Zard Kuh Formation in Iran.

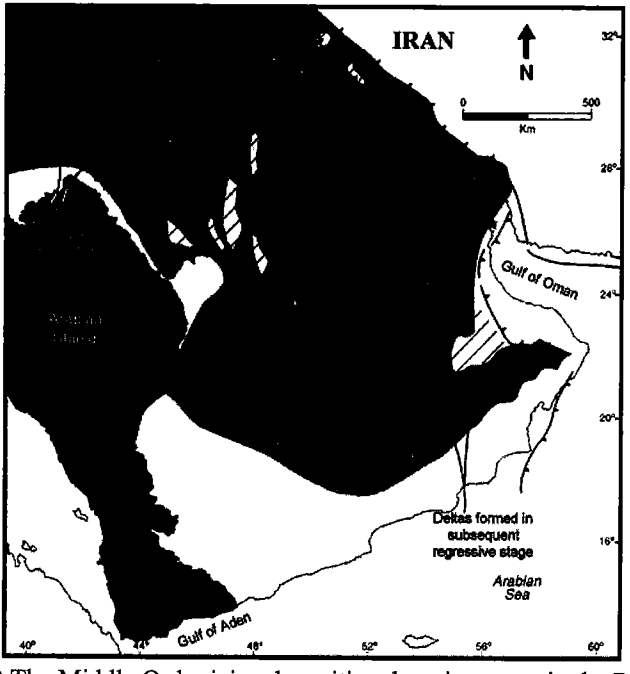

Figure 3-10.The Middle Ordovician depositional environment in the Persian Gulf region. Rapid transgression resulted in deposition of middle to outer neritic shales over most of the Persian Gulf. Locally the shales are rich in organic matter, indication restricted water circulation.

A marine regression dominated the late Ordovician following Caledonian orogenic activities and the extension of glacier ice sheet over a major portion of Gondwana. The upper Ordovician and Silurian sequence illustrate upward increase in shale content and a transgressive-regressive cycle has been recognized (Kornet et al., 2001, p.419). In southern Persian Gulf they are typically terrestrial to shallow marine cyclical clastic-dominated sediments. However, the sandstones pinch out basinwards and the shales contain some source potentials.

ORDOVICIAN IN NORTHERN PERSIAN GULF

Zard Kuh Formation

Ordovician sequence are mainly consists of shales and sandstones belonging to the Zard Kuh Formation. The term Zard Kuh Formation was initially introduced by Setudehnia (1975, p.26) in central Zagros including a sequence of predominantly shales intercalated with beds of sandstones exposed only in the Zard Kuh Mountain range. According to this author, lithologically, the unit can be divided into two members: the Lower and Upper members.

The Lower member is about 93 meters thick and it consists of varicolored micaceous laminated sandstones interlayered with shale. The lower contact with the underlying Ilebeyk Formation is sharp and conformable. The presence of trilobite *Dikelokeephalina cf. Asiatica* which is first found in the area indicates a lower Ordovician age for this member. The Upper member of the Zard Kuh Formation is also cropping out in Zard Kuh Mountain range and consists of sandstone and shales. The *graptolites* found in the siltstones include: *Didymograptus cf. extensus, Temnograptus sp, and Schizograptus sp.* The trilobite specimen collected from the same locality is identified as *Hysterolenus sp*, also of Ordovician age (Setudehnia, 1975).

Seyahou Formation

Seyahou Formation consists mainly of 747 meters thick shales with subordinate sandstones and limestones. The Seyahou Formation is the lowest Paleozoic unit in northern Bandar-Abbas (Tang Zakeen in Kuh-e-Faraghan locality) and consists of alternating shale, siltstone and sandstones (Ghavidel-Syooki and Winchester-Seeto, 2004). It contains well preserved *graptolites, brachiopods, acritarches* and *chitinozoans* (Ghavidel-Syooki, 1997, 2000; Ghavidel-Syooki and Khosravi, 1995 and Richards et al., 2000). As a result this rock unit has been assigned to the late Ordovician (Ghavidel-Syooki, 1997b; 2000; Richards et al., 2000). Ordovician and Silurian shales, rich in graptolite, are also present at Kuh-e-Gahkum and Kuh-e-Faraghan. About 140 meters of shale are exposed in these localities and a transgressive conglomerate lies at its base.

The basal Seyahou Formation consists of 20 meters thick conglomeratic sandstones resting on alternation of micaceous siltstones, sandstones, and fossiliferous sandy limestone (Beyk-Nouri, 1995; Motiei, 2003). Sedimentary structures include; cross bedding, ripple marks, load cast, flute cast and abundant trace fossils (Motiei, 2003). Quartzitic sandstone forms the upper part of the Seyahou Formation, which makes its separation from overlying Sarchahan Formation with ease (Beyk-Nouri, 1995).

In late Ordovician a transgressive-regressive cycle is recognized in southern Persian Gulf. Basinwards, the cycles are hard to recognize as the section

consists of an undifferentiated package of essentially middle to outer neuritic graptolitic shale. A disconformity separates Ordovician shales from Permo-Carboniferous sediments at Zard Kuh. This disconformity becomes more well-defined towards Kuh-e-Dinar where the Permo-Carboniferous sequence overlies the middle and/or upper Cambrian shales and limestones (Setudehnia, 1975, p.18).

Part of the uppermost Ordovician is frequently absent due to erosion. On top of the Ordovician unconformity is the Faraghan Formation, comprising carbonates and sandstones. It is worth mentioning that the hiatus between the Ordovician and Silurian may represent a period of continental glaciation in Arabia (Beyk-Nouri, 1995).

ORDOVICIAN IN SOUTHERN PERSIAN GULF

The earliest post-Najd Rift sediments consist of arkosic sandstone and micaceous siltstones of the middle Cambrian to early Ordovician Saq Formation. A sedimentary package consisting of shallow-marine micaceous sandstone and shale of the middle to late Ordovician Qasim Formation lies above the Saq Formation (Williams et al., 1986; King, 1995).

Sedimentation started with depositional of thick, continental sandstones of the Saq Formation. The sandstones can be divided into two distinct facies: a lower fluvial and upper littoral to shallow marine. The lower facies is a thick, extensive sandstone sequence most likely deposited by braided river systems that drained the nearly peneplaned source area. The sandstones consist of well to poorly sorted red, pink and white quartz, and medium and coarse-grained quartz. Boring identified as *Scolithus spp.*, are common in Saq Formation. The Saq sandstone rests nonconformably on the maturely peneplaned igneous and metamorphic basement rocks. However, Saq sandstone of Saudi Arabia has yet to yield Ordovician fossils (e.g., Williams et al., 1986; King, 1995).

The upper part of the Saq Formation contain siltstone and shales with arthropod tracks identified as species of the *genus Cruziana*, establishing a probable early Ordovician (Tremadocian-Arenigian) age for the upper portion of the Saq. The lower units are assigned to the Cambrian time based on the presence of middle Cambrian trilobites in interbeded limestones and shale units. Thus, the sandstone may record middle Cambrian to early Ordovician sedimentation (Power et al., 1966).

Based on stratigraphic investigation (e.g., Powers, 1968) similar formations to Seyahou have been reported in southern Persian Gulf region which include Tabuk and Qasim Formations. The Tabuk Formation consists of more than 1,700 meters of rhythmically alternating marine shales and continental to marginal marine sandstones of Ordovician and Silurian age. The shale members are the Hanadir, the Ra'an and the Qusaiba.

The Hanadir, Ra'an and Qusaiba shale members represent periods of maximum transgression. These are widespread and probably coeval in part

with the underlying and overlying sandstones that are continental to marginal marine sediments. The sandstone units are readily recognizable along the depositional strike, but basinward, the sandstone interfingered with the shales representing periods of transgression and regressions in the formation.

The maximum phase of the first transgression resulted in the deposition of the Hanadir shale on the Saq sandstone. Because this shale is deposited over a large area, it serves as an excellent marker in Paleozoic sequence. During the late Ordovician, short-lived transgressive and regressive cycles resulted in the deposition of alternating shales, siltstones and sandstones mainly under deltaic conditions.

The Ra'an shale member represents the upper most unit of the Ordovician Tabuk Formation. It is composed of micaceous, graptolite-bearing claystones and thin-bedded sandstone and siltstones containing *Cruziana* tracks. The fauna consists of trilobite, brachiopods and rare cephalopods. *Diplograptus* sp. *Climacograptus* sp. *cf. C brevis* of late Ordovician age were identified from these shales (Power et al., 1966). Late Ordovician palynomorphs have been obtained from the Ra'an shale member.

The Qasim Formation was deposited during middle and late Ordovician times on a gently dipping wide and stable marine shelf bordering PaleoTethys Ocean. The shelf was tilted towards the present-day Persian Gulf to provide accommodation space for the deposition of a siliciclastic wedge more than 1.2 kilometer thick on the edge of Gondwana (Senalp, and Al-Duaiji, 2001).

The age determination is based mainly on the identification of graptolites, trilobites and chitinozoa in the shales of the Hanadir member (the lowest unit of the Qasim Formation) and Ra'an member (forming the upper coarsening and thickening-upward progradational sequence). The Ra'an member is composed of laminated shale and siltstone facies deposited during rapid regional transgression in late Ordovician when a eustatic sea-level rise flooded the underlying shallow-marine/ coastal plain deposits. The sediments mark current-influenced deposition on a stable siliciclastic shelf, with clastic sedimentation sourced from a granitic terrain. The subsequent rapid influx of clastics derived from the erosion of the rising basement and older formation (e.g., Saq Formation) caused a regressive cycle (Senlap and Al-Duaiji, 2001).

The Qasim Formation consists of two siliciclastics coarsening-upward sequences, each with a basal shale/siltstones member an overlying sandstone member. Each sequence is characterized by a different set of conditions acting over a broad and gently dipping shallow-marine shelf. In Saudi Arabia the members of Qasim Formation were deposited in coastal to shallow marine system tract.

There is continuity from the sandstones of storm- and tide-dominated shallow-marine coastal systems to the shales of the shelf/platform system. Basinward, the sand-dominated members are interbedded with the open-marine shales. The thickness and grain-size of each sandstone bed decrease basinward (see Bargrizan, 1998). The large-scale cross-stratification in the sand-

stones is replaced by small-scale hummocky cross-stratification, wave and current ripples. Towards the deepest part of the basin, the entire Qasim become shale dominated, and identification of the storm-and tide-dominated shelf systems is possible only in the shallower parts of the basin.

Sharland et al. (2001) agreed with the interpretation of Sutcliffe et al. (2000) that the Zarqa-Sarah sediments represents subglacial valley systems, mostly above sea level, that were filled with sediment during ice sheet retreat. Although numerous gas shows have been reported from the Late Ordovician Sarah Formation in the Ghawar area, no sustainable flow rates have been recorded there owing to low permeability (Wender et al., 1998).

SILURIAN

In the Zagros Basin, emergence occurred in the late Ordovician or Silurian times and the region was largely above sea level with erosion continuing until near the end of late Paleozoic. The result of this is a Silurian-Carboniferous gap. This was followed by a discordant or a low angularity unconformable, lower Permian, shallow marine clastic sequence, overlain by extensive upper Permian sequence (i.e., Dalan Formation), as was the case elsewhere in the southern part of the Persian Gulf region (Motiei, 2003).

Silurian-Carboniferous sedimentary gap in the northern Persian Gulf and the Zagros (following the Ordovician and/or lower Silurian deposits) is apparently the effect of epeirogenic movement, which led to a regional regression and general emergence of the region by Silurian time (Motiei, 2003).

Early Caledonian tectonic movements resulted in uplifting of western and southern Iran and causing emergence of the south Caspian and Central Alborz area which were temporarily linked to the west of the Iranian platform (Berberian and King, 1981). The pre-Zagros swell emerged with a large lowland area in southwestern Iran and remained free of marine ingressions in Silurian-early Devonian time.

The Silurian system in the southern Persian Gulf region began with a major rapid marine transgression at the early Llandovery, followed by a regressive phase of a prograding delta system. Lower Silurian shales were deposited throughout the Persian Gulf region by repeated regressions and transgression (Beydoun, 1991). They are typically associated with organic-rich graptolitic shales, which are considered as a regional source rock.

During the Llandovery, a major phase of global warming developed which resulted in retreating of glacier and sea level rapidly started to rise flooding the Arabian platform. Carbonates are rare in both the Ordovician and Silurian sequences. The upper Ordovician and Silurian sequences show an upward increase in shale content.

Fairly warm climatic conditions prevailed in the Zagros Basin in early Silurian, as indicated by the high diversity of chitinozoan and achritarch taxa in the Sarchahan Formation, offshore and also in northern Persian Gulf area

(Ghavidel-Syooki, 2000). The presence of *pulvinosphaeridium* p. particularly in the Sarchahan Formation also supports such conditions for early Silurian.

Deglaciation during the early Silurian, as Gondwana drifted towards the tropics, caused a major rise in sea level, sharply flooding much of present south and western Persian Gulf and depositing what is now an extremely important regional hydrocarbon source rocks (Beydoun, 1991) (see Figure 3-11).

Ross and Ross (1988) note a major global sea level rise at the base of the Silurian, probably caused by deglaciation of Gondwana. Deglaciation led to a major sea level rise and transgression with anoxia in intraplatformal basins and widespread deposition of Silurian organic-rich hot shales over the greater part of the Persian Gulf region. Anoxic water bottom conditions in the sediments-starved basin resulted in the preservation of organic rich shales, the prolific Silurian hot shales (Beydoun, 1991; McGillivray and Husseini, 1992).

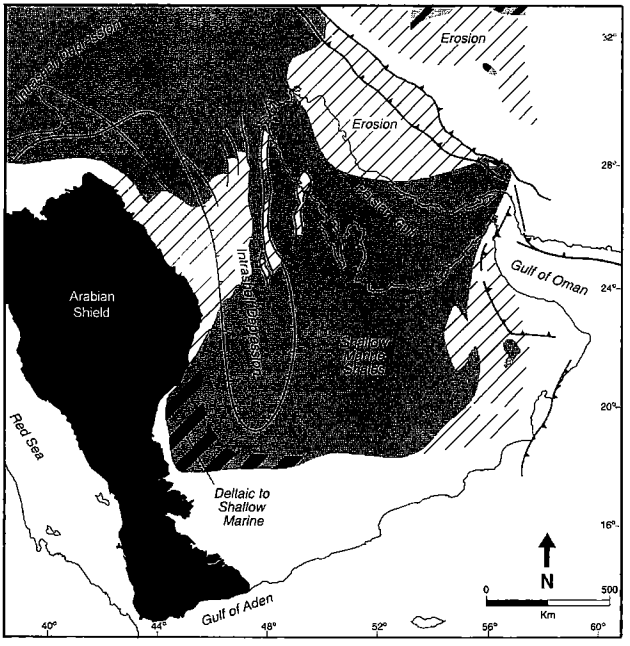

Figure 3-11. In the Early Silurian shallow to open marine depositional environments established in the marginal areas, whilst deeper marine environment covered the inundated platform and extended southward along a subsiding intrashelf depression located in southern Persian Gulf (modified from Konert et al., 2001).

Early Silurian mudstones deposited along the entire northern part of the passive margin of what is now Persian Gulf region, following melting of late Ordovician ice cap. Mudstones are found through the entire Persian Gulf. In Fars area in northern Persian Gulf the Silurian shale is recognized as source rocks for gas. The shale is defined as the Sarchahan Formation and equivalent to the Silurian Qusaiba Member of Southern Persian Gulf.

Thus, organic-rich source rocks existed throughout the basin at the base of the Silurian shales. They contained marine algae, acritarchs, and abundant chitinozoans and graptolites. Rickards et al. (2000) have described graptolitic shales from Sarchahan Formation of the northern part of the Zagros Mountains. Lower Silurian shales representing maximum flooding surfaces were deposited over most of the Gondwana passive margin shelf (Sharland et al., 2001).

The organic-rich, basal hot shales are best developed in the subsurface of southern Persian Gulf and lies immediately above basal sandstone that varies in thickness between 1 and 30 meters. The hot shale has been reported to be as much as 75 meters in thickness, but commonly is about 9-31 meters thick (Cole et al., 1994; Jones and Stump, 1999). Locally, the Qusaiba Member is absent owing to uplift and erosion during the Late Devonian to Carboniferous Hercynian Orogeny. Jones and Stump (1999) suggested that rapid transgression of the Qalibah Formation caused displacement of earlier shallow-marine coarse clastics, allowing organic matter to accumulate undiluted on the continental shelf of northern Gondwana.

SILURIAN IN NORTHERN PERSIAN GULF

Sarchahan Formation

The Sarchahan Formation of Lower Silurian age, previously referred to as Silurian Shales, with an average thickness of about 66 meters in type locality in Faraghan Mountain, comprises of dark shales, rests unconformably on the Seyahou Formation and is disconformably overlain by the Zakeen Formation. The Sarchahan Formation is exposed at only two localities in the Zagros, i.e., Faraghan and Gahkum Mountains.

The thickness of Sarchahan Formation varies from 66 to 86 meters in Faraghan Mountain to 102 meters in the Gahkum Mountain (Ghavidel-Syooki and Winchester-Seeto, 2004). At Kuh-e-Faraghan it comprises mainly of dark graptolitic shales and in exploratory wells in the Persian Gulf reaches thickness ranging between 70 to 75 meters (Bargrizan, 1998).

At the base of this Formation which outcrops at Kuh-e-Gahkum, there are 40 meters of conglomerate; the remainder is an alternation of black shale, siltstone and sandstone. In the type section, the Sarchahan Formation rest unconformably on dolostones of the Barout Formation, however, there is still some doubt (Bargrizan Pers comm). The formation is terminated by an erosional unconformity and stratigraphic gap which is followed by Zakeen Formation.

The Sarchahan Formation is not extended regionally to all parts of the northern Persian Gulf (i.e., Fars region). Such a limited aerial extension might be due to either non-deposition or due to pre-Permian erosion. This Formation is very deep-seated and very few wells drilled in the area penetrate it. Thus,

determination of maturity level and source rock potential is not possible by routine geochemical studies (Rezaee et al., 2001).

Ghavidel-Syooki and Khosravi (1995) have identified a list of graptolites including; *Monograptus intermedius, Monograptus scalaris, Climacograptus Scalaris* indicating a Silurian age for the Sarchahan Formation. Therefore, based on paleontological evidence from acritarches, chitinozoas and graptolites the Sarchahan Formation has been assigned an early Silurian age (early-late Llandovery) (Ghavidel-Syooki, 2000; Rickards et al., 2000; Ghavidel-Syooki and Winchester-Seeto, 2004).

Chitinozoas reported from the Sarchahan Formation in the Persian Gulf area is similar to the samples collected in southern part of the Persian Gulf in Qusaiba Formation (Motiei, 2003). It is also worth mentioning that the sediments representing the middle and upper Silurian seem to be lacking in the Bandar-e-Abbas region which may be due to the Caledonian movements.

The deposition of late Silurian (390Ma) continental sedimentary deposits together with the lack of lower Devonian rocks in central Iran may indicate a late Silurian movement; the cause of it not understood yet (Berberian and King, 1981). However, this might be attributed to the Hercynian orogeny and subsequent uplift and the associated erosion. Whatever the cause, strata of late Silurian age are almost totally absent from southern Persian Gulf region, and the underlying early Silurian shales are substantially eroded. Furthermore, the late Silurian strata are missing from southern Persian Gulf, and the lower Devonian rests on lower Silurian sediments. This regional hiatus represent a period of severe Paleozoic uplift and erosion in Arabia, probably related to the Caledonian movements.

Based on the Paleotological data (Ghavidel-Syooki, 2003), two hiata are recognizable within the Paleozoic sequence of the southern Iran and northern Persian Gulf. The first one is between the Sarchahan (early Silurian) and Zakeen Formations. This hiatus includes the middle and late Silurian sediments, possibly corresponding to the Caledonian Orogeny. The second one occurred between the Zakeen and Faraghan Formations, encompassing the Famennian and the entire Carboniferous deposits, possibly corresponding to the Hercynian Orogeny.

SILURIAN IN SOUTHERN PERSIAN GULF

In the southern Persian Gulf region and the Mesopotamian Foredeep Basin the Lower Silurian "hot shale" is about 65 m thick. The Qalibah Formation of Saudi Arabia is referred to as the Akkas Formation in Iraq, and in the subsurface of Saudi Arabia, the organic-rich hot shale rarely exceeds 50 meters and is usually about 9 to 31 meters thick (Jones and Stump, 1999).

The Qalibah Formation consists of a lower Qusaiba Shale Member, and upper sandstones, and shale of the Sharawra Member. The Qusaiba Member is composed mostly of shale (mudstone) and thin interbeds of siltstone and

sandstone; it is divided informally into upper and lower parts. On a regional basis, the lower Qusaiba is characteristically an upward-coarsening sequence, whereas the upper part is a fining-upward sequence (Jones and Stump, 1999).

Locally, the Qusaiba member is absent due to uplift and erosion during the Late Devonian to Carboniferous Hercynian Orogeny. The absence of Qusaiba is particularly evident in central Saudi Arabia along the central Arabian Arch and Arabian Shield, and along the southern Persian Gulf area.

According to Ghavidel-Syooki and Winchester-Seeto (2004) lithological and palaeontological descriptions of the Qalibah Formation in Saudi Arabia are similar to those of the Sarchahan Formation in northern Persian Gulf. Chitinozoan and graptolites have been established in the Qalibah Formation (Paris et al., 1995 cite in Ghavidel-Syooki and Winchester-Seeto, 2004), providing a base for correlation of the Sarchahan Formation and Qalibah Formation on the northern and southern shores of Persian Gulf respectively.

Significant gas shows have been recorded in the "Mid-Qusaiba Sand," an informal sandstone and siltstone unit within the Qusaiba member. The Mid-Qusaiba Sand is commonly used as a marker bed and represents a progradational, basinal fan related to the Silurian flooding event. The overlying Sharawra member consists of micaceous sandstones, siltstones, and shales, with some recorded gas shows; however, log analysis indicates poor quality reservoirs (Wender et al., 1998).

A hiatus is observed in the uppermost early and late Silurian in the Ghawar area where much of the uppermost part of the Silurian is missing, owing to non-deposition (Mahmoud et al., 1992). The late Silurian is believed to be not presented in southern Persian Gulf, probably because of major erosion or non-deposition.

DEVONIAN

A continental regime dominated almost over the entire Persian Gulf region in the early Devonian and continued well into the late Devonian and Carboniferous. The sea invaded the north in middle to late Devonian time, extending as far as Kerman in northern Persian Gulf region.

The latest Silurian and Devonian periods in the Persian Gulf area are poorly represented in the stratigraphic records. This is primarily attributed to the Hercynian orogeny and tectonism and subsequent uplift and associated erosion. It is also widely accepted that the Hercynian Orogeny had reduced Paleo-Tethys to a shallow epicontinental sea and that the Mesozoic Ocean resulted from late Triassic rifting, obliquely superimposed on the Hercynian structures (Adamia et al., 1982, Ricou, 1976).

Based on the geologic data, Devonian was a period of uplift and erosion of the continental-shelf sedimentary sequences. The collision of Laurasia and Gonadwana to form Pangea began with Hercynian orogenic compression of

middle to late Paleozoic strata, resulting in a regional unconformity at the Carboniferous-Permian boundary (Konert et al., 2001).

The Devonian in general rests unconformably upon Silurian strata. In general, Devonian sedimentary rocks of the Persian Gulf region comprise a generally coarsening upwards, progradational sequence along the passive margin of northern Gondowana that commenced in the Silurian and culminated in the upper Devonian times. The return of marine environments especially during the latest Devonian in northern region, suggest differential downwrap of the northern margin of Gondowana. Similar relationships can be observed in interior Iran.

The uppermost Devonian strata rest directly on Cambrian or lower Ordovician sequences in the Alborz Mountains in Iran, whilst a more continuous Paleozoic section including older Devonian, is preserved in the basin south of the Mountains. These relationships suggest that the northern margin of Gondwana became tectonically unstable, indicating the onset of the Hercynian orogeny.

In the late Devonian (360 Ma), Arabia was situated at 30°S latitude, and had moved to 50°S by the mid-Carboniferous (330Ma). This relatively polward position allowed the formation of glaciers in southern Arabia that were the source of significant clastic reservoir rocks in Oman. At the same time, the Appalachian-Hercynian Orogeny was occurring in Europe, North Africa and North America, after which Arabia began to move northwards (Figure 3-4).

DEVONIAN IN NORTHERN PERSIAN GULF

Prior to the recent investigation it was thought that the Devonian formation were entirely absent or missing in southern Iran and Persian Gulf region (see Beydoun, 1991; Pollastro, 1999). Such an assumption might have been due to the fact that regional uplift affected the Zagros during the Devonian and Carboniferous, and resulted in the removal of much of the lower Paleozoic section in many places (Konert et al., 2001). However, it could be stated that the Devonian strata in general are unconformity-bounded succession of conglomeratic sandstones interbedded with siltstone and shale.

Palynological studies carried out by Ghavidal-Seyooki (1988; 1990) on the clastic sequences indicated the existence of Devonian age biozones. Such finding ended with the introduction of the Zakeen Formation. Motiei (1993) suggested that part of the Faraghan Formation should be called the Zakeen Formation.

Zakeen Formation

The Zakeen Formation represents the Devonian sediments in the Zagros Basin of the southern Iran. It consists of 285 meters of sandstone with interbedded shale and subordinate dolomitic limestones. Based on its stratigraphic

relationships, this formation was originally assigned to the Early Cambrian (Szabo and Kheradpir, 1978). Prior to that, it was assigned to Permo-Triassic succession (Setudehnia, 1975).

The Zakeen Formation consists of clastic sediments commencing with deposition of micro-conglomerates followed by the deposition of highly bioturbated cross-bedded sandstone, siltstone, coal-bearing carbonaceous shales and frequent thin layers of carbonates. The glauconitic-bearing sandstones contain fish scale and fish bones, whereas shale units consist of hematitic nodules.

The Zakeen Formation is disconformably underlain by the Sarchahan and there seems to be a hiatus between the two formations. Another hiatus occurred between the Zakeen and overlying Faraghan Formation and along the contact at the base of the Faraghan Formation there is a paleosole horizon about 25 cm thick (Ghavidel-Syooki, 2003).

The Zakeen Formation which encompasses the Devonian sediments lacks any marine fauna; however, it contains well-preserved and abundant palynomorph taxa. Based on palynological investigations (Ghavidal-Seyooki, 1988; 1990) four different biozones have been recognized representing Devonian (Givetian to Frasnian) age. Further detailed palynological study since then have resulted in the identification of numerous palynomorph taxa (acritarches, microspores and scolecodonts) for the first time in Zagros Ranges. The new species are: *Grandispora zakeenesis, Grandispora owensii, Auritolageniculla Zagrosensis, Saharidia iranicai* and *Papulogabata persica.* Based on the new palynological data, the Zakeen Formation is Frasnian in age (Ghavidel-Syooki, 2003).

Devonian palynomorph taxa reported for the Zakeen Formation have also been recorded in the Devonian strata from many different localities of the American continent, Africa, Europe, Australia and Saudi Arabia. Such finding suggests that the parent plants of these microspores were cosmopolitan and were able to survive under different climatic conditions.

Ghavidel-Syooki's (2003) deduction is in accordance with the fact that the Devonian period was a time of rapid evolution of land plants. Major events were the appearance of leaves, heterospory, secondary growth, and the emergence of seeds (Gensel and Andrews, 1984). This evolution was reflected by rapid developmental changes and increasing complexity of miospore morphology through the Devonian (Gensel and Andrews, 1984).

The sediments which make up this formation differ from any other Devonian sedimentary sequence in the Central Iranian Basin, but they are quite similar to those recorded from Devonian sequence (Tawil, Jauf and Jubah Formations of the Southern Persian Gulf). Therefore, there is a great potential for correlation of the Devonian strata between the southern and northern regions of the Persian Gulf (Ghavidel-Syooki, 2003).

DEVONIAN OF SOUTHERN PERSIAN GULF

The Zakeen Formation seems to have a great geographical distribution and rocks of similar characteristics are identified in the southern part of the Persian Gulf including Saudi Arabia (Motiei, 2003).

In southern Persian Gulf, Devonian sedimentary rocks are only known to be exposed in the western Saudi Arabia, adjacent to the exposed Arabian Shield. Powers (1968) originally divided the Devonian into the lower Devonian Tawil Formation and the lower to middle Devonian Jauf Formation. Meissner et al. (1988) defined the middle to upper Devonian Jubah Formation. The Devonian succession is composed of three homogenous lithostratigraphic units which can not be imaged seismically nor readily discerned with conventional wireline logs. These formations reflect shifts in sedimentation from siliciclastics to mixed siliciclastics and carbonates and return to siliciclastics (Al-Hajri et al., 1999).

Following the Silurian hiatus, fluvial to marginal marine sandstones of the late Silurian-early Devonian Tawil Formation deposited along with thin, discontinuous beds of micaceous siltstone and shale. In Saudi Arabia, above the regional pre-Tawil unconformity the continental clastic of Tawil Formation are followed by the shallow marine Jauf Formation (Wender et al., 1998). Marine incursions also reached Oman where the Misfar Formation was deposited. The latter include anoxic mudstones deposited in lower coastal plain environments. The absence of pre-Emsian deposits in the west and north suggests a structural high with respect to the depocenter in Saudi Arabia.

The Jauf marks a distinct change in the depositional pattern of the entire area where carbonates occurred for the first time in the region. The depositional cycle began with the continental Tawil sandstone member followed by an alternating clastic and carbonates. The lithologic nature of the Tawil sandstone indicates rapid erosion and continental depositional environment. Jauf Formation is conformably underlain by the Tawil Formation and overlain by the Jubah Formation. The Jubah and Jauf Formations together form a progradational fluvio-marine sequence (Wender et al., 1998).

Continental to shallow marine Misfar Formation occurs as clastic pods, along the eastern margin of the South Oman Salt Basin, preferentially preserved within salt-withdrawal synclines. The formation is assigned an early Eifelian to late Emsian age on the basis of in situ palynofloras.

The Tawil clastics vary in thickness locally and are considered poor reservoirs because of extensive cementation by silica and kaolinite. In contrast, Jauf sandstone is of good reservoir quality. Overlying the Jauf Formation is very fine grained to medium-grained, poor reservoir quality sandstones of the middle to upper Devonian Jubah Formation.

During the middle and late Devonian, continental clastics were deposited in southern Persian Gulf (Jubah Formation), which in the north is replaced by mixed marine siliciclastics and carbonates. During this period, continental

marine environments became established in central Arabia and Iraq; whilst marginal marine environments persisted in Turkey and Oman (Figure 3-12).

An extensive period of erosion due to uplift in the early Carboniferous forms the Hercynian Unconformity also referred to as the "pre-Unayzah Unconformity" (e.g., Wender et al., 1998; Konert et al., 2001). The Hercynian Unconformity is particularly evident by deep erosion throughout the stratigraphic section particularly on structural highs such as Ghawar as a result of the Hercynian Orogeny, effectively removing the Devonian (Wender et al., 1998). Thus, the top of Devonian is almost invariably eroded by either pre-Khuff or pre-Permo-Carboniferous unconformities. Thus, sediments are preserved away from the highs, notably to the east. In the offshore Persian Gulf, the succession passes conformably, into the Lower Carboniferous. In deep wells of southern Kuwait, the Unayzah Formation is generally absent and the pre-Dalan/Kangan and pre-Faraghan unconformities converge.

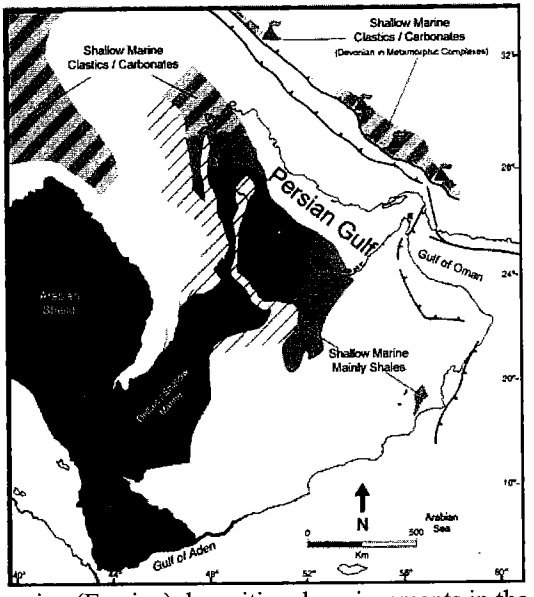

Figure 3-12. Devonian (Emsian) depositional environments in the Persian Gulf region. A large delta front developed in southern Persian Gulf which in the north was replaced by mixed marine siliciclastics and carbonates (adopted from Ziegler, 2001).

CARBONIFEROUS

The Carboniferous is poorly preserved throughout the Persian Gulf region. Carboniferous is largely missing due to widespread uplift and erosion by the Hercynian Orogeny. This orogeny in the early Carboniferous is believed to have caused uplift and erosion over most of the Persian Gulf area. The sediments laid down following this orogeny constitute a thick sequence of clastics. The sediments penetrated by wells in the southern Persian Gulf are pre-

dominantly shaly and of marine origin with some carbonate development in the early to middle Carboniferous.

Mid-Carboniferous was a time of extensive erosion when considerable thicknesses of earlier Paleozoic sediments, measurable in hundreds of meters were removed. Thus, in some localities in southern Persian Gulf, carbonates rest on Precambrian, whereas in northern Persian Gulf in Iran, Permian rocks may rest upon Devonian, Silurian, or Cambro-Ordovician sedimentary rocks.

The distribution of Cambrian to Carboniferous sedimentary sequences in general is affected by numerous intervening regional unconformities in particular by the late Carboniferous Hercynian unconformity. The Carboniferous clastics were mainly derived from the erosion of older clastics in uplifted area.

Regional uplift and exposure during Carboniferous reflects the first updoming along the upper Paleozoic rift belts that began to break up Gondwana. Isolated occurrences of Carboniferous siliciclastics have been presented in Saudi Arabia (Al-Hajri and Owen, 2000). They consist of poorly dated, syn-Hercynian continental sandstones, which were deposited in lowland regions. Traces of late Carboniferous to early Permian glacial deposits are reported from Oman and Saudi Arabia, but in the Zagros Mountains the first sedimentary rocks deposited on the Hercynian unconformity surface were the thin basal sands overlain by fossiliferous middle Permian carbonates (Koop and Stoneley, 1982, p.152).

It is apparent that a considerable part of western Iran was emergent during the late Carboniferous and early Permian. Strong erosional activity is noted during this time, suggested by a major unconformity, especially in the area corresponding to the High Zagros Mountains (Szabo and Kheradpir, 1978, p.59), locally removing the sedimentary cover down to the Cambrian. This area was the source of the turbiditic flysch, together with basaltic flows and tuffs, was laid down over Lower Carboniferous and older rocks (Cherven, 1986). This period of siliciclastic deposition was succeeded by carbonates during the subsequent major transgression of the upper Permian.

The only Carboniferous record from the Arabian margin comes from Precambrian igneous rocks brought up to the surface by the salt plugs, which range from rhyolites, ignimbrite, through porphyritic felsic and mafic lavas to dolerite and dolerite gabbros. Crawford (1977) obtained from four samples of rock of similar petrography a whole rock isochron of 340±15 Ma (Visean).

Hercynian orogenic movements also affected the Zagros Basin in the late Carboniferous. Toofan-Tabrizi (1983) believed that during Devonian and Carboniferous Zagros Basin was uplifted with subsequent subareial exposure caused erosion and pause in sedimentation. He also believed that this was related to Caledonian movements particularly Hercynian orogeny and at this time Zagros was connected to Gondwana. The Hercynian event presumably was related to the development of stresses in this marginal area of Gondwana which culminated later during Triassic in the separation and translation of the Cimmerian fragment(s) of the Gondwana margin.

The sediments laid down following the Hercynian orogeny constitute a thick sequence of clastics. The first sediments deposited on the Hercynian unconformity are considered to be glacial (Murris, 1981). Following clastic deposition, climate became distinctly warm and more arid. A carbonate-evaporite sequence accumulated over an epeiric shelf that was established across the whole region (Murris, 1981).

The first glaciation was in late Ordovician-early Silurian and affected most of the western Arabian plate. The second glaciation occurred in the late Carboniferous-early Permian and reworked the sediments of southern Arabia. Sediments deposited shortly before and also during these glaciations were affected by the repeated erosion and reworking caused by the advances and retreats of the ice sheets. Glaciogenic and shallow marine deposits of late-Carboniferous-early Permian age, unconformably overlying early-late Permian alluvial deposits have been extensively recognized (Le Metour et al., 1995).

The northern margin of Gondwana was the site of continental rifting from the late Carboniferous through Permian, when several microcontinents began moving northward across the Tethys. The precise shapes, rates of motion, and trajectories of these continental fragments are poorly understood, but it is known that most of them collided with the southern margin of Eurasia during the Mesozoic.

Following the Middle Carboniferous to Early Permian, fluvial and cold-climate sandstones of the Unayzah Formation were deposited. The basal Unayzah consists of sandstones that filled relict, erosional topography (Al-Laboun, 1987). Glacial sediments are also recognized in the southern half of the eastern Arabian Peninsula. Dune fields also occur in Oman where the lower Unayzah is equivalent to the glaciolacustrine mudstones of Al-Khalata Formation (McClure, 1980; Hughes-Clark, 1988; Pollastro, 1999).

Glaciation also occurred in southern Persian Gulf region as far as Yemen, and glacial and fluviatile conditions existed in central Arabia. Hughes-Clarke (1988) interpreted the glaciation as having restricted to south of present day 20°N. Further northwards the glacial influence decreases and the equivalents in Zagros regions are of shallow marine to coastal origin. At this glacial episode, it has been argued that southward subduction of the Paleo-Tethys began under the leading edge of northern Gondowana in central Iran.

In Abadeh range, the Upper Carboniferous strata consist of 500 meters of deep waters dark limestones and shales containing reefs and reefal debris. They are unconformably overlain by 2.5 kilometers of platform and reefal limestones of Permian age and one kilometer of interbedded shale and carbonates and 600 meters of dolostones of late Permian to middle Triassic age.

In summary, relatively thick pre-Permian strata almost certainly are present in the subsurface of the Persian Gulf and for some distance westward onshore. The known lithofacies is dominantly terrigenous clastic sediments. The extensive development of pre-Permian clastics suggests that pre-Permian riv-

ers at times flowed from moderately raised lands (Kamen-Kaye, 1970). Permian deposits are mainly limestone, although dolomite makes a definite contribution to the column in some areas of the Persian Gulf (Taraz, 1974).

PERMIAN

From petroleum geology point of view, the Permian was a remarkable period in the geologic history of the Persian Gulf region. Based on that, especial attention has been paid in this chapter to this period and its geologic characteristics. It represents the maximum stage of Pangean continental assembly, and also includes a major global climatic shift from glacial to non-glacial conditions (icehouse-greenhouse transition) terminated by one of the most profound faunal/floral extinction events in the earth history. In addition, Permian Seas, although poorly understood, must have had some quite unique characteristics.

In the Persian Gulf and surrounding area, after a long period of non-deposition, the sea returned and inundated vast areas. Permian Seas reached the most extreme values of carbon, sulfur and strontium isotopic ratios ever achieved in Phanerozoic time, and the isotopic ratios of all three elements abruptly returned to the more "normal" values, or very close to the Permian-Triassic boundary.

Finally, the Permian marked by an abundance of important sedimentary mineral resources. It has large fossil fuel concentration (coal, oil and natural gas), enormous phosphate and lead reserves and very extensive evaporite deposits, including gypsum, anhydrite and halite, as well as a variety of potash salts. These characteristics are all evident in the geologic history and Permian sedimentary succession of the Persian Gulf region.

PERMIAN PALEOGEOGRAPHY AND CLIMATE

Plate tectonic reconstruction for the Persian Gulf region indicate that during the Permian, the region was part of Gondwana landmass (see figure 3-13) near latitude of 30°S (Bambach et al., 1980) and most of the southern Persian Gulf was covered by a restricted evaporite-carbonate shelf platform sea (figure 3-12). Paleoclimatic data from the central Iran block also indicate that it was a part of Gondwana in Permian time (Stoffel et al., 1975). Its geology shows marked similarity with Arabia from Late Proterozoic to Permian time (Stocklin, 1974).

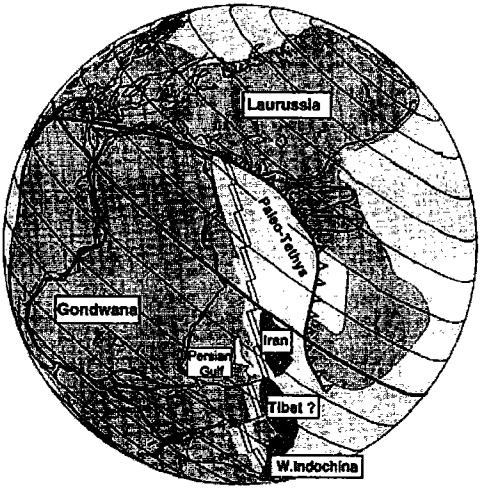

Figure 3-13. Paleogeographic reconstruction of the Tethyan Ocean and its bordering continents during the Late Permian (modified from Stoffel et al., 1976).

Based on paleomagnetic data, Stoffel et al. (1996) disputed that the Central-East Iran microcontinent became detached from the Iran Plate in the Late Triassic and moved toward a paleogeograophic position south of the equator. However, lithostratigraphic evidences strongly indicate that during the Late Triassic and Early Jurassic, the Iran Plate acted as a more or less coherent tectonic unit (Seyed-Emami, 2003).

During the Early Permian time, there existed a vast epeiric sea with a marginal clastic belt. The most important deposits in this sea that covered the whole Persian Gulf and portion of the zone now occupied by the Zagros Thrust Belt were carbonates with subordinate evaporites (Murris, 1980). A passive-margin sequence of carbonate platform also accumulated in the subsiding Esfahan Basin bordering the Zagros Thrust Belt, and a shallow-water carbonate bank, which can be traced into Oman, was also developed.

In general, from the southern Persian Gulf northward to central Iran sediments passed from continental through marine sands, into sabkha carbonates and shelf limestones. The character of the shelf was determined by an eperic sea covering an area of such low slope that even shallow water condition prevailed at its depositional centers.

Rifting along the northeast margin of Gondwana began in the early to Mid Permian. Continental breakup along the line of Zagros continued into Triassic, forming a small basin on the western margin of the Cimmerian continent. Close to the line of the present-day Zagros Crush Zone, however, there was a zone of relative uplift where erosion led to the deposition of the local clastic sequence (Szabo and Kheradpir, 1978). The uplift also served to restrict water circulation and is seen in the pattern of Permian facies distribution to the west, where supratidal evaporitic limestones developed.

The block destined to become the Sanandaj-Sirjan zone and central Iranian microcontinents (i.e., Lut, Tabas, etc.) rifted away and the southern arm of the Neo-Tethys began to open. The Neo-Tethys continued to open via a complex network of spreading centers. An early Cimmerian (Carnain) metamorphic event, recorded in the southeast of the Sanandaj-Sirjan zone, may require concurrent destruction of southern Neo-Tethys crust under part of the Sanandaj-Sirjan zone. The generally accepted model describes northward-directed subduction below Sanandaj-Sirjan zone but convincing evidence of this effect is lacking (Berberian and King, 1981).

Thiele et al. (1968) described a clastic-basic volcanic Permian sequence at Ab-e-Barik immediately northeast of the Zagros Suture, which supports the suggestion of early rifting along this line. Other areas of adjacent Central Iran show a very thick open-marine Permian carbonate section. The oceanic realm of the main Tethys may have lain much further to the northeast at this time, in the vicinity of the present Alborz Range (Stocklin, 1974).

Generally, during the Permian time the climate in the Persian Gulf region became warmer and more arid. By middle Permian time the region was dominated by a large stable evaporitic carbonate platform, flanked to the west and southwest by a narrow clastic fringe derived from the Arabian hinterland (see Figure 3-14. Minor local clastic centers were also developed in the Zagros region and were probably derived from local Hercynian Mountains on the margins of the developing Paleo-Tethys.

The glacial conditions occurred over much of Gondwana, throughout much of the Early Permian and it is significant that close correlations are possible with the palynofloras recovered from Gondwana areas. From mid-Permian times onwards, the glacially influenced sediments and biotas disappeared. During the Sakmarian and Artinskian, the Persian Gulf region drifted north towards warmer, lower latitudes and the changing climatic conditions resulted in an increase in floral provincialism. Thus, Sakmarian marked the end of the widespread Gondwana glaciation. It appeared that the Late Permian was marked by a vast transgression. The Upper Permian facies distribution gives an impression of the position of the emergent zone, bordered by a vast epicontinental platform opening northeastwards to the Tethys.

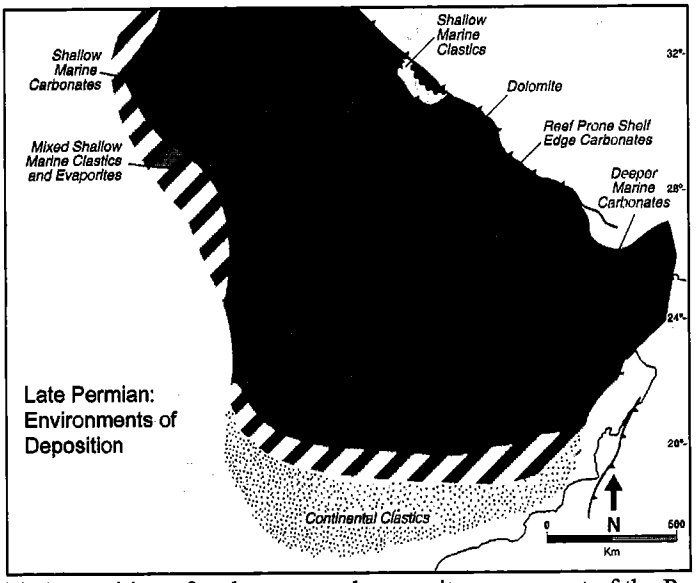

Figure 3-14. Deposition of carbonates and evaporites over most of the Persian Gulf with Deeper marine carbonates occur at the eastern tip of the plate in Oman and Iran (Modified from Szabo and Kheradpir, 1978; Al-Jallal, 1995).

During the Permian, a restricted evaporite-carbonate shelf platform sea covered most of the Persian Gulf region. Short-term sea level oscillations caused recurrent shoaling pulses that culminated in the creation of evaporite sabkha and salinas particularly over the highs. The carbonates indicate a shallow-shelf to a coastal-plain depositional environment. In general, a weakly prograding terrigenous to shallow-marine clastic shoreline existed.

The sediments of the late early Permian on the Arabian plate are characterized by regressive sediments, such as the Unayzah (A and B) Formation. Dolostones appeared to constitute most of the Permian in the Persian Gulf region. At the end of the Early Permian a major marine transgression resulted in the establishment of carbonate platform over much of the region (Figure 3-14).

REGIONAL GEOLOGIC SETTING

Generally, the Permian sequence in the Persian Gulf area is composed mainly of shallow-water carbonates, with several interbedded evaporites, locally changing into a continental red-beds facies. Thus, the carbonate platform was established over most of the region representing the earliest period of major carbonate sedimentation in the area, resulting from the Permian transgression of the Neo-Tethys Ocean.

It has been argued that at the time of the Late Carboniferous-Early Permian, southward-directed subduction of the PaleoTethys commenced under

the leading edge of northern Gondowana plate from a passive to and active margin, with the Sanandaj-Sirjan block of Iran being identified as an ansialic magmatic arc (Sengor, 1990). Evidence of "Hercynian" related metamorphism from the leading edge has been reported from the Oman Mountains and central Iran (Lovelock et al., 1981; Berberian and King, 1981).

The tectonic system led to the opening of the Neo-Tethys Ocean. As a result, the northeastern and eastern edges of the Arabian Platform evolved into passive margins. The Permo-Triassic opening of Neo-Tethys and associated regional extension was the last major tectonic event affecting the Persian Gulf region prior to the Cenomanian time (see Loosveld et al., 1996). This is an important rifting phase, which apparently marks the onset of the opening of the High-Zagros Alpine and the narrow Central Iranian Ocean belt. No previous extensional phase left any evidence of having produced oceanic crust. This phase is mainly developed along the Sanandaj-Sirjan belt with basic volcanic activity (Berberian and King, 1981). Record of Permian volcanism from the Arabian Paleozoic margin is restricted to some basalt flows west of Dehbid in the southern part of the Zagros Mountains (Berberian and King, 1981). It seems obvious that by late Permian time an extensional regime had begun affecting the Arabian Paleozoic margins, at least along the present day Zagros.

The occurrence of volcanoclastic strata in upper Permian strata of the northern Zagros (Zsabo and Kheradpir, 1978) and the presence of basaltic rocks in the Permian sequence of the Sanadaj Sirjan block, as well as in the Alborz Range (Glaus, 1965; Annelles et al., 1975; Vollmer 1987) indicating that the break up and rifting of the once coherent Iranian Paleozoic platform and the succeeding drifting process of the Iranian plate may have taken place in the late Permian (Besse et al., 1998) and the Early Triassic (Stocklin, 1974; Berberian, 1983; Stampfli and Pillevuit 1993). However, Saidi et al. (1997) and Ghassemi et al. (2001) even favor a late Carboniferous and early Permian age of the rifting process.

The opening of the Neo-Tethys led to great changes in regional tectonics that persisted until its final consumption in the Miocene. On the northern and eastern margin of Gondwana, oceanic spreading separated the Cimmerian superterrane (including present-day Iran) that proceeded to drift northeastward (Stampfli et al., 2001). Within a regional tectonosedimentary framework, the sedimentary sequence record a phase of a pre-rift sedimentation following a major crustal uplift in the region followed by the early phase of subsidence and rifting at the western margin of the Tethys Ocean.

The Permian transgressive sea covered a vast area of the present Persian Gulf region (Walfart, 1967). The Persian Gulf Permian basin was an elongated trough with the greatest subsidence occurring in the southeast and the thickest sediments accumulated embraces shallow marine carbonates. There are two areas of greater thickness of the Permian successions situated in Iran and Oman; these areas correspond to the advancement of the Permian Sea (see

Figure 3-14). In general, Permian sediments thicken eastward from the eastern margin of the Arabian Shield towards the Persian Gulf, which appears to coincide fairly closely with the original depocenter of the basin. Further to the east, in southwestern Iran, the section thins and a clastic source (Szabo and Kheradpir, 1978), from a zone of uplift currently delimited by the Zagros Thrust Zone, can be recognized.

The late Permian widespread marine transgression resulted from several factors. Gondowana deglaciation was accompanied by a rapid plate movement to warmer latitudes. Evidence form the Oman allochthon (Hawasina nappes) indicates crustal stretching, rifting, and basaltic volcanicity, presumably associated with crustal thinning that eventually led to Triassic separation of the Iranian blocks (central Iran, Sanandaj-Sirjan, and northwest Iran) from the northeastern Arabian margin along the Zagros line. During the same period, the southeastern and northwestern Arabian margins were formed by separation of formerly adjacent parts of the Afghan-India block and the Turkish blocks, probably along transforms (Sengor, 1990).

These combined events led to widespread deposition of upper Permian carbonates over the newly forming northeastern Arabian passive-margin shelf, with deeper Permian facies in the developing marginal rifts, which is seen in the Hawasina units in the Late Cretaceous allochtons. Away from the plate edge, anhydrites are interbedded, often cyclically, with the shallow-water carbonates constituting good reservoir-seal pairs; these facies continue into the Lower Triassic.

With the initiation of the Permian transgression, carbonate and calcareous sediment deposition prevailed, in contrast to the high proportion of terrigenous clastic deposition during pre-Permian time. Renewed marine transgression in Permian resulted in the deposition of clastics, shallow water carbonates and evaporites.

From the Mid-Permian through the early Turonian (ca. 170 m.y.), an extensive carbonate platform covered large part of the region and about 3.5 kilometers of mainly carbonate strata accumulated (Murris 1980; Harris and Frost, 1984). In general, the mid-Permian to Cenomanian massive marine carbonates formed in the Persian Gulf area. From Kuh-e-Gahkum in northern Persian Gulf southeastward though the Oman Mountains to the Fahud No#1 well, there is a steady decrease in the thickness of the Permian and increase in terrigenous clastic content, indicating Arabian craton provenance, and increasing rate of subsidence towards the northeast.

During the late Permian to middle Triassic a new passive margin developed within NeoTethys. Sedimentation continued without interruption or facies changes through the Permian-Triassic boundary. Similar transitional beds extend into northern Iran, the Zagros, and most likely the Persian Gulf region, although in most places the fossil records are not sufficient to be precise.

SEDIMENTARY PROVINCES

Throughout Permo-Triassic, sedimentary successions were laid down in major depositional provinces in the Persian Gulf region extending from the southwestern Saudi Arabia to Central Iran (Szabo and Kheradpir, 1978).

The first province was the Arabian shield, which operated as a stable landmass sourcing the clastic budget for the depositional centers. Further to the northeast there is an extensive area of shallow water marine carbonates and clastics on the stable Arabian shelf and part of the Persian Gulf. Aramco (1975) subdivided the Arabian shelf into an interior platform, corresponding to the stable shelf and unstable sectors of Beydoun and Dunnington (1975). In the interior homocline or stable shelf, Paleozoic and Mesozoic strata dip away from the shield at rates reflecting the influence of the underlying basement rocks. Further east, the interior platform or unstable shelf is characterized by the presence of basically flat-lying Tertiary deposits that no longer reveal basement configuration.

The interior platform or unstable shelf includes the present-day coastal zone of eastern Arabia, the subsurface of the Persian Gulf and the greater part of the lowlands of southwestern Iran. Among the basins developed along this sector there is the north Persian Gulf basin, located at the head of the Persian Gulf between the present day Arabian shore and the Zagros foreland zone of Iran which extending northwestwards into Iraq.

The third province covering an area from the Persian Gulf to the Zagros Thrust Belt (i.e., the Zagros Basin) also contains shallow water platform carbonates and evaporites. This region was subjected to further subsidence resulting in greater deposition of thick sedimentary successions filling the basin.

The earliest extensive deposits following the Hercynian Orogeny are the Upper Carboniferous-Lower Permian clastics that lie with angular unconformity (Hercynian Unconformity) on older Paleozoic rocks and basement. They were partly deposited coeval with rift tectonics along the eastern and northern margin of the Arabian plate. These sediments appear to be missing over the Central Arabian Arch.

The Central Iranian Basin, which is the most easterly province, represents open marine conditions favorable for deposition of carbonates with insignificant evaporites. Great thickness of carbonates (>3 km) were laid down in this province (Alavi, 2004).

Generally, the Permian sequence consist of braided plain, channel fill, and eolian sandstones and siltstones (Unayzah A and B members in Southern Persian Gulf) that were deposited in semi-arid condition (Senlap and Al-Duaiji, 1995). They are replaced basinward by braid plain deposits overlain by shallow-marine near-shore sediments to essentially shallow marine sands in the northern Persian Gulf (Faraghan Formation; Szabo and Kheradpir, 1978). The thickness of these clastics is variable due to onlap on the Hercynian structures. The Permian sediments were deposited unconformably on the Devonian in

central Iran. A minor break in sedimentation between the Permian and Triassic is indicated over much of the southern Iran (Szabo and Kheradpir, 1978).

Changing the depositional environment is a manifestation of the tectonic activity in the Persian Gulf region and, the Permian time marks the first major marine transgression in the region. Although earlier transgressions have been recorded, they appear to have been of shorter duration and generally were associated with clastic sediments. The carbonates of the late Permian are a precursor of the carbonate sedimentation which dominated the later Mesozoic.

In a tectonic sense, the end of the Permian is the time of the precursory events leading to the formation of the Neo-Tethys, which formed along the Zagros line in the wake of the diminishing Paleo-Tethys, which eventually closed around the end of the Triassic. Beginning with the late Permian, increased accommodation space related to stretching of the crust accompanied the formation of the Neo-Tethys Ocean along the Oman-Zagros suture. Thus, by the Upper Permian a large range of lithofacies developed as a result of the extensional domain experienced during the birth of the Tethys Ocean. With reference to the Late Paleozoic microcontinent rifting, it follows that the so-called "Hercynian" events of the Persian Gulf region may be related to an extensional rather than collisional tectonic regime. The pre-Permian unconformity, dated at 255Ma, marks the birth of the new ocean.

PERMIAN STRATIGRAPHY

The larger part of the Permian stratigraphic sequence lies in the subsurface in the Persian Gulf region and is known only through drilling. However, some subsurface data are available because of the discovery of enormous quantities of gas within Permian reservoirs in the Persian Gulf region. The Permian sedimentary rock sequences rise to the surface in the Zagros Basin of southern Iran in the northern coastal regions of Persian Gulf.

The Lower Permian clastic sequence is best known in northern side of the Persian Gulf. Below the carbonates, a sequence consisting of sandstones with subordinate conglomerate, siltstones and variegated sandy shales has been described (Szabo and Kheradpir, 1978).

In the Iranian side of the Persian Gulf, the lower Permian is best represented by the early Permian (Artinskian) Faraghan Formation. Towards the end of early Permian, an area of the High Zagros was exposed and the basal Permian deposits of the Faraghan Formation represent sands eroded from the exposed area and deposited in a progressive but oscillatory, advancing sea. Thus, in the entire Persian Gulf region, after a along period of non-deposition since the Late Ordovician time, the sea transgressed and inundated the sedimentary sequences.

In the Zagros Mountains and Persian Gulf region during the early Permian clastic series of the Faraghan Formation were deposited; these were succeeded by shallow water fusulinid limestones and dolostones of the Middle Permian

and Late Permian Dalan Formation. Locally there has been deposition of evaporites. Near the Arabian Shield the Permian strata are developed in a littoral conditions, and forming sandier facies.

In Zard Kuh and Kuh-e-Dinar of the Zagros Basin, despite poor exposure, Setudehnia (1975) has described the Permian sequence with the clastic beds of Faraghan Formation underlying carbonates of Dalan Formation. The clastics with the presence of minor carbonates rest on graptolitic shales of Sarchahan Formation but in other localities, the base of the formation may rest on either Ordovician or Cambrian rocks. The widely recognized Hercynian angular unconformity, suggests that the Hercynian orogenic activity affected at least parts of the Zagros Basin (Setudehnia, 1975).

PERMIAN IN NORTHERN PERSIAN GULF

Following the discovery of commercial hydrocarbons in Permo-Triassic sediments in Zagros Basin and Persian Gulf, Oil Service Company of Iran's exploration division initiated a research project in late 1975. Prior to this, during the 1930's, Harrison carried out surface geological investigation in High Zagros area and established the presence of the Permian and Triassic strata in southern Iran. Landmark work on the stratigraphy of Zagros by James and Wynd (1965) had previously established the lithostratigraphy nomenclature for the Zagros Basin from Triassic to Recent nevertheless the older strata including Permian were excluded (Szabo and Kheradpir, 1978).

Stocklin (1968) summarized the tectonic history of Iran with discussion on the geology of the Triassic and Paleozoic sediments of the Zagros Basin. Subsequently Taraz (1974) studied the Central Iranian Basin including the Permo-Triassic sequence of the Abadeh region. Szabo and Kheradpir (1978) investigated these sediments and introduced Dashtak, Dalan and Kangan Formations. The most recent investigation concerning the biostratigraphy and sedimentology of Permo-Triassic succession of Iran is under taken by Baghbani (1993) and Heydari et al. (2003) respectively.

In the surface exposures of southwest Iran, up to one kilometer of sediments composed of carbonates were assigned to the Carboniferous-Permian age (Szabo and Kheradpir, 1978). Southward, in the Persian Gulf wells penetrated a sequence of interbedded dolostones and anhydrite, almost more than 300 meters of which was correlated with the Permian of the southern coastal Persian Gulf (Mina et al., 1967).

In general, Permian strata form thick sequences in the Persian Gulf region especially in the northern coastal areas and Oman and to a lesser extent in the south western regions. These sediments were deposited unconformably on the Lower Paleozoic rocks in western Iran and on basement rocks in the present southern Persian Gulf.

In Iran, the principal carbonates are found in the Dalan Formation which together with the underlying Faraghan Formation and the overlying Kangan

Formation, were placed in "the Deh Ram Group", a term introduced by Szabo and Kheradpir (1978). Deh Ram is a name of a place 20 km SSW of Surmeh Mountain 230 km SE of Shiraz. According to Motiei (1993), the Deh Ram Group encompasses three Formations namely Faraghan, Dalan and Kangan with the later Formation is assigned a Triassic age.

The Deh Ram Group is the world's richest gas-bearing rocks and hosts both giant and supergiant gas fields. Onshore the gas is rather dry but on the Qatar-Gavbandi Arch subdividing the Persian Gulf, wet gas is found in the Qatar North Dome the world's largest gas field and its extension South Pars field of Iran. The carbonate and evaporite sequence of the Deh Ram outcrops in the southern Persian Gulf. However, outcrops more typical of the producing Deh Ram reservoirs are found in the northern Persian Gulf area south of Shiraz.

The lowermost strata representing the Permian time in the northern coasts of the Persian Gulf consists of siliciclastic sediments with some shale partings, and overlies the pre-Permian strata with a well identifiable angular unconformity.

A prominent feature of the Permian succession in southern Iran is the common occurrence of conformable sandstones at their base. Concerning the Permian of southern Iran, Harrison (1937) remarked that its basal part in the Zagros is a rusty colored, bedded, calcareous grit, which passes upwards into massive limestones. In the High Zagros, the basal Permian clastic sequence overlies the Middle Cambrian at Kuh-e-Dinar, the middle-upper Cambrian carbonates and clastics at Kuh-e-Gereh and lower Ordovician shales at Zard Kuh. In Kuh-e-Surmeh this unconformity is marked by a quartz conglomerate resting on a dolomitic limestone with no fossils with an approximately 10° angular unconformity (Bargrizan, pers commun).

During the Middle and Late Permian a facies pattern of inner shelf carbonates and evaporites bordered to the northeast by the partly reefal organic carbonates became established. The earlier Zagros High (pre-Permian arching) remained positive, resulting in a local source of red bed terrigenous sediments (Koop and Stonenely, 1982, p.153).

Faraghan Formation

The Faraghan Formation is a thick terrigenous clastic unit with minor limestone stringers. The Formation is named after the best-developed and most accessible outcrop at Kuh-e-Faraghan, about 80 kilometers north of Bandar-e-Abbas. The subsurface type section of the Formation is in Kuh-e-Siah well#1. The thickness of Faraghan Formation in this well is about 112 meters which also include the Zakeen Formation (Bargrizan pers comm.). Faraghan Formation overlies Silurian graptolitic shales. Previously it was considered as Permo-Carboniferous age.

In the Persian Gulf, in well # 0-4 BIS there is 185 meters of clastic sequence consist mainly of siltstone, sandstone and often shale with quartz microconglomerates and rare carbonates. The lithologic characteristic of this sequence and its stratigraphic position is very similar to the Faraghan Formation characteristic observed in the subsurface type section in Kuh-e-Siah well-1 (Javadian, 1996). Similar correlation can be made in drilled wells in South Pars hydrocarbon field and Golshan (i.e., G3) and Ferdowsi Heavy Oilfield (i.e., F2 structures) in the Persian Gulf. The clastic of Faraghan Formation has been only encountered in the deep well drilled on the Salman Field.

Generally, the Faraghan Formation consists of polymict conglomerates (quartz pebbles up to 5 cm in diameter) overlain by cross-bedded quartzarenite, siltstone, and red shale with thin carbonate intercalations near the top; fluvial siliciclastic strata of alluvial-fan and braided-stream origin resting unconformably on older strata and grading upward into transgressively overstepping Dalan carbonates (Alavi, 2004). In Kuh-e-Faraghan and Zard Kuh the sandstones are gradually replaced by carbonates (Motiei, 2003).

The basal Faraghan sediments were deposited unconformably on the Cambrian to Devonian sediments. For example, in Kuh-e-Dinar and Kuh-e-Gereh this formation is underlain by Cambrian Barout Formation, in Zard Kuh and Kuh-e-Surmeh by the shales of the Seyahoo Formation of Ordovician age whereas in Kuh-e-Faraghan and Gahkum by Zakeen Formation of Devonian age.

Based on Abolhassani's investigation (1997), there are three successive recognizable sedimentary sequences in Kuh-e-Faraghan which commence with subarkosic sandstone and ends with arkosic sandstone, siltstone and shale. Glauconitic arkosic sandstone interbedded with shales and siltstone occurs in the lower part of Faraghan Formation. The majority of the clasts are composed of feldspar. Presence of glauconite and phosphate are indicative of their marine origin (Ghavidel and Sabzehie, 1982).

White arenite sandstone (with siliceous cement) and dark brown sandstone (with dolomitic cement) mostly occur on the top of the formation. The sand grains are well-sorted and have high degree of maturity and have not been subjected to compaction. The sandstones have been cemented by a ferron dolomite.

The lowermost beds of this sequence are generally consisting of coarse quartz conglomerates with sub-rounded clasts, with finer sand matrix and siliceous cement. These beds can be differentiated as Devonian Zakeen Formation. Overlying this conglomerate there is a cross-bedded sandstone and weakly cemented quartzarenite. The rest of the formation composed of varicolored shales with alternation of colored sandstones.

Because of the wide and fairly uniform distribution of the sandstones, it is assumed that the Faraghan sandstone is essentially made up of transgressive marine clastic sand. The exception is in the Chal-i-Sheh outcrop where the

sequence for most part closely resembles alluvial deltaic sedimentation (Abolhassani, 1997).

The sandstone of the Faraghan Formation was probably deposited during progressive fluctuation of the shallow marine transgression of the Permian Seas. Continued transgressive phases leveled the clastic sources and resulted in the deposition of massive limestones overlying the Faraghan Formation.

According to Szabo and Kheradpir (1978), it is generally believed that acidic basement complex of the Arabian shield can be considered as a good candidate as the source area for the sediments forming the Faraghan clastics. However, the Permian subcrop map provided by these authors suggests that much of the sand in the Faraghan Formation could have been derived locally from the Zagros High by the reworking and redeposition of the Cambrian Lalun sandstones. It is hoped that future isotope geochemical work will clarify its origin.

The Age of Faraghan

The age of Faraghan Formation had been subjected to great controversy. This was due to the fact that no marine fossils were found in Faraghan Formation. Initially the Faraghan Formation was assigned a lower Permian age deposited in a fluviated system (Toofan-Tabrizi, 1983). This clastic sequence was also referred to as "Permo-Carboniferous" by most workers in the Zagros Basin, until Setudehnia (1975) proposed that the age of this Formation could be considered as Carboniferous-Permian or Permian.

The use of the "Permo-Carboniferous" is discontinued for the following reasons (Motiei, 2003):

None of the known outcrops in the Zagros Basin contain positively identified Carboniferous fauna,

Paleontological and stratigraphic evidence indicates that the oldest dated Permian beds in the Zagros Basin are not older than Artinskian.

If part of the clastics of the Faraghan Formation were of Carboniferous age, a hiatus or unconformity should exist between the dated Permian and these clastics.

To resolve the age issue, palynological work was of prime importance. Based on such investigations (see Ghavidal-Seyooki, 1990) five different biozones have been recognized in the Faraghan Formation. The topmost biozone which is underlain by the upper Devonian is given the early Permian (Sakmarian to Kungurian) age where the four earlier biozones represent Devonian (Givetian to Frasnian) age. One of the particular aspects of this biozone is that, most of the Devonian morphotype species disappear here and the presence of *gymnospermous* is noticeable. Additionally, these investigations indicate that there is a sedimentary gap from upper Frasnian and Famenian (during the Devonian time) and the entire Carboniferous till early Permian. Such a

stratigraphic gap seems to be due to the erosional processes active in some part of the basin (Ghavidal-Seyooki, 1988, 1990; Motiei, 2003).

Dalan Formation

The dolostones and limestones of the Permian Dalan Formation contain vast gas reserves in the Persian Gulf region. This formation is named after the Dalan anticline situated 110 kilometers S-SW of Shiraz. The formation has a total thickness of more than 630 meters.

Stratigraphic cross section of Dalan Formation measured at Kuh-e-Faraghan is the thickest section of this Formation in northern Persian Gulf. This is overlain conformably by the carbonates and sandstones of Khaneh Kat Formation of Triassic age (Szabo and Kheradpir, 1978). The presence of marine fossils particularly *Fusulinidae* family, indicate open marine conditions during its deposition (Kalantari, 1994).

Dalan Formation consists of medium to thick-bedded oolitic to micritic shallow-marine carbonates, locally reefal, with intercalations of evaporites. It extends up into the lower Triassic Kangan Formation in southern Iran. In its type section, the Dalan Formation overlies the Faraghan Formation and embraces all the continuous carbonates and evaporites of Permian age (Bargrizan pers comm).

A much thinner stratigraphically equivalent unit of Permian carbonates occurs in southern Persian Gulf and it is referred to as the "Khuff Formation". In the thicker sequences of southern Iran and Oman much of the sequence is made up of the coral organic reefs with fusulind-crinoid-brachiopods buildups (Szabo and Kheradpir, 1978; Edgell, 1977). The coral shelf edge facies which extend in an N-S direction form limestones that are an attractive prospect as reservoir rocks.

The thickest Permian section in the greater Persian Gulf area occurs in the eastern Oman Mountains (Glennie, 1995), where more than 1.8 kilometers of sediments, with no basal exposure, are present. However, as a result of the obduction of Upper Cretaceous basic igneous rocks including ophiolites, Permian rocks in this location are partially metamorphosed.

In the Persian Gulf region, Dalan Formation have been encountered in several drilled wells including 0-4 BIS (i.e., in "O" Structure) drilled through the entire Dalan Formation and reaches Faraghan Formation. The thickness of Dalan is 708 meters in this well. Such measured thickness is in accordance with the thickness of Dalan Formation at South Pars #1 well, which is about 759 meters (Bargrizan pers comm). The Dalan Formation in the South Pars field close to the Qatar-Gavbandi Arch attains a thickness of 354 meteres. In addition the formation is reduced in thickness in R-32 (Resalat oil field) (133 meters), and 3H1 wells (253 meters). However based on the well log information the entire Dalan is not represented in these wells (Bargrizan pers comm.).

Thus, such measured thicknesses could only be considered as a minimum for the Dalan Formation at these localities in the Persian Gulf.

The total thickness of the Dalan and its equivalents in the Persian Gulf (i.e., Khuff), increase gradually from west to east (see figure 3-15). A more drastic increase in thickness in Persian Gulf region occurs in Iran at Kish-1, and in central outcrops (>1.5 km) at GHKM and ABDH. The Dalan Formation reported in UAE, ranges in thickness from 650 meters offshore in the Persian Gulf to nearly one kilometer onshore. The dominant lithology is limestone and dolostones with minor anhydrite. In Kuwait, a thickness of about 602 meters of the Dalan Formation was penetrated by the Burgan-A well.

The anhydrite facies is not present in central Iran (i.e., in the Abadeh region). According to the geologic cross section, the Kangan/Dalan carbonate overlies different age rocks from Precambrian basement, in southern Persian Gulf, to the late Permian Faraghan Formation in Iran respectively.

The Dalan transgression started in Iran and Oman during the Wordian (equivalent to early Kazanian, Heydari et al., 2000). The transgressive lower Dalan Formation was deposited in a more open marine environment as indicated by the presence of the open marine fossils. However, with depositional progradation and less subsidence, the depositional environment became progressively restricted. This eventually led to the deposition of evaporites in the Permian Sea.

Northeast of the Zagros Crush Zone, on the Sanandaj-Sirjan Zone, Szabo and Kheradpir (1978) reported Kungurian ages, and attribute Arttinskian age to Dalan carbonates. The Dalan transgression is interpreted to have been rapid, advancing southward. At the end of the Early Permian a major marine transgression also resulted in the establishment of a carbonate platform over much of northern Oman. The thickness can reach up to one kilometer, less than what was measured in the eastern Oman (Hughes-Clarke; 1988). Reef buildups occur in Iran and a small number of deeper intrashelf basins developed in Central Iran and western Iraq.

Majority of the Dalan carbonates were deposited as a restricted evaporitic, carbonate shelf facies and include subtidal carbonate sand shoals, lagoons and bars that spread out as sheets across long distances (see Figure 3-16), along with intertidal and supratidal sabkha facies. Evaporites were deposited over a great extent of the area; the present-day total anhydrite thickness is 107 meters or more.

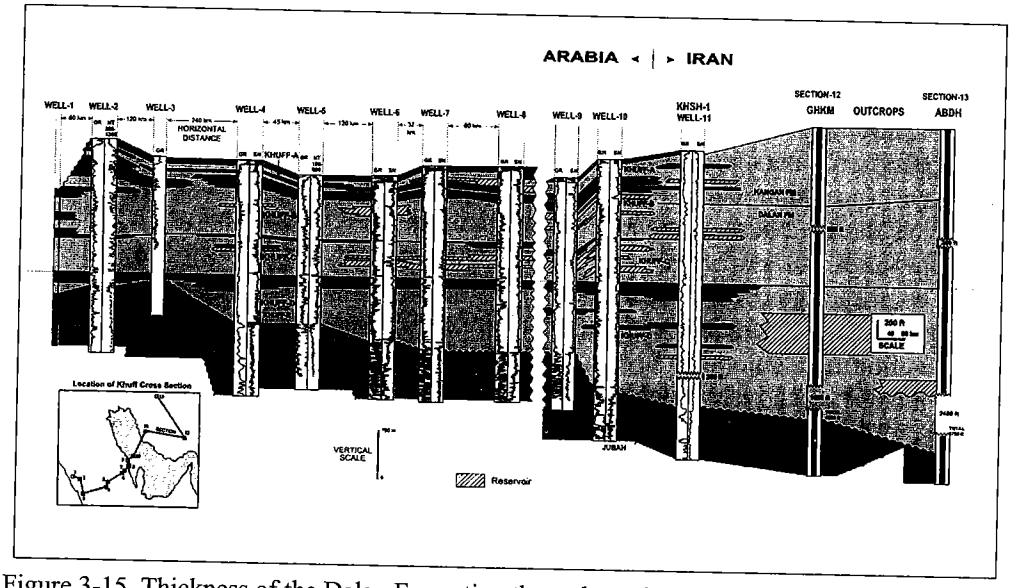

Figure 3-15. Thickness of the Dalan Formation throughout the Persian Gulf (Modified from Szabo and Kheradpir, 1978; Edgell, 1977).

Dalan Facies and Lithologic Divisions

The Deh Ram sequence has a persistent middle anhydrite unit, called the Nar Evaporites member, which provides a convenient three-fold subdivision of the Dalan Formation. The Dalan Formation is comprised of relatively clean limestone and dolomite, with some intervals rich in oolites and/or pallets. The basal part is a bioclastic limestone containing open marine corals, crinoids, bryozones, brachiopods and gastropods. Minor amounts of quartz are found near the boundary with the Faraghan Formation.

Edgell (1977) subdivided the Dalan Formation, based on lithology, into three primary members including; 1) the Lower Carbonate member; 2) Nar Evaporites Member and 3) the Upper Carbonate member. These members are described below:

The base of the Lower Carbonate member composes of fossiliferous limestone and dolostone and the upper part of it contains oolitic to pelletoidal limestone with partial or complete dolomitization. The thickness of this unit ranges from 250 to 300 meters. In the Lower Carbonate member there are two distinct anhydrite horizons. The contacts with the underlying Faraghan Formation and overlying Nar evaporites are gradational. In the surface outcrops the sequence is made up of the corals, crinoides, bryozoans, brachiopodes and gastropodes buildups (Motiei, 1995; Javadian, 1996). In subsurface they show relatively "clean" gamma ray log. In the 0-4 BIS well in the Persian Gulf, the Lower Carbonate member consists of coarse crystalline dolomite with rare

anhydrite. The thickness of this member in the location of the well is about 417 meters.

The Nar member consists of massive evaporites units with alternation of oolitic limestones. The thickness of this member is variable and in well O-4 BIS in the Persian Gulf the Nar member is about 107 meters thick whereas in well located in Kuh-e-Siah the thickness reached 250 meters. The thickness of the Nar member is increased substantially in the Kuh-e-Siah's well. However, in the Resalat oil filed well #32 the Nar member is missing (Bargrizan pers comm.). Thus, there seem to be a substantial increase in thickness towards the north of the Persian Gulf coastal regions. A favorable porosity is observed in oolitic and dolomitic layers. The Nar evaporites and the Lower Carbonate members can be correlated with Khuff-D in southern Persian Gulf.

The Upper Carbonate member consists of oolitic limestones in the lower part and micritic limestone with dolostone beds in the upper part of the succession. The base of this is a boundary indicating facies changes from evaporites to mainly carbonates. On the topmost of this member, there is a widespread and easily recognizable anhydrite zone referred as evaporite Marker "C" (Szabo and Kheradpir, 1978). This marker is also identified in well 0-4 BIS in the Persian Gulf. The microfossiles identified are *Staffelidae*, *Pachypholia/ Geinitzia* sp, *Globivalvulina* sp. *Hemigordius* sp (Javadian, 1996). The upper carbonates correlate with lower parts of the Khuff- B and Khuff- C in the southern Persian Gulf.

Both the Lower and Upper carbonate units consist of fossiliferous coral-bryozoan-crinoidal limestones and dolomite grading up into oolitic, peloidal and partly dolomitized limestones (Motiei, 1993). According to Szabo and Kheradpir (1978), Dalan Formation could be divided into four facies (see Figure 3-14), which are as follows:

Restricted Carbonate Shelf Facies,
Organic Carbonate Shelf Facies,
Near Shore Carbonate Facies with Clastics,
Open Marine Carbonate.

The ***Restricted Carbonate Shelf Facies*** appears in northern Persian Gulf, in Fars region, and represent a low to intermittent energy environment and occasionally the Nar evaporites are also associated with this facies. The rocks belonging to this facies have low primary porosity. There are occasional interbedd oolitic and foraminiferal grainstones in this facies with relatively good porosity.

The ***Organic Carbonate Shelf Facies*** are mostly cropping out in the High Zagros Mountain. They consist of fossiliferous limestones with corals, crinoides, algae, brachiopods and fusulinids. Where the carbonates are massive with no recognizable bedding, they have reefal appearance. Dolomitization have caused increase in crystal size and provided a good porosity. The primary porosity is very high. There are no evaporites associated with this facies, indicating medium to high energy environment. The organic carbonate bank

restricted the open sea water circulation towards the southeast, causing evaporite formation in Fars and Persian Gulf region. Surface exposures showing such evidence are observed in the Kuh-e-Gereh, Zard Kuh, Qaleh Kuh and Oshtoran Kuh section in the High Zagros Mountains.

Near Shore Carbonate Facies consists of fusulinid limestone with interbedded sandstone. The clastics probably originated from the highest part of the High Zagros where the early Cambrian Lalun sandstone might have been emergent during most of the late Permian time, forming a ridge or island and source area for the clastics. Exposures with clastics are present in Kuh-e-Dinar.

Open Marine Carbonate, commonly made up of carbonate with fusulinids, brachiopods and algae indicative of low to medium energy environment. Porosity development is poor and limited to some thin strata. They are found in outcrops near Kuh-e-Faraghan, Kuh-e-Gahkum and Bandar-e-Abbas in the northern Persian Gulf.

The identified carbonate facies indicate progressive transgression, from a low energy shelf, to a medium to high-energy shelf to an open marine, low energy setting. The final facies characterized by near-shore carbonates and clastics marks a return to shallower-water conditions.

Preliminary paleontological investigation by M. Barzegar (cited in Motiei, 1995) on the Permian choronostratigraphic zonation in Fars area indicated *fusulinid* zones and faunal assemblages for the base of the Dalan Formation. These zones are correlatable with Gaudalopian stage of Permian. Biostratigraphically, there are two zones namely A and B.

Zone A corresponds to the lower part of Dalan Formation with the presence of *Schwagerina* sp., and *Afghanela* sp and other microfossils such as *Pachyphloia* sp., *Endothyra* sp. *Globivalvulina* sp., *Archeodiscus* sp., *Cribogenerina* sp., *Tuberitina* sp., staffellids.

Zone B corresponds to the upper part of Dalan Formation (Upper carbonate Member) and containing fossils such as *Codonfusiella* sp., and *Reichellia* sp. In addition there are microfossils such as *Pachyphloia* sp., *Globivalvulina* sp., *Cribogenerina* sp., *Palaeotextularia* sp., *Tuberitina* sp., *Pachyphloia iranica*, staffellids, *Paraglobivalvulina mira*, Dagmartia *chanackchiensis*, *Ichthyolaria* sp., *Mizzia* sp.

Based on six stratigraphic cross sections in the Zagros area, Baghbani (1993) identified ten different biozones in Dalan Formation across the Zagros Basin and reported some new fusulinid including *Persumatrina* spp, *Eoverbeelina* sp. *Verbeekina.* Some of the Foraminifera such as *Soroorina ghezelbashi* started to disappear. The zones introduced by Baghbani (1993) are correlatable with Kubergandinian which is the lowest stage of upper Permian to Changhsingian the uppermost stage of Permian where all the Foraminifera disappear. In the drilled wells in the Persian Gulf, due to the limited sampling and pervasive dolomitization identification of the biozones which are introduced by Baghbani is not possible (Motiei, 2003).

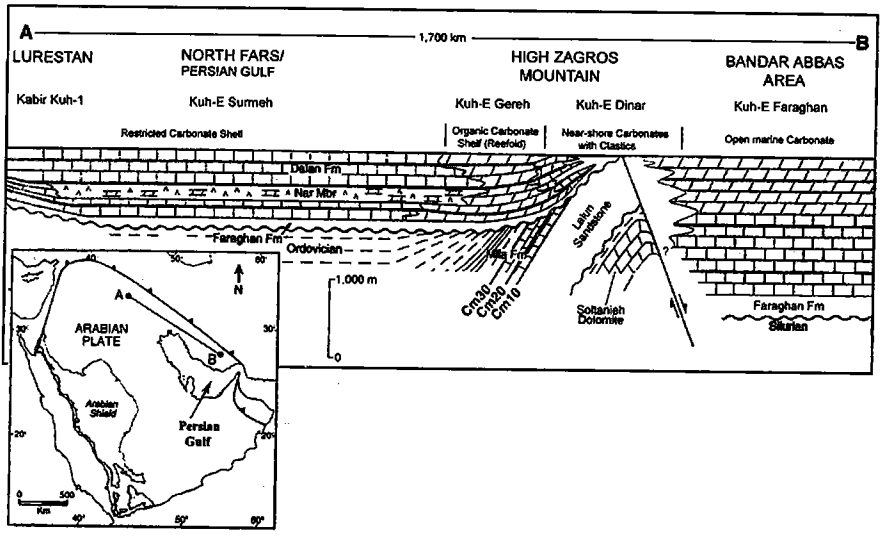

Figure 3-16. Permian sedimentary sequences in the northern Persian Gulf (Modified from Szabo and Kheradpir, 1978).

There is a minor unconformity at the upper boundary of the Dalan Formation marked by erosion, which provide evidence for emergence. Thus, it can be concluded that the upper part of the Dalan Formation in the Zagros Basin was deposited during late Permian, Kungurian-Kazanian-Punjabian and possibly early Julfian time with the uppermost Julfian missing, while in the Abadeh region sedimentation started a little earlier (Artinskian time) and was continuous into the Triassic (Barzegar, cited in Szabo and Kheradpir, 1978).

During the late Permian, a major marine transgression took place throughout the Persian Gulf and surrounding region. The transgression coincided with late Permian rifting along the Zagros, opening of the Neo-Tethys Ocean, and deposition of the cyclic, shallow water carbonates and evaporites of the Late Permian to Lower Triassic Dalan/Kangan Formations and their equivalent Khuff Formation in the southern Persian Gulf region (e.g., Edgell, 1996). Relative sea level also rose slowly throughout the uppermost Permian, drowning the shallow carbonate platform in the Abadeh range in south central Iran (Heydari et al., 2003).

The latest Permian beds that reached a thickness of about 490 meters are placed in the Jamal Formation in central Iran. These deposits formed in a shallow transgressive sea. Above the basal, relatively thin fossiliferous limestones, middle part of the Formation consists of 350 meters of partly dolomitic limestones capped by an upper unit, dominated by 130 meters of black dolostones.

PERMIAN IN SOUTHERN PERSIAN GULF

Unayzah Formation

The Unayzah Formation is presented in this part for the clastic sequence which was deposited between the Kangan/Dalan (=Khuff) carbonates and the Hercynian unconformity. The equivalent of the Faraghan Formation, the Unayzah sandstones contain light oils in part of central Arabia within the Greater Persian Gulf region. The Unayzah Formation clastic sediments and associated impure carbonates units blanketed the entire basin, overlapping truncated and block-faulted pre-existing rock sequences (McGillivray and Husseini, 1992).

A similar sequence of shales, sandstones and limestones of the same age and stratigraphic position are mapped in other areas in southern Persian Gulf. For example, the Unayzah Formation and the Alkhalta and Gharif Formation of the Haushi Group in Oman are the time-stratigraphic equivalents of the Faraghan Formation in the Zagros Basin in Iran. According to Motiei (2003, p.102), the Haushi Group is the time equivalent of the Chal-i-Sheh (Permian age) of the northern Persian Gulf. Regional surface and subsurface data indicate that the Farahgan Formation and its equivalent Unayzah are widespread over much of the Persian Gulf area (see also Figure 3-13 and Al-Laboun, 1987).

The Unayzah is a complex succession of continental clastics consisting of braided-plain, channel-fill, and eolian sand and floodplain silt that were deposited on the Hercynian unconformity (Evans et al., 1997; Kornet et al., 2001). Heine (2003) showed that sandstones of the Unayzah in the southern Ghawar area are cold-climate (periglacial) dunes deposited on an eroded surface that trends across central Saudi Arabia, and possibly over Bahrain and Qatar. Deposition of the Unayzah preceded a major marine transgression and widespread deposition of Dalan/Kangan.

Unayzah Formation is composed of various facies of the conglomerate, sandstone, siltstone, mudstone, caliche, and nodular anhydrite. It rests unconformably on various Formations ranging from Precambrian basement to Devonian. The Unayzah deposited as a series of coalescing alluvial fans dominated by braided streams which graded into playa lakes under arid to semi-arid conditions. It is organized into an overall upward-filling sequence comprising braided stream dominated alluvial fan deposits and eolian sandstones, which vertically and laterally grade into meandering river, floodplain and lake deposits.

The Hercynian unconformity is marked by a thick development of paleosol horizon and floodplain association in the top part of the Unayzah Formation. The presence of the Hercynian unconformity is also confirmed by palynological studies (van der Eem, 1990). Thus, one of the most pronounced unconformities of the Persian Gulf region is the Hercynian unconformity (Pow-

ers et al., 1966), with a regional extent. In Iran and northern Oman, this major unconformity occurs at the base of the Dalan carbonates dated as Kungurian (Szabo and Kheradpir, 1978; Hughes-Clarke, 1988).

The deposition of the continental clastic of the Unayzah Formation marks the beginning of a major change in the sedimentation that preceded a major marine transgression and widespread deposition of carbonates and evaporites. The cyclic nature of the Unayzah suggests a fluctuating sea level.

Within a regional tectono-sedimentary framework, the Unayzah Formation records a phase of a pre-rift sedimentation following a major crustal uplift in the region. On the other hand, the overlying carbonates represent the early phase of subsidence and rifting at the western margin of the Tethys Ocean (McGillivray, 1994).

Gharif Formation

Gharif Formation of Mid-Permian is an important siliciclastic reservoir unit in Oman. It is subdivided into Lower, Middle, and Upper members. The Lower Gharif consists of coastal-plain and lacustraine siliciclastic rocks passing upward into the marine bioclastic-oolitic limestone. The Middle Gharif is characterized by fluvial sandstone interbedded with siltstones and mudstones containing calcrete and root traces and are interpreted to be channel deposits. The top part consists of alluvial-plain mudstone with less calcrete.

This formation records the transition between the glacial deposits of the Al Khalta and the arid coastal plain and the Permian carbonates (i.e., Kangan/Dalan). Gharif deposits pass transitionally up into the arid coastal plain claystones gradually transgressed by marine carbonates.

Khuff Formation

Permian carbonates of Kangan-Dalan and its equivalent "Khuff" regionally developed as a thick carbonate sequence in the southern Persian Gulf region (Figure 3-17). It crops out over a very broad area within southern Persian Gulf. The term "Khuff " was first introduced by Bramkamp et al. (1958) for a 172 meters thick carbonate section of late Permian in Saudi Arabia. Since then, this term has been used by oil companies in the Persian Gulf area.

The Khuff Formation consists of dolostones interbedded with anhydrite and limestones, deposited in a very shallow open marine environment. Deposition occurred during a regional transgression over a stable shelf of very low relief which had a minor clastic supply on the margin of the Arabian Peninsula (Hughes-Clarke, 1988).

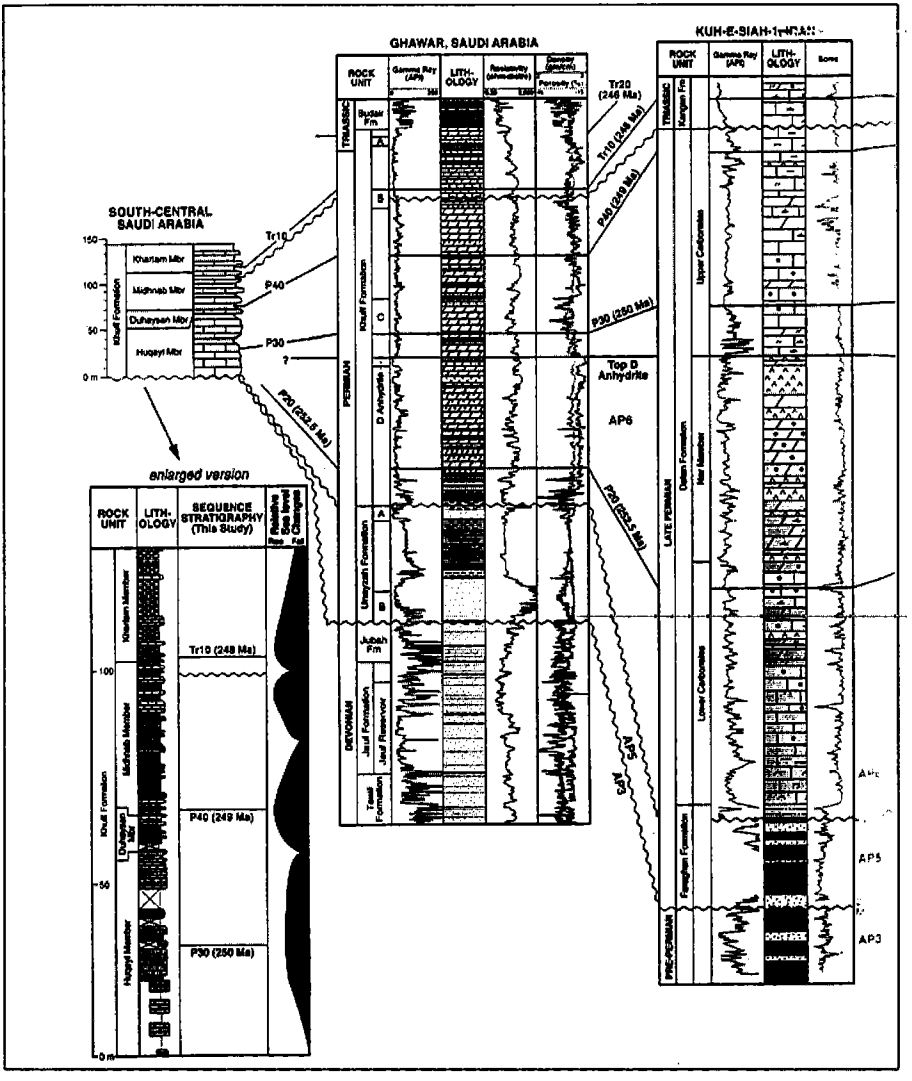

Figure 3-17. Distribution of the Kangan/Dalan Formation throughout the Persian Gulf region (Modified from Szabo and Kheradpir, 1978; Al-Jallal, 1995).

The late Permian carbonates represent shallow open marine deposits and as mention before, are laterally continuous across the Persian Gulf Basin. It comprises an east-southeast dipping series of carbonates and evaporites deposited under coastal sabkha and shallow marine conditions. The carbonate sequence thickens towards a broad depocenter to the west of the Oman Mountains and thins on the Arabian Shelf. There is a condensed sequence in the region of the Qatar-Gavbandi Arch which was gradually overstepped through

Permo-Triassic times. Such setting provides strong possibility for early stratigraphic trap (Edgell, 1977).

Typical thickness of Kangan/Dalan ranges from 365 to 490 meters over most of central and eastern Arabia, 550 meters in Qatar, 600 and 700 meters in Kuwait and Bahrain respectively. But the formation thickens to more than 900 meters eastward (Al-Jallal, 1995). The formation thickens from about 260 meters in southwestern Saudi Arabia to more than 915 meters in Central Rab'al-Khali, 1220 meters in Oman, and 1520 meters in Iran. The Formation is presently buried to depths ranging from 2.5 to greater than 6 kilometers representing present day temperatures from 100° C to greater than 220° C.

During the maximum transgression, carbonates overstepped the clastic realm and rested on the basement over the Central Arabian Arch. During regressions, restricted evaporitic environment was established on the western part of the platform protected by shoals from open seas in the east. In the High Zagros and Oman deep-marine environments were established. Over the Arabian plate the thickness of late Permian carbonates reach 1.5 kilometers whereas beyond the Zagros Thrust Zone and the area of Gulf of Oman the thickness is more, indicating a Paleo-Tethys invasion.

Lithologically, the formation in Qatar consists of massive, tidal flat, oolitic, peloidal, dolomitic grainstones and packstones forming five cycles. The carbonates are terminated by the development of tidal and supratidal dolomitized mudstones, wackestones and anhydrite deposited in very shallow, semi-restricted to open marine environments (Schlumberger, 1981).

In Kuwait the Kangan/Dalan (i.e., Khuff carbonates) is dominated by massive dolostones with rare, thin interbeds of shale in the lower part, grading upwards to alternating anhydrite and dolostones and ending with a massive sucrosic dolomite. Because only a single well has penetrated into the Paleozoic in Kuwait, the stratigraphy of the Permian succession is poorly understood (Bou-Rabee, 1996). Nevertheless, Murris (1980) stated that the Permian formation in Kuwait consists of 406-610 meters of limestones with some clastics comprising mainly shallow-water carbonates. Thus, the formation was deposited under very shallow marine conditions associated with high-energy shoals prior to the advent of lower energy conditions marked by the argillaceous facies of the Triassic Sudair Formation. The lower boundary of the Permian carbonates in Kuwait is well defined by a prominent unconformity marking a major depositional hiatus.

The Kangan/Dalan Formation in Bahrain consists of dolomitized, oolitic, peloidal packstones and grainstones with anhydritic interbeds which passes up, without unconformity, into the beds of the overlying Triassic Sudair Formation.

Al-Jallal (1995) described a cyclic deposition of shallow-water carbonates that shoal upward and developed extensive, multiple evaporite sabkhas. According to this author, in eastern Arabia, there are five depositional members associated with Kangan/Dalan Formation. However, throughout the Persian

Gulf region this formation may comprise as many as seven designated units which four of them might be reservoirs, corresponding to four depositional carbonate-anhydrite cycles where transgressive carbonate are capped by regressive anhydrites. These members in descending order include Khuff-A, -B, -C, -D, and E. The four earlier members showed cyclic sedimentation. Each cycle starts with a steady transgression of subtidal grainstones that make up the reservoirs and end with the gradual deposition of a regressive unit of intertidal and supratidal muddy and evaporitic deposits that represent the caprocks. In contrast, the transgressive E member consists of the 'basal clastics' that consists mostly of silisiclastics including shale, carbonaceous shale, limestone streaks, and incised channel-fill sandstone cutting deeply into Unayzah Formation.

The depositional cycles identified can be associated with the worldwide late Permian eustatic cycles of Haq et al. (1987). Based on the correlation of maximum flooding surfaces, the Khuff-A, -B, -C, and D cycles were also identified by Sharland et al.(2001).

In Oman the Permian carbonate change into a continental red-beds facies (Glennie et al., 1974) and in the Oman Mountains, the Saiq Formation lies with angular unconformity on Ordovician, Precambrian, and basement rocks (Glennie et al., 1974). According to Lovelock et al. (1981), the Akhdar Group equivalent of Kangan/Dalan in the Oman Mountains has overstepped to be with a strong angular contact on basement rocks. However, major oil reserves have been discovered in Central Arabia within the Permian-Carboniferous clastics which lie directly beneath the Kangan/Dalan (McGillivray and Husseini, 1992).

In northern Qatar and Bahrain, a grainstone facies is dominant indicating at least two shallow shelf breaks with higher energy environments. These breaks mark the north and northwest extent of the open marine conditions that existed southward in Oman restricting the evaporitic carbonate shelf for most of Saudi Arabia. The latter is restricted from the deep basinal environment further southeast by a shelf edge facies of coral-algal buildups in Oman and Iran. The coral organic reefs with fusulind-crinoid-brachiopods buildups in Iran follow a Paleozoic high that was partly emerged, during the Permian (Szabo and Kheradpir, 1978; Edgell, 1977). This coral shelf edge facies extends in a north-south direction for more than one kilometer.

Chia Zairi Formation (Upper Permian) was deposited in a transgressive neritic sea with lagoonal conditions prevailing during its final stage of sedimentation (Buday, 1980). The transgression corresponds to the deglaciation of Gondwana and the rapid drift of the Arabian plate into warmer latitudes (Husseini, 1992; Beydoun, 1993).

Based on Power (1968) investigation in Saudi Arabia, the age of the Khuff Formation was restricted to the Late Permian. However, later studies undertaken in Saudi Arabia revealed that the upper part of the Khuff-B and Khuff-A were deposited in early Triassic time (van der Eem, 1989; 1990). In Iran,

Oman and the UAE, the Upper part of the carbonate sequence was documented as early as Triassic. The uppermost of the sequence is of Early Triassic age (Szabo and Kheradpir, 1978; Edgell, 1977; Clarke, 1988). The lower part in Iran was deposited as early as Artkinskin (see Taraz, 1971), and sustained its deposition during the Kungurian, Kazanian, Tatarian and Scythian age over most of the Arabian plate.

PERMIAN DEPOSITIONAL ENVIRONMENT

Depositional environment of the Faraghan Formation appears to be of deltaic to fluvial nature as advocated by Motiei (1995). It can be stated that, in general, the sandstones and siltstones of Permian sequence in southern Persian Gulf were replaced basinward by braid plain deposits overlain by shallow-marine near-shore sediments to essentially shallow marine sands of Faraghan Formation.

The basal clastics and mixed clastic and dolostone series indicate a gradual environmental change from fluvial to shallow marine. Between the continental and marine end members, a transitional coastal-plain environment with hypersaline lagoons was established. Conditions oscillated between peritidal marine (laminated dolostones) and marginal marine to coastal-plain (marls and sands with salt hoppers). Continued arid conditions led to the establishment of extensive evaporite deposits throughout middle to upper Permian.

During Permian depositional period, most of the southern Persian Gulf region was located within a restricted evaporitic carbonate shelf environment. The relatively flatter area over the southern Persian Gulf reflects the continuity of these depositional environments over a wider area. These depositional environments include the subtidal carbonate sand shoals, lagoons and bars that spread out as sheets for long distances in the paleoepicontinental seas.

The Persian Gulf region was invaded by the first, major carbonate sediments that blanketed the entire region during Permian time. The Dalan Formation marked the continuation of subsidence and the beginning of what is called the "layer Cake" sediments that evolved as a recognizable entity about this time. The Permian carbonates thin gradually towards southwestern Persian Gulf from the depocenter to the east and northeast.

Based on the sedimentological evidence, the depositional environments of the Permian carbonates were predominantly intertidal and sabkha together with subtidal carbonates, sand shoals, lagoons, and sandbars. The arid conditions prevailed at the time of the deposition and sabkha features similar to those of today have been observed (see Al-Jallal, 1995).

In northern Qatar and Bahrain, a grainstone facies is dominant indicating shallow shelf break with higher energy environment. According to Edgell (1977) this area seems to be a sedimentary reflection of a structural high referred to as the Qatar-Gavbandi Arch, which is known to have a marked effect on Mesozoic sedimentation in south Oman, northeastern Arabia and the cen-

tral Persian Gulf. The shallow break mark the north and northwest extent of the open marine conditions that existed southward in Oman restricting the evaporitic carbonate shelf for most of Saudi Arabia. The latter is restricted from the deep basinal environment further southeast by a shelf edge facies of coral-algal buildups in Oman and Iran.

The platform becomes much steeper eastward in Iran where the thickness increases beyond the Zagros Suture, further east in Iran, the area represent the argillaceous facies of central Iran (Sharief, 1983; Taraz, 1971) where the environment become deep marine. These facies move down along the shelf margin profile towards the basin where more basinal argillaceous limestones are present. The lithofacies succession of the uppermost Permian is interpreted to represent deposition under increasing water depth related to the rising of relative sea level which led to drowning of the carbonate platform below the storm wave base (Heydari et al., 2003). Sedimentologic characteristic, lithology and wide distribution and low sedimentation rate indicate that strata immediately below the Permian-Triassic boundary were deposited in deep oxygenated waters (Heydari et al., 2003). In Oman, the shelf edge becomes steeper but is gentler than in Iran. Slope debris, cephalopods limestones and radiolarite facies are encountered in Central Oman (Blendinger et al., 1990).

The Late Paleozoic to Recent plate movements provides an important regional context to Persian Gulf regional sedimentary facies and petroleum habitat. In the late Paleozoic, for example, southern Persian Gulf was in the temperate belt below 30°S latitude, thus explaining the propensity of Devonian through Mid-Permian clastics. The region's post mid Permian position within 30° of equator facilitated the maintenance of an enormous carbonate platform, future home of the Middle East huge oil reservoirs.

THE PERMO-TRIASSIC BOUNDARY

Based on National Iranian Oil Company's investigation sedimentation has been continuous without any break in the northern regions of the Persian Gulf. Such result is in accordance with the fact that it is widely accepted that a global drop of sea level reduced flooded shelf areas during the late Permian and significantly restricted the record of end-Permian sediment to a few key areas. Descriptions of almost complete Permian-Triassic boundary section exist only from the Tethyan realm (e.g. Greece, the Indo-Iranian region, Pakistan), north Pangean shelf (Greenland) and Japan.

There has been considerable debate concerning the position and status of the Permian-Triassic sediments in the Persian Gulf region. Szabo and Kherdapir (1978) concluded that the Permian and Triassic in the Zagros Mountain area are separated by a major unconformity, with the Julfian stage missing. In contrast, Rosen (1979) identified Julfian fauna and indicated that at least a part of the Julfian stage is present. The shale and argillaceous limestone and dolomite unit (Szabo and Kheradpir, 1978), which apparently separates the

Dalan and Kangan Formations, has limited areal extent. It is thought to represent only a temporary cessation in carbonate a kind of unconformity deposition and not an angular unconformity (Rosen, 1979). The Julfian on the Salman field was identified and revealed a correlative conformity (sequence boundary type 2) by missing the Dorashamian stage (Lotfpour et al., 2000). The paleontological evidence in the Persian Gulf region shows that there is no unconformity between Kangan and Dalan Formations (Bashari, 1988).

According to Baghbani (1993) the Permo-Triassic boundary in Zagros Basin is not clearly identified. The Permo-Triassic boundary in Zagros area traditionally has been defined at the lithologic boundary between the Dalan and the Khaneh Kat Formation (or coeval Kangan Formation) (Baghbani, 1993). However, he has introduced three different criteria in order to define the Permo-Triassic boundary:

The presence of *claraia* at the onset of deposition of Kangan Formation signaling the Triassic regime, such a boundary between Permian and Triassic is identified at Kuh-e-Surmeh,

Presence of vermiculite limestones in lower part of the Triassic succession, identifiable at Kuh-e- Faraghan,

Lithologic boundary between Dalan Formation contains stromatolites and Khaneh Kat in Oshtoran Kuh.

Late Permian rocks are more widely distributed as the sea level recovered following deglaciation. This deglaciation process was not a continuous event and the cyclicity of the Late Carboniferous and Permian sequence may be the reflection of this periodicity. Late Permian rocks are well-known and represent a major period of carbonate deposition in the entire Persian Gulf region.

Environmental conditions became more arid in Upper Permian to Lower Triassic, and the Arabian shield was uplifted to the west indicating periodic influxes of clastics onto the carbonate-evaporite shelf. These conditions prevailed throughout most of the Triassic.

The Permo-Triassic boundary (251 Ma) is more or less contemporaneous with one of the most extinctive mass extinctions in the Earth history. It marks the most severe mass extinction of marine and terrestrial organisms of the Phanerozoic Era. This occurrence is well evident in the Persian Gulf and the Zagros Basin. Many of the foraminifers extinct at the Permo-Triassic Boundary (PTB) and most of them never pass through the Permian limit. This is in accordance with findings of Baghbani (1993) mentioning that all the foraminifers and algae in Dalan Formation disappeared prior to the deposition of Kangan and Khaneh Kat Formations. This is also in agreement with the findings of Lotfpour and Adabi (2002) attributing excessive growth of microbial mats, thrombolites, stromatolites, and gradual disappearance of the upper Permian marine index fauna indicating global mass extinction. Stromatolite beds in most of the sections in PTB are regarded as the base of the Triassic. In the Zagros area, i.e. Aligoudarz, Wei et al. (2005) showed a dramatic depletion in carbon isotope on top of the Permian succession or negative values

across PTB. They related such an excursion to biomass extinction resulting in a dramatic change in the carbon cycle at the end of Permian.

Heydari et al. (2003) indicated that shallow water to moderately deep waters were well oxygenated during the latest Permian and earliest Triassic in Abadeh region of south-central Iran. According to these authors, general oceanic circulation models have either shown a fully oxygenated Late Permian Ocean or have had difficulty showing anoxic conditions. Therefore, they have suggested that Permo-Triassic mass extinction models postulating widespread marine anoxia should be treated with caution.

In the tectonic sense, the end of Permian and beginning of Triassic is the time of precursor events leading to the formation of the Neo-Tethys, which formed along the Zagros line in the wake of the diminishing PaleoTethys, which eventually closed around the end of the Triassic. The sedimentation and structural development of the Triassic system in the Persian Gulf region is fully related to the opening of the NeoTethys Ocean about Late Permian and the northward drifting of the Iranian Plate away from the Arabian plate.

MESOZOIC OF THE PERSIAN GULF

Introduction

From Early Mesozoic onwards, the pattern of sedimentation in the Persian Gulf region was influence by periods of increased activity alternating with quiet intervals. The Mesozoic was an Era of carbonate, evaporite, and calcareous shale sedimentation. The Mesozoic carbonate systems of the Persian Gulf region form one of the richest hydrocarbon provinces of the world and contain most of the reservoir rocks. This was mostly due to the combination of their vast scale and the presence of source rock, reservoir and seal facies within the same depositional system (i.e. Murris, 1980).

The Jurassic and early Cretaceous was a time of maximum transgression of marine conditions (see Murris, 1980). Extensive carbonate platforms covered the entire Persian Gulf region during Mesozoic. This period of widespread carbonate deposition resulted in a vertical and lateral facies mosaic including evaporite seals that constitutes the richest single oil habitat in the world. The remarkable concentration of these three fundamental ingredients of a petroleum system is to a large extent due to repeated formation of organic-rich shallow basins. Their formation within large carbonate platform successions assured the presence of significant source rock accumulation next to, and in immediate contact with, potential reservoir facies.

In general, the deposition of the sedimentary sequences occurred under calm tectonic regimes. These conditions were broken up only by epeirogenic movements, some of which were of regional extent. The evaporitic facies were restricted to the Triassic and Jurassic successions. However, tectonism

was a major stimulus for the reactivation of basement features, salt movement and withdrawal within the basins, and diapirism during the late Cenomanian and Turonian in the eastern part of the Persian Gulf (Ricateau and Riche, 1980).

The Mesozoic succession of the Persian Gulf was deposited along the eastern passive margin of the Arabian plate. In common with much of the Tethyan belt, this margin evolved from rift in the Permian and Triassic to drift in the Jurassic and early Cretaceous, followed by suture in the Late Cretaceous and Early Tertiary. Due to the development of the Zagros in the northern and the Oman Mountains in the south, a linear foreland basin developed at the margin of the plate during the Late Cretaceous (Murris, 1980; Searle et al., 1983; Patton and O'Connor, 1988).

One of the most important characteristics of the Mesozoic carbonate shelf successions of the Persian Gulf is that, several phases of intrashelf basin formation are observed. These intrashelf basinal settings were filled by shales, deeper water carbonates and organic-rich sediments. Several large, restricted basins developed within the middle Cretaceous in the Persian Gulf region (Murris, 1980). Where rimmed by carbonate platforms, these formed self-contained hydrocarbon systems sealed regionally beneath the marly shales such as Laffan and Gurpi Formations. It is largely in these areas, with interest driven by petroleum exploration, that carbonates of the Sarvak Formation and its equivalent have been considered as important targets.

Paleogeographic and Paleoclimatic Reconstruction

During most of the Mesozoic and Cenozoic, the Arabian plate and the Persian Gulf region were generally located in or near equatorial latitudes and dominated by shallow marine carbonate and evaporite sedimentation in the platform settings, but with important periods of clastic deposition, especially during the Mid-Cretaceous. The interior parts of these platforms are often envisaged as undifferentiated, extensive shallow water areas, where carbonates accumulated by aggradations. This view is based on the fact that individual shallowing-upward carbonate packages are laterally extensive.

Paleogeographic investigation of Jurassic and Cretaceous ammonite fauna demonstrates that northern and central Iran must have been attached to southern Eurasia during the Mesozoic, while southern Iran was a part of northern Gondwana. During some periods of the Mesozoic, clastic sediment supply on the Arabian plate had a much greater influence on the tropical platform and ramp carbonate systems, resulting in a mixed clastic succession. Furthermore, there were periods of global anoxia in oceanic basins. These anoxic waters encroached onto shelf areas during transgressions, resulting in extinction of platform biota and thus, reduced sediment production (Jenkyns, 1991).

As the clastic sediment supply was restricted and the Arabian plate was located in sub-tropical latitudes, much of the sedimentary succession formed

entirely of productive carbonates and sediments deposited on shallow carbonate ramps or platforms of epeiric seas. In such a depositional setting, changes of relative sea level caused sequences to develop differently to those in purely clastic-dominated depositional environments (Ziegler, 2001). In carbonate ramp and platform settings, because of the low angle of the shelf and its broad nature, even small changes in relative sea level, caused by the interaction of eustacy, tectonics and changes in sediment supply have a major impact on depositional system (Harris et al., 1984).

The Triassic paleogeography of the Persian Gulf region is related to the opening of the Neo-Tethys, the detachment of northward drifting of the Cimmerian Continent from the Gondwana, the closure of the Paleo-Tethys and the accretion of the Iranian plate to the southern active margin of the Eurasia. The Iranian plate shifted from latitude of ca 10°S in Early Triassic to ca 35°N in Late Triassic. The drifting was accompanied by large-scale counterclockwise rotation.

In Early Triassic hot arid environments prevailed throughout most of the Persian Gulf region. In the Late Triassic the climate again became less arid and a marine regression caused the resumption of significant clastic deposition. Some pre-Jurassic erosion took place on regional high, such as the Qatar-Gavbandi Arch where Late Triassic tectonic reactivation took place. Continental clastics were deposited responding to a widespread regression phase. There was a regional relative drop in sea level caused by eustatic lowering of sea level or uplift of the basement. In some areas this resulted in widespread progradation of fluvial and coastline clastics and in other areas, erosion and non-deposition.

During Early to Middle Jurassic, the Persian Gulf region was situated in the tropical or subtropical zone. Continued deposition of mostly carbonate and evaporites occurred in warm equatorial latitudes during the Middle and Late Jurassic. Sequence stratigraphic investigations (Al-Husseini, 1997; Sharland et al., 2001) have shown that cyclic changes in lithology (mostly carbonates and evaporites) of the Late Jurassic section were due mainly to cyclic changes in relative sea level.

During most of the Cretaceous period, the Persian Gulf region was located at equatorial position (see figure 3-18), with a semi-arid or humid tropical climate condition prevailing (Murris, 1980; Parrish and Barron, 1986); no evaporites have been described from platform interiors.

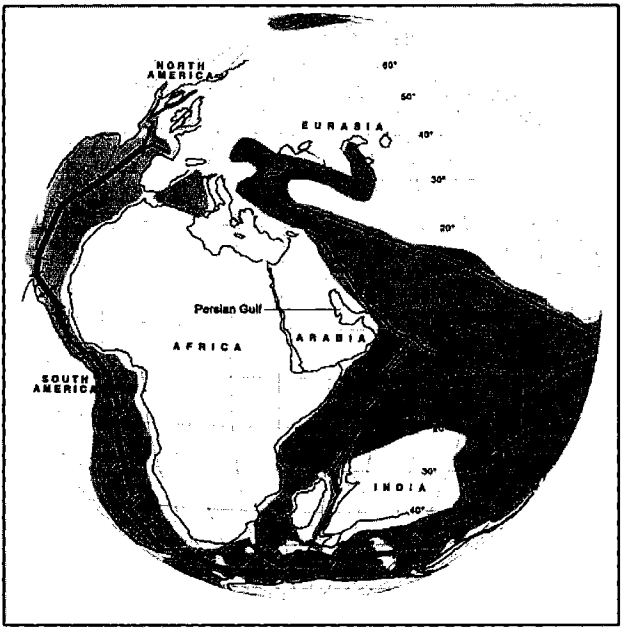

Figure 3-18. Paleogeographic reconstruction, Late Cretaceous times (85 Ma, approximating base Upper Cretaceous Unconformity time. Shell internal compilation)

GEOLOGIC SETTING

The geological history of Persian Gulf region in the Mesozoic Era is of greater significance, since many important geologic events occurred in this time. The tectonic and paleogeographic evolution of the Persian Gulf region during this time was controlled by the geodynamic interaction of Eurasian continental margin and the Tethys oceanic belt.

During most of the Phanerozoic the Arabian plate is interpreted to have been tectonically relatively stable (Bishop, 1995). If this was the case, the signature of global eustatic sea level change, sensu Haq et al. (1988a) should be detectable in the sedimentary succession. The most significant characteristic of the Arabian plate during Mesozoic particularly the carbonate platform and ramps is that it revealed a relatively horizontal substrate.

The geological setting of the Persian Gulf and the surrounding region can be envisaged into three separate domains, which can have enormous influence in the sedimentary regime of the entire region. First, the vast landmass situated in the southwestern part of the Persian Gulf, which mainly consist of the Arabian shield. Second region is a belt of clastic sediments, which extend for hundreds of kilometers forming a rim around the Arabian shield and comprising both continental and shallow marine deposits derived from the shield. And finally, a carbonate shelf hundreds of kilometers in width and lying seaward

of the clastic belt, upon which predominantly shallow shelf carbonates were deposited.

Throughout Mesozoic, relatively simple depositional systems dominated over the region, which carbonate ramp and platform environment developed (Murris, 1980). Such a model has proven a very useful means of considering intracratonic sedimentary sequence.

TRIASSIC

Following the extensive Late Permian carbonate deposition (Murris, 1980; Beydoun, 1988), arid and semi arid conditions characterized the Triassic. As the Triassic advanced, there was an increase in periodic shallow water carbonate deposition commonly interbedded with anhydrite. After uplift and rifting, these shallow-marine conditions became dominant during the late Triassic, as the south Tethys Ocean opened to the east and north, with the separation of Iran and Turkey.

A similar conclusion was arrived at by Read and Horbury (1993), who found that the climate during the Triassic switched between semi-arid conditions in which cyclic sabkha-capped facies developed only on the inner platform, and arid conditions with major evaporative draw-down. This resulted in extension of the inner platform cyclicity into intrashelf basin-center evaporite cycles.

As earlier indicated, sedimentation continued without interruption or facies changes throughout the Permian-Triassic boundary in the Persian Gulf region particularly in the northern regions. The cycle of platform sedimentation which commenced with Permian Sea transgression, continued in Triassic and ended in Late Middle Triassic. Carbonate platforms were widespread in the Mid-Triassic. In fact the overall sedimentary sequence deposited on the entire Persian Gulf region during the Early and Middle Triassic is essentially a continuation of the sedimentary cycle that commenced during the Late Permian.

The Upper Permian-Triassic carbonate and evaporites of the Persian Gulf basin accumulated on an epeiric shelf punctuated by a series of transgressive and regressive events. In the Zagros Basin to the southeast and across the Persian Gulf to northern Oman, thick Permian carbonates pass upward into Triassic carbonates. Hence, the continuous Upper Permian-Lower Triassic carbonates may act as a single reservoir, especially where overlying Triassic Dashtak evaporites served as a caprock (Edgell, 1977; Kashfi, 1992). In the entire region, it is often difficult to separate the Lower Triassic from the Upper Permian. However, in contrast to the generally extensive Late Permian carbonate transgression, the Triassic was distinct by partial, or even locally, quite extensive regressional episodes; there were also phases of minor transgression.

During the Early Triassic throughout the Persian Gulf region, the increasing area of carbonate platform which prevailed through the Permian and corresponding decrease in the areas of thick salt deposition now gave way to a

more clastic-dominated series. Fine-grained clastic shed off from the western hinterland. These had the effect of restricting the carbonate-evaporite platform to a narrow northwest-southeast zone close to the present Zagros Fold-Thrust Belt. A marine influence is seen in the northern part of the region, suggesting a connection with the Tethys Ocean.

Lower and Middle Triassic evaporites and carbonates were deposited in shallow water environmental setting with a period of quiet sedimentation and minor tectonic activity. In northern Persian Gulf a succession of shallow water carbonates with tidal flat evaporites were deposited through Triassic.

The Triassic sequence consists of a succession of northeastward prograding, interbedded evaporites and dolomites with interlayers of shallow-marine but low-energy limestones to the northeast. An unconformity, correlative with the well-known late Triassic unconformity of the Zagros Imbricate Zone, separates this sequence from overlying Jurassic to Cretaceous continental-shelf deposits. Development of the unconformity was associated with extensional tectonic activity, plutonism, volcanism, and metamorphism in the Zagros imbricate zone (Alavi, 2004). This unconformity is attributed to extensional faulting, which was in progress farther to the northeast along the continental margin during the opening of the Neo-Tethyan oceanic realm.

Lower and Middle Triassic sedimentary successions in Iran consist almost exclusively of platform carbonate rocks, overlying by a more or less pronounced disconformity (Seyed-Emami, 1971; 2003). Extensive shallow water carbonates of the Permo-Triassic to Early Jurassic with some of the mudstones and shales in the succession are interpreted to represent high stand tract (HST) regression rather than transgression (Sharland et al., 2001). Although they exhibit gamma ray maxima, they are interpreted with sabkha or salina anhydrite and very shallow water carbonates, and are interpreted to be alluvial, playa lake or lagoonal in origin (Motiei, 1993).

The northeastern Arabian shelf remained amazingly stable throughout much of the Triassic-Late Cretaceous interval. However, slow steady subsidence allowed widespread sheet-like deposition of shallow marine sediments on an extraordinary wide epeiric shelf more than 2000 kilometers long (northwest to southeast) and almost 2000 kilometers wide from shelf break to shield. By Mid-Triassic, the basin was occupied by an evaporitic platform.

The vast aerial width of the shelf (for which no modern analog exists) engendered remarkably broad uniformity of deposition but, nevertheless, with slight differential subsidence and sedimentation, allowing the development of large, but shallow, intrashelf basins. Scale of the shelf prevented efficient water agitation and flushing from the ocean. The shallow basins repeatedly became stratified and anoxic except for their well-lit organically productive surface waters.

Murris (1980) developed a credible model of source-reservoir-seal rock involvement over this remarkably extensive and more or less flat shelf. During transgressive periods, differentiated carbonate deposition gave rise to

stratified sediment-starved basins in which potential source rocks accumulated, separated by higher-energy margins from carbonates-evaporite shelves: marginal mounds, oolite bars and shoals, rudist banks, and regressive carbonate sands from the main reservoirs, and supratidal evaporites and thin shales from the seals.

TRIASSIC OF NORTHERN PERSIAN GULF

In northern Persian Gulf, all exposures of Triassic rocks are established in a narrow zone in the northeastern portion of the area, directly to the southwest of the Crush Zone, except for Kuh-e-Surmeh in Fars region. However, in the past few years, drilled wells have entered the Triassic succession in a number of wells (0-4 BIS, 3H-1 and R32) in the Persian Gulf area permitting an improved understanding of the stratigraphy of this stratigraphic interval.

Over one kilometer of Triassic sediments were encountered in Kuh-e-Mond well in coastal Persian Gulf. This interval is predominantly composed of anhydrite, dolostones and limestones, with minor intercalations of salt and shale, indicating shallow water deposition in an occasionally restricted basin. The same environment seems to have prevailed in the area of the present Persian Gulf where the contact of the Triassic sediments with the Upper Permian rocks is not readily recognizable (Mina et al., 1967). Paleontological study on 0-4#BIS well in Persian Gulf has revealed that the exact position of the Permo-Triassic boundary in this well is extremely difficult to be identified, due to dolomitization of sediment (see Bashari, 2006).

Several cycles of sedimentation have been observed within the Triassic sequence in the coastal Fars, each beginning with shallow marine carbonates and ending with sabkha type anhydrites. According to Setudehnia (1978), the Triassic sediments consist of five distinct correlatable lithologic units as follow:

The lowermost unit consists mainly of thin-bedded argillaceous vermicular limestones, containing the pelecypod genus *Claraia* in outcrops at Kuh-e-Surmeh and Kuh-e-Dinar, indicating Lower Triassic (Scythian) age of deposition (Taraz, 1974). This unit shows pronounced facies variations from argillaceous limestones and shales to limestone and dolostones. Lower Triassic lies unconformably on Upper Permian sequence.

The second unit consists mainly of evaporite with dolomite interbeds and thin shale at the base representing the end of the previous sedimentary cycle and is present in almost the entire region. The thickness variations in this unit indicate either the presence of unconformity on top or, additional development of anhydrite.

The third unit is mainly dolomitic with a minor anhydrite interval. This unit is correlatable in subsurface with a great lateral extension in southwestern Iran. Anhydrite with dolomite intercalations forms the fourth unit. In Bandar

Abbas area the anhydrite passes into dolostone making differentiation of this unit with others difficult.

The overlying predominately evaporitic sequence is known as the "Dashtak" Formation (Motiei, 1993). In Kuh-e-Surmeh and Kuh-e-Dinar, the lower part of the Dashtak Formation consists of anhydrite and minor shales intercalated with dolostones in the upper part. The Lower Dashtak Formation changes into massive dolostone units towards interior Fars in Zagros Basin.

EARLY TRIASSIC

The Early Triassic succession in the northern Persian Gulf region starts with shallow water deposits; consist mainly of limestone with thin anhydrite layers, terminating with shale which forms the end of a sedimentary cycle. The condition is somewhat similar in the southern Persian Gulf areas where shallow water deposits are passing gradually into the predominantly shales and sandstones of continental origin. This is followed by the accumulation of anhydrites and dolostones of Middle and Late Triassic in the Persian Gulf and surrounding lands with a gradual change from the evaporites into clastics (Figure 3-19).

The pattern of sedimentation was, shallow water deposition of dolostones along the NE part of the Zagros Basin, sabkha type deposits in the greater portion of the area from E-SE Iraq through SW Iran and the Persian Gulf with a general shallowing towards central Arabia. The evaporite and dolostone sequence in the northern Persian Gulf region is an extension of evaporites in Arabia and Iraq (Murris, 1978). Towards the High Zagros, the evaporites are replaced by dolostone (Setudehnia, 1978).

A shallow-water carbonate platform with localized paper shale and evaporites occurred in the northern Persian Gulf and Zagros Mountain (Szabo and Kheradpir, 1978). The main platform, extending across through most of the region and as far as northern Iran was a shallow water carbonate region with minor areas of neritic carbonate and lime mud deposition. Thus, the Lower Triassic in the Persian Gulf was deposited in a continental and nearshore and shallow water setting during a period of quiet sedimentation and minor tectonic activity.

The pattern of inner shelf evaporitic facies rimmed by massive shelf carbonates in the High Zagros repeated in the Triassic. Evaporites turned into the dominant facies across the entire Persian Gulf region. In contrast to the Permian time, the entire High Zagros area was now affected by thinning due to the uplift of pre-Jurassic truncation.

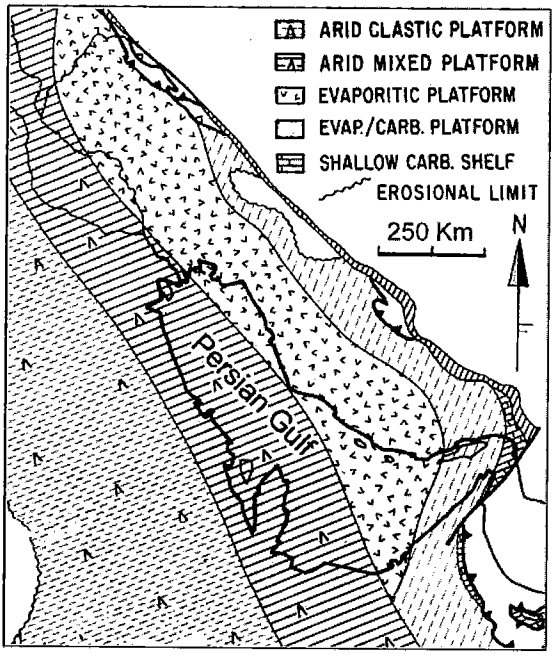

Figure 3-19. Early Triassic sedimentary environments and their distribution in the Persian Gulf region (Modified from Murris, 1980)

The Early Triassic was also a period of regional uplift (Qatar-Gavbandi Arch) and this was the result of tectonic activity. A stable Arabian Shield on the west and southwest of the Persian Gulf basin was a strong source of clastics that spread eastward by Late Triassic. As a result, clastic deposits were increased in southern Persian Gulf and the carbonate-evaporite platform was restricted in the Persian Gulf area and the Zagros belt. Carbonate deposition of the High-Zagros now suggest an open marine sedimentary conditions along the northern margin of the Arabian Platform (Berberian and King, 1981).

Triassic rocks in the northern Persian Gulf consist of the Dashtak and Khaneh Kat Formations, which are thin dolostones and sandstones with local anhydrite and coal. The Aghar shale, deposited at the base of the Triassic Dashatak Formation. In northern Iran flysch deposition occurred in the area of developing Tethys Trough. Sabkha carbonates and evaporites were deposited in the region between the clastics and the carbonates.

The marine carbonate sedimentary regime which persisted throughout Permian and Early Triassic times resulted in deposition of Dalan and Kangan Formation (Szabo and Kheradpir, 1978). The lack of lowstand deposits within the Kangan Formation and comparing it with other carbonate deposits basin wide in the Persian Gulf, in Early Triassic indicate that these sequences formed in the southern margin of the Neo-Tethys on an extensive carbonate ramp.

In southwestern Iran two different lithologic developments of the Lower and Middle Triassic strata have been reported; a carbonate facies (i.e., Khaneh Kat Formation) being mostly developed in the High Zagros, and an evaporitic-carbonate facies mainly developed in the Zagros Fold-Thrust Belt and the coastal range of the Persian Gulf (James and Wynd, 1965; Szabo and Kheradpir, 1978). Few records of *foraminifera involutinida*, pelecypods (*Darnella, Halobia*) and the ammonoid *Paraceratitos* indicate Scythian, Anisian and Canian age (James and Wynd, 1965, Zaneintti et al., 1978); so far there is no evidence of the Upper Triassic in southwest Iran (Seyed-Emami, 2003).

MIDDLE TRIASSIC

The rifting of the Iranian Paleozoic platform and the sedimentary cycle beginning with Permian transgression continued and finally ended in the Middle Triassic. According to Berberian and King (1981), at the stratigraphic boundary of the Middle to Early Upper Triassic rocks (210-195 Ma) there is evidence of major compressional phase. Regional uplift, folding, metamorphism, and erosion took place and were followed by the formation of a new sedimentary basin with rapid facies changes.

Due to the Middle Triassic orogenic movements, the entire Iranian landmass was folded and uplifted, except for the Zagros Basin where the orogenic movements had lower intensity. The Zagros sedimentary basin steadily subsided along faults inherited from Permian and earlier time. The continuous episode of subsidence and sedimentation in the Zagros marginal basin was possibly an isostatic adjustment in response to the spreading of the lithosphere following the Middle Triassic movements (Berberian and King, 1981).

Regressive conditions then occurred in the Middle Triassic, resulting in the deposition of the evaporites of Dashtak Formation, indicating hot and arid climatic conditions. The main platform, extending across through most of the areas as far as northern Iran was shallow water carbonate region with minor areas of neritic carbonate and lime mud deposition. The regressive sequence included shelf, lagoon, tidal flat and supratidal carbonates and evaporites extending across the entire Persian Gulf region (figure 3-20). Slightly deeper marine to shelf margin carbonates were deposited across central, western and northern Iran, while further north again western Tethyan flysch sedimentation took place. Carbonate platform were widespread in the Mid-Triassic in northern Iran and evaporite basins developed in the Zagros region.

The Middle Triassic movements affected the central and southern Persian Gulf regions. In these areas, transgressive Jurassic strata are discordant upon the Triassic sedimentary sequence. Such unconformity and the absence of deposits in some parts of southern Persian Gulf seem to be the effect of the Middle Triassic movements, which presumably led to the emergence of these areas.

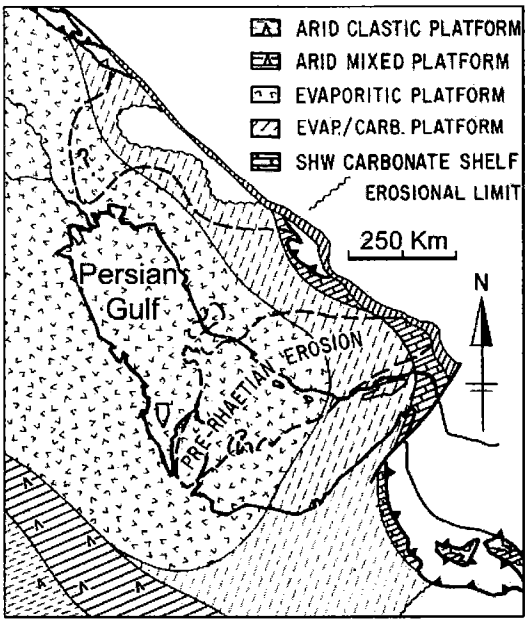

Figure 3-20. Sedimentary depositional environment in the Persian Gulf and surrounding region (Modified from Murris, 1980).

LATE TRIASSIC

By the Late Triassic and Jurassic, the Persian Gulf region was a stable interior platform positioned along the equator (Kornet et al., 2001). A period of sea-level lowstand in the Early Jurassic is marked by a hiatus of non-deposition and erosion. Subsequent to this depositional hiatus, a transgression flooded southern Persian Gulf and a shallow-marine carbonate platform developed. The regional relative drop in sea-level together with increased aridity, lead to the dominant deposition of continental clastics and in several areas resulted in widespread progradation of fluvial and coastline clastics (see figure 3-21).

A major period of uplift and erosion occurred, affecting the southern part of the Persian Gulf. Erosional activity during the late Triassic tectonism removed the upper part of the Triassic sediments in Zagros Basin. Why this period of stable gentle subsidence was so long (over 150 m.y.) is one of the greatest unanswered questions in the geology of the Middle East.

There is no reliable proof of Upper Triassic strata in Zagros region or the Persian Gulf (Szabo and Kheradpir, 1978; Setudehnia, 1978). No Upper Triassic sedimentary deposits have been mapped. Their absence most likely indicates a possible fall in sea level due to eustatic sea level change (Murris, 1980). The reason might be the absence of diagnostic fossils and partly the existence of a widespread pre-Liassic erosional phase (James and Wynd,

1965; Szabo and Kheradpir, 1978; Setudehnia, 1978; Motiei, 1993; Seyed-Emami, 2003).

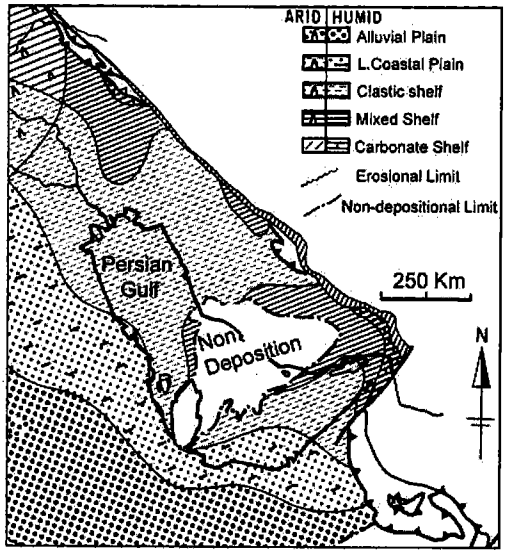

Figure 3-21. Late Triassic sedimentary depositional environment in the Persian Gulf region (Modified from Murris, 1980).

The Late Triassic hiatus in southwestern Iran and the Persian Gulf area could also possibly be related to eustatic sea-level fluctuations, rather than to large scale tectonic activity. Nonetheless, the partial coincidence with the post-collisional hiatus in the late Triassic (Early Cimmerian) of north and central Iran is remarkable (Seyed-Emami, 2003).

The Middle Triassic evaporite sequences of the Zagros are unconformably overlain by the Liassic terrigenous clastics and transitional terrigenous-to-open-marine sediments of the Neyriz Formation. Upper Triassic rocks are also believed to be unconformable on the Middle Triassic in other localities (Bellen et al., 1959).

Kangan Formation

The Kangan Formation is named after the village of Kangan in the Fars region in the coastal Persian Gulf. This formation is considered as a member of Deh Ram Group and has a total thickness of about 178 meters in subsurface at Kuh-e-Siah-1 and is estimated to be around 140 meters in outcrop at Kuh-e-Surmeh (Motiei, 1993, p.82). The thickness of the Kangan Formation in the drilled wells is 180 meters in 0-4 BIS, 166 meters in R-32 (Resalat) and 170 meters in 3H-1 in the Persian Gulf. In Salman field located also in the Persian Gulf, the thickness of Kangan Formation is about 190 meters.

Kangan Formation represents the first transgression of the Triassic Sea in the Zagros and northern Persian Gulf region. The Lower part of Kangan and

Dalan Formation form hydrocarbon reservoirs and that is the reason for both formations to be assigned to the Deh Ram Group.

Kangan Formation overlies disconformably on Dalan Formation, but passes upward into the Aghar shale member of Dashtak Formation. A more or less barren zone appears at the base of Kangan which is followed by microbial mats and thrombolitic beds across the Zagros Basin and Arabian Peninsula. This marker bed specifies the Lower Kangan Formation. The age of Kangan is considered Scythian which is acceptable for the lower part of the Formation (Motiei, 1993). Kangan Formation correlates with Khuff-A member and the lower part of Khuff-B in southern Persian Gulf (Szabo and Kheradpir, 1978).

Kangan Facies and Lithologic Divisions

Kangan Formation consists of three principle facies which includes; 1) clean carbonate facies; 2) basal argillaceous and shaly facies and 3) evaporite-carbonate facies (Szabo and Kheradpir, 1978).

Clean pelodidal carbonates: This lithofacies include a basal, clean pelodidal unit with oolitic grainstone and mudstones which is completely dolomitized in certain parts and include minor evaporites with sand and silts. This facies is identified in subsurface by a distinctive low gamma-ray signal on geophysical logs.

Basal argillaceous facies: This lithofacies consists of the basal argillaceous facies with shale, argillaceous carbonates including limestone and dolostones. On the surface this facies is identified by laminated weathered vermicular argillaceous limestones. The *Claraia pelecypods* are abundant at some horizons indicating an early Triassic (Scythian) age for the Lower part of the Kangan Formation. The contact with the lower facies, the "clean carbonates facies" is gradational. This facies is identified in subsurface by high radioactivity gamma-ray during drilling.

Evaporite-carbonate facies: The third and final lithofacies is made up of evaporites and carbonates, dolomitic limestone, dolostone and anhydrite. This is a marker bed in Kangan Formation in Lorestan but in the High Zagros the Triassic sediments have been subjected to erosion and only limited thickness of the sediments has escaped erosion. At Kuh-e-Dinar the erosion has cut down the Kangan Formation and except the lower shaley unit, the rest of the formation is missing.

The carbonate sequences and the evaporite facies have been deposited in an arid homoclinal ramp platform, with the environmental conditions changing from sabkha to open marine settings.

Kangan Formation in some of the wells drilled in the Persian Gulf consists of the clean pelodidal carbonates and it is highly comparable and correlatable with the type section in Kuh-e-Siah. However, the other two facies which were introduced are not present in these wells. In addition the Kangan Formation in these wells is lacking any identifiable microfossils.

Early Triassic has been extensively investigated in the South Pars field in the Persian Gulf (Lotfpour and Adabi, 2002). Based on stratigraphic and facies observation and evidences, there are significant different in Kangan lithologic units in the South Pars field in the Persian Gulf and Zagros region. However, this has to be verified on a regional scale and basinwide. Lithologically the formation in the Persian Gulf consists of carbonate, shales and anhydrite and the main carbonate units are dolomitic.

The lower part of the Kangan in the Persian Gulf is mainly consists of carbonate facies, very similar to what is observed in the Zagros region. Four distinct facies belt have been identified in lower Kangan showing shallow marine environment of sedimentation. These include, 1) arid peritidal settings, 2) restricted to semi-restricted ramp lagoon, 3) carbonate sand shoal, and 4) proximal to distal open marine. These sedimentary environments can be viewed within a homoclinal ramp with frequent shoals (Lotfpour and Adabi, 2002).

According to Lotfpour and Adabi (2002) thrombolitic bed does not appear at the contact of Dalan and Kangan Formation. According to the facies, this horizon appears a few meters above the actual contacts of the two formations. Gradual disappearance of the upper Permian marine index fauna in the upper parts of the Dalan Formation may be an indicative of the global mass extinction. Paleoecologically, such evidence indicates that mass mortality has occurred. Excessive growth of biogenic structures such as microbial mats, thrombolites, stromatolites, and onccolites developed at the base of the sedimentary succession demonstrate such an event.

Dashtak Formation

The Dashtak Formation is named after an anticline structure which is situated 75 kilometers west of Shiraz where Dashtak No#1 well has been drilled. This formation represents the lower part of the "Kazerun Group" with a total thickness of about 660 meters. The Dashtak Formation includes almost entirely the Upper Triassic evaporites (Motiei, 2003).

Complete sequence of Dashtak Formation has been drilled in the Persian Gulf. This is the case in wells such as wells 0-4 BIS, R-32 (Resalat) and 3H-1. In well #U-1 drilling penetrated down to middle part of the formation (i.e., Evaporite-B). The thickness of Dashtak Formation in the R-32 (Resalat) well is 456 meters whereas in 0-4 BIS and 3H-1 is 335 and 346 meters respectively. In the Salman field the thickness of Dashtak formation reaches 304 meters.

The formation consists of massive to thick-bedded, shallow-marine carbonates (dolostones, dolomitic limestone) interbedded with evaporites (anhydrite, gypsum, subordinate halite) and with intercalations of shale and rare siltstone. Local disconformities within upper part marked by layers of monomictic carbonate-clast conglomerate and increased content of argilla-

ceous impurities are the main characteristics of this formation (Alavi, 2004). Based on M. Barzegar (cited in Motiei, 2003) the age of the Dashtak Formation is Middle to Upper Triassic.

Micro-fauna identified in the Dashtak Formation include; *Trocholina multispira., Trocholina* sp., *Agathammina* sp., *Frondicularia* sp., *Frondicularia woodwardi*, *Nodosaria* sp., *Trochammina*. Some of the fossils mentioned such as *Frondicularia woodwardi* have been identified in Middle Triassic of Germany whereas *Trocholina multispira* have been reported in Triassic successions of Austria, Poland and Italy (Javadian, 1996).

Dashtak Facies and Lithologic Divisions

In the type section area, Szabo and Kheradpir, (1978) divided the Dashtak Formation into six different divisions in ascending order including; 1) Aghar shale, 2) Evaporite-A, 3) evaporite-B, 4) Evaporite "C", 5) Sefidar dolomite Member and 6) evaporite-D.

Aghar shales Member: previously named the Beduh Shale (cited in Motiei, 1996), (i.e., the lowermost member of the Dashtak) extend throughout the Persian Gulf region and it is also well identified in Zagros region and considered to be a marker horizon (Alavi, 2004). Prior to this, it was assumed that this member was indicative of Permo-Triassic boundary separating the Permian rocks from Triassic sequences. Based on sedimentological similarities it was considered to be equivalent of lower part of Sudair in southern Persian Gulf, however, such correlation is still unclear (Motiei, 1993).

The Aghar shale is weathered varicolored clastic (i.e., shale and silty argillite) thin interval (50 m thick) which occurs within a thick succession of carbonates and evaporites, and is provisionally interpreted as continental in origin (Szabo and Kheradpir, 1978). Based on the well information from northern Persian Gulf area the thickness of this unit is between 10 to 40 meters. In the Salman oil field in the Persian Gulf the thickness of Aghar shales is about 9.2 meters and the shales are considered as a marker bed for the recognition of the Kangan Formation.

Evaporite-A: the lowest major evaporite unit is called evaporite "A" with an approximate thickness of about 220 meters. The lower part of the evaporite"A" interval consists of argillaceous carbonates, shale stringers, dolomite and limestones with interbedded anhydrite. Massive anhydrites dominate the upper part of the interval, with the exception of a characteristic shaly zone near the top. Above the top of evaporites "A", a siltstone unit is present in some wells and in Kuh-e-Surmeh surface section. Towards the Arabian shield and southern parts of the Persian Gulf, increasing shale content is also apparent in these beds (Szabo and Kheradpir, 1978).

Evaporite-B: this member is represented by a relatively well-developed thin anhydrite zone with minor dolostone stringers in northern Persian Gulf. The thickness of this member is 40 meters and is it well identifiable on the

logs. In the type section area, the top of the Evaporite B is located at about 160 meters on top of the Evaporite A and in between there are shale and argillaceous layers associated with siltstones.

Evaporite-C: The thickness of this member is extremely variable and it ranges from non-existence to 250 meters. Such variations might have duel nature including post-Triassic erosion and partly due to facies changes in an easterly direction from evaporites to dolostones.

Sefidar Dolomite: is named after DEMINEX Sefidar No#1 well drilled about 60 km south of Shiraz. It comprises a thickness of about 40 meters with great aerial extension throughout the Persian Gulf region except where it has been truncated by erosion. The dolostone are mainly coarse-crystalline with low radioactivity and it is identifiable by low gamma-Ray logs. This member is present in Kuh-e-Surmeh and Khaneh Kat surface outcrops but missing in Gahkum and Faraghan regions due to truncation by post-Triassic erosion.

A disconformity surface has been identified at the base of Sefidar in No-1, 2, and 3 wells in Kangan field in the northern coast of the Persian Gulf (Doron, 1977, cited in Javadian, 1996). Furthermore, at Kuh-e-Surmeh, there is a conglomerate bed made up of carbonate clasts at the base of the Sefidar which indicate an erosional phase prior to the next depositional cycle which ended up with deposition of Evaporite A, B, and C. The presence of this disconformity has also been reported in Pars Gas field of the northern Persian Gulf (Motiei, 1987). Szabo and Kheradpir (1978) and Koop and Stoneley (1982) noted a marked erosional truncation of the Sefidar Dolomite member in the northern Persian Gulf in Fars region, central Persian Gulf, and Qatar regions. The Dashtak dolostone and evaporite sequence has been eroded in this area, or may have changed facies across the Fars region.

Evaporite-D: is the uppermost member of the Dashtak Formation that is bounded on top by Triassic-Jurassic unconformity and underlain by Sefidar Dolomite Member. It consists of alternation of dolostone; anhydrite and shale with limited aerial extension and in many localities have been eroded by the unconformity. This member has been identified in Sabzpoushan No#1-well, Dashtak No#1 well, Kuh-e-Siah well and many others.

The extensive uppermost unit consists of coarse crystalline dolostones, truncated by Triassic/Jurassic unconformity. This unconformity is well recognized in logs from the onshore as well as offshore in the northern Persian Gulf. The dolostone, (Sefidar Dolomite Member) is also present in the Persian Gulf, where, it has been referred to as "Jilh Dolomite" in the southern Persian Gulf.

Dashtak Formation has great geographical distribution and this is evident through the isopach and lithofacies maps (see figure, 20 in Motiei, 1993). However, due to extensive erosion large part of the Evaporite C and Sefidar Dolomite Member and Evaporite D members are missing in the Persian Gulf. Apparently, the erosion has acted more intensively in eastern parts of the Persian Gulf. However, the decrease in thickness might be a function of basinal

paleomorphology and in a local scale such erosional trend might not be applicable.

Khaneh Kat Formation

The name Khaneh Kat Formation was initially introduced for the upper part of the Triassic carbonate succession cropping out near the village of Khaneh Kat, approximately 110 kilometers east of Shiraz in the northern Persian Gulf. The thickness of the Formation is about 400 meters or more (James and Wynd, 1965).

The Khaneh Kat Formation of the Lower to lower Upper Triassic age consists of thin-bedded dark gray (lower part) to brown (upper part) siliceous dolostones and dolomitic limestone with slump and breccia bodies near top; grades toward the southwest into time-equivalent Kangan and Dashtak (Alavi, 2004). Thus, this formation embraces the carbonates of the Triassic whilst no distinct evaporites are recognizable in the outcrops. The presence of some evaporites is suggested by solution breccia, evaporite casts, in some cases (Oshtoran Kuh) and strongly contoured beds in more argillaceous zones (Szabo and Kheradpir, 1978). Such features indicate the former presence of evaporite beds within the formation.

In the type section area, the upper contact with the Sefidar Dolomite is conformable and there is no sedimentary break observed and it continues to limonitic shales and quartzarenite.

The lower part of the formation consists of argillaceous carbonates and shales and the upper part is mainly composed of shallow water limestones and dolostones with mud cracks, stromatolites and solution breccia, argillaceous limestones with gypsum casts and rare gypsiferous shales. Such evidence also indicates intermittent subaerial exposure and occurrences of erosional surfaces suggesting paleokarst and breccia developments, which was accompanied by soil formation and a series of hiatuses.

TRIASSIC IN SOUTHERN PERSIAN GULF

In the southern Persian Gulf the Triassic sediments consist of carbonates, anhydrite and shales in the lower portion, grading upwards into predominantly sands and shales of shallow water environment. Characteristic fossils of the Triassic are: *Frondicularia woodwardi*, *Aeolisaccus* sp, *Agathammina-Glomospira*, and *Trocholina* sp., (Mina et al., 1967).

Sudair Formation

Following the deposition of Permian carbonates, the impervious argillaceous rocks, red beds and shale, interbedded with dolostones and evaporites of the Lower Triassic Sudair Formation were formed on a flood-plain to la-

goonal and tidal flat environment across the southern Persian Gulf (Sharief, 1986).

The calcareous shales of the Mirga Mir Formation in Iraq (Lower Triassic) conformably cap the carbonates of the Upper Permian Chia Zairi Formation (Al Shadidi et al, 1995). Also in Saudi Arabia, a 50 meters thick sequence of massive Sudair shale, equivalent to the lower part of the Dashtak Formation, considered to be of Latest Permian age conformably overlies the Permian carbonates. In southern Persian Gulf, the lower part of the Sudair Formation forms a caprock for the Permian carbonates in the southeastern part of the Arabian Peninsula (Grantham et al., 1988; Alsharhan, 1994; Simmons, 1996). In northern Persian Gulf, Lower Triassic calcareous Aghar shales overlay the Permian carbonate reservoirs.

Sudair Shale is conformably overlain by an upward-coarsening sequence of the Middle Triassic Jilh Formation. In aerial distribution, the Sudair in Oman occurs only in the western and northern subsurface of the Oman interior, truncated to the south and east by Jurassic and Cretaceous sediments.

The Sudair Formation comprises mixed carbonate and terrigenous limestones deposited as three cycles. The lower cycle formed by limestones interbedded with terrigeneous mudstones and minor dolomite deposited in a variable-energy shallow marine conditions. The middle cycle is dominated by anhydritic dolomitic mudstones deposited in a supratidal to subtidal setting. The upper cycle is composed of a shallow marine to sabkha facies consisting mainly of interbedded terrigenous mudstones and dolomite with minor oolitic-peloidal packstone/grainstone. In offshore Dubai the percentage of shale increase toward the upper part of the formation, and the top of the formation is marked by thin salt streaks and shale and siltstone (Pollastro, 1999).

The Sudair represents a continuation of lagoonal/supratidal sedimentation, which began in Late Permian (Alsharhan and Kendal, 1986, Alsharhan and Whittle, 1995). The Arabian Peninsula was relatively quiescent in terms of both sedimentation and tectonic activity during the Lower Triassic.

Towards the center of depositional basin, the discovery of Late Permian palynomorphs in the shales of Sudair Formation (Delfour et al., 1982; Al Laboun, 1986), and the presence of a microfauna and marine microplankton such as *Densosporites playfordi* (regarded as Early Triassic in age) in beds of the upper Khuff Formation in the UAE, indicate there is a facies relationship between the Sudair and Khuff Formations and the boundaries are lithofacies boundaries not lithostratigraphic.

The Jilh Formation displays a great diversity of siliciclastic and carbonate facies because it was deposited in a non-marine (continental) and near shore to shoreline complex (Sharief, 1986). Overlying the Jilh Formation is thick, continental, siliciclastic sedimentary sequence of the Injure Formation that was deposited during regression and increased aridity. The Injure was deposited over a broad area during the Late Triassic and is mostly poorly sorted, cross-bedded quartz sandstone with some conglomerate and shale lenses.

Near the end of Early Triassic, the southern Persian Gulf region underwent a period of tectonic activity. At this time, the Qatar-Gavbandi Arch was reactivated and part of the Arabia were uplifted and subjected to erosion. This period of tectonism corresponds to the Early Kimmerian Orogenic phase. In southwestern Persian Gulf this period is reflected by the expansion of Jilh Formation on the down thrown sides of basement seated faults (McGillivray and Husseini, 1992) and the local erosion of Sudair/Khuff from the higher fault blocks. Rejuvenation of faulting occurred during deposition of the Sudair and Jilh Formations of the Lower to Middle Triassic age, respectively. These movements were the most pronounced in early to middle Jilh time and by late Jilh time they had mostly ceased.

In the southern Persian Gulf, in Abu Dhabi region, the lower and Middle Triassic sediments were deposited in a more arid and shallow marine setting and consist of carbonates, anhydrite and shale. During the Late Triassic, continental clastics were deposited responding to a widespread regressive phase. These rocks are missing in offshore UAE in southern Persian Gulf where an unconformity marks the termination of the Upper Triassic depositional period.

GEOLOGICAL EVOLUTION OF TRIASSIC BASIN

The Tethys Ocean began to open up in Middle to Late Triassic times, producing a series of substantial tectonic movements and inducing a profound change in the depositional setting of the Persian Gulf region.

The opening of Neo-Tethys was apparently accomplished in two stages. The first stage occurred during the Permo-Triassic time causing the Iranian microplate to drift away from the Arabian plate and be confronted with, and accreted to, the Eurasian plate. The second stage followed in the Late Triassic to Middle Jurassic, when the width of the Neo-Tethys reached a maximum of 4000 kilometers. This phase of extensional tectonics subsequently produced localized troughs on the adjacent Arabian platform aligned in a remarkable arcuate pattern delineating two main trends: the western Taurus and an eastern Zagros trend (Sengor, 1990).

The extensive Triassic rifting is one of the most characteristic features of the Neo-Tethyan terrains that extend throughout the eastern Mediterranean and into adjacent areas. The major rifting became progressively younger westward from the late Permian in the Oman Mountains, the early Triassic in southern Turkey, the Middle Triassic (Anisian-Ladinian) in Greece, the Dinarrides, and Italy, to the early Jurassic (Liassic) in the Atlantic Tethys. Therefore, the best-developed assemblage of rift sediments is probably located in rather southerly positions in the Neo-Tethyan fold belt (Dixon and Robertson, 1984).

The development of a sedimentary basin during the Late Triassic in northern Iraq marked the initiation of the Neo-Tethys Sea in the region (Sadooni and Alsharhan, 2004). The rocks belonging to this time period are believed to

have been deposited over a complex shallow-marine shelf under the influence of clastic accumulation and development of salinas.

The movement of the Arabian plate toward warmer latitudes at the southern parts of the tropical zone was associated with thick clastic rocks in the Arabian plate. This includes the Sudair of the southern Persian Gulf region.

The closing of the Neo-Tethys completed the process during the Neogene. The tectonic effects of the closing of Paleo-Tethys can readily be identified in the sea-level fluctuations recorded in the lithofacies changes seen in the stratigraphic records. In general regional changes in sedimentation pattern during the Jurassic and most of the Cretaceous appear to have been controlled by sea-level fluctuation and tectonic (Glennie et al., 1995).

In northern and eastern Iran Late Triassic orogenic movements caused a complex horst and graben pattern to develop. The Iranian block experienced intense rifting and block-faulting at about the time as the Triassic-Jurassic boundary, and the faulting was locally accompanied by continental or shallow-marine alkali-basalt volcanism (Stocklin, 1974). Therefore, in late Triassic time another major tectonic event resulted in complete partition of the Paleozoic platform, such that the two parted areas subsequently experienced different sedimentary and tectonic histories. These areas later were rejoined during the Tertiary Alpine tectonic phase. The suture is a 5 to 10 kilometers wide northwest-southeast belt of intense tectonic disturbance termed the "Main Zagros Thrust" or the "Crush Zone" (Stocklin, 1974).

The Tethyan rift zone suffered rapid facies and thickness changes in the Late Triassic. The thickness of the sequence range from a few meters to more that 2 kilometers of predominantly non-marine coal-bearing sandstones, with occasional marine intercalation and thin layers of basalts. The Hercynian horst and graben structures appear to have had only minor influence on the distribution of the evaporites in the northern Persian Gulf region (Glennie et al., 1995).

REGIONAL COMPARISON

Carbonate sedimentation started in Late Permian when a marked change occurred from the earlier predominantly clastics to mostly carbonates. During this epoch, the Tethyan Ocean spread over a vast area depositing a sheet of shallow water carbonates extending from Turkey and Iraq through southwestern Iran and Persian Gulf region into Oman and covering much of Arabia. The relationship of this unit to the underlying lower Paleozoic is generally unconformable.

Similar conditions existed northeast of the Crushed zone in the Abadeh area of south central Iran and those of Zagros Basin, where a thick and complete section of carbonates is present (Taraz, 1974). For example, the Lower Triassic vermicular limestones, containing the lamellibranch *Claraia*, have been found in both the Zagros and Abadeh areas. The general subsidence pro-

duced a great thickness of these sediments at Abadeh, when the Permian-Triassic boundary is conformable. The Middle Triassic dolostones of the Abadeh succession may represent the dolostones of the middle part of the Khaneh Kat section, about 180 km to the SSE in the Zagros Basin. Uplift occurred at the end of the Permian and was accompanied by erosion of the uppermost part of the Permian in some areas of the Zagros Basin, particularly in Fars and NE Khuzestan.

In central Iran, no detailed regional stratigraphic studies have been published, and the best available sections worked in detail are those described by Taraz (1974) from the Abadeh area (Deh Bid-Surmaq). Taraz et al. (1981) identified five lithologically distinct units (A to E) of Triassic age in Abadeh section and provided general descriptions. Lower Triassic unit 'A" deposition began with two enigmatic layers. Immediately above the P-T boundary is a one meter of syn-sedimentary carbonate cement which consists of large crystals perpendicular to the bedding grading up to wackestone. The second enigmatic layer is a 1.5 meter thick packstone-grainstones interval overlying the cement layer. The remainder of unit "A" consists of lime mudstones that overlies the packstone-grainstone layer and contain the distinctive Triassic bivalve *Claria*. It is mud dominated.

The synsedimentary cement layer was previously interpreted as thrombolites (Taraz et al., 1981; Heydari et al., 2000, 2001b). Thrombolites are microbial build-ups similar to stromatolites, but lacking laminated texture (Pratt and James, 1982). Thrombolites assume a wide range of shapes and internal structures, possess large amounts of lime mud, and commonly exhibit clotted textures (Kennard and James, 1986). The syn-sedimentary cement and grainstones layers have been interpreted (Heydari et al., 2003) to have been deposited in shallow water indicating a rapid and major drop in relative sea level at the end of Permian time in the area followed by a relative sea level rise during the earliest Triassic.

The Upper Triassic of the central Iran, in particular Abadeh area, shows marked differences from that in the Zagros Basin. It contains a thick sequence of shales, sandstones and conglomerates which, in the Abadeh area, follows upward through an interval of sandy limestones and calcareous sandstones into limestones which are topped by reefal limestones (Taraz, 1974). Marine Upper Triassic rocks are missing from many other parts of Central Iran (Stocklin, 1972).

TRIASSIC-JURASSIC TRANSITION

As far as is known, the passage from Triassic into Jurassic is usually represented by an unconformity in the Zagros region (Setudehnia, 1978). This is in accordance with Mina et al. (1967) who stated that the sediments of the Lower Jurassic unconformably overlie Triassic in the greater part of the Persian Gulf area. In Zagros Basin an Early Jurassic marine transgression deposited sedi-

ments lying with major unconformity over Middle Triassic or older rocks. This unconformity is evidence from coastal Arabia to coastal Iran and also in surface sections of the south Iran.

By Late Triassic-Jurassic time the High Zagros Basin had subsided by rifting to the depth of radiolarian chert accumulation, and oceanic crust was clearly developed. The deposition of late Triassic black marls was followed in early Middle Jurassic to Early Cretaceous times by a thick sequence of red radiolarian cherts, and siliceous limestone (Ricou, 1974) along the High-Zagros-Oman belt.

The High-Zagros ophiolite-radiolarite belt in Neyriz and Kermanshah area is composed of three imbricated units which are progressively thrusted onto the carbonate platform sediments of northern Zagros along a series of northeast dipping thrust sheet, which transported material from the northeast to the southwest. At this transitional period, the Persian Gulf region was still influenced by the central Arabian horst and graben system. The northerly directed supply of deltaic to coastal sands gave way to evaporitic, shallow-marine shales. The sands were possibly derived from the southern edge of the Arabian shield or, more probably, supplied by meandering river systems from further southwest in Yemen.

Furthermore, at the end of Triassic time there was a regional drop in sea level caused by a eustatic lowering of sea level or uplift of the basement. In some areas this resulted in widespread progradation of fluvial and coastline clastics and in other areas erosion or non-deposition.

Breakup of Gondwana and Pangea began in the Triassic and resulted in erosional unconformities at the tops of the Triassic and Jurassic sequences. The Paleo-Tethys Sea was consumed, and the Neo-Tethys Ocean was created as the Cimmerian microplate moved away from northern Arabia during rifting. A carbonate ramp formed on the north-facing passive continental margin. During Middle Jurassic extension, the Lut microcraton moved northeastward, and then northward, as carbonate were deposited. The uplift, erosion, and evaporitic conditions occurred over much of this region in the Late Jurassic. A eustatic drop in sea level at the Triassic-Jurassic boundary resulted in the development of an erosional unconformity over most of the region (Searle et al., 1983).

The Triassic tectonic phases initiated the separation of much of Iran from the rest of the Middle East, which continued to be dominated by shelf deposits. Much of the region underwent erosion during regional regression and the Arabian Massif was flanked to the east by a broad swathe of non-marine clastics. Further north, marine carbonates and evaporites were deposited in an area which may have developed as a late Triassic transform system which subsided, allowing a transgressive sequence to develop. In western Iran and northeastern Turkey, the Zagros and Taurus troughs began to develop and the shallow carbonate deposition keeping pace with subsidence. This produced a strong differentiation of facies towards the northeastern edge of the shelf.

The Triassic-Jurassic boundary is in general marked by a sand layer and penecontemporaneous weathering surfaces and their subsequent effects. A basin wide late Triassic to early Jurassic unconformity extending across Central Iran is also recognized as marking the onset of drift separation of the Arabian plate and the Central Iranian Plate. This boundary in the High Zagros area and in Lorestan is marked by a major unconformity. The Zagros area after a relatively stable period during Permian and early Middle Cretaceous time became active again uplift and the associated erosion removed most of the Triassic and in some areas the uppermost part of the Permian sediments in the High Zagros Mountains, while the erosion was less severe in the more stable Fars and Lorestan area.

JURASSIC

Introduction

The history of the carbonate platform in the Persian Gulf region during the Jurassic and Cretaceous is of immense importance because of the remarkable richness of hydrocarbons in these horizons. The Jurassic rocks in the Persian Gulf region in general, have high petroleum potential and the principal exploration objectives and targets are formations of Middle and Late Jurassic age as these contain the near-ideal association of source rocks and high porosity/permeability limestone reservoirs below excellent caprocks. The rocks form broad open structures that hold large accumulations of petroleum.

During the Jurassic through Late Cretaceous on the northern margin of the Arabian plate an immense passive margin developed which produced a broad, stable shelf environment, allowing the deposition of shallow marine carbonates. Thus, Jurassic geologic conditions resulted in deposition of ideal sequence of primary petroleum system elements, which include thick oil-prone source rocks, extensive reservoir facies, and excellent seals.

GEOLOGIC SETTING

The fragmentation of Pangea, which began with the rifting of the Sanandaj-Sirjan terrain and the central Iran continental plate in the early Kazanian (255Ma), accelerated in the Jurassic time. Early Jurassic Toarcian rifting occur at this time represents the third major rift event to affect the Persian Gulf region. After this event, a considerable modification in isopach and facies pattern is seen on the Lower-Middle Jurassic maps (Koop and Stoneley, 1982).

By the end of Jurassic time subsidence was widespread. For example, in western Persian Gulf area subsidence was accompanied by increased precipitation of evaporites whereas in the eastern part deep waters, created local development of euxinic environment and smaller amount of sediment deposi-

tion. Subsidence continued to be pronounced during the Cretaceous and in many areas deposition equated subsidence.

Earliest Jurassic time merits special attention as it clarifies considerably the general paleogeographic conditions. At this time the entire north and central Iran was a part of the great Russo-Siberian platform, with coal-bearing paralic and continental deposits over the entire region and northern Persian Gulf area. The continental area was rather abruptly limited against a northwest-southeast-trending basin (Stocklin, 1968) in which shallow marine to lagoonal sedimentation with local evaporite deposition continued from Triassic into the Jurassic. According to Stocklin (1968, p.169) the basin, which subsequently developed into the Zagros basin, is for the first time clearly recognizable in Lower Jurassic sedimentary facies.

Throughout Jurassic, the Arabian plate was situated in the tropical or subtropical zone where the northeast passive margin of the Afro-Arabian plate evolved as an extensive continental shelf (Murris, 1980; Beydoun, 1991). Murris (1980) indicated that a broad stable shelf was present at this time across the northern half of Arabia facing towards the Neo-Tethys passive margin. In much of southern Iran, the Jurassic consists of thick massive limestones.

In Middle and Late Jurassic time, Arabia including the Persian Gulf region was situated about 10° south of the equator along the western margin of the Neo-Tethys oceanic embayment. Its eastern margin constituted a trailing plate boundary that had been in existence since the initiation of rifting and northward transport of Turkish and Iranian continental fragments in Permian time.

The Jurassic and Early Cretaceous was a time of maximum transgression of marine carbonates onto the platform (Murris, 1980). This period of widespread carbonate deposition resulted in a vertical and lateral facies mosaic including evaporite seals that constitute the richest single oil habitat in the world. Cyclicity within the range of fourth-to six order frequency (10-100 ka) is a marked of Jurassic sedimentary patterns world-wide (e.g., Valdes et al., 1995; House, 1985).

The Neo-Tethys passive margin developed on the northern margin of the Arabian plate. Passive margin conditions along the Arabian plate during the Jurassic through the Late Cretaceous periods produced a broad, stable shelf environment. Flooding of this platform in warm equatorial latitudes allowed for continued deposition of shallow marine carbonates over the entire area (Murris, 1980).

DEPOSITIONAL ENVIRONMENTS

Deposition in the present location of the Persian Gulf during the Jurassic, and much of the Cretaceous was characterized by platform carbonates. The Middle Jurassic platform was characterized by minimal platform-interior bathymetric relief and widespread shallow-marine, carbonate sedimentation.

However, beginning in the upper Jurassic, a series of intrashelf basins formed (see Figure 3-22).

A distinct, long-standing, sea level lowstand occurred from early Zagros rifting and structural growth during most of the Early Jurassic, resulting in a period of non-deposition marked by a widespread hiatus. Despite a delay of deposition in the west until Middle Jurassic time, the thickest Jurassic sequences were deposited.

In central Iran, in contrast, the Early Jurassic is generally represented by plant and coal-bearing sandstones and shales; with calcareous deposits restricted to the Middle and Upper Jurassic. The Early Jurassic transgression of the sea over Triassic paleotopography led to the deposition of shallow water carbonates and silty shales in the SE parts of the Zagros Basin. These were followed by marine carbonates, which continued until the Late Jurassic time. In western part of the present day Persian Gulf, however, the Jurassic began with the deposition of Liassic anhydrites and dolostones, and in the Middle Jurassic, deeper water shales and limestones were deposited over the area to the west of 50°E.

During the Toarcian stage of the Early Jurassic, a widespread marine transgression produced by a major rise in relative sea level flooded the Arabian shelf, forming a shallow-marine platform. A well-defined marine cycle began with a regional transgression in the Toarcian to Middle Jurassic and ended with an important evaporite phase toward the close of the Jurassic.

In general, the Early and Middle Jurassic depositional setting of the central Arabian plate and the Persian Gulf area varied from non-deposition/erosion to an arid clastic platform in the west and to a shallow-marine, mostly carbonate platform on the north and east (Al-Husseini, 1997) (Figure 3-23). This period is represented by the formation of basal shales, sandy shales, calcareous sandstones, limestones, and dolostones (Cole et al., 1994).

The lower and Middle Jurassic in central and northern Saudi Arabia is characteristically represented by shallow water shales and carbonates except, further towards the south, these pass into sandstones. In a southerly direction, this change first take place in the lower beds and progressively affects higher beds so that ultimately, the entire section becomes sandstones of apparently continental origin (Powers, 1968).

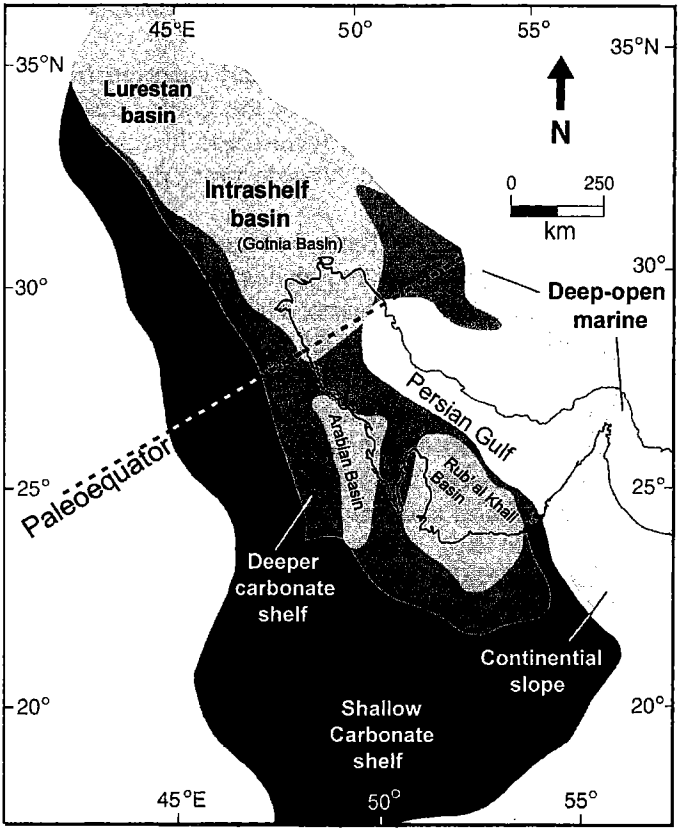

Figure 3-22. The major intrashelf basins and their paleogeographic positions with respect to the paleoequator in the Persian Gulf (modified from Ehrenberg et al., 2007).

Continued deposition of mostly carbonates and anhydrites occurred in warm equatorial latitudes during Middle and Late Jurassic. Sequence stratigraphic studies have shown that cyclic changes in lithology (i.e., carbonate/evaporite) of the Late Jurassic were due mainly to cyclic changes in relative sea level (Al-Husseini, 1997; Sharland et al., 2001). The whole patterns of the Upper Jurassic remained very similar to those of the Lower and Middle Jurassic. As a consequence, basin tectonics, facies differentiation and arid climate conditions became more pronounced.

In the late Jurassic, shallow water carbonates expanded over the greater part of northern and central Arabia and extended towards the Persian Gulf and southeastern parts of the Zagros and Oman. Thus, transgression of the Tethys Sea, which had started early in the Jurassic, now covered the entire region and sedimentation continued with no apparent interruption into the late Jurassic.

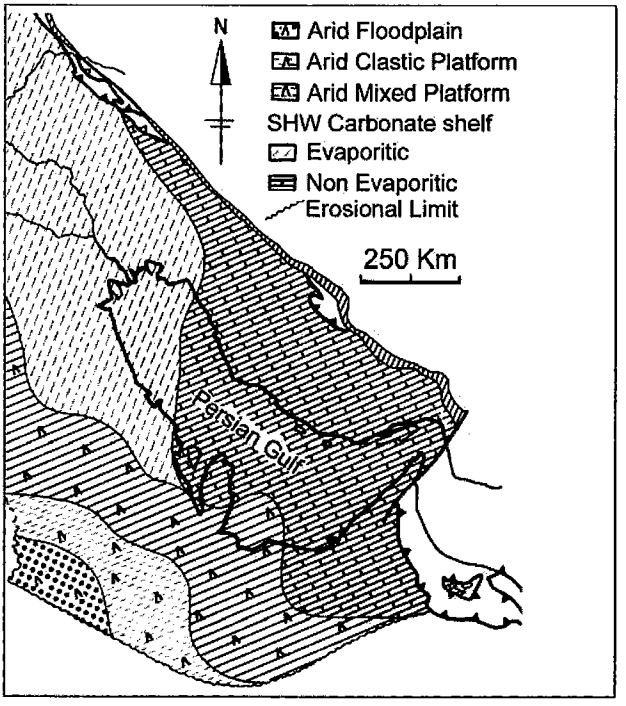

Figure 3-23 Liassic depositional environments in the Persian Gulf and surrounding region (Modified from Murris, 1980).

Late Jurassic (Tithonian) eustatic variations of the Arabian platform resulted in deposition of carbonate-anhydrite cycles that constitute the dominant reservoirs and caprocks (Arab carbonates and Hith evaporite seal rocks). Late Tithonian evaporitic conditions on a vast platform produced the Hith anhydrite and formed inland salt lakes in southern Persian Gulf and Gotnia Basins (Al-Husseini, 1997). Significant loss of hydrocarbons generated within these petroleum systems was prevented by the regionally extensive, overlying evaporite seals; thus, only limited vertical migration occurred.

Large-scale regional depositional style in the Upper Jurassic and Lower Cretaceous of southern Persian Gulf shows only small lateral thickness variations. This suggests that the area was tectonically stable while expansion of the Neo-Tethys was ongoing.

The most significant facies change in the Upper Jurassic occurred in western Persian Gulf and Zagros region, where massive anhydrites deposited. This change marks the beginning of the evaporitic conditions that ultimately spread over much of the sedimentary basin. With the approach of the evaporitic conditions, the shoaling of the sea produced widespread deposits of calcarenitic limestones over much of Saudi Arabia and the Persian Gulf, extending into southwestern Iran. These limestones represent the transition from the deposition of shallow water carbonates into pure anhydrites. Cyclic sedimentation,

resulting from fluctuations of sea level, eventually gave rise the deposition of the supratidal anhydrites of the Hith (Setudehnia, 1978).

The Upper Jurassic limestones are linked to evaporites (salt) over the large portion of central and eastern Iran where the end of the Jurassic was a period of folding and emergence, locally accompanied by granite intrusions and metamorphism (Stocklin, 1972). The change is rapid across the Zagros Crush Zone from the quieter shelf conditions of the Zagros Basin with its gradual shallowing towards southwestern Saudi Arabia. At the closing stages of Jurassic, uplift caused some truncation of the uppermost Jurassic beds, particularly in southern Fars and the Bandar Abbas area.

In southern Persian Gulf, the deposition of the regressive Upper Jurassic anhydrite was followed by transgression which flooded most of the Persian Gulf region with the Qatar-Gavbandi Arch affecting sedimentation throughout the early Cretaceous, with sediments generally increasing in thickness in all direction away from it.

JURASSIC INTRASHELF BASINS

The Jurassic and Cretaceous sedimentary succession filled the intrashelf basins that developed as a result of repeated generation of large volume of accommodation space on the Arabian plate (Murris, 1980). Frequently the sedimentary fills in these intrashelf basins contain both reservoir rocks, predominately shallow-water facies along the prograding margins, and source rocks in slightly deeper ramp settings within the central part of the intrashelf basins. However, the quality of both reservoir and source rocks are highly variable through time in the different intrashelf basin infill cycles.

Beginning in Oxfordian time load induced and isostatic sagging (Aigner et al., 1989) transformed the low-relief Arabian platform interior into a series of interashelf basins and intervening arches (see Figure 3-24). As a result, the wide, 2000 kilometers long platform contained several intrashelf basins (Murris, 1980).

Subsidence together with marine transgressions is believed to have caused the development of a differentiated platform in Early Oxfordian. As a result, three major intrashelf basins were created along the northeastern margin of the Arabian platform from Lurestan in the north to Abu Dhabi in the south (Murris, 1980; Al-Husseini, 1997). These intrashelf basins were depocenters for the main Jurassic source rocks, as well as several important reservoirs. Several major oil fields occur within the intrashelf basins of the Arabian platform. They also define the major Jurassic petroleum systems.

Although a relative lowstand in sea level existed during most of this time interval, widespread carbonate sediments indicate a shallow-marine environment. Murris (1980) considered the Lurestan basin, as an enormous intracratonic basin that dominated the northern Persian Gulf region, to have started forming near the end of the Early Jurassic.

Similar intrashelf basins were developing in the northwestern Persian Gulf and Iran. From the Middle Jurassic to the Turonian the Lurestan Basin became differentiated into the Gotnia Basin (Basrah Basin) and the Rub'al Khali Basin (Murris, 1980). A structural arch, the Rimthan Arch, which separates the two basins, stood high relative to the basins on either side, as suggested by the thick grainstones deposited there during Kimmeridgian time (Wilson, 1975). This grainstone belt and the northern side of the Rimthan Arch probably formed a fairly well defined shelf margin that faced the Gotnia Basin to the present-day north.

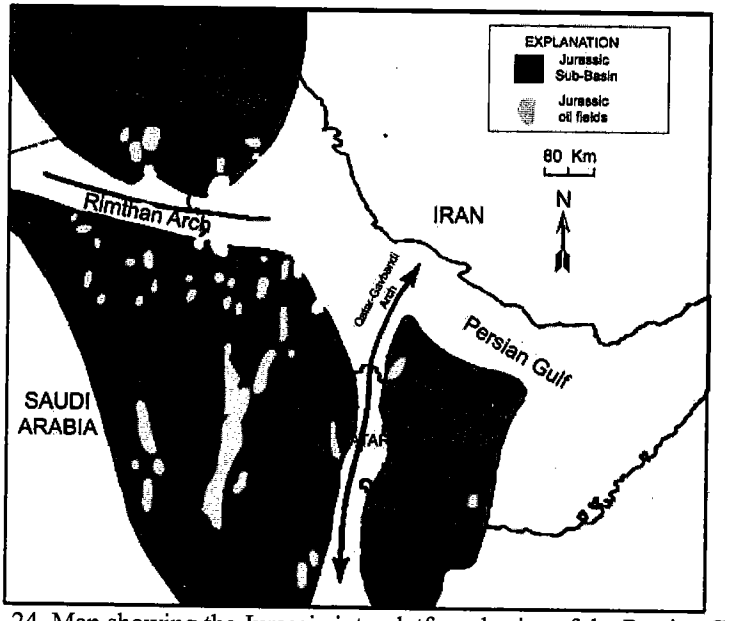

Figure 3-24. Map showing the Jurassic intraplatform basins of the Persian Gulf region. Intrashelf Central Persian Gulf sub-basin is separated from the south Persian Gulf sub-basin by the Qatar-Gavbandi Arch and from the Gotnia basin by the Rimthan Arch (Modified from Handford et al., 2002).

The Rimthan Arch divided the Central Persian (Arabian) Basin structurally from the northern Gotnia Basin. A third, smaller and shallower, intraplatform basin to the east, the South Persian Gulf Sub-Basin, existed during the Late Jurassic (from late Oxfordian to early Kimmeridgian) and was separated from the Central Persian sub-basin by the Qatar-Gavbandi Arch (Murris, 1980; Alsharhan and Kendall, 1986; Droste, 1990). Cyclic changes in sea level during the Middle and Late Jurassic led to the development of a stacked series of shallowing-upward, carbonate platform sequences.

Gotnia basin, a deep-water basin, existed in the northern Persian Gulf region from Middle Jurassic to Early Cretaceous (Christenson et al., 1977; Murris, 1980; Ayres et al., 1982). The intrashelf basin in which Kuwait is located

has been referred to as the Gotnia basin (Ayres et al., 1982) or as the Lurestan Basin (Murris, 1980). While most of these basins were dominated by carbonate deposition, the Gotnia basin was the location of evaporite deposition in Kuwait.

The intrashelf basins accumulated low-energy, organic-rich lime muds under anoxic bottom water conditions. These intrashelf basins were generally relatively shallow. Organic rich carbonates were deposited within them under euxinic conditions, and shallow-water grainstones, coral/stromatoporoid patch reefs, and oolites formed along the margins. These extensive basinal deposits ultimately became the major source of oil for fields throughout the Persian Gulf region.

A complementary negative element, the deeper water silled evaporite-carbonate-shale basin of the Basreh-Lorestan area, was initiated during the Lower-Middle Jurassic interval (Koop and Stoneley, 1982). High energy carbonate grainstones on the Surmeh shelf extend as sheets over large areas. The margin of the Surmeh carbonate platform rimming the Basreh-Lorestan basin remained in the same position but the basin became increasingly restricted with portions reaching the halite evaporite stage in Kuwait area, while others including Dezful area were apparently sediment-starved with a pronounced basal unconformity or depositional hiatus (Koop and Stoneley, 1982).

The southern Persian Gulf area was the site of intrashelf basinal marls alternating with high-energy grainstones and finally anhydrite as the shelf depressions became infilled and more restricted. This sequence resulted in the ideal source-reservoir seal juxtaposition responsible for the giant oilfields in the Arab Formation underlying the Hith Anhydrite (Koop and Stoneley, 1982). These source and reservoir rocks together constitute the major Jurassic petroleum systems. The intrashelf basin in the southwestern Persian Gulf is thought to be source of the Jurassic production in offshore/onshore Qatar and western offshore Abu Dhabi (Murris, 1980; Dorste, 1992).

The sedimentary infilling coincides both with an episode of long term relative sea level fall and with the onset of more environmentally restricted depositional conditions across the Arabian platform. The restriction led to the development of carbonate-evaporite successions in the latest Jurassic carbonates and Hith evaporites. The final depositional phase culminated with platform-wide Hith evaporite deposition that filled remaining intrashelf bathymetric lows.

The basinal facies consist of cycles of laminated, organic-rich, lime mud-wackestones. The thickest and most extensive Jurassic source-rock facies of central Arabia is the Tuwaiq Mountain Formation. It is considered the main Jurassic source rock of this region and was deposited in the southern part of the intraplatform Central Arabian sub basin between reservoir facies of the Dhruma (Fadhili zone) and Hanifa Formations.

The intrashelf basins within the platform were generally surrounded by ramp margins (Burchette and Wright, 1992) and geologically short-lived. Dif-

ferential subsidence within the shelf, combined with a relative increase in sea level, led to the formation of relatively short lived intrashaelf sub-basins (Murris, 1980; Ziegler, 2001). Mild vertical movement of ancient structural features may have been the cause of the intra-shelf basins in the Persian Gulf region (Ayres et al., 1982). Most probably, the origin of the intrashelf basin was due to the combination of eustatic sea level rise and subsidence.

The creation of the intrashelf basins in the Persian Gulf region appears to have been based on rejuvenated north-trending Hercynian tectonic structures between the Arabian and Gotnia basins. The Southern Persian Gulf basin, however, was probably controlled by the Dibba fault zone. The Late Jurassic intrashelf basin was structurally active during the Late Oxfordian to Early Kimmeridgian time because of structural growth of the Qatar-Gavbandi Arch.

Widespread Early and Middle Jurassic marine transgression deposited a thick sequence of shallow-marine shelf carbonates and platform evaporites. The Late Jurassic (i.e., Oxfordian and early Kimmeridgian) differential subsidence and sea level rise resulted in the formation of broad, intrashelf basins. The Central Arabian intrashelf basin of onshore east-central Saudi Arabia and adjacent offshore Persian Gulf formed in the late Middle Jurassic (late Callovian) and existed into the Late Jurassic (early Kimmeridgian).

To the east and south of the Central Persian sub-basin, organic-rich facies of the overlying Hanifa Formation form the major source rock for the Jurassic Hanifa/Diyab-Arab petroleum system of the intraplatform South Persian Gulf sub-basin and within the greater Rub 'al Khali Basin proper. In the Central Persian Gulf sub-basin, the organic-rich facies of the upper part of the Hanifa is of secondary significance compared to organic facies of the Tuwaiq Mountain (Cole et al., 1994). Overlying the Hanifa Formation are dolomites and lime mudstones of the Jubailah Formation.

As the intrashelf basins shallowed in the late Jurassic, platform carbonates extended across the basin to form the major reservoir sequences. By Tithonian times, a sabkha environment had developed, and with increasing aridity the evaporites of the Hith Formation were widely deposited across intrashelf basins. A gradual return to more humid climate in the Early Cretaceous coincided with the establishment of the Early and Middle Cretaceous shelf carbonate depositional environments.

NEO-TETHYAN CONTINENTAL SHELF

Overlying the Permo-Triassic platform successions, the lowermost Jurassic to upper Turonian strata (James and Wynd, 1965; Kheradpir, 1975; Shakib, 1990) form a number of megasequences that accumulated on a shallow continental-shelf, facing north and northeast toward Neo-Tethys in a paleoequatorial setting containing many petroleum systems (e.g., Ala et al., 1980; Bordenave and Burwood, 1990; Beydoun et al., 1992).

These sequences are separated from one other by major pronounced disconformities, marking short hiatuses. The oldest unit of this group, the Neyriz Formation received argillaceous and sandy detritus from a sediment source to the northeast, most probably formed by fault-bounded ridges associated with extensional break-up of the continent at the time of Neo-Tethys opening (Alavi, 2004).

According to Alavi (2004), the overlying units of megasequences all display gradual facies changes from coastal and sabkha-type clastic strata, evaporites, and dolostones on the southwest to shallow-water, high-energy-environment limestones, and finally to deep-marine, pelagic and hemipelagic lime mudstones and marls on the northeast. The facies changes have been recognized at various stratigraphic levels, and are thought to be at least partly a result of reactivation of pre-existing, predominantly north-south trending structural elements inherited from underlying Neo-Proterozoic Pan-African belts (Alavi, 2004).

The concept of reactivation of older structures is supported by the observation that thicknesses of some stratigraphic units change rapidly within short distances. For example, the uppermost Jurassic to lower Cretaceous Fahliyan, Gadvan, and Dariyan inner and outer shelf carbonates and argillites (Shakib, 1994), which are collectively about 750 meters thick in the central part of the belt (Khuzestan region), but thin to the southeast (Fars area) to only 250 to 300 meters in thickness. This change occurs across a north-south trending lineament known as the Qatar-Kazerun line, whose structural characteristics are discussed by Falcon (1969), Pattinson (1970), Pattinson and Takin (1971), Baker et al., (1993) and Alavi (2004).

JURASSIC IN NORTHERN PERSIAN GULF

The Jurassic sedimentary sequences in northern Persian Gulf are represented by two contrasting facies. These facies can be divided into two major units: 1) Terrigenous and transitional terrigenous to shallow marine sediments and, 2) Open marine sediments (i.e., the Surmeh Formation).

In the entire northern region of the Persian Gulf, Liassic sedimentation started with the deposition of silty shales and carbonates of the Neyriz Formation of shallow water origin, followed by the accumulation of true marine carbonates of the Surmeh Formation. The carbonate deposition continued during Middle and Late Jurassic time. The arid conditions prevailing over the entire Persian Gulf region and the existing platform during the latest part of the Jurassic gave rise to a widespread sheet of supratidal (sabkha) replacement anhydrites (Hith Formation), which extended across the Persian Gulf and as far north as coastal Fars region.

At the end of the Early Jurassic, a major change in the regional depositional pattern occurred (Murris, 1980). The climate became more humid and at the same time a more pronounced tectonic differentiation of the platform

led to the creation of an intrashelf depression in the north (i.e., the Lorestan Basin), with a wide carbonate platform. Clastic material was supplied from the west and the south. During the late Callovian a major inundation of the platform was initiated which continued until Late Tithonian-Earliest Berriasian time. This event had a profound impact on the paleography of this area and on the formation of its oil resources (Murris, 1980).

In Lorestan and neighboring parts of Dezful Embayment, Jurassic sedimentation began with the deposition of predominantly carbonates and evaporites in Liassic, followed by the deeper water shales and carbonates of the Sargelu Formation in the Middle Jurassic. The Sargelu basinal shale and algal and pellety limestone of Najmeh Formation, are followed by, and interfingured with the Gotnia evaporites. The Middle-Upper Jurassic stage, in the Zagros area is represented by the Surmeh Formation, the Hith anhydrite and partly by the deposition of carbonates. The pelagic limestones and basinal shale-limestone facies in the Neyriz and Esfandagheh areas, along the southern part of the Main Zagros Thrust, indicate the approach to deeper basinal conditions.

At the end of Jurassic, a period of emergence, particularly in southern Fars and in Lorestan/northern Khuzestan, is indicated by an unconformity. Also in Late Jurassic, Saudi Arabia was uplifted and subjected to heavy erosion.

Tithonian climate was arid and as a result extensive evaporites were deposited in the southwest Lorestan basin. During the Early Cretaceous the climate gradually became humid and evaporites disappeared. The sea level dropped, and carbonates replaced the differentiated shelf deposits.

EARLY JURASSIC

Since the separation of Lower and Middle Jurassic is not possible everywhere, this interval has been mapped as one. However, the boundary of the Jurassic with underlying Triassic is unconformable. The top of the Middle Jurassic in Fars, SE Khuzestan and the neighboring portion of the Persian Gulf has been taken as the top of a biozone called the "*Pfenderina Zone*". This coincides with the top of a clean limestone unit recognizable at outcrop and characterized by high radioactivity in the subsurface section, providing a good correlation zone. This unit, informally called the Mond Member, is in part correlateable with the Uwainat Formation of Qatar in the southern Persian Gulf. Early Jurassic time coinciding with the deposition of Neyriz and lower Surmeh Formation, characterized by attached ramp systems, with some local platform shoals.

From Jurassic to Miocene time the subsidence possibly along inherited faults allowed up to 14 kilometers of sediments (mainly marine carbonates) to accumulate in the basin). Some of the faults along which subsidence took place controlled the sedimentary facies in the Zagros Basin.

Neyriz Formation

The Jurassic marine transgression in the northern Persian Gulf is represented by the Neyriz Formation. For the most part, these sediments deposited in shallow water and occasionally restricted environment in the Zagros Basin including the Persian Gulf region. The Lower and Middle Laissic Neyriz Formation are present and concordantly overlying the Triassic (i.e., Khaneh Kat Formation). The thickness of the formation varies between 100 and 350 meters. It is followed by the lower part of the Khami Group, which includes the lower Surmeh Formation of southern Iran.

The Neyriz Formation is mainly consists of thin-bedded carbonates and shale grading upward into quartzose sandstone (some conglomeratic beds) derived from the northeast, with intercalations of thin argillaceous limestone near the top; unconformably onlaps Triassic strata. The formation is occasionally argillaceous with intercalations of silty shales, sandstones and siltstones. Further to the northwest the facies found in northern Iraq, which are mainly dolostone and gypsum, reappear.

The majority of the wells drilled in the Persian Gulf have penetrated the Lower Jurassic. This interval consists of limestones, marls, dolostones and anhydrites. In the Persian Gulf region, the thickness of Neyriz Formation in well 0-4 BIS and U-1 well are approaching 21 and 19 meters respectively. The Neyriz Formation in well R-32 (Resalat) is represented by 27 meters of shales with few dolostone layers in the middle of the sequence whereas it contains traces of glauconite in 3H-1 and the thickness is reduced to 17 meters. In the Salman oil field the thickness of the Neyriz Formation is about 35 meters. The depositional environment was shallow water and lagoonal to open neritic.

The distances between these wells in the Persian Gulf are about a few tens of kilometers. Although the thicknesses and the detailed lithology of the formation are not identical in these wells but their general facies pattern can be correlated. It is important to note that in none of the drilled wells and most probably in other locations in the Persian Gulf, no microfossil reported so far in the Neyriz Formation. Only in U-1 well microfossil *Glomospira* sp., has been observed (Javadian, 1996).

Shallow water silty shales and carbonates of Neyriz Formation, displaying ripple marks, mud cracks and algal stromatolites with minor anhydrite represent the Lower Jurassic. The sediments were deposited in shallow water environments (subtial-intertidal to supratidal deposits). It forms a low-weathering unit lying between the more resistant carbonates of the Surmeh on top and dolostones of the Triassic underneath. Directly overlying the Triassic erosional surface are glauconitic and limonitic shales.

The age of the Neyriz Formation has been assigned as Liassic in coastal Persian Gulf and Liassic to Early Dogger in interior Iran (Kashfi, 1992). According to Kashfi, equivalent of this formation in northwestern Persian Gulf

are called, the "Baluti Shale" in Iraq, the "Marrat Shale" in Saudi Arabia and "Musandam Limestones" in Oman, all of Liassic to Early Dogger age.

A shelf edge, trending generally NNW-SSE from Kermanshah through Central Lorestan and east Khuzestan to Kharg Island in the northern Persian Gulf, separated an area of restricted basin and evaporite deposition from an area of mainly shelf platform sedimentation. A depocenter with more than one kilometer of shelf to deep-shelf carbonates occurs in the Interior Fars, and a swell with reduced (about 150 meters) thickness extended along the Fars and Lorestan coast.

The great variation in thickness of the Neyriz formation is mainly due to depositional onlap over the irregularly eroded Triassic paleotopography. The presence of this unconformity is well established in subsurface by extensive gamma-Ray log correlations.

The basal unit of the Neyriz Formation contains more clastics consisting of sandstones, shale, limestone, and subordinate coaly shale in some localities (James and Wynd 1965). The lower Neyriz member has many similarities with the Shemshak Formation of central and northern Iran, and represents Liassic shallow water facies resembling tidal flat deposits. Szabo and Kheradpir (1978) have also reported the deposits of coaly shale and carbonized plant remnants with bauxite pebbles in the Dopolan area of the High-Zagros.

The top of Neyriz Formation is marked directly below the first appearance of the *Lithiotis* beds of the Surmeh Formation, a well recognizable zone in the surface exposures, with abundant large calcified *Lithiotis* shells, corresponding in the subsurface with a clean, low gamma-Ray log response carbonate interval.

Minor unconformity is present in some areas (i.e., Kuh-e-Surmeh) at the base of the *Lithiotis* beds; it is marked by a carbonate breccia. There are only few fossils and occasional arenaceous foraminiferid *Orbitopsella praccursor* (GUMBEL), *Hemigordius* sp *Ophtalmidiidiae* and few scattered occurrences of gastropodes and ostrocodes. Therefore the age of the Neyriz Formation could be assigned to Lower Jurassic (Liassic) (Motiei, 1993).

During the Middle Jurassic in central Iran, a marine sedimentary regime prevailed over the lagoonal-fluviatile environment, and ammonite-bearing limestone was laid down. The Liassic coal and the Jurassic limestones rich in fauna indicate the position of Iran in an equatorial position (Berberian and King, 1981).

The Central Arabian hinterland and other highland areas such as the Qatar-Gavbandi Arch (Murris, 1980) seems to have been the prime areas for providing the source for the detrital material required for deposition of the basal unit of the Neyriz Formation. During the deposition of the Neyriz Formation, the Zagros Basin with marine carbonate platform sedimentation became established, with the greatest subsidence being in the northeast, possibly along several faults (Berberian and King, 1981).

The upper part of the Liassic and the Middle Jurassic are mainly composed of feature-forming, massive shallow-water carbonates of the Surmeh Formation which rest on the Neyriz Formation with minor local unconformity in northern Persian Gulf. A widespread marker bed containing abundant *Lithiotis* is present near the base of this carbonate unit almost everywhere in the Zagros Basin (Setudehnia, 1978).

The sequence is very different in Lorestan and northwest Khuzestan, where it starts with sandy shale at the base overlain by dolostones followed by anhydrites. These are then overlain by a limestone unit, correlatable with the *Lithiotis* zone, and topped by anhydrites. Shales and argillaceous limestones of the Sargelu Formation, which is capped by an unconformity, represent the greater portion of the Middle Jurassic.

In the Persian Gulf region, a reversal of the depositional pattern of the Triassic to Jurassic transition took place at this time. Where formerly there have been a structural uplift of the Arabian Arch combined with a lowstand in sea level, there now appeared to have been relaxation and the distinct subsidence of the Summan Platform.

The Lower and Middle Jurassic units of the Persian Gulf are part of major sedimentary megacycle deposited in a relatively deeper water mudstone, wackestones and shale to shallow-water high energy grainstone and packstone. These sediments accumulated uniformly over carbonate platform shelf.

Lower Liassic marine deposits have been reported in Iraq and Oman, and widespread Jurassic transgression in Saudi Arabia began with the deposition of the Marrat Formation of Toarcian (Power 1968). The Marrat Formation, exposed in the surface sections of central Arabia, represent the typical Lower Jurassic deposition in this area. The section is composed of a lower and an upper limestones-dolostones sequence, separated by a shale member (Mina et al., 1967).

The Lower Jurassic Formation in Saudi Arabia and Bahrain are being equivalent to the Lower part of the Izhara Formation as deduced by de Matos et al. (1994) in their study of the subsurface biostratigraphy from Abu Dhabi and Qatar. Accordingly, the Izhara Formation is assigned as early age of Early to Middle Jurassic. A major hiatus occurred in the Middle part of the Izhara Formation (Al-Husseini, 1997 p.366). It unconformably overlies the Gulaiah Formation and the Hamlah Formation in Central and western Qatar respectively, and is conformably overlain by the Araej Formation.

In the UAE, the Marrat is a mixed facies of terrigeneous clastics and shallow-marine, peloidal to bioclastic limestones in its lower part, and an upper sequence of interbedded micritic sandstones and sandy carbonates. The Marrat Formation is not present in offshore of southern Persian Gulf (i.e., Dubai). This may be due to either tectonic uplift prevailing deposition, or to erosion of this formation (Alsharhan and Scott, 2000). These sediments represent a slowly deepening sedimentary sequence from flood plains, through tidal flats to shallow marine, and finally to deeper, quieter-water environments. The

Marrat Formation also represents a regressive sedimentary succession deposited in a marginal marine setting. This sequence is the Hamlah Formation.

On the Qatar-Gavbandi Arch (by now only weakly expressed), the Hamlah or Marrat Formations rest unconformably on the Middle Triassic Jilh and Gulailah, probably as a result of a global Early Jurassic lowstand (Haq et al., 1988). The lower Surmeh Formation of southern Iran is a similarly ill-defined long-lasting sequence of massive to thick-bedded crystalline dolostones that includes the basal Liassic *Lithiotis* (pelecypod) bed (James and Wynd, 1965).

MID TO UPPER JURASSIC IN NORTHERN PERSIAN GULF

The deepest part of the Persian Gulf basin, from at least the Middle Jurassic through the Lower Cretaceous time, covered an area which included the northwestern corner of the present Persian Gulf area, SE Iraq, and part of Kuwait. Lithologies observed in these areas in the Middle Jurassic (see figure, 3-25), Upper Jurassic and Lower Cretaceous are characteristically different from those of southern and eastern adjoining areas where platform and reefal deposition prevailed (Mina et al., 1967).

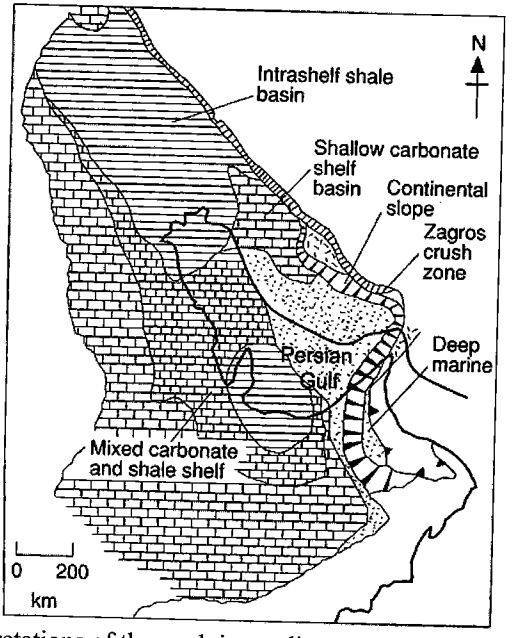

Figure 3-25. Interpretations of the evolving sedimentary environment in the region of the Persian Gulf during Mid-Jurassic (after Shannon and Naylor, 1989).

Surmeh Formation

Surmeh Formation of the Lower to Upper Jurassic age consist of massive *Lithiotis*-bearing carbonates grading upward to marly and silty *ammonoid-*

bearing limestone overlain by cherty dolostones; overlain gradationally by Hith evaporites. The upper part of the Surmeh Formation is mainly consists of massive shallow-water carbonates resting on the Neyriz Formation in Fars region in the northern Persian Gulf region. According to Setudenia (1978), very extensive and widespread marker bed which contains abundant *lithiotis* is present near the base of this carbonate unit almost everywhere in the Zagros Basin. More than 25% of this bed contains oyster-like shells and Kents (1951) has referred to it as thick dark grey limestone layers. The age of this basal bed is lower Jurassic (Motiei, 2003).

The thickness of the Surmeh Formation is about 672 meters at its type section locale. In the Persian Gulf particularly in the Salman oil field the thickness of Surmeh Formation is about 650 meters. In the Persian Gulf region, the Surmeh Formation has been encountered in several drilled wells and shows variable thickness. The thicknesses of the Surmeh and its equivalent Arab zone in the Persian Gulf have been given in Table 3-1. In two of the wells in the Persian Gulf which are highly correlatable with the type section of the Surmeh (i.e., 3W1 and FRB-1), the drilling extended to the Mond member of the Surmeh.

In all of these wells in the Persian Gulf similar to the Zagros, the Surmeh is represented by index units which are identifiable and traceable in different fields. These index layers are from bottom to top include; *Lithiotis* unit, Lower Surmeh shales, *Posidonia* unit and Mond carbonate member.

Table 3-1. The thickness of Surmeh Formation in various wells in Persian Gulf.

Well #	Thickness of Surmeh	Thickness of Arab zone
0-4 BIS	602	65
3H-1	610	ND*
Resalat	754	95
U-1	768	128
3W-1	588	98
FRB-1	444	ND*

*Not Determine

Surmeh Facies and Lithologic Divisions

Lithologically the Surmeh Formation has been divided into three parts by Kent (1951). The lithologic characteristics of the Surmeh Formation have been described by Kent (1951) as follow:

The lower part of the Surmeh Formation has a thickness of about 92 meters consisting of thick to massively-bedded calcareous dolostones and it is considered to be a good marker horizon. The Middle part is about 77 meters thick and consists of thinly bedded soft argillaceous limestones alternating with marlstones with abundant fossil fragments. The feature-forming upper part with a thickness of about 507 meters is mainly composed of thick to mas-

sively bedded coarse crystalline limestones and siliceous calcareous dolostones containing chert.

The lower contact with Neyriz Formation is reported to be conformable. In the area where the topmost part Neyriz Formation are mainly consists of carbonate rocks, the presence of abundant *Lithiotis* units is considered to be near the base of Surmeh Formation. However, in many areas due to a sedimentological gap, the Surmeh Formation is lying directly upon older formations. Where the Hith formation is present in areas such as interior coastal Fars and southern parts of the Dezful Embayment, the Surmeh Formation is covered by Hith Formation.

In most places in northern Persian Gulf region (i.e., Fars) the Surmeh Formation changes to Fahliyan Formation and sedimentation has been continuous and without a break. The two formations are indistinguishable and are considered as Khami Group but these are identified from one another on the basis of their fossil contents and biozones. The lower part of the Khami Group includes the lower Surmeh Formation of southwestern Iran. Between the two formations there is a zone containing deep-water species such as *Calpionella* or *Thintinnid* making the separation of the two formations possible. This marker horizon is of great significance because of the fact that it makes the recognition of the Jurassic Cretaceous boundary.

From coastal Fars towards the Persian Gulf and to the Saudi Arabia, the Surmeh Formation is overlain by Hith Anhydrite. However, from the coastal Fars toward the north, where the Hith anhydrite is absence, the Surmeh Formation is covered by pelletic and oolitic Fahliyan Formation.

In summary during Middle to Late Jurassic when the deposition of Surmeh Formation was taking place, vast normal marine lagoonal platforms existed in Fars, while the Dezful and Lorestan areas were emergent.

Mond Limestone Member

In some of the drilled wells south of the Dezful Embayment area, Fars and the Persian Gulf, the middle part of the Surmeh Formation contains index carbonate layers that are termed "Mond Member".

The informal type section of Mond Member is measured at Kuh-e- Mond well#2, which is located 65 kilometers to the north-northeast of Persian Gulf port of Bushehr at a depth between 2521 to 2624 meters. In addition to this, the Mond Member was encountered at the Balal oil field in the Persian Gulf with a thickness of 88 meters.

Lithologically, the Mond Member consists of two clean limestone units which are separated by an argillaceous-shaly layer with a thickness of about 103 meters marked by a very high gamma-ray peak. Microfossils found in this member consist of *Pfenderina trochoidea, Hauranai* sp., *Pseudocyclammina* sp., *Trocholina palastiniensis, Meyerdorffina* sp., *Kurnubia Jurassica, Clypeina Jurassica, Radiolaria, Saccocoma* Sp., *and Calpionella* Sp. It is worth

mentioning that the *Pfenderina trochoidea,* have been reported in Upper Dhruma Formation in Arabia belonging to Batonian-Calovian age (Motiei, 1995).

Sargelu Formation

The shales and argillaceous limestones of the Sargelu Formation represent the greater section of the Middle Jurassic. The Sargelu Formation received its name from a village situated at Soleymanieh region in Kurdestan of Iraq. The thickness of the formation ranges from 160 to 220 meters of deeper water marine shale and argillaceous limestone. Lithologically, this formation consists of dark laminated bituminous carbonates and fissile shales and the topmost layer consists of thin chert layers.

Sargelu Formation of Middle Jurassic (Bajocian to Bathonian) consists of thin bedded, bituminous limestones with interval of organic-rich papery fissile shale; which might be a possible source for hydrocarbons. Source rock potential of this interval have been rated highly by Dunnington (1958, p.1201).

The presence of Sargelu and Garau Formations in Zard Kuh area in south western Zagros indicates the possibility of a deeper water basinal sedimentation during Middle Jurassic and also Lower Cretaceous time. Similar conditions existed in Iraq suggesting the probable connection of the two areas during Middle Jurassic and Lower Cretaceous. This basin extended as far southeast as Kuh-e-Gereh where interfingering of the shelf and basinal sediments is well evident (Setudehnia, 1975).

In Lorestan the Sargelu Formation attains a thickness of approximately 306 meters of limestones and shales which are overlain disconformably by Najmeh Formation (Javadian 1996). In addition to *Posidonia* which frequently occur in the topmost layers of the Sargelu Formation, Bajocian ammonites are also present in the northeast of Lurestan. In Lurestan and neighboring parts of Khuzestan, Middle Jurassic sedimentation is mainly deeper water shales and thin-bedded limestones of the Sargelu Formation in the Middle Jurassic. The following fossils are present in this formation: *Posidonia ornati, Posidonia somaliensis, Parkinsonia sp. Stephanceras sp. Rhynchonella curviceps, Rhynchonella delottoi,* indicating Batonian to Liassic age for the Sargelu Formation.

Anoxic conditions under which the Sargelu shale was deposited developed during the Middle Jurassic in a basin established in the Early Jurassic over northeastern Iraq and Lorestan extending into the Dezful Embayment. *Gammacern* biomarker has been observed in the Sargelu Formation which indicates the saline depositional environment (Ashkan, 2002).

MIDDLE JURASSIC IN SOUTHERN PERSIAN GULF

The sediments deposited in an open marine environment, as the Arabian plate now had passive margins to Neo-Tethys to the northeast and north. During Middle Jurassic time the Arabian platform was situated at about 10°S and faced the Tethys Ocean which lay to the present-day east and northeast. This time period represents a phase of general sea level rise (Haq et al., 1988) and with it the westward transgression of marine environments far onto the Arabian Craton. Coastal and near shore environments are represented by coastal sands that pass eastward into shallow-marine shales and then into shallow marine detrital carbonates. Examples are Izhara and Araej (Qatar and UAE) and the lower Surmeh (Iran) Formations.

In southern Persian Gulf coastal district, the Middle Jurassic is represented by the Dhruma Formation, composed of limestone, generally argillaceous. These sediments are predominantly tight; however, varying proportions of calcarenitic developments provide porosity in the Dhruma Formation. The most prominent and the thickest occurrence of these porous zones (Fadhili Pay Zone) are found near the Dhruma Formation (Mina et al., 1967).

Izhara Formation

The Izhara Formation in Abu Dhabi is made up mainly of argillaceous lime mudstones, partly dolomitized and silty quartzose, bioclastic lime-mudstones. The formation was deposited in a calm-water shelf setting as suggested by the argillaceous lime mudstones. The formation was assigned an age range from Bajocian to possibly Early Bathonian (Middle Jurassic) (Hewaidy and Al Saad, 2000).

The occurrence of fine-grained and bioturbated limestones in the Lower and Middle Izhara indicates low-energy environmental conditions, while the accompanying fairly diverse biota suggests deposition in an open marine-shelf environment. The limestones of the upper most Middle Izhara member in southeast Abu Dhabi are locally rich in pyrite and contain abundant pelagic bivalves and shell debris, suggesting deposition under deeper open marine conditions. A major hiatus occurred in the middle part of the Izhara Formation (Al-Husseini, 1997, p.366).

The lithology and bioclasts of the lower part of the Upper Izhara indicate deposition in a marine euxinic environment with periodic silisiclastic influxes. Phosphate particles are abundant in the condensed shaly and packstone layers closer to the maximum flooding surface (MFS), which is marked by a very high gamma-ray peak. Shallow, low-energy-shelf conditions probably prevailed during deposition of the topmost Izhara.

In the southern part of the Persian Gulf (i.e., offshore UAE) the Izhara Formation consists of dolostones with anhydrite streaks and inclusions of some pyrite with negligible shales. It grades upward to dolomitic packstone/

wackestones with shales. Minor high-energy fluctuations in the depositional regime occurred, as evidences by the grain-supported sediments.

In the subsurface, the Izhara Formation typically lies unconformably over the Marrat Formation. The lower contact is conformable in some parts of the eastern onshore Abu Dhabi where lowstand deposits exist at the top of the Marrat. Above the Qatar-Gavbandi Arch, the Izhara Formation directly overlies the Triassic.

The upper contact with the Araej Formation is conformable. In Abu Dhabi, there is a westward thinning of the Izhara as a consequence of the onlap of the Lower Izhara Member over the Marrat, plus, the gradual thinning of the Middle and Upper Izhara member to the west. The occurrence of the Miospores *Classopolis* spp. and *Araucariacites australis* cookson in the Izhara Formation indicate that arid climate conditions were dominant.

Araej Formation

The Araej Formation was introduced by Sugden (cited in Sugden and Stranding, 1975) and is named after Jebel Araej in central Qatar. As-Saad et al. (1992) concluded that the Araej Formation conformably overlies the dense argillaceous mudstones interbedded with dolomitic packstone/grainstone of the Izhara Formation and unconformably underlie the dense limestones and interbedded marls of the Upper Jurassic Hanifa Formation. The Araej Formation passes westwards into the equivalent upper and middle Dhruma Formation in Saudi Arabia (Sugden and Stranding, 1975).

In the southern Persian Gulf particularly offshore UAE and Qatar, the contact with the underlying Izhara is conformable. The contact with the overlying Upper Jurassic Hanifa/Diyab Formation is taken at the transition from the oolitic-peloidal grainstone of the Upper Araej member to the argillaceous of the Diyab and its equivalent. The contact is marked by a burrowed and eroded surface and is clearly unconformable. This unconformity is regional in extent and its intensity increases to the north of the southern Persian Gulf area.

The Araej Formation includes a suite of epeiric shelf carbonates with limited lateral variation across the southwestern Persian Gulf. During the Middle Jurassic, a shallow to very shallow warm-water carbonate ramp prevailed across the southern Persian Gulf and gave rise to the deposition of the relatively clean carbonates of Araej Formation. The thickness of the Araej varies from 265 to 207 meters reflecting the effect of the structural growth of the Qatar-Gavbandi Arch and possible diapiric movements. In general, the Middle Jurassic succession shows good lateral continuity reflecting a passive tectonic period and a steady structural growth during deposition.

The lower Araej Formation consists predominantly of lime mudstones and wackestones in the lower part, grading upwards into bioclastic-intraclastic and peloidal packstone/wackestone with minor grainstone. In the deeply buried sections, the Lower Araej exhibits poor reservoir characteristics because of

burial diagenetic effects. The Callovian Upper Araej and Upper Fadhili Formations were deposited on a relatively shallow-water, stable platform that covered a vast area of present-day eastern Saudi Arabia and the southern part of the Persian Gulf.

The Araej Formation represents the continuation of a quiet-water, marine-shelf setting. Intraclasts and peloidal grains imply higher-energy environment and considered to be storm-deposited, whereas the sections corresponding to muddy sediments imply a slightly deeper, lower-energy setting.

The sedimentology and paleontology of the Araej Formation indicate one major shoaling-upwards cyclic sequence with deposition occurring in a vast shallow to very shallow shelf area with little terrigeneous input (very shallow ramp). Although representing a gross coarsening upward sequence, there were many fining upwards subcycles of storm origin which had no obvious or consistent orientation.

Tectonically the sedimentary basin was remarkably quiet, resulting in a fairly uniform condition over a large area of the southern Persian Gulf (Alsharhan and Kendall, 1986). There was, nonetheless, slight to moderate fluctuations in water depth in the order of few meters which in turn, affecting sedimentation.

Due to tectonic stability of the Middle Jurassic period, the cyclic nature of the Araej Formation and the related fluctuations in water depth could have been produced in large part by high-frequency sea-level fluctuations. The sea level oscillations caused lateral facies shift which made meteoric diagenesis, and associated dissolution and dolomitization possible. Diagenetic processes were the primary reasons responsible for the creation of porosity and permeability making the Uwainat and the Upper Araej Formations good reservoir.

LATE JURASSIC

Upper Jurassic sequence records an event of steady change from relatively deeper water sedimentary conditions to a lagoonal environment and subaerial to supratidal conditions. In many parts of the present day Persian Gulf the Tithonian period seems to be typified by evaporite deposition (e.g., the Hith and Gotnia evaporite succession), although there is a scarcity of reliable age data. It is most likely that the evaporites of the Hith and correlated formations represent subaerial to subaqueous deposition within the intrashelf basins. Changes from restricted carbonate/evaporite-dominated the Late Jurassic sediments to significantly more silisiclastic-rich Cretaceous sediments, exhibiting more open marine bioclastic carbonate systems.

This significant environmental change may have resulted from the fact that, from the Tithonian, a new subsiding (southeast) passive margin was present in southeast Oman (Loosveld et al., 1996). Thus, from this time the Arabian plate was now surrounded on three sides by subsiding passive margins,

probably causing sufficiently increased subsidence rates to result in generally pervading open marine environment.

The Upper Jurassic and basal Lower Cretaceous rocks crop out extensively in the Persian Gulf region. In general, they are shallow water carbonates with widespread evaporitic episodes at the top of the Kimmeridgian. The Upper Jurassic depositional environment in the Persian Gulf area is characterized by cyclic shallow water platform to reefal and evaporitic sediments (Mina et al., 1967).

Tithonian stage of Upper Jurassic was dominated by evaporite and shallows marine carbonates (figure 3-26). In the Persian Gulf and most of the surroundings, an arid climate prevailed during early Tithonian time and resulted in extensive evaporite deposits interbedded with carbonate beds (Murris, 1980). There was significant relative sea level rise initiated in the Late Tithonian continued into the early Berrisian, finally terminating evaporite deposition and re-establishing open marine carbonate deposition across the Persian Gulf and Arabian plate.

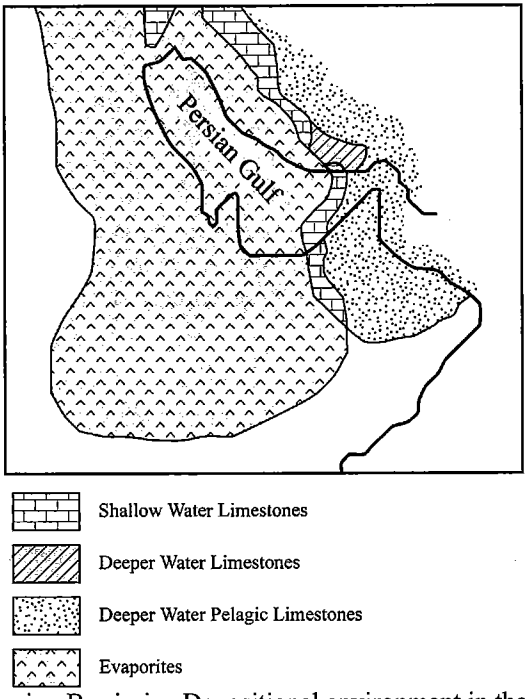

Figure 3-26. Tithonian-Berriasian Depositional environment in the Persian Gulf and surrounding region (Modified from Murris, 1980).

According to Mina et al. (1967) three different facies are present in the Upper Jurassic sequences in the Persian Gulf region which include:

Shallow marine, massive, clean, and generally dense carbonates represent the main part of the Upper Jurassic deposition in the Zagros foothills and the Iranian coastal area. These sediments are incorporated into part of the Surmeh Formation in southwest Iran.

The Gotnia Formation, a relatively deeper water evaporitic facies, was deposited in the NW corner of the present Persian Gulf and in Kuwait and SE Iraq. It consists of over 300 meters of salt and anhydrite.

Alternating shallow water, lagoonal, reefal, detrital, porous carbonates and anhydrites were deposited throughout the rest of the Persian Gulf and coastal Arabia. These sediments are represented by the Tuwaiq Mountain, Hanifa, Jublia, Arab, and Hith Formations and their equivalents.

This time period spanned the deposition of Arab, Hith and Gotnia Formations and their regional stratigraphic equivalents. Deposition of evaporites was widespread. This time interval corresponded to an overall progressive rise in sea level, and a corresponding widespread deposition of predominantly shallow-marine carbonates.

With apparent regularity, shoaling-upward cycles formed a complex system on arid intratidal carbonates and supratidal evaporites. The late Jurassic movements were of minor tectonic importance, causing slight and short-lived marine regression of the sea. This regression laid down Hith Anhydrite from the Arabian platform to the present foothills of the Zagros, indicating an arid climate. In the interior of the Zagros Basin, near Shiraz, there was more or less continuous sedimentation during Late Jurassic and Early Cretaceous time (James and Wynd, 1965; Setudehnia, 1978).

As a result of the Late Jurassic movements, the entire western part of Saudi Arabia was uplifted and heavily eroded. Subsequent movements associated with the reactivation of faults led to the extrusion of basalts in northwest Arabia until Albian time (Saint-Marc, 1978; Berberian and King, 1981).

In the offshore southern Persian Gulf (i.e., Abu Dhabi), the interval between the top of the Araej Formation and the base of the Arab-D reservoir (Oxfordian to middle Kimmeridgian) is correlated with the Diyab Formation of Qatar. The two lowermost formations of the Upper Jurassic in coastal Arabia and much of the present Persian Gulf are the Tuwaiq Mountain and Hanifa Formations consisting of shallow water reefal carbonates. The Hanifa/Jubaila contact is often obscure and difficult to establish. The overlying Jubaila Formation is represented by shallow marine carbonates in much of the present Persian Gulf area. In Qatar and southernmost portion of the Persian Gulf, the Diyab and Darb Formations are the lithologic and time equivalents of the Tuwaiq Mountain (Mina et al., 1967).

Najmeh Formation

After a period of emergence, the area again submerged during Late Jurassic and covered by pellety limestones of Najmeh Formation. The informal

type section of this formation is in Najmeh well#29 which belong to Mosel Oil Company. In this well, the Najmeh Formation is encountered at depth between 1458 to 1799 meters (Javadian, 1996).

Lithologically the Najmeh Formation consists of oolitic limestones with coarse scattered crystals of dolomite alternating with thin anhydrite layers and incompetent limestones layers. It is unconformably underlain by Sargelu Formation and in turn overlain disconformably by Garau Formation. The observed fossils in this formation include, *Valvulinella cf. Jurassica, Valvulinella Wellingsi, Nautiloculina oolithica,Pfenderina spp.Trocholina Elongata, HauraniaElongata, Haurania Amiji, Pseudochrysalidina* sp., indicating a Late Jurassic age (Javadian, 1996, Motiei, 1993).

Najmah Formation has been encountered only in wells that also penetrated the Sargelu Formation. It is made up of about 19 meters of shallow marine, pellety, algal limestone. It is underlain disconformably by the Sargelu Formation and overlain by the anhydrite of the Gotnia Formation. In the northern Persian Gulf region particularly in Lorestan and Khuzestan (Central Zagros) the basinal shale and algal limestone of Najmeh Formation, is followed by, and interfingured with the Gotnia evaporites of the northern Persian Gulf. Najmeh Formation is consist of cyclic alternations of limestones (grain-stone, packstone, wackestone, lime-mudstone), in part oolitic and in part pelletal with sponge spicules, interlayered with coarse porous dolostone or dolomitic limestone; disconformably onlaps Sargelu (Motiei, 1993; Setudehnia, 1972).

Gotnia Formation

The informal type section of Gotnia is in Owasil well No#5 of the Mosel Oil Company. The thickness of Gotnia in this well is about 192 m of mainly anhydrites alternating with bituminous calcareous shales and recrystalized limestones which are rarely pelletic (Motiei, 1993). In the time equivalent formation in Kuwait the salt content is increased substantially (Murris, 1980).

The Gotnia Formation, which crops out at Tang-e-Haft, has also been found in wells in the Emam Hassan and Masjid-e-Suleyman fields. It has a subsurface thickness of about 141 meters of anhydrite with subordinate dolostone and shale. It is considered primarily as a relatively deep-water anhydrite. Solution breccias occur in outcrop. A disconformity may be found at outcrop at the top of the Gotnia, where it lies under the Garau Formation.

Due to the evaporitic nature of this formation very few fossil species has been recovered. However, the following fauna has been discovered in the carbonates and shale units in Gotnia Formation including: *Glomospira sp. Textularids Ostracods.,* indicating a late Jurassic age (pre-Middle Tithonian-Lower Kimmeridgian to Upper Callovian) for the Gotnia Formation.

As discussed previously, during the Late Jurassic the Persian Gulf region was the site of several intrashelf basins. In Gotnia basin interbedded salt and anhydrite-limestone facies of the Gotnia Formation and overlying Hith For-

mation were deposited. Thus, the upper Jurassic Gotnia Formation forms much of the major basin-filling sequence with a thickness of more than 500 meters. It consists of cyclic alternation of salt and anhydrite/limestone units and is the time equivalent of the shelfal Arab Formation, which is an important reservoir in the Persian Gulf region. Variations in thickness of the Gotnia are partly controlled by the configuration of the basin.

The Gotnia basin also contains about 800 meters of deep-marine shales and cherty limestones of Garau Formation (James and Wynd, 1965). In contrast, shallow-marine Fahliyan Formation composed of oolitic, pelletal and brecciated calcarenites formed a shallow passage from the Fars region to the Southern Persian Gulf basin and UAE.

Adaiyah, Muss, Alen Formations are only observed in Lorestan, Fars and Darkhoain area and there are no evidence of their extensive distribution in the Persian Gulf region (James and Wynd, 1965; Motiei, 2003) except in Balal oil field in the Persian Gulf where Rus Formation have been encountered in the drilled well. Butmah, Adaiyah, Mus and Alen Formation consist of varying proportions of anhydrite, carbonates and shale. Their deposition took place under semi-barred basin conditions, although the total organic content of the sediments is not reported to be very high, they are thought to have generated some petroleum (Dunnington, 1958, p.1200).

According to the Setudehnia (1972), Adaiyah Formation consists of about 63 meters shallow marine, subtidal to supratidal carbonates where anhydrite is interbedded with dolostone and shale. It is conformably overlain by the limestone of the Mus Formation and rests conformably upon shale and limestone.

The Mus Formation comprises about 56 meters of shallow marine limestone, in part correlated with the Mus Formation of Iraq (Setudehnia, 1972). It is underlain by the anhydrites and dolostones of the Adaiyah Formation and overlain by the anhydrites of the Alan Formation. Both contacts apparently are conformable. Alan Formation (Middle Jurassic) consists of about 90 meters bedded anhydrite with subordinated limestone deposited in a restricted supratidal to intertidal setting.

Arab Formation

The original formal use of the term Arab as formation was by Steineke and Bramkamp (1952). The carbonates of the Arab Formation form one of the most important petroleum reservoirs of the Persian Gulf regions (Murris, 1980). It is overlain by the Upper Jurassic anhydrites of Hith Formation and overlying the Darb and Diyab Formations. The Arab and its related formations and members (Hith, Manifa, Arab-ABC, Upper and Lower Arab-D and Asab oolite) are Late Jurassic (Kimmeridgian to Tithonian) in age.

The Arab Formation was deposited in the shallow Tethys Sea on a broad, relatively stable shelf. This broad shelf lay between 10-15°S latitude, and was bounded to the north by the Gotnia Basin and to the south by Rab'Al Khali

Basin. To the west lay the Arabian shield and a high was located to the east (see figure 3-25). The overall abundance of grain-rich, mud-poor sediments suggests that generally high-energy conditions prevailed across much of this shelf. Overall, the paleoclimatic conditions were probably hot and arid. The Arab Formation reveals a time of marine regression with a shallowing-upward trend. Sedimentation of the Arab Formation and the overlying Hith Formation took place with a NW-SE depositional strike and a regional thinning eastward. These formations are absent in the eastern Abu Dhabi and Oman.

Lithologically the Arab members consist of dolostones and anhydrites. The dolostones have replaced former limestone and appear to display little evidence of depositional texture. Porosity occurs only in the dolostone interval whist the anhydrite layers act as permeability barriers. The Arab Formation is characterized by cyclic sedimentation. Each cycle starts with restricted, shallow marine carbonates and ends with the precipitation of evaporites. This formation represents a good example of a large inner shelf development due to successive sea level falls, consisting of a thick section of shallow-water limestones, capped by Hith anhydrite.

The Arab Formation viewed as being deposited in tidal flat and sabkha environment. Dolomite and anhydrite replacement of precursor limestones is regarded as the product of diagenesis immediately below the surface in supratidal conditions.

It has long been known that the Arab and the Hith Formations form four main cycles of carbonates and evaporites. Deposition of these cycles resulted in the four members of the formation in ascending order: Arab-D, C, and B, each consisting of a lower carbonate rock (grainstone) unit and an upper anhydrite unit, and the Arab A carbonate unit that is overlain by the Hith Anhydrite. Each of these Arab reservoirs represents a single depositional sequence capped by an evaporite (Meyer et al., 2000; Lucia et al., 2001).

The grainstone units comprise the most important petroleum reservoirs in the southern Persian Gulf area. The evaporite cycles within the Formation provide the seals for the "B", "C", and "D" reservoirs. The thick sequence of Hith Anhydrite directly overlies the "A" Member and concludes the Jurassic depositional sequence.

Minor disconformities and erosional surfaces are common throughout the Arab Formation either separating the major cycles or within individual subcycles. These breaks in sedimentation which can be attributed to local shallowing, short duration immersions or increased current activity are principally evident in the Arab "C" and Arab reservoir zones. General environmental conditions were progressively more restricted upwards with a resultant increase in anhydrite and dolostone towards the top of the formation.

Correlation of the Arab zones shows a regional thinning to the east. The Arab-ABC, Hith and Manifa Formations pinch out toward the southern part of the Persian Gulf. There is progressively more dolomitization from west to east with anhydrite being replaced by dolomites in offshore Abu Dhabi (Azer,

1989). This trend is also evident onshore (de Matos, 1994). Discontinuity of some anhydrite layers exists within the Arab zones and in the anhydritic intervals separating the Arab zones (Lapointe and Karakhanian, 1990; Ayers et al., 1982).

Generally, the thick anhydritic units in Arab-ABC and the Hith represented periods of limited accommodation space and of cycle amalgamation, and therefore of rapid progadation. The Arab Formation is a large-scale eastward prograding intrashelf basinal depositional system that encompasses several sedimentary environments on the Arabian platform. Hence, the Hith anhydrite represented a period of maximum progradation (low accommodation space) with lateral equivalent, the Asab Oolite, forming a paleocoastal environment. The last stage of the Arab intrashelf basin cycle was represented by the Manifa Formation. This unit is interpreted as a drowning succession of the Arab cycle that culminated in a major backstepping of the platform and the onset of the first intrashelf-basin infill cycle of the Cretaceous Formation.

The Arab D is one of the largest oil-bearing carbonate reservoirs in the giant Ghawar Field (Ayers et al, 1982). The first study of the Arab D from wells from various fields, carried out by Power (1962), defined the sedimentation patterns during Arab D depositional period. This resulted in establishment of detailed litho-palaeontologic correlations, zonations and determined the sequence of diagenetic events. Arab D Member as defined by power (1968) was identical to both the upper Arab D reservoir and the anhydrite between Arab C and D reservoir. The Lower Arab-D was considered to be an intrashelf basinal deposit time-equivalent to the Arab-ABC. Coastal deposits were distinguished by oolitic grainstone of the Upper Arab-D and its younger facies equivalent, the Asab oolite.

The uppermost Arab D is mainly developed in a fine grained lagoonal or restricted middle shelf. The upper part of the Arab-D formation shows the most important sea level fall of the entire series. This sea level fall is characterized by an sudden transition from an offshore environment to a lagoonal backshore environment. A few stromatoporide build-ups are scattered within this lagoonal complex. Seismic interpretation of the Arab D horizon in a small island located in western Abu Dhabi also inclined to indicate the existence of a carbonate build-up or mound, possibly of stromatoporoids. The absence of the Arab Formation in some area can be interpreted as an remainder of either Late Jurassic erosion or non-deposition.

Significant portions of the Arab D reservoir are dolomitized. Dolomitization seems to be related to refluxing brines from an overlying Arab D evaporite lagoon. The A, B and C reservoirs, however, contain little dolomite although they also occur immediately below relatively thick evaporite units much like the Arab D (Power, 1962; Wilson 1985). It would seem that these evaporites (B and C) were deposited in a coastal salina, rather than a sea-linked evaporite lagoon. The base of the salina was sealed with evaporites not allowing brine reflux to dolomitize the underlying reservoirs.

It has long been recognized that the Arab-D reservoir especially in Ghawar field contains a significant amount of dolomite, and that the occurrence of dolomite is highly variable. Arab-D dolostones typically have poor systems and reservoir characteristics that are fundamentally different from those of nearby limestones, and thus represent a distinct petrophysical and fluid-flow unit in the reservoir (Cantrell et al., 2004).

Primarily, dolostone occurs in two broad categories in the Arab-D, as either stratigraphic or non-stratigraphic dolostone (Mitchell et al., 1988). Stratigraphic dolostones are thin, lenticular or sheet-like beds with typical thickness up to 5 meters, and usually occur within fairly well defined stratigraphic interval within the Arab-D. They can be quite extensive, covering tens of square kilometers. Vertical transitions from limestone to dolomite are typically gradational in character, usually occurring over a vertical distance of less than 1 meter (Mitchell et al., 1988).

Non-stratigraphic dolostone is vertically pervasive in nature, with thick sections of it cross-cutting stratigraphic reservoir zones. They have a very limited areal extent, generally extending for only one to two kilometers.

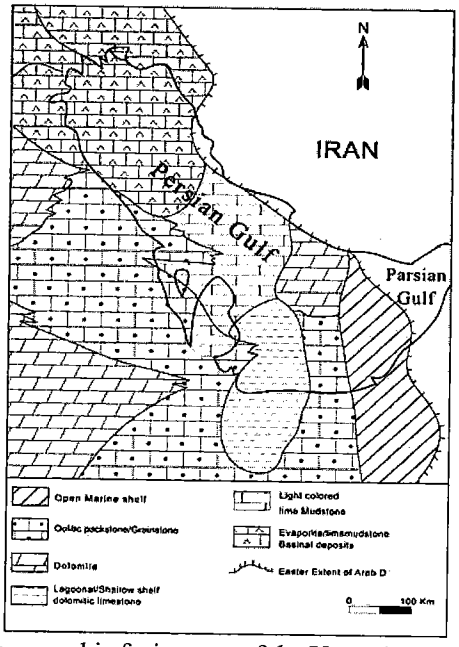

Figure 3-27. Paleogeographic facies map of the Upper Jurassic Arab Formation.

The dense interval between Arab C and Arab D is anhydritic and named the Lower Anhydrite and changes to a dense *ostracod*-bearing lime mudstone to wackestone informally called the Dense Limestone in western Abu Dhabi. The dense Limestone is mainly composed of brown, *ostracod*-rich lime mudstone to wackestone, occasionally dolomitic, with anhydrite inclusions. The

fossil assemblages include abundant *valvulinids* and *miliolids* and rare gastropodes, and mollusc and echinoid debris. Locally there are indications of freshwater environments, particularly in the area of the Bab Field where common *charophyte oogonia* were found in an ostracod-rich lime mudstone of the Dense Limestone.

The Arab C succession includes dolostones, anhydrites and limestones interpreted to have been deposited in a sabkha-lagoon complex. Three major carbonate facies can be documented in the Arab C: 1) Oolitic skeletal grainstones; 2) *Favreina* and *Prethocoprolithus* pelletal grainstones and packstones and ostracod-rich lime mudstones; and 3) A complex of carbonates with common algae (*Clypeina* sp.).

Similar facies were recognized over 500 kilometers west of Abu Dhabi (Wilson, 1985). The fossil content of the Arab C mainly consists of *C. Jurassica*, the *coprolites Favreinal salevensis* (Parejas, 1948) and *Prethocoprolithus centripetalus* (Elliot 1962), and gastropodes and ostracod, which are particularly abundant in some layers. *Echinoids, miliolids* and *valvulinids* are also occasionally abundant. *Favreina salevensis* (Parejas, 1948) and *Prethocoprolithus* pelletal grainstone facies are always present in the Arab C. The significance of coprolitic limestones as a regional marker must be highlighted. The crustacean faecal pellets *Favreina salevensis* are recorded from Upper Jurassic of Iran as well (Golesstaneh, 1965).

Typical Arab B succession consists mainly of interbedded dolostone and anhydrite. Minor laminated dolomitic lime mudstone, packstones and grainstones may occur in the Lower part. Ostracods, foraminifera, gastropodes, shell debris, algae and *Favreina* pellets can be found in some levels.

The upper anhydrite is composed mainly of chicken-wire anhydrite with minor dolomite streaks. Arab "A" is characterized by the presence of four crystalline dolostone intervals separated by anhydrites. The upper three dolomites are porous and consist of oomoldic dolo-grainstone, while dolostone at the base includes anhydrite nodules and abundant anhydrite replacement, resulting in a strong reduction of porosity. Streaks of well-sorted, peloidal, ostracod-bearing grainstones occur occasionally.

The Arab A member and Hith Formation represent the termination of increasingly restricted environmental conditions, which probably resulted from worldwide falls in sea level (Haq et al., 1988a). The terminal anhydrites of the Arab sequences have often ascribed to a sabkha environment because of their common nodular texture (Wilson, 1985). However, they are relatively thick (15-35 meters) and include minor interbedded carbonate toward the center of the Arabian shelf. These attributes point to subaqueous lagoonal or coastal salina deposition rather than a sabkha origin.

Facies and sequence analysis demonstrates that the Arab sedimentation is developed through an offshore to an inner and proximal shelf area. During the Arab C, B and A the shore to back-shore areas were largely developed. The shallowing and regressive cycle evolution observed for the depositional se-

quence is similar to that at the scale of both reservoir units and the Arab formation.

The Arab carbonate/anhydrite cycles are the result of progressive basin infilling that culminated in a regressive sabkha complex punctuated by short episodes of transgressive carbonates. Such depositional setting reflects the predominance of sedimentation relative to subsidence and eustatics. The Arab-D reservoir facies of high-energy grainstones was the final upward-shoaling, "basin-filling" phase, whereas the Arab-A, B, and C reservoirs are transgressive phases.

The depositional environments for each Arab reservoir facies from the Arab-D upward are progressively most restricted phase of Jurassic sedimentation, with increasing proportions of lagoonal and intertidal sediments. Wilson (1975) noted this to be true regionally for the Arab sequence. Each reservoir facies terminated with the deposition of evaporites, which are inferred to have sealed the underlying carbonates at an early stage of burial, forming a closed system protected from extensive late diagenetic cementation.

SEQUENCE STRATIGRAPHY

The Arab intrashelf basin-infill cycle including Upper Arab-D, Arab-ABC, Manifa, Hith, and Asab Oolite, was a major depositional system that prograded from west to east through central southern Persian Gulf. This was the opposite direction of the intrashelf basin cycle of the underlying Diayab Formation (de Matos and Hulstrand, 1995; Al-Suwaidi et al., 2000). In a chronostratigraphic framework, the dolomite-anhydrite shallowing-upward cycles of the Arab-ABC are time-equivalent to the Upper Arab-D oolitic grainstone belt. This formed the progradational coastline during the Kimmeridgian and Tithonian and its trend can be derived from the seismic data. The lower Arab-D forms the time-equivalent ramp deposits leading into the intrashelf basin center.

McGuire et al. (1993) and Sharland et al. (2001) correlated the Arab Anhydrites to lowstand wedges and transgressive deposits, and the carbonates to highstand deposits. Al-Husseini (1997) interpreted the Arab sequence as a late highstand of the Arab, Hith, and Gotnia evaporites.

Following maximum flooding surface (MFS) based notion of Sharland et al. (2001), approximately 330 meters of Arab were deposited between MFS J70 (152.75 Ma) and MFS J110 (147 Ma) within about 5 to 6 million years. The two flooding surfaces can be considered as reliable correlation markers in the Persian Gulf and surrounding countries. The MES J80, J90, and J110 of Sharland et al. (2001) could potentially coincide with three aggradational cycle sets in the Arab-ABC.

Hith Formation

The Hith Formation (Power et al., 1966) is the last major cycle of the Upper Jurassic sequence in the Persian Gulf region. In other word, the evaporites of the Hith Formation (Tithonian in age) represent the final regressive, supratidal stage of the last major Jurassic depositional cycle which is persistently present throughout the Persian Gulf region.

In Kuh-e-Surmeh, the formation is made up of 24 meters of brecciated dolostone, with the evaporites having been removed by dissolution. In the interior Fars, the evaporites give way to a dolomitic facies, and the formation pinches out toward northern Persian Gulf. The precise age determination of anhydrites is not possible due to the lack of fossils. A Late Jurassic age, however, has been assumed for this formation. In northern Persian Gulf, the Hith Anhydrite overlies the limestone and dolostones of the Surmeh Formation and underlies the carbonates of the Fahliyan Formation. Both the upper and lower contacts seem to be conformable. It is a very efficient seal, mainly for gas accumulations in the Surmeh Formation.

The thickness of the Hith Formation encountered in wells in Lavan and Kish Islands in the Iranian waters of the Persian Gulf ranges from 73 to 92 meters. However, in many localities in Iran the thickness of this formation ranges from 30 to 150 meters (Javadian, 1996). The formation pinches out and disappears completely in the Bandar-e-Abbas area (Golestaneh, 1962 cited in Javadian, 1996). This is also the case in southern Persian Gulf (see later paragraph).

In the Persian Gulf offshore wells the thickness of Hith Anhydrite is 47 meters in well 0-4#BIS, about 61 meters in U-1, 64 meters in R-32 (Resalat oil field), and 76 meters in FRB-1. Locally, 32 meters of the Hith Anhyrite have changed facies to dolomitic anhydrite and that is the case which is observed in well 3H-1.

Sedimentation of the Hith Formation took place with a northwest-southeast depositional strike and with a regional thinning eastward. The Hith Formation is characterized by repetitive shallowing-upward progradation carbonate-to-evaporite depositional sabkha cycles. The anhydrites progressively thicken upwards and eventually dominate the sequence. The entire Hith Formation shows progressive thinning eastward and it disappears entirely in Central Abu Dhabi and further east due to erosion or facies changes. The Hith isopach shows a regional thinning to the east (figure 3-27). The maximum values are in the range of 115 to more than 130 meters. The isopach map of the Hith Formation shows thickness variations from zero in southern Persian Gulf to 146 meters in the western area Abu Dhabi.

At the base of this formation, transgressive units occur as local minor lagoonal and intertidal thin, porous carbonate horizons (Alsharhan and Kendall, 1994). The top of the Hith and the Jurassic have been considered equivalent horizons for practical purposes, although the age of Hith is still uncertain.

Since the Hith attains a thickness in excess of 150 meters and the subjacent carbonate are generally not dolomitized, it would seem that the Hith also was deposited in a salina or playa setting.

Alsharhan and Kendall (1994) distinguished the development of a limestone barrier separating the Hith evaporite lagoon from the open Jurassic ocean to the southeast and east forming a coastal salina. The Hith has a number of laterally extensive interbedded dolostones, which might signify marine incursions.

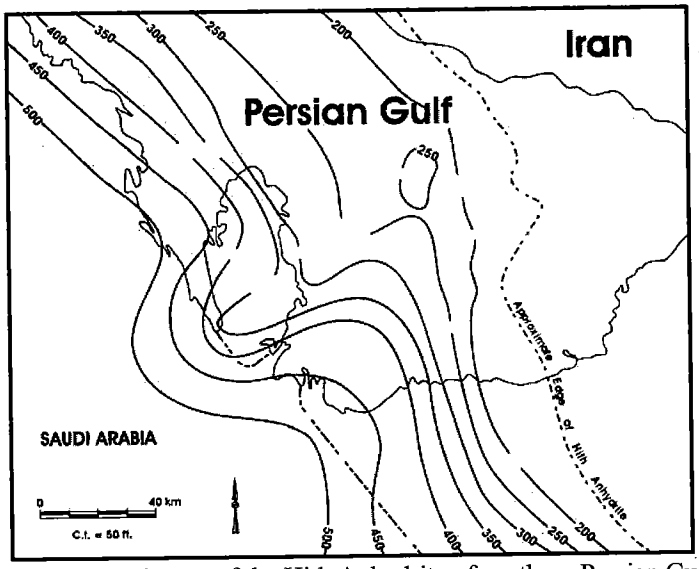

Figure 3-27. Isopach map of the Hith Anhydrite of southern Persian Gulf (after Moore, 2004).

The uppermost part of the Hith Formation consists of a porous sequence of limestone possibly similar to the Manifa reservoir of Saudi Arabia. The exact stratigraphic position of this interval is still doubtful. The top of the Jurassic in eastern Abu Dhabi is taken at the base of a glauconitic, pyritic, detrital limestone layer, which marks the lowermost part of the Rayada Formation.

Towards western and northwestern part of the Persian Gulf the Hith is replaced by Gotnia Formation anhydrite. The Hith anhydrite passes eastward to oolitic shoals and shelfal carbonates of the Asab Formation. De Matos (1994) shows the Asab Formation oolite is stratigraphically equivalent to the Hith Formation and the Arab-A member.

East of the Hith Anhydrite edge, the depositional environment ranged from shallow open marine to shoal, grading eastward to outer-shelf deeper open marine. The Asab Formation or Asab equivalent strata were deposited in this area. The Asab oolite has been interpreted as the lateral equivalent to the Hith

Formation (Alsharhan, 1989) and this seems to be the most probable interpretation.

Hith/Gotnia evaporites deposited during probable extensional reactivation of basement faults. Latest Jurassic age (Gotnia, Hith, upper Surmeh), is characterized by rimmed hypersaline platforms and adjacent salina basins (van Buchem et al., 2002). Typically, the Hith Formation acts as a seal for the Arab reservoirs and the Drab and Diyab Formations act as source rocks.

Diyab Formation

Late Jurassic tectonic differentiation in response to the combination of a eustatic sea-level rise and differential subsidence over the platform resulted in the development of the Diyab intrashelf basin in western Abu Dhabi (Alsharhan and Kendal, 1986).

The Diyab Formation is a thick succession of relatively deep-water, argillaceous lime mudstones and wackestones (Al-Suwaidi et al., 2000). It is rich in organic matter and changes laterally eastward into relatively clean, shallow water carbonates, peloidal packstones and grainstones. The Diyab Formation is the equivalent of the Dukhan Formation of onshore areas and equivalent to Hanifa and the Jubaliah Formation of Qatar and Saudi Arabia respectively.

The Diyab Formation differs in thickness from 250 to 450 meters. It is directly overlain by the Upper Kimmeridgian Arab Formation. The formation is underlain by the Middle Jurassic Araej Formation. It is part of the pre-Arab intrashelf basin infill. However, unlike the Arab Formation, the pregradational trend in southern Persian Gulf during the Oxfordian to lower Kimmeridgian was from east to west. This is the opposite direction to that in the upper Kimmeridgian to Tithonian Arab intraself-basin infill.

Based on the paleontological and palynoloical evidence, Diyab Formation has been dated as Oxfordian to Mid Kimmeridgian and is interpreted to have been deposited in an intrashelf basin, slope, shelf margin, and shelf interior (Al-Suwadi et al., 2000). During the deposition of the lower Diyab, an intrashelf basin-basinal slope environment occupied major part of the southern Persian Gulf. Organic rich (notably bitumen) lime mudstones were deposited under euxinic conditions. The deposition of the Upper Diyab marks a regression phase where lagoonal environment with shoal deposits took place.

The Diyab Formation was deposited during a marine transgression, resulting from regional subsidence. The sea-level rise allowed rapid up-building of a carbonate rim, while the basin floor lagged behind, because of lower rates of subsidence (Al-Suwaidi et al., 2000).

Late Jurassic Early Cretaceous Unconformity

The Jurassic-Cretaceous boundary corresponded to a drastic change of environment. The arid Jurassic conditions were replaced by a warm and humid

climate as the northward drifting Afro-Arabian plate reached equatorial latitude (Roth and Bowdler, 1981). The alternating carbonate and evaporitic episodes observed during the Jurassic were replaced by a succession of widespread thin carbonates interspersed with clastic influx. The rapid alternation of lithology reflected sudden uplifts of the Arabian Shield (Koop and Stoneley, 1982) and a persistent humid climate. The common plant remains and the occurrence of coals in the clastics confirm the humid climate (Lehner et al., 1984).

The Late Jurassic-Early Cretaceous was the time of a major regional unconformity throughout the Persian Gulf region. Truncation of the uppermost Jurassic rocks particularly in southern Fars and northern coasts of Persian Gulf have also been observed. Tectonic movements caused a regression of the sea from large parts of Iran and as a result, Tithonian-Neocomian sediments are missing in the respective areas.

During the whole interval from the Cambrian to the Late Jurassic merely occasional epeiroenic movements have been documented, accompanied in places by block faulting (Stocklin, 1968). This long period of stability was interrupted by a time of instability at the end of the Jurassic and in the early Cretaceous.

The Iranian region was leveled by the Late Jurassic and Early Cretaceous erosion and covered by an extensive though thin sheet of Neocomian continental redbeds corresponding to the Hith evaporites of the Persian Gulf and world-wide desiccation. As a result of important orogenic movements between Jurassic and Cretaceous the entire western part of Arabia was uplifted and heavily eroded. The products of this erosion are found in the clastic series bordering the region. Subsequent movements, linked probably to the reactivation of faults, led to the extrusion of basalts up until Albian times. Marine sedimentation was remarkably continuous in the Zagros and over much of the Eastern Arabia.

Following the orogenic phase, the uplifted and emergent Jurassic beds in the Arabian Peninsula were also subjected to intense erosion. Thus, uplift of many areas and intensive erosion of the elevated blocks resulted in the removal of Upper Jurassic deposits from much of the Persian Gulf region. Block faulting is apparent in some areas except in the subsiding zone and margins where there is continuity of sedimentation with local breaks. These activities were associated with the opening of the Neo-Tethys, which had commenced at the start of the Mesozoic Era.

CRETACEOUS

Introduction

Cretaceous carbonate platforms are some of the largest and most widespread sedimentary units in the geologic column. They have great economic

significant and contain approximately 16% of the world's hydrocarbon reserves. They developed throughout the Cretaceous period in the Tethyan region which included the Persian Gulf region. Furthermore, they have yielded significant amounts of the world's oil production (Scott et al., 1993).

The Cretaceous carbonate platforms of the Persian Gulf form world class giant fields and contain large amount of organic rich sediments. Traps have a number of configurations (salt domes, faults, and folds) and most are sealed by regionally continuous marine shales or anhydrites. The depositional and diagenetic setting of the Aptian-Maastrichtian reservoirs is investigated by various workers (e.g., Alsharhan and Narine, 1997; Keyvani and Heydari, 2004).

The history of the carbonate platform during the Jurassic and Cretaceous is of overwhelming importance because of the extraordinary richness of hydrocarbons in these horizons. Carbonates are the major Cretaceous rocks, but some thick clastic units are also present. This was due in part to the low stand of sea level and the prevalence of humid conditions during certain periods of the Cretaceous (Murris, 1980; Beydoun, 1991).

Despite the fact that the Early Cretaceous carbonate successions in the subsurface of the Persian Gulf region contain major hydrocarbon reservoirs, very little has been published on the various formations. In spite of this, it can be expressed that the Cretaceous was a period of profound change along the northeastern continental margin of Arabia extended from the Persian Gulf to Mediterranean Sea.

Late Cretaceous was one of the most significant periods in the geologic history of the Persian Gulf region. This period was a time of tectonic adjustment and shallow-marine carbonate sedimentation across the Persian Gulf region. As a consequence of the tectonic history, the stratigraphic records display a great diversity in its sedimentologic and paleogeographic patterns and in its fossil content.

TECTONOSTRATIGRAPHIC EVOLUTION

The last step in the Permian-to-Cretaceous evolution of most of the Persian Gulf region was the creation of vast carbonate shelf. Furthermore, the Arabian platform was the passive margin of the Neo-Tethys Ocean. Eustatic movements (Haq et al., 1987) mostly governed major transgression, and the Late Cenomanian appearance of deep-sea deposits indicates the existence of a local intra-shelf basin, rather than general tectonic subsidence.

In addition to global eustatic sea-level changes, Cretaceous sedimentation in the Persian Gulf region was controlled by a combination of both regional and local factors. Tectonic, climatic and eustatic were the main three factors contributed to the nature and distribution of the Cretaceous sediments in the Persian Gulf.

Rifting in the Persian Gulf region began in Triassic, with continental separation following in Jurassic (Alavi, 1980, 2004; Robertson and Searle, 1990). Tectonic activity continued during Jurassic and Early Cretaceous in the form of vertical motions of underlying rift blocks that disrupted the passive margin. The Jurassic-Cretaceous boundary is characterized by the opening of the southern Atlantic, leading to major changes in Tethys. Africa and South America moved northward; as a result, Tethys recorded compression, tectonic events between North and South America and between the Arabo-African block and Eurasia.

The Cretaceous period encountered the maximum rifting of the Neo-Tethys. The limits of the Cretaceous flooding extended beyond most of the previous Jurassic shoreline, and it evolved later into small isolated and playas during the Tertiary.

Throughout much of the Persian Gulf region a substantial phase of uplift marks the onset of the Alpine orogeny and marks the reactivation of pre-existing structural elements and the formation of a deep open marine foredeep parallel to the Zagros Fold Belt in the present position of the Persian Gulf. An orogenic front, marked by nappes, developed along the Zagros zone with nappes emplaced from the northeast.

Early Alpine movements in the Late Cretaceous accentuated the basin-and-swell pattern of Persian Gulf basin. The central basin trough received thick radiolarite and flysch deposits mixed with ophiolitic intrusions and a chaotic melange of huge blocks derived from and advancing thrust front in the northeast.

Ala (1974) and Sadooni (1993) suggested that the movement of the Infra-Cambrian Hormoz salt might have influenced sedimentation during most of the Cretaceous. This halokinetic tectonism played a minor role in controlling sedimentation pattern during most of the Early Cretaceous, but during the Late Albian (i.e., at the commencement of the Middle Cretaceous), tectonism became more prominent, with possible activation of the basement faults and relative displacement of blocks.

In the northern Zagros area there is no occurrence of ophiolites within the nappes, which are made up of Jurassic shelf carbonates. This suggests that the region is underlain by continental crust with no evidence for oceanic crustal involvement comparable to that found in the Oman Mountains.

The Zagros orogenic front is accompanied by distinctive Alpine tectonic-related sedimentological assemblages. Olistostromes, wild flysch and typical flysch sequences occur while to the north the open marine clastic basin separates the thrust belt from the platform. In Oman Mountains huge gravity slide deposits and ophiolitic emplacement characterize the orogenic setting. The platform itself, largely stable and uniform until Campanian time now became significantly more complex. Both shallow and deep-water carbonates were deposited and clastic-dominant and mixed environment developed in a variety of the intrashelf basins.

The major phase of tectonic activity in the Persian Gulf region occurred in the Middle and Late Cretaceous (Aptian to Maastrichtian) in response to the closure of Neo-Tethys and continental collision. During the deposition of the Middle Cretaceous sequence, the initial sign of growth of present-day major structures is indicated by somewhat reduced formation thickness in several fields.

By late Maastrichtian the main orogenic pulse had declined and a more consistent depositional pattern had started again. The area at this time showed two major depositional trends. These were the northwest-southeast basin parallel to the Zagros chain, with deep marine conditions predominating and the area to the southwest where a carbonate/evaporite platform emerged with local carbonate shoals trending north-south parallel to the reactivated Mesozoic lineaments. The Qatar-Gavbandi Arch was still a prominent positive element and was the site for a shallow carbonate/evaporite platform with a central salt pan.

The southern Persian Gulf region, centered on the oceanic crustal Oman region, remained stable following the orogeny but the continental crustal northern region began rising isostatically producing a clastic apron. Around the fringe of the Oman Mountains, uplifted during the Upper Cretaceous-Paleocene time and Eocene strata are predominantly of shallow water carbonate facies with reefal development fringing the mountains. These strata thicken southwards across the site of the previous South Oman High and onto the south Oman Shelf. A deeper water facies, perhaps possessing some source potential, could be anticipated in a southwards direction.

REGIONAL SETTING

Some of the most characteristics depositional locations of the Cretaceous Tethyan realm were carbonate platforms and shelves where reef and bioherms were significant sites of carbonate production. The Cretaceous carbonate platforms and shelves differed remarkably from Holocene shallow water carbonate depositional settings since the Cretaceous Tethys Ocean was characterized by periods of high geodynamic activity. In addition, sea level was 100-200 meters higher than present-day.

Therefore, Cretaceous platforms and ramps occupied larger shallow-water regions than modern carbonate shelves and extended farther north and south in paleolatitude. Carbonate platforms and shelves with reefal environments developed in the Tethys and the Persian Gulf and many other places during this time.

In general the time interval from Lower Cretaceous to Middle Cretaceous was a time of continental and shallow marine sedimentation reflecting regressive and transgressive depositional sequences. The present Persian Gulf area was the site of marine sedimentation and a carbonate platform covered the entire region.

During the Tithonian and Early Cretaceous several long, narrow troughs developed in high Zagros along the Zagros suture (Davoudzadeh and Schmit, 1982). At the same time, in southwestern Iran, there were widespread regressions with deposition of red continental and evaporitic sediments or even sedimentary gap (Seyed-Emami, 1988).

The Early to Middle Cretaceous was a time of a predominantly "calcite sea" when marine hypercalcyfying taxa were abundant and secreted massive skeletons (Hardie, 1996; Stanly and Hardie 1999). Prior to this during the Early Jurassic the major reef builders were aragonitic scleractinian corals in an "aragonitic sea". Eustatic sea-level rise terminated platform growth by drowning at least three times.

An epeiric sea covered the Persian Gulf region during the Early Cretaceous (Figure 3-28). Early Cretaceous platforms were widespread and thick, and complex biotic associations formed reefs that contributed significant amount of carbonate sediments. A carbonate horizon with orbitolinids, which form the Daryian Formation and its equivalents, covers a vast area.

The Lower Cretaceous (Neocomian to Aptian) is composed of platform carbonates deposited in a shallow-marine environment and subject to notable variations in thickness. The Lower Cretaceous to Middle Cretaceous was a period of continental and shallow marine sedimentation which is reflected by regressive and transgressive cycles.

The sedimentary succession of the Persian Gulf region deposited upon an eastward-dipping carbonate ramp similar to that described by Murris (1980). The Early Cretaceous ramp was a typical homoclinal ramp. The paleoslope dipped gently and uniformly from central Arabia (the shoreline) to the east, toward Oman (the basin) (Murris, 1980).

Stable platform conditions persisted over the region until the Middle Cretaceous, resulting in predominately carbonate deposition over a large area. The principal controls on sedimentation were sea level fluctuations and continuing post-rift subsidence of the platform. Thick marine carbonates and marls predominated in the Middle and Upper Cretaceous sedimentary sequences over most of the Persian Gulf region, with sandstones indicating the approach to the continental mass in the southwestern part.

The Cretaceous time was also a period of maximum rifting of the Neo-Tethys Ocean (Glennie, 1997 and 1995). The major phase of tectonic in the Greater Persian Gulf region occurred in the Middle and Late Cretaceous due to the closure of Neo-Tethys with major continental collision. Sedimentation varied from non-deposition to the formation of thick successions. These dramatic changes in sedimentary accommodation space, highly suggest that there was some periods of basinal setting instability characterised in some areas by active salt tectonism.

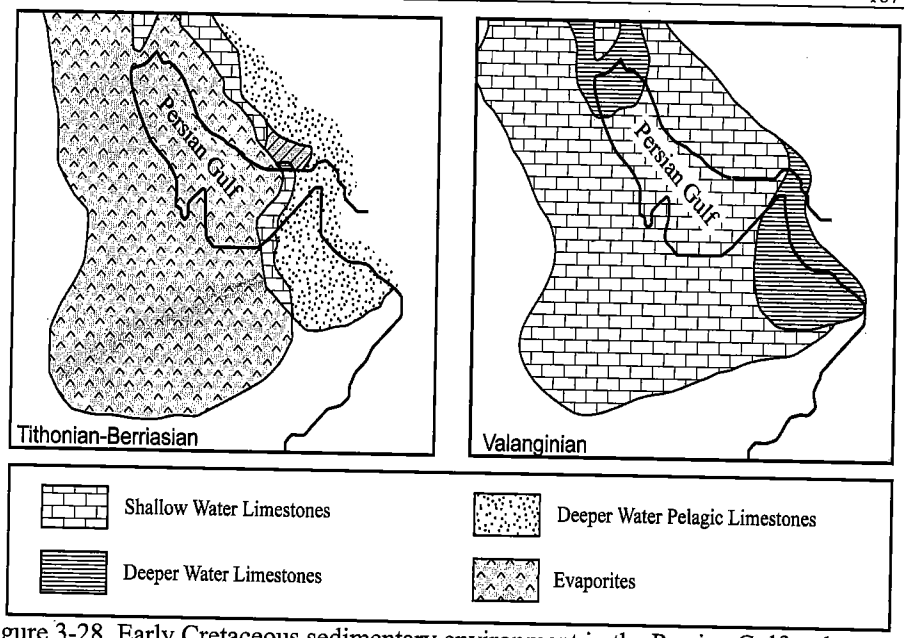

Figure 3-28. Early Cretaceous sedimentary environment in the Persian Gulf and surrounding region (Modified from Murris, 1980)

During the Late Turonian to Early Campanian, a major adjustment in basin configuration took place signaling the earliest phase of Alpine compressive tectonics (Murris, 1981). Thickness and facies variations of sediments enormously increased from Late Cretaceous times onward. These features are related to two different origins as described;

1) Koop and Stoneley (1982) have related it to the reactivation of N–S deep-seated faults after the Late Cretaceous ophiolite obduction and to the Zagros thrust belt formation which started in the Early Miocene;

2) Hessami et al. (2001) proposed that the thrust belt formation starts during Late Eocene. However, Sherkati and Letouzey (2004), based on their fieldwork, updated isopach maps, subsidence curves and a balanced cross section, supports these two origins.

During Maastrichtian contraction resulting from the continued subduction of the northern margin of Arabia under Neo-Tethys ultimately caused relatively rapid emplacement of the supra-subduction ophiolites into the embayments. Emplacement of the ophiolites depressed the margin and created a foredeep, the effect of which, were widely felt over the platform.

The carbonate bank retreated rapidly to the southwest, and a flysh/shale apron (Amiran-Gurpi) developed in front of the advancing allochtones. For the first time since the break-up of Gondwana, the dominant source of clastic deposition on the northern margin of the Arabian platform was from the north; this situation would remain to the present day.

Cretaceous Paleogeography and Paleoclimate

In a general paleogeographic sense, Murris (1981) and Koop and Stoneley (1982) believed that during the Early Cretaceous there was gradual establishment of ramp-type carbonate deposition related to a rise in sea-level with shelf carbonate, covering most of the Persian Gulf area. Although the area was predominantly a carbonate province during the Early Cretaceous, the presence of detrital clastics can not be ignored (Murris, 1980).

The Cretaceous period is referred to as one of several warm intervals of Earth's history (Huber et al. 2000) but warm climates were not distributed evenly across all stages of the Cretaceous. Rather the Cretaceous is generally divided into a relatively cool Early Cretaceous, a warm to very warm Mid-Cretaceous interval, and a relatively cool, Late Cretaceous. The movement of the Arabian plate to the tropical or subtropical zones occurred at this time (Murris, 1980; Beydoun, 1991, 1993).

Throughout the Cretaceous period the Arabian platform was situated off the paleo-Indian Ocean. At the beginning of Cretaceous, the Persian Gulf region was located just north of the Equator. The large scale basin configuration had changed from one of a differentiated passive-margin of shallow shelves and deeper, interashelf basins which characterized Jurassic to that of a very low relief passive-margin ramp setting, with the stable Arabian shelf passing northwards into the deeper water realm of the Mesopotamian-Northern Persian Gulf Basin (Murris, 1980).

The Mesopotamian Foredeep Basin of northwestern Persian Gulf was dominated during the Early Cretaceous by a low-energy carbonate ramp that underwent frequent gradual clastic invasions reflected in fluvial-deltaic-marine clastic sequences. This ramp was converted into a block-faulted shelf/platform by the end of the Cretaceous (see figure 3-29).

Since the Persian Gulf was in the tropical to subtropical regions in the Early Cretaceous the climate became more humid. Murris (1980) noted that the association of clastic materials with humid tropical periods. Evaporite formation was terminated, as shallow marine carbonate deposition once more became dominant.

Following extensive flooding of the Arabian Shield, a shallow, easterly-dipping carbonate was established. No major tectonic event disrupted the platform during the Early Cretaceous, although it may be argued that tilting occurred. As a result the overall characteristics of the sedimentary successions were controlled by relative sea-level fluctuations, although compressional tectonics associated with the closing of the Neo-Tethys Ocean and basement faulting also played minor roles.

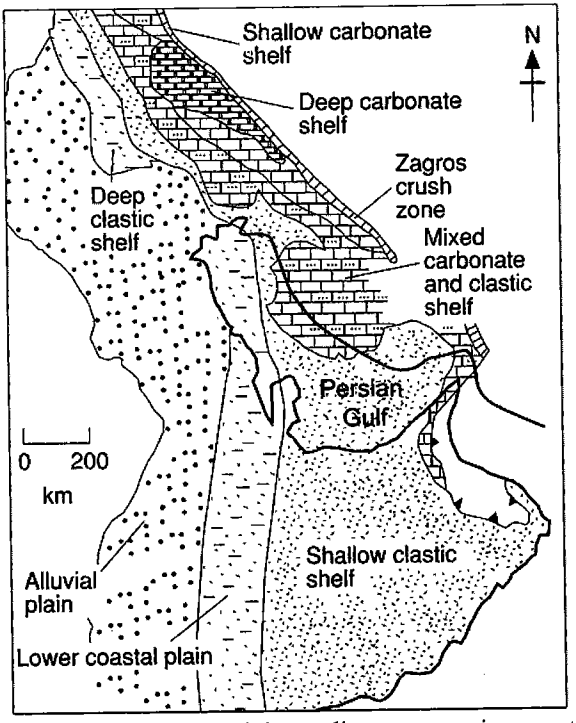

Figure 3-29. Interpretations of the evolving sedimentary environment in the region of the Persian Gulf during Mid-Cretaceous (after Shannon and Naylor, 1989)

During the Middle Cretaceous, the general area of the Persian Gulf was equatorial, with a semi arid or humid tropical climate (Parrish and Barron, 1986); no evaporites have been described from platform interiors.

The brief, but major pre-Albain regression was followed by a low-amplitude transgressive episode, marked by an abrupt influx of clastic during the Early to Middle Albian. The transgressive Albian sediments reveal a rise in sea level. A relative sea-level rise initiated deposition of the organic rich shales of the Kazhdumi whereas the limestones of the overlying Sarvak Formation formed during the highstand.

Global sea level was at a highstand in Late Cenomanian-Early Turonian interval of the Late Cretaceous. In northwestern Persian Gulf region, sedimentation was continuous from Cenomanian to Turonian, as deep-water facies of fine-grained limestone with marls were deposited. Relative to today the level of Late Cretaceous seas was high and the major continents of the world were flooded for about 40 Myr. Not since Ordovician and Silurian had continents been so inundated by shallow-marine waters. Later Cretaceous reef patterns are most clearly visible in low- to mid-latitude Northern Hemisphere regions centered between the Americas and the Arabian Peninsula.

The thick basinal deposits were over the flooded foreland during uplift of the platform in the Oman-Zagros peripheral buldge and indicates major drowning, probably corresponding with an early Turonian sea level highstand (Haq et al., 1988). Correlative sections in the Persian Gulf region which include Iran, Kuwait, and Saudi Arabia show that the Turonian deepening of the basin was regional.

A major sea-level drop at the Cenomanian-Turonian boundary exposed carbonates of the Sarvak Formation. In the southeastern Zagros and Oman, this major disconformity (i.e., Cenomanian-Turonian) is recorded by rubbly, karstic topography and hematite nodules that cap Albian to Cenomanian platform carbonates (Cherven, 1986). Cenomanian-Turonian disconformity of the southern Zagros dies out to the northwest, and the entire Upper Cretaceous series is present, consisting entirely of deep-water chert, shale, and marl (James and Wynd, 1965).

The fall in relative sea level during Cretaceous also resulted in increase clastic input. By Mid to Late Barremian time a broad apron of continental to marginal marine alluvial coastal plain clastic sediments pushed the shrinking carbonate shelf eastwards. The Lorestan Basin, a site of euxinic shale deposition, had also reduced in size considerably, while there was non-deposition and erosion on the Qatar-Gavbandi Arch. During the Barremian and Aptian stages, a shallow sea covered more or less the whole Iran.

Gealey (1977) suggested that this period of emergence and weathering occurred as the Arabian platform passed over the outer bulge of the Iranian subduction zone and that the overlying deep-water Santonian marl (Gurpi Formation, James and Wynd, 1965) and Coniacian turbidites (Muti Formation, Glennie et al., 1973) represent renewed subsidence as the Arabian platform was drawn down into the subduction zone to the northeast.

The post-Cenomanian and post-Turonian unconformities are less apparent in Lorestan region, where basinal sedimentation continued through the Coniacian to become more calcareous in the Santonian-Early Campanian.

The introduction of the subduction caused wrapping of the Arabian continental margin to create both basins and erosional highs (Murris, 1980; Masse et al., 1997), the depositional details of which can now be realized by means of high-resolution sequence stratigraphy (Van Buchem et al., 1996).

The Aptian was a period of renewed marine transgression with the reestablishment of a shallow carbonate platform across much of the Persian Gulf region (Figure 3-30), and this thinned in a westward overstepping direction (Murris, 1980). The Qatar-Gavbandi Arch was largely reduced in area during the transgression. Rudistid reefal carbonates, interbedded with basinal limestones, offer significant potential in Oman and elsewhere in the region. The Lorestan intrashelf shale-dominant basin again enlarged, with a southern sub-basin forming in the Khuzestan area and a large southern basin forming south of the Qatar-Gavbandi Arch.

During the Aptian, the entire present day Persian Gulf area and its surroundings were covered by a layer of shallow water limestone (figure 3-30).

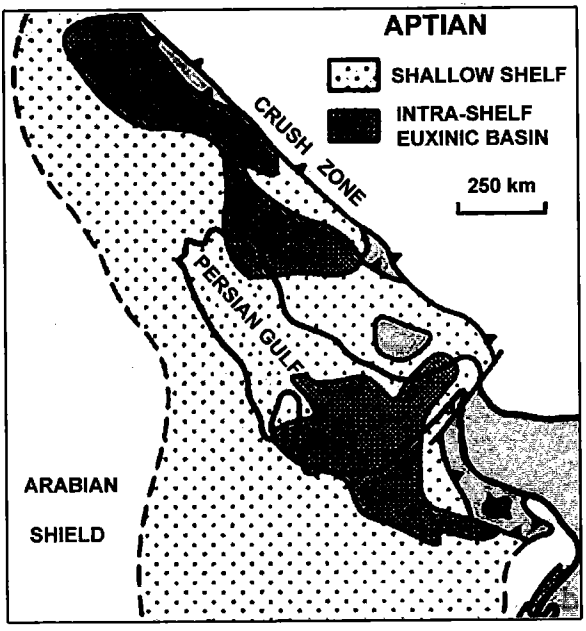

Figure 3-30. Paleoenvironmental reconstruction during the Aptian in the Persian Gulf region (Modified from Murris, 1980)

On top of the Upper Aptian the facies indicate the inception of regression (shales, sandstones, a few bands of neritic limestone). A temporary flooding in Early Aptian is followed by a pronounced regression (Murris, 1980; Haq et al., 1987). This regression, along with large-scale regional tilting, led to basement emersion, the formation of a significant regional disconformity, and Middle to Late Aptian stratigraphic hiatus. Thus, Mid-Aptian witnessed yet another regression phase with eastward progradation of alluvial to shallow marine shelf clastic facies, hence carbonate deposition became restricted to the northwest of the region in the vicinity of the Lorestan intrashelf basin. The sandstones are important reservoirs being sealed by interbedded shales and sourced from the intra-basinal shales.

The end of the Aptian was marked by a regional emergence producing an unconformity over the entire region, except for the deeper part of the Lorestan basin. The Albain to Santonian physiography of the region is generally accepted to be an intrashelf basin, with no deep-water connection to Neo-Tethys.

In the Mid-Albian, regression was prevalent throughout the Persian Gulf and the region was the site of deposition of terrigeneous clastic sediments. During Late Aptian to Late Albian time a major influx of terrigenous material

from the emerged Arabian-Nubian shield to northwest onto the Arabian platform (figure 3-31) led to the deposition of the argillaceous Azadegan Sandstones (i.e., Nahr Umr Formation). The shelf area became increasingly carbonate dominated during the Cenomanian during the deposition Sarvak Formation.

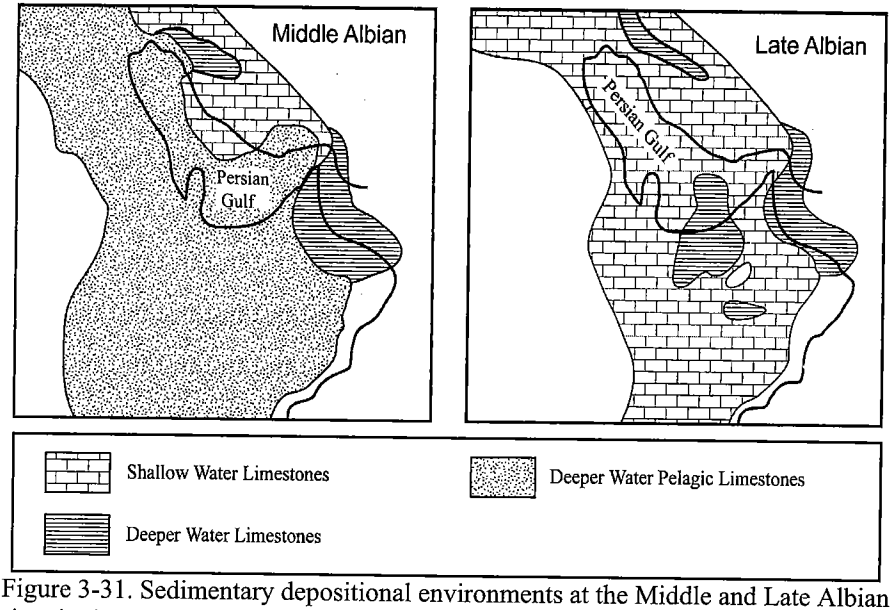

Figure 3-31. Sedimentary depositional environments at the Middle and Late Albian time in the Persian Gulf and the surrounding region (Modified from Murris, 1980).

Paleogeographic maps of the Berriasian to Barremian demonstrate depositional environments active in the Arabian Peninsula at this time. The Berriasian Valanginian shows conditions during the early phase of the first carbonate cycle (figure 3-32). To the north, and southwestern Iran, the broad intrashelf Gotnia Basin, persisted through the first cycle.

At this time Fahliyan platform limestone covered much of the Persian Gulf region. In the north, the Garau basin was an intrashelf basin with up to 200 meters of bathymetry and a marginal reef facies (Sarmord Formation). Within the Garau basin the Garau formation was deposited in source rock facies.

True basinal conditions are confined to the Levant margin and the Oman margin of the Neo-Tethys. Two major intra-shelf basins are apparent; in Lorestan and the southern Persian Gulf. The northern "Garau basin", at least in northern Iraq, was characterized by a steep, possibly structurally influenced, reefal margin (Henson, 1959). Deeper water Balambo and Garau (source) facies were deposited in this area.

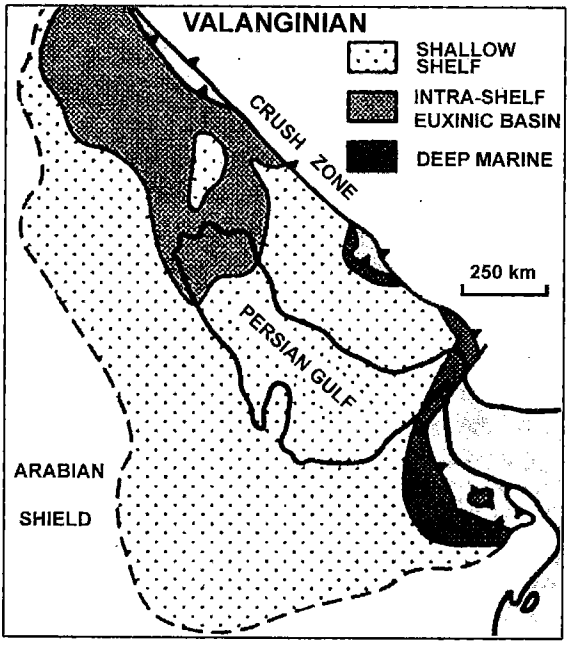

Figure 3-32. Sedimentary environment at the Valanginian time in the Persian Gulf region (Modified from Murris, 1980).

In the Dezful Embayment area, it is unclear whether abrupt lateral facies changes to deeper water facies (Motiei, 1993) represent the margin to a true intra-shelf basin or simply the limits of deeper water, outer shelf embayment with a wide connection to the open ocean. There is no preserved evidence of a shallow water lip on the northeastern side that would confirm the former interpretation and this remains an area for further investigation. In the southern Persian Gulf intra-shelf basin, the deeper water Hawar Shale was deposited. Platform carbonates dominated the remainder of the area.

The Campanian-Maastrichtian time interval corresponds to a period of a relatively highstand of sea level, which ended with a regression close to the Cretaceous-Tertiary boundary (Haq et al., 1987). During this time a marine transgression left a large part of Central Arabia and the entire Iraq covered by carbonate deposits. Shallow-water deposits, as shales and limestones with *Globotruncana*, are known in subsurface in the vicinity of Ghawar and in eastern part of Rub al Khali. At the onset of the Maastrichtian, regression took place as indicated by the low specific diversity in the *Globotruncana stuarti* zone. During the Maastrichtian, the sea level continued its gradual fall from the highstand it had achieved in the Campanian.

An overall regressive trend in the Late Maastrichtian is recorded over the Indian Plate where shallow-water silisiclastic platforms were widespread except on the northern margin, where carbonate platform prevailed. A similar

trend is reported on the African-Arabian plate where the sea reached its maximum extent during Mid-Maastrichtian time. Shallow marine environments primarily were occupied by shallow silisiclastic platforms, except on the northwestern margin of the Arabian plate (Atlasic Domain) and on the Arabian-Nubian shield, where a marine transgression initiated during the late Campanian left a large part of these areas covered by carbonate platforms in the Maastrichtian.

In Oman, similar to the southwestern Iran (Zagros), the late Maastrichtian platform carbonates rest unconformably on ophiolite complexes obducted during Santonian to Campanian time, and they also characterize an overall regression trend close to the K/T Boundary. This part of the Persian Gulf neighboring areas was marked by important orogenic movements, which seem to have began also during the Turonian and continued to the Campanian-Maastrichtian time interval where they reached their maximum intensity.

In summary the sedimentary succession in the Persian Gulf was greatly influenced by sea level fluctuations and also tectonic movements. Shallow marine platform carbonates accumulated due to marine flooding and sea water invasion over the platform during the initial period of sea level rise. The depositional environments and lithofacies change during the cycle of relative sea level.

CRETACEOUS BASINS

In general, the Cretaceous pattern of sedimentation in the region indicates a basin covering all of the Zagros which includes the Persian Gulf area. Platform conditions prevailed during the Cretaceous. The deeper part of the basin was probably centered in Lurestan and eastern Iraq and the change of facies from mainly carbonates to mainly clastics towards southwest Arabia indicating a general shallowing of the sea in that direction. This is where the deposition of deeper water sediments persisted through early and middle Cretaceous time. The basin retreated northward to cover only a small portion of Lurestan by the end of the middle Cretaceous. Continuity of the sedimentation across the crush zone cannot be established during Cretaceous time.

From Late Jurassic to Middle Cretaceous three intrashelf basins developed around the Persian Gulf region. The Mesopotamian Basin is part of the larger Zagros foreland basin associated with the closure of the Neo-Tethys Ocean and the collision of the Arabian passive margin and Eurasian plate (Nowroozi, 1972; Beydoun et al., 1992; Bahroudi and Talbot, 2003). Convergence in the Zagros collision zone still continues, and the region is currently tectonically active (see Nowroozi, 1972; Berberian, 1995). The Mesopotamian Basin is floored by Neoproterozoic crystalline basement rocks of the Arabian shield (Bahroudi and Talbot, 2003).

In the remaining areas of the Zagros, after a period of emergence in the late Neocomian, the shallow water carbonates were followed by an influx of

argillaceous material during Barremian-Aptian time. Towards the southern Persian Gulf, these shales and limestones pass into the sandstones again indicating a shallowing towards the southwest.

During the Early stages of Cretaceous (i.e., Aptian), intrashelf basins developed in the Persian Gulf Basin perhaps as the results of the activation of Hormoz salt, most notably in the area of the southern Persian Gulf (i.e. UAE), where the basin formed (Murris, 1980). These intrashelf basins mainly contain sediments deposited following relative falls in sea level. Subsidence, eustatic sea level and tectonic movements created an intrashelf basin in the region, whereas shallow shelf sediments were deposited to the east.

During the deposition of the Aptian to Albian successions the intrashelf Bab Basin formed in the Southern Persian Gulf (Scott, 1990); in the Zagros (Ricou, 1976) a mixed, neritic, hemipelagic facies developed. The Bab basin occupied approximately the same location as area as the Late Oxfordian-Early Kimmeridgian intrashelf basin (Diyab Formation) and the Cenomanian (Late Albian-Early Turonian) intrashelf basin (Shilaif Formation) (Murris, 1981). Tectonic differentiation of the formerly uniform shelf environment led to the development of this intrashelf basin (i.e., Bab Basin) in central Abu Dhabi fringed by the shelfal Lower Cretaceous platform. The Aptian intrashelf basin in the southern Persian Gulf marks a major change in sedimentary basin orientation and extension.

The Bab member, equivalent to the Shuaiba buildup, developed in an intrashelf basin in southern Persian Gulf (i.e., central Abu Dhabi). It is characterized by mud-supported limestones with shaley and argillaceous partings and a deep marine fauna (Bordenave and Burwood, 1990, p.187). Toward the end of the Aptian, epeirogenic movements and/or a sea level fall terminated the deposition of the Thamama Group and caused a period of emergence and erosion. Basinwide Aptian transgression was abruptly terminated by a major pre-Albian regression. This resulted into the higher areas of the Arabian Platform to become emergent (Bordenave and Burwood, 1990).

By the Early Cretaceous (Berriasian), an intraplatform basin had again developed in central Arabia in which sediments forming the dark mudstones of the lower part of the Sulaiy Formation deposited. Shelf grainstone carbonates then prograded from north to south over the lower Sulaiy. The overlying Yamama Formation represents the transition from intrashelf basin conditions to shelf sedimentation and the existence of a wide carbonate platform (Murris, 1980).

During Cretaceous oceanic anoxic events, an immense mass of organic carbon was buried and thick sections of black shales accumulated. Subsequent to anoxia shallow neritic deposition commonly resumed above the formerly drowned shelf sectors (e.g. Jenkyns, 1991). The shales often were sandwiched between potential reservoir limestones. Updip migration of hydrocarbons from basinal shale sources into bioclastic slope reservoirs locally produced significant hydrocarbon accumulation.

The euxinic nature of the rocks is a widespread feature of the Tethys-platform deposits during this period (Phillip et al., 1993). The development of this euxinic basin was important in providing oil source for the neighboring carbonate reservoirs which developed either as the carbonate platform or as reefs on the margins of the basins. A great similarity is observed between the upper Jurassic and Aptian stage. Both reveal periods of extensive transgression and have the enhancement of the shale intrashelf basin, although Aptian climate was more humid, with evaporite formation restricted to the northwest portion of the platform.

CRETACEOUS SEDIMENTARY BREAKS

The Persian Gulf region, as in many parts of the world has been influenced by major and minor unconformity throughout its geological history. Sea level fluctuation, epeirogenic movements and volcanic activity have all played their part in controlling sedimentation.

Tilting of large parts of the Arabian Peninsula and Persian Gulf at several periods has left a clear record in the sedimentary sequence, generally as unconformities at which truncation is primarily on a regional scale. Erosion of older rocks is observed, commonly over wide distances, at rates as low as a few tenths of meters per kilometer. Important unconformities of regional type are pre-Permian or older, pre-Lower Jurassic, pre-Upper Jurassic, pre-Middle Lower Cretaceous, pre-Middle Cretaceous. The extent of erosion of older rocks at various unconformities shows moderate variations. Some are important only in certain moderately large areas, whereas others show gradual systematic truncation over much of the area of their outcrop.

Two important unconformities marked themselves mainly by local and regional effects, primarily by truncation of strata on the crests of individual folds and anticlines. These are the Middle Cretaceous (i.e., post Cenomanian/Turonian) and pre-Miocene unconformities.

Over the entire Persian Gulf region a substantial phase of uplift and erosion at the end of Turonian removed a considerable amount of sedimentary cover, especially in the Zagros area and over regional paleohighs. The break in sedimentation and concomitant erosion that developed over Arabian Platform was caused by doming. The Early Turonian doming was the first reaction of the continental margin to the process of closing the NeoTehtys. Differential erosion profile shows that the erosion was much stronger on the northeastern edge of the Arabian Platform.

The cycles with large-scale lithic units of the Cretaceous are separated by regional unconformities of major importance (see figure 3-33). They include:

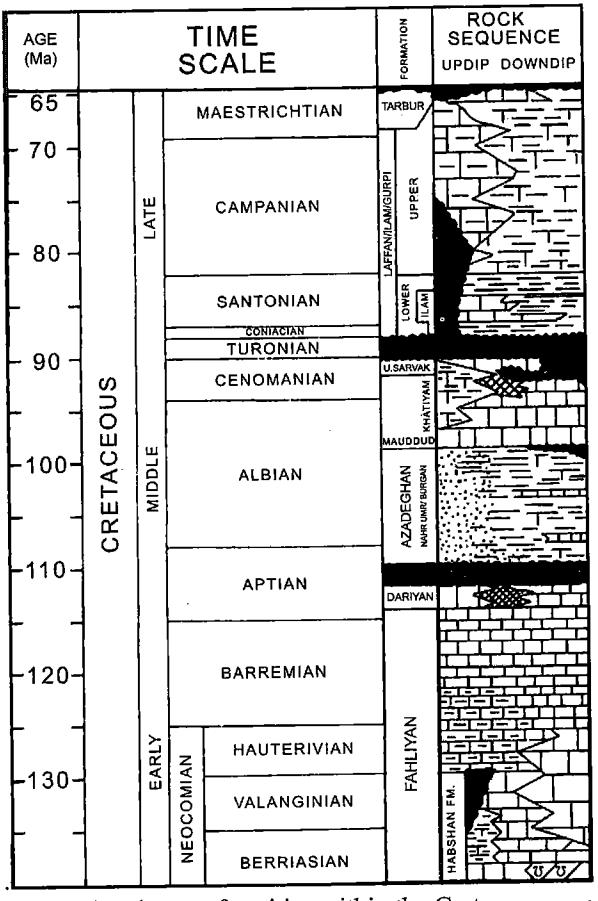

Figure 3-33. Major regional unconformities within the Cretaceous successions in the Persian Gulf region (modified Harris et al., 1984).

1) An unconformity that reflects erosion or non-deposition of the middle Aptian section and marks a major change in depositional facies from shallow shelf limestones below to shallow shelf clastic sediments above,

2) An unconformity, during which Turonian deposits were removed, representing a break between shallow shelf limestones and overlying deep water deposits; and

3) An unconformity that defines the boundary between the Cretaceous and Tertiary and caps a shallow shelf limestone deposits.

The widespread Middle Turonain unconformity resulted from both a combination of localized uplift, following initiation of ophiolite obduction on the northeast plate margin, and possibly a global eustatic fall in sea level (James and Wynd, 1965; Setudehnia, 1978; Murris, 1980; Koop and Stoneley, 1982). The dating of the upper unconformity at 92 Ma is well constrained by the age of the onlap sediments in northern Oman (Bechennec et al., 1995).

Three regional unconformities were found in the Middle Cretaceous of the Persian Gulf region. The lowermost is at the base of the interval in the southern Fars and the Bandar-e-Abbas area. The post-Cenomanian break and the post-Turonian unconformity are present throughout the Persian Gulf area. Regional uplift late in Cretaceous resulted in an unconformity that affected most of the elongate basin, except in parts of Lorestan where pelagic sedimentation was continuous from Late Cretaceous to early Miocene.

The Middle Cretaceous sequence of the Persian Gulf is bounded below and above by regional unconformities (see Figure 3-33, Harris et al., 1984), and capped by a major ferruginous hardground (break in sedimentation) after the earliest Turonian, and was related to the emergence of most of this platform. The emergence can be marked by a simple microkarst that also affects the Turonian carbonates (Pattinson and Takin, 1971; Bechennec et al., 1992), or by more clear-cut erosion of earliest Turonian and older rocks.

Several authors have pointed out the significance of unconformities in providing permeable reservoir rocks and stratigraphic traps, and have suggested that unconformities are an asset to a petroliferous basin. This is true where rocks with primary permeability are absent or where alternative traps are not available to trap oil during its migration. Throughout the Persian Gulf basin, Mesozoic and Tertiary unconformities though numerous were all short duration.

CRETACEOUS STRATIGRAPHY

Despite the apparent complexity of the terminology and detailed correlation of Lower Cretaceous sedimentary sequence, lithological changes are relatively minor and can be readily interpreted based on a simple carbonate ramp model (Murris, 1980; Koop and Stoneley, 1982).

The succession of depositional environments during Early Cretaceous is therefore one passing from alluvial and coastal plains to supratidal and subtidal flats, lagoon and open shelf environment on which shoal, biohermal accumulations, and intrashelf basins can be characterized by their lithologies (Connelly and Scoll, 1985).

In the Persian Gulf region, the Cretaceous stratigraphic successions are normally divided into three distinct large-scale parts. These major Cretaceous sedimentologic cycles including: 1) the Lower Cretaceous consisting of Berriasian to Middle-Late Aptian age sequences, 2) the Middle Cretaceous formed during the late Aptian-latest Cenomanian or earlier Turonian, and 3) the Upper Cretaceous which consists of rocks of Coniacian-Maastrichtian age.

The Lower Cretaceous (i.e., Thamama Group), Middle Cretaceous (i.e., Wasia Group), and Upper Cretaceous (i.e., Aruma Group) are designated for the southern Persian Gulf region. The initial Cretaceous lithostratigraphic study (Sadooni and Aqrawi, 2000) shows that the Cretaceous Formations in

Mesopotamian Basin can also be divided into the same three main groups used in the whole Persian Gulf region. These groups are easily recognizable in the Cretaceous successions of the Mesopotamian basin. The bases for such division are the major unconformity surfaces, which are initially used as separating time lines between the main Cretaceous sedimentary cycles for regional studies (Bellen et al., 1959; Buday, 1980).

In the Aptian time, the Persian Gulf region was covered by shallow water carbonates which did not extend to Saudi Arabia. The Middle Cretaceous witnessed a renewed transgression of the sea in which the shales and limestones of the Kazhdumi Formation accumulated. This was followed by a shallowing of the environment represented by a great quantity of Cenomanian shallow marine carbonates.

A Cenomanian carbonate platform is well developed in Oman in both outcrops and in the subsurface. The Natih Formation is dated by foraminifera and ammonites to range from lower Cenomanian to lower Turonian (Phillip et al., 1995a; Van Buchem et al., 1996). The paleogeographic setting is a shelf platform with a board margin, which is not seen because of subsequent ocean-floor obduction. Three main rudist associations formed bioherms on the shallow platform.

A subsequent regional emergence, accompanied by local uplifts, at the end of Cenomanian caused truncation of these limestones in northern Persian Gulf. The Turonian forms the last cycle of sedimentation in the Middle Cretaceous and was followed by another regional emergence.

Towards southern Persian Gulf, the Middle Cretaceous shales and carbonates pass into the marine sandstones of Burgan and Wasia Formation. Still further inland, these marine sands pass into the continental sandstones (Powers, 1968). Further transgression of the sea produced a great quantity of marls and shales until late in the Campanian, when a flourishing shoal of large pelecypods extended from Iraq into western and southern Lurestan. This was followed by further influx of mud, which continued until the end of the Maastrichtian, and early Paleocene in central and southwest Lorestan (Figure 3-34).

Over the greater part of the northern Persian Gulf area, the sea further transgressed over the shallow water carbonate shelf, which had developed in Santonian, so that the shales and marls of the Ilam-Gurpi Formation covered the entire area of the Zagros Basin extending southwest into the Persian Gulf.

Towards the southwest, the Gurpi shales of Upper Cretaceous age passed into the shallow water carbonates of the Aruma Formation, and marginal areas of the basin are defined by sandstones in southwestern Arabia (Power, 1968). In the Maastrichtian, shelf carbonates and reefal limestones developed along the northeastern part of the Zagros, making the opposite side of the basin similar to the limestones in the Persian Gulf area which occupied its southwestern margin.

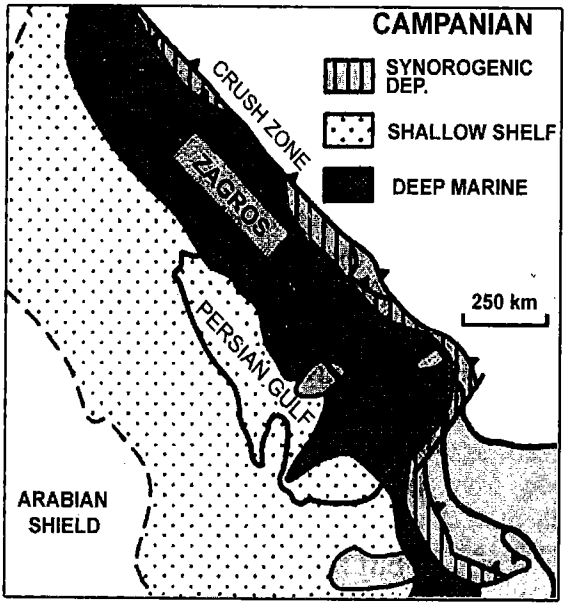

Figure 3-34. Paleogeographic reconstruction and different sedimentary environment in the Persian Gulf and neighboring region during Campanian time (Modified from Murris, 1980).

In the southern Persian Gulf and in the Oman Mountains, and locally along the northeast boundary of the Zagros, deposition of a thick radiolarian chert sequence was followed by large-scale emplacement of allochthonous sediments and ophiolites. At the end of the Cretaceous period, a general regression of the sea produced the regional unconformity over a large part of the region.

To the north of the Zagros Crush Zone, in central Iran, the Cretaceous sedimentary rocks were still mainly consists of carbonates and marls but the sections are less complete. In particular, the Neocomian seems to be missing over a large area of Iran. The sequence usually starts with unfossiliferous red clastics, followed by limestones and marls of different ages. The oldest known marine beds are limestones containing *Orbitolina*, ranging from Barremian possibly to Cenomanian in age. Deformations are hypothesized in Central Iran where the early Aptian "*orbitolina limestones*" overlies a structurally deformed, early Cretaceous basement (Davoudzadeh and Schmidt, 1984).

Uplift and erosion to the northeast produced a great quantity of clastics including silts and sands, which emptied into the Zagros Basin during the Maastrichtian and throughout the Paleocene in northern Lurestan and eastern Iraq.

LOWER CRETACEOUS IN NORTHERN PERSIAN GULF

The Cretaceous system was introduced in the Persian Gulf and the rest of Iran as a marine transgression and the end of the Jurassic was marked by a widespread regression. Despite the continuous Jurassic-Cretaceous marine carbonate sedimentation in southwestern Iran, the Cretaceous sequence of the Zagros covers the underlying Jurassic sediments disconformably with deposition of marine carbonates over the greater part of the Zagros region. Subsidence patterns continued to reflect the Jurassic basin elements, but uplift of the Arabian Shield margin provided an abundant source of terrigenous clastics; evaporitic conditions ceased at this time.

From the Barremian up until the end of Cenomanian the sea transgressed over the emergent area. The lower Cretaceous (i.e., Neocomian) sequence is represented by the Fahliyan, Gadvan, and Dariyan limestone, sandstones, and shales of marine origin. An unconformity separated the Dariyan Formation from the organic-rich shales of the overlying Kazhdumi Formation. Two types of facies represent the lower Cretaceous in the Persian Gulf Basin;

The first type is exposed in Fars and southeast Khuzestan, where Early Cretaceous sedimentation began with deposition of shallow water carbonates (i.e., Fahliyan Formation) and continued through most of the Neocomian time. These carbonates lie unconformably on the Upper Triassic Surmeh Formation.

The second type of Early Cretaceous succession in the Zagros Basin is identified in Lurestan area, where the Early Cretaceous is represented by the radiolarian-bearing shales and argillaceous limestones of deeper water origin (Garau Formation). This facies was most extensive at the beginning of the Cretaceous, covering Lurestan and northwestern Khuzestan.

Towards the northwestern Persian Gulf, the shales and limestones of the Gadvan Formation pass laterally into sandstones of the Zubair Formation and are indicative of a general shallowing of the basin toward Arabia (Fig 7.5 Shakib 1990 p.132). In this region (i.e., at Burgan area in the northwestern Persian Gulf), a thin Hauterivian oolitic limestone of the Ratawi Formation conformably overlies the Valanginian and underlies by a thick series of sandstones of the Barremian-basal Lower Aptian (i.e. Zubair Formation). The sandstones are transgressed by the Aptian carbonates (i.e., Shuaiba Formation). The contact of the two formations is marked by apparent conformity.

Sedimentation began with shallow water pellety limestones (i.e., Fahliyan Formation) and continued almost throughout Neocomian time. Therefore, shelf carbonates persisted in the Persian Gulf areas. The limestones lie unconformably either on the carbonates of the Jurassic (Surmeh Formation) or on the evaporites of the Hith Anhydrite in the Bandar Abbas area or in southern Fars and southeastern Khuzestan respectively.

The Lower Cretaceous strata were deposited during an extensive marine incursion over the entire Persian Gulf while carbonate shelf to shallow basin

conditions were established over a time span of nearly 30 m.y. Although the Lower Cretaceous varies regionally, it consists of deep-shelf carbonate deposits for most of the Lower lower two third of its thickness and in its upper one-third changes to a shallowing upward sequence. Deep-water carbonates occur locally in the Upper one-third of the sequence where intrashelf basins were developed. Clastic sediments are more prevalent in the southwestern Persian Gulf (Power et al., 1966) than they are in southern offshore region (e.g., Abu Dhabi).

The Neocomian-Aptian sequence and associated sedimentary cycle is terminated by a hiatus during the Late Valanginian. Much of the Valanginian section is missing in eastern Saudi Arabia, through the section appears to be complete in both central Oman and offshore Abu Dhabi. In addition, a continuous layer of shallow water limestones of the Dariyan Formation indicates the shallowing of the sea during the Aptian over the entire Persian Gulf. Uplift of the Fars Platform at the end of the Aptian, accompanied by erosion, produced an interval of strongly iron-stained, sandy and glauconitic sediments generally found at the Dariyan Formation in this area. Towards Khuzestan, this uppermost limestone unit passes laterally into shales and limestones of lower Kazhdumi Formation.

The Habshan Formation ranges from Valanginian to Hauterivian, which is supported, by the ranges of foraminifers, calcareous algae, and rudists. It is a shallow-water depositional system that prograded from northwest to southeast across the shelf. It consists of coral-stromatoporid reefs and high-energy rudists sand banks. The deposition of this formation started with a transgressive cycle, in a restricted or semi-restricted shallow marine setting. The lower part is composed of argillaceous, dense lime mudstone and wackestones, which grade upwards to dolomitic peloidal packstones and dolomitic peloidal grainstones. The upper part of the Habshan Formation is composed of lagoonal to intertidal lime mudstones and wackestones, with subordinate dolostones.

During the Early Cretaceous cycle, ramp-type conditions were established and clastic influx was low, reflecting the paleogeographic conditions of the continental region. A new transgression of the sea led to the deposition of shallow water carbonates over the southeast Zagros, the greater portion of the Persian Gulf, in the early stages of Cretaceous. Meantime, more basinal radiolarian shales and limestones covered the NW part of the Zagros Basin extending into eastern Iraq. These strata were deposited during an extensive marine incursion over the Arabian Peninsula when carbonate shelf to shallow basin conditions were established (Setudehnia, 1978).

Significant relative sea level rise which initiated in the upper Jurassic (late Tithonian) continued into the early Berriasian, finally terminating evaporite deposition and re-establishing open marine carbonate deposition across the Arabian plate. Although relative sea level appears to have been rising through the Late Jurassic, the sedimentation rate on the carbonate shelf kept pace,

maintaining shallow shoal to arid supratidal depositional conditions over much of the Persian Gulf and surrounding region.

In Iran and Oman the relative rise in sea level was probably very rapid, leading to sediment starvation in basinal locations and deposition of condensed sediments as for example the Lower Garau Formation of Iran. Carbonaceous shales with ammonites are at the base of the Garau Formation of southern Iran (Stocklin and Setudenia, 1972). In the Iranian side of the Persian Gulf, according to Mina et al. (1967) the Lower Cretaceous is represented by the Upper part of the Khami Group in which three Formations have been identified, in ascending order; the Fahliyan, Gadvan and Dariyan.

Fahliyan Formation

The regionally extensive carbonates of the Fahliyan Formation are the main productive units within Iranian territorial waters of the Persian Gulf. The Fahliyan Formation forms a prominent limestone within the Khami Group. This formation consists of shallow water massive limestones with a predominance of very thick-bedded strata. It usually forms steep sloping ridges. The measured thickness is 172 meters in the Fars region.

The Fahliyan Formation is present throughout the Persian Gulf. In the eastern part of the Persian Gulf and around the Straight of Hormoz, 43 meters of micritic limestones have been identified in well HD-1. Towards the top, the carbonates are slightly dolomitized and at the topmost layer the sequence is of argillaceous nature. In Hengam area, in well HEE-1, a thickness of 393 meters of Fahliyan Formation consisting of pelletal dolomitic limestones often oolitic in the lower part and micritic towards the top have been encountered in the well.

In the Sirri oil fields the thickness of the Fahliyan varies from 205 to 375 meters in SIF-1 and SIE-2 respectively. The formation consists of limestone sequence with some sandy and argillaceous units on top in SIF-1 to mainly dolomitic limestone in SIE-2. Further to the west in the well FRB-1, the Fahliyan show a thickness of 424 meters and in U-1 well it reaches 383 meters. The Formation is completely dolomitized with a thickness of 198 meters in 0-4 BIS. In northwestern parts of the Persian Gulf the thickness of Fahliyan is 352 meters in R-32 (Resalat), 270 meters in 3W-1 and 195 meters in 3H-1.

As indicated the Fahliyan Formation in the entire Persian Gulf is made up of carbonate facies and in spite of pervasive dolomitization the sequences encountered in the wells could be correlated to the type section. The best development of the Fahliyan Formation is in the northern Persian Gulf area which extend towards southwestern Lurestan and Khuzestan, where the Fahliyan grades and interfingures with shales and limestones of the Garau Formation (Setudehnia, 1971).

The Fahliyan Formation consists of shallow water, massive limestones and its equivalent of the Lower Ratawi and Minagish Formations of Kuwiat and

southern Iraq, and the Sulaiy and Yammama Formations *Valvuliniella* Zone, covering the northwestern part of the Persian Gulf (Motiei, 1993).

In most of the region the Fahliyan Formation rest unconformably either on carbonates of the Jurassic Surmeh Formation or on the Hith anhydrite. In most of the well which were drilled through Fahliyan Formation, such as well U-1, the lower contact with Hith is gradational and microfossil *Clypeina Jurassica* FAVRE is identified at the base of Fahliyan.

A disconformity was suspected at the contact of the Fahliyan and Surmeh Formations, but this feature has not yet been demonstrated paleontologically, expect in sections near Bandar Abbas in the northern coast of the Persian Gulf (Gollestaneh, 1965).

In the coastal Fars region the Fahliyan Formation is separated from the underlying dolostones of Surmeh Formation by the anhydrite of the Hith Formation. Where the Hith Formation is not present the contact is placed at the boundary of the limestone (Fahliyan Formation) and the underlying dolomites of Surmeh Formation.

The upper boundary of the carbonates of the Fahliyan Formation with the overlying shales and carbonates of Gadvan Formation of Barremian/Aptian age is unconformable over the greater portion of northern Persian Gulf and also possibly in Bandar Abbas area (Shakib, 1994). Siltstones, sandstones and glauconite are usually found at the boundary in this area, indicating a period of regression of the sea, emergence and erosion which was followed by a general transgression producing shale and limestone of the Gadvan Formation. A relative fall in sea level during the Aptian is indicated by deposition of shallow water carbonate of Dariyan Formation.

Mina et al. (1967) listed the diagnostic fossils of the Fahliyan Formation as *Pseuocyclammina lituus* (Yokoyama, 1980 cited in Shakib, 1994), *Nautiloculina oolithica, Lithocodium aggregatum* Elliot, 1956 and *Trocholina* spp. In Qatar, Sugden and Standring (1975) reported the following fossils from the Ratawi Formation of the Qatar: *Choffatella decipiens* Schlumberger, 1904; *Lituola sp.*; *Trochlina* sp., *Cyclammina greigi* Henson, 1948 and *Cardita* cf. C. *Neocomiensis* d'Orbigny, 1840. These are similar to those recorded from Fahliyan Formation.

Sampo (1969) have suggested that the Fahliyan Formation is of Berriasian-Hauterivian age. However, the results of the detailed micropaleontological investigation by Shakib (1983) showed that the Jurassic-Cretaceous boundary almost coincides with the Upper part of Member One of the Fahliyan Formation. Thus, the Fahliyan which is assigned the uppermost Jurassic-Cretaceous; (Tithonian to Hauterivian) is mainly massive oolitic or pelletal limestone resting disconformably upon Jurassic strata.

In the northwestern portion of Persian Gulf the Lower Ratawi consists of euxinic to neritic sediments. The Lower Ratawi deep water argillaceous limestones and marls, and typical euxinic deposits with abundant radiolaria were formed during Early Cretaceous times. In the remaining portion of the present

Persian Gulf which includes the coastal Arabia, the shallow water carbonates of Sulaiy, Yamama and *Valvulinella* Zone were deposited during the Early Cretaceous time. The Yamama Sulaiy Formations underlie the *Valvulinella* Zone (Mina et al., 1967; Power, 1968).

Towards the end of the Fahliyan deposition, the sub-basin covering the northwestern corner of the present Persian Gulf lost its unique euxinic nature. From here on, the changes in the sedimentary facies take place along lines almost parallel with the axis of the present Persian Gulf. In general, the facies grade from continental, littoral in coastal Arabia to shallow marine-lagoonal-neritic towards the Iranian mainland (Mina et al., 1967).

Garau Formation

In Lurestan and northwest Khuzestan, Lower Cretaceous is made up of black radiolaria-bearing shales and deep-water argillaceous carbonates of the Garau Formation. This unit rests unconformably either on the evaporites of the Gotnia or on the limestone solution breccias exposed in the northeastern part of the area. The deeper water facies was most extensive at the beginning of Cretaceous time, covering the region however, the basin retreated gradually northward and as a consequence, interfinguring could be observed at various levels between this unit, and the shallow water carbonates of southeastern area.

Garau Formation of Neocomian to upper Turonian age consists of radiolaria and ammonoid-bearing shale and argillaceous (locally pyritic) micritic limestone and marl that are sandy and glauconitic near top; deposited on deeper parts of a continental shelf as the lateral equivalent of Gadvan, Kazhdumi, Dariyan, and Sarvak Formations; probably a significant source rock for oil. Garau Formation is also characterized by narrow radiolarian-rich sea-ways that cut the emerged Zagros platform area.

At the Jurassic-Cretaceous boundary certain genera and species become extinct which are indicators of Upper Jurassic age. In the strata just above this boundary certain species appear for the first time, for example *Nautioloculina oolithica* Mohler 1938, *Cuneolina hensoni*, Dalbiez, 1953 and *Pseudochrysalidina Arabica* Henson 1948.

Garau facies extends into northeast Dezful, towards Gachsaran. During Late Neocomian to Early Aptian time its extension embraced northern Fars. Here it is known as the Gadvan Formation and is only locally organic rich. Garau Formation was deposited locally in northwest and also between center and eastern region of Persian Gulf. Thickness of Garau Formation increases toward northwest of the Persian Gulf.

Eight lithological units of deep-marine origin have been recognized by Setudehnia (1972) for the Garau Formation. These unites consist of black shales and thin-bedded limestones. The Garau is overlain by the beds of the Albian-Turonian Sarvak Formation, but there is diachronous relationship, be-

cause in the deeper part of the basin, the lower part of the Sarvak Formation is a lithofacies equivalent to the top of the Garau. Where the boundary between the two is seen on the shelf, the presence of a sandy, glauconitic interval suggests the presence of an unconformity.

Gadvan Formation

Gadvan Formation of Lower Cretaceous (upper Barremian to lower Aptian) age consists of marl and shale, and associated pelecypod-bearing argillaceous limestone, resting gradationally on Fahliyan Formation. Gadvan Formation in southern Iran is 218 meters thick. It consists of shallow marine to neritic marls made up of massive, crystalline, occasionally chalky limestones (James and Wynd, 1965). The contact is characterized by a zone of abundance of iron oxide nodules. In comparison to the underlying formation there is a high percentage of clay. The formation is light grey to whitish yellow, while the strata are thin to medium bedded. The formation is not well exposed because of coverage by slum blocks and scree material from overlying Dariyan Formation. Megafossils found include: *Spondylus* spp.; *Exogyra* spp.; corals in the lower most beds and small bivalves and echinoids in the upper beds.

The Gadvan Formation forms a low relief unit below the Dariyan Formation in the Khami Group. In the northern Persian Gulf region, the Gadvan Formation consists of argillaceous limestones. From Khuzestan towards Lurestan, the formation grades into limestones of the Garau Formation.

In coastal Persian Gulf of Iran the formation is characterized by shallow marine to neritic marls, shales, and argillaceous sediments. Equivalent to the Gadvan in the southern Persian Gulf (i.e., Saudi Arabia and Qatar) are the Kharaib-Hawar, and Buwaid-Biyadh Formations. In the Neutral Zone, Kuwait and SE Iraq, the Upper Ratawi and Zubair Formations are the time equivalent of Gadvan. They consist mainly of deltaic sands and subordinate shales. The Upper Ratawi, underlying the Zubair, is more shaly and calcareous, with occasional marls. In the Arabian coast of the Persian Gulf and Qatar northward to an area including the Salman oil Field, the Upper Ratawi-Zubair facies are in general more calcareous than the area to the west (Mina et al., 1967).

From the Strait of Hormoz towards the Sirri and Farur Islands to the west and in well HD-1, HEE-1, SIF-1, SIE-2, and FRB-1 the sedimentary sequence of Gadvan Formation consists of alternation of micritic limestone and argillaceous limestones. However, further west and toward the Pars Gas field the lithology of the Formation has more resemblance to the type section. The maximum thickness of the Gadvan Formation is measured in well HD-1 in the Strait of Hormoz which is 90 meters, whereas in the rest of the well the Gadvan thickness vary from 40 to 66 meters and the variations do not follow any particular trend.

According to the acquired data from the wells, in the Persian Gulf both the lower boundary with Fahliyan and the upper contact with Dariyan Formations

are gradational. In Bahregansar area in the Persian Gulf, the limestone of Upper Fahliyan Formation is extremely argillaceous and their identification and separation from Gadvan Formation become very difficult. The microfossiles reported are present in both formations and do not play any significant role in formation identification. However, the presence of the Khalij Formation is instrumental in the identification of the Gadvan Formation in the Persian Gulf (Motiei, 1993).

The Early Cretaceous rimmed carbonate platform sediments of Garau, Fahliyan, and Gadvan Formations, were regionally deposited and evolved in a mixed carbonate-siliciclastic ramp system. The dominant controlling factor on the sedimentation pattern was the tectonic control, which defined changing mosaic of subsiding domains and paleohighs. (Van Buchem et al., 2002).

Towards the southern and southwestern Persian Gulf, the shales and limestones of the Gadvan Formation pass laterally into the sandstones of Zubair Formation indicative of general shallowing upward of the basin. Thus, the Gadvan shale and shaly limestone is considered to be the equivalent of the Zubair sandstone reservoir and Kharaib/Hawar formation.

Kharaib Formation with its Hawar limestone member is corresponding to shelf sediments in which repeated sequences are spread over a large area. This transgressive-regressive sequence is made up of restricted marine sediments overlain by a sequence of open marine shelf deposits. Kharaib consists of a series of upward-shallowing cyclic units. It was deposited in a vast, shallow, epicontinental shelf commencing with a regressive phase of cycles and characterized by predominantly regressive sediments. The basal transgressive parts of the cycles are characterized by argillaceous lime mudstones, wackestones with subordinate peloidal packstones, which represent normal open marine shelf conditions (Alsharhan and Sadd, 2000). The succeeding regressive parts of the cycles begin with a mud-supported limestones deposited as inner-shelf or deep lagoon facies, which shallows upward into grain-supported limestones representing higher energy conditions.

In northwestern Persian Gulf regions the Gadvan Formation is represented by Ratawi Formation and partially replaced by sandstones of the Zubair and Biyadh Formations (see Motiei, 2003 p. 194). It is of importance to point out that in the northwestern Persian Gulf the Gadvan Formation attains its greatest thickness. To the southwest in Saudi Arabia, Gadvan basinal shale is represented by Biyadh Formation (James and Wynd, 1965).

The Zubair Formation covers most of the Mesopotamian Basin and is considered identical in both age and lithologic variation to the Biyadh Formation of Saudi Arabia (Power et al., 1966; Buday, 1980). The "*Dictyoconus Arabicus* limestone" is a significant feature in the Zubair Formation. This shallow water chalky limestone unit extends throughout most of the Persian Gulf area (Mina et al., 1967). The formation shows wide vertical and horizontal variations. The Zubair Formation may have been deposited on a fluvial-deltaic complex a marine influence in some parts of the basin is indicated by the

presence of thick shale units and the regional distribution of sandstone bodies of relatively regular thickness (Sadooni and Aqrawi, 2000).

In the northern coastal Persian Gulf, James and Wynd (1965) pointed out that the Minagish and Makhul Formation of Kuwait and southeastern Iraq might also have fingered out into the shales of the Gadvan Formation towards the northeast. However, Gollesstaneh (1965) considered the Makhul Formation as a part of the *Globochaete alpina/Saccocoma* Zone of Lower Tithonian age.

Khalij Member

In the middle part of the Gadvan Formation there is a distinct limestone unit which was called the "Brown Blocky Bed" (cited in Motiei, 2003). This unit was later identified by Wells (1965) in electric logs in the drilled well in Kharg Island well No#1 which was termed the "Khalij Member". The Khalij member has been identified in many drilling wells in the Persian Gulf including Nowrooz, Kharg, Lavan, and IMINCO and makes the identification of the Gadvan Formation possible.

In all the wells with Gadvan Formation present, the Khalij member becomes more distinct and simply identifiable with a thickness which varies from 12 to 25 meters. However, in 0-4 BIS the thickness of Khalij member is about 7 meters and the porosity is also diminished. In the Tabnak field the Khalij member is up to 12 meters.

The Khalij member consists of shallow water open marine limestones, lacking any clay mineral or argillaceous material, containing *Dictyoconus arabicus HENSON* which is also found in Daryian Formation. Javadian (1996) indicated that this fossil is observed in both formations.

The important point to notice is that despite of sedimentary conditions prior to the deposition of the Khalij member, at the time of deposition of this member, stable conditions prevailed throughout the basin.

Dariyan Formation

The early Aptian sea level rise brought about the deposition of widespread, shallow water limestone known as the Dariyan Formation in southern Iran and the entire Persian Gulf. Dariyan Formation of the Lower Cretaceous (i.e., upper Aptian) consists of regularly thick-bedded to massive and locally cherty orbitolina-bearing limestone. Dariyan Formation is present almost throughout the Persian Gulf region (see Figure 3-35). In most of the drilled wells in the Persian Gulf Dariyan Formation is present and its thickness varies from 88 meters in 0-4 BIS to 146 meters in U-1 well. The thickness variation appears to be local with no particular trend. However, the thickness of the Dariyan Formation increases from the Qatar-Gavbandi High (i.e., adjacent to the Gol-

shan oil Field) towards the northern most part of the Persian Gulf and also toward the present northern coasts of the Persian Gulf.

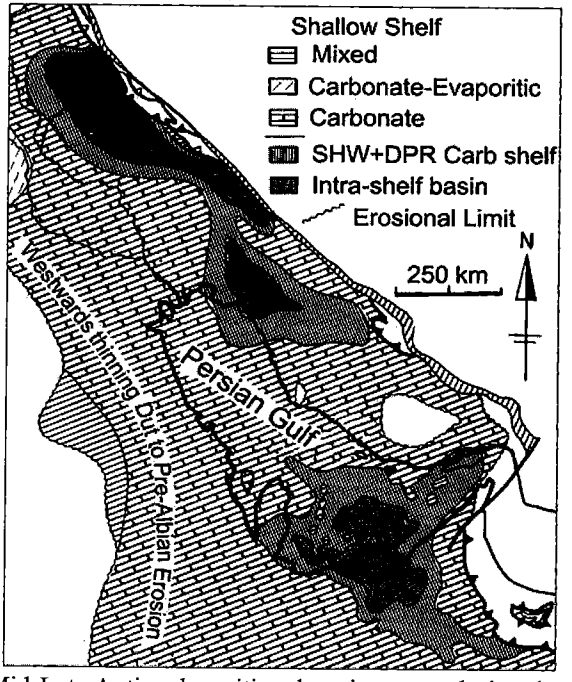

Figure 3-35. Mid-Late Aptian depositional environment during the deposition of Dariyan in Persian Gulf and surrounding region (after Murris, 1980).

The contact with overlying Kazhdumi Formation is sharp and sometime corresponds to an unconformity. The Dariyan Formation is characterized by the abundance of larger foraminiferal, especially *Orbitolina* spp, *Hensonella cylindrica* and *Choffatella* sp. which is typical of this formation. All the lithologic characteristics and litho and biofacies are identical to the type section of the Formation in Kuh-e-Dariyan northeast of Shiraz. The age of the Dariyan Formation can be constrained by *orbitolinidea* and *formminifera*. The recognition of *Orbitolina (Mesorbitolina) texana* and *Orbitolina (Mesobitolina) parva* suggests continued sedimentation into the late Aptian.

The Dariyan Formation is the uppermost member of the Khami Group. It is generally a feature-forming limestone unit, present throughout most of the southwestern Iran and the Persian Gulf, except for central and southwestern Lurestan, where it is replaced by the deep water shales of the Garau Formation. In northern and coastal Persian Gulf, evidence of a disconformity is generally found at the top of the Dariyan Formation.

An unconformity separates the Dariyan Formation from organic-rich shales of the overlying Kazhdumi Formation. At the contact, a surface of strongly iron-stained, sandy and glauconitic sediments is found. From the coastal Persian Gulf in Fars towards the interior Fars to the northeast, the top

of the formation is diachronous and the disconformity disappears (Setudehnia, 1971).

As mentioned earlier during the Mesozoic, the Persian Gulf was located at the NE edge of the Arabian plate and extensive carbonate platforms covered the area. Carbonate deposition was frequently interrupted by subaerial exposure and the influx of siliciclastics attributed to tectonic movements of the Arabian Shield and eustatic sea-level fluctuations (Sharland et al., 2001).

In general, shallowing of the sea during the Aptian is indicated by deposition of a sheet of shallow water limestones (i.e., Dariyan Formation and its extension Shuaiba Formation). At this time purely carbonates are restricted to the SW Iran and eastern Iraq in the Persian Gulf region. Available geological reports gave no direct information about the facies or depositional setting of the Dariyan limestone in the Resalat and Reshadat fields in the Iranian part of the Persian Gulf. However, based on well data obtained by Nassery (2002) and Moradi (2002), Daryian carbonate sediments were emerged during Aptian time in the northern part of the Persian Gulf with iron-stained ooids identified in the wells, probably related to this subarial exposure.

In the southern Persian Gulf, Dariyan Formation has been correlated with the Shuaiba Formation. However, in northern Persian Gulf, to a great extent the Kazhdumi Formation is also considered as an equivalent of the Dariyan Formation. In fact according to Moradi (2002) the shale content of the Dariyan Formation increases from the Iran's maritime border with Saudi Arabia in the Persian Gulf towards the coastal region of the northern Persian Gulf.

Dariyan was deposited on a laterally extensive, shallow-marine carbonate platform which consisted mainly of mud-supported and some grain-supported limestones with rudist debris (Farzadi, 2006). The overall regional setting during deposition of the Dariyan Formation was a shelf to shallow-basin complex, resulting in progradational mounds. A lowstand or shelf margin wedge of the equivalent Shuaiba platform (Bab Sand Member) is observed in the UAE (Farzadi, 2006) but is probably thinly developed in the SE Persian Gulf. An offshore development of calcareous shales with rudist debris occurs in this area and corresponds to the lower Dariyan Formation. The deposition of the Dariyan Formation corresponds to a 3rd order sea-level highstand (Sharland et al., 2001).

Banner and Wood (1964) and Dunnington (1967) described several foraminifera from Shuaiba Formation in the region which are similar to those from the Dariyan Formation of coastal Persian Gulf in Fars (e.g., *Marssonella sp., Orbitolina sp.* and *Hedbergella sp.*). Thus, the Dariyan Formation is extended to the entire Persian Gulf region. Simmons and Hart (1987) using foraminifera and algal assemblages, suggested an Early Aptian age for the Shuaiba Formation of the Oman Mountains, with an unconformity separating it from the overlying Nahr Umr Formation.

The Dariyan Formation was deposited over an extensive stable platform during a period of relative tectonic quiescence. The Persian Gulf region at that

time was located at approximately 8°S of the equator and the Aptian paleogeography was similar to that of the Albian. Rudists preferentially colonized the rim of the basin (Grabowski and Norton, 1995).

Based on petrographic investigation of the Dariyan Formation in numerous wells in the Iranian waters of the Persian Gulf, eight different microfacies has been identified. Vertical succession of the facies in the Persian Gulf drilled wells indicate a shallowing upward cycles whereas lateral distribution points out to a shallow ramp (Nassery, 2002; Moradi, 2002).

These microfacies belong to different belts in a ramp platform setting including inner, middle and outer facies zones. Most of the microfacies belong to the inner to middle ramp facies zones with maximum lateral geographic distribution whereas the outer ramp facies have extremely limited distribution. The studies indicate a shallow ramp platform environment for the Dariyan Formation (Nassery, 2002; Moradi, 2002).

In general the Dariyan Formation in the east and western parts of the present day Persian Gulf was deposited on a shallow water carbonate ramp environment with consisted of outer, middle and inner ramp environments (Nassery, 2002; Moradi, 2002). Distribution of the inner ramp facies are mainly in the Strait of Hormoz area whereas the middle ramp facies are observed in the Qatar-Gavbandi High region and the outer ramp facies are in further to the west and mainly observed in well FR-B1 in the Iranian waters of the Persian Gulf.

LOWER CRETACEOUS IN SOUTHERN PERSIAN GULF

Following the deposition of regressive Hith anhydrite, a marine transgression occurred that resulted in flooding of the most of the Persian Gulf area. The Qatar-Gavbandi Arch, which remained as a positive feature, appears to affect sedimentation throughout the Early Cretaceous (i.e., Thamama Group deposition) with sedimentation generally increasing in thickness in all direction away form it. The Thamama Group is characteristically represented by its limestones, which is clearly distinguishes it from both the underlying Hith and the overlying Barremian and younger Biyadh sandstones.

Early Cretaceous Thamama Group (Berriasian to Aptian), approximately 600 meters thick, deposited over a time period of about 30 million years, during a cycle of extensive flooding and extensive marine incursion as cycles of porous grainstones and tight wackestones and packstones. It is overlain unconformably by the Middle Cretaceous Nahr Umr shale and underlain by the Upper Jurassic Asab Formation. The succession was deposited over an extensive carbonate ramp platform.

The carbonates of the Thamama Group were laid down on a shallow marine platform which dipped gently to the east. The platform formed a carbonate ramp overlying the Upper Jurassic evaporites in most parts of eastern Arabia, except for shallow water oolitic limestones in eastern Abu Dhabi (Murris,

1980). The succession was deposited upon an eastward-dipping ramp which is a typical homoclinal ramp.

The upper part of the Thamama Group consist of thick sands of the Zubair Formation of Barremain to Early Aptian age (Gharib, 1979) and is an important oil producing horizon in the Raudhatain Field and in southern Iraq. The Zubair Formation with a thickness of about 420 meters consists of sands and sandstones intercalated with siltstones, shales, and few thin limestone beds (Al-Rawi, 1981). Zubair clastics are overlain with apparent conformity by about 80 meters of carbonates with well developed secondary porosity of the Shuaiba Formation.

The Habshan Formation formed during the initial Cretaceous flooding of the stable cratonal platform and embodies the proradational and subsequent filling of the old Middle to Late Jurassic cratonal marine depression.

DIVISION OF THE EARLY CRETACEOUS

The most obvious division of the Early Cretaceous is that it is composed of three carbonate cycles;

The first cycle appears to be separated from the second cycle by a local, Early Hauterivian unconformity at the top of the Yamama Formation in Central Arabia. The early stages of the first cycle represent the initial phase of the carbonate ramp where grainstone appears updip and pass into pelagic mudstones downdip towards southeastern Abu Dhabi and Oman (Rayada Formation).

The second cycle of the Early Cretaceous formed during the increase and subsequent decrease in water depth over the shelf. The Hauterivian whose depositional conditions extended into Early Barremian time, marked an early phase of the second carbonate cycle. It has a vast carbonate ramp sloping from the Arabian Shield to the east towards Oman, with the persistent deposition of broad, shallow intraplatform carbonates and intermediate to deep water carbonates near the present thrust zones of Oman and Zagros. The second cycle is distinguished from the first by the invasion of a clastic wedge from the west and northwest (Biyadh Formation). At their maximum extent, the clastics spread into Qatar where they are represented by the basal Ratawi Shale.

The end of the cycle brought clastic sediments from the shield (but neither the significant influx of clastics nor evidence of exposure is present further east on the carbonate shelf (Power et al., 1966). The Gotnia Basin persists, although it is now receiving clastic sediments, presumably from a source to the northwest. Close to the Shield alluvial and coastal plain sediments were deposited. This was a period of low stand sea level with minor subcycles and a later moderate rise of the sea (Haq et al., 1988). Sediments were deposited in shallow-marine shelf and intrashelf settings on the plate passive margin with Neo-Tethys, and were influenced by the strong clastic sediment supply.

Towards the end of the second cycle, shallow water carbonate setting was generally re-established over most of the area. In the Southern Persian Gulf intrashelf basin was the site of the deposition of deeper-water argillaceous limestones with shaly partings. The shelf break bordering this basin was the site of the development of rudist and algal mound (Alsharhan and Nairn, 1997). In the southern Persian Gulf area Lower Cretaceous carbonate sequence was terminated by the Middle Aptian, Thamama-Wasia unconformity.

The third cycle of the Lower Cretaceous sequence is the most interesting because it contains reservoir-bearing carbonates. The cycle, beginning in the early Barremian and ending in the early middle Aptian, is capped by a significant regional unconformity.

The Early Cretaceous terminated with an extremely widespread Aptian carbonate transgression, which blanketed most of the earlier deposits. In the southern Persian Gulf area local intrashelf basins were flanked by rudistid reefs that form the Shuaiba limestones.

APTIAN IN SOUTHERN PERSIAN GULF

Early Cretaceous (Aptian) was a period of renewed basin-wide inundation, and a shallow carbonate shelf sediments spread westward over the previously deposited clastic rocks. It has been suggested that during the Aptian, in the southern part of the Persian Gulf (i.e., UAE), an intrashelf basin has developed and fringing shelf-margin rudist buildups grew where conditions were favorable, creating the prolific Shuaiba reservoirs (Murris, 1980).

In the southern Persian Gulf Aptian commenced with Shuiaba Formation which consists entirely of carbonates that mostly accumulated as rudist-rimmed, shallow marine platform. It has an average thickness of about 130 meters (Hughes, 1998). In the subsurface of Saudi Arabia, the formation consists of massive, commonly porous and vuggy dolostone with occasional limestone with some levels containing orbitolinoids. The thickness ranges from 25 to 100 meters (Sheble and Asharhan, 2000).

The Shuaiba Formation was deposited during a shallow-marine transgression during the Middle to Early Cretaceous on a vast shelf covering the eastern Arabian Peninsula. It is conformably underlain by the dense Hawar limestones of the Kharaib Formation and disconformably overlain by the Nahr Umr Formation shales. Its upper boundary is marked upward by an abrupt increase in the gamma-ray readings and decrease in density readings. This signals the termination of the Lower Cretaceous major sedimentary cycle, and the beginning of a new major sedimentary cycle. The formation is the uppermost portion of the Lower Cretaceous Thamama Group, deposited during an extensive marine inundation, and was marked by a series of thick rudist grainstone buildups.

As mentioned before Dariyan and its equivalent the Shuaiba is composed of thick, porous shelf carbonates which show considerable lateral and vertical

lithofacies change over much of the Persian Gulf. They were deposited during an extensive Tethyan transgression on the northeastern part of the Arabian Shield. The deposition took place in various environments, ranging from shallow shelf to intrashelf starved basinal facies, influenced by paleogeogaphy and sea level changes, represented by deep-water shelf sediments and shallow-water rudist carbonates.

The Shuaiba Formation as a full cycle of carbonate sedimentation consists of two informal members (Hughes-Clarke, 1988): a lower member dominated by algal-laminates (*lithocodium*) and Bacinella structures and an upper member, rich in rudists. The top of the Shuaiba Formation corresponds to a major stratigraphic unconformity, that is, an early exposure surface, overlain by the Nahr Umr Formation, either Albian (Simmons and Hart, 1987; Scott, 1990) or upper Aptian (Immenhauser et al., 1999).

The lowest paleoenvironmental layer (i.e., Lower Shuaiba) represents a widespread, low relief, moderately deep carbonate shelf with a laterally extensive, uniform biocomponent characterized by the absence of rudists. It contains a distinctive basal succession informally equated with the Biyadh Formation, and characterized by orbitolinoid-dominated beds that alternate with beds containing the algae *Lithocodium aggregatum* (Hughs, 1999). Rudist colonies become established in the Middle Shuaiba, possibly on the rims of fault-controlled blocks that caused the differentiation of the platform into lagoonal, rudist-bank and offshore marine provinces.

The Upper Shuaiba contains a characteristic macro and microfaunal lagoon assemblage. The lagoon has a minor rudist-bank rim that is narrower than that of the middle Shuaiba. Many cores from the upper Shuaiba show evidence of karstic feature (with pyritic mud infill in the northern part of the field), and provide support for an episode of emergence and dissolution prior to the deposition of the overlying Nahr Umr Formation. On top of the Shuaiba Formation there is a major karst surface, in which meteoric diagenesis has selectively altered portions of reservoir. Thus, the interplay of stratigraphic architectural elements and diagenesis controls reservoir quality in the Shuaiba. The Shuaiba is terminated in the southern part of the Persian Gulf by a shale seal of the Nahr Umr, the lower formation in the Wasia Group of the Middle Cretaceous. Thus, deposition of the "Middle" Cretaceous Wasia Group began with the sheet-like neritic deposits of the transgressive Nahr Umr Formation, which consists of a sequence of variegated shales with some lenses of limestones and sandstone.

Recent efforts have provided new insight into stratigraphic architecture and depositional framework of the Shuaiba reservoir particularly in Saudi Arabia. Within this reservoir interval, three major early Aptian sequences and one late Aptian sequence have been identified which record changes in water depth and depositional energy from a shallow-marine platform interior and shelf margin environment to deeper marine offshore setting (Cantrell et al., 2004).

The lower Shuaiba sequence shows the development of an intra-shelf basin during overall sea-level rise, with the contemporaneous accumulation of basinal source rocks (minor clay) and backstepping microbial platform deposits. During sea-level high stands, rudists accumulated and progradation occurred. The organic-rich basinal facies of Lower Shuaiba consists of a series of argillaceous dense layers in the Lower Thamama Group. In general the formation is interpreted to represent deposition during one major eustatic rise (Kendall et al., 2000), forming as a prograding carbonate shelf around the interior-shelf Bab Basin in central onshore offshore Abu Dhabi and at the outer shelf margin in the eastern Emirates, and was dominated by rudists (Skelton and Masse, 2000) and calcareous algae. Rudists have also contributed significantly to the paleontological interpretation of the Shuaiba and to its reservoir quality. According to published literature, regionally the reefs are distributed along a sub circular trend in eastern Arabia and the eastern Persian Gulf and are bordered basin ward by a belt of forereef sediments (Hughs, 1999).

Taking into consideration the benthonic foraminifera and calcareous algae, the Shuaiba Formation closely resembles the underlying middle and upper Kharaib Formation. Nevertheless, the genus *Praeorbitolina* is restricted to the Shuaiba Formation, whereas *Palorbitolina* ranges throughout this formation and the Kharaib, the latter being characterized by *Dictyoconus arabicus* Henson (Simmons, 1994; Witt and Gokdag, 1994). The rudists, especially the *caprinids*, allow the two formations to be distinguished. *Offneria rhodanica Paquier* characterizes the Kharaib Formation, whereas *O. italica Masse* and *O. arabica Chartrousse* and *Masse* are typical for the Shuaiba Formation (Chartrousse and Masse, 1998; Masse et al., 1998b). In addition the *genus Agriopleura* appears to be limited to the Shuaiba Formation (Hughes, 2000; Skelton and Masse, 2000). This stratigraphic analysis confirms that the Shuaiba Formation is a lithostratigraphic unit, comprised between the Hawar Member of the Kharaib Formation and the base Nahr Umr unconformity, with a specific biostratigraphic assemblage that is diagnostic of the early Aptian.

Sulaiy Formation

The Upper Jurassic-Lower Cretaceous (=Tithonian-Berriasian) Sulaiy Formation is mainly composed of highly bituminous, pyrite-rich carbonates. The carbonates alternate with massive and laminated mudstones that contain sponge spicules and foraminiferas in the northern part of Kuwait.

The Sulaiy Formation is about 165 to 180 meters thick and consists of massively bedded bioclastic wackestone to packstones with interbedded thin layers of mudstones and recrystalized Coquina and oolitic grainstones mostly at its base (Alsharhan and Narin, 1997). According to Al-Sakini (1992), the Sulaiy Formation is a possible source rock in the major Cretaceous reservoirs of the southern Persian Gulf region.

The contact between the Upper Jurassic Hith anhydrite and brecciated limestone of the Sulaiy is disconformable (Steinke et al., 1958). Powers et al (1966) considered the boundary to be conformable and the brecciation to be the result of subsurface solution collapse rather than subarial exposure. The Upper boundary is placed where the detrital limestone of the Yamama Formation overlies the dense massive limestone of the Upper most Sulaiy Formation. Water depth decreased late in the early Valanginian due to a eustatic drop or tectonic uplift and the sediments of the Yamama Formation reflect this change as they are shallow-shelf limestones that progrades eastward across the area as a bank marine carbonate shoal.

Power (1968) listed the following fossils in the Sulaiy Formation; *Bramkampella arabia, Redmond, Nautiloculina* sp., *Pseudoccyclammina Sulaiyana Redmond., Trocholina* Spp., *Everticyclammina* Sp., *Anchispirocyclina Lusitanica Egger; Nerinea* sp. aff. *N. blancheti Pictetandcampiche, Nerinea* sp., *Apoorrhais* sp., and miscellaneous *cidaroid radioles.*

Yamama Formation

The Yamama Formation, about 25 to 45 meters thick is composed mainly of bioclastic carbonates. It rests conformably on the Sulaiy Formation and forms the major Lower Cretaceous carbonate reservoir in southern Iraq.

The Sulaiy-Yamama Formations were deposited as broad, shallow-marine carbonates. An outer-platform edge the northeast is characterized by stacked grainstone deposits whereas, in the inner platform, muddy sediments were deposited in a low-energy, shallow subtidal, and often stagnant, brackish environment. Increased subsidence rates on the inner-platform are indicated by a thickening of the sediment column compared to the platform edge.

Later in the Early Cretaceous, an advancing sea pushed clastic sources westward toward western Arabia, and a differentiated carbonate shelf replaced the ramp. In extreme eastern Arabia during Early Cretaceous, the Oman foredeep trough was a deep shelf carbonate environment (Harris et al., 1984). In the southern part of the Persian Gulf, an intrashelf basin developed on the differentiated carbonate shelf during middle Aptian time. Around the margin of this basin, rudist reefs developed (the subsequent Shuaiba reservoir facies). During the Albian regression, a siliciclastic regime advanced across almost the entire Arabian platform only to be replaced in latest Albian by shallow shelf carbonates as carbonate shelf conditions were re-established.

Cyclic sedimentation of the Thamama Group shallow-shelf carbonates followed. By mid-Early Cretaceous (Barremian) time, a clastic regime occupied the western half of the basin pushing the carbonate ramp environment to the east (Murris, 1980).

In the southern parts of the Persian Gulf region, Berriasian-Hauterivian age follow the Valanginian concordantly. They consist of limestones with *radiolaria* and *Nannoconus*, a facies which persists in the Barremain to the tip of

Oman (Jabal Habhab). The Aptian, over the entire Persian Gulf region, is represented by massive orbitolinid limestones.

The lower part of the Early Cretaceous in the southwestern and the head of the Persian Gulf comprises up to 460 meters of neritic limestone overlain by approximately 150 meters of black shale. The sequence contains stringers of limestone in its lower part and of sandstone in its upper part. These sections have traditionally been referred to as the Ratawi Limestone and the Ratawi shale, sometimes as separate formations, sometimes as members of a multimember Ratawi Formation. The Ratawi *sensu lato* is of early Cretaceous age and forms the lower part of the Thamama Group. The Ratawi limestone-shale section is overlain by the clastics of the Zubair Formation.

The Ratawi Formation was first introduced by Nasr (1958 cited in Owen and Nasr, 1958). Owen and Nasr (1958) described the formation in southern Iraq, where it consists of marine, pyritic, shales interbedded with pseudooolitic, detrital, pyritic limestones. The main fossils are *pseudochrysalinids*, *cyclamminids*, *trocholinids*, and oyster. The age of the formation was considered to be Neocomian, but Bellen et al. (1959) and Buday (1980) suggested a Hauterivian-Valanginian age. The Ratawi Formation represents the beginning of the clastic front that culminated during deposition of the Zubair Formation.

Facies and Depositional Setting during Early Cretaceous

The Late Early Cretaceous (Aptian-Albian) period spanned the deposition of Kazhdumi Formation and their regional equivalents Burgan Formation (northwestern Persian Gulf). A marked late-Aptian regional unconformity and sedimentary hiatus separates rocks of Aptian age from those of Albian age. Late Aptian regression in the Persian Gulf caused a sedimentary gap after the deposition of Dariyan carbonates. This break probably coincided with a worldwide lowstand in sea level (Haq et al., 1988) and was followed by a gradually rising sea level that culminated in maximum flooding by the end of Albian.

Lower Cretaceous platform limestones in the Persian Gulf area accumulated in one of the great epeiric seas (Murris, 1980) that bordered the Neo-Tethys (Fourcade et al., 1991). Facies deposited at the passive margin of the Arabian platform and in the adjacent basin are now exposed in uplifts, nappes and imbricate thrust sheets generated by Late Cretaceous collisions (for review see Robertson and Searle, 1990).

Significant deltaic systems prograded northeasterly from the Arabian Shield toward the Persian Gulf, and formed the Lower Cretaceous (Barremian-Aptian) Zubair Formation and the Middle Cretaceous (Albian) Burgan and Kazhdumi Formations. Three major sand wedges were emplaced during the middle-late Barremain (Zubair Sands), mid Albain (Azadegan sandstone or Nahr Umr-Burgan Sands).

An alluvial plain covered the northwestern Persian Gulf region (Powers, 1968). The more distal part of the basin, between the Burgan-Safaniya delta located on the western half of the Persian Gulf, and the shallow water carbonate shelf bordering the open sea was the locus for the deposition of the Kazhdumi Formation (Bordenov and Barwood, 1990). Tectonically the platform was relatively stable throughout the Triassic to the Middle Cretaceous interval.

SEDIMENTARY FACIES

Bacinella wackestones are associated with miliolid packstones and algal-laminates. The high contribution of microbial elements to which Bacinella is related, the low biodiversity, the absence of rudists and finally, the dominance of miliolid foraminifera are attributed to the strong restriction of the shallow-marine waters (Luperto Sinni and Masse, 1982). The paleogeographic setting of this facies group corresponds to a restricted inner shelf. Neither supratidal to intertidal facies nor evaporites are observed in the Dariyan and Shuaiba interval in the outcrop and the subsurface. Therefore it might be concluded that the Bacinella facies represents the most restricted facies preserved.

Rudist facies correspond to more open environments in the inner shelf zone. The rudist-rich sedimentary rocks might correspond to an intermediary facies belt situated between the so-called Bacinella facies and the outer shelf that is dominated by so-called caprinid facies. The rudist communities are typically associated with muddy sedimentary rocks that reflect low water energy.

Outer-shelf successions are represented by caprinid wackestone-grainstone and coarse bioclastic grainstone-rudstones. The location of caprinid communities in open-marine environments has been documented for many Early Cretaceous Tethyan carbonate platforms (Masse, 1976; Masse and Philip, 1981).

MIDDLE CRETACEOUS OF PERSIAN GULF

Throughout the Persian Gulf region, Middle Cretaceous sedimentary sequence is of primary importance in terms of carbonate petroleum system. During the Middle Cretaceous the Arabian Platform was subdivided into several paleodepositional belts.

A carbonate platform developed during the middle stages of the Cretaceous from the Hauterivian through the Cenomanian (see figure 3-36). During this 37 to 45 million years time interval at least twenty cycles of relative changes of coastal onlap were proposed by Haq et al. (1988). The eastern margin of the Arabian platform has been tectonically active and was subjected to intense deformation during Cretaceous and Tertiary. Dating these events depend upon dating the unconformities. However, separating the effects of tectonics from eustasy is difficult.

Several large restricted basins formed within the Middle Cretaceous in the Persian Gulf region (Murris, 1980). Where rimmed by carbonate platforms, these basins developed into self-contained hydrocarbon systems which are sealed regionally beneath the marly Laffan and its stratigraphic equivalents. It is largely in these areas covered by carbonates of the Middle Cretaceous where high potential for petroleum exploration exists. In the southern Persian Gulf, the largest such basin is the Shilaif Basin.

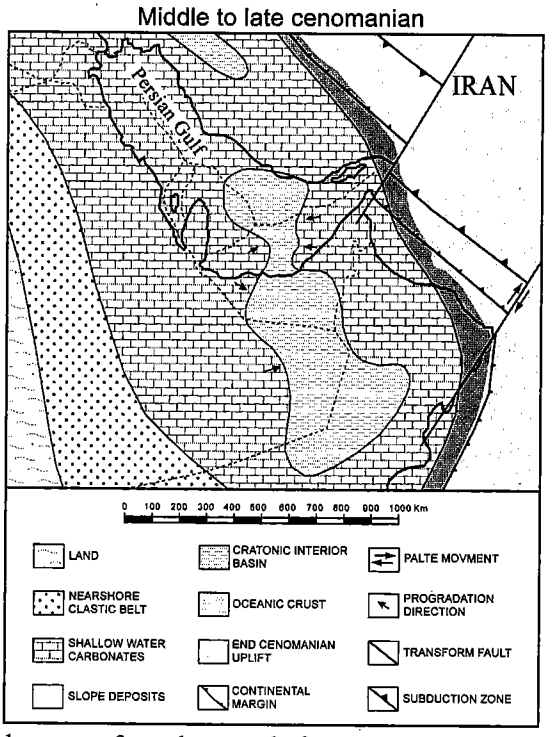

Figure 3-36. Development of a carbonate platform sequence in the Greater Persian Gulf region during the Middle to Late Cenomanian stages of Cretaceous (Modified after Murris, 1980; Harris at al., 1984 and Scott et al., 1988).

The regional distribution, facies, and stratigraphy of the Middle Cretaceous around the Persian Gulf have been discussed by Murris (1980), Harris et al. (1984), and Scott et al. (1988). In the Persian Gulf region, Middle Cretaceous sediments have been penetrated by numerous petroleum exploration and development wells.

Middle Cretaceous sedimentation in northern Persian Gulf commenced with a new transgression and sea level rise, which resulted in an extension of the shales and limestones of the Kazhdumi Formation during the Albian time. However, a widespread emergence is reported during Albian time, but was followed by Cenomanian sedimentary sequence (Power, 1968).

As mentioned previously and shown in figure 3- 33, three different regional unconformities were observed within the Middle Cretaceous successions. The lowermost is at the base of the interval in southern Fars and the Bandar Abbas area. The post-Cenomanian break is present everywhere except in Lurestan and the post-Turonain unconformity also is present throughout the area except in Lurestan.

Major salt diapirs and basement structures formed different highs in the Persian Gulf in Middle Cretaceous, causing modification of Middle Cretaceous facies distribution by localizing high energy grainstones and rudist reefs and generating local intraformational unconformities (Burchette and Britton, 1985; Videtich, et al., 1988).

The general features (thins in Fars and Lurestan with the intervening thick in the Shiraz/Khuzestan area) are still apparent on the isopach of the Middle Cretaceous. The uplifts during the Cenomanian-Turonian, however, also produced several NNE-SSW trends well evident in southeastern Khuzestan and the Persian Gulf. Some of these highs had persisted since the Triassic. Especially notable is the one in the coastal areas of Fars north of Qatar-Gavbandi Arch, where Middle Cretaceous sediments are totally absent.

Over the greater part of the northern Persian Gulf (i.e., Fars Platform and Zagros area), the Albian shales rest unconformably on top of the neritic limestones of the Daryian Formation. This unconformity causes some truncation of the Aptian carbonates with thinning of the Albian shales particularly in coastal Fars in northern Persian Gulf. At the contact, a weathered zone with glauconite, sand and ferruginous material is developed. The ferruginous crust and lateral equivalent (glauconitic or phosphatic surfaces recognized in other parts of the platform) are generally considered as typical of a transgressive episode occurring before a highstand sea level is being established.

The siltstone, sandstone and glauconite found at the upper part of the Fahliyan Formation, and the strongly iron-stained sandy and glauconitic sediments on top of the Dariyan Formation indicate a period of regression, emergence, and erosion at the end of Aptian time and an 'Aptian-Albian (105Ma) disconformity in the Fars area (James and Wynd, 1965; Setudehnia, 1978). A very widespread emergence is reported from Arabia during Albian, followed by the Cenomanian Wasia (sandstone-shale) Group (Powers, 1968).

Regional uplift at the end of Cenomanian caused erosion of carbonates including Sarvak Formation particularly over the Fars Platform and in the Bandar Abbas area, where only about 30 meters of the Albian-Lower Cenomanian carbonates are preserved. Evidence of this unconformity is found almost everywhere in Fars and Dezful Embayment, and in many wells in this later area. Conglomerate and breccia with ferruginous materials have been found associated with it (Setudehnia, 1978). Such horizons have also been reported in other areas in the Persian Gulf region. The ferruginous surface (phosphatized or ferruginous hardground in Jabal Akhdar; glauconitic level in Abu Dhabi;

Alsharhan, 1987; Rabu et al., 1990) may also delineate a flooding surface related to a rapid drowning of the platform.

The rapid drowning event may have been accompanied by the eastward tilting of the Arabian Platform. Tilting of the platform could explain the abrupt deepening recorded by the Azadegan sandstone and its equivalent Nahr Umr deposits and the influx of terrigeneous sediments that were eroded from the exposed western Arabian platform. Scott (1990) suggests that a sea-level rise provided the major influence; while Pratt and Smewing (1993) favor the dominance of platform tilt. It is important to mention that platform tilting was the dominant cause, the comparison of paleodepth curves of the eastern Arabian Platform, around the Aptian unconformity, should show significant dissimilarities.

Towards the Late Albian the influx of continental detritus ceased, and predominantly carbonate deposits formed the upper part of the Nahr Umr and overlying Natih Formation (Van Buchem et al., 1996). These authochthonous sediments were later buried by the Hawasina Complex and the Semail Ophiolite in the Campanian.

A general shallowing of the sea during latest Albian and Cenomanian time produced an interval of shallow water thick carbonates over the region. Sedimentation continued with the shallow marine carbonate of Sarvak Formation (late Albian to Turonian). In coastal areas of Fars and neighboring parts of the Persian Gulf, some shaley units are developed in the Cenomanian and may represent the northern extension of the Ahmadi shales of Saudi Arabia.

Fars and Dezful Embayment area subsided again during Turonian time but basinal depths remained shallow and shelf carbonates were deposited to form the upper part of the Sarvak Formation. Locally, some of paleohighs remained emerged during the Turonian causing non-deposition.

The late Turonian movements (88 Ma) reactivated many trends in southwestern Iran. These trends had existed since Permian and Triassic times (Setudehnia, 1978). At the end of the Turonian, uplift of the region caused truncation of the upper part of the Turonian carbonates and even locally the total interval. This regional unconformity is also well marked by ferruginous materials and a stratigraphic break.

The configuration of the Arabian platform changed irrevocably in the Early Santonian (85Ma). The northward-directed subduction zone within Neo-Tethys began to impinge upon promontories on the Arabian margin.

In central Lurestan, deeper water sedimentation continued from the Albian to the Turonian depositing shales and argillaceous limestones. In southern Lurestan, however, the Middle Cretaceous beds interdigitate with pelagic limestones containing *Oligostegina* while in time pass laterally southwards into the neritic carbonates of Khuzestan. No evidence of sedimentary gaps or truncation has been observed in these facies in Lurestan.

Thickness differences in excess of 700 meters are found in short distances between some of these highs and lows. Usually on the highs, Maastrichtian

(or locally even Tertiary) shales rest on Cenomanian limestones, whereas in the lows, the section contains more sediments of Turonian and Santonian/ Campanion age.

Deposition continued without any apparent break in Lurestan during Middle Cretaceous. However, the rate of sedimentation was probably lower in this area, producing thinner sediments of deeper water origin. The NW-SE trends of Lurestan and NW Khuzestan are still well evident, while the NE-SW trends continue to be more pronounced in Fars and SE Khuzestan.

Kazhdumi Formation

Albian stage occupies one of the most important places in the Mesozoic stratigraphy of the Persian Gulf with high frequency tectonic changes. A rapid sea level drop in early Albian initiated the deposition of Kazhdumi and Burgan over the Dariyan and Shuaiba carbonates. In the deeper part of the basin, where break in sedimentation is documented between the Dariyan carbonates and the Kazhdumi, deposition may have commenced in the Late Aptian.

The Arabian Shield became the source for the clastic sediments in the northern corner of the Persian Gulf including coastal Arabia, southeast Iraq, Kuwait and northwestward to the middle of the present Persian Gulf. From the Arabian Shield to the Iranian coast these clastics pass into the neritic marls and shales of the Kazhdumi Formation. In the Iranian offshore fields such as the Dorood Field, the formation consists of shale/marl and limestone formed predominantly in a neritic environment, although minor, thin sandstone beds may be present. In the Soroosh oil Field, the proportion of sand increases considerably and in this location 40 meters of sand facies occurs between a lower and an upper shale-limestone unit (Mina et al., 1967).

Kazhdumi consists of dark, bituminous, ammonoid-bearing limestone, interbedded with dark argillaceous limestone and calcareous shale, disconformably overlying Dariyan Formation. They also provide the seal for the underlying Dariyan carbonate reservoir in most of the fields. This formation is a significant source for hydrocarbons and its distal equivalents are the plant-bearing deltaic sandstone and shale.

The type section is located in the Tang-e-Gurguda, 10 km north of Gachsaran (Kent et al., 1951). The formation consists of 210 meters of dark, bituminous shale with subordinate, dark, argillaceous limestone. Glauconite is common oxidation zones in the lower half of the formation, especially in the lowest 91 meters, whilst the lowest 30 meters contain several reddish, oxidized ferruginous zones which may indicate a diastem (James and Wynd, 1965). At the type locality, the microfauna are mainly planktonic, but include conical *orbitolina* in the basal beds. A rich fauna of *Hedbergella, ticinella, Biglobigrinella*, and *Planomalina* spp., together with radiolarian and spicules is found.

The basal contact with the underlying Dariyan Formation is associated with a zone of rubification, suggesting either a shallowing or a possible diastem. The upper contact shows a gradational transition to the basal of the Sarvak Formation (James and Wynd, 1965; Stöcklin, 1972). The formation is present throughout the Fars region, but it passes into the black shale and limestone of the Garau Formation in central and southwestern Lurestan. Southwest of Khuzestan, the Kazhdumi Formation interfingers with the sandstone of Burgan and Azadegan Sand.

The Kazhdumi Formation is present throughout the Persian Gulf as a relatively thick dark bituminous shale and limestone of marine origin. They contain subordinate argillaceous limestone beds that have an open-marine basinal biota of planktonic foraminifera, radiolarians, and sponge spicules (James and Wynd, 1965). Dark organic-rich shales and argillaceous limestones of the Kazhdumi and Balambo Formations characterize the intrashelf basins of Iran and Iraq in the Persian Gulf region.

Thickness of this formation increases toward northwest and east of the Persian Gulf. In the three wells, HD-1, HEE-1 and HA-1, located in the Strait of Hormoz domain, the Kazhdumi attains thicknesses of 142, 110 and 134 meters respectively. Towards the west and in the Pars Fields, the thickness decreases from 78 meters in Sirri to 45 meters in 0-4 BIS. The total thickness of this formation is approximately 60 meters on the Resalat field and 65 meters on the Reshadat structure in the Iranian waters of the Persian Gulf. The thickness of the formation increases to the north and northeast. Such thicknesses are similar to what is reported for the Kazhdumi Formation in Fars where it reaches a maximum of 100 meters. Here, the formation consists mainly of marl deposited in shallow water oxic conditions, but low-energy environment and contain little organic matter (Bordenave, and Burwood, 1995, p.192).

Overlying the Kazhdumi Formation are skeletal carbonates and restricted lime mudstones of the Mauddud Formation followed in some areas by the organic rich deep marine limestones of the Khatiyah Formation.

The Kazhdumi sediments were deposited during a relative sea level rise, in low energy environments and act as a regional source of hydrocarbons mainly in the eastern part of the Persian Gulf and in southwestern Iran. The formation has been divided into five depositional units or members in the Persian Gulf region. These members in ascending order include Sandy-C, -B, -A, Dair limestone, and Upper Kazhdumi. The presence of significant amount of clay and silt in the sandy-C indicate the deposition in a calm environment. In addition, there is black shale layers associated with this unit. This Formation has been also shown two different facies which include pelagic and neritic facies (Motiei, 1993).

Deposition of the Kazhdumi Formation also occurred in the great and calm Dezful Embayment in anoxic environment. These shales deposited further than the limits of the deltaic sands on the Aptian surface. The presence of

ammonites (*Parahoplites*) and a *foraminiferal-oligosteginid* fauna indicate a deeper-marine depositional setting and connection with Neo-Tethys (Ziegler, 2001, p.437).

During the Albian a large mild depression was established over the Dezful Embayment and northern part of the Persian Gulf. The depression was limited to the southeast by the Fars Platform, where the deposition of shallow-water thin oxic marls was interrupted by temporary emergence.

To the north, it was restricted by the east-west Bala Rud carbonate shoal, which separated the Kazhdumi depression centered on the present day Dezful Embayment from the Lurestan depression. To the east, the depression was bordered by a sill, on which anoxic and oxic facies fluctuated according to sea level changes, however little information is available on a possible eastern extension.

Towards the southern parts of the Persian Gulf, the intrashelf basin extended into the lobate intracratonic Rub'Al-Khali Basin whose filling is of an open-marine, off-bank nature containing planktonic foraminifera and skeletal debris that fines away from the bank/fore-bank sediment source area.

Stratigraphically, the equivalents of the Kazhdumi Formation in south and southwestern Persian Gulf area are the Burgan and Azadegan sand member (=Nahr Umr sandstone). In south and southwestern Persian Gulf area, the post Dariyan succession is clastic dominated resulting from the influence of the "Burgan" delta. The Kazhdumi were deposited as prodelta/offshore in front of the Safaniya-Burgan delta lobe in the Persian Gulf area.

The basin-wide Aptian marine transgression was abruptly terminated by a major pre-Albian regression that resulted in some erosion and another major clastic regime the Burgan-Safaniya delta system, which pushed the carbonate shelf facies of the Dezful-Lorestan area further to the northeast. A late Albian transgression initiated deposition of the shallow-water carbonates.

At the end of Aptian, a major regression caused the shallow water Aptian carbonates of the Khami become emergent. The Khami Group carbonates were followed by a low amplitude transgression and this was associated with the influx of clastics and marls and argillaceous limestones of the Kazhdumi Formation, synchronous with the Burgan sands of northwestern and southern Persian Gulf. As result, most of the southern Persian Gulf region including Saudi Arabia, Kuwait and Iraq, west of the Euphrates river, were covered by alluvial plain facies, while deltaic sediments rapidly prograded in the Safaniya-Burgan area. The more distal part of the basin was the locus for the deposition of the Kazhdumi Formation dated as Albian.

The Albian stage also occupies an important place in Mesozoic stratigraphy of Kuwait. The lower Burgan Formation was deposited in a lowstand systems tract represented by massive sandstone reservoirs. High frequency sea level changes have resulted in deposition of shoreface sands and extensive marine shales within an overall fluvial setting.

Burgan Formation

Following the transgressive Dariyan Formation and its stratigraphically time equivalent (i.e., Shuaiba Formation), carbonate phase and a period of mild emergence, the Burgan sands and shales deposited during a transgressive-regressive phase under shallow marine, littoral to inner shelf environmental conditions with deltaic influence (Brennan, 1990). Deposition of the Burgan sandstones grading eastward into the shales or shaley limestones of the Azadegan sand member (=Nahr Umr Formation) began in the late Aptian and continued into the late Albian (Motiei, 1993).

The Burgan and Azadegan sand member of Kazhdumi Formation (i.e., Nahr Umr) involve the initial deposits of the Middle Cretaceous cycle of flooding after a period of subaerial exposure. They embody a major incursion of terrigenous clastic sediments from the shield eastward onto the former carbonate platform. The depositional setting contains terrestrial and near shore marine sandstone, grading into a vast offshore shale belt up to 500 kilometers wide.

The amalgamated braided channel sands of Lower Burgan Formation traps giant pools in Kuwait with active bottom water drive. Estuarine channel sand deposits dominated upper part of the Burgan Formation. The high-energy grainstones and clean packstones preserve primary rock fabric. The mud-rich packstones and wackestones show high degree of degradation of reservoir properties due to growth of carbonate concretionary cements. Early emplacement of hydrocarbons stopped the concretion growth, while in water leg the growth continued till the primary porosity was destroyed.

The Burgan Formation underlies the Mauddud carbonates and consists of approximately 290 meters of soft, clean, porous, well-sorted quartz sandstones of littoral to possibly deltaic aspect, interbedded with sitlstones and dark shales.

Burgan Formation has been unofficially subdivided into the Lower, Middle and Upper Burgan members. The lower Burgan member includes thick clean high quality reservoir sandstone and contains most of the reserves. The upper Burgan member, though smaller, is also considered as a huge reservoir interval, and consists of soft, clean, porous, well-developed sandstones. The Middle Burgan is an interbedded sequence of shale, argillaceous siltstone and thin beds of very fine to fine sandstones.

The lower Burgan to Mauddud interval represent an overall transgressive sequence. Lower member was deposited in dominantly non-marine conditions whereas the upper Burgan is interpreted as having been deposited in Paralic (Deltaic to shallow marine) to offshore environments and have a complex architecture of alternating shoreface and channel-dominated units (Davis et al., 1997). The rapid vertical changes are interpreted as reflecting short term of high frequency changes in relative sea level.

The Upper Burgan paralic to marine sedimentation process signifies a complex cycle of transgressive-regressive sequences during Late Albian period in Kuwait. The shoreface and channel sandstones deposited in this environment hold significant quantity of in-place oil.

Deposition of the Burgan has been described as follows: The lower Upper Burgan consists of cycles of shoreface sands and marine shales. The marine shales are laterally extensive reflecting important high frequency sea-level changes. A lowstand system tracts (LST) is interpreted for the Middle Upper Burgan and represents a time during which a complex pattern of stacked channels were deposited. The estuarine shales are discontinuous and act as local baffles. The upper Burgan was deposited during a transgression.

Thus, no single depositional model is representative of Burgan Formation, although it can be classified as paralic (deltaic to shallow marine). Several different orders of relative sea-level change influenced deposition. An overall long-term (low frequency) rise in sea level occurred. Its net effect was the fluvial processes which were dominant in the low part of the lower Burgan member but that the influence of marine processes becomes stronger upward. Medium-term changes in relative sea level are shown by the advance and retreat of the upper Burgan depositional system. High frequency fluctuations in relative sea level gave rise to the complex reservoir architecture of the Upper Burgan member.

The lower Burgan was deposited in a lowstand systems tract represented by massive sandstones. High frequency sea level changes resulted in deposition of shoreface sands and extensive marine shales within an overall fluvial setting. The Middle part of the formation deposited in a transgressive systems tract, whereas the upper part witnessed a relative sea level fall in a lowstand systems tract with deposition of sand prone facies in estuarine channels. The clastic cycle was terminated by initiation of Mauddud carbonate sedimentation in transgressive systems tract. A combined effect of allocyclic nesting of sequence stratigraphic packages and autocyclic ramp profile were the primary factors controlling the lithofacies association. The overlying carbonates of highstand systems tract comprises of large-scale stepwise regressive packages, terminated by a transgressive systems tract.

Safaniya Sandstone

Safaniya sandstone is the stratigraphic equivalent of the upper part of the Azadegan Sand Member in northwestern Persian Gulf which grades into shales of Kazhdumi Formation towards the northeast and east in the Khuzestan subbasin in the northern Persian Gulf (James and Wynd, 1965; Murris, 1980). Safaniya Sand Member was deposited as fluvio-marine deltaic sediments in northeastern Arabia and the northwestern Persian Gulf. It is underlain by the principally clastic, basal Khafji Member and overlain by the Mauddud Limestone.

Safaniya Sandstone Member of Albian age is the second lowest member of the Mid-Cretaceous Wasia Group which is part of a gently eastward dipping sedimentary sequence of Cambrian to Recent age resting on the Arabian platform to the east of the Arabian Shield. This formation is a succession of clastics with carbonate intercalations in its upper parts deposited in a fluvial dominated and near-shore environment in central and northeastern Saudi Arabia (Power et al,. 1966; Moshrif, 1978). Safaniya Sandstone Member is underlain by the clastic, basal Khafji Member and overlain by the Mauddud limestone Member. In northeastern Saudi Arabia, the only other siliciclastic rocks found between the Upper Jurassic Hith Anhydrite and the Wasia Group are the Mid-Cretaceous Biydah Formation, which consists of 425 meters thick sandstones with some shale interbeds and which is overlain by the Shuaiba Formation (Power et al., 1966; Murris, 1980). To the northeast in Iran, the Biyadh Formation is represented by basinal shales of the Gadvan Formation (James and Wynd 1965).

Safaniya Member consists of clean quartz sandstone, laminated argillaceous sandstone and carbonate-cemented sandstone lithofacies. Clean quartz-sandstone lithofacies show a coarsening-upwards sequence with cross and horizontal lamination suggesting a river mouth bar to tidal current shoal environments. The laminated argillaceous sandstones show parallel lamination and associated flatter strata indicating deposition from alternating low-flow-regime currents below fair-weather wave base (Cagatay et al., 1996). The common presence of glauconite in the carbonate-cemented sandstone lithofacies indicates essentially marine conditions. The basinal equivalent of Safaniya sandstones, the Kazhdumi shale, is an important source rock in the Persian Gulf region (Ala et al., 1980).

Close to the Persian Gulf, the Safaniya Sandstone Member is about 110 meters thick and consists mainly of sandstone with some shale and local limestone interbeds. The sediments were derived under tropical to subtropical weathering of the Proterozoic crystalline rocks of the Arabian Shield during the Cretaceous (Cagatay et al., 1996). The depositional environment of this unit in northeastern Saudi Arabia and in the northwestern Persian Gulf region was, in general, a delta front and delta plain with fluvial and distributaries channels. These rocks were subjected to uplift during the Late Cretaceous. Structural movements continued during the Eocene and Plio-Pleistocene.

UPPER MIDDLE CRETACEOUS OF THE PERSIAN GULF

As it was pointed out in the preceding section, in the Persian Gulf and surrounding area, Middle Cretaceous sediments have been infiltrated by several petroleum exploration and development wells. Middle to Upper Cretaceous strata in the Persian Gulf region consists of the Bangestan Group, including the limestone of the Sarvak Formation, separated by an unconformity from the overlying Upper Cretaceous Ilam carbonates.

Bangestan Group represents Albian to Cenomanian rock units of the Zagros area, excluding Surgah and Ilam Formations. During this period, the massive, neritic wackestone and packstones of Sarvak were deposited over Kazhdumi. In Lorestan the neritic Sarvak interfingures with Garau-type basal shale and only in the Santonian shelf carbonates of the Ilam Formation return (James and Wynd 1965; Huber, 1979). In Dezful Embayment area, Ilam limestones (Santonian age) overlie Sarvak strata; again the contact is a sharp weathering surface. Farthest northwest, ferruginous Sarvak limestone of the Turonian age, with a limonite-rich, weathered layer of about 1 meter thick at the top, underlies Santonian shale of the Surgah Formation (Alavi, 2004).

Wasia Group in Persian Gulf

The Middle Cretaceous stratigraphy of the southern Persian Gulf has been complicated by a history of nomenclature that is even now evolving, and also by the fact that the names of formations and lithofacies units have been used interchangeably. The Wasia Group consists, in ascending order, of Nahr Umr, Mauddud, Shiliaif (or Khatiyah in Dubai) and Mishrif Formation. These formations are separated from each other on the basis of vertical position and lithologies. As a result this has led to some confusion in the description of the formations and in the understanding of their stratigraphy.

The Wasia Group was accumulated over a span of 20 million years. Their deposition began with the sheet-like neritic deposits of the transgressive sequence. Overlying the Thamama Group is shales, siltstones and sandstones of the Wasia Group. The "Middle" Cretaceous covers the time range from above the Mid-Aptian unconformity to the uppermost Cenomanian-lower Turonian unconformity. It represents an upward change from shallow-shelf clastics to shallow-shelf carbonates. The sequence is as much as 610 meters thick. Again, there was localized development of deep-water carbonates within intrashelf basins.

Over much of the Persian Gulf, the Wasia Group consists of several major depositional sequence separated by less significant and discontinuous unconformities. Distinct lithostratigraphic units contained by these sequences in the southern Persian Gulf are Nahr Umr, Mauddud, and Mishrif Members. Each of these units shows signs of regional differentiation into shallow and deeper water facies, the distribution of which closely reflects the tectonic evolution of the area (Murris, 1980).

There is a division of the Wasia Group into the lower, mainly clastic units of the Nahr Umr Formation and upper carbonate units (Powers, 1968). The lower clastic section is widely distributed over most of the Persian Gulf area, where it consists of shale with subordinate limestones.

The Nahr Umr Formation is overlain by the Mauddud Formation with intervening shale and unconformably overlies by the carbonates of the Shuaiba Formation. The basal contact is a regional unconformity having a complex

history that in outcrop may span up to 2.2 million years or more (Scott et al., 1988). The widespread occurrence of clastic sediments of the Nahr Umr Formation clearly manifests the prevalence of marginal marine deltaic regime with an easterly progradation in a north-south oriented depositional strike.

During Aptian to Albian times a major influx of terrigenous material from the emerged Arabian shield led to the deposition of the Nahr Umr within the intracratonic basin. The transgression resulted in deposition of a sequence of variegated shales with some lenses of limestone and sandstones. The shale acts as a regional seal for the Shuaiba.

Because of its high shale contents the Nahr Umr Formation is not a major oil reservoir in the Mesopotamian Basin. The contact between the Nahr Umr shale (Albian age) and the Shuaiba limestones (Aptian age) is unconformable and corresponds to the regional unconformity that affected the entire Persian Gulf region.

The Nahr Umr Formation of the UAE is a direct equivalent of Azadegan Sandstone Member of Kazhdumi Formation of southern Iran (James and Wynd, 1965). Similar to the Kazhdumi Formation, its lowest part may be of latest Aptian age. In this region, deposition of the Middle Cretaceous began with the sheet-like neritic deposits of the transgressive Azadegan Sandstone Member, which consists of a sequence of variegated shales with some lenses of limestone and sandstone.

Nahr Umr sediments point to a change to a mixed silisiclastic-carbonate system. Pratt and Smewing (1993) assumed that the sediments deposited during sinking of the shelf in the Albian time. Detrital sediments constituting the Nahr Umr were produced by uplift on the western side of the platform. Large-scale evolution of the margin in the Central Oman Mountains imposed major sedimentological changes on the platform in generating the siliciclastics of the Nahr Umr. A regional unconformity, representing erosion or non-deposition of Middle Aptian succession, marks the contact between the Shuaiba and the overlying Nahr Umr in the area.

Shales of the Nahr Umr provide a regional seal, and locally a hydrocarbon source rocks, in southern Persian Gulf. Farther to the west and northwest in Saudi Arabia, clastic units become more distinct in the Wasia Group and are divided into the Safaniya and Khajfi Members (Alsharhan and Nairn, 1997; Christian, 1997). The primarily carbonate part of the Wasia Group in Saudi Arabia is subdivided into four members in ascending order as follows: the Wara, Ahmadi, Rumaila, and Mishrif Members.

Ibrahim (1981, 1983) investigated the Albian depositional system, in particular Nahr Umr, in southern Iraq and suggested that the formation was deposited in a continental setting that ranged from floodplain to delta with probable marine and eolian influence. However, earlier interpretations described it as having been deposited in a bar or channel environment (Clark, 1980).

Azadegan Sandstone with duration of about 8 million years represents a broad, eastward, storm-dominated, largely clastic ramp (Murris, 1980). These

siliciclastic sediments are dated as middle to late Albian. The basal part of it accumulated in a marine prodelta or shallow-shelf environment, whereas the upper part was deposited in deeper, normal marine conditions of the inner-middle shelf in water depths of from 10 to 80 meters (Ibrahim et al., 2000). Marginal deposits in Saudi Arabia and Kuwait are sandstones of the Burgan Formation.

Nahr Umr-Mauddud boundary represents an abrupt regional facies change from siliciclastic to carbonate-dominated sedimentation with little subaerial exposure or erosion. Thus, at the end of Nahr Umr deposition, shallow marine carbonate sediments were deposited as bioclastic wackestone/packstones of the Mauddud Formation.

Alsharhan (1991) studied the stratigraphic status and sedimentological setting of the Azadegan Sandstone in the UAE and noted that the deposition of this formation follows the sea level curve of Haq et al. (1987). Reviewing the sedimentological setting and petroleum potential of the Albian clastics in western part of the Persian Gulf region, including southern Iraq, Alsharhan (1994) noted that the Albian clastics (with different local names) were deposited in a complex setting of alluvial plain to lower coastal plain and shallow marine shelf.

Wasia Group in Oman consists of Nahr Umr (i.e., Azadegan Sandstone) and Natih Formations. The Wasia is bounded below and above by regional unconformities, it overlies the Aptian Shuaiba Formation and underlies the Coniacian and younger Aruma Group. The Nahr Umr is an interbedded shale-limestone unit 150 to 200 meters thick. This unit represents a regional clastic depositional phase. The contact with the overlying Natih is conformable.

Oman lies on the eastern margin of the Arabian platform and became the site of carbonate deposition from the Early Jurassic to Late Cretaceous following the break-up of Gondwana and opening of the Neo-Tethys (Hughes-Clark et al., 1995). The Natih Formation represents the youngest prograding carbonate sequence of this succession (Van Buchem et al., 1996). Local erosion and karstification of its top indicate the uplift and emergence. This uplift signals the onset of the Alpine tectonic event during which the opening of the Atlantic Ocean led to the closure of the Neo-Tethys (Bechennec et al., 1995; Loosveld et al., 1996).

The Natih Formation consists of thick carbonate series. It represents a carbonate ramp depositional system, in which back shoal, shoal complex, for shoal and open shelf depositional environment is recognizable. The Natih Formation is a sequence of chalky limestone of the Wasia Group (age equivalents of the Mauddud and Mishrif Formations in the UAE (Harris and Frost, 1984). It represents the earliest prograding carbonate sequence of the succession (Van Buchem et al., 1996). Local erosion and karstification of its top indicate that uplift and emergence ended its deposition.

The Natiah Formation of Oman was deposited on a shallow stable tropical marine carbonate platform that dipped gently to the west into an intrashelf

basin (Bruchette, 1993). During Late Cretaceous, a plate collision to the northeast led to thrusting and building of the Oman Mountains. As a result, excellent outcrops of the Natih Formation are exposed in the canyons of the Mountains and smaller anticline that crops out. Natiah Formation occurs in the uppermost portion of the Aptian to Cenomanian-unconformity bounded Wasia Group that also includes the underlying Azadegan Sandstone (i.e., Nahr Umr Formation). The Natih Formation is uppermost Albian, Cenomanian and lower most Turonian in age.

Deposition of Late Cenomanian deep shelf sediments (top of the Natih Formation) on the Arabian Platform was the result of slow subsidence of an intrashelf basin. Such development of the Arabian platform shelf, known from Late Albian and Aptian times (Murris, 1980), could not be perceived as a specific response of the platform to Neo-Tethys intra-oceanic subduction (Patten and O'Conner, 1988), but did emphasize the generally euxinic character of the sedimentation during this period on the Tethys shelf (Phillip et al., 1993).

The Sarvak Formation

The regional emergence and periods of clastic and deltaic that initiated the Middle Cretaceous was followed by a significant transgressive phase which is marked by the deposition of the carbonates of Sarvak Formation that blankets most of the Persian Gulf area. The sediments of the Sarvak Formation were deposited on a passive margin of the Neo-Tethys Ocean.

The Sarvak Formation is named after Tang-e-Sarvak in Kuh-e-Bangestan in Khuzestan region. In its type section, the formation consists of three main limestone units totaling 832 meters (James and Wynd, 1965; Setudehnia, 1972) (figure 3-37). The Sarvak Formation is a part of the Bangestan Group and stratigraphically equivalent to Mauddud, Ahmadi, Rumaila and Mishrif Formations of the Persian Gulf region. Thus, the formation is divided into four depositional members, the Mauddud, Khatiyah bituminous shaly limestone in the central and western parts of the Persian Gulf, the Ahmadi with shaley facies in the northern Persian Gulf and the Mishrif reefal limestones member.

Carbonates of the Sarvak Formation are exposed extensively in the southern Iran and have been penetrated by drilling in many exploration and production wells in the Persian Gulf.

The Sarvak (upper Albian to upper Turonian) consists of resistant (cliff-forming) shallow-marine limestones (in part argillaceous and micritic and in part sparry) including grainstone, rudist-bearing packstone, and stromatoporoid-bearing wackestone, with thin intercalated intervals of marl grading upward to massive chalky limestone; containing a 30 to 60 meters interval of shale.

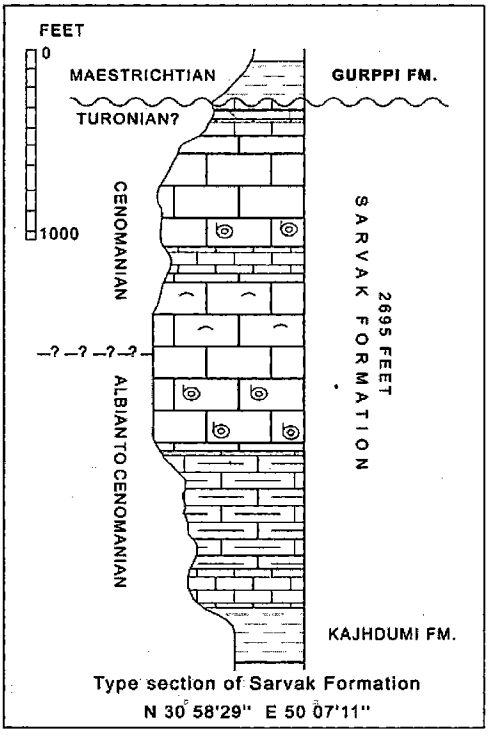

Figure 3-37. General stratigraphic column of the Sarvak Formation in its type locality in Kuh-e-Bangestan (modified from Motiei, 1993)

The Sarvak Formation is present in all the wells drilled in the Persian Gulf with facies correlateable to its type section. The thickness of the formation varies from 41 meters in 0-4 BIS well, 210 meters in U-1 well to a maximum of 223 meters in the BS-1 well in the Bahregansar field in the northwestern Persian Gulf.

The formation conformably overlies the Kazhdumi Formation with a transitional contact. The upper contact with the marl and shale of the Gurpi Formation is sharp. This unit is broadly distributed in the Dezful Embayment area and the northern Persian Gulf. In coastal northern Persian Gulf, the Sarvak Formation is identifiable by two members, namely Ahmadi and Mauddud.

Ahmadi member is a continuation of the Sarvak in northwestern Persian Gulf. Lithologically, it consists of 30 to 60 meters of highly eroded shale with thin limestone partings. Most of the present Persian Gulf area was beyond the deltaic influence, and until the deposition of the Ahmadi shales, continued to receive sub-littoral to shallow marine carbonates (Mina et al., 1967). The Ahmadi member also consists of fossiliferous limestones. The shales and limestones of the Ahmadi member were deposited during as Early to Middle Cenomanian in open-marine conditions on the outer shelf at depths of between 100 to 200 meters.

At the end of the Albian-Cenomanian time shallowing of the sea produced thick shallow water carbonates over the entire Persian Gulf area. The sedimentation continued with the deposition of shallow marine carbonate of the Sarvak Formation. In Fars region and areas surrounding the Persian Gulf, shaley parts deposited during the Cenomanian time representing the northern extension of the Ahmadi shales of Saudi Arabia.

The Lower part of the Sarvak Formation represents the establishment of a Middle Cretaceous carbonate ramp and the first subtle differentiation into intrashelf basins and platforms. It is dense, micritic shelf limestone that can be interpreted to represent a Late Albian stillstand. In most places the Sarvak limestones shoal upward from Orbitolina-dominated packstone and wackestone into shallow water rudists limestones. Deposition of this part of the formation occurred during a period of about 4 to 5 million years (Harris et al., 1984).

The Middle Cretaceous carbonate sediments were deposited in shallow warm, tropical seas. The Upper part of the Sarvak Formation represents a broad carbonate ramp or low gradient shelf that fringed the margin of the Arabian craton and interior basins during the Cenomanian and early Turonian. The margin varies in style locally from ramp to low gradient rimmed shelf, probably reflecting both the dominant wind direction and the subsidence regime, but isolated rudists buildups with steeper slopes developed locally on diapirs or basement highs. In general the basin had overall progradational architecture (Burchette and Britton, 1985).

At the top of the Sarvak Formation, there is a significant disconformity throughout the Persian Gulf, one that is less apparent in the Lurestan, where the formation has a deeper-water character. The facies at the base of the Sarvak in the Lurestan extends down into Albian, with the disappearance of the facies characterizing the Kazhdumi Formation. In the coastal Fars the top of the formation have been removed below the post Cenomanian-Turonian disconformity. The upper part of the Sarvak is sometimes absent due to erosion during the Turonian unconformity. Figure 3-38 is a cross section of some of the sedimentary sequence including the Sarvak Formation and its associated unconformity in Persian Gulf.

There have been some studies showing erosion and karstification of the Upper part of the Sarvak Formation in some of the oil fields including the Resalat and Sirri oil fields in the Persian Gulf (see Bashari 2002; Hajikazemi et al., 2002). More recently Farzadi (2007) studying the geophysical data of the Sirri fields revealed that the Sarvak carbonates were subjected to periods of regionally extensive subaerial exposure.

Thus, the Upper Sarvak succession terminates in a karstic unconformity characterized by breccia-filled dolines, paleosoles, and mature flint claystones (Pattinson and Takin, 1971; Burchette and Britton, 1985). Regional geologic investigations in the southern Persian Gulf and Oman (Robertson, 1987a, b; Patton and O'Connor, 1988) have suggested that the uplift might be due to the

growth of a peripheral buldge associate with the obduction of the Semail Ophiolite. However, the possibility that some early uplift may have resulted from compression along the southeastern side of the Dibba transform zone cannot be excluded.

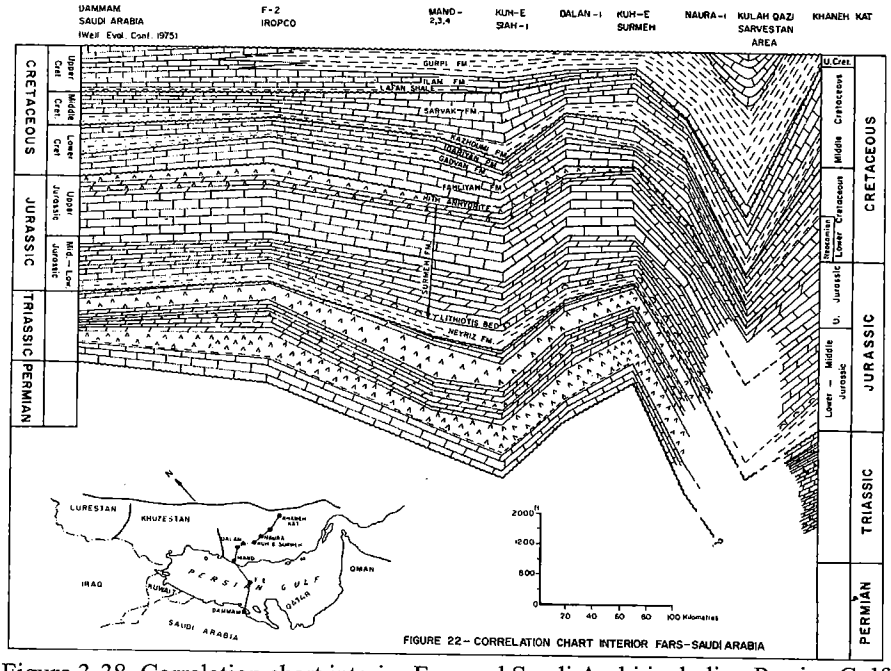

Figure 3-38. Correlation chart interior Fras and Saudi Arabi including Persian Gulf showing the erosion of Sarvak Formation (Setudehnia, 1978).

Rudist reefs occur in the Sarvak limestones of oil fields in the productive Bangestan Group. Stratigraphic equivalent of the Sarvak Formation also contain rudist reef reservoirs on local structural highs of the offshore UAE. Figure 3-39 shows the distribution of the Sarvak Rudists in eastern Persian Gulf. In the Persian Gulf area, the lateral facies change of Sarvak Formation is so great that the formation and its equivalents have been assigned different names.

Lateral and vertical facies variations of Sarvak Formation across some of the wells in some parts of the Persian Gulf such as the Sirri fields are due to the effect of the Turonian unconformity and basinal configuration and topography. The trend of the anticlines, acting as hydrocarbon reservoirs, is attributed to halokinetic movements of the Precambrian Hormoz salt that began in the late Aptian-Albian due to basement structural reactivation.

The platforms separated by various intrashelf basins are the sites of shallow-water carbonate deposition. The bioclastic skeletal lime grainstones are the 'rudist limestones' of James and Wynd (1965). In part, they are composed

of rudistid banks (reefs) and aprons of large-scale, cross bedded bioclastic debris and brecciate limestones. Rudists are common components in the Cretaceous carbonates of the Persian Gulf basin. Rudist fragments were described as "horned limestone" or horn shelled fragments. The Sarvak carbonates formed during the highstand but a major sea-level fall at the Cenomanian-Turonian boundary exposed carbonate of Sarvak Formation.

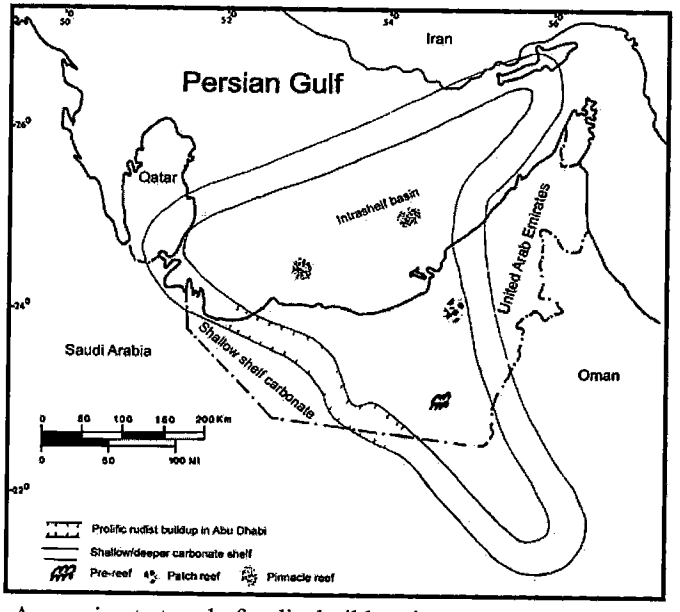

Figure 3-39. Approximate trend of rudist build up in eastern and southern parts of the Persian Gulf (after Frost et al., 1980).

The Tethys Ocean margin at this time was deformed in the Oman and Zagros Mountains, but was characterized by grainstones, rudist reefal tracts, and slope deposits (see James and Wynd, 1965; Watts and Blome, 1990). Other correlatives of the Upper part of the thick Sarvak Formation in Persian Gulf area and its surrounding regions occur in the Mishrif Formation and in Natiah Formation in Oman (James and Wynd, 1965; Scott, 1990). Similar carbonate platforms developed widely in the Middle Cretaceous along the northern and southern Tethyan margins.

By the end of Turonian, regional uplift and associated disconformity resulted in erosion of the carbonates over the Fars Platform. Conglomerate, breccia, ferruginous materials, and a weathered zone on top of the Sarvak Formation mar this event. Evidence of this pronounced unconformity is recognized almost everywhere in northern Persian Gulf and in many wells conglomerates and breccias with ferruginous materials have been found associated with the unconformity surface.

Laffan shales form the caprocks for the Upper Sarvak reservoir. The regional Turonian unconformity marks the upper boundary of Sarvak Formation. In Sirri-A, the Ilam Formation (Santonian-Campanian age), which is mainly, consists of dense shelf carbonates and exhibits fracture porosity forms the main reservoir unit and account for the storage of the hydrocarbons.

Lower Sarvak Formation (=Mauddud Member)

Overlying the Upper Burgan is the Mauddud Formation that was deposited under platform conditions. Lower Sarvak (i.e., Mauddud) is a carbonate succession of bioclastic packstones, gainstones, and wackestones associated with a shallow marine environment. Recognized fossils include benthic foraminifera (*Orbitolinids, Miliolids*), echinoderms, bivalve, and rudist materials.

A late Albian transgression initiated deposition of the shallow-water carbonates of the Mauddud. Mauddud commenced with flooding of Azadegan sandstone member clastic ramp and the establishment of a regional carbonate platform. It is a shallow water thin carbonates with widespread distribution in the subsurface of the Persian Gulf region.

Mauddud Member was originally designated to represent the orbitolina-bearing limestone of the southern Persian Gulf. The orbitolina-bearing limestones form a large bulk of the Mauddud Member over the Persian Gulf basin. The vertical and horizontal extension of the facies in Muaddud all over the Persian Gulf basin indicates long term stability of the basin.

The carbonate facies of the Mauddud are assigned a Late Albian to Cenomanian age. This is the beginning of a cycle of carbonate deposition which lasted until the latest Cenomanian or earliest Turonian. The transgression is indicated in the Khatiyah Formation basinal facies by the appearance of a planktonic foraminiferal fauna dominated by *Planomalina buxtorfi* and *Hedbergella* spp.

Mauddud Formation was deposited in an inner to middle shelf marine environment in waters from 20 to 100 meters deep, representing a brief shallow marine transgression toward the end of Early Cretaceous time, comparable to the earlier transgression represented by the carbonates of the Dariyan Formation.

Vertical and lateral facies variations in the formation have resulted in a variety of names that have been compounded further by varying terminology developed by the operating oil companies. Prior to its formal definition, the rocks of the Mauddud Formation were designated as the *Orbitolina concava* limestones by Barber (1948).

The formation consists of foraminiferal limestone ranging from lime mudstone at the base through wackestone to pelletal and skeletal packstone and wackestone at the top. In some horizons, the formation consists predominantly of tests of *Orbitolina* and *Trocholina*. In the northern offshore areas of

Qatar in the Persian Gulf, the Mauddud Formation consists of rudist grainstone and packstones with peloidal *orbitolina*-bearing limestones. Orbitolina-bearing limestones form a large bulk of the Mauddud Formation all over the Persian Gulf basin.

In northern head of the Persian Gulf, the Mauddud Formation consists of organic to detrital limestones (Owen and Nasr, 1956) interbedded with minor shale breaks and sandstones at the lower part which represents a transition zone from the sandy Burgan facies to massive carbonates. The lower part of the formation is generally tight except for some localized sandstone development. The upper part of the Mauddud Formation contains a number of upward-shallowing depositional sequences that have some porous intervals.

In northern Kuwait, the base of shales and siltstones of Muaddud forms the seal to the Burgan reservoirs (Goodall et al., 1996 cited in Al-Eidan et al., 2001). In this area, the Mauddud transgression was succeeded by a brief return to sand deposition, represented by the oil-bearing Wara Formation. Thus, above the Burgan sandstone reservoirs lies the Mauddud muddy carbonate formation, above which lies another interbedded sand-shale reservoir, the Wara Formation.

The Mauddud Formation represents a brief return to transgressive shallow marine conditions at the end of the Early Cretaceous. The Lower Burgan to Mauddud interval signifies an overall transgressive sequence. As a result of Mauddud transgression, the Burgan delta and other clastic shoreline systems were pushed far back to the southwest part of the Arabian plate.

Khatiyah Formation

During the Middle Cretaceous cycle in late Albian-Cenomanian time, the Shiliaf-Khatiyah interashelf basin formed in the southern part of the Persian Gulf. It was filled by deeper water sediment, however along the margins of the basin the carbonates show substantial lateral facies variations with rudist buildups occurring in some areas. Jordan et al. (1985) proposed that the rudist bioherms, and the subsequent development of secondary porosity was controlled by the same salt structures over which the present day Upper Sarvak reservoirs are found (e.g., Fateh Field).

The Khatiyah consists of calcareous shales grading upward into argillaceous pelagic lime mudstones that contains abundant calcispheres (Oligostegina sp.) and planktonic foraminifera. Thin-walled pelecypodes and ostracodes also occur but are generally scarce. Planktonic foraminifera and calcareous nannofossils are abundant; benthic foraminifera and molluscs are sparse.

The Shilaif to Upper Sarvak and their equivalents contain evidence of six small rises in sea level (Kendal et al., 1991). The transgression is indicated in the Khatiyah Formation basinal facies by the appearance of a planktonic foraminiferal fauna dominated by *Phanomalina buxtorfi* and *Hedberella* spp.

The shales are laminated and locally borrowed; stylolites are common. The Khatiyah (Shilaif) Formation is well-laminated bituminous carbonaceous marl that locally is considered as a source rock. It overlies Mauddud Formation and locally is equivalent to the Upper Sarvak Formation. Beds in the deeper parts of the intrashelf basin are dark-colored, potential source rocks. This also suggests that the basins were sufficiently large to have had substantial circulation in the upper part of the water column. In addition they were deep enough to have developed an oxygen minimum zone at or near the sediment-water interface.

The depositional sequence within the Khatiyah increases from east to west. Sedimentological and geochemical studies have demonstrated the Khatiyah sequences to be basinal deposits. The Khatiyah limestones were deposited in an intra-shelf basin, in which euxinic conditions favored preservation of organic matter. The Kazhdumi shale source rocks on the other hand contribute to the hydrocarbons found in the Ilam-Sarvak formation encountered in the Hengam-West Bukha area.

Upper Sarvak Formation (= Mishrif Member)

The Sarvak Formation of the coastal Fars and the northern Persian Gulf has affinities with the equivalent units of the Mid-Cretaceous Wasia Group in southern Persian Gulf. The Mishrif Member which can be considered as equivalent of the Upper Sarvak is of early Cenomanian-Turonian and a part of the Wasia Group. It is a prolific hydrocarbon reservoir and host to a number of giant oilfields in the Persian Gulf including Sirri and Fateh.

The Upper Sarvak, (i.e., Mishrif Member) is developed throughout the Persian Gulf region, forming an extensive lithostratigraphic unit comprising a sequence, up to 600 meters thick, bounded by two regionally important unconformities (Harris et al., 1984). During Late Cenomanian and Turonian, uplift and erosion of the Upper Sarvak platform occurred in a north-south trend paralleling the Oman Mountain front. Thus, at the end of Cenomanian, a major period of emergence and erosion completed the deposition of Wasia Group. As result of the exposure and erosion, platform growth was terminated during this interval in the eastern Persian Gulf and Oman, while in other parts of the southern Persian Gulf, the lowstand was less prominent and the platform sank during early Turonian highstand.

A basin developed in central Abu Dhabi in which bituminous shales and mudstones of the Shilaif Formation, with abundant *pinthonella* deposited in it. Shalaif limestones are typically wackestones and packstones dominated by small *miliolid* foraminifers, as well as large benthic foraminifera including *Dicylina schlumberger, Cuneolina pavonia, Rotalia skourensis,* and *Chubbina* sp. *radiolite* and *caprinid* rudists and other molluscs are common. The Shilaif Formation is interpreted to have accumulated in euxinic depression where conditions favored preservation of abundant organic material.

On both sides of the Shilaif Basin, the Mishrif platform showed initial vertical, and then strong lateral, accretion associated with thickening of the slope facies (Burchette and Britton, 1985), pointing to an increase in slope height and thus an increase in basinal water depth during the period of Mishrif deposition. At the end of Shilaif time, a minor period of uplift affected the central basin area. On the edge of this intrashelf basin, the Mishrif Formation formed as a carbonate shelf deposits characterized by mollusc-fragment grainstone and packstone. The Turonian-Cenomanian Shilaif interashelf basin is considered as a modified shape of the Aptian basin. Depocenters of both basins are closely related.

The Mishrif formed the progradational rim of the Shilaif Basin and is a bioclastic carbonate that is locally dominated by *radiolitid* rudists. The lower part which consists of shelfal packstones and wackestones contain rudist buildups. Much of the upper part of the Mishrif, particularly to the east has been eroded.

The Mishrif was interpreted to be a rudist reefs complex that prograded basinward in several stages. Backreef reef/near reef, and for-reef facies were recorded from a wide shallow marine carbonate shelf. The outershelf was rimmed by a series of discontinuous radiolitid rudists reef shoals. The rudist reef/shoal complex belt is 8-10 kilometers wide and extends for 20-25 kilometers; depositional relief was low (Jordan et al., 1985).

Radiolitid rudists of the constructor guild dominated some of the reef mound, but caprinid and monopleurid rudists were also common (Johnson et al., 2002). Corals were rare, and the reefs were crested with *Chrondrodontid* bivalves. Rudist patch reefs occurred in the backreef (Jordan et al., 1985).

Cores, cutting and wireline logs from 30 wells distributed over 200 km^2 showed a mid-Albian through Early Turonian low-relief platform with platform margin slope through lagoon facies. The biota and geometries of biota accumulation are undifferentiated in age, except for the notation that the Mishrif carbonates were subaerially exposed during the Late Cenomanian and Turonian and are locally overlain by fresh water mudstones with plant material (Burchette and Britton, 1985).

According to Burchette and Britton (1985), the Upper Sarvak (Mishrif) in southern Persian Gulf and surrounding area has an overall progradational architecture and major platform drowning events are absent in all but the final sequence. Transgressive deposits are not well developed and have only been recognized in core as thin muddier horizons, with increased benthic faunal diversity (Pascoe, 1995, p.752).

Platform margin shoals and biostromes contained *radiolitid, caprinid*, and *monopleurid* rudists associated with bioclastic packstones and grainstones. These carbonate units also contain rare corals *chondrodontid* bivalves, and *tylostomid* gastropod. Backshoal facies contain abundant chondrodonts and scattered rudists.

The time period spanned the deposition of the Mishrif where sedimentary record indicates the presence of widespread shallow-marine platform carbonates. The repetitive interbedding of limestones with silty shales and shales indicates a decreased input of terrigeneous clastics from the hinterland to the west. Generally, the succession developed into pure limestone toward the Late Cenomanian. Detrital limestones with rudistid remains and coralline algae were present in Kuwait and southwestern Iraq.

The bioclastic shoal facies of the Mishrif are initially aggradational locally, in response to an overall rise in the sea-level in the latest Albian to Early Cenomanian. In the Middle to Upper Cenomanian they became progressively more progradational into the Central Abu Dhabi Basin.

Deposition of the Khatiyah and Mishrif occurred as a single transgressive/ regressive sequence, some 230 meters in thickness. The Khatiyah represents the transgressive phase having been deposited initially in the axis of the Khatiyah embayment and later having spread across the shield area surrounding the basin. The Mishrif is basically a rudist reef complex that prograded basinward with several well-developed stages of reef advancement.

In summary the Upper Sarvak in the southern Persian Gulf is a regional shallow water limestone succession that shoals upward, due to progradation, from basinal deposits. The platform rimmed a cratonic interior basin, the Shilaif basin, at the margin of the Arabian craton for a linear distance of over 2000 km, prograding into the basin for up to 75 kilometers in some areas. Six lithofacies associations, ranging from basinal, through slope and shoal, to shallow lagoonal deposits, have been recognized.

MID-CRETACEOUS SEA LEVEL CHANGES

During the Middle Cretaceous, global sea level rose to its highest level in Mesozoic-Cenozoic history, reaching a maximum during the Cenomanian/ Turonian. However, across the entire Arabian passive margin a renewed clastic influx occurred, spreading clastic across large parts of the basin.

High global sea level prevailed during Late-Hauterivian to Late Aptian but despite this, uplift of the Arabian-Nubian craton resulted in the influxed of the Zubair delta from the west, inundating the entire offshore area with an interbedded sequence of sands and shales.

Uplift of the cratonic source areas to the west caused a renewed influx of sands over large parts of the basins in the nearly middle Albain. The Burgan Formation is characterized by thick deltaic sands in the west, thinning somewhat to an average thickness of more than 370 meters in the offshore (including the basal shales).

Towards the east the sand content diminishes but not so considerably as in the Zubair. Carbonates onlapped in a westerly direction and progressively displaced the clastics westward into interior Kuwait, resulting in the deposition of the Upper Albian Mauddud carbonates. Mauddud Formation shows a

gradual overall thickening towards the east and northeast, ranging from depositional feather-edge in the Minagish area to more than 140 meters in the Bubiyan area.

Two sedimentation cycles can generally be recognized during this period, both ranging from clastics at the base to carbonates at the top. In offshore Kuwait the lower cycle (Burgan and Mauddud Formations) is readily distinguished. However, the upper cycle (Wara, Ahmadi, Rumaila and Mishrif) in the offshore consists essentially of carbonates and shales only. The isopach of the Middle Cretaceous sequence increases from 530 to 750 meters, through the 'thinning' over the Burgan Arch and this is the results of erosion below the base upper Cretaceous unconformity.

At the end of Albian-Cenomanian-Turonian cycle, a major unconformity developed marking the first phase of orogenic events (Robertson and Searle, 1990; Scott, 1990). At this time, the initial thrust sheets were emplaced in the eastern and northeastern UAE. Erosion of these structures supplied the sheet of synorogenic deposits that spread across the platform. Shelf deposits beyond this fringe are lithologically more variable. The clastic influx mixed with shelf carbonates, which included some rudists buildups formed during the late Maastrichtian (Simsima Formation).

UPPER-MIDDLE CRETACEOUS BOUNDARY

Following the deposition of Upper Sarvak shelf sediments in the Middle Cretaceous, the region was uplifted and eroded during a coincident Turonian relative fall in sea level. Major unconformities including the Turonian which occurred in the sedimentary sequence of the Persian Gulf are interpreted to have resulted from eustatic fluctuations (Harris and Frost, 1984) or regional tectonic events (Murris, 1980; Burchette and Briton, 1985). Several local and regional unconformities, in addition to thickness and facies variations have been related to continuous convergence and reactivation of deep seated faults in the Zagros basement between Late Cretaceous and Early Miocene times (Berberian and King, 1981; Koop and Stoneley, 1982). Hessami et al. (2001) documented local post-Eocene unconformities and attributed them to the beginning of folding and uplift in the NE of the Zagros, which progressively propagated south-westwards through time.

The regional well log correlation over Hengam oil field in eastern Persian Gulf shows that the Ilam-Sarvak thickness variation across the wells due to erosion by the Turonian unconformity.

The widespread Turonian unconformity resulted from both a combination of localized uplift, following initiation of the ophiolite obduction on the northeast plate margin, and possibly a global eustatic fall in sea level (James and Wynd, 1965; Setudehnia, 1978; Murris, 1980; Koop and Stoneley, 1982 and many others).

Carbonate sedimentation continued at the end of Albian with the deposition of the Sarvak, Surgah and Ilam Formations. Platform facies with rudists and *Orbitolina* developed in most parts of the Persian Gulf.

Ilam-Sarvak sediments comprise of bioclastic and chalky limestone that overly the Kazhdumi shale and are underlain by the Gurpi shale. The Gurpi shale is the regional seal or caprock of the Ilam-Sarvak reservoirs. Although a disconformity separate the Ilam and Sarvak, it is difficult to separate these units especially where the Laffan shale is thin or completely absent.

In the uppermost part of the stratigraphic section along the Persian Gulf, Middle Cretaceous clastic deposits are replaced by carbonates because of sea level fluctuations in the Zagros foredeep as the Zagros Mountains rose.

The regional Wasia/Aruma unconformity separates uppermost Cretaceous rocks from Middle Cretaceous strata (Glennie et al., 1974; Harris et al., 1984; Scoll, 1990). The magnitude of this unconformity varies from place to place throughout the Persian Gulf region.

UPPER CRETACEOUS OF THE NORTHERN PERSIAN GULF

The deposition of Upper Cretaceous sediments over the Middle Cretaceous paleotopography started in much of the Zagros Basin with the neritic carbonates of the Santonian-Lower Campanian Ilam Formation (figure 3-40). This was followed by a more extensive transgression of the sea producing the deeper water shales of the Gurpi Formation (Campanian-Maastrichtian). Thus, the Upper Cretaceous in Zagros includes Surgah and its equivalent Laffan, Ilam and Gurpi Formation.

The sequences of latest Turonian to Middle Maastrichtian age shaped a progradational-retrogradational blanket of strata bounded by two major unconformities. These formations include Surgah, Ilam, Gurpi, Amiran, and Tarbur. The basal unconformity is a hematite-stained, erosional surface, locally associated with conglomerates composed of reworked carbonate clasts (Stoneley, 1990), representing a hiatus of approximately 4 to 15 m.y. (Alavi, 2004). Locally, a number of areas remained emergent for longer periods and consequently reveal a wider gap than the adjacent depression.

The deeper water sedimentation in Lurestan sustained during Coniacian to form shales and thin argillaceous limestones of the Surgah Formation. This was followed by the argillaceous limestones of the Ilam Formation of Santonian-Campanian age. Subsequent transgression of the sea ubiquitously produced the marls and shales of the Gurpi Formation.

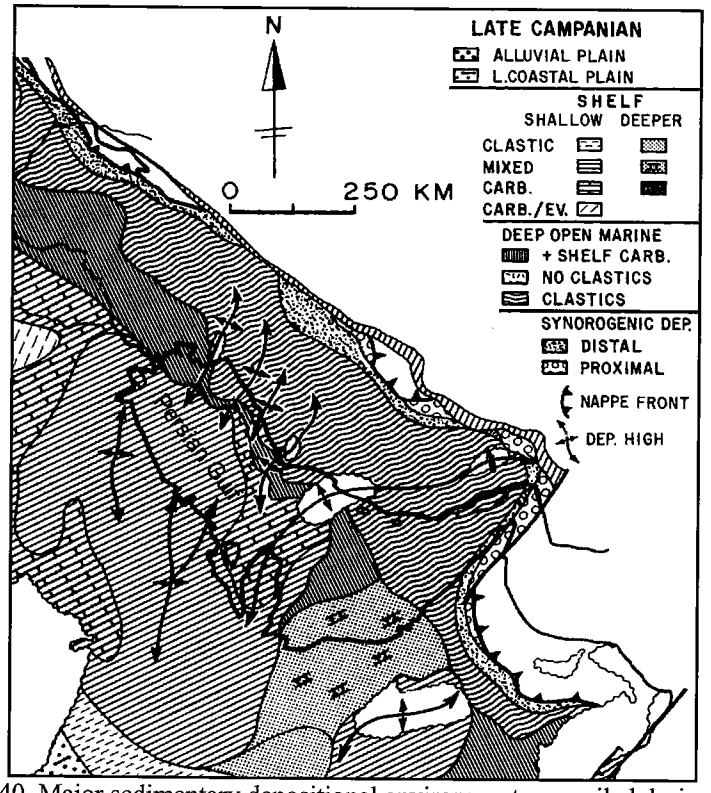

Figure 3-40. Major sedimentary depositional environments prevailed during the Late Cretaceous in Persian Gulf and surrounding areas (After Murris et al., 1980).

To the southeast (i.e., Fars region), the unconformity is the contact between basal Gurpi marls of Santonian (84 Ma) age which overlie Sarvak limestones. Farther southwest, in the central part of the Persian Gulf, where the middle and upper parts of the Sarvak Formation are missing, Santonian shales of the Surgah (or Laffan) Formation overlie the lower (most probably Albian) part of the Sarvak along a ferruginous weathering surface (Alavi, 2004).

At upper stratigraphic level (i.e., Middle Maastrichtian), the Gurpi Formation is conformably overlain by the Tarbur carbonates. The Tarbur Formation transgressively expands towards the northeast well into the Zagros imbricate zone, and shows distinctive lateral facies variations. In the external part of the belt, the Tarbur Formation consists of thin-bedded pelagic and hemipelagic marls and argillaceous lime mudstones with planktonic foraminiferal faunal assemblages (Wynd, 1965); in this part of the region, having a gradational contact with the underlying Gurpi Formation, the two formations are practically indistinguishable from one another.

To the northeast, in the internal parts of the Zagros Fold-Thrust Belt, the Tarbur Formation unconformably onlaps either the ophiolite complexes (with a basal 2 meters thick polymict pebble-conglomerate layer) or the Amiran

Formation, and is composed of shallow-water (littoral-zone) limestones with high-energy characteristics including biohermal reef build-ups. In this internal part of the belt, the Tarbur carbonates interfinger with gypsum and dolostones of the lower part of the Sachun Formation. However, In the external part of the belt, during the late Maastrichtian to earliest Paleocene erosion removed the upper part of the Tarbur, and the relationship between this unit and the Ilam and Surgah Formations to the southwest is uncertain; presumably, these two units, following the Tarbur Formation and onlapping it, also migrated towards the northeast.

Near the end of the Campanian, a thriving shoal of large lamellibranchs extended briefly from Iraq into western Lurestan and produced the Lopha limestone of the Gurpi Formation. This was shortly followed by a further influx of mud with which developed into progressively more and more calcareous until, in the middle of Maastrichtian, the argillaceous limestones of the Emam Hassan Limestones Member of the Gurpi formation were deposited.

Tectonic deformation of this very long and wide margin commenced in association with the onset of events leading to ophiolite obduction around the Arabian shelf began in the late Turonian; these formed the peri-Arabian ophiolitic crescent extending from the northwest Arabian margin to the southeast margin in Oman (Ricou, 1971).

Laffan Formation

Late Cretaceous deposition began with Coniacian Laffan Shale, a prodeltaic sedimentary rock probably related to either the 89 or 88 Ma sea-level rise of Haq et al. (1988). In the coastal area of the northern Persian Gulf and the adjacent portion of the Fars, brackish to fresh water shale of the Laffan was deposited over the eroded surface of the Turonian carbonates. The type section is described in well No #25 of the Dohkan oil field in Qatar.

The thickness of Laffan Formation at its type locality in southern Persian Gulf (i.e., Qatar) is approximately 29 meters which is lithologically composed of shales. However, its reference section in Iran is located on the northern shore of the Persian Gulf and it is composed of 84.5 meters of shale with thin layers of argillaceous limestone. The maximum thickness of the Laffan is 190 meters and occurs in western Abu Dhabi. The dense argillaceous limestone of the Halul conformably overlies the shaley limestones of the Laffan.

Following Turonian subarial erosion, relative sea level rise resulted in the flooding of the Sarvak surface and the transgressive deposition of the Laffan shales. In the Upper Cretaceous renewed subsidence led to the deposition of a shale sequence with minor argillaceous limestones representing the Laffan. Thus, the Laffan shale was deposited on the unconformity surface and acted as an efficient regional seal for the Sarvak reservoir. This is in fact the case in the majority of the wells drilled in the central portion of the Persian Gulf. For example, the Laffan shales are encountered in drilled wells of the Faurur, Sirri

and Hengam Islands. However, approaching the Strait of Hormoz the Laffan Formation is thinned out. In the Sirri Field the microfossiles including *Globotruncana Sp* and *Heterohelix* were identified and they indicate open marine depositional environment (Hajikazemi et al., 2003). Westward, approaching the Qatar-Gavbandi Arch the thickness of Laffan shale is also decreasing and pinching out completely towards the Arch.

The Laffan shale grades upward into the regressive Ilam carbonate which in turn is overlain by another transgressive unit, Aruma shale. The overlying Ilam Formation and its lateral equivalents consist of two Coniacian-Santonian facies: shelf limestone and platform-slope marl. Thus, the deposition of the Laffan shale was followed by the shallow water carbonates of the Santonain Ilam Formation. In other word, the Laffan shales are separating the Ilam from Sarvak Formation and stratigraphically equivalent to the Surgah Formation.

In the drilled wells from eastern Persian Gulf near the Strait of Hormoz to Sirri Island the thickness of the Laffan shale is between 3 to 6 meters. However, the thickness is increased in Sirri field to 23 meters and reaches a maximum of 41 meters at U-1 well. In some localities such as well 3H-1, the Laffan shale is absent and the Ilam limestone directly overlies the Sarvak Formation. Generally the Laffan shale can locally form a major seal over the Upper Sarvak. It interfingures with and is overlain by interbedded calcareous shales and argillaceous limestone of the Halul Formation. In terms of geographic distribution, in addition to Qatar, the Laffan shales are encountered in the deep wells drilled in southern Persian Gulf including Bahrain and UAE (Motiei, 2003).

At the end of Maastrichtian time, a general regression created a major widespread unconformity throughout the northern Persian Gulf (James and Wynd 1975; Setudehnia, 1978). The isopach map of the upper Cretaceous indicates a general thinning over the oilfield area of Dezful Embayment area and southern Fars region. This is possibly due to the effects of the two regional unconformities on the top and base of the section. All of the paleohighs present on the Middle Cretaceous isopach map are well apparent also on the Upper Cretaceous map. The thin sedimentation over the Fars platform and the NE-SW trend near Oman are again well indicated.

The striking feature on the Upper Cretaceous isopach map, however, is the extension of the general northwest-southeast trend of Lurestan into the northeastern part of the region, through Khuzestan and Fars. This is associated with a general thickening towards the northeast, which is due to:

Development of the reefal limestones of the Tarbur Formation,

The presence of thick radiolarites in part of this region,

The development of Cretaceous sandstones, conglomerates, and siltstones to the northeast.

Ilam Formation

The Upper Cretaceous Ilam Formation (Santonian to Campanian in age) is a thin transgressive interval (150-200 meters thick) consisting of shallow-marine *hippurites*-bearing limestones with intercalations of fissile shale and broken by several intraformational disconformities; rests unconformably on Surgah. The sequence represents forebulge deposits onlapping back-bulge deposits during prograde south-westward migration of proforeland depozones.

In the Persian Gulf district, and also on the Iranian mainland, the Ilam Formation and its equivalent the Gudair Formation are composed of shallow marine and backreefal limestones. The characteristic fauna include: *Pseudodomia complanata, Rotalia skourensis* and *Globotuncanaelevata* (Mina et al., 1967). In most of the wells drilled in the Persian Gulf, the facies of Ilam Formation are shallow marine with the lowest thickness around the Strait of Hormoz. In well HD-1 the thickness of Ilam Formation is 11 meters whereas in wells HA-1 and HEE-1 it reaches 19 and 27 meters respectively. In the Sirri oilfield area the Ilam Formation is up to 85 meters thick. Toward the western part of the Persian Gulf the thickness of the Ilam Formation increases from 55 to about 100 meters. Except in the Qatar-Gavbandi Arch area and Palinorooz, the Ilam Formation seems to be present in the central Persian Gulf.

The lower contact of Ilam Formation with shales of Laffan is gradational. This is the case in well #U-1. The upper contact with the Gurpi Formation is continuous and there appears to be no gap in sedimentation whereas in most places in northern Persian Gulf there is an erosional surface.

Ilam Formation consists of both shallow water and deep water limestones and is present over the entire Persian Gulf area. Ilam has an average thickness of 100 meters in the Persian Gulf area. It is important to mention that the top of Ilam limestone is a remarkable geological and seismic marker within most part of the Persian Gulf area.

As mentioned, the Ilam Formation consists of two facies: shelf limestone and platform-slope marl. Shelf limestones are typically wackestones and packstones dominated by small miliolid foraminifera, as well as large benthic foraminifera including *Dicyclina schlumbergeri, Cuneolina pavonia, Rotalia skourensis* and *Chubbina* sp. Radiolite and caprinid rudists and other molluscus are common. *Dasycladacean* green algae and *Oligostegina* type *cacisphers* characterize the deeper shelf facies of Ilam. Platform-slope marls contain abundant calcareous nanno-fossils and planktonic foraminifera.

Hajikazemi et al. (2003) identified several species of microfossils in the Sirri field in the Persian Gulf which include; *Pseudolithonella reichelli, Marsonella* Sp. *Hemmicyclamina sigali, Textularids, Chryssalidina* Sp. *Nezazatinella piccardi, Globigerina pseudoampliapertura* and *Hetrohelix* Sp.

Facies analysis indicated that the Ilam carbonates have been formed in tidal flat, lagoon and bar environments. In the Izeh area six microfacies were

identified consisting of mudstone with bird's eye structures, bioclast pelloidal packestone, bioclast mudstone-wackestone with bioturbation, pelloidal grainstone, ooid grainstone and intraclast ooid grainstone (Adabi and Moradi, 2005).

The deeper water sedimentation in Lurestan continued through Coniacian to provide the shales and thin argillaceous limestones of the Surgah Formation. The argillaceous limestones of Ilam Formation of Santonian to Campanian age succeeded this. The subsequent transgression of the sea ubiquitously produced the marls and shales of the Gurpi Formation.

Upper Cretaceous Surgah Formation (uppermost Turonian to Santonian) includes the Laffan shales of northern Persian Gulf refers to a thin interval (~150 meters thick) of calcareous and pyritic shales with minor intercalations of thin-bedded calcarenite and micritic limestone; interpreted as the initial deposits of the back-bulge depozone of the pro-foreland basin.

Still farther to the southwest, the Surgah grades laterally into time-equivalent Laffan Formation (lowest part of the Aruma Group) in the UAE, Qatar, and Bahrain, and into the Khasib and Tanuma Formations in Kuwait and southern Iraq. These units onlap underlying weathered older strata and pinch out against a regional subaerial unconformity that is well documented in the stratigraphy of the southwestern Persian Gulf, as well as in Saudi Arabia (Steineke et al., 1958; Powers et al., 1966; Jones and Racey, 1994).

Gurpi Formation

The Gurpi Formation is found throughout most of southwestern Iran, although the age range of the formation is variable; it extends from Santonian to Maastrichtian in Fars region and parts of the Dezful Embayment area and from the Campanian to Paleocene in the Lurestan.

In the Late Cretaceous, the hemipelagic sediments of the Gurpi Formation filled the fore deep, while shallow-water carbonates of the Ilam Formation accumulated on the forebulge and the calcareous argillites and argillaceous lime mudstones of the Surgah (or Laffan) were deposited in the back-bulge depozone.

The Gurpi Formation consists of thin-bedded, deep-marine, *Globigerina*-bearing pelagic marl (and marly limestone) and hemipelagic claystone; foredeep facies (resting unconformably on Sarvak and onlapping Ilam) resulting from prograde southwestward migration of proforeland depozones. The thickness of Gurpi is about 320 meters at its type section north of Masjed-e-Sulayman (Setudehnia, 1972). The southwestward onlapping relationships between Gurpi and Ilam Formations, as well as Ilam and Surgah Formations are thought to reflect the southwestward migration of the basin depozones.

In the external part of the Zagros Fold-Thrust Belt, near the Zagros deformational front, the Gurpi Formation unconformably overlies shallow-marine limestones of the Ilam Formation, which includes several hematite-stained

subaerial intra-formational disconformities and disconformably overlies argillites, argillaceous lime mudstones, and wackestones of the Surgah Formation.

It overlies the Ilam Formation with minor disconformity, and underlies the Tertiary (Pabdeh Formation) with the contact placed at the base of sandy, silty, purple shale forming the lowermost Pabdeh. The Gurpi Formation is well developed in the eastern part of the Persian Gulf area. The Gurpi shale overlies the Ilam limestone. Its lateral facies, changes to shallow water facies which are extended to Fars region of the northern Persian Gulf. In its type section in Kuh-e-Gadvan the Gurpi Formation consists of massive limestone with shell fragments and anhydrites.

Based on the drilled-wells information the Gurpi Formation was deposited almost everywhere in the Persian Gulf with the exception of the area around the Qatar-Gavbandi Arch in the central part of Persian Gulf. Thickness of Gurpi Formation increases eastward as exceeding about 500 meters near the Hormoz Strait. The isopach map of the Gurpi Formation in the northern Persian Gulf area has been presented in Figure 3-41.

In two of the drilled wells in the Persian Gulf, Gurpi and Tarbur have facies interference. In well HD-1 north of the Larak Island the sequence is 1192 meters thick. South of the Qeshm Island the thickness reaches 340 meters whereas in south of the Hengam Island the thickness is 635 meters of the Gurpi deep water facies and there is no sign of Tarbur limestones. Only in Qeshm Island horizons of Tarbur limestones with bentic microfossils have been reported. Approaching the Qatar-Gavbandi Arch and also Ferdowsi and Kharg fields the Gurpi Formation is missing.

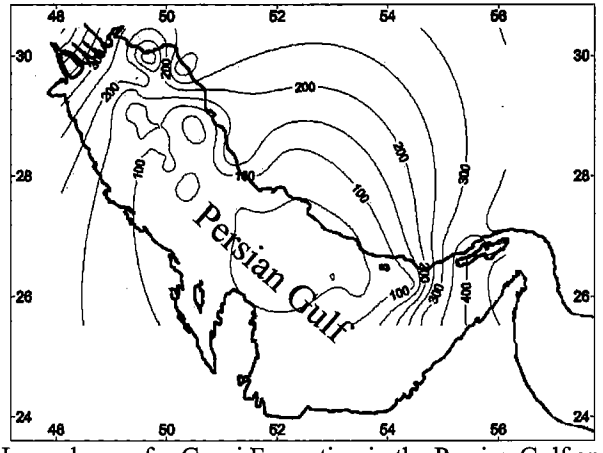

Figure 3-41. Isopach map for Gurpi Formation in the Persian Gulf and its northern regions. Counter line represent 100 meters interval (Peimani, 2003).

In well HEE-1 the Gurpi Formation attains it maximum thickness (i.e., 635 meters) but there is a lack of fossil and only *Globotruncana arca, G. stuarti* and *G. elevata* sp and *heterohelis* sp have been reported. In the Salman field

the thickness of Gurpi Formation is 186 meters. Westward in the Persian Gulf, in addition to the disappearance of the clastic facies, the thickness of Gurpi Formation decreases substantially and in Sirri field where it reaches 236 meters. Further to the west, and east of the South Pars Field the thickness of Gurpi reaches 21 meters. The Gurpi Formation towards the southern regions of the Persian Gulf changes to carbonate sequences with very minor facies variations.

In the Iranian coastal and offshore areas the marly limestones of the Gurpi Formation were deposited in a mainly neritic environment. Overlying the Gudair or the Lower Aruma in coastal Arabia and Kuwait areas, Gurpi equivalents, the Upper Aruma and Bahrah-Tayarat, consists of limestones with minor shale interbeds. On the Arabian side of the Persian Gulf the carbonate of Bahrah-Tayarat Formations are somewhat dolomitic and the Tayarat in particular shows secondary dolomitization. The contact between Gurpi and the underlying Ilam (Gudair) is unconformable. However, this unconformity is not distinguished in the Saudi Arabia where the entire Upper Cretaceous interval is referred to as the Aruma group.

Tarbur Formation

This formation is named after the village of Tarbur in Fars region in northern Persian Gulf with the type section about 1.2 kilometer from the village. Previously, this formation was called "Maastrichtian" or "Upper Cretaceous limestone".

Tarbur Formation of Maastrichtian age is composed of thick-bedded to massive, locally rudist-bearing and partly reefal, shelly anhydritic limestone with a basal polymict conglomerate (1-2 meter thick). It unconformably overlies ophiolites and Amiran erosional products of the wedge-top depozone to the northeast, but to the southwest it grades laterally initially into deep-marine lime-mudstone and afterward to the Gurpi clastics of the foredeep depozone.

To the northeast of interior Fars, a thick sequence of deep-water sediments, known as the radiolarites accumulated during late Cretaceous time, partly in conformity with the older shelf carbonates and partly in an oceanic basin further to the northeast. The sedimentary condition prevailed in the basin at this time indicate that similar conditions existed in the Zagros region at time of sedimentation. The only difference is that the deposition of clastic materials in the Persian Gulf.

In the interior Fars, the deposition of shales and marls over the eroded surface of the Cenomanian/Turonian limestones continued from the Santonian to the latter part of the Campanian, when linear development of rudistic reef started. These developed very rapidly during the Maastrichtian to form the Tarbur Formation.

During the Middle Maastrichtian time, deep-facies foredeep carbonates of the Tarbur Formation expanded towards the hinterland (northeast), and the

time-equivalent shallow-marine reefal carbonates transgressively covered subaerially exposed ophiolites and Amiran siliciclastic sediments.

Northeastward retrogradational migration of the foredeep and associated depozones of the proforeland basin is interpreted as a response to intensified thrust stacking and consequent enhanced loading of the lithosphere along the edge of the Afro-Arabian continent as it began to collide with the Iranian plates. Thus, the initiation of the collisional episode of the Zagros orogeny is considered to be a Middle Maastrichtian event (68 Ma).

Upper Cretaceous of the Southern Persian Gulf

During the early Late Cretaceous, widespread clastics of the Aruma Group were deposited in the southern Persian Gulf following a major erosional emergence in the Turonian. The deposition of Upper Cretaceous Aruma Group took place over a period of 25 m.y. (Harris et al., 1984). The Aruma Group related to a major transgressive-regressive sequence, the maximum flooding surface of this sequence represented in the Lower part of the Khanasir Limestone Member by ammonite-rich unit. The formations which belong to the Aruma Group are the record of a shallow-marine transgression across the partially eroded surface of the underlying Wasia Group.

The Aruma foredeep formed while a westward-migrating tectonic high passed through the northern UAE. These events were the combined result of the subduction at the Arabian continental margin in Mid-Cretaceous time and the associated sediment loading of the continental lithosphere (Patton and O'Conner, 1988). Thus, syntectonic Aruma Group was deposited during the Campanian to Maastrichtian. The post-emplacement period was followed by the deposition of the Tertiary and Quaternary cover rocks, and the Miocene Zagros collision event.

Based on regional geologic investigations in the southern Persian Gulf and Oman, Robertson (1987) and Patton and O'Connor (1988) suggested that the area had been uplifted due to the growth of a peripheral buldge associated with the obduction of the Semail Ophiolite. Subsequent collapse of the bulge and deepening of the foreland basin (Aruma basin) due to continued nappe emplacement in Coniacian-Maastrichtian resulted in the deposition of Laffan, Muti and Fiqa Formations, which overlie the Upper Sarvak (i.e., Mishrif) and Shilaif Member throughout the area.

The sediments of Aruma Group have the most complex lithofacies patterns and thickness changes of any of the major Cretaceous rock units in the southern Persian Gulf. The lateral and vertical changes are the result of a complex interplay of; a) regional subsidence, b) plate collision and partial subduction to the east, c) eustatic sea-level fluctuations, and d) differential sedimentation rates. In particular, many of the Hercynian faults bounding the major north-south uplifts in central Arabia were reactivated especially during the Late Cre-

taceous, as indicated by dramatic thickening of the Aruma Group on the flanks of these uplifts (Kornet et al., 2001).

The deposition of the upper Cretaceous Aruma Group began with the transgressive Laffan shales and its lateral equivalent Halul Formation, which lie unconformably on the Wasia Group. The Laffan basal transgression deposits, contains thin beds of limestone, dolostone and marl. It composes mainly of slightly calcareous shale, lies at the base of the Aruma Group. The lower Laffan and Halul Formations of Aruma form the initial transgressive cycle, whereas the Fiqa-Simsima cycle is more directly related to tectonic events (Alsharhan and Nairn, 1997).

The Halul limestone and marls were deposited in Santonian to early Campanian and are related to two sea-level rises during this time (see Haq et al., 1988). As with the rest of the Upper Cretaceous Fiqa, Simsima, and equivalent formations, deposited during the Campanian and Maastrichtian, it is difficult to recognize the tie to worldwide sea-level events.

The Halul Formation is overlain by the Fiqa Formation, which composed of calcareous shales, marls, and argillaceous limestone with a deep marine fauna. It is followed by the Maastrichtian Simsima Formation, which is composed of fossiliferous and shaley limestone and peloidal-bioclastic packstone and wackestone and dolomitic limestone with coral and rudist buildups (Schumann, 2000).

In Santonian time, a neritic carbonate shelf developed over much of the Persian Gulf. The Halul Formation represents the shallowing of epeiric seas with the occurrence of high-energy shelf limestones on top of the formation. Renewed subsidence together with transgression in the Campanian resulted in the deposition of basinal shales and limestone of the Fiqa Formation. Thus, by the Campanian time Fiqa formation was deposited, the foreland region was being affected by a major compressional phase in response to emplacement of the Oman Mountain ophiolite thrust sheets. This caused folding and subsequent wrench faulting that took place on reactivated, deep-seated WNW-trending lineaments. Wrench faulting and folding in southern Persian Gulf and thrusting along the Oman Mountain front ceased at Maastrichtian. It had created the anticline structures of the present-day major oil and gas fields and had created crestal erosion and thickening of the Fiqa on their flanks.

The Lower Fiqa Formation was deposited as dominantly hemipelagic fine terrigenous fill in the subsiding Omani fore-deep through and as the westward extension of these fine clastic sediments. Non-calcareous shales form characteristically the lower part of the Fiqa. Deep-sea clastic facies equivalent to the Lower Fiqa and basal Upper Fiqa are termed the Muti Formation. The Muti probably represents erosion of uplifted carbonates on an older cratonal marine to the east.

Basin shallowing led to the deposition of the neritic shoal and shelf carbonates of Simsima Formation. Shallow marine Simsima carbonates conformably overly the Fiqa Formation. The Maastrichtinan Simsima Formation

filled part of the residual morphology over the major tectonic structures. It is thicker in the west due to isostatic uplift of the eastern area during the Maastrichtian that caused exposure. The shelf breaks of the shallow Rub' Al-Khali Basin and the Lurestan intrashelf basin of Iran are marked by carbonate shoal deposits that merge basinward into bioclastic micrites with oligiteginid and pelagic foraminifera. Rudist facies are recorded from most of the fields all around the northern end of the Persian Gulf (Ziegler, 2001).

The Simsima Formation from the northwest Oman Mountains and UAE consists of cliff-forming, massive to well bedded, often nodular, bioclastic packstones and grainstones with minor wackestones exhibiting great species diversity and representing shallow open marine depositional conditions. The Simsima Formation contains a wide range of fauna. The limestones are rich in foraminifera (e.g. *orbitoides* sp. and miliolids) as well as rudist scaleractinia, and echinoderm platelets and spines.

Smith et al. (1995b) established the paleoenvironmental setting of Simsima sediments and concluded that the succession was deposited during a single sea level cycle and that the basal transgression preserved beach hardground faunas and substantial shoreface sands. Shallow water offshore sediments deposited below storm wave base make up the majority of the low beds. The upper strata are composed of semi-reclining rudists and well-sorted calcarenites deposited on stable shoals above active wave base.

The Simsima Formation represents the last sedimentary event in the Cretaceous, and is bounded at its top by a regional Cretaceous/Tertiary unconformity. Its deposition is interpreted to have been on a shallow carbonate platform, composed mainly of forminiferal packestones, wackestones and dolostones with shaley limestones and black organic shales with some dolostones. The Aruma Group was apparently affected by epeirogenic movements punctuated by sea-level changes (Scott, 1990). A late Maastrichtian regional unconformity marks the boundary between the Cretaceous and Tertiary.

The Significance of Cretaceous Rudists

The geologic history and locations of the rudist-bearing formations in the Persian Gulf are relevant to hydrocarbon occurrences because they have high primary porosity.

In the Lower and Middle Cretaceous of the Middle East and particularly in the Persian Gulf region the dominant framework reef builders have been the rudists. Generally, rudists are common components in the Cretaceous carbonates of the Persian Gulf basin. The peculiar, asymmetrical pelecypods, with a coral-like appearance, grew in colonies in shallow, warm waters of the Cretaceous, especially during the Lower and Middle Cretaceous (Albian-Turonian). They built reefs and formed hydrocarbon reservoirs with high permeability and porosity.

Rudist bivalves are among the most characteristics and abundant macrofaunal elements in Cretaceous Tethyan carbonate-platform deposits. Growing either upright forms implanted in sediments (elevators) or lying prone on the surface as sub-strate hugging clingers, or free-lying recumbent, vast congregations of their shells formed extensive biostromes interbedded with related bioclastic units, together constituting rudist formation.

The diversity of rudists in lower Cretaceous carbonate platform deposits in the Persian Gulf basin offer much potential both for biostratigraphy and for paleo-environmental analysis, and hence for the development of facies models for production development. In relation to biostratigraphy, the uppermost Barremian to Lower Aptian interval is especially well marked by a diverse fauna. With respect to paleoecology, distinct biofacies becomes especially evident in the Dariyan Formation and it's stratigraphically time equivalent Shuaiba Formation reflecting the diversity of rudists present.

Philip (1998) referred to the decrease in rudist population during the Late Maastrichtian as a "stepwise diachronism"of rudist's extension that occurred during the substage. About the Maastrichtian of the Middle East area, Steuber and Loser (2000) stated that the extinction of rudists probably occurred in Late Campanian and Early Maastrichtian.

On the Arabian Platform, Ozer (1993) noticed the difficulty of assigning ages to Maastrichtian strata using various biotic groups and the difficulty of assigning ages on the basis of stratigraphic positions. He noted that rudists occur in the Arabian Maastrichtian deposits often as reworked individual, with ages that span from the Middle through the Late Maastrichtian.

MESOZOIC CLOSURE

The end of the Cretaceous is defined by a regional unconformity that forms the boundary between the Upper Cretaceous and Tertiary successions in the entire Persian Gulf. Therefore, the Cretaceous-Paleocene transition period was one of widespread regression, which bared most if not all of the region, permitting very uneven erosion of different areas, but producing in most localities quite marked evidence of disconformity in sedimentation.

The Alpine Orogeny was the result of the closure of Mesozoic Tethys and the deformation of its continental margins. Increased plate movement and higher rates of sea-floor spreading world-wide during the Middle Cretaceous signaled the beginning of the plate-margin tectonics and the closure of the Neo-Tethys (Hays and Pitman, 1973).

During Turonian time, a major regional emergence and lack of deposition occurred throughout the region. The closure of the Neo-Tethys was accompanied in late Cretaceous by the destruction of the Mesozoic passive continental margin and the emplacement of the Triassic and Mid-Cretaceous oceanic sedimentation and crust on the shelf margin, forming the Oman Semail ophiolites and Hawasina nappe complex to the NE (Glennie, et al., 1974). In front

of this nappe complex, a Late Cretaceous flysch foredeep (foreland basin) developed on the subsiding broad continental margin (Glennie, 1974).

The major tectonic phase of the end of Cretaceous is clearly evidenced tectonically and sedimentologically by flysch along the northern, eastern and northeastern margin of the Peninsula. End of Mesozoic was also marked by a marine transgression, which increased from Coniacian to the Maastrichtian. The distribution of sediments and the related facies was mainly structurally controlled. This was the period of emplacement of ophiolites and radiolarites. The origin of these formations is still under discussion for they are regarded as autochthonous by some and allochthonous by others.

Within the framework of plate tectonics a great number of hypotheses have been proposed to explain these sedimentary and orogenic phenomena. These hypotheses offer tempting models, but, often contradictory; in addition, they leave unexplained important features.

A variety of alternative explanations for the evolution of the Afro-Arabian margin and its collision and/or suturing with the Turkish-Iranian portions of the Eurasian plate exist. The bulk of these agree however that the principal event which led to ophiolite/radiolarite emplacement occurred in the late Cretaceous and prior to Maastrichtian, deposits of which unconformably overlie the ophiolite/radiolarite suits in a variety of places.

Evidence of pre-Maastrichtian emergence and reworking is seen in a number of places and marginal flysch troughs appear to have developed adjacent to these uplifts, but this was short-lived and orogeny was aborted. These could have been, perhaps, because the compression was being taken up by closure of the small ocean basins surrounding the micro-continents of central and eastern Iran, as suggested by Takin (1972), or to accretion of the island arc with which the leading edge of Arabia may have collided (rather than with a continent) and continuation of subduction beyond this zone. Evidence for shallow marine to continental sedimentation in the Maastrichtian to Early Tertiary immediately following nappe emplacement, led some workers (Takin, 1972; Stocklin, 1974; Berberian and King, 1981) to suggest that continental collision occurred along the Zagros Suture in the Late Cretaceous, where others (e.g., Sengor and Kidd, 1979) argued that the collision of Arabia and Central Iran did not take place until the Mid to Late Tertiary.

Regionally, general uplift and erosion marked the late Maastrichtian and early Paleocene and that the Eocene normally rests on various older formations with marked unconformity, including some flysch-like Paleocene in deep troughs. Thus, a regional unconformity, which caps the Cretaceous lithologic sequence, was formed in the Upper Maastrichtian and marks the boundary between the Cretaceous and Tertiary formations. This Paleocene folding corresponds to the first Alpine folding.

CENOZOIC OF THE PERSIAN GULF

INTRODUCTION

The Cenozoic stratigraphy of the southwestern Iran, Arabian Peninsula and to a lesser extent the Persian Gulf has been the subject of detailed study ever since the first petroleum reservoir (Oligo-Miocene carbonates of Asmari Formation) was discovered at Masjed-e-Suleyman in southwestern Iran in 1908. The recognition that several richest oil fields in the Middle East occur in the younger Cenozoic rocks in the Persian Gulf region, makes the understanding of the stratigraphic evolution of the region of prime importance.

The stratigraphy of the Persian Gulf region is highly compatible with that of the entire region. In this context, one of the earliest systematic accounts of the stratigraphy of the Zagros fold-thrust belt was that of James and Wynd (1965), which included only Mesozoic and Cenozoic units. More recent research has added considerable amount of information which require a more comprehensive analysis and major revision of the stratigraphy of the region. Specifically, it is now well-established that a significant part of the stratigraphy of the Zagros fold-thrust belt developed in an epicontinental, synorogenic foreland basin, whose evolution has been intimately related to the tectonic and structural events of the associated Zagros orogen.

The main Cenozoic sedimentary sequences consist of Paleocene-Eocene shallow water limestone and dolostones (i.e., Sachun-Jahrum) and basinal marl and marly limestone (i.e., Pabdeh Formation). The Oligocene-Miocene Asmari and Gachsaran Formation are of shallow-water, neritic limestone.

General aspects of the Cenozoic stratigraphy of the Persian Gulf region have also been discussed by Henson (1938, 1951), Lees (1950), Dunnington (1958, 1967), Kamen-Kaye (1970), Beydoun and Dunnington (1975), Murris (1980, 1981), Adams et al. (1983) Beydoun (1986, 1988, 1991) and Motiei (1996, 2003). Published works on the Cenozoic stratigraphy of the Persian Gulf and adjoining area include those of Thomas (1950, 1952a,b) BP (1956), Falcon (1958), Bozorgnia (1964), James and Wynd (1965), Wynd (1965), Mina et al., (1967), Sampo (1965), Hull and Warman (1970), Kalantari (1972, 1986) Stocklin and Setudenia (1972) Rahaghi (1984), Stampfli et al. (1978), Kashfi, (1980), Mojab (1982) and Ross et al. (1986).

DEVELOPMENT HISTORY

From the opening of Neo-Tethys during Triassic, through the Jurassic and the Early Cretaceous, the Persian Gulf and the Arabian platform were parts of the passive northern margin of Gondwana, and the sites of principally carbonate deposition. With the continuing subduction of the Arabian plate under Eurasia, Neo-Tethys narrowed until in the Late Cretaceous when ophiolites were emplaced as the two plates collided. The process involved the incorporation of small cratonic masses according to Takin (1972), Stocklin (1974) and

Stoneley (1974). Subsequent formation and uplift of the Zagros Mountains was accompanied by the imposition of the Zagros foreland basin over the edge of the old Arabian carbonate platform during the Late Cretaceous and Cenozoic.

The geologic development history of the Cenozoic is thus one of the progressive restrictions of the Arabian platform, and is divisible into two phases, Paleocene and Neogene, separated by Neogene tectonic activity, and illustrated by distribution of the sediments outcrops.

A distinction can be made between the Paleogene and Neogene history of the Persian Gulf region. The conditions which existed during the Paleogene time were essentially the prolongation of those existed during the greater part of the Mesozoic. On the other hand, the Neogene marks the onset of a new tectonic environment which exists today with a foredeep, imposed over the old Mesozoic shelf margin. The sedimentary basin was gradually being filled with sediments transported along its axis.

The Neogene folding of the foreland basin sediments led to the development of structures and traps which host many productive giant and supergiant oil and gas fields. The majority of the fields show a characteristic northwest-southeast trend parallel to the fold axes and contesting strongly with the north-south trend or the equi-dimensional shape of the older fields on the Arabian Platform.

Collision of the Arabia-Eurasia was preceded by Campanian-Maastrichtian ophiolite obduction onto the Arabian passive continental margin (Stoneley, 1990). Continental collision probably began in the Oligocene at the northern promontory of the Arabian plate (Yilmaz, 1993). Rebound of the Arabian margin following emplacement of ophiolitic allochthones in the embayment in Late Cretaceous (Maastrichtian) lead to accelerated erosion, sediment loading and a general widening of the foredeep. Deformation stopped rapidly during the Late Cretaceous when a new subduction zone developed in offshore Iran (Le Metour et al., 1995). Stable conditions characterized the Early Cenozoic.

West of the Musandam Peninsula, Arabia and Eurasia are colliding. The process of collision commenced in the Oligocene or Early Miocene with the Zagros Mountains beginning to form in the Mio-Pliocene. Precambrian Hormoz salt deposits seems to have acted as a plan of decollement between basement and overburden, above which long anticline folds of younger strata are pierced by many diapirs.

Thus, based on the development history presented here, the northeastern margin of the Arabian platform seems to have been deformed into the Zagros parallel to the present day Persian Gulf, which achieved their current stature only during the Neogene.

Persian Gulf Geologic Setting during Tertiary

The Cenozoic history of the Persian Gulf region commenced with a major regression at the end of Maastrichtian (i.e., Danian boundary) leaving most of the Persian Gulf including the Arabian Peninsula emergent with the exception of the basinal areas specially the Pabdeh Basin and northern part of the Persian Gulf, the Zagros Basin of southeastern Iran.

Regional folding in Late Cretaceous-Paleocene time produced a regional unconformity at the base of the Tertiary, throughout the greater parts of Iran. A definite regional unconformity between Cretaceous and Paleocene has also been reported in several areas in the Persian Gulf region (see Power et al., 1966). This hiatus marking a major sequence boundary is recognized in Cenozoic carbonate strata throughout the Arabian Platform and Persian Gulf at the base of Tertiary (Danian to lower Selandian) separating the Tertiary from the Upper Cretaceous. This hiatus is often regarded as being of short duration.

Major Early Paleogene transgression reestablished marine conditions over eastern Arabia and the entire northern part of the shelf extending over the Zagros trough (Buday, 1980). Marine environments remained throughout Paleocene time in flysch troughs and subsiding shelf area particularly in the Zagros Basin. During Lutetian stage, flysch troughs continued to subside along the zone between Zagros and central Iran. These conditions prevailed into the Early to Mid-Eocene, and only some areas such as western Saudi Arabia, parts of the uplifted ranges of Iran and Iraq, and the Semail and Hawasina nappes in the Oman Mountains remained emergent.

Emplacement of the ophiolites caused the depression of the margin and as a result created a foredeep. The flysch at some localities consists almost entirely of radiolarite and some ophiolite debris. The present scattered flysch deposits along the northern margin of the High-Zagros suggests a seaway from northwest of Makran to the present Main Zagros reverse fault line to northwestern Iran.

The flysch/shale apron aggraded up to several hundred kilometers away from the allochthons. The margin slowly stabilized and as the foredeep increasingly filled, the flysch/shale/carbonate system withdrew northeastward towards the allochtnones. Flysch sedimentation eventually gave way to finer clastic materials and the carbonate bank (Asmari) once more began to build out to the northeast over the Amiran foredeep. The source for clastic sedimentation remained from the north.

Amiran Formation (Upper Cretaceous, Maastrichtian and probably older toward the northeast) consists of polymict siliciclastics composed mainly of ophiolitic detritus, in addition to lime-clasts and recycled conglomerate cobbles, with syn-deformational growth strata. The presence of cannibalized and re-incorporated pebbles, cobbles, and boulders of Amiran conglomerates, as well as the existence of growth strata in this formation, suggest that the proc-

esses of uplift and thrust faulting were still in progress during deposition of the Amiran Formation.

The earlier Amiran foredeep was imbricated and carried piggy-back on the developing fold belt. The resultant facies that developed in response to this include from northeast to southwest, molasse of the Razak Formation, Asmari Formation limestones, Pabdeh shales and proximal to the Arabian shield, Ahwaz sandstone. Subsequently, evaporitic formation of the Gachsaran succeeded the Asmari in the new Zagros foredeep that developed in front of the orogen encroaching from the northeast. These eventually gave way to northeast-derived clastic sedimentation (i.e., the Agha Jari Formation) shed from the upwelling orogen. Deformation across the Zagros intensified at the end of Miocene, based on the widespread appearance of coarse terrestrial clastic deposits (Bakhtiari Formation), which were deposited concurrently with the growing folds (James and Wynd, 1965; Mina et al., 1967).

Foreland basin sedimentation resumed when continent-continent collision occurred along the Zagros Sutur in the Oligocene. There seems to be slight doubt that the Zagros Basin is a foreland basin that reflects attempted subduction of the Arabian plate beneath Uromieh-Dhotar block. Dickinson (1974b) and Stoneley (1994) suggested that the late Miocene change from Asmari Limestone to Gachsaran evaporites records restriction and drying up of the basin during emergence caused by isostatic uplift as the Arabian plate resisted further subduction. Falcon (1974) argued that the rapid change to evaporitic conditions at the end of deposition of the Asmari Formation during the Lower Miocene indicated the onset of tectonic activity in the Folded Belt.

In Zagros the residual Tethys was entirely closed by Oligocene-Miocene time. A rapid shift in sedimentation towards more detritic facies (the Mishan and Agha Jari Formations) marks the passage from passive margin to foreland basin conditions on this part of the Arabian margin and the onset of collision between the Arabian and Iranian Plates (Hessami et al., 2001; Sherkati, 2005).

This timing is consistent with the opening of the Red Sea, with intense deformation along the Arabian-Iranian Suture (known as the Zagros Crush Zone; Wells, 1969), and with similar events in the Kashan-Gavkhooni Basin on the opposite side of the Suture. Wells (1969), Stoneley (1974), and Gealey (1977) related the fold belt and crush zone to the Red Sea spreading. Dickinson (1974a) termed this type of basin, formed on the downgoing continent in a continent-continent collision, a "peripheral" foreland basin in order to differentiate it from foreland basins on the overriding continent to from foreland basins behind magmatic arcs. Cherven (1986) preferred the term "suture" basin, emphasizing the genesis of the basin along the suture belt and the causality of the suturing process. Many of the Tertiary basins along the Alpine-Himalayan chain are of this type.

In summary the downward flexure of the Arabian Peninsula underneath the Zagros Mountains of Iran and Iraq to form basin was caused by the northeastward consumption of the Tethys Ocean at the Zagros suture zone and

eventual Cretaceous-Holocene convergence and collision of the Arabian plate against the Eurasian Plate (Hessami et al., 2001). This prolonged convergence event has created the Persian Gulf and Mesopotamian lowlands as a modern topographic foreland basin and the formation of the Zagros Mountains with the culminations of fold-thrust deformation in Miocene and Pliocene. The sedimentary fill of the foreland basin comprises the post-Zagros fold-thrust sedimentary succession of mainly upper Eocene to Holocene units and reflects the timing and duration of the main collisional events (Beydoun et al., 1992; Hessami et al., 2001). Giant fields of the Persian Gulf are concentrated in a large foreland basin formed during the late Cenozoic collision of the Arabian Peninsula with Iranian Plate.

FORELAND BASIN

In recent years, as a result of extensive geological mapping in various segments of the internal and external parts of the Zagros orogen, an improved understanding of the evolution of the Zagros Mountain Belt and its foreland basin has come into sight (see Alavi, 2004).

Foreland basins, as synthesized by DeCelles and Giles (1996), have attracted interest of many earth scientists. These basins are the sites of favorable conditions of hydrocarbon generation, migration, and accumulation. Additionally, they have also been the subjects of a considerable amount of stratigraphic, paleontological, structural, and geodynamic investigations.

The Zagros foreland basin being a specific type within the general category of the foreland systems (Willett et al., 1993; Johnson and Beaumont, 1995) is an integral part of the Zagros Fold-Thrust Belt. With all its economic significance, however, it has remained problematic.

Geological investigations of Zagros Fold-Thrust Belt have extended over nearly a century since the earliest petroleum discovery in the region, and many petroleum geologists have contributed significantly to a better understanding of the geology of this petroliferous tectono-sedimentary zone (Lees, 1950; Falcon, 1974; Dunnington, 1967; James and Wynd, 1965; Mina et al.,1967; Kamen-Kaye, 1970; Setudehnia, 1978; Murris, 1980; Koop and Stoneley, 1982; Beydoun et al. 1992; Hessami et al., 2001; Sherkati, 2005).

Through these contributions, the belt has repeatedly been referred to as a "foreland" or "foredeep" basin, however no detailed explanations have been offered for the stratigraphic architecture and various depozones, nor have any specific correlations been suggested between sedimentological evolution and related tectonic events that shaped the interior part of the orogen.

The foredeep is the classic expression of subsidence in front of the rising mountain in an unstable tectonic environment. However, in the Zagros and adjacent region, the period of maximum instability during Phanerozoic was at the close of the Tertiary. The area of the present fold belt was covered by a widespread shallow sea as late as Early Miocene (Asmari time). Restriction

began in post-Early Miocene time, and deposition of evaporites increased (i.e., Gachsaran). Initially, anhydrite was deposited and deposition of salt followed later (Kamen-Kaye, 1970). As the mountain front rose, Paleozoic and Precambrian strata were exposed and subsequently eroded providing sand and gravel to the foredeep and adjacent areas. The rise of the mountain front was accompanied by tectonic strain, which was released by yielding in those formations containing anhydrite and salt. The area of the present platform remained largely unaffected by forces which deformed the fold belt. However, as Figure 3-42 shows, the Tertiary isopachs of the platform parallel those of the foredeep(s).

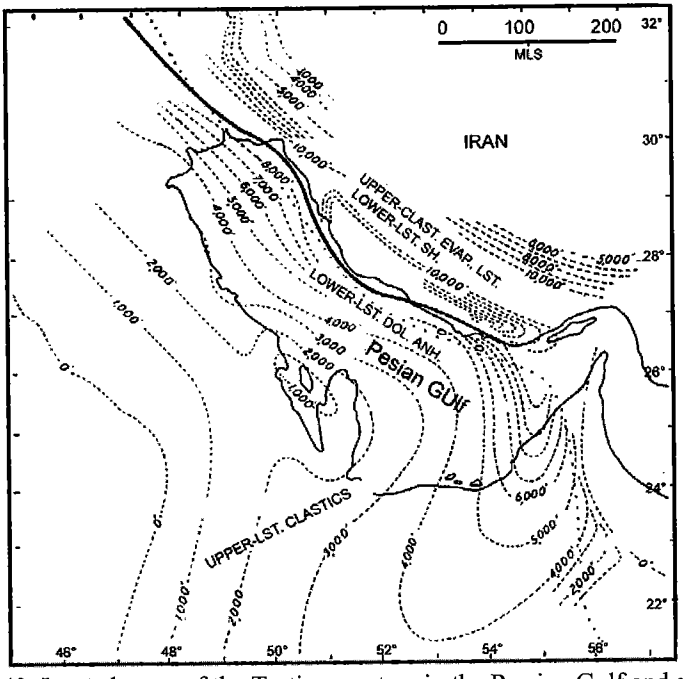

Figure 3.42. Isopach map of the Tertiary system in the Persian Gulf and suggested lithofacies providences. Contour interval is 1000ft. Thick line along eastern coast of the Persian Gulf marks presumed main Tertiary foredeep (Kamen-Kaye, 1970).

Other than minor folding, large areas of the foreland appear to be relatively undisturbed by the latest phase of Pliocene-Holocene (?) phase of Zagros-related convergent deformation that resulted in broad folds. This resulted in the formation of the giant, elongate fields proximal to the Zagros belt in Iran, Iraq, and beneath the Persian Gulf (Hessami et al., 2001). The tectonic setting of these elongate giants closely controlled by folds and thrust in the Zagros Mountain and foreland basin can be classified as a continent-continent collisional margin.

Continued subduction ended in continent-continent collision as the northeast margin of the Arabian platform came together with Eurasia and the intervening microcontinents of central Iran. The Sanandaj-Sirjan zone was thrusted over the distal portion of the Arabian margin juxtaposing low-grade metamorphic rocks of the Sanandaj-Sirjan zone against outer-platform rocks of the Arabian Platform along what has become known as the Zagros Main Thrust.

The Arabian margin must have been relatively high as it received comparatively little or no sedimentation during this time especially on the promontories. Subduction of the Arabian plate continued under Sanandaj-Sirjan zone, progressively destroying Neo-Tethys and amplifying igneous activity in the Sanandaj-Sirjan zone. Southern NeoTethys was all but closed by the Late Oligocene and the Sanandaj-Sirjan zone had tied up with the Arabian platform. The closing was dischronous, beginning earlier in the northwest and progressing to the southeast.

Paleocene- Eocene Sedimentary Environment of Persian Gulf

During the Paleocene and Early Eocene, a good deal of the Persian Gulf region and Eastern Arabian plate was a broad, shallow carbonate and evaporitic platform in response to withdrawal to the south of the Neo-Tethys Sea. Rocks of Paleocene-Eocene age were generally calcareous with typical shallow-water characteristics and lithologies. They differ in thickness, with a maximum-recorded thickness in the western part of approximately 330 meters; however, they are more than twice as thick to the east.

Paleocene-Eocene sediments unconformably overlie the Upper Cretaceous. The Early Paleocene transition period was one of the widespread regression, non-deposition or erosion associated with major inversion in most if not all the region, causing uneven erosion of different areas, but producing in most localities quite marked evidence of disconformity.

On the Iranian mainland the Pabdeh-Jahrum Formations represent the early Tertiary sequence. Pabdeh Formation in its characteristic facies primarily consists of *globigerina* marls, shales and thin marly limestones. A deeper trough in the early Tertiary Seas that covered the area of the Iranian oil fields was the location of the marly deposition (Mina et al., 1967). Bordering the trough appear the shallow water facies of Jahrum Formation consisting of massive limestones and dolostones with occasional anhydrites. In the location of the present Persian Gulf and Arabian coastal regions, lagoonal and shallow water porous limestone and dolostone and anhydrite represent the Paleocene-Eocene deposition (Mina et al., 1967).

In the foredeep toward the Zagros Mountains, clastic content of these units increased. Over the entire southern Persian Gulf, shallow-water, Paleogene platform sediments generally are assigned to three Formations of the Hasa Group, in ascending order the Umm Er Radhuma, Rus, and Dammam passing into the basinal facies of the Pabdeh Formation (Mina et al., 1967).

Eastern Arabia underwent uplift and subaerial erosion from the Oligocene into the Miocene.

The Umm Er Radhuma Formation is characterized by a thin basal bed of shales, capped by bioclastic, argillaceous carbonates deposited in a shallow marine setting. In the Lower Eocene, a wide evaporitic platform is represented by a sequence of restricted-marine evaporites and dolostones of Rus Formation. Thus, sabkha conditions developed over a wide area along a NW-SE axis from Iraq to Oman, parallel to the present Persian Gulf axis, giving rise to the anhydrite deposition. The depositional conditions remained almost unchanged in south-western Iran. The Paleocene-Early Eocene depositional environments and related formations deposited in various paleogeographic locations have been given in Figure 3-43.

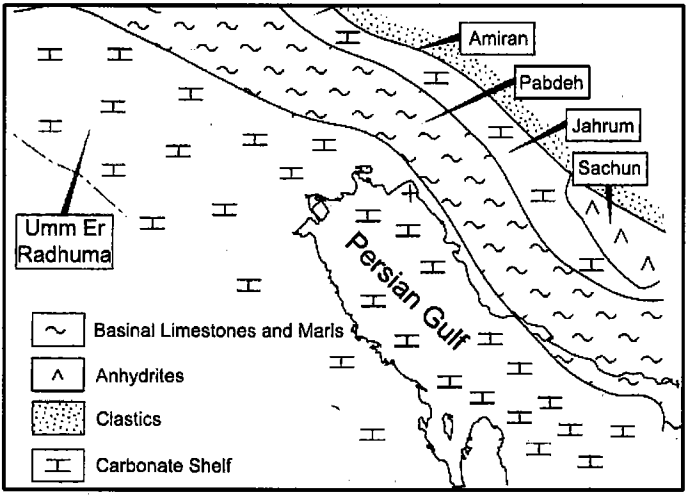

Figure 3-43. Paleocene-Early Eocene gross depositional environments and facies (Modified from Mina et al., 1967).

In the Middle Eocene, open marine shelf environmental conditions led to the thick development of *Nummulitic* shallow-water carbonates of the Dammam Formation. Due to transgression in the southern Persian Gulf and the Arabian Peninsula, sabkha conditions were replaced by a shallow marine neritic environment where the Dammam Formation sediments rich in *Nummulites* and *miliolids* were deposited. Local sabkha conditions, on the other hand, continued in the central and northern part of Kuwait, where thick deposits of anhydrite formed.

Deep marine conditions continued to prevail in southwestern Iran, where Upper Pabdeh Formation was laid down. The time period from the Middle Eocene to Miocene was one of structural growth and non-deposition in the southwestern part of the Persian Gulf. Marine sedimentation continued in the Zagros trough in Late Eocene and Oligocene, although the western shelf became largely dry land.

Pabdeh marine shales, Radhuma limestones, and locally Sachun evaporites rest unconformably on Maaestrichtian Gurpi shales in northwestern Persian Gulf and Dezful Embayment areas. The Pabdeh sediments extend upward into the Eocene, terminated by a regional unconformity caused by the uplift associated with thrusting and folding of the Zagros Mountains.

There were two areas of deep water sedimentation, the Zagros and its continuation, the Khuzestan trough extending from Iraq to southeast and coastal Fars. These basins represent the continuing subsidence of the large Cretaceous foredeep, which extend from Oman through the southern onshore and offshore region of the Persian Gulf and the Fars region of Iran. Thus, there was a situation where the stable landmass of the Arabian shield to the west was bordered by an extensive carbonate shelf, which deepened towards the two eastern troughs partially separated by the shallow water carbonate Fars Platform. Towards the north and east of the Arabian Peninsula, the sedimentation gradually changes to argillaceous and marly facies of the Pabdeh Formation, significantly deepening of the basin occurs in this direction.

The Late Paleocene-Eocene witnessed the development of a foreland basin in response to a collision between the Arabian and Iranian Plates. Flysch and arguably molasse-type clastics and pelagic carbonates were deposited in the north and northeast. Shallow-water marine carbonates fringed the 'flysch' trough.

During the Late Eocene time, a widespread regression occurred and lasted through almost the entire Oligocene. Uplift producing local unconformities brought about the contraction of the Tethyan Seaway connecting the Indian Ocean with the Mediterranean. This widespread regression caused the greater part of the Zagros Basin (except for the most central part which include Lorestan where pelagic sedimentation was continuous) to emerge. The Paleocene-Eocene isopach-facies map (see figure-10 in Koop and Stoneley, 1982) shows a thin veneer of pelagic marls along the central axis of the basin where the carbonate margin and the mountain front foredeep persisted from Cretaceous. This regression is marked by a strong unconformity at the top of the Jahrum Formation and above the Dammam Formation in the stable shelf area.

The pre-Neogene unconformity, separating the underlying formations from the overlying Neogene sediments, is one of the most important erosional surfaces in the Tertiary sequence of the Persian Gulf. The unconformity determined the degree and extent of diagenesis particularly karstification of the underlying formation. This was rapidly followed by a transgression starting in early Oligocene. However, the interior Fars, northeastern Lorestan, and the Persian Gulf area remained above sea level for most of the Oligocene Epoch. On the stable shelf, however, the Asmari limestone in southwestern Iran was deposited in a shallow marine environment during the Oligocene and Lower Miocene, overlying the Pabdeh Formation with conformable contacts with minor breaks.

During late Eocene-Oligocene regression the troughs while not exposed, had almost disappeared as distinctive features and the upper two thirds of the Paleogene sedimentary succession in the troughs merged with the sediments on the bordering shelves. The paleogeography during this interval of relative tectonic calm between the two regressions once marine conditions were established did not vary significantly. The broad pattern has a stable landmass in the west bordered by an extensive carbonate shelf which deepened towards the two eastern troughs adjacent to tectonically active areas in Iran and Oman (Murris, 1980).

The last regional marine transgression took place in the Late Oligocene and Early Miocene (see Figure 3-44). The former Zagros basin had by then developed into a broad, shallow foreland basin in front of the rising Zagros chains. The sea covered most areas where carbonates of the Asmari Formation were deposited. Gradual narrowing of the northwest-southeast trending open marine basin of the Zagros owing to the convergent movement is evident throughout the Middle Alpine.

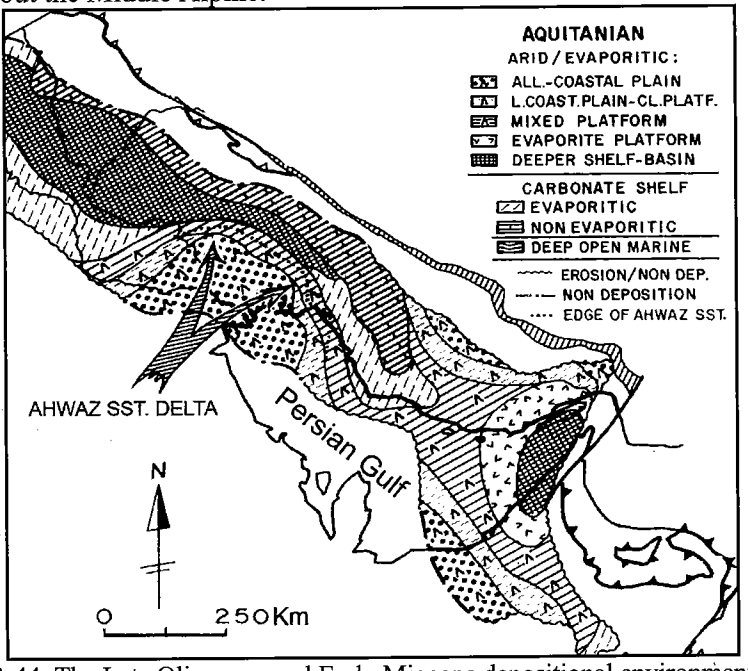

Figure 3-44. The Late Oligocene and Early Miocene depositional environments in the Persian Gulf and surrounding region (after Murris, 1980).

In southwestern Iran and also at the head of the Persian Gulf, the upper part of the Asmari Formation represents the facies equivalent of the Euphrates Formation. Towards the west, the Asmari Formation grades into the clastic Ghar Formation suggesting a change towards fluviodeltaic to continental environmental conditions.

During the Late Tertiary folding, the present day NW-SE giant anticline traps were shaped. The Campanian-Oligocene marls and shales, which until then formed an effective seal to the Cretaceous reservoirs, were fractured and hydrocarbons escaped upward into the Asmari traps, capped by very efficient seals of Gachsaran Evaporites of early to Middle Miocene age (Murris, 1980).

At the end of Lower Miocene, the orogenic activities ceased, and there was transgression of the sea to the northeast. Over much of the unstable shelf, the Middle Miocene deposition started with the shallow water reefal limestones of the Jeribe Formation in Iraq, and Mishan Formation in southwestern Iran. With renewed vertical block movements, lagoonal conditions re-emerged and a prominent thickness of lagoonal evaporitic sediments (Gachsaran Formation) was produced. When the Miocene sea ultimately withdrew, one of the most important salt deposits of the Persian Gulf region, Gachsaran Formation, and its equivalents formed.

With the progressive uplift of the northeastern part of the basin, the terrigenous components of the sediments increased towards the end of the Middle Miocene. In the western and southern Persian Gulf covering the eastern part of the stable shelf, the shallow marine littoral sediments with the terrigenous clastics of the Dam Formation were deposited in southern Persian Gulf. Continental (fluvial) clastics continued to be deposited over much of the head of the Persian Gulf during Middle Miocene, with some interfinguring with the Gachsaran towards the east.

The final phase of the thrust movements in the northern Persian Gulf region to the northeast and uplift in the stable shelf area occurred during the Upper Miocene-Pliocene, with the compensating progressive subsidence of the fore deep zone on the unstable shelf. The foredeep basin was filled in with coarse molasse sediments of the Bakhtiari Formation supplied by the rising orogenic belt to the northeast. In the SW of Iran, this phase started with the shallow marine to estuarine sediments of the Agha Jari Formation which were followed upward by the Bakhiatri sediments. In the southwestern part of the Persian Gulf basin, the clastics of the Dibdibba Formation in Kuwait and southern Iraq, and of the Hofuf Formation in Saudi Arabia, were mainly supplied by the uplifted stable shelf.

Pliocene deformation is characterized by continental collision in the Zagros Mountains. North-south continental subduction beneath the Zagros belt control the tectonic and sedimentary evolution of the area: the deflection of the Arabian platform allows the creation of a northwest-southeast foreland basin in the Persian Gulf dipping to the northeast.

At the end of the Pliocene, the foredeep area was uplifted, and molassic sedimentation came to an end. The present day Persian Gulf took it present shape during this period. This event resulted in folding with NW-SE trends and uplift in the Persian Gulf basin area. Fluvial sedimentation was prevalent in the Euphrates-Tigris valley, and aeolian sediments were deposited over part

of the Arabian Peninsula. The Plio-Pleistocene Zagros orogeny was the final major event in the history of the area and continued to the present.

Pabdeh Formation

Following the Late Cretaceous tectonic activities, the Paleocene-Eocene transgression resulted in deposition of neritic to basinal marls and argillaceous limestones of the Pabdeh Formation and Dammam limestones. Thus, in front of the shallow water Dammam Formation ramp carbonates the Pabdeh were deposited along practically the entire length of the foredeep basin (Sharland et al., 2001). Bathymetry in these deep basins was too great for carbonate productivity, resulting in deposition of fine clastics. Over the rest of the plate the shallow water ramp carbonates of the Umm Er Radhuma, Rus and Dammam Formations were deposited.

Pabdeh Formation of the upper Paleocene to the lowermost Oligocene is a thin-bedded grey and greenish blue (reddish brown near base), *Globigerina*-bearing deep-marine hemipelagic-pelagic calcareous shale, marl, and lime-mudstone with subordinate argillaceous limestone containing fish fossils; foredeep facies grading toward the northeast into sandy dolomitic limestone and toward the southwest into sabkha-type Jahrum carbonates. The unconformity again displays characteristics of a subaerial weathering surface, which is associated with a thin layer of hematite-stained, sandy and glauconitic shale or argillaceous lime mudstone. The Jahrum, in turn, extends southwestward toward analogous time-equivalent facies of the Umm Er Radhumma-Rus-Dammam Formations of southern Persian Gulf, which onlap and pinch out against a subaerial unconformity (Owen and Nasr, 1958; Powers et al., 1966).

In the type section the basal contact with the Upper Cretaceous Gurpi Formation is conformable, however in the northern Persian Gulf and in Fars region, there is a disconformity marked by the presence of a cherty limestone with shark teeth, glauconite, or even a local pebble conglomerate (Setudehnia, 1972). The upper contact with Asmari Formation is apparently conformable in the Zagros Trough, and there appears to be transition to clean limestones of the Dammam Formation.

The Pabdeh shales of southwestern Iran change facies into platform-interior carbonates (Umm Er Radhuma equivalent). In Fars region, foredeep sediments grade into a mixed Pabdeh (shale) and Jahrum (limestone) facies. The Jahrum appears to be directly comparable with Umm Er Radhuma Formation (Seyrafian, 1998).

The Oligocene marl deposition continued in the central part of the Zagros Basin from Iraq to northern Fars (upper Pabdeh Formation) with neritic carbonates (Asmari Formation) at the margins. A detla centered on head of the Persian Gulf extend towards the Dezful Embayment (Ahwaz sandstone Member). In Early Miocene the shallow water carbonates, and locally evaporites spread over the deeper marine marls and eventually over the Ahwaz delta.

In the Dezful Embayment region in northwestern Persian Gulf the Pabdeh Formation was described by James and Wynd (1965) and Setudehnia (1972) as an 870 meters sequence of calcareous shales with interbedded cherty limestones and marls. In this region, Pabdeh Formation, with a thin (1-3 meters), purple, sandy to silty and locally conglomeratic, shale layer at the base overlies the top of weathered, glauconitic, phosphorite-rich Gurpi Formation, representing a significant erosional unconformity. To the southeast, in Fars, the unconformity has the same characteristics, except that local erosion prior to deposition of the Pabdeh Formation removed not only the entire Late Cretaceous but also the underlying Sarvak carbonates. Thus, the basal strata of the Pabdeh rest directly on weathered and glauconitic calcareous shales of the Kazhdumi Formation (Alavi, 2004). Based on paleontological data (Wynd, 1965) the unconformity represents a hiatus of about 10 m.y. (Alavi, 2004).

Pabdeh Formation was deposited locally in northwest and eastern parts of the Persian Gulf. The lower Tertiary in the northern UAE is also represented by Pabdeh basinal shales. This formation has not been deposited in the central region of the Persian Gulf. The geographic distribution of the Pabdeh Formation in the Persian Gulf includes the area from the Sirri Island to the Strait of Hormoz. In addition, the thickness of the formation increases substantially from Sirri Island toward the Strait of Hormoz where the thickness reaches 2 km. As mentioned previously, the Pabdeh Formation is the shale-marl facies of the Paleocene, Eocene and Oligocene sediments. In the eastern part of the Persian Gulf shaly facies is well developed between the Sirri and Qeshm Islands. To the west of Sirri Island, the Pabdeh shale changes facies progressively into Jahrum-Dammam carbonates. At this locality the upper part of the Pabdeh Formation belongs to Oligocene and it is overlain by a series of evaporites and the Asmari Formation is missing. In Sirri-D field in the eastern part of the Persian Gulf, the thickness of Pabdeh reaches 457 meters whereas in west of the Farur Island the thickness is 327 meters.

The Pabdeh succession is virtually continuous in Iran and most places in the Persian Gulf however less complete in UAE. Consistent with its more marginal position in the trough, the Pabdeh Formation in farthest southeastern part of the Persian Gulf contains high carbonates, consisting of hemipelagic biogenic limestones, marl, calcareous shale and clay.

The Pabdeh Formation in northern parts of the Persian Gulf and southwestern Iran consists mainly of deep marine shales, marls and limestones which deposited in the Zagros and southern Persian Gulf troughs. The sediments of the Pabdeh Formation were deposited in a subsiding part of the earlier Cretaceous basin which extended from western Oman Mountains through both offshore and onshore region of the southern Persian Gulf into southern Iran.

Marls near the base of the Asmari Limestones in Iran (James and Wynd, 1965) and the UAE (Jones and Racey, 1994) are precisely age-constrained as early Oligocene. However, in southern Iran, initial transgression occurs within

the basinal Pabdeh Formation, into which Asmari Limestone prograde. The Asmari is thus underlain and laterally equivalent to (depending on location) the Pabdeh.

The Pabdeh Formation comprises pelagic carbonate sediments. It contains the index taxa *G. velascoensis*-G. *psudomenardi-G. rex*-G. *aragonesis-G. formosa*, *Truncorotaloides-Porticulasphaera-G. spinulosa-G. cerroazulesis-Hantkenina* and *Globigerinid-H. Slingeri Zeauvigerinal /Lepidocy-clina-Operculina* Zones, indicating a Paleocene-Early Oligocene age (Wynd, 1965).

Based on lithological characteristics, the Pabdeh represents deposition in a deep water, anoxic, bathyal environment in an overall transgressive sequence. The lower parts include predominantly black mudstones with common thin intervals of lighter color, faintly bioturbated wackestones deposited below normal wave base during periodic episodes of high energy. The higher energy intervals probably resulted from storm events or minor slope failures, which transported material from adjacent shallow shelf into deeper water.

Limited increased oxygen levels allowed burrowing organisms to rework the sediments before a return to anoxic conditions and deposition of black mudstones resumed. Upwards, mudstones become less well developed as distal flow facies, and thin shelf-derived wackestones increase in occurrence. Massive debris-flows represent deposition as the shelf sediments were being eroded or slumped into the basin (Reading and Richards, 1994). As deposition of the flows decreased these units became thinner and are interbedded with thin mudstones and wackestones of fairly deep-water origin.

Bordenave and Huc (1995) reported the presence of *oleanane* biomakers in oils from the Dezful fields, and attributed them to source rocks in the Pabdeh Formation. As these biomarkers suggest an input of terrigenous angiosperm material to the source rock, it is possible that the climatic conditions were humid during deposition of the Pabdeh Formation. The presence of plant remains in the lower part of the section, especially in the upper part of Purple Shale member, is consistent with this possibility.

The presence of phosphatic grains including intraclasts, foraminifera and ooids in the Pabdeh Formation suggests a strong upwelling system at the edge of the shelf associated with a fluctuating oxygen minimum layer. Phosphatization of foraminiferal tests has been described from different part of the Tethyan realm during the Paleogene (Baturin, 1980; Al-Bassam and Al-Allak, 1985; Prevot and Lucas, 1986). The presence of random trace fossils on bedding planes, such as escape borrows and low diversity Chondrites, implies oscillations in the free oxygen level, leading to the dominance of suboxic environments in the basin (see Mohseni and Al-Aasm, 2004).

The Pabdeh Formation and the underlying Gurpi Formation contain pelagic microfauna which are interpreted to have been deposited as a deep-water facies with poor reservoir characteristics (James and Wynd, 1965; Stoneley, 1990). In contrast to previous investigation which suggested that the Pabdeh Formation is dominated by pelagic shales, Mohseni and Al-Aasm (2004) pro-

vides evidence for the presence of shallow-water carbonates and marls in addition to the shales.

Facies analysis of the Pabdeh sediments (see Mohseni and Al-Aasm, 2004) indicates that facies evolved upwards from deep outer-ramp deposits to inner-ramp deposits within a shoal complex, suggesting progradation of the ramp depositional system. They were deposited in a deep ramp setting that laterally emerged into a shallow, storm-influenced ramp. Subsequently, shoreward, the formation gradually passes into a shoal complex with a back shoal setting and good circulation.

Storm events significantly influenced the ramp system. Storm-generated surges transported sediments from nearshore to deeper outer-ramp environment where they were deposited as shell-lag deposits. Sedimentary structures in the Pabdeh Formation are typical of storm deposits, such as hummocky cross-stratification, ripple cross-lamination, ripple marks, escape burrows on the tops of the beds, couplets of fine- and coarse-grained laminae and mixed fauna, as well as intraclasts derived from underlying facies. These distinctive sequences are interpreted to have been generated by waning storm-generated currents. The dominance of fine sediments; lack of large-scale hummocky cross-stratification; minor amounts of intraclasts derived from underlying facies; the paucity of amalgamated tempestite beds; and the finely-laminated couplets of coarse and fine lamina all suggest a distal tempestite facies.

In a sequence stratigraphic framework, the Purple Shale at the base of the Pabdeh belongs to a transgressive system tract beginning in the late Paleogene. The thin beds with a mixed fauna (shallow water and pelagic) and mud rip-up clasts of pebble size may represent a transgressive surface, above the Purple Shale. The final stage of the HST, in the Late Eocene-Early Oligocene, filled out the ramp with packages of shallow-water sediments typical of shoal facies. In the Lower Oligocene, evaporitic beds occur in the Pabdeh, implying a lowering of sea level in a regressive system tract. Some areas include pelagic deposits that are consistent right up to the contact with the Asmari. Thus, it can be concluded that most of the Pabdeh is characterized by TST and HST deposits. A regressive system tract may be indicated by the presence of evaporitic beds that terminate the Pabdeh (Mohseni and Al-Aasm, 2004).

Sachun, Kashkan and Shahbazan Formations

The uppermost Maastrichtian to Paleocene Sachun Formation comprises a variety of clastic, carbonate and evaporite lithologies. It contains the index taxa of the *Miscellanea-Kathina* and *Opertorbitolites* Zones, representing a Paleocene-Early Eocene age (Wynd, 1965).

The Sachun Formation is a dolomitic evaporitic sulfate bearing sequence, about 150 meters thick in Fars region of the northern Persian Gulf (James and Wynd, 1965). It is mainly consist of *Loftosia*-bearing argillite, shale, and also evaporites (i.e., mainly gypsum) deposited in restricted basins and intercalated

with thin-bedded dolostones; displaying rapid lateral facies changes, becoming richer in siliciclastic strata toward the northeast where it is overlain either by Kashkan conglomerates or by Shahbazan (previously "Jahrum") carbonates, and unconformably downlaps Tarbur carbonates toward the southwest.

Kashkan (Paleocene to middle Eocene) Formation which is composed of polymict conglomerate (containing ophiolitic detritus as well as pebbles and cobbles of carbonates, shale, and sandstone) grading progressively toward the southwest to sandstone, siltstone, and shale; a cyclically-deposited, syn-deformational, upward-coarsening fluvial siliciclastic wedge (having locally growth stratification) derived from the northeast.

The Sachun Formation is restricted to the northeastern internal part of the Zagros Fold-Thrust Belt, and consists of evaporites and thin dolostones interbedded with red shales and sandstones becoming sandier and more argillaceous to the northeast and interfingering in that direction with the Kashkan Formation. Based on the results of drilled wells within the Persian Gulf proper this formation has not yet been reported and presence of evaporites in Jahrum is not related to Sachum Formation. However future investigation might be more assertive.

Shahbazan Formation of Eocene age consist of thick-bedded *Nummulites*-bearing dolomitic limestone, locally sandy and argillaceous, forming a transitional facies between distal Sachun and Kashkan siliciclastics to the northeast and Pabdeh lime-mudstone and argillite to the southwest; includes a narrow belt of dolomite ("Jahrum" locally).

The Shahbazan Formation forms a transitional facies between fluviatile siliciclastic strata of the Kashkan Formation and deep-water facies lime mudstones, calcareous shales, and marls of the Pabdeh Formation. This progradational stratigraphic arrangement is inverted in the middle to upper Eocene part of the megasequence in which retrogradational Pabdeh Formation transgressively onlaps Shahbazan carbonates in a northeastward direction, and Shahbazan carbonates in turn overlie Kashkan conglomerates (Alavi, 2004). Near the present-day Zagros Deformational Front (ZDF), the upper part of the sequence, composed of deep-marine argillite sand carbonates of the Pabdeh is overlain by Jahrum dolostones, again indicating northeastward migration of basin depozones.

PALEOCENE-EOCENE IN SOUTHERN PERSIAN GULF

The sedimentary sequence representing Paleocene-Eocene are generally calcareous with typical shallow-water lithologies. They vary in thickness, with a maximum-recorded thickness in the western part of about 330 meters; however, they are more than twice as thick to the east. In the foredeep toward the Zagros Mountains, these units increase in the amount of clastics they possess. In the southern parts of the Persian Gulf, shallow-water, Paleogene plat-

form deposits generally are assigned to three formations of the Hasa Group, in ascending order the Umm Er Radhuma, Rus, and Dammam (Alavi, 2004).

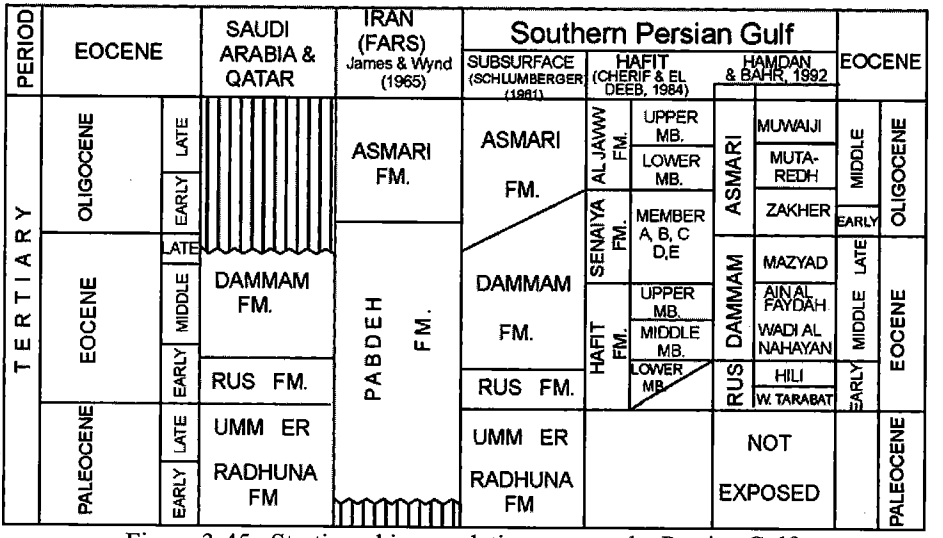

Figure 3-45. Stratigraphic correlations across the Persian Gulf.

Umm Er Radhuma Formation

In southwestern Persian Gulf the formation comprises about 300 meters of fossiliferous lime mudstones to packstone and dolomitic limestone (Steineke et al., 1958). The Umm Er Radhuma rests disconformably on the Maastrichtian sediments. The formation consists mainly of limestones over most of the Persian Gulf area, becoming anhydritic and marly in places. The Umm Er Radhuma Formation indicates a major change in the environment, marked by the disappearance of rudist-bearing marine-platform carbonates. Based on foraminiferal evidence, the Umm Er Radhuma Formation was dated as Late Paleocene to Early Eocene (Powers et al., 1966).

The formation displays no major facies variations, however, in Bahrain and Qatar there is a slightly greater proportion of shale present, and is considerably thicker in Kuwait. The fauna suggest that the carbonates belong to the sublittoral to neritic bathymetric zone. The wide variety of pelecypodes indicates more specifically a protected lagoonal depositional environment. The Umm Er Radhuma depositional environment ultimately shoaled to develop into restricted lagoons to sabkha setting in which the Rus Formation was deposited.

In southern Persian Gulf, (i.e., UAE), the Umm Er Radhuma Formation includes some shales, and thin, argillaceous or sandy anhydrites and thick dolomitic limestones atypical of the formation. The section thickens offshore and appears to have developed in fairly deeper water.

Rus Formation

The Rus Formation was proposed by Bramkamp (1946) to describe the "chalky zone" applied to Lower Eocene beds. Rus Formation in the Persian Gulf area consists of evaporitic-carbonate sequences. The Formation extends over a large area in southern Persian Gulf.

The contacts of the Rus Formation with underlying Umm Er Raudhuma and the overlying Dammam Formation are conformable in the eastern Arabia (Willis, 1967; Power, 1968). However, there is an abrupt facies change between Rus Formation and the middle member of the overlying Dammam Formation in the northern region of Qatar. This local unconformity is probably related to the activation of paleohighs of northern part of Qatar such as Qatar and Simsima Dome. In UAE, the Dammam Formation unconformably overlies the Rus Formation.

In Saudi Arabia the formation consists of microporous limestones with irregular masses of crystalline gypsum, finely crystalline anhydrite, and minor amounts of dolomitic limestone and shale. The thickness of Rus Formation shows some variability. In outcrops in southern region of the Persian Gulf the thickness is commonly in the range of a few tens of meters, up to 70 meters in Bahrain where it is mainly composed of chalky, cherty dolomitic limestones with strikes of anhydrite.

The Rus Formation that dates to Eocene (Ypresian) in Kuwait is split into three lithologic units, which are mainly limestone at the base, alternating marl and limestones in the middle and porous limestone and calcarenite on top. In southern Iraq the subsurface Rus Formation is composed of consolidated sequence of anhydrite interbedded with limestones, shale and marl (Willis, 1967).

Fossils are few, the most characteristic being the *miliolids*, *Nummulites affatacitus Levmere. Cardium* sp. and *Corbulla* sp. The formation can be traced over the whole area from south Iraq to Oman. It is most distinctive in Kuwait where it is a prominent surface unit of hard, dense anhydrites and unfossiliferous limestone (Power, 1968). In UAE, the Rus Formation is composed of fossiliferous dolomitic limestone with thin argillaceous limestone grading upward to well-bedded limestone (Whittle and Alsharhan, 1994).

The Rus Formation is probably correlated to the middle part of Jahrum Formation in southwestern Iran (Beydoun, 1988; Seyrafian, 1998), which is made up of thick sequence of fossiliferous dolomitic limestone. These facies reflects relatively deeper basin than that of the eastern Arabia.

The depositional environment of the Rus Formation carbonates remained shallow marine to supratidal but shallow water normal marine environments were established during deposition of the lower part of the Damman Formation (middle-Late Eocene). The Rus Formation does not extent to the northern coast of the Persian Gulf into Iran.

Dammam Formation

The Dammam Formation of the Lower Eocene to the early Upper Eocene age is the youngest unit of the Paleocene-Eocene succession in the southern Persian Gulf region. On the basis of paleontological evidence, a middle Eocene age has been assigned to the southern Persian Gulf (Power et al., 1968; Clarke 1988), and the same age has been inferred for the formation in Bahrain from the close lithological correlation with the exposures in the Dammam dome.

The thickness of the Damman Formation increases in an east-northeasterly direction from only 28 meters in Saudi Arabia to 125 meters in southwestern Kuwait, and 230 meters in southern Iraq to more than 300 meters in offshore Kuwait in the northern Persian Gulf. The formation has a rather uniform lithology of mostly limestone and dolostone with intercalations of shales and some lignite towards the base (see Owen and Nasr, 1958). Al-Hashimi (1973) reported that to the south of the Euphrates River, the Dammam Formation passes into a marly facies containing globigerina and planktonic and benthic fauna.

The Dammam Formation (Lutetian) rests unconformably on top of the Rus Formation. The post-Eocene deposits overlie the Dammam Formation with a pronounced regional unconformity. The top-most part of the Dammam Limestone Formation in Kuwait is highly silicified, possibly as a result of a widespread solution and precipitation activities during the exposure of this formation to surface during the Oligocene time. The whole Oligocene and possibly parts of the Miocene records are missing as a result of this unconformity. The Lower Miocene Ghar Formation of northern head of the Persian Gulf and Hadrukh Formation of eastern Saudi Arabia are the continental clastics resting unconfromably over the Dammam Formation.

The Dammam Formation represents a transgressive sequence where the sabkha and subtidal to continental lagoon were progressively transformed into an open-marine environment. The typical feature of the Dammam Formation in eastern Abu Dhabi is that the succession is continued upwards, and the Oligocene-Early Miocene Asmari limestone, which rest conformably upon the beds of Dammam, spreads a blanket of shallow water carbonates over the Southern Persian Gulf trough.

Eocene of Oman

Nolan et al. (1986) noticed that the early Eocene strata of the Oman Mountains are appreciably less evaporitic than the Rus Formation of Saudi Arabia. During this time Arabia still lay in the tropics (Smith and Briden, 1977) but probably in a rain shadow because of the northward drifting of the Indian plate across the line of the prevailing easterly paleo-wind direction which would have brought precipitation to the area (Nolan et al., 1986). Presence of

fluvial clastics in the Rusayl Formation of Oman indicates that noticeable precipitation did occur on the western seaboard of Arabia at this time where there was some relief. Well-developed paleosoles ferruginous (possibly representing iron-pans) and incipient caliche horizons in Rusayl Formation occurs providing further evidence for a humid, perhaps seasonal paleoclimate.

Normal, shallow marine *Nummulitic, alveolinid* and *rhodolithic* limestones of the Seeb Formation conformably succeed and interdigite with the Rusayl Formation. The Seeb Formation is overlain by, and possibly interdigites with, deeper marine calciturbidites, shale and debris flows of the Ma'ayah beds.

Jahrum Formation (Paleocene-Late Eocene)

Jahrum Formation of the Paleocene to upper Eocene age consists of cliff-forming sabkha-type dolostones interbedded with *Alveolina*-bearing and *Nummulites*-bearing dolomitic limestone. It grades toward the northeast into deep-marine Pabdeh foredeep carbonates and toward the southwest to the Radhuma-Rus-Dammam carbonate-evaporite units of the southern Persian Gulf and pinch out above a regional unconformity (Owen and Nasr, 1958; Alavi, 2004). The Jahrum Formation has been erroneously called Jahrum dolomite, predominantly based on the presence of intensive dolomite layers (Seyrafian, 1998).

Jahrum Formation is part of the lower Tertiary sedimentary sequence deposited during early transgression from Hormoz Strait to wide areas of the Zagros Basin, including, northeast-southwest part of the basin. The formation is part of the shallow marine sedimentation of such a transgression. At the same time, the pelagic shale, marl and argillaceous limestone of the Pabdeh Formation deposited along the troughs of the basin (Wells, 1967). The Jahrum Formation is exposed at the northeastern portion of the high Zagros Mountains.

At its type locality at Tang-e-Bal in the northern flank of the Jahrum Mountains (Motiei, 1993), the Jahrum Formation consists of 468 meters of dolostone and dolomitic limestones which are overlain by an unconformable and erosional contact of the Asmari Formation. Beneath the Jahrum Formation are the evaporites of the Sachun Formation (Motiei, 1993). The formation is composed of basal massive weathered dolostone, changing upward to medium-bedded dolostone to massive dolomitic limestone with abundant microfauna from Paleocene to Upper Eocene in age (James and Wynd, 1965). The Jahrum carbonate facies is present over most of the eastern Persian Gulf region particularly from the Sirri Island area to the northern parts of the Persian Gulf.

Lithologically, the Jahrum Formation is characterized by massive dolomite and dolomitic limestone (see Stocklin, 1977). Several shallow marine benthonic microfaunas are present in the Jahrum Formation (Kalantary, 1986; Jalali, 1971; Seyrafian, 1998). Lithologic characteristic of Jahrum Formation

indicates depositional environments ranging from supratidal-shallow marine to deeper marine condition in parts of the Zagros Basin.

West of the Farur Island, the thickness of Jahrum Formation is 171 meters. In well 3W-1 in the Resalat oil field in Persian Gulf is 579 meters and in South Pars Field it reaches 536 meters. In the U-1 well Pabdeh Formation gradually replaced by carbonates of Jahrum Formation. In the Salman oil field the thickness of Jahrum Formation has been estimated to be about 427 meters.

The Jahrum Formation in southern Iran have been described by Setudehnia (1972), and show a considerable lateral extension reaching the southern Persian Gulf, and are shallow water equivalents of the deeper water Pabdeh beds. They were formed along the shallowing, northern margin of the Zagros trough as the depocenter was displaced southwards. Although in the type locality the beds only extend up to Middle Eocene, in the coastal Fars region there is no evidence of the post Middle Eocene sedimentary break, and the Eocene succession is relatively complete (Setudehnia, 1972).

The Jahrum Formation is present throughout the interior and coastal parts of central Zagros Basin. It is also present in the subsurface in the extreme southwestern part of the basin. The Jahrum Formation is equivalent to carbonates of Taleh Zang and Shahbazan and conglomerates and sandstones of the Kashkan Formation in northwestern Zagros Basin.

The Jahrum Formation is replaced by pelagic sedimentation of the Pabdeh Formation in deeper parts of the Zagros Basin including west, southwest and central part. The Jahrum formation is disconformably overlain by the Asmari Formation. However, in some localities of interior central part of the Zagros Basin, the Razak Formation disconformably overlies the Jahrum Formation. The Jahrum Formation is time equivalent to the Umm Er Radhuma-Dammam Formations of Saudi Arabia, Kuwait and southern Iraq (James and Wynd, 1965).

In some localities, the uppermost strata of the Jahrum Formation were erosionally removed before Asmari deposition, and the lower part (lower Oligocene) of the Asmari sequence is not present. To the southwest, close to the present-day Zagros deformational front, Jahrum dolostones are overlain by Ahwaz sandstones (Alavi, 2004). Paleontological data from Kharg Island and Darkhovin boreholes (Adams, 1969) suggest an early Miocene age for the lowest beds of the Ahwaz and a Middle Eocene age for the uppermost strata of the Jahrum, indicating a hiatus of 20 m.y. Farther southwest, outside of the Zagros Fold-Thrust Belt (i.e., at the northern head of the Persian Gulf), the same unconformity is recognized between lower Miocene Ghar sandstones (an equivalent of the upper part of the Ahwaz) and the underlying Dammam (Jahrum equivalent) dolostones (Owen and Nasr, 1958; Al Naqib, 1967).

Towards the northeast, along the central part of the Zagros Fold-Thrust Belt, where the Jahrum Formation is missing, thick-bedded, Asmari limestones deposited in high-energy environments, overlie thinly-and uniformly-bedded and locally limonitic, calcareous argillites and argillaceous limestones

of the middle part of the Pabdeh Formation. The contact between the Asmari and Pabdeh Formations is an erosional unconformity, where upper parts of the Pabdeh were removed by erosion. Farther northeast, in the interior part of the belt, upper strata of the Eocene Shahbazan carbonates are also partly missing at the unconformity, and lower Shahbazan strata, capped by a layer of low-weathering, rubbly limestone formed by solution brecciation, underlie either Middle Oligocene Asmari limestones or Lower Miocene (Burdigalian) Razak evaporitic and siliciclastic strata.

OLIGOCENE

Sea-level drop in Oligocene time caused the removal of underlying Eocene beds over substantial areas. The pronounced sea level fall exposed almost the entire Arabian plates including Persian Gulf. The Mid-Oligocene global sea level drop, and subsequent sedimentation, constricted marine circulation from the Mediterranean to the Indian Ocean. This began to be reflected in sediment type, fossil diversity, and other factors (Ricou et al., 1986).

Zagros Basin gradually shallowed in Oligocene-Lower Miocene time and was covered by the biostromal limestone, marl and evaporites of the Asmari Formation (James and Wynd, 1965). In Zagros Basin, the Asmari Formation conformably covered the Pabdeh shale. Note that prior to the Oligocene time a minor phase of uplift appears to have rejuvenated the ancestral inner Zagros Mountains, shifting the axis of the depocenter to the southwest and then confining marine sedimentation to a shallow elongate basin in the Oligocene-Early Miocene. A major deltaic province, the Ahwaz Delta, prograded eastwards from the Arabian mainland and these deposits, together with the age-equivalent carbonate shelf sequence to the east, the Asmari Limestone, form significant Tertiary reservoirs in Iran.

By Late Oligocene to Early Miocene times, sedimentation occurred only on a narrow northwest-southeast evaporitic shelf with a series of deeper basin centers. Tectonics and eustacy combined to cause a major relative sea level fall throughout the late Oligocene, resulting in widespread erosion and non-deposition across the entire region (Jones and Racey, 1994). Deposition was reinitiated in the Early Miocene, and led to the deposition of marine carbonate of the Middle Eocene age in many parts of the region.

From late Oligocene to Early Miocene time, the Asmari Sea retreated from the Zagros Basin. On the Fars platform no important evaporite series were deposited. The evaporation products of the lagoons and relict sea patches are the gypsum, anhydrite and salt beds of the Gachsaran Formation, 2 kilometers thick in the type section of the Gachsaran oil field. They have interbedded dark red and purple salt clay beds and thin limestone layers, which have a brackish water fauna of *ostracods, bryozoa, rotalids, and miliolids with associated Peneroplis, farsensis, Dentritina ramgi* and mioygypsina.

The last major period of marine deposition in the southwestern Iran ended in the Oligo-Miocene, when the trough developed into a broad, shallow foreland basin in front of emerging Zagros Mountain chains (Stocklin, 1968, p.173). Locally, favorable conditions for deposition of evaporites had developed during this time as evidenced by the Kalhur Gypsum Member of Asmari Formation and other thin evaporite tongues (Gill and Ala, 1972).

Kalhur Member consists of evaporites interbedded with calcareous shale, argillaceous limestone, dolomitic limestone, and minor marl (near base) deposited within a restricted (narrow and elongate) paralic basin; interfingers toward the northeast with Ahwaz and Asmari, dying out toward the northern head of the Persian Gulf region.

Shallow water carbonate deposition enabled closed intrashelf lows to develop suitable for deposition of evaporates (i.e., Kalhur Member). A significant pulse of clastics input from the craton occurred in the Early Miocene causing deposition of Ghar and Ahwaz sands in the northwestern Persian Gulf (Motiei, 1993).

The Ahwaz sandstones, with restricted distribution along the strike of the basin, are shoreface deposits forming a number of elongate NW-SE trending and northeastward-thinning parasequences displaying rapid lateral facies variations. Their distributions and lithologic characteristics are indicative of repeated subaerial exposures, probably induced by tectonic uplift. Farther southwest, the Ahwaz stratigraphic unit grades into Kalhur evaporites, argillaceous lime mudstones, and dolostones. Towards the southwest and northern Persian Gulf, Kalhur onlaps underlying strata and pinches out against an Oligocene subaerial regional unconformity (Al Naqib, 1967; Adams, 1969).

In Oman, the equivalent strata, at the base of the Gachsaran Formation, rest unconformably on older strata. The sequence represents the deposits of shallow shelf sea in which neritic carbonates and evaporites formed away from the emergent Oman Mountains. The limestones are commonly sealed by evaporites which interdigite with clastics and carbonates developing sabkha deposits in this region but probably forming thicker marine evaporite in the deeper part of the basin.

In general, Oligocene sediments which are peri-reefal and pelagic carbonates in nature are essentially confined to a narrow linear belt running through the Persian Gulf to Syria with isolated outcrops in southern Oman. They are absent elsewhere owing either to non-deposition or to uplift and erosion associated with Red Sea Rifting at the end of Oligocene.

The uplift and unroofing of the Oman Mountains possibly started in the Late Cretaceous as indicated by intermontane deposits. However, the major uplift began in the Late Oligocene and was probably related to tectonic events on the nearby plate boundaries of the Zagros collision zone and the Makran subduction system.

A major sea-level fall in the Late-Oligocene-Early Miocene is reflected in a major unconformity. This was the time of the tectonic activity related to the

opening of the Red Sea. The final phases of Alpine activity, from the Miocene to Pleistocene, are associated with uplift and folding of the Zagros.

The Neo-Tethys Ocean finally closed in the Late Oligocene to Early Miocene (Hopper et al., 1995) following the collision between the Arabian plate and Eurasia to form Zagros Fold Belt. Moreover, the prevailing carbonate foredeep sedimentation was also replaced by clastic deposition in a sub-aerial (i.e., continental) foreland basinal setting. During the rapid closing the Zagros foredeep along the northeastern plate margin once more became a narrow trench in which principally limestones were deposited along its margin. The Arabian plate was progressively tilted to the northeast as a result of collective uplift and rifting of Arabia from Africa, and structural loading of the northeast margin by the Zagros fold belt.

Asmari Formation (Oligo-Miocene)

The Asmari limestone and its time-equivalents in the Persian Gulf region are one of the world's most important reservoirs, estimated to hold more than 90% of the recoverable hydrocarbons of Iran and Iraq; together they represent reservoirs for hydrocarbons that have migrated from Mid-Cretaceous source rocks and possibly re-migrated from older reservoirs as a result of the arrival of the Zagros deformation front (James and Wynd, 1965; Murris, 1980; Berberian and King, 1981; Beydoun et al., 1992; Motiei, 1995).

Initially the Asmari Formation was referred to as a sequence of the Cretaceous-Eocene age (Busk and Mayo, 1918). Subsequently the formation was investigated by Richardson (1924), Van Boeckh et al. (1929) and Thomas (1948) and assigned Oligocene-Burdigalian age. In the following years the Asmari Formation was investigated in detail and formally defined by landmark work of James and Wynd (1965).

Despite its economic importance, the sedimentology of the Asmari Formation has received relatively little attention. This is surprising, as the formation could be examined in exposures within narrow valley and ravines cutting through the huge and striking whaleback anticlines that make up the Zagros Fold Belt particularly in terms of outcrop studies and subsurface. However, in recent years, biostratigraphic studies including microfacies analysis and depositional environment of the upper part of the formation have been conducted (Kalantari, 1986; Jalali, 1987; Seyrafian, 2000; Horbury et al., 2004; Nadjafi et al., 2004).

The Asmari Formation at its type locality in the Asmari Mountains to the SW of Masjed-Solayman and NE of Haftgel (Motiei, 1993) consists of 314 meters of limestones interbedded with shales. In the Dezful Embayment area the formation consists of 340 meters of thick well-bedded limestones with shelly horizons. The basal third consists of calcareous sandstones and sandy limestones with minor shales (i.e., the Ahwaz Member of James and Wynd, 1965). The Ahwaz Member is present within the lower and middle portions of

the Asmari Formation in the southwestern Zagros Basin with a thickness of 213 meters at its type section.

Generally the lithology of the Asmari consist mainly of medium to thick-bedded, locally shelly or oolitic, *nummulites*-bearing limestones (grainstone, packstone, wackestone) shoaling upward above a thin basal conglomerate from fine-grained (low-energy) deep-marine marly limestone to high-energy shallow-marine skeletal grainstone. The formation composed of a number of sequences; an unconformity-bounded, highly prolific reservoir; interpreted as transgressive-regressive foredeep facies of the pro-foreland basin (Henson, 1950; James and Wynd, 1965; Murris, 1980; Motiei, 1993; Alavi, 2004). It varies in thickness from 100 meters to more than 500 meters, and depositional facies range from massive limestones to evaporitic rocks (Beydoun et al., 1992; Motiei, 1993).

In the Zagros Basin Asmari limestone disconformably overlies Paleocene to Eocene deep-water shale and marl (i.e., Pabdeh Formation) on the southwest side of the Zagros Thrust and records Middle Tertiary onset of subsidence in the incipient Zagros Basin. It also covered the Jahrum and Shahbazan Formations to the northeastern part in the Fars region, respectively (see fig. 8 in Sherkati and Letouzey, 2004) while the contacts with the underlying Pabdeh and overlying Gachsaran Formations are transitional to conformable. Although the lower part of the Asmari Formation interfingers with the Pabdeh Formation in the Dezful Embayment (Motiei, 1993), the upper part of it covers nearly the entire Zagros Basinal sediments.

Although Asmari Formation gives the impression that it is conformably overlying the Pabdeh Formation in Fars region, the base of the formation is diachronous and varies from Oligocene along the Zagros front in the north of the Dezful Embayment, to lower Miocene further south-eastward. The reverse is true of the top of the formation, with a conformable contact with overlying Gachsaran Formation in the latter two regions other than showing a dischronous relationship in Fars. In southeastern Iran the Asmari grades into the marls of the uppermost part of the Pabdeh Formation as observed in wells drilled in Qeshm Island (James and Wynd, 1965).

According to Motiei (1993) the underlying Paleocene-Eocene deposits are either conformable or non-conformable. However, north of the Dezful Embayment, the Asmari Formation is unconformably overlain along the mountain front fault by the Gachsaran evaporites, the famous hydrocarbon seal in the Persian Gulf and surrounding region.

Depocenters of the Asmari Formation, in places with more than 750 meters thickness, were developed in East Khuzestan, west central Fars (mainly marl and limestone facies) and in the Chehel Basin (southwest of Bandar Abbas, more than one kilometer of mainly evaporite units). In Interior Fars, the Asmari was partly eroded before the deposition of the evaporites. Towards the southwestern Persian Gulf and on the southeastern part of Fars platform the Asmari Formation diminishes to less than 100 meters thickness. Thus, the

variations in the thickness of the Asmari facies are somewhat irregular, but the general trend in thickness reduction to the southeast remains. The maximum thickness of the Asmari Formation occurs to the northeastern corner of the Dezful Embayment (i.e. on the hangingwall of the Mountain Front Fault), where its thickening was clearly controlled by the 'Mountain Front' and 'Bala Rud' Fault Zones (see Figure. 9 in Sherkati and Letouzey, 2004).

The Asmari limestones extend over most of the Persian Gulf, excluding places where there have been sedimentological breaks. It is also present throughout the Zagros Basin. Proceeding westwards, the Asmari interfingers with the continental-littoral sandstones of Ahwaz Sand Member (Mina et al., 1967). According to Falcon (1957) in the northern most part of the Persian Gulf, there is no development of the Asmari facies. In the southern side of the Persian Gulf, the equivalent of the Asmari and Gachsaran Formations are the Hadrukh-Dam Formations of the Saudi Arabia and the Ghar-Gachsaran Formation of southern Iraq and Kuwait.

The Asmari limestone is also found underlying the eastern and southern Persian Gulf. The limestones have also been encountered in the subsurface in the offshore southern Persian Gulf and in outcrop in Abu Dhabi close to the Oman Mountains. In UAE, the Asmari consists of shelfal carbonates, while marls and shales thicken into the basin. It also occurs in the down-faulted part of coastal Dhofar, Oman, as an Oligocene shoal facies and nummulitic limestone (Edgell, 1955).

Within the Persian Gulf district, Asmari limestone overlies Jahrum carbonates where the defining the boundary between Jahrum and Asmari is often accomplished with difficulty. Furthermore, in the Eastern Tertiary Basin (Hengam Basin) the Asmari carbonates facies change to Pabdeh shales. In this area the deposition of Asmari has been lacking and is mainly replaced by the Pabdeh Formation. This includes an area in the Persian Gulf which extends from Strait of Hormoz to Oman and to the northwest to Bandar-e-Lengeh and to the Sirri "E" and "F" fields.

In Shiraz area, north of the Persian Gulf two depositional successions can be recognized and differentiated by sequence stratigraphy and depositional history. A thin paleosol separates the lower sequence equivalent to the Jahrum Formation from the overlying Asmari Formation. Changes in relative sea-level between the Paleocene and the Oligo-Miocene could be tentatively identified. A major sea-level fall recognized at the Eocene-Oligocene boundary is consistent with that of world-wide, and minor differences in the sea level curve are probably related to regional factors such as tectonism (Nadjafi et al., 2004).

The thickest part of the Asmari has been encountered in the northwestern part of the Persian Gulf. For example, in the Dorood oil field the thickness of Asmari ranges between 91 to 183 meters (Lotfi, 2003). However, the Asmari Formation is typically around 500 meters of thin to massive bedded, dolomitic, and argillaceous carbonates (Motiei, 1993). In fact the thickness of As-

mari Formation decreases from north to south and in some region of the Persian Gulf. Isopach map of the Asmari in the Persian Gulf has been presented in figure 3-46.

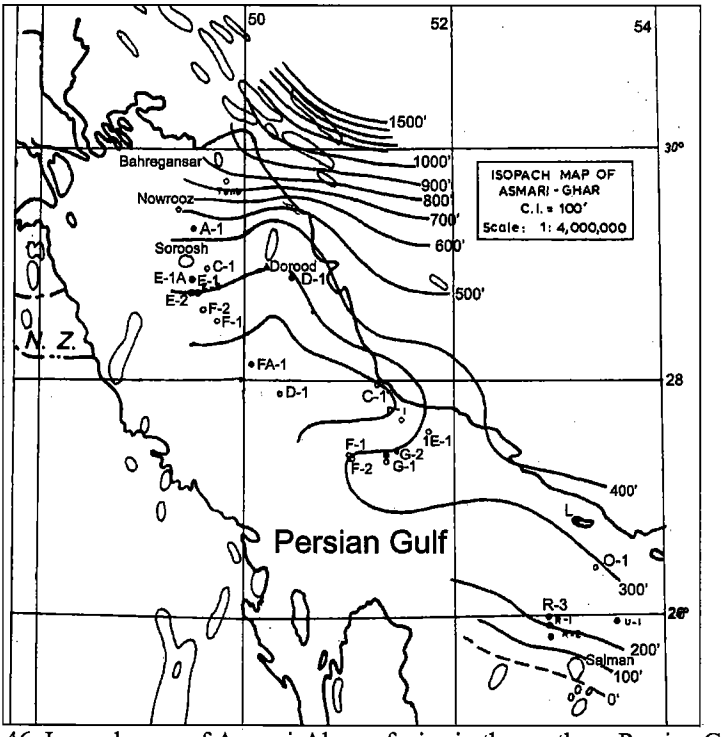

Figure 3-46. Isopach map of Asmari-Ahwaz facies in the northern Persian Gulf and southwestern Iran with some of the oil fields and some of drilled sites (modified from Mina et al., 1967).

The Asmari Formation is generally subdivided into three parts. The Lower part is marly in nature near the base, overlain by foraminiferal and coralline algal limestones. The middle part comprises dolomitized, lagoonal limestones, while the upper Asmari is more evaporitic. In general, Asmari Formation is characterized by complex lateral and vertical facies variability. Such variability is described as an alternation through time between ramp and rimmed shelf platform morphologies for the Oligocene limestones (Bassant and van Buchum, 2004). These were deposited during a time of rapid marine flooding of a complex antecedent topography during the Early Miocene, Burdigalian stage.

The detailed sedimentological data collected by Noad et al. (2003) has been used to develop a sequence stratigraphic framework, subdividing the Asmari limestone into four cycles, and then into several subordinate cycles.

The local variations in lithology within the Asmari Formation are mainly recognized as members such as the Kalhur anhydrite and the Ahwaz (i.e., Ghar) sandstone. The Kalhur anhydrite (with some salt) occurs in a narrow fold-delimited structural basin along the mountain front in the north of the Dezful embayment (Koop and Stoneley, 1982; Motiei, 1995).

The calcareous sandstones and sandy limestones of the Ahwaz Member unconformably overlie the Eocene-Oligocene Jahrum Formation in the Dezful Embayment. They record near-shore deltaic (possible eolian) environments which passed eastward into shallow carbonates (James and Wynd, 1965; Murris, 1980; Motiei, 1993).

In the northern Persian Gulf, late Oligocene-Early Miocene sands were deposited from an easterly directed wadi system from which intermittently, during major flooding stages, sands were carried far out onto the carbonate platform. The exact age equivalents of these sands in not always clear, and in all probability the sands are diachronous, for example the Ahwaz sands of Iran may replace middle or lower Asmari, whereas the Ghar sands of Kuwait are overlain by lower Miocene deposits.

Many local facies and onlapping relationships in the Asmari and younger Formations recorded syn-deformation deposition near the Zagros deformation front as it advanced southwestward (Hessami et al., 2001). Thus, the Ahwaz and Kalhur Members onlapped Zagros anticlines developing in the Jahrum and Pabdeh shales and the lower Miocene Dhiban Formation in Iraq (the local time-equivalent of the Kalhur anhydrite) onlaps the front limbs of Zagros anticlines in the Dezful Embayment without reaching their crests (Van Bellen, 1959).

Due to recent exploration and development activities in southwestern Iran, a series of Tertiary paleogeographic maps, based on sequence stratigraphic concepts have been updated. According to Horbury et al. (2004) the maps provide a regional basis for studies on the Asmari Formation in order to resolve problems such as locations and orientations of the shelf margins, directions of clastic input into different parts of the basin, and likely stratigraphic geometries. They represent distinct sequence stratigraphic events (usually MFS + HST, LST + TST) during the depositional period of the Asmari Formation in southwest Iran. The maps start with the demise of the Jahrum shelf carbonate system and end with early Gachsaran Formation deposition in Early Miocene. The sequence stratigraphic framework was established using a modified version of the Arabian plate maximum flooding surface. Broadly speaking, the Aquitainian of Iran appears to embrace both the uppermost part of the Oligocene and the Aquitainian (Horbury et al., 2004).

In southern Persian Gulf (Saudi Arabia and Qatar), the Oligocene was a time of emergence and erosion (Power et al., 1968). In addition in the Upper Eocene and Lower Oligocene times, uplift and erosion affected the western part of the UAE causing some erosion of the Eocene Platform. Subsequently, transgression followed causing the deposition of shallow water fossiliferous

limestone of the Asmari Formation. In the subsurface of UAE and offshore, the Asmari Formation consists of shallow-water, fossiliferous partly dolomitic limestone (Schlumberger, 1981; Hasson, 1985), which has been divided into three members (Braga and Bahar, 2003). Here, the Asmari consists of marl with recrystallized gypsum in the lower interval and algal, coralline and nummulitic limestone with dolomitic marly and chalky interbeds in the upper part of the succession. In nearly the whole sequence, fragments of nummulitides, pelecypodes, gastropods, echinoids and bryozones are common.

Age of the Asmari Formation

Although Motiei (1993) ascribed the Middle Asmari as Aquitanian age, there is biostratigraphic evidence in both Slinger and Crichton (1959) and Motiei (1993) that the Middle Asmari is in fact Late Oligocene in age due to presence of *Miogypsinoides*. It is worth noting that foraminiferal assemblages ascribed by James and Wynd (1965) and Motiei (1993) to the Aquitanian are in fact better interpreted as late Oligocene.

The Asmari limestone ranges in age from Oligocene (with rich microfauna including *Nummulites intermedius d'Archiac* and *Nummulites vascus Joly* and *Leymerie*) to early Miocene. The Upper Asmari has a rich microfauna including, *Miogypsina* at the base and *Neoalveolina Melo Curdica* at the top. It is conformable with the overlying evaporitic marly Gachsaran Formation.

The Asmari platform and peri-reefal carbonates contain the index taxa of the *Nummulites intermedius-N. vascus, Globigerina spp., Austrotrillina howchini-Peneroplis* and *Neoalveolina* (Borelis) *melo curdica* Zones, indicating an Oligocene-early Miocene age (Wynd, 1965). The Asmari Formation of the UAE comprises platform and 'peri-reefal carbonates similar to those of southwest Iran. Although Hull and Warman (1970) claimed that this formation contains no reef material, a coralline Upper Oligocene reef facies of the Asmari occurs in the High Zagros Ranges (Sampo, 1969) in the vicinity of the Shurum oil field. Based on the field observations by the authors there are many occurrences of coral reefs in Asmari.

The Ahwaz sandstone member contains the index taxa of the *N. intermedius-N., Vascus* and *A.howchini-P.evolutus* Zone, indicating age ranging from Oligocene to earliest Middle Miocene (Wynd, 1965). Stratigraphic relationships (the presence of overlying strata of an age in the range latest Early-earliest Middle Miocene age) probably restrict its age to within the range Oligocene-Early Miocene.

The Kalhur Member contains the index taxa of the *Globigerina* spp. Zone, indicating an age in the range Oligocene-earliest Middle Miocene (Wynd, 1965). Stratigraphic relationships which include the presence of underlying and overlying strata of ages within the range latest-Early Middle Miocene age probably restrict the age of Kalhur member to the Early Miocene.

Strontium isotope age dating combined with biostratigraphy data show that the Ahwaz Asmari Formation was deposited from 30 to 18 Ma (Arne et al., 2004) (Rupelian-Burdigalian). The lower Asmari sands were deposited in a restricted area during lowstands, while the Middle and Upper Asmari were deposited over a widespread carbonate ramp and contain transgressive and highstand sands.

Furthermore, the strontium-isotope method of dating minerals precipitated from sea water was applied to core samples from the Asmari Formation using microanalyses of mollusk shells and lime mud matrix. The 400 meters of cyclic platform limestone, dolostone, sandstone, and shale of Asmari correspond to the global strontium isotope curve between 31 to 18 Ma (Rupelian-Burdigalian) (Ehrenberg et al., 2004).

Age-depth profiles in Ahwaz, Bibi Hakimeh, and Marun oilfields show that a distinct decrease in sediment accumulation rate occurred abruptly at around 24.5-24.0 Ma (near the Oligocene/Miocene boundary). Accumulation rate decreased from 41-93 meters/million years (m/my) in Oligocene time to 14-28 m/my in early Miocene time. Major depositional sequences defined from facies relations and cycle-thickness patterns have durations of 1.1-2.6 m.y., whereas depositional cycles represent average time intervals of 100-300 thousand years (Ehrenberg et al., 2004).

Ahwaz Member of Asmari Formation

In the northern head of the Persian Gulf Late Oligocene-Early Miocene sands were deposited from an easterly directed wadi system (Figure 3-47) from which intermittently, during major flood stages, sands were carried far out onto the carbonate platform. A major delta system, the Ahwaz delta was supplied from sources on the Arabian Shield which suggests significant uplift in order to provide the source area for the Ahwaz Sand Member.

Ahwaz lithology consists of current bedded, wavy-laminated calcarenite inter-layered with sandy limestone, sandstones (quartzarenite and litharenite derived from the southwest), and sandy to silty shale. It is well-bedded, coarse-gained to pebbly sandstones with variable porosity; interbeds of clay are common. It is shallow-marine to non-marine deposits of a sabkha-type environment interpreted as forebulge facies of the basin.

Motiei (2003) considered the Asmari sandstone member to be correlative with the Ghar Formation in Kuwait. Indeed the Ghar Formation of Kuwait and southeastern Iraq are time equivalent of the Ahwaz sandstone Member can be considered a facies continuation of this member.

According to Mina et al. (1967) between the Ahwaz sands facies of the western Persian Gulf and the Asmari Formation of southwestern Iran, there is a zone of transitional environment. This zone is represented by interfingering of the continental-littoral facies of Ahwaz and the rich marine facies of the Asmari Formation. Sediments with such transitional characteristics have been

encountered in IPAC and SIRIP Agreement areas. The Ahwaz Sand Member in the Abouzar oil field in the offshore Persian Gulf directly overlies the Lower Asmari limestone and has a thickness of about 80 meters in this field.

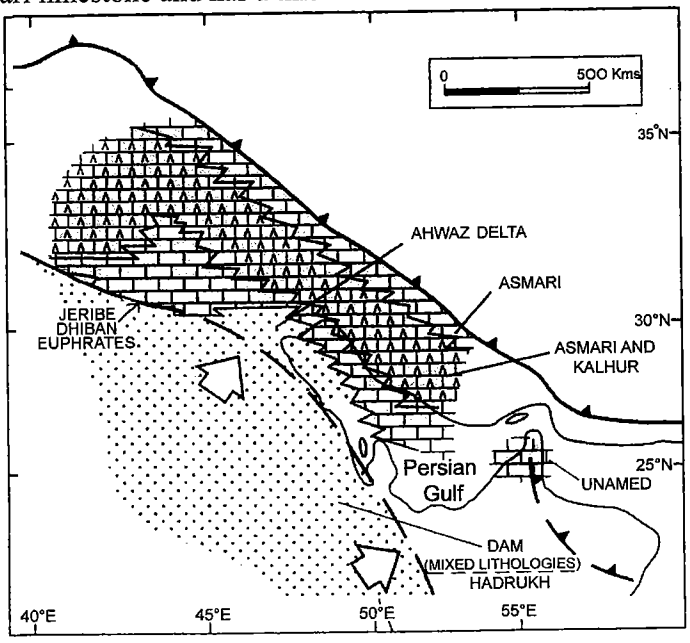

Figure 3-47. The distribution of Asmari sedimentary sequence and its depositional members in the Persian Gulf and surrounding regions. The source and direction of sands for Ahwaz Member Delta is also indicated (modified from Buday, 1980; Murris, 1980; Beydoun 1991).

Owen and Nasr (1958) first described the Ahwaz Sand Member (i.e., Ghar) in the Zubair field of southern Iraq, where it consists of sands and gravels with rare anhydrite, clay and sandy limestone interbeds. Although considered as Lower Miocene in Iraq, its range extends to include latest Oligocene in Kuwait. The outcrop thickness of 33 meters expands in subsurface to 195 to 260 meters of predominantly terrestrial clastic deposits with some crystalline carbonates although in the extreme southeastern part of Kuwait it passes to silicious limestone and sandstone. In southern Persian Gulf, the Ahwaz Sand Member consists of continental clastics resting unconformably over the Dammam Formation. The Euphrates Formation of central and northern Iraq is the marine equivalent of the Ghar Formation.

At its type locality in southern Iraq the Ghar Member is composed of porous sands and gravels. It is generally consists of uniform body of continental to littoral-lagoonal sands with minor intercalations of anhydrites and clays. In southern Iraq and northeast Kuwait the Ghar sands of Oligocene to Lower Miocene age unconformably overlie the Middle-Upper Eocene carbonates (Mina et al., 1967).

Asmari Depositional Environment

Sedimentation of the deep-marine shales of the Pabdeh and Jahrum Formations was followed by the deposition of the shallow-marine carbonates of the Asmari Formation and stratigraphically its time-equivalents following a major regression in the upper Eocene and broadened along the Zagros Mountain front in Oligocene-lower Miocene times. The Asmari-Jahrum Formations are composed of lithofacies reflecting open-marine, shoal, semi-restricted and tidal flat depositional environments (Nadjafi et al., 2004).

The Asmari sediments deposited as a transgressive succession in environmental conditions varying from shelf to the restricted and normal marine shelf to foreslope, and then to basin margin setting. Deposition was followed by a regressive cycle from basin margin to foreshelf and restricted shoal, and to limited platform sediments.

The transgressive Middle Alpine Sea in which the Asmari Formation was deposited invaded the central basinal area from the southwest (Kashfi, 1992). In the Middle Miocene, major focus for sand deposition was at the northern head of the Persian Gulf with deposition of the Ahwaz Sand Member. The northeastward progradation of the sandstones is interpreted to have driven by a combination of inversion and rifting in the Red Sea area, thus providing a clastic source, and a eustatic fall in sea level. The localization of the Ahwaz delta of northern end of the Persian Gulf and southwestern Iran was probably influenced by deep-seated 'Hercynian' age lineaments that extended north from the central Arabian Arch (Ziegler, 2001, p.485).

The Ahwaz Sand Member dies out eastward. This member of the Asmari believed to have been deposited in nearshore, shoreline, and possibly eolian environments. The deposition of the contemporaneous Ghar and Ahwaz Sandstone implies that the northeastward progradation of these sand bodies may have been constrained by relative variations in sea level. This may in turn allow the potential stratigraphic position of lowstand wedges to be predicted.

The Ahwaz Sand Member is inferred to have been deposited in a high-energy forebulge depozone that was overstepped by foredeep Asmari carbonates. Evaporites and calcareous argillites of the Kalhur Member may represent deposits of a low-energy, coastal to nearshore environment in the back-bulge depozone whose deeper part is represented by lime mudstones of the same unit.

Strata of the Asmari Formation and its time equivalent were removed by erosion over much of the Arabian Platform area, if indeed they were deposited during the second regression. The area in the eastern Abu Dhabi is thus the platform margin linking with southern Persian Gulf Basin where deposition was essentially continuous throughout the Cenozoic. However, the Asmari Formation in the UAE comprises platform and 'peri-reefal' carbonates analogous to those of southwestern Iran. Therefore, it might be inferred that the

Asmari Formation deposited in the entire Persian Gulf region might have the similar lithofacies characteristics.

The change from shallow water, Asmari limestones to lagoonal-supratidal, evaporitic sequence of Gachsaran Formation may indicate the closing of the Tethyan Ocean resulting in the establishment of a restricted basin. The extent of restriction gradually diminished, and normal-marine conditions are in the process of being reestablished in the modern day Persian Gulf.

With the lowering of the global sea level (from 40 to 70 meters) during the Miocene, these last seaways were restricted and isolated, and ultimately desiccated after the deposition of vast evaporite deposits. It has been suggested (e.g., Dickinson, 1974b; Stoneley, 1974) that the Late Miocene modification from carbonate depositional system (i.e., Asmari Limestone) to evaporites (i.e., Gachsaran Formation) signify basinal restriction and drying up of the basin for the period of emergence caused by isostatic uplift. This timing is consistent with the opening of the Red Sea, with strong deformation along the Zagros Suture Zone.

The Asmari carbonates deposited in the Zagros Basinal trough are the last open marine deposits of the Neo-Tethys Seaway, a body of water that extended from the Indian Ocean across the Middle East into southern Europe. The larger foraminifera found in Asmari Formation indicate that the Tethys became divided about 4.5 Ma ago. From now on, organisms in the Indian Ocean and the Mediterranean Sea were isolated from one another and evolved separately.

In summary, the environmental modification from the shallow marine (i.e., Asmari carbonate) to very shallow lagoonal-supratidal, evaporitic sequence (i.e., Gachsaran Formation) characterizes the classical seal-reservoir sequence and records the restriction and drying up of a basin emerging as a result of the isostatic uplift as the Arabian plate resisted further subduction. The timing is consistent with the opening of the Red Sea and the intense deformation along the Zagros Crush Zone.

NEOGENE (MIOCENE-PLIOCENE)

Significant environmental changes occurred in the sedimentary framework of the Zagros and Persian Gulf area in the Neogene. The region developed into an unstable element in the Middle East during the Early Miocene, as a result of which the basin depocenter shifted to the southwestern Iran and remained there until the Pliocene Zagros orogeny. Consequently the Neogene sedimentary section is extremely thick and is dominated by evaporites and continental clastics and red beds with a brief intervening marine episode. Evaporites were deposited over wide areas during the Early Mid-Eocene.

The combination of uplift which occurred due to the opening of the Red Sea and associated depression of the northeast margin of the plate, due to the Zagros collision resulted in a marked northeast tilting of the plate. This caused

the elevation of the paleoaquifers in the west, the recharge of fresh meteoric waters through the elevated outcrop, and the initiation of a significant hydraulic head. The surface effects of this are evidence by hydrodynamic trapping components into some traps (Wells, 1987) as well as the likely spillage of oil and gas westwards out of the traps previously full-to spill.

Regional uplift and erosion at the end of the Eocene may have been caused by isostatic rebound following earlier thrust-loading (in the north and east) or by Red Sea rifting (in the south and west).

Eastern Arabia appears to have undergone subaerial erosion from late Paleogene into Early Neogene and sedimentary continuity, represented by the Asmari limestone and in part by the younger Dammam, was restricted to the Zagros and South Persian Gulf Basins.

MIOCENE

The Miocene witnessed the extensive deposition of increasingly marginal and non-marine sediments, especially evaporites and clastics, both in the east and west, with marine sediments restricted to the Tethyan Seaway. Tectonic activity during Oligocene-Miocene brought about the emergence of the 'Western Arabian Highlands' and a further contraction of the Tethyan Seaway which ultimately resulted in the closure of its western Mediterranean end.

In the lower Miocene times, the onset of the Zagros orogeny, representing the final collision of Arabia and Eurasia caused uplift and erosion in the southern Persian Gulf represented by a regional unconformity. The orogenic activities started in the Miocene or upper Miocene and produced folding that climaxed at the end of the Pliocene. Folding, as well as post-orogenic uplift is still going on. It shows truncation and gentle arching over most of the major oil fields, whilst the succeeding development and infill of the Zagros foredeep generated the regional northeasterly dip which is such a feature of the offshore area today.

In Arabia, the Miocene sequence forms a thin wedge of lacustrine, fluvial, and coastal plain deposits, peripheral to the main area of the Zagros Basin. Following the deposition of largely Middle to Late Eocene (Lutetian) the Damman Formation and its equivalents (Steinkee et al., 1958), inversion and eustatic sea level fall resulted in widespread emergence, erosion and non-deposition across the Arabian plate. The stratigraphic sequence above the Lutetian beds consists of a relatively thin succession of Lower-to-Upper Miocene and Pliocene (i.e., 200 to 300 meters), almost entirely non-marine in origin (Power, 1968).

Deposition of the clastics overlying the Dammam Formation might have started as early as the Upper Oligocene (Chattian). In the offshore of the UAE in the Persian Gulf, the Oligo-Miocene carbonate sequence of the Asmari, Gachsaran and Mishan Formations overlie the Dammam Formation. In Qatar peninsula, clays and sandstones with chalk beds are the youngest units overly-

ing the Dammam Formation. These are possibly equivalent to the Dam and Hofuf Formations of Saudi Arabia.

Around Mid-Miocene time (~15 Ma) terminal suturing occurred between Arabia and Eurasia along the Bitlis and Zagros Sutures, producing widespread horizontal shortening throughout the region (Hempton, 1987). This collision caused shortening in the Zagros (Ala, 1982).

By Mid-Miocene, as the shelf began to be further broken up by the rising folds into a network of subbasins, poor circulation of the sea water allowed intense evaporite production in the growing synclinal lows with thick salt from the Dezful Embayment to northern Iraq. In the west Musandam Basin, conjoining the southeast end of the Zagros foreland basin, separate thick salt-bearing evaporite sequence was developed at this time (Kashfi, 1980).

Miocene sequence is succeeded by a coarsening upward clastic succession in uppermost Miocene and Pliocene time which signaled the commencement of the Tertiary orogeny. Molasse sandstones and conglomerates are coincident with folding, thrusting and nappe emplacement induced by crustal spreading in the Gulf of Eden and the Red Sea. The Zagros area, the site of the main Alpine orogeny, at this time was a dextral strike slip zone. The Gulf of Aden has opened up and the Red Sea rift had began to separate Arabia from Africa. On the eastern flank of the Arabian plate, the thrusting of the Sanandaj-Sirjan Zone onto the plate is an evidence of the continental collision with Eurasia and the Iranian Plate. As a result, a massive supply of continental to deltaic clastic came about and shallow-marine shales accumulated in the rapidly subsiding Zagros foredeep basin. The post-Asmari to Recent sediments reached a thickness in excess of five kilometers in Dezful Embayment (Koop and Stoneley, 1982).

The sedimentary sequences in the foreland basins were deposited in a series of elongated troughs separated from each other, and from the open sea to the southeast by a shallow sill. Qatar-Gavbandi Arch was a positive feature, which served to separate the Zagros and southern Persian Gulf Basins. To the north of the Arch, limestones of the upper Asmari were deposited whereas the Miocene strata in the southern part of the Arch were more evaporitic, and evaporites equivalent to the Gachsaran formed in isolated and asymmetric basins. These basins became progressively more saline during the early Miocene time leading to the precipitation of gypsum and halite and, in extreme cases, precipitation of potash salts. A marine influx from the southeast restored a more normal marine environment as represented by the Gachsaran Formation.

General regression in the Late Miocene and the deposition of continental clastics continued through the Pliocene, although in southern Iraq the marine evaporite beds did not give way to clastics until Pliocene time. In the Late Miocene and Pliocene, regression of the sea and mountain buildings (i.e., due to thrusting) produced an estuarine and lacustrine environment, and large quantities of clastics, red beds, and evaporites were developed in adjacent

synclines forming the Agha Jari Formation. Syn-orogenic sedimentary rocks of the Agha Jari overlying shallow marine sediments of the Gachsaran and Mishan Formations have been related to earlier movements before a major unconformity (Mina et al., 1967; Colman-Sadd, 1978; Koop and Stoneley, 1982; Motiei, 1993).

The final Zagros collision took place at the end of Pliocene causing extensive folding and faulting of earlier sediments. Thus, towards the end of Pliocene Epoch, the whole Zagros Belt was folded and uplifted (James and Wynd, 1965; Stocklin, 1968).The collision resulted in uplift, erosion and deposition of a suite of essentially continental clastics over most of the region. Marine sediments became restricted to the Persian Gulf. In spite of the severe Plio-Pleistocene diastrophic phase in Zagros, little trace of tectonic activity has been found in Arabia, where rocks of presumed Pliocene age have a low average dip, which increases only gradually toward the Persian Gulf (Powers, 1968).

As long as the Miocene-Pliocene uplift of the Zagros and the upheaval of individual structures progressed, erosion and sedimentation produced localized unconformities within the Agha Jari Formation. This formation is unconformably overlain by conglomerates of the Bakhtiari Formation (possibly Pliocene in age; James and Wynd, 1965) indicating a Mio-Pliocene unconformity. The deposition of Bakhtiari conglomerate was concurrent with the growth of the foothill structure of the Zagros.

Early to Middle Miocene in Persian Gulf

During the Neogene, the Fars Group which includes Gachsaran, Mishan, Agha Jari Formations (James and Wynd, 1965) consisting of sandstone, marl, limestone, and evaporites, was laid down conformably on the Asmari limestone in Zagros Basin (Figure 3-48).

Figure 3-48 illustrates the generalized stratigraphic succession of the entire 'post Asmari' sedimentary thickness, embracing the entire Fars Group and also in some syncline areas the Bakhtiari syn-orogenic conglomerates. The Zagros folds were already forming so that the true isopach map could properly indicate some thinning over every rising fold. The map, however, emphasizes the major subsidence of the pre-Zagros foredeep in the Dezful Embayment, where in excess of 5 km of post-Asmari sediments accumulated.

The sediments of the Fars Group had their depocenters in the Naft-e-Shah area (more than 3 km) in north Khuzestan (4 km) in Interior Fars (2.5 km) and in the Bandar Abbas area (3 km) closed to the Zendan Trough and east fault limit of the Zagros Basin. In west central and coastal Fars and across the Persian Gulf, the thickness diminished to less than one kilometer.

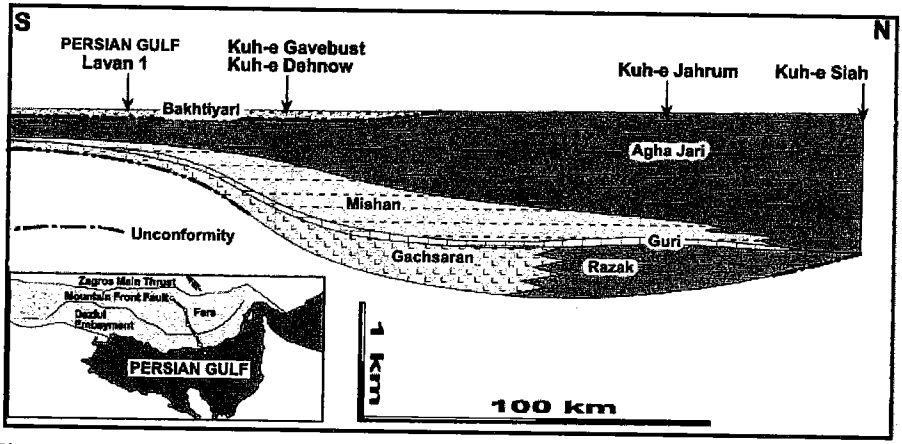

Figure 3-48. The Neogene sedimentary units including Gachsaran, Mishan, and Agha Jari Formations in Zagros Basin (Modified from Sepehr and Cosgro, 2004).

The lithofacies of the Gachsaran, Mishan and Agha Jari Formations (James and Wynd, 1965), represent a general regressive cycle that started in a NW-SE-trending basin in the Early Miocene. A regional regression exposed the entire area to subaerial weathering and erosion (James and Wynd, 1965; Mina et al., 1967; Motiei, 1993). In the present location of the Persian Gulf, clastic sediments accumulated after the end of Eocene (Mina et al., 1967; Motiei, 1993). Salt and evaprorite sequences deposited during the initial stages of this interval which constitute the all-important seal or caprock over the Asmari oil accumulations. This is the incompetent layer that forms the upper detachment zone above the buried folds of the Dezful area.

Near the end of Early Miocene, an evaporitic environment prevailed with production of extensive sequence of evaporites (see Figure 3-49). The Miocene evaporites and carbonates were succeeded by Upper Miocene-Pliocene 'molassic' redbed clastics as the depositional axis of the sedimentary basin shifted westward towards the present position of the Persian Gulf.

The Fars Group of southern Persian Gulf (i.e., Qatar and UAE) comprises essentially marginal to non-marine coarse clastic and associated evaporites similar to those of northern Persian Gulf and southern Iran. In Qatar two lithofacies units are recognized, the lower 91 meters is composed of marls and interbedded sandy limestone, sandstone and shale and the upper 31 meters of limestone and marl with thin beds of gypsum representing a marginal facies to the more typical developments found in the bordering regions.

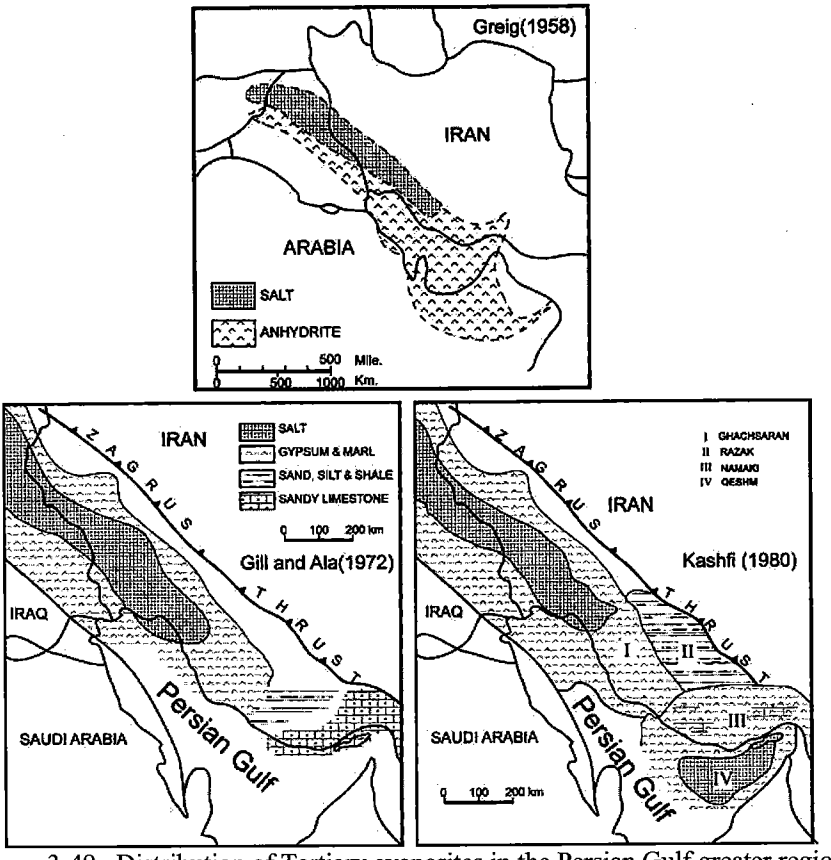

Figure 3-49. Distribution of Tertiary evaporites in the Persian Gulf greater region. The top map is showing the general distribution of salt and anhydrite in southwestern Iran and the entire Persian Gulf. The lower left is the facies distribution map where the left right is the map shows different members of the Gachsaran Formation (modified after Greig, 1958; NIOC, 1978; Gill and Ala, 1972; Kashfi, 1980).

The Upper Fars is essentially non-marine and lacks age-diagnostic fossils. It is assigned a Late Miocene age on regional considerations (Dunnington et al., 1959). Although overlain by the Gachsaran Formation in terms of local lithostratigraphy, some workers regard the Jeribe Formation as the equivalent to the Gachsaran Formation in terms of usage in Kuwait and southern Iraq (Owen and Nasr, 1958a, b; van Bellen et al., 1959).

Gachsaran Formation

After the deposition of the Asmari Formation, evaporative conditions set in, leading to the deposition of the well-known Gachsaran evaporites. The difficulty involved in the stratigraphic study of this highly mobile group is clearly appreciated by reference to O'Brien's (1950) study of its tectonic state.

The Gachsaran Formation is considered to be one of the major evaporitic sequences in the geological column of not only the Zagros Basin but also the Persian Gulf region. It is very thick and extensive, covering large areas and it belongs to Fars Group as named by Busk and Mayo (1918). The Gachsaran is an important formation economically because it forms the caprock in some of the major oilfields in the Persian Gulf region, and also contains major reserves of native sulfur. The Gachsaran shows considerable mobility and its thickness is difficult to estimate, though generally it ranges from 700 to 1500 meters.

This formation was named after its best developed sequence found in the Gachsaran field in southwest Iran, where it consists of a thick and extensively developed series of anhydrite with minor limestone, shales and Marls (James and Wynd, 1965). Setudehnia (1972) also indicated the presence of some bituminous shale and halite.

The Gachsaran evaporite sequence in Iran has been studied extensively by several workers (Harrison, 1924; Lees and Richardson, 1940; Lees, 1950; O'Brien, 1950; Hull and Warman, 1970; Gill and Ala, 1972; Kashfi, 1980). Because of the importance of this formation as a caprock for large oil fields, a very detailed series of key beds have established (Slinger and Crichton, 1959) which can be recognized over great areas. The Lower and Middle Gachsaran Formation locally contain markers for Middle Miocene (Parazk, 1978). The basal contact is conformable; the upper contact is gradational and probably diachronous. The formation is widely distributed and extends into Iran covering the marginal areas of the stable shelf and most of the unstable shelf.

The age of the Gachsaran ranges from the Early to Middle Miocene (e.g. Van Bellan et al., 1959), and is diachronous ranging from Lower Miocene in southwestern Iran, to Middle Miocene in central Iraq (James and Wynd, 1965). Because the formation comprises clastics and evaporites and contains mostly undiagnostic benthonic foraminifers, it is difficult to be date biostratigraphically. However, a local age in the range of latest Early-earliest Middle Miocene can be assigned on the basis of the occurrence of the index taxa of the *A. howchini-P. Evolutus* and *N. melocurdica* Zones (Wynd, 1965). Both the base and top of the Gachsaran Formation appears to be diachronous (Wynd, 1965).

Gachsaran consist mainly of multiple sequences of variable thickness and lithology including alternations of evaporites (gypsum, anhydrite, and subordinate halite), dark bituminous to red shale, marl, cross-bedded quartzose sandstone (derived from the northeast). Locally, the formation is conglomeratic calcarenite (to the southeast in Fars region, a thick interval of detrital limestone is termed Champeh) and has been interpreted as a distal facies of the wedge-top depozone of the proforeland basin, and progradationally overlaps time-equivalent Jeribe carbonates of southern Iraq toward the southwest. A thick evaporite layer near its base serves as the seal for hydrocarbon reservoirs in the underlying Ahwaz and Asmari units.

Seismic evidence shows that a great deal of halite was originally deposited while halokinesis in addition to tectonic compressing and leaching near the surface seems to have redistributed and removed halite from the crest of the Asmari anticlines. In the Fars region the formation is clearly diachonous, becoming younger from southwest to northeast where evaporites replace the younger beds of the Asmari Formation.

In the Persian Gulf region, the Gachsaran Formation, in general, conformably overlies the Asmari limestone except in Qeshm Island. In the eastern part of the Persian Gulf Pabdeh marl replaces the Asmari and directly underlies the evaporites (Gill and Ala, 1972). The Gachsaran-Asmari boundary is sharp and generally considered to be isochronous. In the eastern part of the Persian Gulf (i.e., Hengam Tertiary Basin), thick Miocene salt is developed within the base of the Gachsaran.

The Mishan Formation overlies the Gachsaran for the most part and by Agha Jari Formation in the extreme northwestern part of the Zagros; regionally it is underlain by the Asmari carbonates. In the foothills of the Zagros Mountain range, the Gachsaran contact with the Asmari is sharp and its lithology dominantly consists of anhydrite with intervening marl and limestone with alternating thin beds of salts. The salt forms well-defined stratigraphic zones in almost all the wells of the Khuzestan oil fields.

In Dezful Embayment, the thickness of the Gachsaran Formation changes very rapidly from several hundred to two kilometers. The thickness variation is related to faulting, folding and diapirism after deposition and also syntectonic sedimentation during the folding. It consists of salt at the base, which is overlaid by anhydrite, marls and thin-bedded carbonates (Sherkati and Letouzey, 2004). According to their observations differences in size, structural configuration and tectonic complexity of the structures across are interpreted as being related to sedimentary facies variations.

In Kuwait, the Gachsaran Formation has a thickness ranging between 76 to 91 meters and consists of alternating sandstones with interbeds of clay. In northern Kuwait and southern Iraq where the succession is thicker, it contains anhydrite, gypsum, clay, marl, and limestone typical of shallow water offshore environment suggesting a relatively rapidly sinking basin frequently isolated from marine conditions. Clay balls within the sandstone suggest erosion and redistribution of bottom sediments.

Evaporitic sequences similar to the Early to Middle Miocene sequence penetrated in the wells adjacent to the offshore oil fields. The Gachsaran Formation uncomformably overlies an eroded, channeled and weathered surface of Hormoz series and consists of marl becoming highly calcareous and changing to limestone. Bands of gypsum are also recorded at some locations. Iron staining is notable in the upper part of this unit.

Division of Gachsaran

The regional extent and facies distribution of the Gachsaran Formation in the Persian Gulf and adjacent area has long been a subject of considerable debate. This includes sedimentary geology of the evaporitic strata (Goff et al., 1995).

Generally the formation has been divided into Lower, Middle and Upper Gachsaran Formation. The Lower and Middle part of the formation comprise essentially marginal marine carbonates, evaporites and fine clastics while the upper part of the formation is basically non-marine coarse clastics. In general, evaporites regionally dominate the lithofacies of the Gachsaran Formation. Carbonates with marl and subordinate siltstone-sandstones are also present (James and Wynd, 1965).

A detailed stratigraphic and sedimentologic investigation performed by Kashfi (1980) reveals that the strata of the Gachsaran Formation in the Persian Gulf region can be divided into four distinct lithofacies. Although these units are time-equivalent, each characterized by its own dominant lithology indicating different environment of deposition. These units are as follows: 1) Anhydrite salty facies (Gachsaran Formation); 2) Sandy silty facies (Razak Formation); 3) Gypsum-anhydrite facies (Namaki Formation) and; 4) Massive salty facies (Qeshm Formation). The first three units were deposited within the offshore of the present day Persian Gulf where as the fourth Formation is mainly distributed in the subsurface of the Persian Gulf (see Figure 3-50).

Sandy Silty Facies (Razak Formation of Kashfi)

James and Wynd (1965) described this unit as a succession of 775 meters of low-weathering silt, red to green to grey marl with subordinate silty limestone in the type section at Kuh-e-Jahrum. The unit comprises fine clastics and it is correlative with the lower part of the Gachsaran Formation (Wynd, 1965; Stocklin and Setudehnia, 1972).

Lithologically, it consists of variegated, coarsening-upward siliciclastics (including polymict conglomerate derived from the northeast and pinching out toward the southwest), of highly variable thickness (150-1300 meters), interbedded with calcareous argillite and argillaceous limestone; interfingers with and progradationally oversteps Asmari limestones toward the southwest, and also interfingers with lower Gachsaran evaporitic beds to the northeast; deposited in the distal wedge-top depozone of the proforeland basin.

The facies conformably overlies the Asmari Formation and underlies the Mishan Formation. It is mapped in interior Fars region (Lee, 1938; O'Brien, 1950; Sahabi, 1978) and considered to be a non-evaporitic red-bed equivalent of the evaporitic Gachsaran Formation which progressively interfingures into the Razak Formation in the interior Fars region. The base of the Razak Formation gradually replaces the upper part of the Asmari Formation toward the

southeastern segment of the Zagros. In many places within the Simply Folded Zone of the Zagros close to Shiraz, the Razak Formation onlaps the Asmari Formation. Similar conglomerates are reported at the same stratigraphic level in the NW Zagros of Iraq (Motiei 1993). Such onlaps and conglomerates are due to gentle movements at the end of Asmari times (Burdigalian) (Hessami et al., 2001).

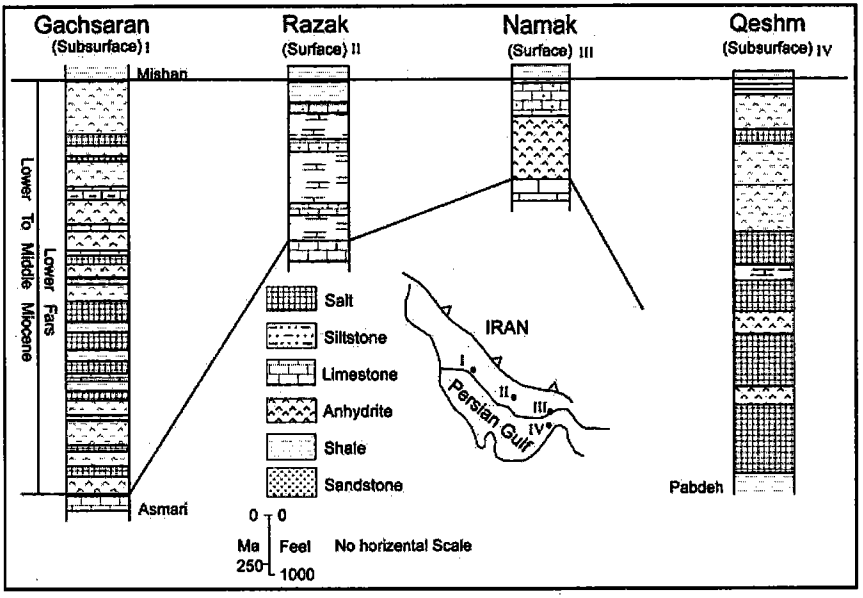

Figure 3-50. Stratigraphic columns of the lower Fars from east to west parts of the Persian Gulf area (modified from Kashfi, 1980).

The Razak Formation mainly consists of interfingering thin carbonates and calcareous argillites toward the southwest and of interbedded shales, siltstones, sandstones, and conglomerates toward the northeast. The Razak facies relations suggest that the coarser siliciclastic strata may have existed farther to the northeast in the Zagros imbricate zone, nevertheless removed erosionally and (or) denudated tectonically after deposition. To the southwest, Razak Formation grades laterally to the Asmari carbonates, which progradationally overstep Ahwaz sandstones.

The Razak Formation is interpreted as the distal facies of a clastic wedge whose proximal facies presumably extended to the northeast into the Zagros imbricate zone but has been eroded away. The wedge progradationally overlapped deeper-facies Asmari carbonates, which can be interpreted as a foredeep facies.

Gypsum-Anhydrite Facies (Namaki Formation)

The names of Namaki and Qeshm are designated to two distinct units with different lithologies within southern extension of the Gachsaran Group. The unit has a thickness of more than 450 meters and is divided into three distinct members. The lower member (i.e., Chehel member) is a prominent gypsum and anhydrite unit. The middle member (i.e., the Champeh member) is a marly limestone and dolostone with thin evaporite layers, whereas the top member (i.e., Mol member) has a distinct red color and forms an excellent key bed with similar lithology to the Chapeh member. Favre (1974 cited in Motiei, 2003, p. 460), attributed the deposition of Gachsaran evaporite sediments in southern Persian Gulf and Strait of Hormoz to the lateral facies changes of the Chehel member.

Massive Salty Facies (Qeshm Formation)

Considering the geology of the Persian Gulf itself, this unit is directly deposited in the Persian Gulf. The name Qeshm Formation is advocated to a unit, which is composed mainly of massive salt and sand and subordinate anhydrite with thin interbedded bands of marls. This formation is a subsurface unit in the Persian Gulf which extends throughout much of the southeastern Persian Gulf as well as the western part of the Qeshm Island (Figure 3-51). The name Qeshm Formation is taken from Qeshm Island in the Persian Gulf. The formation has been drilled in various parts of the Persian Gulf. The above figure shows the configuration and extension of the evaporitic basin. The maximum thickness of 1911 meters of this unit was penetrated in the Mubarak 1 well in the Persian Gulf (Kashfi, 1980).

Generally the lower part of the formation consists entirely of salt; the upper part is mostly anhydrite with thin beds of marl. Where the salty part of the formation is developed, the Asmari-type lithology is absent. Therefore, for the most part, Qeshm Formation is directly underlain by Pabdeh Formation, whereas Namaki, Razak, and Gachsaran Formations generally conformably overlie the Asmari Formation.

SEDIMENTARY ENVIRONMENT

During the deposition of the Gachsaran Formation the basin was rapidly infilled with halite in the central part of the basin, and more anhydrite to carbonate facies on the margin of the basin. There was little clastic input, only a basal conglomerate beneath the Gachsaran Formation.

The basin was an asymmetric, northwest-southeast trending feature, with a steeper northeastern flank. Its axis passed through Lali, Masjed-e-Suleyman, and Gachsaran oil fields (O'Brien, 1950, p.50). The basin extended from the Bandar Abbas region through southwestern Iran into Iraq and eastern Syria, a distance of about 1,500 kilometer, with a maximum width of 300 kilometers.

A southern extension occupied the region between Qatar and Oman Peninsula. On the northwest, possibly through gaps in the Hamedan area, a branch of the basin reached into central and northwest Iran and Anatolia, joining with the Mediterranean basin (Stocklin, 1968, p.174). Towards the southeast extension of the basin, the Gachsaran passes into redbeds and thin limestones.

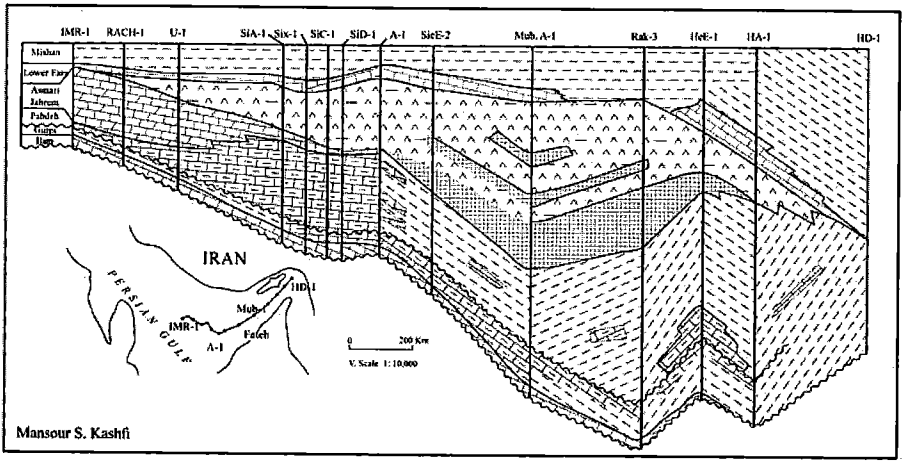

Figure 3-51 East-West extension of the Qeshm Formation (lower Fars) in the Persian Gulf (Kashfi, 1980).

The rising Zagros trough, by Mid-Miocene time, had developed into local lagoonal and evaporite basins and this emergent condition progressed from the extreme southeastern segment northwestward. Basinal subsidence did not succeed to keep pace with sedimentation during Miocene, and as a result the connection between the main part of the trough and the open sea might have been restricted.

A north-south-trending submarine high, in line with the Oman Peninsula, exited in the Bandar Abbas region, and acted as a threshold over which the evaporite basin maintained a connection with the Indian Ocean. Sandstone and sandy evaporitic limestone facies constitute sediments on the basinward slope of this ancient high. The western shore of the basin approximately coincided with the western shore of the present day Persian Gulf.

Salt was deposited only in the deeper central parts of the basin, where it forms well-defined and locally massive beds (Slinger and Crichton, 1959). As it is rarely preserved in outcrop, its former presence could be deduced from indirect evidence such as formation of massive brecciation in overlying strata (i.e., collapsed breccia). For example, Falcon (1958, p.1288) suggested that the areas with important disturbances in the outcrops of Gachsaran Formation may indicate the sites of original salt deposition. Accumulation of great thickness of evaporitic facies was made possible through steady subsidence of Gachsaran sabkha plains.

The evaporitic Gachsaran deposits present a succession of relatively small cycles of sedimentation between the fully marine deposits of the Asmari carbonates and the continental development of the Agha Jari sandstone (Gill and Ala, 1972). Thus, the entire Gachsaran Formation records many minor transgression and regressions in early-Middle Miocene times. It is also presumed that the transgressive part of each cycle is controlled tectonically, representing practically contemporaneous subsidence over remarkably large areas (Gill and Ala, 1972). These minor events took place between the major transition from almost entirely marine Asmari carbonates, and the ultimate, dominantly continental Agha Jari redbeds.

LATE MIOCENE

Continental collision along the Zagros created an uplift which shed great quattities of sediments towards the southwest reaching the present Persian Gulf Basin. The post Mid-Miocen stratigraphy of the Persian Gulf comprised of up to 2 km wedge of fine-grained sediments thickening to the northeast.

The isopach maps based on wells indicate that the sedimentation was relatively uniform across the region until the Middle to Late Miocene. Sediments deposited since the Late Miocene thicken from 100-200 meters on the Arabian side to more than one kilometer near Iran reflecting deposition of sediments eroded from the rapidly uplifting Zagros Fold Belt (Swift, 1998). The Upper Fars has a thickness of about 2 kilometers in the central part of a depression in the foothills region in SW Iran where it consists mainly of silty marlstones and shale. The depositional environment changed through time from lagoonal to lacustrine to fluvio-lacustrine.

Mishan Formation

The widespread deposition of Gachsaran terminated by a marine influx from the southeast, depositing marine sediments of the Mishan, upper Guri and Middle Fars that thinned and died out to the northwest. This transgression was probably a response to a global rise in sea level (Vail et al., 1977) but available date (i.e., Middle Miocene) is not sufficiently accurate to confirm this. The lagoonal-evaporitic phase of Early Miocene time was followed by a marine transgression and the subsequent deposition of marls, and localized reefal limestones of the Mishan Formation. In some areas in the northern Persian Gulf the Mishan Formation becomes undifferentiated from overlying and underlying Agha Jari and Gachsaran Formations (Mina et al., 1967).

During the Lower to Middle Miocene, the Mishan Formation (dominantly marl in nature) was deposited in the Zagros foreland basin. It is composed of a shallow-marine marl, calcareous shale, siltstone, and sandstone (derived from the northeast) interbedded with ridge-forming ribs of carbonates and shelly detrital limestone. It becomes conglomeratic near top and transitional between

distal (partly marine) and proximal (predominantly fluvial) facies of the wedge-top depozone of the proforeland basin, progradationally oversteps the Gachsaran along an unconformable contact, and is overlain gradationally by Agha Jari conglomerates.

The Mishan sediments indicate a relatively minor marine transgression across the Zagros Basin in Mid-Miocene. It is well developed in the eastern part of the Persian Gulf and involves argillaceous clastic facies with subordinate carbonates (i.e., the Guri Limestone Member). In the Dezful Embayment region the formation is approximately 752 meters thick and consists primarily of marls alternating with more resistant shelly limestone (James and Wynd, 1965; Setudehnia, 1972). Here, the Mishan Formation is conformably overlain by the regressive phase of Agha Jari Formation, while the Agha Jari sediments deposited in a largely estuarine environment; yet, they become partially marine origin in the southern Zagros areas.

Kent et al. (1951) described that marls in the footwall of the Mountain Front Fault in the Dezful Embayment, thinning rapidly and sometimes changing to reef limestone when traced northeastward towards the Mountain Front Fault. They also reported a conglomerate (apparently in the upper part of the Mishan Formation) containing fragments of the Asmari Formation.

The basal part of the formation, with a thickness of approximately 62 meters consists of alternating marl and limestone and rests with a sharp contact marked by a gypsum bed on the underlying beds of the Gachsaran Formation. Locally a biohermal limestone referred to as "the Guri Member" may develop in these lower beds.

It is difficult to date the Mishan Formation biostratigraphically, since it contains mostly undiagostic benthonic foraminifera. However, it locally contains the larger benthonic foraminifera *Flosculinella bontangensis* and *Tabernia* (Pseudo-tabernina) *malabarica*, indicating a latest Early-earliest Middle Miocene age. Both the base and the top of the Mishan Formation appear to be diachronous (Wynd, 1965).

The Mishan Formation is well developed southeast of the Asmari oil-field belt where it is more than 650 meters thick, but wedges out near the eastern margin of the belt. The marine Mishan Formation passes gradationally upward into thick redbeds sequence of the Agha Jari Formation, which consists of 1.6 to 3 km of interbedded red shale and sandstone devoid of marine fauna.

As described by James and Wynd (1965), the Mishan Formation is equivalent to the Middle Fars depicted by Ion et al. (1951) and Slinger and Crichron (1959) and correlateable with marine intervals in the Middle Fars (also regarded as lower Upper Fars) of northern Iraq (van Bellen et al., 1959).

The Guri limestone member is well developed at the base of the Mishan and extends over most part of the eastern area. The limestones indicate the passage into more marine environments (reefal Guri). The Guri member (James and Wynd, 1965; Kashfi, 1982) is a succession clearly deposited under open marine conditions in the Mishan Formation and contains fauna (Miogys-

ina, Orbulina universa) indicating a probable Middle Miocene age. In addition, the deposition of Guri member of Mishan Formation represents a final marine flooding event (Motiei, 1993).

Van Bellen et al. (1959) regarded the age of Gachsaran as Middle Miocene whilst Jones and Racey (1994) suggested that it is probably Middle Miocene, Mid-Serravalian, following Prazak (1978) who suggested correlation with global planktonic foraminifera. Jones and Racey (1994) date Mishan as latest to earliest Middle Miocene. However, Fuchs et al. (1968) provide a latest Miocene age to limestones with a marine fauna in the Gachsaran of Kuwait, which they correlate with the Mishan of Iran.

In terms of depositional environment of Mishan, sediments were deposited in a shallow, northwest-southeast trending trough. In this trough the facies replacement of Mishan carbonates by Agha Jari clastics may begin early in the Late Miocene in north and southern part of the Persian Gulf (Setudehnia, 1972). The equivalent of Mishan-Agha Jari Formations is the Upper Fars-Bakhtiari Formation of southern Iraq and Dibdibba and Hofuf Formations of Kuwait and Saudi Arabia in southern Persian Gulf.

Miocene in the Southern Persian Gulf

At the time of continental collision between Arabia and Eurasia during the early Miocene (Early Neogene), shallow-marine sedimentation was replaced by terrestrial depositional environments over much of the Persian Gulf region. In southern Persian Gulf, the Shuwaihat Formation comprises deformed evaporitic sediments that are replaced upwards by sands dunes which, similar to those of the present time, were deposited under the influence of a northern (Shamal) wind; the sands are riddled with the moulds of plant roots (Glennie and Evamy, 1968), which indicate the former proximity of the water table at fairly shallow depth.

With an erosional interval indicating several million years, the sand dunes are overlain by fluvial gravels and sands. The changes from arid dune and sabkha to the more humid conditions needed for the hippopotamus and crocodile to thrive required a considerable modification in climate, a change that seemed to have taken place repeatedly during the past million years or so. The erosional time gap between the Shuwaihat and Baynuna Formations is possibly the result of a considerable fall, probably in the order of 100 m in world-wide sea level when Antarctica utilized that volume of water to form its substantial ice cover.

Eastern Arabia underwent uplift and subaerial erosion from the Oligocene into the Miocene. The Oligocene through Pliocene (Neogene) of Saudi Arabia is composed of four formations with total thickness of about 350 meters, which in ascending order are the Hadrukh, Dam, Hofuf, and Kharj Formations. These are the equivalents of the Asmari and Gachsaran Formations.

The early Miocene Hadrukh Formation is mostly non-marine sandy limestone and calcareous sandstone and is conformably overlain by the marls, limestone, and claystones of the Middle Miocene Dam Formation. The late Miocene-early Pliocene Hofuf Formation consists of marls, sandy limestones, conglomerates, and argillaceous sandstones of continental origin. The overlying Pliocene Kharj Formation consists of irregular-bedded limestone, sand, and gravel conglomerates, with some sediments indicating deposition in a freshwater, lacustrine environment (Alsharhan and Nairn, 1997).

At this time, the northern Arabian plate was covered by shallow-marine sediments with the exception of the tectonically affected zones along the northern margins of the plate. The sediments were deposited within the Zagros foredeep and foreland. Strong compression now occurred as Arabia separated from Africa and was driven into Eurasia.

Hadrukh Formation

The Hadrukh Formation in Saudi Arabia consists of 84 meters of sandy limestones with chert and minor gypsum. It rests unconformably on the Eocene, Dammam Formation (Powers et al., 1966). The top is selected at the junction between calcareous sandstones with limestones of the Dam Formation. The age is assigned from stratigraphic position. It passes laterally to Ahwaz Sand Member of the Asmari Formation (Ghar Formation in northern head of the Persian Gulf).

Deposition of mainly continental Hadrukh to transitional-marine sedimentary sequence of the Dam Formation occurred around the Arabian Arch. In the interior of the Arabian plate, age-equivalent lacustrine sediments belong to Hofuf Formation. The Early Miocene Hadrukh (Aquitanian to early Burdigalian, 23.7 to ca.20 million years) is mostly non-marine sandy limestone and calcareous sandstone and is conformably overlain by marls, Echinocyamus limestone, and claystones of the middle Miocene Dam Formation. The basal strata of the Hadrukh are a few meters of sandy limestones resting unconformably on the Dammam Formation. The Hadrukh Formation represents continental to shallow marine facies (Power et al., 1966) and comprises coarse clastics presumed correlative with those of the Ghar Formation of southern Iraq and Kuwait.

The Miocene to Pliocene sedimentary environment of the Persian Gulf was dominantly pluvial, depositing a rather large volume of Hudrukh and Hofuf rocks (Whybrow and McClure, 1981). These formations in turn provided the source for part of the huge volumes of sand now stored in the sand seas of southern Persian Gulf (McClure, 1978).

Dam Formation

The Miocene carbonate sequence of the Dam Formation (southern Persian Gulf) consists of four major lithofacies. They are limestones, marls, clays, and evaporites of which limestone is the most important in terms of thickness and faunal content. The limestones in turn have been subdivided into six subfacies as follow (Power et al., 1966); clayey limestone, sandy limestone, oolitic limestone, stromatolitic limestone, and dolomitic limestone. Lithofacies and associated faunal assemblages indicate that the sediments of the Dam Formation were deposited in a very shallow tidal flat setting under warm climatic conditions.

The Dam Formation deposited as a result of a major Neogene transgression and is dominated by shallow marine, warm-water fossils such as stromatolites and species of reef facies. It represents a bioherm reef facies and contains in situ corals, blue-green algal growths and mollusks (pelecypodes and gastropods)(Power et al., 1966).

Agha Jari Formation

The Agha Jari Formation is a mudstone and sandstone sequence of continental nature with a thickness of approximately 3000 m thick in its type section in the Agha Jari oil-field in northern Persian Gulf. The Agha Jari is the highest Tertiary sedimentary sequence seen in the Persian Gulf area.

This formation consist almost entirely of terrigenous clastics ranging in size from silt to boulder conglomerate ranging in thickness from 650 to 3250 meters (although the dominant lithologies consist of calcareous sandstones, marls and siltstones) deposited under lacustrine conditions in Dezful Embayment and Lorestan. It is partly marine origin in northern Persian Gulf coastal Fars and passes into the Hofuf Formation and the Dibdibba Formation in southern Persian Gulf.

The upper Miocene to Pliocene Agha Jari Formation consists of a thick succession derived from the northeast, mainly marine near its base but paralic to continental at higher horizons. It is composed of carbonate-clast and polymict conglomerate, calcarenite, cross-bedded sandstone (chert grains a major constituent), siltstone, marl, and lime-mudstone (with interlayered lenses of gypsum). The formation also is displaying syndeformational growth strata; multiple upward-coarsening intervals toward the southwest as proximal facies of the wedge-top depozone of the proforeland basin (Alavi, 2004). In terms of the depositional environment, the Agha Jari Formation sediments were deposited in both shallow-marine and estuarine environments, with the latter being dominant (James and Wynd, 1965; Mina et al., 1967; Pedrami, 1987; Motiei, 1993).

In many ways the Agha Jari Formation to a great extent resembles Upper Red Formation of Central Iran. This formation was deposited from the rivers

flowing from the Zagros range under arid climatic conditions. The rivers spread a large sand delta in the Lorestan region and, in episodic flood event, mud and sand sheets covered the entire area. Some of the sand fans in southern Lorestan originated from the Arabian platform.

Channel incisions and other paleocurrent indicators in the Lower Agha Jari Formation produce paleoflow directions mainly oriented towards the southeast, subparallel to the axis of the foreland basin. This longitudinal paleoflow for Agha Jari deposits is similar to present Tigris and Euphrates fluvial systems in the Mesopotamian foreland basin.

The Agha Jari Formation is made up of silty-clay layers intercalated with sandstone beds, which form channels with variable extensions. In the basal 50 meters of the formation, sandstone beds are separated by silt layers. At the top, they exhibit some ripple marks that are mainly symmetrical. Gypsum veins are very common. Towards the middle part of the formation, well-consolidated sandstone beds abruptly become more spaced and thicker, with metric thickness and extension ranging from several tens to several hundreds of meters. They display numerous well-developed cross bedding structures. In the upper part of the Lower Agha Jari Formation, observed on the Changuleh anticline, sandstone layers also present paleoflow indications, principally oriented toward the southeast (Homke et al., 2004).

Closer to the Zagros Thrust, coarse conglomerates were deposited in the Bazuft Depression. In marine-brackish and playa-type shale intercalations, the Agha Jari Formation contains a fauna of Elphidium, Rotalia and ostracod assemblages and in the Lahbari mudstone Member in Dezful Embayment, while Hiparion bones indicate a Pliocene age.

Lahbari (Upper Miocene to Pliocene)

The upper part of the Agha Jari Formation consists of siltstone, marl and sandstone of the Lahbari member and has a questionable age, but is generally considered to be Pliocene and younger (James and Wynd, 1965; Pedrami, 1987).

The Lahbari member consist of thick (up to more than 1.5 km) upward-coarsening interval of brackish to fresh-water calcareous argillite, siltstone, and cross-bedded lime clast-sandstone containing conglomeratic beds derived from the northeast and interlayered with gypsum lenses; interpreted as a distal facies equivalent of Agha Jari molasse deposited farther to the northeast. According to Homke et al. (2004), the Lahbari Member of the Agha Jari was deposited between 5.5 Ma (upper most Messinian) and 3 Ma (late Pliocene).

Repetition, dimensions and granulometry of sandstone layers increase significantly in the 130 meters preceding the transition to the Lahbari Member. Some conglomeratic levels, characterized by thin gravels, appear at the base of sandstones. The sandstones of the Lahbari Member are less consolidated than those of the Lower Agha Jari Formation. A large part of sandstone lay-

ers, generally thinner than five meters, are covered by mud, presenting a relatively smooth topography that contrasts clearly with the relief of the lower part of the formation. The beige color of the mud is equally a distinctive characteristic. Near the top of the formation, several sandstone beds contain thin dark gravels with pebbles smaller than 5 cm. This fine-grained member is followed by deposition of conglomerates of the Bakhtiari Formation, starting at 3 Ma. The last age control is located 50 meters above the base of the Bakhtiari Formation, which is dated at 2.5 Ma (Homke et al., 2004).

Age of Agha Jari Formation

A Miocene to Pliocene age is assigned to the Agha Jari Formation. The age of the base of the fluvial Agha Jari is little constrained. If the sedimentation has been continued through the deposition of the top of the Gachsaran and the Agha Jari Formations, the transition between the two formations would be dated around 12.8 Ma in the Zarrinabad syncline and at 12.3 Ma in the Changuleh syncline, both in the middle part of the Serravalian (late Middle Miocene). The transition could however take place as soon as the early Miocene, as suggested by biostratigraphic age of the Gachsaran Formation (James and Wynd, 1965), implying the presence of a hiatus at the base of the series. The deposition of the Lahbari Member begins in the Changuleh region at 5.5 Ma, at the end of the Messinian (latest Miocene).

The long-term sedimentation derived from magneto-stratigraphy averages 26 cm/ky, which is well in the range of the Miocene alluvial sedimentation in the Himalayan foreland. Short-term sedimentation trends are smooth and vary gradually during the deposition of the Agha Jari. The sediment accumulation rate does not vary greatly during the deposition of the Agha Jari. At the base of the series, the depositional rate of the lowermost Agha Jari Formation is about 19.5 cm/ka. The rate increased regularly, reaching 30.5 cm/ka around 700 m, and slowed down to 19.5 cm/ka after the deposition of the lower part of the Agha Jari growth strata. The rate seems to have started to increase by few tens of meters below the top of the Lower Agha Jari, until reaching about 33 cm/ka in the upper part of the Lahbari Member and in the lower 50 meters of the Bakhtiari Formation (Homke et al., 2004).

Hofuf Formation (Equivalent to Agha Jari)

The Late Miocene-Early Pliocene Hofuf Formation consists of marls, sandy limestones, conglomerates, and argillaceous sandstones of continental origin. In Saudi Arabia, this formation consists of 75 meters of marl, conglomerate, and boulder and pebble limestone in lower part while the upper part consists of chalky and sandy limestone alternating with argillaceous sandstones covered by marly limestone and limestone boulders in a marly, quartz sand matrix (Powers et al., 1966). Quaternary and Holocene surficial

deposits unconformably overlie the formation. It is the lateral equivalent of the Upper Fars Formation in southern Iraq.

The overlying Pliocene Kharj Formation consists of irregular-bedded limestone, sand, and gravel conglomerates, with some sediments indicating deposition in a freshwater, lacustrine environment (Alsharhan and Nairn, 1997). The Hofuf Formation represents continental facies, but its age is poorly-constrained, estimated to be Miocene to Pliocene by Power et al. (1966), but Middle to Late Miocene by Thomas et al. (1978).

Dibdibba Formation

The Dibdibba Formation refers to the sedimentary beds which are exposed near Basra close to the head of the Persian Gulf and in northern Kuwait. In this area about 150 meters of ungraded fluvial, locally cross-bedded sands and gravels with subordinate intercalations of lenticular carbonate or argillaceous cemented sandy clays sandstones conglomerates and siltstones are exposed. These beds have an age ranging from Pliocene into Pleistocene and overlie the Gachsaran Formation. They are thus facies equivalent to Upper Fars and Bakhtiari Formations (Power et al., 1966; Thomas et al., 1978).

The Dibdibba Formation can be divided into two members: the Lower Member of the Mio-Pliocene and the Upper Member of Plio-Pleistocene age. The lower Member is typically made up of very coarse-grained, poorly sorted, gritty and pebbly sandstone cemented with chalky carbonate cement. The Upper Member is composed of gravelly sand and sandy gravel. Gypsiferous cement is quite common and limited occurrence of calcareous cement is also observed.

Bakhtiari Formation

Following and throughout the Zagros orogeny, coarse conglomerate molasse-type deposits accumulated in southwestern Iran known as Bakhtiyari Formation. They display great thickness variations and locally overlie older rocks with an angular unconformity. Thus, the Bakhtiari conglomerate rests unconformably above terrigeneous materials and filled the basins.

Thick molasse sediments accumulated in the recently established Zagros foredeep while its depocenter drifted through time from northeast to southwest to its present position, the Persian Gulf (Edgell, 1996). The widespread occurrence throughout the ZFTB of Plio-Pleistocene Bakhtiari conglomerates marks the most recent and vigorous phase in the collision process (James and Wynd, 1965).

The Pliocene to Pleistocene Bakhtiari Formation consist of massive to thick-bedded, upward-coarsening fluvial strata (alluvial-fan and braided-stream deposits) composed of polymict conglomerate, cross-bedded sandstone, siltstone, and shale exhibiting rapid lateral changes in facies and thick-

ness including syn-deformational growth stratification; interpreted as proximal facies of the wedge-top depozone formed atop the frontal part of southwestward propagating Zagros thrust sheets, and covered locally by unconsolidated modern alluvial deposits (Alavi, 2004).

Pilgrim (1908) was the first geologist to refer to a sequence rich in conglomerates overlying the older formations both conformably and unconformably, as Bakhtiari Formation. It comprises essentially of non-marine coarse clastics. Busk and Mayo (1918) divided this formation into two parts: the lower Bakhtiari, in which sandstone and shales are dominant, and the upper Bakhtiari, which consists mainly of massive conglomerates. However, James and Wynd (1965) considered only the upper Bakhtiari as representative of the entire formation and classified the lower Bakhtiari as the Lahbari member of the Agha Jari Formation.

No age-diagnostic fossils have been found in the Bakhtiari Formation, but it is generally considered to be Late Pliocene or younger because it overlies the fossiliferous Agha Jari Formation of Late Miocene-Pliocene age (Dunnington et al., 1959; James and Wynd, 1965; Mina et al., 1967; Falcon, 1974; Motiei, 1993). This is coherent with biostratigraphic data, which indicates a Miocene to Pliocene age for the Agha Jari Formation.

Pedrami (1987) used lithologies, geomorphic levels, and unconformities to divide a sequence of fan deposits about one kilometer thick into two halves (similar to Busk and Mayo's 1918) in the north of Dezful. The lower part of the sequence formed during the Late Pliocene and is mainly composed of medium to fine grain clastic sediments above a 7 meters thick basal conglomerate, whereas the upper part is mainly consists of conglomerate deposited in the Early Pleistocene. The upper part of the Bakhtiari Formation is similar to Busk and Mayo's upper Bakhtiari and synonymous with the conventional Bakhtiari Formation defined by James and Wynd (1965). Pedrami (1987) named the equivalent fine-grained estuarine sandstones and siltstones the Lahbari Formation and divided it into two parts; the Upper Pliocene and the Lower Pleistocene. Towards the NE, both the Lahbari and (lower) Bakhtiari Formations tend to correlate with the upper part of the Agha Jari Formation (James and Wynd, 1965; Pedrami, 1987; Motiei, 1993).

After the strong uplifting of the Zagros Mountain Range in the Late Alpine phase, Bakhtiari conglomerates were spread from rivers of the Zagros range in irregular thickness and distribution over the Fars beds and in the valleys of the fold belt. These conglomerates consist of pebbles and cobbles of Cretaceous, Eocene and Oligocene age firmly held in a matrix of calcareous cement. In the delta in the Persian Gulf area, the Bakhtiari conglomerates interfingured with calcarenites and lumachellic limestones of the Kharg and Lavan Island type.

The most remarkable phase of the Zagros orogeny in the Simply Folded Zone was when estuarine sediments of the Agha Jari (and lower Bakhtiari) gave way to the massive conglomerates of the (upper) Bakhtiari which were

then folded across entire Simply Folded Zone at the end Pliocene. The present foreland basin is located along the Mesopotamian foredeep and the Persian Gulf.

The major angular unconformity between the Bakhtiari conglomerates and the underlying Agha Jari Formation has long been interpreted as indicating that orogeny in the Zagros Simply Folded Zone took place in Plio-Pleistocene times, marking the Late Pliocene climax of orogeny in the Simply Folded Zone (James and Wynd, 1965; McQuillan 1974; Kashfi, 1976). However Hessami et al. (2001) used field evidence of unconformities between older units in conjunction with geological maps and cross sections to argue that the front of the Zagros Simply Folded Zone has propagated in time and space.

These unconformities indicate that the deformation started as early as the end of Eocene in the northeast of the Simply Folded Zone and propagated progressively to the southwest, where unconformable contacts are only seen between younger units. As shortening continued, the southwest migration of the deformation front drove the foreland basin in front of it to its present position along the Persian Gulf and Mesopotamia. The culmination of orogeny took place at end Pliocene time when the most extensive unconformity in the Zagros Simply Folded Zone developed between the (upper) Bakhtiari and the older units. Active seismicity and documented present uplift imply that the Simply Folded Zone is still propagating southwestward.

The conglomerates of the Bakhtiari Formation have a characteristic rough topography which is often difficult to access. They consist of conglomerates mostly made of carbonate clasts with a varying amount of interbedded sandstones. The clast size increases toward the top of the formation. The deposition of conglomerates of the Bakhtiari Formation started after 3 Ma.

The Bakhtiari Formation in Iraq is an almost entirely terrigenous clastic unit from silt size particles to boulder conglomerates is ranging in thickness from 25 to 30 meters. It is a fresh water molasse deposited in a rapidly subsiding foredeep. The lower contact with Upper Fars is gradational. The upper surface is erosional and appears to interfingure with the Dibdibba Formation of Kuwait.

Kharg Formation

The name of this formation has been taken from the Kharg Island, the only locality where this formation has been mapped. According to Motiei (2003, p.542), generally five lithostratigraphic units form the rock units cropping out in the Kharg Island in the Persian Gulf. From bottom to the top these units consist of; Agha Jari, Kharg (Lower and Upper), marine platform and Recent sediments. The lower part of the formation has an average thickness of about 7.5 meters consisting of calcareous oyster beds with Pecten sp., light colored calcareous muds with echiniderma and mollusks with an average thickness of 4.5 meters, calcareous sands showing current beddings and calcareous marl-

stones reaching up to 6 meters of thickness. The latter unit is resting on the Agha Jari Formation. In the type section there is an angular unconformity separating the Kharg Formation from Agha Jari Formation with a measured angle between 3 to 5 degrees.

SUMMARY OF THE CENOZOIC STRATIGRAPHY

The Cenozoic sedimentary of the Persian Gulf appears to have started with a marine transgression at the beginning of Paleocene. This transgression led to the accumulation of pelagic marl, shales and limestones. Contemporaneous massive carbonates accumulated on shallow ridges besides the northeastern part of the present Persian Gulf until the end of Eocene.

A second marine transgressive cycle developed early in Oligocene time. This started with deposition of the shallow-marine limestones continuing till Early Miocene. In the northeastern part of the basin, the uppermost part of the carbonate sequence often consists of a sequence of conglomerates with clasts derived from the limestone itself.

The Early Miocene commenced with formation of evaporites, marl and limestone. Towards the northeastern Arabia and southwestern Persian Gulf there was a change in depositional environment during the Early Miocene with deposition of clastics.

Stable conditions reestablished in the Oligocene time, allowing a return to deposition of the carbonates over most of the Persian Gulf region and the Arabian Platform. Finally the northeastern margin of this platform was deformed and arrived at the current stature during the Neogene.

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CHAPTER-4

SOURCE ROCKS IN PERSIAN GULF

INTRODUCTION

The Persian Gulf region is blessed with many petroleum systems based on a large number of extensive active source rocks in this area. At least a dozen good source rock formations of reasonable thickness and/or of wide extent are present in the Persian Gulf area. The source rocks occupy separate levels and geographical settings from upper Proterozoic to Tertiary.

The Persian Gulf basin has many sedimentary rock types which fulfill the source rock requirements. Most of the sediments present are of marine origin. Shales and marls which are often bituminous occur at many horizons and are likely source rocks for hydrocarbons. The most notable of these rocks are the Lower Cretaceous shales, on both sides of the Persian Gulf and the Middle Cretaceous to Miocene sedimentary sequence.

Figure 4-1 shows all the identified source rocks in the entire Persian Gulf and surrounding regions (where over 98% of the reserves are from the Infracambrian to the Miocene), in relation to the productive reservoir rocks (mainly carbonates but with sandstones differentiated) and highlights the stratigraphic position of the regional evaporite seals.

In general, Gurpi, Kazhdumi, Dariyan, Gadvan, Garau, Surmeh, Kangan and Sarchahan Formations are considered as source rocks of unequal importance in the Persian Gulf region. However, there are only five major source rocks identified in the Persian Gulf region which have gone through different stages of maturation, oil generation expulsion and migration (see for example, Ashkan, 2002; Rabbani, 2001, 2003; Peimani, 2003).

Source rocks are not distributed haphazardly, but are preferentially located in specific geologic settings, such as passive margin, intracratonic lacustrine and deltas environments where conditions were favorable for the accumulation and preservation of organic matter. The example of the Persian Gulf region described in this chapter is one of the most efficient "oil generating systems", covering a vast region of intrashelf silled basins which has generated and emplaced billions of barrels of recoverable oil.

Unlike reservoir rocks, petroleum source rocks are not normally field specific and their study and geochemical investigation is commonly viewed at a more basinal scale. Consequently, this chapter is not based on field studies of a specific area or particular location but rather on broader, regional investigation. Thus an attempt has been made to describe the source rock characteristics on a large scale regional Persian Gulf.

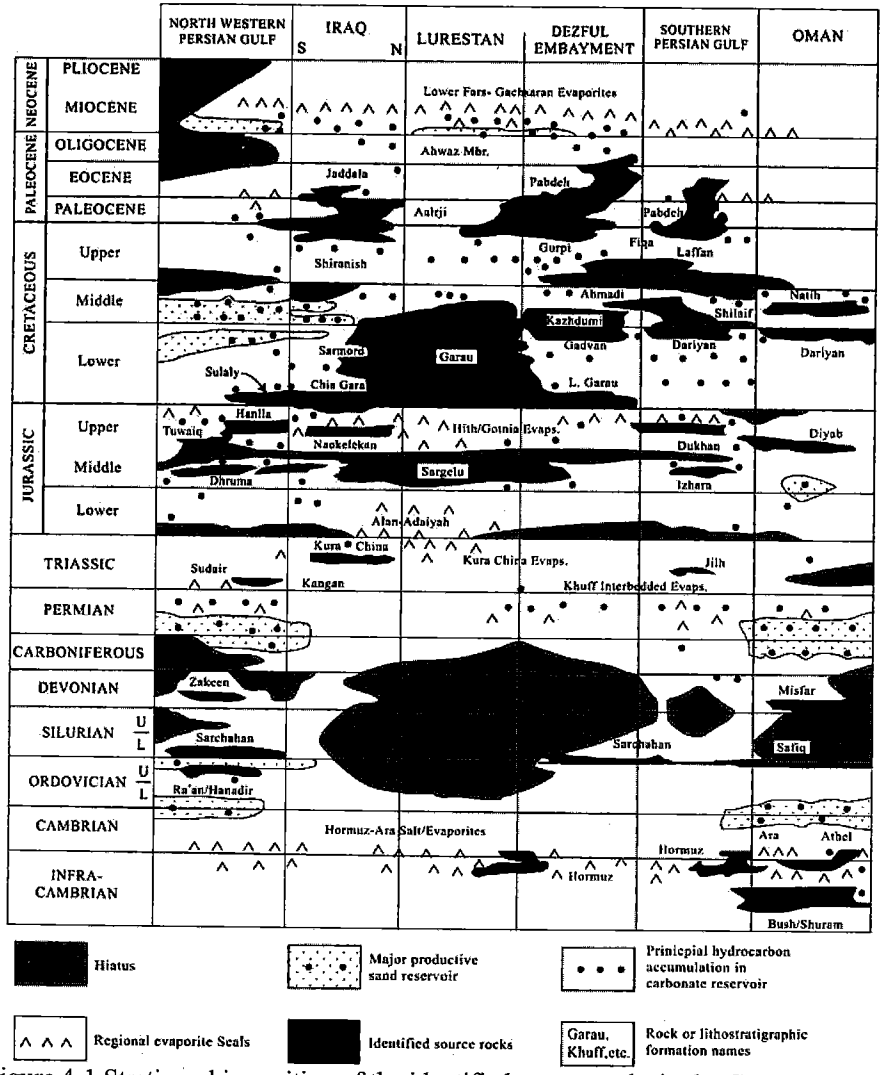


Figure 4-1 Stratigraphic position of the identified source rocks in the Greater Persian Gulf region (from Beydoun et al., 1992; expanded and modified from Stoneley, 1990)

Source Rocks Depositional Environment in Persian Gulf

A range of marine environments in which organic rich source rocks are developed occurred during the Jurassic and Cretaceous time interval in the Persian Gulf region. Such environments are preferentially developed in times of worldwide marine transgression, and include stratified oceans, anoxic silled basins and oceanic margin upwelling associated with anoxic layers.

Weeks (1952) draw attention to the importance of silled basins in producing stagnant reducing conditions, and of the Persian Gulf basin he remarked:" The Persian Gulf basin was silled to close throughout the greater part of its

long history. Only a small change in basin closure was necessary to pass from a silled basin with huge volumes of associated oil to a more completely closed basin with salt or anhydrite deposition". Whether silled basins existed or not, there is no doubt that source and reservoir rocks were in close association all through the huge area of the unstable shelf and not merely along one hinge line or facies trend.

In contrast to the Silurian shales which were deposited in a near-polar setting and which were related to a marked transgression resulting from the melting of Ordovician glaciers, the other source rocks in the Persian Gulf region were deposited in tropical or equatorial, dominantly calcareous environments. The Mesozoic and Cenozoic source rocks were deposited in intracratonic depressions at a time when anoxic conditions prevailed as a result of water-column stratification, during high stands (Bordenave and Hegre, 2005).

There are several periods of extensive oceanic anoxia events when organic-rich sediments accumulated during global sea-level rises. The anoxia in the basins gave rise to large areas of potential source rocks at several levels from the Triassic to Early Tertiary in the Persian Gulf region (see Murris, 1980, Stoneley, 1987) and the distribution allowed optimum juxtaposition of source, reservoir, and seal facies over wide area, permitting very efficient migration from aerially extensive source kitchens.

Anoxic conditions extended over large areas in the Middle Jurassic, Oxfordian, Neocomian, Albian, Campanian/Maaestrichtian, and Middle Eocene to Early Oligocene. Among these events, two are of particular importance to the oil industry as they are responsible for the accumulation of about half of the world's oil reserves (Klemme and Ulmishek, 1991).

Generally the source rocks were deposited during the time of long-standing relative sea-level rise associated with major carbonate platforms in the Persian Gulf and many other places in the world. Excellent source rocks were deposited in intrashelf basins, when the environment became anoxic due to sea level rises, locally increased subsidence, and either a humid climate or the existence of upwelling in the Tethys Ocean. During high sea level stands and consequently suppressed clastic influx, excellent source rocks were often formed in the euxinic intra-shelf basins.

The source rocks are deposited either in intraplatform basins or seaward of the platform margin. During Aptian-Albian, intraplatform basins developed on their ramp margins generally were occupied by rudist-dominated associations of increasing biotic diversity. Thus, most effective marine source rocks of the Middle Cretaceous time were deposited during the Aptian-Albian, in the beginning of the transgression that culminated in Turonian in the Persian Gulf region.

One important feature of the petroleum geology of the Persian Gulf is that it is also evident that during transgressions source rock strata were deposited in the basins on the platform and interfingered with laterally-equivalent plat-

form carbonates to give a close mixture of reservoir and source materials. During periods of regression, clastic reservoirs were deposited.

As described later, source rocks in the Persian Gulf were entirely of marine origin. Marine origin of the source rock increased their hydrocarbon generating potentials. They have marine sapropels with Type II kerogen, and hence the oils generated from these rocks have many similarities. The lack of significant amounts of terrestrial organic materials associated with the deposition of these rocks not only has reduced possible differences in oil composition but also provided limited levels with vitrinite in the sequence to assist maturity estimates; the Albian and Eocene are important exceptions (see for example the data presented by Ashkan, 2002).

Excellent type II-S source rocks deposited in intracratonic depressions when anoxic conditions prevailed as a result of water stratification during the Middle Jurassic (Sargelu Formation), Valanginian (base of the Garau Formation), Albian (Kazhdumi Formation), and Middle/Late Eocene (Pabdeh Formation). In the northern part of the Persian Gulf, organic-rich layers were also deposited in the Ahmadi Member of the Sarvak Formation. In addition, marginal source rocks were deposited during the Barremian (Gadvan Formation) and the Late Cretaceous (Gurpi Formation), but their contribution to the charge of the Iranian fields is negligible (Bordenave and Huc, 1995).

MATURATION

The significance of presence of the potential source rocks was described in the previous section. However, the presence of potential source rocks is not the only requirement for hydrocarbon generation. Source rocks supposed to be subjected to suitable temperature and pressure in order to thermally become mature and generate hydrocarbons.

Previously, it was suggested that hydrocarbon generation begins soon after deposition of source rock (Dunnington, 1958). However, later studies (Ala et al., 1980; Ala, 1982; Tissot et al., 1987) showed that a minimum critical depth of burial of 1.4 km for a particular source (unless there are abnormally high temperatures) is required essential for generation of hydrocarbon to begin. Such a burial depth does not seem to have been achieved in the entire Persian Gulf region or at least not until the Eocene or later times (i.e., during the Alpine orogeny).

Ala et al. (1980) employed various geochemical techniques to study the nature and distribution by weight of both solvent extractable and insoluble organic matter in the five potential source rocks of Eocene-Paleocene (Pabdeh Formation), Maaestrichtian (Gurpi Formation), Noecomian-Turonian (Garau Formation), Albian (Kazhdumi Formation) and Silurian (Sarchahan Formation) age in southwestern Iran. Crude oil-source extract correlations were also carried out, and the results could be summarized as follows, the organic matter in Pabdeh and Gurpi Formations was found to be generally immature (Ala

et al., 1980) and therefore incapable of generating significant amount of hydrocarbon. The organic matter in these formations is almost exclusively of marine algal origin (type II kerogen). The Albian Kazhdumi Formation is the major source of the oil in both the Middle Cretaceous Sarvak carbonate reservoir and the Oligocene-Miocene Asmari in the Dezful embayment area (Ala et al., 1980), extract from these source rocks showed little similarities to the nearby crude oils.

There are differences in the thickness of the sedimentary cover throughout the Persian Gulf which have been controlled by basement tectonics which in turn had direct impact on hydrocarbon generation. This implies a greater depth of burial and, hence, a more favorable conditions for hydrocarbon generation from the Silurian, to Middle Jurassic to Upper Cretaceous source rocks. In addition, the basement tectonic pattern affected the hydrocarbon resources in the Persian Gulf region. It was mainly dominated by uplifting which resulted in poor development of the source rocks.

As demonstrated in later sections, the changes of burial depth, temperature and the degree of maturity are in agreement with increasing the burial depth toward northwest and east of the Persian Gulf for the majority of the source rocks encountered in the Persian Gulf.

Paleozoic Source Rocks of Persian Gulf

The Paleozoic and Mesozoic (i.e., mainly Jurassic) organic-rich source rocks of the Persian Gulf region form two of the most productive petroleum-producing systems in the world; these systems also include regionally large reservoirs, seals, and great structural traps that combine to develop many supergiant oil and gas fields. For instance, about 29% of the world's petroleum reserves have been produced by Aptian-Turonian basinal source rocks (Klemme and Ulmishek, 1991). Even though Jurassic and Cretaceous strata provide the predominant source rocks, possible older source rocks also enhance the prospectivity of both early Mesozoic and older reservoirs.

The greater Paleozoic and Mesozoic petroleum plays of the Persian Gulf and eastern Arabian Peninsula are extensive in both geographic scale and hydrocarbon-producing potential; each includes a regionally extensive source facies.

During Paleozoic, the Arabian Plate including the Persian Gulf region was located in the southern hemisphere as part of the northern passive margin of Gondwana and principally in high latitudes with predominance of clastic sedimentation. Of particular interest in this connection in the Persian Gulf region is the development of the Silurian graptolite shale, similar to shales considered to be possible source of several gas discoveries in southwestern Iran. In fact the deposition of the organic-rich shales was primarily controlled by global transgressions and consequently regionally extensive, Silurian source facies deposited throughout the Persian Gulf region.

In the Zagros Foothills of the northern Persian Gulf, a variety of Proterozoic rock sequences were uplifted by salt diapirs (Hormuz Formation), but no source rock characteristics were found in the few Hormuz samples analyzed by Bordenave and Burwood (1990). Furthermore, no source rocks were discovered either in the Cambro-Ordovician layers outcropping at the base of the thrusted units in High Zagros Mountains, or at Kuh-e Surmeh in central Fars region. The same observation was made in the few exploration wells drilled deep enough to go through the pre-Permian sediments.

Reddish micaceous cross-bedded sandstones, dolomitic limestone and micaceous shales deposited in fluvial to shallow marine environments during the Cambrian and the Ordovician, have TOC values lower than 0.4%. At Kuh-e-Mond anticline along the northern Persian Gulf coastal region the Ordovician and Cambrian source rocks could have reached the gas window but contains little organic matter (Kamali and Rezaee, 2002).

Pre-Permian sediments are known just in a few places at the base of the Zagros thrust, at Kuh-e-Surmeh and in Kuh-e-Gahkum area, north of Bandar Abbas in northern Persian Gulf. According to Bordenave and Burwood (1990) field observations and analytical measurements have revealed that most of the Paleozoic rocks have very low organic contents. The only Paleozoic source rock recognized in Iran was dated back to Silurian on the basis of graptolites.

According to Rudkiewicz et al. (2002), in a cross section starting in the foreland close to the Persian Gulf through the entire fold belt perpendicular to the main structural trend, Paleozoic source rocks generated and expelled liquid hydrocarbons during Late Cretaceous and Early Cenozoic, i.e., before the Zagros folding started. Currently, only gas from Paleozoic source rocks charges the structures shaped during the Zagros orogeny.

Silurian Source Rocks

The Silurian organic-rich shales account for 9% of the world's petroleum reserves. The widespread anoxic Silurian episode is related to a worldwide sea level rise after brief Ordovician glaciations (Combaz, 1986). Early Silurian deglaciation resulted in a major sea level rise and the extensive deposition of the upward-coarsening, progradational sequences. These shales accumulated in at least two rapidly subsiding regions along the eastern Arabian Peninsula (Jones and Stump, 1999).

In Paleozoic sequences of the Persian Gulf region, Silurian source rocks are linked to the Permo-Triassic carbonates. Thus, organic-rich graptolitic shales are considered as characteristic Silurian source rocks. Organic matter in these shales is composed mostly of typeII kerogen, a part of which was derived from planktonic fauna (graptolites, tentaculitids). Graptolitic shales were widely deposited on platform of the northern margin of Gondwana including the Persian Gulf region.

Silurian carbonaceous shales can be a very good source rock for Permian limestones and dolostones. The generated hydrocarbons from these potential source rocks could have migrated to the limestone, dolostones and the sandstone reservoirs. It has been inferred that the supergiant South Pars Gas Field and Qatar North Dome and neighboring fields on the Qatar-Gavbandi Arch were sourced from the nearest underlying level, the Silurian (Ala et al., 1980; Bordenove and Burwood, 1990). Nonetheless, the Silurian has not been penetrated there by wells and is absent by unconformity in the adjacent surface outcrops of Kuh-e-Surmeh in Fars region (Stocklin and Setudehnia, 1972).

As no post-Silurian source rocks were found in northern Persian Gulf, south of the latitude of Bushehr, the oil, gas, bitumen seepages, and indirect hydrocarbon evidences such as sulfur springs, widespread in the region, are likely related to the existence of hydrocarbons generated from Silurian source rocks. According to Grunau (1981), the lower Paleozoic Silurian graptolite shales (rich in organic matter), deposited in restricted environment, could be the main source rocks for gas in the Dalan/Kangan reservoirs southeast of the Dezful Embayment area.

For the similar reason, the huge gas reserves accumulated in the carbonates of Kangan/Dalan Formations are assumed to have similar origin. This is also applicable to fields such as North Pars, Mond, Kangan, Nar, Varavi, Shanul, Tabnak, and Homa, to the North Dome field and its South Pars extension in the Iranian waters, and to several major gas fields found in the Abu Dhabi offshore.

The end of Ordovician was marked by a glaciation which extended widely over the Gondwana Continent. The rapid retreat of glaciers caused an abrupt sea level rise during the Early Llandoverian, which caused the deposition of graptolitic black shales, almost everywhere at the edge of the Gondwana Continent.

Paleozoic of the Persian Gulf comprised of a regionally broad, Silurian source facies. The basal hot shale is the primary and most effective source rock for Paleozoic hydrocarbons throughout the Persian Gulf (Beydoun, 1991; Bishop, 1995; Milner, 1998; Jones and Stump, 1999), with as much as 75 meters of hot shale containing total organic carbon as high as 14% (Kornet et al., 2001).

At the onset of the sea level rise, the basal transgressive layers, deposited in a very low-energy environment are organic-rich and highly radioactive. They are easily identified in wells by using gamma ray and density logs. The basal Silurian shales, known as the "hot shales" due to their radioactivity, contain between 4 and 12% of organic carbon. This unit is considered the principal source rock for Paleozoic hydrocarbons in many parts of the Persian Gulf (Milner, 1998; Jones and Stump, 1999; Sharland et al., 2001).

The base of the Silurian shales contains regionally correlative, organic-rich shale with a unique high gamma-ray signal on geophysical logs. The lower,

organic-rich part of the Lower Silurian shale was deposited as a graptolitic sheet of mud on the middle to outer continental shelf.

The Silurian "hot-shales" are extensively distributed in the Persian Gulf region, but showing a marked thinning on the western side of the old Qatar-Gavbandi Arch (Mahmoud et al., 1992), which would have, as during the Proterozoic, separated a Western from an Eastern Silurian Basin. The Eastern Silurian Basin extended from NW Oman to the north of Bandar Abbas, while the Western Basin extended from North Africa to NE Saudi Arabia, and probably to most of the Lurestan and Khuzestan regions of Iran.

It is possible that source rocks occur in the areas where Hormoz salt diapirs are present. Lower Silurian source rock found in Sarchahan Formation of southern Iran, and the Silurian anoxic event is related to the global transgression after late Ordovician glaciation (Bordenove and Burwood, 1990). Silurian rocks crop out in the northern region of the Persian Gulf at Kuh-e-Gahkum and Kuh-e-Faraghan. They contain from 0.1 to 4.3% organic matter (Galimov and Rabbani, 2001; Kamali and Rezaie, 2003).

In the western Fars region, notable oil seepage could help to confirm the chronology of the oil accumulation, and to revert to the related source rocks. In the cliffs next to Khurmuj salt plug, east of Bushehr, layers of bitumen-impregnated limestone were observed in the Sarvak and Asmari Formations (Bordanove, 2002). In both cases, the bituminous limestone, with its porosity fully saturated with bitumen, is limited above and below by extremely porous limestone, devoid of bitumen. The limit between the bituminous and the clean limestone is abrupt, linear, and parallel to the stratification. Khormuj salt plug was previously breached at the base of Cenomanian and created an island, as it is the case for present day salt plugs in the Persian Gulf (Bordanove, 2002).

The bitumen assumed to be detrital accumulating for some tens of thousand years, because of the breaching of an existing field (Bordanove and Burwood, 1990). The breaching was contemporaneous with a readjustment of the "Hercynian" N-S fault system observed at the end of the Middle Cretaceous.

Considerable accumulation of bitumen may have been lost by the seepage. Since a minimum burial was necessary for a source rock to have generated oil, it was concluded from a reconstruction based upon a set of isopachs, that this oil was generated by source rocks deeper than Permian (Bordenave and Burwood, 1990). Furthermore, since no source rocks were identified either in the Proterozoic or in the Cambro-Ordovician, a Silurian origin was assumed.

Based on the available geological information, it is likely that the Silurian source rocks in the Persian Gulf region thicken northwards. Dezful Embayment was a vast depression during most of the Mesozoic. The existence of Silurian source rocks is also very probable in the southern Persian Gulf and in the Rub al Khali Basin, where enormous gas reserves are known, however, no wells drilled deep enough to reach pre-Permian sediments. It is also possible that the horsts observed in Saudi Arabia continue northwards in the direction

of the Kabir Kuh-1 and Huleylan-1 Lurestan wells, where pre-Permian erosion reached dolomitic limestone assumed to be of Middle Cambrian age.

The presence of hydrocarbon source rocks of Silurian age are also known in both Oman, where the Safiq Formation is considered to be a good source rock (Grantham et al., 1987), and in northern Saudi Arabia in Tabuk Basin, and might be viable for the generation of oil also in other areas in southern Persian Gulf. However, very few wells have been drilled deeply enough to check the distribution and the characteristic of Silurian source rocks over the Persian Gulf area. These wells have shown that the Silurian is not ubiquitous, either because of non-deposition or due to the pre-Permian erosion.

Super-light, high (43°-56°) API gravity, low-sulfur crude oil and natural gas occur in north-trending, block-faulted anticlines that formed over reactivated basement blocks. Highly mature hydrocarbons might have migrated vertically along basement-rooted faults and fracture zones in structures into fluvial and eolian, quartzose sandstones of the Carboniferous to Early Permian Faraghan.

A set of isopachs, prepared for individual formations, throughout Jurassic to Early Miocene period, show the permanence of some structural features, i.e., a very wide low-relief high extending from Qatar to the south of Lavan Island (O-4BIS area) and to the central part of the Fars region (Gavbandi High), surrounded to the southeast, to east, north and to the northwest by pronounced depressions. Regional highs are also observed north of Bandar Abbas and in southwestern Lurestan. These features are well observed on the Jurassic and Cretaceous isopachs, and on cumulative isopachs, from the base Permian to the Jurassic, Early Cretaceous, Cretaceous, Asmari (Early Miocene) and Mishan (Middle Miocene) tops. The set of cumulative isopachs also shows the thermal evolution of the Silurian source rocks through time for the various structural units, regional highs and depressions.

Organic Geochemistry of Silurian Shales

In the northern Persian Gulf, Silurian rocks crop out only in two places, north of Bandar Abbas, at Kuh-e Gahkum and Kuh-e Faraghan. The shales at these two localities contain relatively high TOC (1 to 4.3 wt %) and can be considered as potential source rock. However, pyrolysis indicates that they have undergone strong evolution (Khosravi-Said, 1987). The organic matter of the graptolite shale is transformed almost to the state of graphitization (Galimov and Rabbani, 2001). Estimated vitrinite reflectance (R_o) performed by CSIRO of Australia ranged from 1.2 to 1.3%, indicating the end of oil generation and beginning of gas generation (Dr. M. Kamali, pers. Comm.)

The late Paleozoic sediments generally have a very low organic content. The source for the Deh Ram Group (Faraghan, Dalan and Kangan Formations) is still a matter of speculation but is thought to be organic-rich Silurian-

age Sarchahan Shale (more than 400Ma old) which lies underneath the Deh Ram Group where it has not eroded.

At Kuh-e Faraghan, 600 m of barren shales are overlain by 70 m of black shales which contain a Middle Llandoverian fauna. At Kuh-e Gahkum, black platy-bedded shales with a "coaly aspect" are radioactive and contain residual TOC values as high as 4.1%, although the organic matter is late mature (T_{max} of 457°C, and Hydrogen Index varying from 50 to 200 g HC/kg C). Cumulative isopachs showed that Silurian rocks at Kuh-e Gahkum were buried to some 6000 m before the Zagros orogeny. The $\delta^{13}C$ of Silurian shales (-30.8‰) is comparable to those of other Silurian shales of southern Persian Gulf (Bordenave and Burwood, 1990). This is in agreement with the carbon isotopic composition of the Silurian shale analyzed by Galimov and Rabbani (2001) which covering a range between -31.19 to -29.36 ‰.

Stratigraphic reconstructions indicated that the Silurian shales at Kuh-e-Gahkum have been buried to at least six kilometers before their ascent to the present levels, proceeding the main phase of orogeny (Bordenove and Burwood, 1990). In terms of maturity in the deeper parts of the Zagros foredeep, the Silurian source rocks are overmature (R_o >2.6) and thought to be the source for the gas in this unit.

The basal hot shale in the southern Persian Gulf is a dark-gray to black, commonly micro-laminated, euxinic shale with as much as 20 wt% total organic carbon (TOC). The hot shale averages about 3-5 wt% TOC in Saudi Arabia (Abu-Ali et al., 1999; Jones and Stump, 1999) and 6 wt% in Iraq (Aqrawi, 1998). The basal hot shale maintains good to excellent TOC whether in an immature or a mature setting (Cole et al., 1994) and considered the principal source rock for hydrocarbons of the Silurian-Paleozoic Petroleum system throughout the Persian Gulf region (Bordanove and Burwood, 1990; Bishop, 1995; Cole et al., 1994). According to Jones and Stump (1999), the hot shale should contain more than 2.0 % TOC to be considered a source bed. They calibrated TOC to gamma-ray response in API units and found that 15° API units correspond favorably to greater than 2% TOC.

Jones and Stump (1999) suggested that the hot shale was likely deposited in an essentially uniform thickness and afterward reworked and eroded by turbidites that preferentially moved down the axes of the depocenters. Mapping of the hot shale by Stump and van der Eem (1995) and Jones and Stump (1999) showed that great areal extent of these favorable source rocks.

Oil-oil and oil-source rock correlations show that oil and condensates from Paleozoic reservoirs in the Persian Gulf have been generated from a common source the basal hot shale (Abu-Ali et al., 1991; Cole et al., 1994). Oil-to-source rock correlations show a high resemblance in biomarker distribution between extracted bitumen and oils, and an excellent isotopic compatibility between extracted kerogen and oils (Mahmoud et al., 1992).

Organic material in the basal hot shale consists mostly of oil-prone Type II (amorphous marine algae) kerogens with rich chitinozoans and graptolites.

Paleozoic oils derived from basal hot shale source rocks are geochemically greatly different from and more mature than those generated from younger, carbonate source beds of Jurassic and Cretaceous age.

The Paleozoic-sourced oils have lighter API gravities and lower sulfur and trace metal contents (Abu-Ali et al., 1991). API gravities of Paleozoic oil range from 40° to 53°, whereas Mesozoic oils are commonly in the range of 20°-40°. Sulfur content of oils from the Silurian shale is less than 0.1 w%. In contrast, oils from Jurassic carbonate source rocks are commonly greater than 1.0 w% of sulfur. Silurian-derived oils have an average $\delta^{13}C$ of -29.8 ‰ relative to the PDB, and Mesozoic oils are isotopically heavier, averaging -26.5 ‰ (Abu-Ali et al., 1991).

A number of light oil discoveries in Early Permian sandstones (i.e., Unayzah Formation) were originated from Silurian source rocks, as demonstrated by similar isotopic and biomarker composition (Mahmoud et al., 1992). Oil fields accumulated in the Haushi clastics of Carboniferous age, at the western limit of Oman, have also a Silurian origin, as shown by the oil-to-source rock correlation.

Maturation, Generation, and Expulsion

It is assumed by many researches (e.g., Ala et al., 1980; Bordenave and Burwood, 1990; Khosravi-Said, 1987; Galimov and Rabbani, 2001) that the Silurian source rocks have contributed significantly to the generation of vast amount of hydrocarbon and enormous gas accumulation discovered in the Permo-Triassic Dalan/Kangan Formations and in pre-Dalan/Kangan sedimentary sequence in the Persian Gulf region. Practically three-quarters of the Petroleum reserves generated from Silurian rocks is found in the Persian Gulf Basin where the source rocks are overmatured and dominant type of hydrocarbon is gas.

The Dalan and Pre-Dalan gas accumulation in the southern Persian Gulf region has been attributed to a Silurian source (El Bishlawy, 1985; Ali and Silwadi, 1989). Sourcing from the Hormoz levels that provide the salt domes to the east and west of the Qatar-Gavbandi Arch remains equally possible; a further but less likely possibility is that the gas could have been sourced from the Dalan/Kangan (El Bishlawy, 1985). Grunau (1985) assigned a significant role of the Silurian shales as a source for hydrocarbons in the main petroleum-producing basin of the Persian Gulf. However, there is not adequate valid documentation.

Silurian organic-rich strata which have been studied in the Persian Gulf region are at an advanced stage of maturity and are capable of generating gas (Ala et al., 1980). Silurian and older sedimentary successions are commonly within the gas generation window. Thus, it was concluded that the younger Formations can not be considered as the main source rock for great gas reserves in the Fars area in northern Persian Gulf (Zeinalzadeh et al., 2000).

One of the decisive factors to reconstruct the set of events eventually led to the formation of large size gas accumulations is the thermal evolution of the Silurian source rocks, and more precisely the time of oil expulsion and the beginning of the gas window.

It is clear that primary migration has played a very important role in the accumulation of Dalan/Kangan gas reserves of the Persian Gulf region, the Jurassic oil reserves of Arabia and the Cretaceous oil of Kuwait, southern Iraq and offshore Persian Gulf.

The hydrocarbons generated from the Silurian source rocks appears to have migrated and accumulated in the Lower Dalan, in areas where the anhydritic Nar Member is acting as a seal, i.e., in the part of the Persian Gulf located north of the Qatar Peninsula. Elsewhere, the hydrocarbons would have reached the Kangan/Upper Dalan reservoir.

Hydrocarbon maturation and generation from the Silurian source rocks largely ceased in the Early Tertiary, but maturation and generation were reactivated by the Zagros collision in the Miocene and may continue into the present day. The source rock was thermally mature by the Late Jurassic, but hydrocarbon expulsion was not initiated until the Early Cretaceous. Thus, the source rock was thermally mature by the Late Jurassic in the deepest parts of the sedimentary basin and hydrocarbon expulsion began in the Early Cretaceous about 120 Ma.

Oil and gas were expelled simultaneously, but gas expulsion continued for a longer period of time. Most of the gas was expelled during the Late Cretaceous; expulsion of oil nearly ceased after the Late Cretaceous. In summary, oil and gas expulsion are linked to three events: (1) primary kerogen cracking, causing the first episode of expulsion about 120 Ma; (2) secondary cracking of heavy components and oils, causing a second episode of expulsion at about 100 Ma; and (3) a later uplift and erosional event, resulting in a third pulse of expulsion at about 20-10 Ma during which the gas was separated from the oil, causing remigration.

Several studies have modeled the thermal maturation of the hot shale in southern Persian Gulf (Abu-Ali et al., 1999, 2001; Milner, 1998; Jones and Stump, 1999). Cole et al. (1994) showed that present-day maturity, as expressed in Ro, at the base of the Silurian generally increases from less than 0.5% along the exposed western rim of the basin in central Saudi Arabia, eastward to thermally mature oil generation and expulsion of greater than 0.7%, to mature for gas at greater than 1.3%, and finally into areas further to the east of greater than 2.0% where the Silurian is considered as a spent hydrocarbon source.

Bishop (1995) calculated maturation and geohistory curves of the Lower Silurian source rock in southern Persian Gulf and published maps showing present-day level of thermal maturity, time of onset of significant oil and gas generation. He concluded that present-day thermal maturities range from immature to overmature (exhausted) and that charging of traps with oil and then

gas probably began during the Triassic and progressed during the Cretaceous. Maturation and generation of Silurian source rocks largely ceased in the early Tertiary, but maturation and generation were reactivated by the Zagros collision in the Miocene and might have continued into the present day.

Cretaceous, Jurassic, and Silurian source rocks of the southern regions of the Persian Gulf were analyzed by Milner (1998) for both source-rock richness (Rock-Eval analysis) and thermal maturity (as determined by vitrinite reflectance). Milner employed regional geologic and structural framework data, combined with heat flow measurement and source-rock quality data, to construct burial-history models and map the geographic extent of the source facies and maturity stages.

Maturity modeling of Silurian-sourced hydrocarbons was verified by (1) location of Paleozoic oil fields (for example, Sahmah field, Oman) within mapped levels of thermal maturity (R_o) for oil generation, and (2) occurrence of Paleozoic gas fields (such as South Pars in the Persian Gulf, Ghawar, and North Field, Qatar) within the mapped level of thermal maturity for gas generation.

Jones and Stump (1999) found that the basal hot shale source-rock facies is gas prone to gas condensate prone near the axis of the shale trough depocenter, and more oil prone east and south of the depocenter. The shale is overmaturing with respect to oil generation over most of the Persian Gulf Basin, and Rub 'al Khali Basin.

The areas prospective for Permo-Triassic gas correspond to pre-Zagros Highs, where oil, then gas progressively accumulated. The extension of the pre-Zagros gas fields and their oil rims could be deduced from the geometry of the Kangan/Dalan layers, as shown by the cumulative isopachs from the top of Kangan to the top of the Mishan Formation, and by the distribution of the known gas fields, the gas oil and bitumen seepages, and the hydrocarbon indirect evidences.

Based on the present-day thermal maturity trend of the shales, and the maturity of oils analyzed from the oil fields of the southern Persian Gulf, most oils in these fields migrated a long distances. The present-day maturity of the shale in the vicinity of the oil fields is insufficient for the generation of oil, whereas the API gravities of oils in these fields range from 40° to 53°. Therefore, oils might have migrated westerly from downdip and deeper, eastern "kitchens" where the source rock is thicker and thermally mature for oil. Moreover, the excellent seal capacity provided by the overlying Permian evaporites and carbonates contributes to the efficiency of migration and containment of the petroleum system.

In terms of hydrocarbon migration in the Persian Gulf region, Kamali and Rezaee (2003) have demonstrated that formations with source rock potential such as Pabdeh, Gurpi, Gadvan and Kazhdumi Formations, have not reached the oil window in the Mond wells (see figure 4-2). In addition, their organic carbon content is very low as they were deposited in oxic, shallow-water set-

tings. The absence of source rocks suggests that the gas and heavy oil accumulations at Kuh-e Mond and at nearby offshore structures have most probably undergone long-distance lateral migration from distant source kitchens.

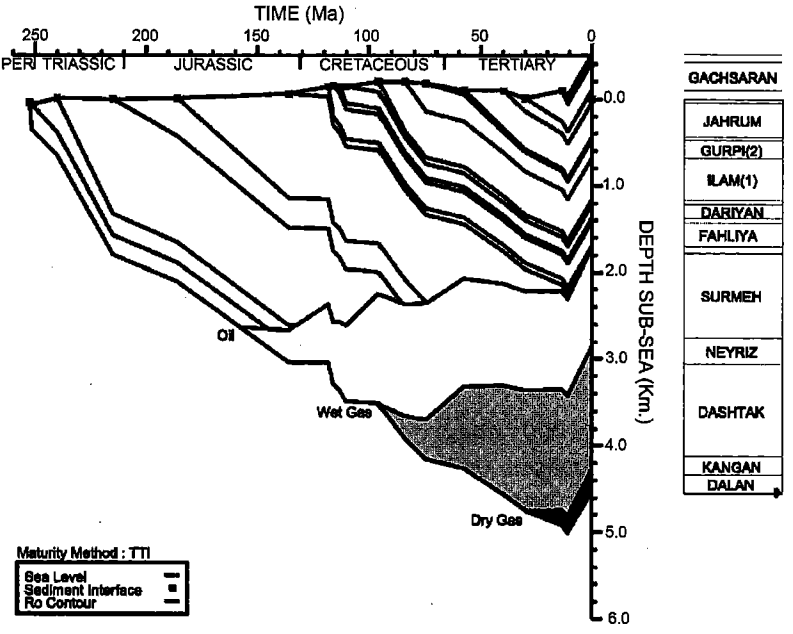


Figure 4-2. Burial history plot for well MD-5, Kuh Mond showing progressive burial during the Mesozoic (cited from Kamali and Rezaee, 2003)

Lateral migration from the Silurian source rock kitchens to the north and south of the Qatar-Gavbandi Arch, onto this northern extension of the Arch is the most likely origin for the significant natural gas accumulations in the Persian Gulf area. Migration of Silurian hydrocarbons was mainly from an easterly direction, up regional dip and into the crestal portion of the Qatar-Gavbandi Arch, forming the supergiant North and South Pars fields. Vertical migration occurred along the flanks of numerous salt structures. Reservoirs are mainly shelf carbonate grainstones and reef carbonates of the Upper Permian Kangan/Dalan Formation.

A large part of the oil generated in the eastern and western Silurian basin accumulated on the Qatar-Gavbandi High, but some oil accumulated also on the north Bandar Abbas and in the SW Lurestan Highs, in the Late Jurassic and the early Middle Cretaceous. The end of Cenomanian corresponded to the readjustment of the old Palaeozoic N-S fault network. From the end of Cretaceous onwards, large amounts of gas produced on both sides of the Gavbandi High progressively pushed the oil downwards, to form oil legs on the edge of the Highs.

Thus, migration of the Silurian hydrocarbons is considered to be mainly vertical in basement-involved structures in the central part of the basin, and moderate- to long-distance lateral migration is inferred along the basin margins with Faraghan sandstones as the major carrier beds. Source of gas found in Jurassic reservoirs such as Golshan Structure in Iranian waters of the Persian Gulf is likely older Paleozoic, i.e., Silurian source, where Paleozoic (mainly Kangan/Dalan) seals have been breached (Pallastro, 1999).

Sarchahan Formation

Graptolite-bearing, organic-rich Sarchahan shales of lower Silurian age are one of the possible petroleum source rocks in the Persian Gulf region. This formation is very deep-seated and very few wells drilled in the area penetrate it. Therefore, determination of the level of maturity and source rock potential has not been possible by routine geochemical studies (Rezaee et al., 2001).

The Sarchahan Formation has been considered as a main source rock for gas generation in the Persian Gulf where it contains good quantity and quality organic matter. Based on the available information obtained from NIOC, G-3 Well (i.e., Golshan) is the only available well in the Central Persian Gulf that has been drilled to depths of Sarchahan Formation. Peimani (2003) calculated maturation and geo-history curves of these source rocks in Persian Gulf showing present-day level of thermal maturity, time of onset of oil and gas generation. He concluded that at the location (G-3 Well), Sarchahan Formation is at the end of oil window at present time and this formation has entered oil generation about 170 Ma before present (Middle Jurassic) (Figure 4-3 and 4-4).

Independent burial history reconstructions (Galimov and Rabbani, 2001) demonstrate that the Sarchahan shales occurred at the stages corresponding to the isotopic characteristics of the gas in the Kangan/Dalan at about Late Jurassic- Early Cretaceous time. These rocks could generate gas with the same geochemical characteristics as those now observed in gases from Kangan/Dalan reservoirs.

There are no geological data to calculate maturity of this formation in further places of Persian Gulf. However, by extrapolation of the maturity state of Kangan Formation, it is possible to estimate maturity of Sarchahan Formation. Thus, it can be estimated that Sarchahan Formation is at the end of oil generation window in central region and gas generation window in the northwest and east of Persian Gulf. Thus, it might be concluded that the Sarchahan Formation can be a main source rock for gas generation in the Persian Gulf provided that it contains good quantity (TOC) and quality (kerogen type) organic matter. Thus, the Silurian shales in the entire Persian Gulf region have good potentials for hydrocarbon generation.

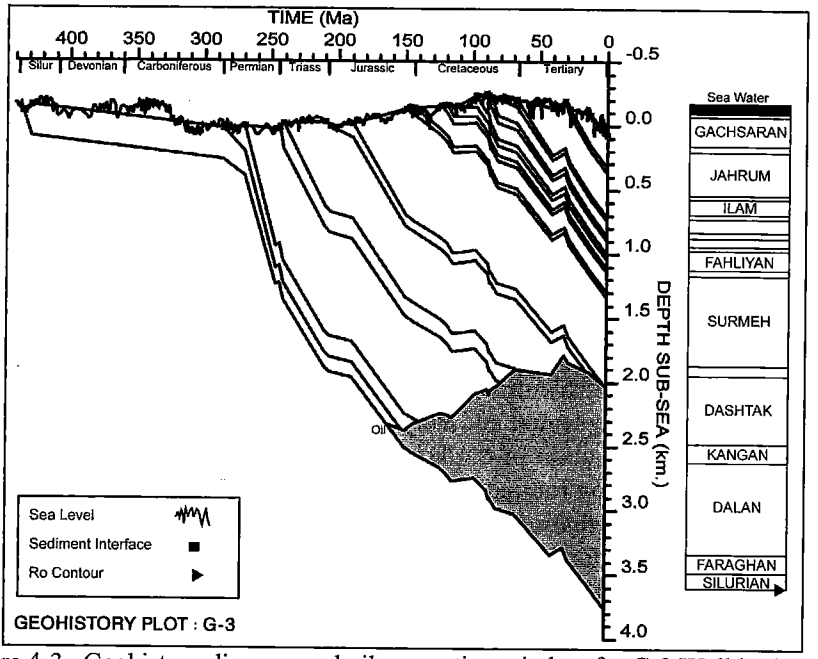


Figure 4-3. Geohistory diagram and oil generation window for G-3 Well in the Golshan field in the Persian Gulf (cited from Peymani, 2003).

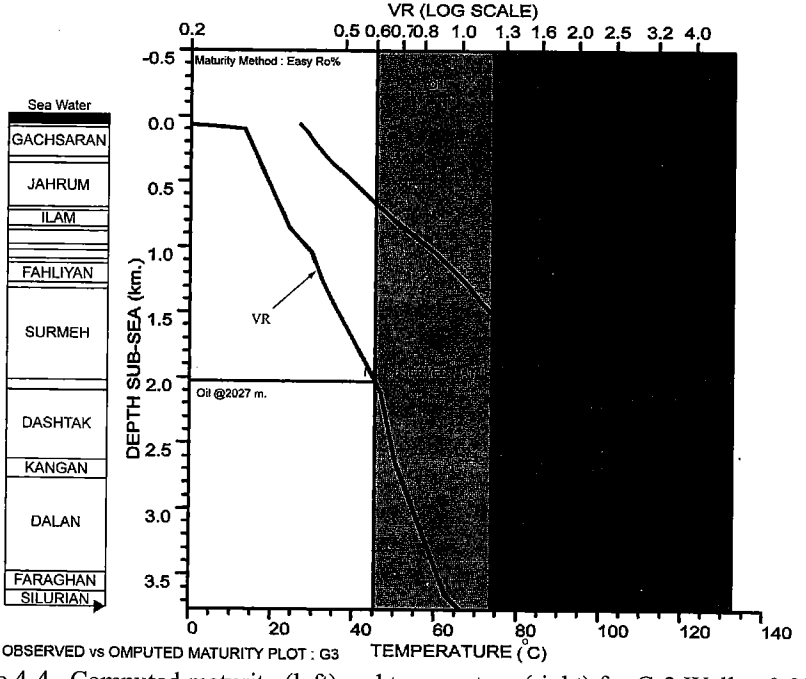


Figure 4-4. Computed maturity (left) and temperature (right) for G-3 Well at 0.00 Ma (cited from Peymani, 2003)

According to Zeinalzadeh et al. (2000) Silurian and pre-Silurian sediments are in the gas generation window. Timing of oil generation for Silurian sediments is Early Jurassic to Early Cretaceous then wet and dry gas have been generated until Late Paleocene and present time respectively.

During Silurian period, organic-rich graptolite shales with type-II kerogen were deposited on extensive platforms along continental margins. The majority of the original Silurian source rocks have been deformed and often metamorphosed, and most of the remaining are overmature. Consequently most of the Silurian petroleum reserves are gas.

In summary, Silurian source rocks appear to have supplied the huge gas accumulations in Permian carbonate reservoirs, which are capped by Triassic evaporites, on regional highs and in salt-related structures, as early as the Early Cretaceous (Bordenave, 2002b; Bordenave and Hegre, 2005).

Permian Source Rocks

Kangan Formation can be considered as a source rock for some of the oil and gas generated throughout the Persian Gulf region. Such consideration is based on geochemical data showing that this formation contains good quantity (TOC) and quality (kerogen type) organic matter. Also it can be considered locally as a source rock for gas generation at the head of the Persian Gulf and also in the Hormuz Strait general area.

According to Galimov and Rabbani (2001) in the middle part of the Dalan Formation, anhydrites show relatively high abundance of organic matter (~1.7%). They believed that the organic matter was deposited under conditions of relatively shallow, density stratified waters with brine in the bottom zone. This was affected by significant microbiological transformation in the sediments.

Based on some uniform geochemical characteristics such as the equal concentrations of CO_2 and N_2 of the analyzed gases and uniformity $\delta^{13}C$ it was concluded that gas pools in the carbonates of Kangan/Dalan represent a single gas reservoir throughout the entire section. In addition, the carbon isotopic composition of methane and its homologues (i.e., ethane and propane) is compatible with the suggestion that their source may have been rocks of almost the same age, in particular Dalan dolomite and anhydrite (Galimov and Rabbani, 2001). However, such a conclusion must be further substantiated.

Maturity of Kangan Formation

Maturity assessment of the Kangan Formation has been made by Piemani (2003) based on the available information on 12 wells drilled through the complete Kangan sequence in the central part of the Persian Gulf (excluding Farsi-B1 Well).

Burial depths of the Kangan Formation increase toward northwest of the Persian Gulf. This corresponds to an increase in thermal maturity of Kangan Formation towards northwest of Persian Gulf. The basal Kangan is in oil generation window in central region of Persian Gulf. Based on the thermal modeling and also considering the maturity status of Surmeh Formation, it has been estimated that Kangan Formation is almost mature for oil generation in a large part of the Persian Gulf. In addition, Kangan Formation is probably in gas generation window at northwestern parts of Persian Gulf and also in the vicinity of the Hormuz Strait. Finally, it can be estimated that Kangan Formation reached oil generation window before Early Eocene.

According to Piemani (2003), Kangan Formation reached oil generation window at about Middle Cretaceous in the central region of the Persian Gulf. It is clear that Kangan Formation has reached oil generation window earlier than this time in other places that burial depth is relatively more. Kangan Formation can be considered as a source rock for oil generation across the Persian Gulf provided that it contains good quantity (TOC) and quality (kerogen type) organic matter. This Formation can also be considered locally as a source rock for gas generation at the extreme edges of Persian Gulf's northwestern regions and in vicinity of the Hormuz Strait.

In summary hydrocarbons of Paleozoic are sourced mainly by organic-rich hot shale that occurs in the basal part of the Lower Silurian. The source rock seems to have been thermally matured by the Late Jurassic in the deepest parts of the sedimentary basin. In terms of migration, hydrocarbon expulsion began in the Early Cretaceous about 120 Ma. Oil and gas are produced from fluvial and eolian sandstones of the Permian Formation and porous shallow marine sandstones of the Devonian Formation.

THE MEZOSOIC SOURCE ROCKS

Rock sequences with potential source characteristics are identified within the Mesozoic successions of the Persian Gulf region. The first comprehensive review of the source rocks in the Persian Gulf region was presented by Murris (1980) where he discussed some of the main Mesozoic source rocks of the Persian Gulf region. A decade later, Stoneley (1990) made a brief review of the main Mesozoic to Early Cenozoic source rocks of the Persian Gulf region highlighting the main features of southwestern Iran and the Persian Gulf petroleum system. His contribution undoubtedly makes the cornerstone of future source rock studies in the Persian Gulf region.

During the Mesozoic and Cenozoic, the Arabian Plate which encompasses the Persian Gulf region was principally in tropical regions where carbonate deposition prevailed and organic productivity was very high. Throughout Jurassic, Cretaceous and even Paleogene, the Arabian shelf was the scene of high organic productivity. This is clearly indicated by the tremendous volumes of skeletal debris in the predominantly carbonate succession, as well as

the high organic accumulated under anoxic conditions in the fine-grained sediments. Such conditions prevailed in many of the intrashelf depressions, producing potential source rocks of somewhat limited lateral extent at various levels.

The reasons for high productivity must have been the climatic conditions and oceanographic circulations. Possibly the margin of Southern Tethys to the north was the site of oceanic upwelling, although Irving et al. (1974 cited in Stoneley, 1990) suggested that the organic material might have been concentrated in a narrowing ocean way by prevailing southeasterly trade winds.

Under such special environmental conditions, organic-rich carbonates or organic-rich argillaceous sediments were deposited and as a consequence, rich source rocks were laid in the basin. Several levels of source rocks occur in the Mesozoic strata of the Persian Gulf. By contrast with the older levels, however, most of these seem to be much more distinctly limited in initial depositional extent, although still covering large areas.

The Mesozoic-aged source rocks appear to be mainly marine deposits forming in irregular anoxic shallow intrashelf basins. However, some of the source rocks formed mainly by differential shelf sedimentation (Murris, 1980, 1981) and in some cases coeval with documented global anoxic events. The common occurrence of these events are in the interval from Mid-Jurassic to Mid-Cretaceous accounting for the bulk of the recorded source rocks that are most widely considered to have given the region its enormous oil charge (Stoneley, 1987).

Generally, two major levels of Mesozoic production occur throughout the Persian Gulf region. These are namely the Upper Jurassic and Cretaceous. In both types there is a fortuitous juxtaposition of source, reservoir and seal. The facies are laterally extensive and the structures broad and simple. Source beds for the oil are the Upper Jurassic and Lower Cretaceous intrashelf basinal shales. These are interbedded with and overlain by, porous reservoirs, generally limestone, and are capped by Hith anhydrite in the Jurassic and the Azadegan sand member of Kazhdumi (=Nahr Umr) Shales in the Cretaceous.

Excellent source rocks were deposited in intrashelf basins, when the environment became anoxic due to the sea level rise, locally increased subsidence, and either a humid climate or the existence of upwelling in the Tethyan Ocean. Anoxic conditions extended over large areas during the Middle Jurassic, Oxfordian, Neocomian, Albian, and Campanian to Maaestrichtian, and Middle Eocene to early Oligocene. Among these events, two are of particularly importance to the oil industry. These are namely the Upper Jurassic and Cretaceous. Effective source rocks have been established in lime mudstones of the Middle and Upper Jurassic, which accumulated in temporary intrashelf basins.

Thus, the prime source-rocks are deeply buried Jurassic silisiclastics, which in southern Iran have been depressed into the gas-generating window, but there are also leaner, yet still prolific, source-rocks in the Upper Creta-

ceous and Eocene sequences. Deposition of the source facies in the Jurassic intraplatform basins was initiated by a eustatic sea level rise (Christenson et al., 1977; Ayres et al., 1982).

The organic matter in the potential source rocks of the Mesozoic of the Persian Gulf region is almost entirely TypeII marine sapropel. Organic content commonly exceeds 10% and may reach more than 15% (Stoneley, 1987).

TRIASSIC SOURCE ROCKS

Triassic source rocks are among the least studied strata of the Persian Gulf region. The absence of thick marine shales suggests a lack of potential source rocks to generate commercial quantities of hydrocarbons.

In northern Persian Gulf the Triassic sedimentary sequence consist of platform carbonates sediments forming thick dolomitic carbonates and thin layers of evaporite which generally contain little organic matter. Platform conditions persisted in northern Persian Gulf in the Fars region from the Early Mesozoic onwards with the deposition of organically lean sediments. This is true for a monotonous succession of limestones of the Surmeh and Sarvak Formations, as well as for depositional intervals such as the Kazhdumi and Gurpi Formations which are often incomplete, relatively thin and oxidized.

JURASSIC SOURCE ROCKS

Generally, the Jurassic source rocks in the Persian Gulf region have very high petroleum potential. During the Jurassic time, geologic and sedimentologic conditions of the Persian Gulf region resulted in deposition of the following ideal sequence of primary petroleum system elements: thick oil-prone source rocks, extensive reservoir facies, and excellent seals.

Many of the source rocks began forming in the Jurassic. Shallow seas periodically inundated the northeastern section of the Arabian plate, where the Persian Gulf currently sits. Those seas crowded with life, stimulated by the warmth of the equatorial latitudes. Thick layers of organic-rich shales and marine carbonates accumulated in expansive basins and compressed into source rocks that remained little disturbed for millions of years.

In Jurassic time, the wide, 2000-km-long Arabian Platform accommodated several intrashelf basins (Murris, 1980;, Ayres et al., 1982; Beydoun, 1988). Three intraplatform and relatively shallow water sub-basins existed in the Persian Gulf region during the Late Jurassic (figure 4-5). These sub basins were the depocenters for sediments that formed the main Jurassic source rocks, as well as the sites of several important reservoirs. These source and reservoir rocks together constitute the major Jurassic petroleum systems of the Persian Gulf region and surrounding areas.

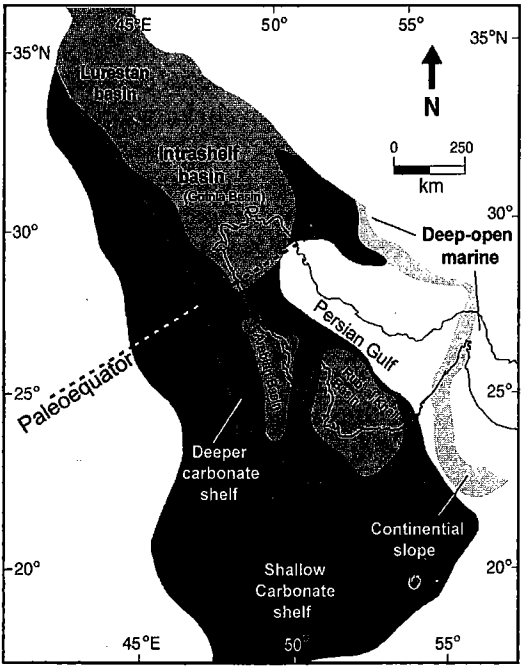


Figure 4-5. Location map of the intrashelf basins in the Persian Gulf region during the Oxfordian and Kimmeridgian (modified after Murris, 1980 and Ziegler, 2001).

Oil of the Persian Gulf system is sourced by organic-rich marine carbonates of the Jurassic that were deposited in one of three intraplatform basins during the Jurassic and form a superfamily of oils with distinctive geochemical characteristics. Hydrocarbons were generated and expelled from these source rocks beginning in the Cretaceous. Production is from cyclic carbonate-rock reservoirs of the Arab Formation in several giant and supergiant fields including Ghawar field, Saudi Arabia.

The intrashelf basin facies are the major source rocks in off shore of southern Persian Gulf and one of the major source rocks defined in the UAE are Diyab-Dukhan Formation (Oxfordian Lower Kimmeridgian) and Shilaif-Khatiyah Formations (late Albian to Cenomanian).

Substantial amounts of organic-rich source-rock shales, which formed under anoxic conditions, accumulated in the basins. These are the rich source rocks analyzed by Bordenave and Burwood (1990) and Ayres et al. (1992) (e.g., the Hanifa and Naokelekan shales and the Diyab Formation of Qatar and the southern Persian Gulf). In general, organic-rich carbonates were deposited within the basins under euxinic conditions, and shallow grainstones, coral/stromatoporoid patch reefs, and oolites formed along the margins.

Deposition of the source facies in the Jurassic intraplatform sub-basins was initiated by a eustatic sea-level rise (Christenson et al., 1977; Ayres et al., 1982). During Late Jurassic (Oxfordian and early Kimmeridgian), due to the

differential subsidence and sea level rise broad intrashelf sub-basins developed in the Persian Gulf and surrounding region. For example, the combination of a eustatic sea-level rise and differential subsidence over the platform resulted in the development of the Diyab intrashelf basin. This basin was filled with bituminous lime mudstones, which pass laterally into non-source, shallow-water platform carbonates. As the basin shallowed, platform carbonates extended across the basin to form the major reservoir units. The intrashelf basin in the southwestern Persian Gulf is thought to be the source of the Jurassic production in onshore/offshore Qatar and western offshore Abu Dhabi (Murris, 1980).

A deep-water intraplatform basin, the Gotnia sub-basin, existed in the northern Gulf region (Murris, 1980). This extensive and deep water basin persisted from Middle Jurassic to Middle Cretaceous times around the head of the Persian Gulf (Sargelu- Garau) where shales and argillaceous limestones are of source rock quality (Ayres et al., 1982; Ziegler, 2001). Shales also filled temporary anoxic basins in the Persian Gulf and in Iran during the Cretaceous. The Albian Kazhdumi Formation (Ala, 1982) characterizes one of them and is the source of most of the oil in the Persian Gulf.

The Central Arabian sub-basin was separated structurally from the northern Gotnia sub-basin (see figure 4-5) by the Rimthan Arch (Langdon and Malacek, 1987). A third, smaller and shallower, intraplatform basin to the east, the South Persian Gulf sub-basin, existed during the Late Jurassic (from late Oxfordian to early Kimmeridgian) and was separated from the Central Arabian sub-basin by the Qatar Arch (Murris, 1980; Droste, 1990). Cyclic changes in sea level during the Middle and Late Jurassic led to the development of a stacked series of shallowing-upward, carbonate platform sequences. The basinal facies consist of cycles of laminated, organic-rich, lime mudwackestones. The Oxfordian in southern Persian Gulf has also been identified as a major source rock (Ayers et al., 1982).

Due to sedimentation in these sub basins, the Upper Jurassic succession in offshore Persian Gulf has considerable lateral and vertical lithofacies variations from east to west. As a result, the investigations conducted in the region could not have provided a very reliable chronostratigraphic framework for the Oxfordian and Kimmeridgian sequences.

In the Tertiary, subduction of the Arabian plate beneath the Eurasian plate drove the Mesozoic source rocks down into a "thermal generating window". High heat and pressure converted the shale and carbonate-rich rocks into oil and gas. Much of the oil migrated up into anticlines sealed by thick layers of salt and anhydrite left behind from the Jurassic seas as they dried out.

A major rise in sea level started in the Callovian (Late Middle Jurassic), combined with differential subsidence, led to drowning of the platform and the formation of the Central Arabian intraplatform sub-basin (Meyer and Price, 1993). The Central Arabian sub-basin was separated from the deeper, more extensive intraplatform Gotnia sub-basin to the north and from the shal-

lower and shorter lived South Persian Gulf intraplatform sub-basin to the south and east by shallow grainstone shoals and dolomitized facies. Tropical to subtropical climate and restricted circulation created anoxic conditions and with production, accumulation, and preservation of organic-rich, mostly algal material over large parts of the intraplatform sub-basins (Cole et al., 1994). Water depths were probably on the order of a few tens of meters; subsidence and depositional rates were minimally different because basinal intervals are only slightly thicker than surrounding shelf intervals.

In the northernmost part of the Persian Gulf, and sourced within Jurassic Gotnia sub-basin, oil and gas accumulated in Middle to Upper Jurassic high-energy calcarenites and oolites of bar or shelf-margin origin. These reservoirs are cyclic and interbedded with organic-rich (2 to 5 wt% TOC), muddy lime source rocks that were deposited under anoxic and dysoxic conditions in the restricted, intrashelf Gotnia sub-basin (Cole et al., 1994).

These source-rich facies marginally extend into Dezful embayment in the northern Persian Gulf, although basal Cretaceous extends as far as the Kharg Island in the Persian Gulf waters and is believed to have sourced the Lower Cretaceous accumulations there and at the Gachsaran oilfield. These source levels are capped by persistent top Jurassic evaporites (Gotnia Formation), but further source rock facies were deposited in the basin almost continuously throughout the Early and Middle Cretaceous (Garau Formation).

In Lorestan, 100-200 meters of black paper shales containing *Posidonia* spp., are rich in organic matter, TOCs varying between 1.5-4.5%, and are often associated with *Gilsoniteveining*. In the northeastern Dezful M.I.S. 306 deep well, 100 meters of bituminous Sargelu Formation are capped by 500 meters of the Gotnia Formation are capped by 500 meters of Gotnia massive anhydrite (James and Wynd, 1965).

JURASSIC SOURCE ROCK IN NORTHERN PERSIAN GULF

Sargelu Source Rock

From the Early Jurassic, a depression developed over northeastern Iraq (i.e., the northwestern extension of the Persian Gulf) and Lurestan and persisted through most of the Mesozoic. From Mid-Jurassic till Mid-Cretaceous, anoxic conditions developed in Lorestan and extended into the Dezful Embayment and to the northern Persian Gulf with deposition of Sargelu shales. The large and extensive deepwater Sargeleu-Garau basin was the depositional site for high source quality fine clastics argillaceous carbonates with source quality sediments region (Murris, 1980; Ayres et al., 1982; Ziegler, 2001).

However, it is of prime importance to mention that at least in Lurestan and northern Dezful, the potential of the sediments deposited as an effective source rock, can be discounted, as organically rich layers are often isolated from good reservoirs by thick evaporitic layers.

Middle and Upper Jurassic source are recognized in the Sargelu and Neokelekan Formations of northwestern Persian Gulf; these source rocks were deposited in the Gotnia/Garau intrashelf basin and were probably tectonically controlled (figure-11 Beydoun et al., 1992). TOC of the Sargelu and Neokelekan ranges from 0.49 to 4.66 wt% respectively. The Sargelu facies extended towards the Kharg Island area in the Persian Gulf. In Kuwait, the Middle Jurassic Sargelu Formation is composed mainly of shallow marine low-energy limestones (Alrefai, 1967). At the type locality, the Sargelu Formation is bituminous phosphatic marl with thin argillaceous limestone beds.

The TOC of the Sargelu shows a relatively good range from 0.5 to 3wt%. The kerogen in this formation is mainly typeIII. However the surface samples contain TypeII organic matter. It is expected that due to weathering and alteration the surface samples consisting of kerogen type-II convert to kerogen type-III (Dr. M. Kamali, pers. Comm.). These are the samples that display high degree of maturity and seem to have generated hydrocarbon. Considering the limited data, the Sargelu Formation can be viewed as a good source.

The Sargelu Formation and its equivalent the laminated argillaceous limestones of the Hanifa Formation in the southern Persian Gulf; the argillaceous bituminous limestone of the Shilaif/Khatiyah (Albian-Early Cenomanian); the upper Cretaceous marly limestones in northwestern Persian Gulf have good potentials for oil generation.

The organic-rich facies of the Hanifa Formation and its equivalent, the Diyab Formation, are the major Jurassic source rocks that generate hydrocarbons which are produced from Jurassic reservoirs in the Southern Persian Gulf intraplatform sub-basin, respectively (Ayres et al., 1982). The Hanifa source rock is in the zone of gas generation over a large area. Hydrocarbons in Arab reservoirs have been confidently traced back to Hanifa source rocks, using a broad range of geochemical parameters. In the east of the Central Persian Gulf area, where, at and beyond the Upper Jurassic shelf edge the Hith is depositionally absent, hydrocarbon generated in Hanifa have migrated upwards into Lower Cretaceous reservoirs.

The black limestone of the Hanifa Formation probably accumulated in shallow water of the middle shelf in anoxic bottom-water conditions. The organic matter is mature, highly oil-prone type I and typeII kerogen (mean TOC is 0.6 wt%, maximum 0.93%). It is considered to be the main source rock for the underlying (Bathonian Uwainat) and overlying (Kimmeridgian Arab-D) limestone reservoirs.

Maturation, Generation, and Expulsion

Extensive geochemical modeling has shown that oil generation in the Zagros Domain of Iran and in the Iranian Waters of the Persian Gulf began in the Middle Jurassic in some areas, while the onset of gas window was reached locally as early as Middle Cretaceous (Bordanove, 1990).

Most of the gas was expelled during the Late Cretaceous; expulsion of oil nearly ceased after the Late Cretaceous. Oil and gas expulsion are linked to three events: (1) primary kerogen cracking, causing the first episode of expulsion about 120 Ma; (2) secondary cracking of heavy components and oils, causing a second episode of expulsion at about 100 Ma; and (3) a later uplift and erosional event, resulting in a third pulse of expulsion at about 20–10 Ma during which gas was separated from the oil, causing re-migration (Peimani, 2003).

With the onset of maturity, the areal setting allowed large hydrocarbon kitchen to drain into extraordinary large but typically gentle structural closure, ensuring minimal loss of seal efficiency and large trap volumes (e.g., Grunau, 1977). Throughout this interval, differential sedimentation/compaction draped over generally north-south-trending basement features, or slow salt pillowing, provided the principal mechanisms for formation of these potential traps (Sugden, 1962). Facies were predominantly carbonates with lesser intervals of fine clastics (marls, shales, argillaceous carbonates) and periodic evaporites. Continental clastics from the Arabian shield tongues out through deltas into the inner shelf areas during the early-Middle Cretaceous, interfinguring to the east with marine clastics and carbonates; they provide the main reservoirs for the very large oil fields in Kuwait and southern Iraq.

Mesozoic and Tertiary source rocks and crude oils from the Iranian sector of Persian Gulf have been characterized by means of a variety of organic geochemical techniques (Rabbani, 2003). Some geochemical parameters were measured in oil fields such as Resalat, Salman, Sirri and Nousrat in the eastern part of the Persian Gulf. The Biomarker characteristics (molecular fossils) were combined with other geochemical data in order to interpret the sources, depositional environments, diagenesis and catagenetic processes, migration and alteration. According to the biomarker and geochemical investigation, oils in the eastern part of Persian Gulf can be classified in two groups. Groups 1 include the Sirri and Nousrat oil fields. Based on the C28/C29 Sterane and Dia/reg ST this group sourced from the Jurassic and lower part of the Cretaceous shaley rocks. Group 2 which includes Resalat and Salman oil fields sourced from the upper Paleozoic Carbonate rocks (Rabbani and Kamali, 2003).

Temperature and hydrocarbon generation and expulsion in the Zagros Belt and its foreland have been modeled through geological time. At the same time, the history of folding and thrusting show which structures did exist at peak expulsion time (Rudkiewicz, et al., 2002). According to Rudkiewicz et al. (2002), the Mesozoic source rocks in the synclines and the anticlines sometimes have very contrasted behavior. The 300 kilometers long cross section starts in the foreland near the Persian Gulf and crosses the entire fold belt perpendicular to the main structural trend.

When present, Jurassic source rocks might be at the peak of oil window before the Zagros folding in the deepest synclines and only in the condensate or wet gas zone after the development of structures.

Surmeh Source Rock

The Middle Jurassic period spanned the deposition of Surmeh Formation in the Persian Gulf. Differential intraplate subsidence led to the development on intrashelf basins. Although a relative lowstand in sea level prevailed during most of this time interval, widespread carbonate sediments indicate a shallow-marine environment.

Surmeh Formation is organic-rich and its TOC averages about 4.75 wt% in the samples obtained from Salman oil field in the Persian Gulf. Kerogen in Surmeh source rocks is primarily Type II; nevertheless, Type III kerogen in Surmeh Formation has been reported by Rabbani and Babaii (2004).

The Surmeh source interval has good pyrolysis yields (S2 Rock-Eval yields) averaging 5.40 mg hydrocarbons/g rock and hydrogen indices 113 mg hydrocarbon/g TOC. T_{max} of the analyzed samples vary from 400 to 426 and such values indicate that the samples are immature and have not reached oil generation window.

The Surmeh Formation was drilled to its total thickness only in the central part of the Persian Gulf. Due to the lesser depth of burial, thermal maturity of Surmeh Formation increases toward northwest and eastern region of Persian Gulf. The top of Surmeh Formation is at the end of oil generation window in vicinity of the Hormuz Strait.

The basal Surmeh Formation is immature in central region of the Persian Gulf, however, considering maturity status of the top of Surmeh, it can be estimated that it is completely in oil generation window in the northwest and at the end of oil window in vicinity of the Hormuz Strait. Based on the maturity modeling in Lavan-1 Well performed by Piemani (2003) the Surmah Formation is positioned entirely within the oil window and further the lower portion of this Formation is within the peak of oil generation (see Figure 4-6).

The Surmeh Formation reached oil generation window in Lavan-1 Well about 60 Ma (Early Eocene). This Formation also reached oil generation window before Late Cretaceous in the west and northwest region of the Persian Gulf before Early Paleocene. It is important to note that these times of oil generation belong to particular wells which have been drilled to bottom depth of Surmeh Formation. Thus, it is clear that Surmeh Formation has reached oil generation window earlier than these times in other places that burial depth is relatively more.

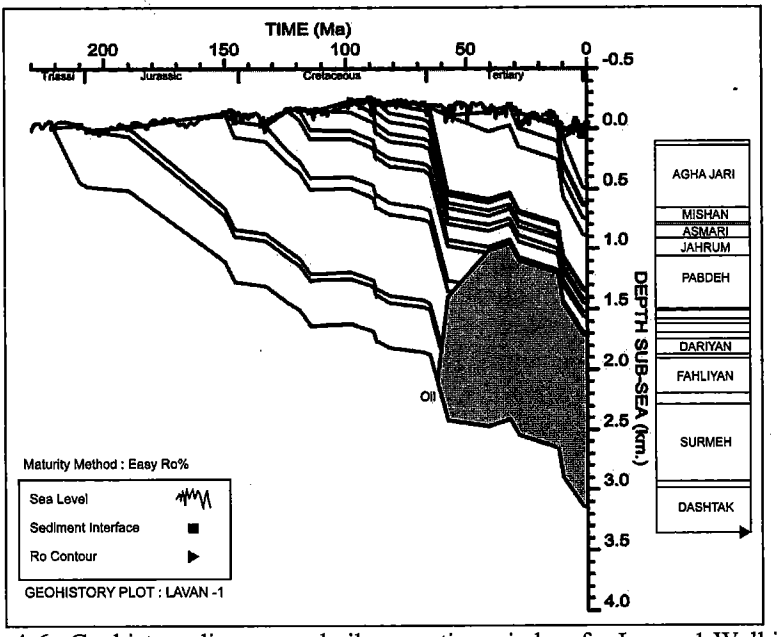


Figure 4-6. Geohistory diagram and oil generation window for Lavan-1 Well in the Persian Gulf (cited from Peymani, 2003).

The Surmeh Formation can be considered as a source rock for oil generation in the northwest and eastern regions of Persian Gulf provided that it contains both good quantity (TOC) and quality (kerogen type) organic matter. It is also important to note that the top of Surmeh Formation is at the end of oil generation window in vicinity of the Hormuz Strait.

Changes of burial depth, temperature and degree of maturity are in agreement with increasing burial depth toward northwest and east of the Persian Gulf. In the west and northwest region of Persian Gulf, Surmeh Formation reached oil generation kitchen in D-1 Well about 68 Ma, F-2 Well about 52 Ma, Foroozan-1 Well about 40 Ma and Doroud-6J well about 25 Ma respectively.

In the eastern region of the Persian Gulf, Surmeh Formation reached oil generation window in Hulur-1 and Qeshm-4 wells prior to 65 Ma while in the Lavan-1 Well about 60 Ma. These times of oil generation belong to certain wells which have been drilled to bottom depth of Surmeh Formation. It has also been concluded that the oil accumulated in the fields such as Nowrooz, Foroozan and Dorood are sourced from Surmeh Formation (Afrapoli, 2003).

Jurassic source rocks are immature to early mature in the northern Persian Gulf and north of Qatar along the Qatar-Gavbandi Arch. Similarly, burial-history modeling in a structurally deep part of the basin west of Safaniya field shows that Jurassic source rocks first entered the main level of thermal maturity for oil generation during the Late Cretaceous, about 75 Ma.

At Awali oil field in Bahrain, Chaube and Al-Samahiji (1995) showed that the Hanifa source facies is as much as 46 m thick. They concluded that the onset of oil generation began in the Eocene (about 45 to 50 Ma) and charged Jurassic reservoirs; however, to the north and east of Awali, oil generation was afterward, or source rocks are immature at present day. Such an interpretation is analogous to the data of Cole et al. (1994). In addition to that, in southern Persian Gulf basin, Milner (1998) presented R_o data showing similar maturities of the Jurassic Hanifa source rock in the southern part of Ghawar Uplift Province to those reported by Cole et al. (1994) and Chaube and Al-Samahiji (1995).

In summary, Jurassic source rocks and oils produced from Surmeh Formation and its time equivalent (i.e., Arab and Hanifa) reservoirs are of similar bulk composition, and have similar carbon isotopic, gas chromatographic, and biomarker signatures. In addition, Jurassic oils are different from the Silurian-sourced oil in pre-Permian Faraghan and Kangan/Dalan reservoirs.

Jurassic Source Rock in Southern Persian Gulf

Effective source rocks have been identified in lime mudstones of the Middle and Upper Jurassic, which accumulated in intrashelf depressions. At this time, large intrashelf euxinic basin existed along the western side of the Persian Gulf which laminated kerogenous micrites sequences accumulated in it (Murris, 1980; Ayers et al., 1982). The lower Hanifa source rocks deposited in this basin as described by Ayers et al. (1982) have as much as 5% TOC. Tuwaiq Mountain and Hanifa Formations are the two most important source rocks in the southern Persian Gulf region. In northwestern Persian Gulf and in the Mesopotamian Foredeep basin the organic-rich, argillaceous limestone facies (as thick as 150 m) of the Tuwaiq Mountain Formation is the primary source rock; however, the overlying Hanifa Formation is also a significant source.

These formations accumulated in an intrashelf basin during Callovian to Oxfordian times. Their time equivalent the Diyab Formation in the offshore area of the Persian Gulf is also a primary source rock whose kerogen typically consists of oil-prone sapropelic material and the TOC content ranges from 0.72 to 1.8% in Abu Dhabi area (Schlumberger, 1981). They appear to have generated a single superfamily of oils that constitute some of the world's largest single oil-field reserves.

The organic-rich argillaceous carbonate intervals of the Jurassic Hanifa and Tuwaiq Mountain Formations are widely recognized as the main source (if not the only source, Ayers et al., 1982) of the Mesozoic and younger oils. Ayers et al. (1982) identified these organic rich source rocks as being thermally mature and containing amorphous algenite mostly derived from blue-green algae. They are the thickest and most extensive Jurassic source-rock facies in southern Persian Gulf.

Tuwaiq Mountain is considered the main Jurassic source rock of this region and was deposited in the intraplatform environment between reservoir facies of the Dhruma (Fadhili zone) and Hanifa Formations (Cole et al., 1994). To the east and south of the Central Arabian sub-basin, organic-rich facies of the overlying Hanifa Formation form the major source rock for the Jurassic Arab Formation. The organic-rich facies of the upper part of the Hanifa is of secondary significance compared to organic facies of the Tuwaiq Mountain (Cole et al., 1994).

TOC of the Tuwaiq Mountain exceeds 13 wt% and averages about 3.5 wt%. In comparison, the Hanifa source rock is less than 30 meters thick and averages about 2.6 wt% TOC. Kerogen in both the Tuwaiq and Hanifa source rocks is primarily Type II (oil-prone) and is believed to consist primarily of blue-green algae (Ayres et al., 1982; Cole et al., 1994).

The oil-prone Tuwaiq Mountain source interval has excellent pyrolysis yields (S2 Rock-Eval yields) averaging 22.2 mg hydrocarbons/g rock and hydrogen indices greater than 600 mg hydrocarbon/g TOC. In contrast, the Hanifa of the southern Persian Gulf has hydrogen indices less than 400 mg HC/g TOC, tending toward mixed oil and gas formation (Cole et al., 1994).

The carbon isotopes of the Middle Surmeh Formation (i.e., Arab D) oil are significantly heavier than that of the Paleozoic and Precambrian samples in the region. The isotope values of the oil, however, are very similar to the values of the extracts from Jurassic source rocks. The isotope values of Paleozoic oils, on the other hand, are close to those of the basal hot shale extracts suggesting it as the source of the Paleozoic oils in the area.

Oil-source correlations classify these oils into one Jurassic family. The evaporitic Gotnia Sub-basin to the north is a separate Jurassic system with different source-rock facies. An important point to mention is that the large accumulations of oil in Middle Cretaceous reservoirs in northern Saudi Arabia are geochemically and physically similar to Jurassic oils. The loss of continuity of Jurassic seals along the margins of the Gotnia source rocks basin may have allowed vertical migration along salt solution collapse or fold-related fractures along the edge of the basin. Another possible source for oil is the Albian of northern and eastern Saudi Arabia, where an intrashelf basin developed.

Diyab Formation

Diyab Formation (Oxfordian to Mid-Kimmeridgian) widely distributed throughout the southern Persian Gulf is a thick succession of relatively deep-water, argillaceous lime mudstones deposited in an intrashelf basin. During the deposition of the Lower Diyab, the major part of the southern Persian Gulf (i.e. Abu Dhabi) was occupied by an intrashelfal basin-basinal slope environment. Organic rich (notably bitumen) lime mudstones were deposited under

euxinic conditions during a marine transgression, resulting from regional subsidence.

The Diyab Formation shows sufficient organic kerogen richness in the offshore Persian Gulf (TOC in offshore areas ranges from 0.3-5.5%) and provides source potential and is the main hydrocarbon generating interval. TOC and the kerogen is sapropelic oil-prone type, sometimes mixed sapropelic-humic. The Upper Jurassic Diyab Formation is a major source rock for the Surmeh Formation and its equivalent the Arab Formation; the geochemically similar Araej oils are considered to have been sourced from the Diyab.

The onshore areas are generally characterized by low TOC values (<1 wt %) and low pyrolysis (Alsharhan, 2002). Vitrinite reflectance ranges from 0.55-1.3%, with most of the onshore being overmature to highly mature. The offshore demonstrates much lower maturity, decreasing toward the north and northwest. This is the area within the maximum oil generative stage. The isopach and paleomigration maps show initial hydrocarbon generation occurred during the Campanian and maximum oil generation occurred during the Eocene. The Early Tertiary was the major explosion phase, with more than 75% of the total oils being generated from Diyab source.

Large deposits of heavy oil (6-16° API) and bitumen, accumulated in the Cretaceous and Tertiary reservoirs of large structures such as Mand, F, H and FB are assumed to have migrated laterally from the Hanifa/Tuwaiq Mountain kitchens, located in the northern part of Saudi Arabia and in the offshore of Abu Dhabi. Such an assumption seems to be confirmed by the high sulfur content of these heavy deposits (3.5 to 5%).

Organic Geochemistry

Oil-to-oil and oil-to-source rock correlations by Cole et al. (1994) showed that most of the oil in Jurassic reservoirs of southern Persian Gulf can be grouped into a single superfamily having several specific characteristics. Generally, these oils consist of 30 to 40% saturate, 30 to 45% aromatics, and 20 to 30% resin plus sulfur and are classified as aromatic-intermediate oils. Sulfur content is high (1-4% or greater) and consistent with a marine carbonate source. Most oils from Upper Jurassic Arab and Hanifa reservoirs have API gravities ranging from 25° to 35° (Cole et al., 1994). Lower sulfur content is normally associated with higher API gravities, as noted for Silurian sourced oils.

Jurassic oils have very similar light hydrocarbon characteristics are quite different from deeper Permian reservoir condensates from Silurian sources. Gas chromatograph-mass spectrometer analysis shows that most oils of central Arabia Jurassic reservoirs have similar biomarkers, particularly hopane and tricyclic hopane (m/z 191) and steranes (m/z 217), which are indicative of oils derived from source rocks deposited in a carbonate environment under anoxic, reducing conditions (Cole et al., 1994).

Maturation, Generation, and Expulsion

Most investigators who modeled the maturity of potential sources considered the onset of oil generation and the migration from Diyab Formation source rock to the traps to have occurred in the Late Middle Cretaceous (i.e., Turonian) and the Late Cretaceous (Santonian-Campanian), respectively. The onset of gas generation took place in the Early Eocene time.

The Tuwaiq and Hanifa source rocks are mostly at mid-maturity and within main phase oil expulsion stage (R_o = 0.7 to 1.0%). The Oxfordian Hanifa formation has TOC content with a maximum value of 0.93% and a mean of 0.60%. The estimated vitrinite reflectance (R_o) ranged from 0.7 to 0.8 (peak oil generation) with highly oil-prone kerogen I-II. This is also the case at Iran's Golshan (G-Structure) gas field and along the Zagros is marginally mature in respect to oil generation.

Carbon isotope ($\delta^{13}C$) values are between -26.0 and -26.5‰ for immature Tuwaiq Mountain and Hanifa source rocks and show excellent correlation to average $\delta^{13}C$ values (-26.6‰) for whole oils from reservoirs of the Jurassic Arab and Hanifa Formations. In contrast, the $\delta^{13}C$ of hydrocarbons in Permian age reservoirs of Kangan/Dalan and their equivalent, the Khuff Formation range between -28.0 and -30.5‰ (Abu-Ali et al., 1991; Cole et al., 1994) and are clearly a different family of oils than those from the Jurassic Arab and Hanifa reservoirs.

Modeling of source rock maturity and time of oil expulsion in Jurassic has shown that the main phase of oil generation began in the Cretaceous about 75 Ma (Campanian) for source rocks with greater than 1.0 wt% TOC (Cole et al., 1994). However, the present-day high maturity of the analyzed rock samples suggests that the original source potential could have had higher TOC values than those recorded in the analysis.

Burial curve also shows that the Tuwaiq/Hanifa source rocks near Safaniya field in the southern coast of the Persian Gulf are presently in the late stage of oil generation, consistent with the "end of oil expulsion to oil preservation" stage. According to the model of Cole et al. (1994), initial generation (early maturity) in these Jurassic source rocks occurs at a mean vitrinite reflectance (R_o) of about 0.45%; thus, rocks having an R_o of less than 0.45% are immature. Generation of oil at relatively low maturity (R_o equal to 0.45%) is due to the predominantly high sulfur, type II-S kerogen comprising the source rocks. Type II-S kerogen characteristically generates hydrocarbons at comparatively low thermal maturity (Baskin and Peters, 1992; Lewan, 1998).

In southern Persian Gulf this occurred in three principal areas, as follows: (1) southwest Kuwait in the Gotnia intraplatform sub-basin; (2) west-central northern Persian Gulf near Safaniya and Abu Hadriya fields; (3) southwestern northern Persian Gulf south of Bahrain at Dammam field, Qatar, and to the east and southeast of Ghawar field. According to the model presented by Cole et al., (1994), oil expulsion began to cease in portions of the northern Persian

Gulf (areas 2 and 3) about 25 Ma (Oligocene) and in southwestern Kuwait by present day. Also, main-phase oil expulsion in Jurassic source rocks is occurring today in many parts of the Central Arabian intraplatform sub-basin.

The migration pathways of the oil generated from the Diyab source are interpreted to have been mainly toward the offshore and central onshore structures. The Arab and Araej oils were sourced mainly from Diyab Formation and form giant fields in the area (Alsharhan, 2002). The main oil generation phase from the Jurassic source rock to the traps occurred in Upper Cretaceous with migration of the hydrocarbon during the Early Tertiary. Migration is vertical from the Jurassic source into mainly Surmeh and stratigraphically time equivalents (i.e., Arab) reservoirs.

CRETACEOUS SOURCE ROCKS OF THE PERSIAN GULF

Early Cretaceous

Several Cretaceous source-rock intervals are recognized in the Zagros and Mesopotamian Cretaceous-Tertiary which are also extended into the Persian Gulf. The source rocks of this time span include shales of the Fahliyan Formation and its equivalents the Sulaiy, Lower Ratawi and Minagish Formations, Gadvan and Zubair Formation of the northwestern Persian Gulf region.

Source rock facies developed in intrashelf Cretaceous basins characterized by laminated argillaceous and shaly lime mudstones-wackestones and kerogen-rich limestones with abundant planktonic foraminifera. The Lower Cretaceous can also be considered as potential source rocks, but is not as thick or as rich as Upper Jurassic. The Berriasian-Valanginian sediments have adequate organic richness in the northwestern Persian Gulf, with oil accumulation in reservoirs of this age.

Aptian age Dariyan source rock is only mature in limited areas, where sufficient Upper Cretaceous and Tertiary overburden has accumulated on top. Part of the hydrocarbon occurrences clustered around the Dariyan and Shuaiba can be attributed to this source. However in areas where the rocks are immature the charge is provided by deeper sources as proved in some places by geochemical fingerprinting. These occurrences are restricted to fields where the intervening Hith Formation is breached through faulting or which are located over the zone of Hith non-deposition (Murris, 1980).

In northwestern Persian Gulf, particularly in Iraq towards Kuwait, the oil in the sandstone reservoirs is attributed to the underlying Lower Cretaceous succession (Ibrahim, 1983). Migration is subsequently assumed to have taken place in Paleocene to early Eocene in the southeast and during the Miocene in the northeast of the area, with vertical migration as the prevailing pathway. Shale beds of the Nahr Umr sequence form the seal for the reservoirs.

Although the shales of the Nahr Umr Formation provide a good regional seal, but locally could be considered as hydrocarbon source rock. The Nahr

Umr clastic front changes to clastic marine shelf near the central part of the present Persian Gulf (Murris, 1980). There are few published studies on the source potential of the Nahr Umr and its equivalent formation in the Persian Gulf region as a source rock or its thermal maturation. But the shales of the Nahr Umr might also be a potential source rocks in the Persian Gulf.

In the southern Persian Gulf (i.e., UAE) Lower Cretaceous marls and shales are regarded as sourcing reservoirs in the area and long-range lateral migration of oil is thought to have occurred (Clark, 1975). However, this has been questioned by later workers who regarded the oil as being Jurassic in origin with the feather-edge of Hith evaporite seal allowing vertical migration into the Cretaceous.

Geochemical investigations carried out by Young et al. (1977) and Ala et al. (1980) have demonstrated that the greater portion of the oil in the Asmari and Bangestan pay zones is derived from the lower Cretaceous.

Young et al. (1977 cited in Ala., 1982) have developed a method in order to estimate the age of the reservoired hydrocarbons on the basis of their present day maturity level. Since the chemical composition of oils changes as they mature, the time required to attain a certain degree of maturity provides an estimate of the age of given oil. Age calculations are made for two ranges of hydrocarbons: the high gasoline C_5-C_7 fraction, and the heavy C15+ components. According to Ala (1982) these authors analyzed eight crude oil samples from Asmari reservoirs and six from Bangestan pay zones. The former group had a calculated age range of 104 to 120 m.y., whereas most of the latter ranged in age from more than 65 to 120 m.y. An early Cretaceous age for the Asmari and Bangestan oils is therefore indicated by these calculations.

Fahliyan Formation

On the basis of their organic richness (i.e., extractable organic matter-total organic carbon (EOM-TOC) relationship), carbon and sulfur isotopic composition similarities of oils, extracts, pyrite and kerogen, the Fahliyan Formation and its equivalent the euxinic-neritic sandstones of the Lower Ratawi and Minagish Formations of Lower Cretaceous in northwestern Persian Gulf showed indications of source potentials.

The source of the oil in the lower Cretaceous Zubair and Nahr Umr sandstone reservoir in northwestern Persian Gulf is ascribed to a deeper pre-Dariyan Lower Cretaceous succession. This makes the Dariyan Formation as a prime source rock candidate.

The thermal history reconstruction (Duddy, 2004) strongly suggests that the probable TypeII source rocks in parts of Neocomian Fahliyan Formation (and lower Ratawi Formation) are the most likely source for oil accumulated in the Burgan sequences of the Soroosh and Nowrooz fields in the Iranian waters of Persian Gulf.

Apatite Fission Track Analysis and Vitrinite Reflection, (AFTA and VR) data in the Soroosh field are interpreted by Duddy (2004) in terms of the entire drilled sections of Quaternary to Cretaceous/Jurassic age being at maximum post-depositional temperatures, and maximum burial, at the present-day. This thermal modeling history indicates that Fahliyan Formation (and Lower Ratawi Formation) source rocks became early mature (VR=0.5% R_o (max) in the Late Cretaceous (~100 to 70 Ma), and increasingly attained maximum maturity in the range of ~0.65 to 0.85% (late-early to mid-mature for oil) at the present day.

Gadvan Source Rocks

After the deposition of the thick Gotnia anhydrite during the late Jurassic, anoxia returned to the Lurestan depression. This resulted in the deposition of the low energy Garau facies, from Valanginian to Aptian times and even up to the Coniacian in the axial part of the depression.

The Garau Formation is one of the formations with good source rock potentials in the Persian Gulf region and in onshore areas of the Persian Gulf. This formation has excellent source rock characteristics with initial organic content values range between 1-2% and Hydrogen indices (HI) varying from 150 to 400 gHC/kgC and maximum thickness in excess of about 300 meters (Bereave and Hud, 1995). The organic matter is mainly algal with higher sulfur content, qualifying them as typeII.

The sediments were deposited in well established depressions included in an overall shallow water intercratonic basin communicating with the Southern Tethys Ocean. These depressions become anoxic as the result of a water stratification caused by the conjunction of high stand waters, humid climate and the existence of a sill separating the depression from the open sea.

The Gadvan Formation was deposited almost everywhere in the Persian Gulf, however, the thickness of the formation increases toward northwest and east of the Persian Gulf. It is mature and has reached the oil kitchen producing substantial hydrocarbon (Ashkan, 2002).

TOCs are high in the marl (2-9%) and as much as 1-2% in the limestone. The Gadvan facies also extend into northern Fars, where it is referred to as the Garau Formation however, it is only locally rich in organic matter. In the absence of regional geochemical sampling, inference are applicable only to central Lorestan, where the kerogens show thermal alteration and the organic matter has a dark-brown color so that it must be considered a likely source for the Asmari and Bangestan oils.

Gadvan Formation can not be considered as an effective source rock in most parts of the Persian Gulf. This is due to the fact that the thickness of Gadvan Formation increases toward northwest and also between center and eastern region of the Persian Gulf and has not been deposited in other places in the Persian Gulf. As a result, the maturity of Gadvan Formation increases

toward northwest of Persian Gulf and in the central region and it is in oil generation window. Thus, the Gadvan Formation could be considered as a source rock for oil generation in the northwestern region of Persian Gulf on condition that it contains good quantity (TOC) and quality (kerogen type) organic matter.

Based on the available information, TOC of the Gadvan Formation rarely exceeds 1.6%. In addition, the amount of T_{max} has not been measured thus far and in area where measurements performed the T_{max} ranges from 410 to 430. Furthermore the S_2 parameter has been determined (Ashkan, 2002) and with regards to the petroleum generation potential it can be concluded that this Formation might be immature and at most it is moderately mature.

Maturation of Gadvan Source Rocks

Thermal maturity modeling of the Gadvan Formation performed by Paymani (2003) shows that upper and lower parts of it are within peak of oil generation stage ($\%R_o$ = 0.80-0.90) at the end of northwest region of the Persian Gulf. Furthermore, Gadvan Formation is at the end of oil generation kitchen in the vicinity of the Hormuz Strait. These are due to increasing burial depth and thickness of formation toward northwest and eastern part of the Persian Gulf. Gadvan Formation is completely immature in central regions of the Persian Gulf (Piemani, 2003). Based on such information, the Gadvan Formation may not be considered as an effective source rock in most parts of the Persian Gulf.

In the western part of the Persian Gulf, Gadvan Formation appeared to have reached oil generation stage in PaliNowrooz # well about 75 Ma, Abouzar #1 well about 65 Ma, Bahregansar-10 well about 50 Ma, Esfandiyar-1A about 28 Ma and in Soroosh-1 well about 15 Ma, in Tanb #1 well about 68 Ma and in Binak-4 and H-1 wells about 64 Ma. The lower part of the Gadvan Formation reached oil generation window in location of Lavan-1 Well about 40 Ma (see figures 4-7 and 4-8).

In the eastern regions of the Persian Gulf, Gadvan Formation seems to have reached oil generation window in HEE-1 well about 65Ma and in Gevarzin-1, Hulur-1 and Qeshm-4 wells about 60Ma and in SIE-2 well about 53Ma. Gadvan Formation reached oil generation window about Late Cretaceous-Early Paleocene in the northwest of the Persian Gulf and about Early Paleocene in the eastern region. Therefore, the Gadvan Formation can be considered as a source rock for oil generation in northwestern and eastern parts of the Persian Gulf if good quantity (TOC) and quality (kerogen type) organic matter are present.

It is important to mention that based on the preliminary evaluation of Zubair (equivalent to top of Gadvan Formation), Ratawi shale (equivalent to bottom of Gadvan Formation) and Sulaiy Formation (equivalent to Garau Formation) they are all mature (Abdullah and Kinghorn, 1996).

Dariyan Formation

Carbonate source rocks of the Dariyan Formation and its equivalent the Shuaiba Formation provide some hydrocarbons for much of the Persian Gulf region. Dariyan Formation was deposited almost all over the Persian Gulf. The thickness of the Dariyan Formation increases toward northwest and east of the Persian Gulf.

The organic-rich, basinal facies of the Dariyan Formation, and argillaceous dense layers in the Lower Cretaceous Thamama Group and argillaceous basinal facies of the Middle Cretaceous Shilaif (Khatiyah) Formation of the Wasia Group are the primary source rocks. These source rocks contain Types I and II organic matter and as much as 10 w% TOC (2.0 w% average).

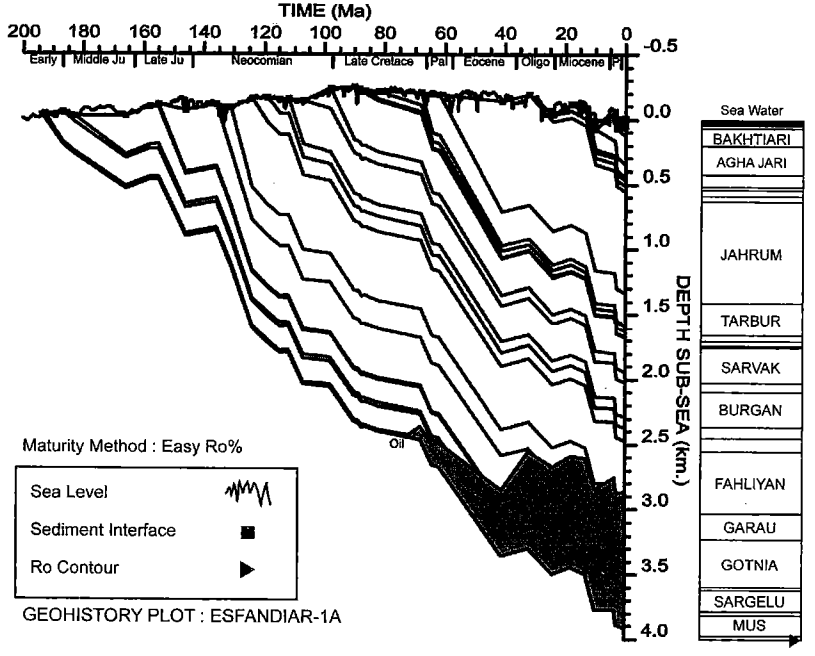


Figure 4-7. Geohistory diagram and oil generation window for Esfandiar-1A Well (cited from Peymani, 2003).

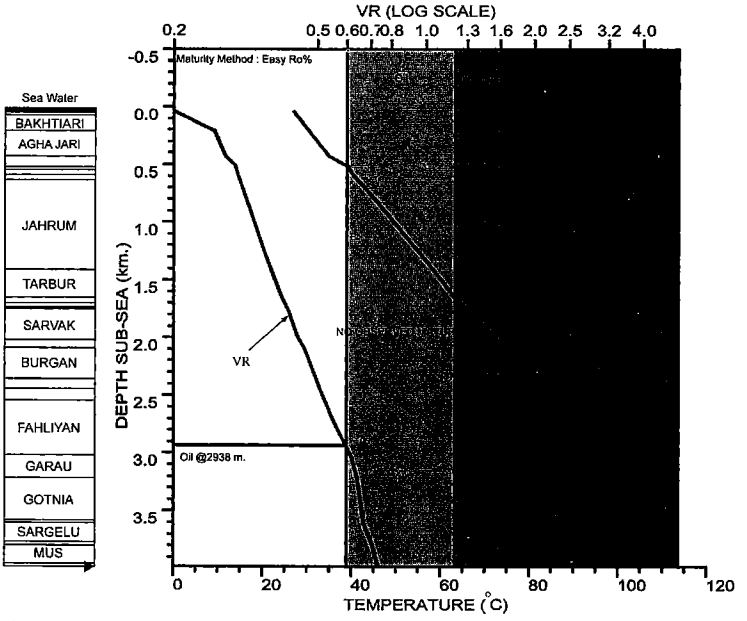


Figure 4-8. Computed maturity (left) and temperature (right) for Esfandiar-1A at 0.00 Ma (Cited from Peymani, 2003).

Maturation, Generation, and Expulsion in Dariyan Formation

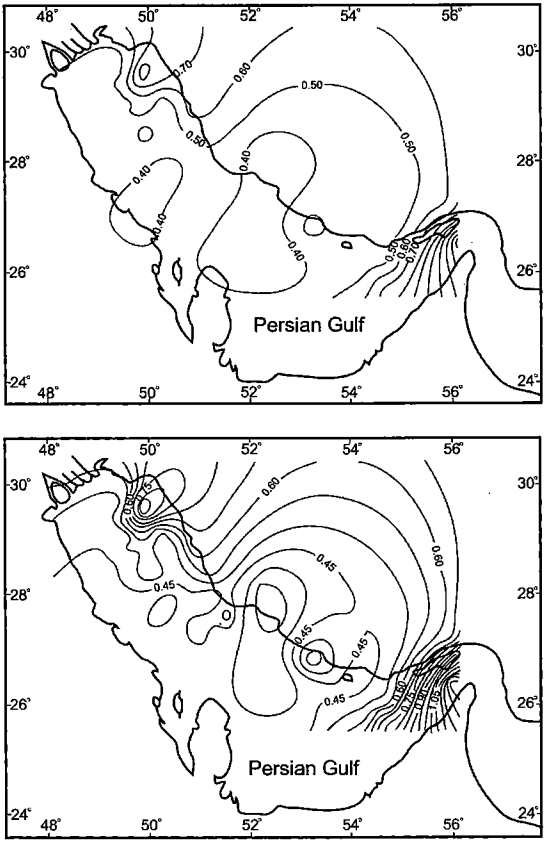
Modeling of thermal maturity of Dariyan Formation demonstrates that the entire thickness of the formation is in oil generation window in northwestern region of the Persian Gulf and also in vicinity of the Hormuz Strait. This is due to increasing burial depth and thickness of formation toward northwest and east. Dariyan Formation is completely immature in the central part of Persian Gulf. Changes of burial depth, temperature and degree of maturity are in agreement with increasing burial depth toward northwest and east, indicating increase in temperature and vitrinite reflectance (Figure 4-9).

In terms of source potential, provided that there is good quantity (TOC) and sufficient quality (kerogen type) organic matter, in the northwestern and eastern regions of Persian Gulf, Dariyan Formation reached oil generation window in Binak-4, H-1 and Tanb-1 wells about 60 Ma whereas in the eastern parts of the Persian Gulf, the Dariyan Formation reached oil generation window in HEE-1 Well about 64Ma, Hulur-1 well about 60 Ma and in Gevarzin-1 and Qeshm-4 wells about 57 Ma and in Si-E-2 well about 50Ma. Peak generation occurred in Middle Miocene time. This timing is coincident with Zagros collision and a thick accumulation of orogenic clastics in the Zagros foredeep. This is also in agreement with oil generation from the Dariyan source rocks which started generating oil as early as Eocene (65 Ma) with major expulsion

of petroleum from the Falaha syncline and Oman foreland basin commencing about 40 Ma.

The thermal history reconstruction (Duddy, 2004) strongly suggests that the Dariyan Formation reached oil generation window at approximately Late Paleocene in the northwest of Persian Gulf and around Early Paleocene in the eastern regions.

In the southern Persian Gulf, a deeper facies (Bab member) of the shallow-shelf Shuaiba rudists-bearing carbonates was deposited in a low lying mainly within the UAE. This unit was initially thought to be likely source for oils in Lower Cretaceous and some Middle Cretaceous reservoirs of the southern Persian Gulf (Clarke, 1975; Murris, 1981), however it is now inferred that these oils were sourced mainly from the Upper Jurassic (Diyab Formation) levels around the edge of intervening Hith anhydrite seal (Hassan and Azer, 1985; Loutfi and El Bishlawy, 1986). However, Shuaiba source-rock facies is present and mature for oil generation (R_o = 0.65) along the Rub 'al Khali basin axis in southern Persian Gulf.



4-9. Iso-reflectance map for base and top the Dariyan Formation (cited from Peymani, 2003)

MIDDLE CRETACEOUS SOURCE ROCKS

For a period of over fifteen years (i.e., from 1958 till 1974), Dunnington progressively provided strong arguments supported by field evidence such as oil gravities, chemical composition, pressure data, in favor of common pre-Tertiary (Lower and Middle Cretaceous) origin for the oil found in the Tertiary reservoirs of the Zagros Basin. Based on his ample argument, it could be deduced that any investigation concerning the source rock in the Persian Gulf region would make a strong emphasize on the Lower and Middle Cretaceous sediments.

One of the most important factors during this time period was the special environmental conditions. Across the Middle Cretaceous, several global anoxic events appear to coincide with good source rock deposition in southern Iran and also in the Persian Gulf region. As pointed out previously, in the late Aptian and Albian, two intrashelf basins developed new source rock sequences, whereas in the Gotnia/Garau basin, organic-rich sedimentation continued. Within the shallow basins, water density stratification gave rise to anoxic bottom conditions favorable for the preservation of organic matter derived from prolific organic productivity in warm surface waters. Combination of all these factors resulted in the deposition of a succession of organic-rich source rocks.

The Middle Cretaceous Burgan and Upper Sarvak are also important source rocks in the Zagros Fold Belt and foreland basin areas. The Khatiyah Formation is the primary source rocks with high organic matter. The Aptian also saw the development of an intrashelf basin in the Dezful Embayment area in which Aptian-Albian anoxia induced deposition of rich source rocks (Gadvan-Kazhdumi Formations).

Two further levels in the Middle Cretaceous over much of the northern Arabian shelf are found to be variably organic rich and in some areas sufficiently so to be classed as potential source rocks. A lower level lies close to the Albian-Cenomanian boundary and is considered to be a potential source rocks in southern and eastern Arabia ("Safaniya source rock," Granthem et al., 1988), and upper level occurs close to the Cenomanian-Turonian boundary (lower Upper Sarvak, Newell and Hennington, 1983). In southern Persian Gulf, the oil in the Middle and Upper Cretaceous sequences and also Simsima reservoirs are geochemically typed to the Shilaif source rock (Loutfi and El Bishlawy, 1986).

Peak generation occurred in Mid-Miocene time. The timing is coincident with Zagros collision and a thick accumulation of orogenic clastics in Zagros foredeep. The onset of the Zagros orogeny facilitated hydrocarbon movement within the limits of the Mesozoic reservoirs. As folding intensified, fractures developed in the overlying tight, competent, and typically argillaceous carbonates, promoting vertical migration across the bedding via poor, tight but fractured, Upper Cretaceous reservoirs into Tertiary (Eocene and Oligocene-

Miocene) porous and fractured carbonate reservoirs capped by the widespread and very efficient Gachsaran evaporite cover. Where this cover was breached or developed in a non-sealing facies in the eastern part of the fold belt, the volume of oil lost could well have been prodigious.

Kazhdumi Source-Rocks

During the Albian time a large but gentle depression developed over the Dezful Embayment and extended to the northern part of the Persian Gulf. Strongly anoxic paleoenvironmental conditions prevailed and up to 300 meters of bituminous marls were deposited in the central part of the depression located near Rag-e-Sefid in Khuzestan. This depression was restricted to the southeast by the Fars Platform, where the deposition of shallow-water thin oxic marls was interrupted due to short-lived emergences.

Based on the plate tectonic reconstruction, in the Albian time, the Arabian Platform was close to the Equator and climatic conditions were humid. Under humid climate, large volumes of fresh water flowed into the Dezful Depression through the river (Bordenave and Burwood, 1995) (see figure 4-10). This fluviatile water, outwash from the Arabo-Nubian land mass, was nutrient rich (nitrates and phosphates) and ideal conditions were realized for a high planktonic productivity in the shallow low-density oxygenated fresh water.

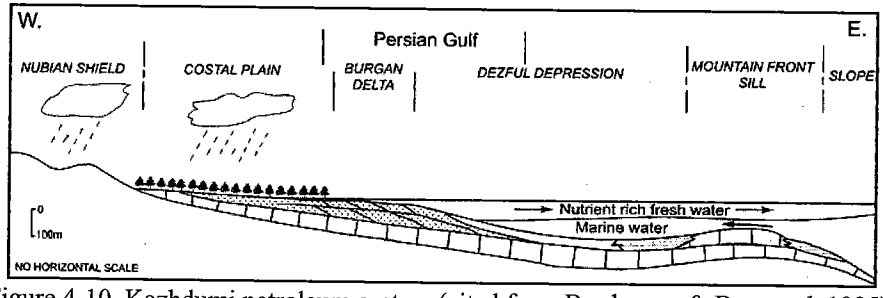


Figure 4-10. Kazhdumi petroleum system (cited from Bordenave & Burwood, 1995).

Density stratification and the fall of organic matter in the oxygen-deprived zone is a typical mechanism for anoxic conditions. Sulfate-reducing bacteria were very active as demonstrated by the sulfur incorporated in the Kazhdumi organic matter. The organic matter contains algal with high sulfur content, and can be considered as typeII.

The high productivity of the Kazhdumi source rock resulted from the coincidence of numerous favorable factors resulting from post-Albian geological history. Some of them, such as the existence of excellent reservoirs, the efficient caprocks of the Gachsaran evaporites sealing the Asmari, and large anticlines, have been known since the early days of petroleum exploration.

A high separated the Kazhdumi intrashelf basin from the Garau depression and restricted the marine influence from the Tethys Ocean, thereby facilitating the creation of anoxia. On this paleohigh the Kazhdumi Formation is generally thin (Bordenave and Burwood, 1990; Setudehnia, 1978).

To the north, the anoxic basin was restricted by the east-west Bala Rud carbonate shoal, which separated the Kazhdumi depression centered on the present day Dezful Embayment from the Lurestan depression. To the east, the depression was bordered by a sill, on which anoxic and oxic facies fluctuated according to sea level changes, however minor information is available on a possible eastern extension.

Up to 300 meters of marls and subordinate argillaceous limestone, containing pelagic fauna of *Globigerina*, *Globotruncana* and radiolaria, deposited in strictly euxinic conditions and the organic matter was of algal origin. The Kazhdumi Formation was deposited in an oxic environment in Fars region, however, the origin of hydrocarbons and several noticeable seepages in this region is not fully understood, but might come from an eastern development of the Kazhdumi source rocks.

The Kazhdumi source rocks are well extended into the Persian Gulf. For example, in Hengam oilfield and northern parts of it, the Kazhdumi Formation with a total thickness merely under 140 meters consists of mainly organic rich slightly calcareous shales, which are considered as primary source rocks. Comparable thickness is measured in the deepest part of the basin. In the Persian Gulf, the Kazhdumi consists of predominantly shale, it is moderately to well indurated, pyritic and slightly calcareous to non-calcareous. The shales were deposited under moderately low energy conditions.

Kazhdumi Formation is assumed to have produced oil in the Foroozan, Hendijan and Nowrooz fields and oil and gas in the Soroosh and Bahregansar fields. Also the shale is a fair seal for important oil and gas accumulations in the Dorood, Foroozan, Soroosh, Nowrooz, Hendijan and Bahregansar fields of the northeastern Persian Gulf and for subordinate oil reserves in the southern Persian Gulf.

When Kazhdumi source rock contains favorable facies, it is in the peak oil expulsion phase in the deepest synclines during the peak time of folding, whereas it is not mature or early mature in the shallowest anticlines. It contributes to the major charge in oil to the Tertiary reservoirs. Ultimately, the Tertiary Pabdeh is a potential source rock only in the northern part of transect though it is immature in the anticlines and early mature in the deepest synclines.

Two potential source rock horizons have been identified in Soroosh oil field: the Kazhdumi terrestrial coaly section within the Burgan sequence and the algal sequence within the lower Ratawi Formation (Fahliyan). The organic petrological observations show that the Burgan (Kazhdumi) organic matter in Soroosh and Nowrooz oilfields in the Persian Gulf is basically terrestrial in origin from a coal measures part of the section without much lamalginite and

some of the samples show evidence of lacustrine environment. In contrast the Fahliyan (=lower Ratawi) are dominated by carbonate and contain abundant to major lamalginite and abundance of algal material and terrestrial influence are minor.

Another noteworthy source rock in the Middle Cretaceous of the Persian Gulf is Ahmadi Member. The Ahmadi Member of the Sarvak Formation, which is bituminous in the northern Persian Gulf and in Binak area, accumulated in front of the prograding wedge of the Wara Formation during the Late Cenomanian. In so far as oil generation is concerned, the significance of the Ahmadi Member is limited to the southern tip of the Dezful Embayment and to the northern part of the Persian Gulf (Bordenave and Hegre, 2005). According to Bordenave and Hegre (2005) locally, in the SE of Dezful Embayment and in the northern part of the Persian Gulf, some additional oil was expelled from the locally euxinic Ahmadi Member of the Sarvak Formation which supplemented that expelled from the Kazhdumi Formation (Bordenave and Hegre, 2005).

Source-Rock Richness and Organic Geochemistry

Prior to the development of good geochemical typing, the deeper marine facies in the Upper Cretaceous and Paleocene were argued by many petroleum geologists (e.g., Weeks, 1950) to be the source rocks for hydrocarbons in reservoirs of Cretaceous and Tertiary age. Moreover, it has always been considered by geologists working in southwest Iran that the Upper Cretaceous and Eocene marls, which include pyro-bituminous shales, were probably an important source group for oil found in the Asmari. Such a proposal was presented mainly based on proximity of the source and reservoir rocks. This can be regarded as significant only if primary oil migration over long distances at very low gradient is accepted (Falcon, 1957).

Two excellent source rocks are related to the Asmari and Bangestan reservoirs, which include the Kazhdumi of Albian, and the Middle Eocene Pabdeh Formation. Sargelu and Garau, are not associated with reservoirs, because they are limited above and below by basinal facies, either massive evaporites or thick marls and tight argillaceous limestone. Additionally, organically rich Garau potential source rocks are seldom associated with suitable traps and their contribution to the oil accumulated in the Dezful Embayment is limited to 1 or 2%. Thus, only the two source rocks, the Kazhdumi and the Pabdeh, are considered to play a vital role in the charge of the Dezful Embayment oil reserves (Bordenave, 2002). In Central and southern Dezful Embayment, very prolific thick mature Kazhdumi source rocks associated with excellent reservoirs, very large structures and the efficient Gachsaran cap rock, formed one of the most efficient petroleum systems, which could account for the accumulation of more than 95% of the onshore Iranian oil in place (Bordenave and Huc,1995).

In Fars region, the Kazhdumi Formation is generally less bituminous, and its source-rock potential is noticeably reduced because of the facies transition that occurs close to the boundary between Fars and Dezful Embayment. The results of the Rock-Eval show the TOC in this region is close to zero and the organic matter has been completely oxidized (Ashkan, 2002). Based on the available information (Ashkan, 2002) the majority of the organic matter is of marine origin or kerogen typeII with presence of minor amount of kerogen type III.

All the available geochemical data point to the Kazhdumi Formation as the dominant source rock for the accumulations found in the main fields (Ala et al., 1980). The best evidence is the similarity between the chromatograms of the saturated alkane components and those of the corresponding fractions in crude oils. The TOC of the Kazhdumi Formation in this area is on average 2.5% and it is enriched in organic matter. The oil-prone Kazhdumi often shows excellent pyrolysis yields (S_2 Rock-Eval yields) averaging 22.2 mg hydrocarbons/g rock and hydrogen indices greater than 600 mg hydrocarbon/g TOC.

Kazhdumi TOC values vary from 1 to 11% with average values in the 5% range in central part of the depression. The potential S_2 may reach 50 to 60 g HC/kg rock and HI reaches values as high as 500 and rarely to 700 g HC/kg C. The Source Potential Index (SPI) may be in the excess of 25 tonnes/m^2 categorizing Kazhdumi Formation as one of the richest source rocks in the Persian Gulf region. The Kazhdumi organic matter contains up to 5 to 7% per weight of sulfur which explains the high sulfur content of the oil generated.

Alizadeh and Sepahvand (2001) have evaluated the source rock potential of the Kazhdumi Formation in the northern Persian Gulf area. Based on their investigation the TOC are close to the threshold value and range from 3-11%. The hydrogene index ranges from 300 to 450 mg hydrocarbon/g TOC.

Maturation, Generation, and Migration

Extensive geological investigations concerning the potential source rocks in southwestern Iran substantiates that the basal Tertiary potential source rocks are commonly immature and extracts from these rocks show small resemblance to the geochemistry of the Tertiary oil (see Ala et al., 1980).

Based on the available geological and geochemical data (Ala et al., 1980; Ala, 1982), it is indicated that one of the major sources of the oil in the Asmari reservoirs and the Bangestan Group in the oil fields of the southwestern Iran is the underlying the Kazhdumi Formation. Geological and geochemical data presented by Ala (1982) also clearly point to the Kazhdumi Formation as the source rocks for oil present in reservoirs in the Kirkuk Group in Iraq. The results of further geochemical investigation (Khosravi Said, 1987) confirmed that the Kazhdumi Formation was the major unit for the Bangestan Group

(Middle and Upper Cretaceous) and Asmari oil in the Dezful embayment of southeastern Iran.

Young et al. (1977) investigated the dating of oils based on maturation changes in specific hydrocarbon structures and applied this technique, among others, to some of the Middle East oils. They concluded that oils from four large Dezful Embayment fields has ages ranging from 102 to 109 m.y. which is close to the Albian Kazhdumi source, whereas the Lurestan Cheshmeh Khush oil was older than 120 m.y. (the Garau source rock or older level). The southern Persian Gulf oils studied by these authors were given ages of 146 to 174 m.y., consistent with the accepted Middle-Upper Jurassic sources.

The evolution of the Kazhdumi source rock depends on the following stratigraphic and tectonic events, which influenced its maturation, petroleum generation, and entrapment. At the end of the Asmari deposition (Late Oligocene-Early Miocene) thickness of the post-Kazhdumi sedimentary succession were greater than 1.5 km in the eastern part of the Persian Gulf. Assuming the typical geothermal gradient for the region, the temperatures at the end of the Asmari Formation appears to be slightly lower for the Kazhdumi Formation to have attained the onset of oil kitchen. However, the situation might have been different by the end of Gachsaran deposition where the overburden was much greater. In addition if a higher than normal geothermal gradient is assumed, especially in a basin with massive salt deposition, it might be highly probable for the Kazhdumi Formation to achieve the onset of oil window (Bordenave, 2002).

The rapid accumulation of 1.5 to 2 kilometers of the Gachsaran evaporites deposited in the northwestern and central parts of the Persian Gulf in the early Miocene might have resulted in the Kazhdumi source rock reaching at least marginal maturity over most of the Persian Gulf area. It is noteworthy that according to Weeks (1957), major oil migration from basin to reservoir may have awaited deposition of substantial thickness of overburden upon the source sediments, and so that major incursion of oil from the basin may have occurred after the deposition of the Lower Gachsaran seal.

Overburden on the Kazhdumi source rock increased very rapidly during the Agha Jari depositional times, resulting almost everywhere, in maturity level sufficient for oil to be generated in northern Persian Gulf. At the time of Agha Jari deposition, Kazhdumi overburden might be well over 4 kilometers where the hydrocarbon generated (Bordenave, 2002).

Modeling of the thermal evolution of the Kazhdumi and the Pabdeh source rocks was carried out in order to determine the onset of the oil expulsion. A value of $36 mW/m^2$ was chosen as it gives a best fit between the observed and the calculated values of the thermal indicators such as the vitrinite reflectance, the Rock-Eval T_{max} and the Hydrogen Index. The onset of oil expulsion was assumed to happen for a 30% oil saturation of the source rock pore space. It means that the onset of oil expulsion was reached earlier for rich source rocks (Bordenave, 2003).

The thickness of the eroded sediments is one of the significant points. The onset of oil expulsion from the Kazhdumi seems to have reached, when its base was buried to 3.9 to 5 km between 16 and 1Ma depending on the localities. Thus, the hydrocarbon expulsion in northern region of the Persian Gulf might have commenced later than 8Ma, i.e., after the beginning of the Zagros folding. It is likely that the fracturing of the Sarvak to Asmari interval in the anticlinal part of the high-relief structures facilitated the oil expulsion and its upward migration to the first cap rock encountered, the Gachsaran Formation. The main contributor, the Kazhdumi Formation, would have generated some 95% of the oil generated in Zagros Foothills (Bordenave, 2003).

Apatite Fission Track Analysis and Vitrinite Reflection, (AFTA and VR) data in the Soroosh field are interpreted by Duddy (2004) in terms of the entire drilled sections of Quaternary to Cretaceous/Jurassic age being at maximum post-depositional temperatures, and maximum burial, at the present-day. The thermal history presented by Duddy (2004) shows that any hydrocarbon source rocks at the Soroosh field are actively generating hydrocarbons at the present-day. Heat flow model predicts that any Kazhdumi (Burgan) source rocks are immature or just early mature for oil (VR=0.5%) at the present day.

In contrast the AFTA and VR data obtained form the Nowrooz field are interpreted in terms of a single Paleothermal episode, with the majority of the drilled section undergoing significant cooling that began at some time in the last 15 Ma, most likely between ~5 and 1 Ma (Pliocene-Quaternary), due to uplift and erosion of ~1250m of previously deposited Agha Jari-Bakhtiari Formation. It follows that active source rock maturation at Nowrooz also ceased at this time (Duddy, 2004).

The thermal history reconstructions also imply that the Kazhdumi-source (TypeIII kerogen) oil is not likely to make a significant contribution to the reservoired oils in the Soroosh and Nowrooz Fields, although some input is possible at Nowrooz from migration from potential Kazhdumi source rocks in a kitchen typified by Hendijan-1 well location.

Speculative modeling of Hendijan-1 well, down dip from Nowrooz field in the Persian Gulf, does allow some hydrocarbons to be generated from the Kazhdumi sequence at that location, and this might be available for migration to Nowrooz field (Duddy, 2004).

Further, modeling of the thermal maturity of Kazhdumi Formation conducted by Peymani (2003) showed that both top and bottom of Kazhdumi Formation are in oil generation window in northwestern areas of the Persian Gulf. Additionally, the Kazhdumi Formation is at the end of oil generation window in vicinity of the Hormuz Strait whereas the Kazhdumi Formation is completely immature in the central parts of the Persian Gulf. These are because of increasing burial depth and thickness of formation toward northwest and east. Changes of burial depth, temperature, vitrinite reflectance and level of organic maturity are in accordance with increasing burial depths toward northwest and east (Figure 4-11).

The Kazhdumi Formation reached oil generation window about at Early Eocene in the northwest of Persian Gulf and about Early Paleocene in the eastern Persian Gulf region. In the NW of Persian Gulf, it reached the oil generation window in Binak-4 well about 55 Ma, H-1 well about 45 Ma and Tanb-1 well about 35 Ma. In eastern region of the Persian Gulf, Kazhdumi Formation reached oil generation window in HEE-1 well about 63Ma and in Gevarzin-1 and Hulur-1 wells about 55 Ma, Qeshm-4 well about 50 Ma, and SIE-2 Well about 43 Ma respectively. Also, in HA-1 well it reached oil generation window about 64 Ma and since 37 Ma to present time it has been in wet gas generation window.

Thus, Kazhdumi can be regarded as a source rock in the Persian Gulf provided that it is rich in organic matter (TOC) with improved quality (kerogen type) organic matter (Peimani, 2003). A preliminary evaluation shows that Burgan (equivalent to Kazhdumi Formation) is early mature (Abdullah and Kinghorn, 1996).

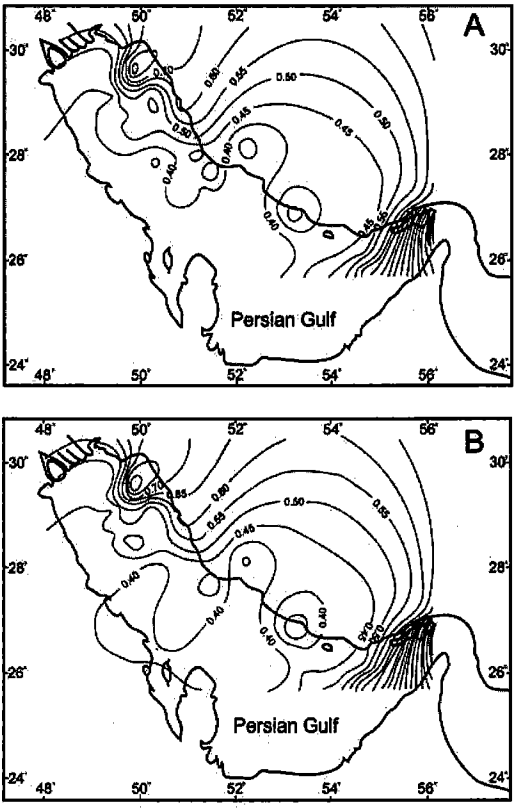


Figure 4-11. Iso-Reflectance maps for the top (A) and basal (B) Kazhdumi Formation in Persian Gulf (Cited from Peimani, 2003).

The measured corrected borehole temperatures in the Safaniya member in the Persian Gulf area is about 68°C at a depth of about 1700 meters. In view

of the burial history of the region, the maximum burial temperature for the Safaniya sequence was probably no more than 75°C. This is in agreement with the source-rock maturity studies which indicate that the thermal maturity of all the Mid-Cretaceous succession in southwestern Persian Gulf is too low for the oil generation (Ayers et al., 1982). To the northwestern Persian Gulf in Saudi Arabia, however, the basinal equivalent of the Kazhdumi Formation is an important source rock in the region (Ala et al., 1980), probably provided the oil for the Middle Cretaceous clastic reservoirs (Safaniya sandstones) in Saudi Arabia (Ayers et al., 1982).

Modeling showed that Kazhdumi and Pabdeh reached the onset of oil expulsion, 1 to 10 Ma, after the commencement of the Zagros folding. Therefore, migrations took place almost vertically and were facilitated by intense fracturing in high-relief anticlines. The distribution of source rocks, thickness, characteristics, and maturity were used to forecast if an undrilled structure is expected to be oil, gas or water-bearing, and what would be the order of magnitude of the oil-in-place (Bordenave, 2003).

As the oil expulsion from the source rocks happened when the Zagros folds were already individualized, oil migrated almost vertically to the reservoirs of the neighboring structures. Hydrocarbons appear to have migrated vertically from the Kazhdumi source rocks into the Sarvak and the Asmari reservoirs.

Results of the geochemical investigation by Khosravi Said (1987) not only confirms Kazhdumi Formation as a major source rock in Dezful Embayment but also indicates hydrocarbon generation and migration as being contemporaneous with the Zagros orogeny.

Middle Cretaceous Shilaif-Khatiya

The argillaceous basinal facies of the middle Cretaceous Shilaif (Khatiyah) Formation which was deposited under anoxic basinal conditions contains sediments that include highly bituminous, pelagic, shaly lime mudstone-wackestone and *Pithonela* limestones. It is primarily organic-rich limestone containing Types I and II, and is proposed to be the source rock for Upper Sarvak reservoirs (Videtich et al., 1988). Burchette (1994) has suggested that the source for oil reservoired in the Upper Cretaceous is the time-equivalent Shilaif (or Khatiyah) Formation. Timing of maturation of this stratigraphic interval is variable, depending on its position with respect to the Oman foredeep.

O'Connor and Patton (1986) state that the source for Mishrif/Mauddud oils which are time equivalent to the Upper Sarvak Formation in the southern Persian Gulf and Oman may be the adjacent Khatiyah Formation. Thus, the source for oil accumulated in the Mishrif Formation is the time-equivalent of Shilaif (or Khatiyah) Formation. Primary reservoirs are bioclastic shoal build-ups of the middle Cretaceous Mishrif Formation.

The Khatiyah Formation is the most probable source rock for the hydrocarbons accumulated in the Upper Sarvak rocks accumulated in the Sirri area, but in the Hengam area Kazhdumi Formation mainly present. Khatiyah is a mature oil-prone source rock and the source for the hydrocarbon trapped in the Upper Sarvak. The Shilaif Formation is interpreted to have accumulated in a euxinic depression where conditions favored preservation of abundant organic materials.

The Shilaif Formation has TOC values ranging from 1 to 6% and at some intervals may reach up to 15%; pyrolysis results confirm that the formation has a good to excellent source rock potential (Hassan and Azer, 1985). Vitrinite reflectance values range from 0.21 to 0.53% showing that the formation is immature or at best marginally-mature, while in some areas in the southern Persian Gulf is just approaching maturity (Hassan and Azer, 1985).

Timing of maturation of this stratigraphic interval is variable. In western Emirates and southwestern Persian Gulf, Shilaif, although still a potentially excellent source rock, is mostly immature (Newell and Hennington, 1983). In the southern Persian Gulf, however, source maturation, migration, and trap charging, as determined by fluid inclusion studies carried out by Videtich et al. (1988), was initiated in the Oligocene to Miocene and may continue today. The present-day maturity of the Middle Cretaceous Shilaif-Khatiyah Formation (equivalent to Sarvak Formation) in the southern Persian Gulf is shown in Figure 4-12.

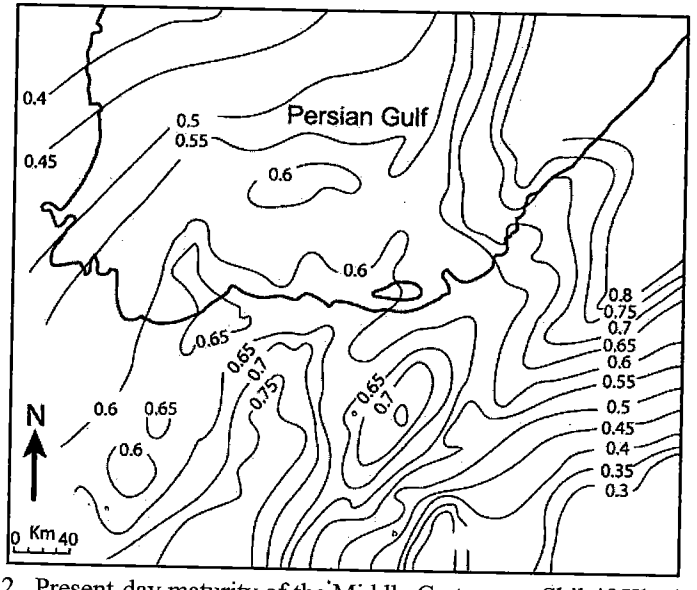


Figure 4-12. Present-day maturity of the Middle Cretaceous Shilaif-Khatiyah source rocks (equivalent to Sarvak Formation) in the UAE based on vitrinite reflectance (R_o). (Modified from ADNOC Staff; Lutfi and El-Bishlawy, 1986).

According to the previous figure, there is an increase in maturity from the Persian Gulf to the south, most of the offshore area is immature or has just reached the oil-generation threshold. Maturity decreases towards the Qatar-Gavbandi Arch so the mentioned formation is immature in the central regions of the Persian Gulf. On the other hand, maturity of this formation increases towards Hormuz Strait and as a result Shilaif Formation is at the peak of oil generation near this region.

The sedimentological and geochemical studies demonstrated that Khatiyah basinal deposits are likely source rock for the hydrocarbons found in younger Middle Sarvak reservoir rocks seen in the Sirri area, but in the Hengam area Kazhdumi Formation mainly acts as an active source rock. Geochemical data indicate that the Khatiyah is a mature oil-prone source rock and the source for the hydrocarbon trapped in the Upper Sarvak (Hedayati, 2003). The Khatiya limestone were deposited in an intra-shelf basin, in which euxinic conditions favored preservation of organic matter, and do make a significant contribution to oil in the Upper Sarvak reservoir.

Gurpi Formation Source Potential

Local dysoxic conditions occurred in northern Persian Gulf region during Campanian to Maaestrichtian with the deposition of marginal source rocks of the Gurpi Formation. The Gurpi marls of Campanian to Maaestrichtian age are transgressed on the limestones of the Bangestan Group. These marls generally have a low organic content (0.5-1.5%) except in two areas of higher subsidence in northern Persian Gulf (i.e., Fars region) and the northeastern Dezful Embayment area. From the distribution and thicknesses of organic layers in the Gurpi Formation, it can be concluded that their source contributions to the main oil fields of the Persian Gulf region and northern areas would be very limited (Bordenave and Burwood, 1990).

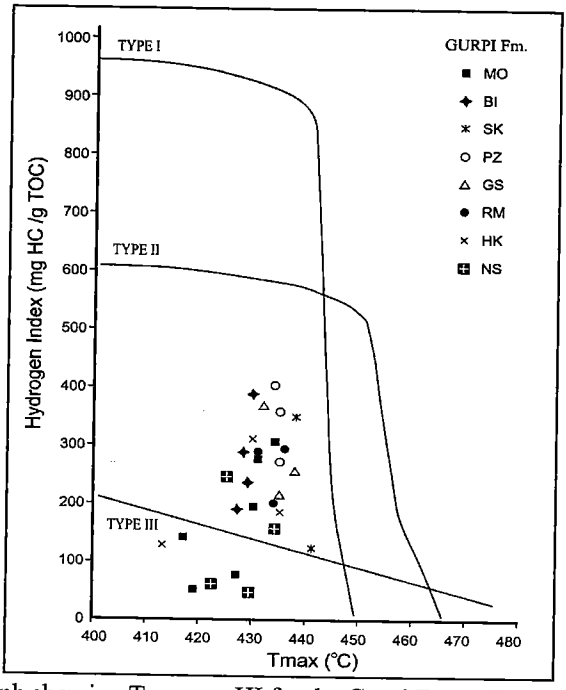


Figure 4-13. Graph showing Tmax vs. HI for the Gurpi Formation based on the Rock-Eval results (cited from Ashkan, 2002 figure5-21).

Gurpi Formation generally exhibits low TOC values (less than 1%) except in Ramin #4 well that reaches 2.5%. The average TOC values of the Gurpi Formation in Sirri and Salman oil fields in the Persian Gulf waters are 0.68 and 0.56% respectively. The S_2 value may reach 10 to 20 g HC/kg rock and HI reaches values as high as 410 g HC/kg C (Ashkan, 2002 see Figure 4-13). The hydrogen index range is between 50 and 400 mg hydrocarbon/g TOC. The Gurpi Formation also contains mainly Type II organic matter with minor amount of kerogen TypeIII.

Based on the Tmax and Hydrogen index, two groups of samples from Gurpi Formation have been identified (Ashkan, 2002). The first group have organic matter which is immature (T_{max} of 410 to 430°C, and Hydrogen Index varying from 40 to 150 (g HC/kg C) and the second group which are very close to the coastal regions of the Persian Gulf with medium to good hydrocarbon potential (T_{max} of 425°C to 440°C, and Hydrogen Index varying from 180 to 410 (g HC/kg C). It appears that the samples analyzed by Rabbani and Babaii (2004) from the Salman and Sirri fields fall within these two domain with T_{max} of 416 and 432°C and Hydrogen Index varying from 156 to 159 g HC/kg C.

As already stated the Gurpi marl generally has low TOCs, except in two areas in northern Fars and the northeastern Dezful Embayment. TOC curves (see Ashkan, 2002) show that these values are less than 1% and when the S_1

and S_2 are compared, it could be concluded that the Gurpi samples do not contain pristane and there is a possibility of oil and hydrocarbon contamination (Ashkan, 2002).

Therefore, even with its greater thickness (100 meters), its source contribution is probably small. Samples that have been analyzed by Ashkan (2002) appear to be immature. Fracturing limits the seal efficiency of this formation, allowing partial communication of the underlying Albian-Campanian Bangestan reservoirs and also with the Oligo-Miocene Asmari reservoir.

Modeling of the thermal maturity of Gurpi Formation (Peimani, 2003) has been presented in figure 4-14. According to this figure, the top and bottom of Gurpi Formation is respectively at the beginning and the end of oil generation window in the vicinity of Hormuz Strait. This is due to the increasing burial depth and thickness of the formation toward eastern Persian Gulf. Although maturity increases toward northwest of Persian Gulf, Gurpi Formation is still immature in this part of the Persian Gulf. The Gurpi Formation which changes to the Fiqa Formation in southern Persian Gulf is immature over most of the area. Changes of burial depth, temperature, vitrinite reflectance and degree of maturity are in accord with increasing burial depth toward northwest and east of the Persian Gulf.

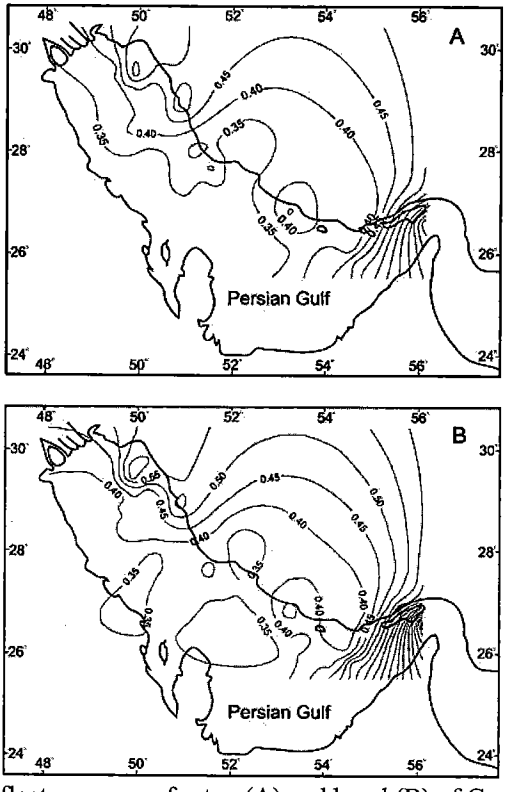


Figure 4-14. Iso-reflectance maps for top (A) and basal (B) of Gurpi Formation in the Persian Gulf (cited from Peimani, 2003)

The Gurpi Formation appears to have arrived at oil generation window at approximately Late Paleocene. However, the Gurpi Formation could not be taken into account as an effective source rock in most of the Persian Gulf since it is thermally immature.

The Gurpi Formation reached oil generation window in HA-1 and HEE-1 wells about 62 Ma, Gevarzin-1 well about 45 Ma and in Hulur-1 and Qeshm-4 wells about 40Ma. This finding is in line with Rock-Eval analysis performed by Ashkan (2002) indicating that the Gurpi Formation is not a very suitable source rock and the TOC of the formation is also low. Also this formation has not reached the maturity stage and there is no geochemical correlation between the oils and the Gurpi Formation. As a result the Gurpi Formation has not been considered as a source rock.

To sum up, it is still true that the majority of the Persian Gulf conventional and heavy oils were generated from Jurassic or Cretaceous source rocks, with the remainder mostly from the Tertiary and Silurian periods of the Paleozoic. These were also the periods of highest TOC deposition and incorporation of organics into the sediments. This does not mean that other periods produced no hydrocarbon. The non-uniformity does show, however, that not all time periods were equivalent in deposition of such rocks, just as not all rocks are equivalent in generating oil.

PALEOCENE-EOCENE

Even though Tertiary sequence may be thick, apart from the local development in the Pabdeh Formation sediments and the deepwater Paleocene limestone, the source rock potential is low. The rich giant fields in Iraq and Iran are sourced by Mesozoic rocks with oil which migrated along faults into folded, fractured reservoir rocks sealed by shale and evaporite units.

Geochemical investigation has suggested that source potential in those levels is not widespread and that they are generally immature. The best recognized exception is the Paleogene pelagic marls of the Pabdeh Formation in northern Dezful Embayment area, which have been shown to have sourced geochemically characteristic oil (Bordenave and Burwood, 1990); they seem to contribute to some of the hydrocarbon accumulation regionally including the Persian Gulf.

Pabdeh Formation

Although the principal sources of the Persian Gulf petroleum accumulations are Jurassic to Cretaceous in age, there is some evidence indicating that the Paleocene to Early Oligocene Pabdeh Formation is locally source-prone (Ala et al., 1980; Bordenave and Burwood, 1990). According to Ashkan (2002) after Kazhdumi Formation, the Pabdeh Formation can be considered as one of the best available source rocks in northern Persian Gulf region.

The last anoxic episode in the Persian Gulf sedimentary regime led to the deposition of the excellent potential source rock sequence of the Pabdeh Formation, which developed throughout northwest Lurestan, Dezful Embayment area and northern Fars region during the Middle to Late Eocene and locally in early Oligocene (Bordenave and Burwood, 1990). The Pabdeh Formation is enriched in marine organic matter type-II which is linked with the continental organic matter including *Oleanane* biomarker.

Source Rock Richness

Rock-Eval analysis performed on the Pabdeh Formation proves excellent source rock potential for the formation in the Zagros basin and has reached optimum maturation in Dezful Embayment where subsequent hydrocarbon generation and migration charged Asmari reservoirs (Ashkan, 2002; Bordenave and Burwood, 1995). The presence of the *Oleanan* biomarker and their excellent correlation with Pabdeh Formation further substantiate such an assessment (Ashkan, 2002).

Argillaceous sedimentation continued through Paleocene and Eocene time in the Dezful Embayment area and northern Persian Gulf, and until the end of the Oligocene. A well-defined and undivided northwest-southeast trending depression, parallel to the Zagros Suture, extended from Fars to Lurestan, during the Paleocene-Eocene and even Oligocene in Lurestan with dominant anoxic conditions (Figure 4-5). This anoxic basin was bordered to the southeast by platform carbonates covering most of the Persian Gulf. To the southeast, the depression was limited by the Fars Platform, where the shallow water carbonates of the Jahrum Formation surrounded a subsiding sabkha (Sachun Formation). A monotonous and thick (200 to 1000 meters) sequence of grey marls, containing a rich planktonic fauna of Globorotalia and Globigerina were deposited.

Euxinic conditions prevailed in the central part of the depression during Middle to Late Eocene and even Early Oligocene. Approximately, 150 to 200 meters of organic-rich marls contain up to 11.5% organic carbon, the average TOC values varying from 3% in Fars to 7.5% in Lurestan. The organic matter is mostly algal (Tasmanacea), with Hydrogen Index up to 500/650 g HC/kg C, however terrestrial influences are visible in the vicinity of the NE shoreline. According to Ashkan (2002), the type of kerogen in Pabdeh Formation can be considered as a mixture of marine and terrestrial with their percentages varying in different parts of the Zagros Basin (Bordenave, 2003).

In most bituminous samples, TOC values are between 3 and 4%, but reach as high as 5.5% in northern Fars region to as much as 11.5% in southwestern Lurestan. The kerogen is primarily of algal origin with only limited terrestrial organic matter. Geochemical analysis shows that the rocks still contain considerable quantities of convertible, light-colored kerogen and, hence, are relatively immature in the Dezful Embayment and Lurestan. Only in the north-

eastern part of the Dezful Embayment has there been a good deal hydrocarbon generation (Bordenave, 2003).

The Pabdeh Formation and its stratigraphic time equivalents, the Rus and Umm Er Rhadhuma, have been encountered in the southern Persian Gulf particularly in the Ras Al Khaimah area. In some wells, the formation is highly sapropelic, being at early to middle stages of maturity, suggestive of an extremely rich source rock.

One of the most interesting points to note is that the main oil fields area corresponds almost closely to the depression where the Kazhdumi source rocks were deposited. Moreover, oil-to-oil and oil-to-source rocks correlations, based upon carbon and sulfur isotopes and biomarkers composition, have shown that most of the oil accumulated in the main fields in the Asmari and Sarvak reservoirs is originated from the Kazhdumi, while only the oil of the northern Persian Gulf and NE Dezful fields received most of their oils from the Pabdeh (Ashkan, 2002; Bordenave and Burwood, 1990; 1995).

Based on the data presented by Khosravi Said (1987) in Lurestan and in northeastern Dezful, hydrocarbons were sourced from Garau and from the Pabdeh and Gurpi Formations, respectively.

Maturation, Generation, and Expulsion of Pabdeh

Thermal maturity of Pabdeh Formation in eastern parts of the Persian Gulf is presented in Figure 4-15. According to these figures, top of the Pabdeh Formation is immature (R_o<0.60) in the entire Persian Gulf region while lower part is in oil generation window in the eastern section and close to the Strait of Hormuz. This is due to the increasing burial depths and immense thickness of the Pabdeh Formation towards the eastern part of the Persian Gulf. Sediments in the center of the Persian Gulf (around the Qatar-Gavbandi Arch) have lower depth of burial compared to rest of the Persian Gulf with maximum burial, i.e., one kilometer near the Hormuz Strait. Increasing depth of burial, temperature and level of maturity, vitrinite reflectance is more prominent toward northwest and east of the Persian Gulf.

The basal Pabdeh Formation reached oil generation window in HA-1 and HEE-1 wells about 57 Ma, and in Gevarzin-1 and Hulur-1 wells about 10 Ma. Thus, basal Pabdeh Formation reached oil generation window at about Early Eocene. As a result, Pabdeh Formation can not be considered as an effective source rock in most parts of the Persian Gulf region because it is thermally immature. However, the Pabdeh Formation can still be a good candidate as being a good source rock for oil generation in the vicinity of Hormuz Strait if the formation holds good quantity (TOC) and quality (kerogen type) of organic matter.

In northern Persian Gulf and Fars area, the Pabdeh Formation is immature. Likewise, based on the maturity modeling in Lavan #1 well near Bushehr performed by Piemani (2003) the Pabdeh Formation is outside of the oil window

and the source rocks are all immature. As a result, the Pabdeh Formation could not be an effective source rock in the Persian Gulf because it is thermally immature.

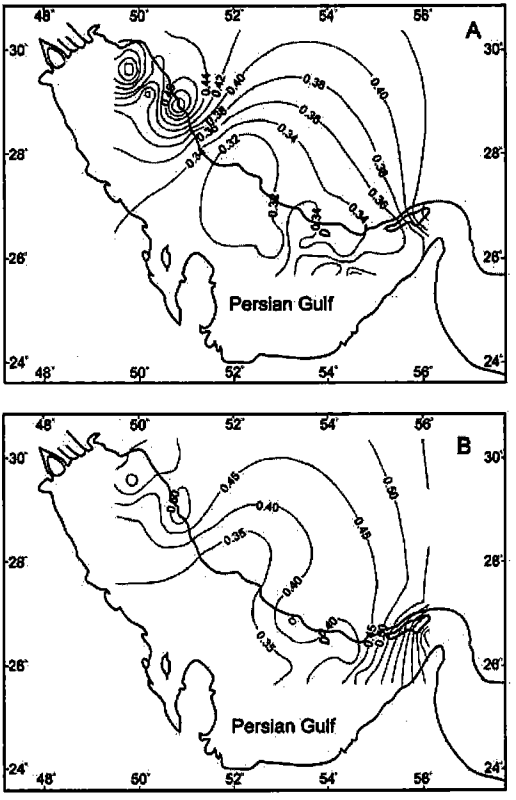


Figure 4-15. Iso-reflectance maps of top (A) of and basal (B) of the Pabdeh Formation in the Persian Gulf region (cited from Peimani, 2003)

Oil Generation, Maturation and Migration in the Persian Gulf

According to estimated reflectance values, basal Jurassic and Cretaceous sedimentary sequences reached their early stages of petroleum maturation (R_o=0.5%) by the end of Cretaceous in some of the areas in the Persian Gulf region.

Based on Kaman-Kaye's (1970) regional isopach maps and Waples (1980) method of estimating vitrinite reflectance, Sail and Magara (1985) constructed regional maps of hydrocarbon generation zones. Figure 4-16 shows such a map for the basal Jurassic Formations, superimposed on oil field distribution map of the Jurassic reservoirs.

A similar composite map was constructed for the Cretaceous formations and is presented in Figure 4-17. Such maps show excellent matches between the estimated oil-generation zones and the oil field distributions, except that

virtually no oil fields were discovered in the area north of the Qatar peninsula. This is a northern extension of the Qatar-Gavbandi Arch where sedimentation rate was relatively slow. This is in agreement with the results of the data presented here for the Cretaceous sequences which are immature in the area of shallow depth of burial. Thus, without source maturity, no hydrocarbon could be generated meaning that no commercial accumulations take place and are possible even if all the other elements and processes of reservoir trap and seal are present.

Figure 4-18 shows a similar composite map of the hydrocarbon generation and oil-field distribution for the Tertiary formations. In this case, there is a significant mismatch because most oils in the Tertiary reservoirs were derived from the older source rocks (Young et al., 1977).

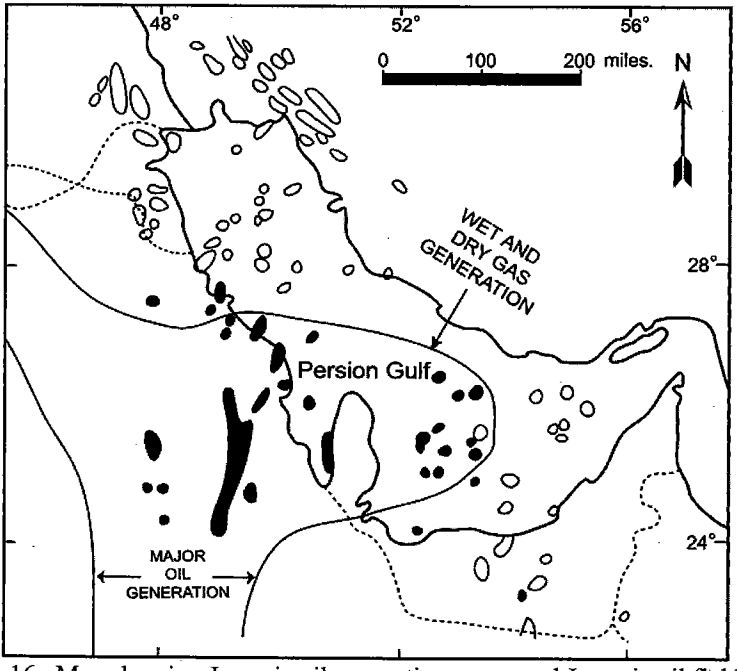


Figure 4-16. Map showing Jurassic oil generation zones and Jurassic oil fields (solid areas). Open areas show oil fields of other geologic ages (cited from Magara, 1986).

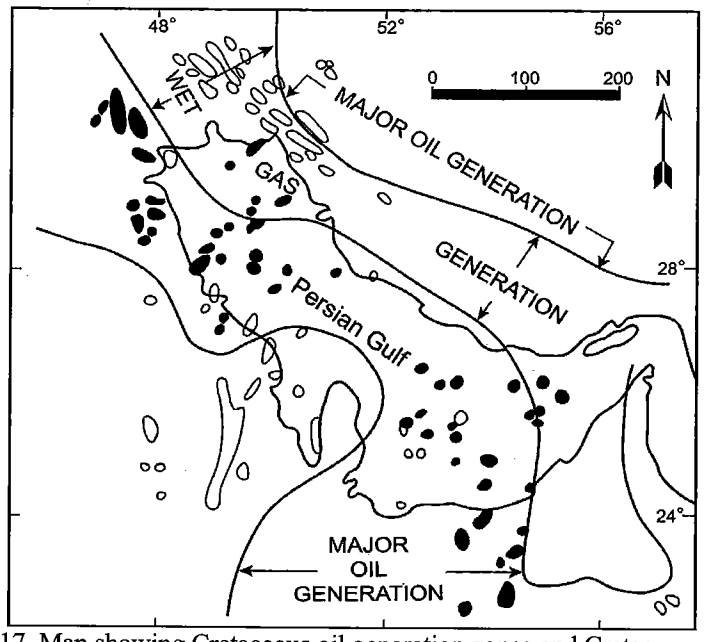


Figure 4-17. Map showing Cretaceous oil generation zones and Cretaceous oil fields (solid areas. Open areas show oil fields of other geologic ages (Cited from Magara, 1986).

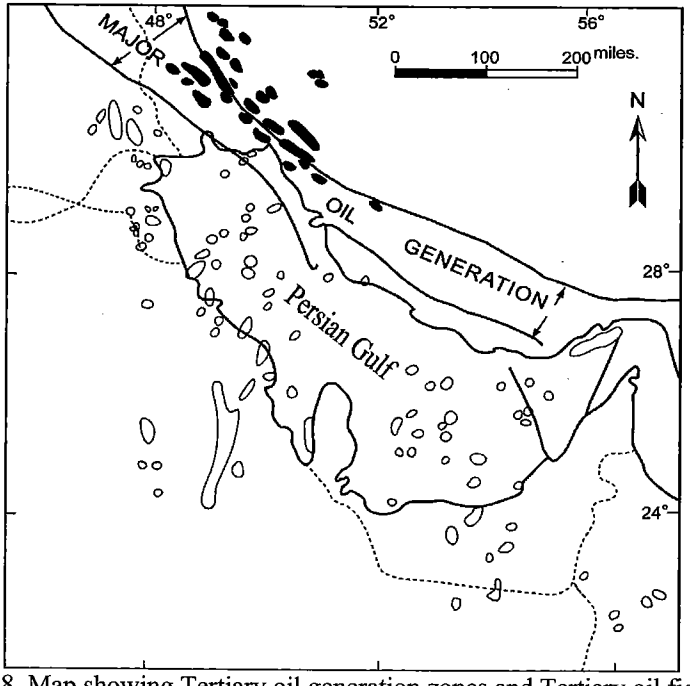


Figure 4-18. Map showing Tertiary oil generation zones and Tertiary oil fields (solid areas). Open areas show oil fields of other geologic ages (cited from Magara, 1986).

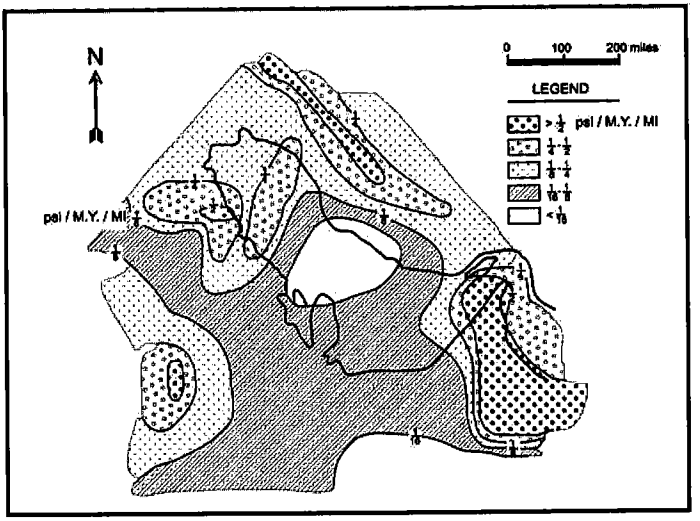


Figure- 4-19 Contour showing horizontal change of excess fluid pressure increase (psi/MY/mile) for Cretaceous (cited from Magara, 1986).

In fact some reservoir sections are missing due to both erosion and non-deposition. The lack of oil fields in this region of the Persian Gulf may be at least partially attributed to this reason. However, there are also some porous sections of both the Jurassic and Cretaceous ages which are water-saturated (Schlumberger, 1981). Relatively weak horizontal fluid movement as shown in figure 4-19 may be a reason for the relative scarcity of oil fields in this area.

Long Distance Oil Migration in the Persian Gulf

One of the main problems concerning the Cretaceous sequences as being source rock for hydrocarbon is that they might not have reached the maturity stages and are immature in the areas of shallow depth of burial. As a consequence, without reaching maturity, generation of hydrocarbon could have taken place and no commercial accumulations would be expected even if all the other requirements are present. Such a scenario might be indeed the case in some of the areas which has undergone preliminary exploration activity in the Persian Gulf.

In order to explain the presence of hydrocarbon trapped in some of the structures without the presence of suitable source rock in their proximity it would be possible to advocate long distance migration as prime mechanism to explain occurrences of the hydrocarbons.

The horizontal scale of the basin is extraordinary, whereas the vertical dimensions are rather average; the horizontal dimensions are greater than in most basins. The pre-erosional Mesozoic depositional platform was 2000 to 3000 kilometers wide and at least twice as long. Differentiation was minimal

and source rocks, reservoirs, and seals have consequently a very wide extent. Because of the wide extent of the lithologic units, horizontal migration is very efficient and the large structures have a high degree of fill because they could drain very large kitchen area (Murris, 1980).

It appears that the depth of burial of source rocks for generation and expulsion of hydrocarbons was not achieved until the Alpine orogeny. At that time, burial depths in many localities were controlled by tectonic activity and thrusting and hence resulted in increase in the sedimentary cover adding to the original thickness.

The tectonic event, however, provided an abnormal and sudden overburden load onto relatively still shallowly buried earlier Cretaceous source rocks, accelerating their maturation (through deeper burial and hence higher temperature) and resulting in unquantifiable loss of oil to the surface in Late Cretaceous to Paleogene times. The evidence for it can be found in bitumen impregnation of Upper Cretaceous reefal limestones (ca. 70 Ma) and water-worn bitumen pebbles in some Paleocene-Lower Eocene conglomerates (65-50 Ma ago) along the Zagros, indicating that a large oil accumulation was undergoing dissipation at the time of deposition of these rocks (Beydoun et al., 1992). With the onset of the later collisional event of the Zagros orogeny, huge quantities of sedimentary bitumen spread over large areas of the northwestern Persian Gulf.

It should be pointed out that in the Zagros foothill structures, secondary migration played a more important role in the creation of the prolific Asmari reservoirs from the oil generated in the underlying Pabdeh and Gurpi source rocks by upward migration of oil and gas due to the Alpine Orogeny towards the end of the Pliocene and the formation of huge anticlines in the folded Zagros belt. However, in the high Zagros region, wherever the structures are broken down to the Asmari or the Bangestan and Khami the oil has been destroyed and the remnants are left as asphalt seen in the Asmari or the Bangestan and the Khami fractures.

Continuous subsidence and sedimentation from the end of Paleozoic to late Tertiary were responsible for deposition of more than 10 kilometers of sediments on the northern side of the Persian Gulf. Isopach maps of different geologic periods of the region show the thinnest sedimentary cover on the southern side of the Persian Gulf geosynclinorium. In addition the Cretaceous isopach map shows the least thickness in the area of Kangan. Epirogenic movements in association with salt diapirism persisted in the region from late Jurassic to early Cretaceous resulting in geologic structures and the rising of salt plugs. These structures with over 1000 meters thickness of the Permian Limestone and dolostone (Kangan/Dalan Formation) with the anhydride seal have resulted in the prolific accumulation of hydrocarbons.

To date, no commercial gas accumulations have been discovered on the northern side of the geosyclinorium. However, giant gas fields on the Iranian Platform in the area of Kangan, Persian Gulf and part of northern Arabia have

been discovered. This is attributed to the huge sedimentary thickness and the resultant overburden pressure on the source rocks on the northern and south eastern side of the Persian Gulf geosynclinorium. The organic material was transformed into hydrocarbons and the excessive pressure pushed the generated oil to migrate into the then present paleogeographic high structures on the southern side.

In the case of gas, however, it migrated towards the Kangan high at the end of the Cretaceous to early Tertiary. This primary migration of hydrocarbons entered the porous limestones and sandstones. According to Dunnington (1967) the primary migration was responsible for filling all the available pore spaces of the reservoir rocks by the hydrocarbons before compaction and has preserved the primary porosity. Consequently, this primary porosity has withstood later digenesis and pressures from the overlaying sedimentary cover. This is one of the reasons for the creation of giant oil fields due to the primary migration.

Primary migration plays a very important part in the formation of giant oil and gas reserves. If the primary migration in the formation of giant oil and gas fields is accepted the subject of source rock (in the region of the Persian Gulf and especially the Arabian Peninsula) can be resolved which has been named in books and periodicals as the extraordinary geological from the presence of mainly continental and evaporitic deposits on the Arabian Peninsula and the large scale shaly and limy favorable source rocks on the northern sides of the geosynclinorium. Likewise, Kazhdumi, Gadvan and Garau shales and marls can be the source rocks for the Burgan sandstone, the Bangestan and the Khami formations respectively.

CONCLUDING REMARKS

In summary in can be stated that generally the probable source rocks in the offshore in the Persian Gulf are Pabdeh, Gurpi, Kazhdumi, Dariyan, Gadvan, Garau, Surmeh, Kangan and Sarchahan Formations. Among these Formations, the most prolific source rocks are the shales of the Kazhdumi Formation (Albian) and Jurassic Surmeh Formation in the Persian Gulf region. The oils in the prolific Asmari Formation and in the Cretaceous Bangestan limestone reservoirs have been correlated positively with extract from these shales.

Burial history reconstruction and thermal modeling indicated that sediments in the central part of the Persian Gulf and around the Qatar-Gavbandi Arch, have lower depth of burial compared to northwest and east region and depth of burial is maximum in the vicinity of the Hormuz Strait. For this reason, maturity of formations increases toward northwest and east of Persian Gulf. Changes of burial depth, temperature and degree of maturity were in good agreement with increasing burial depth, temperature and vitrinite reflectance toward northwest and east of the Persian Gulf.

The main Lower Cretaceous source horizons reached thermal maturity (burial depth of 1.4 kilometer) in the Eocene (Powers et al., 1966) but oil migration did not take place until after deposition of the Asmari limestone in Miocene times with the normal lag between generation and migration extended by the tight nature of the carbonates. It has therefore been suggested that it is not necessary to propose early storage of hydrocarbons in pre-Miocene traps with the formation of later traps in the Asmari limestone breaching these older structures. This suggestion argues that the most important phase of entry of oil in the Asmari reservoirs is geologically recent and postdates the initiation of the Zagros orogeny. To date, sufficient closure to accommodate the vast volumes of oil in the Asmari field have not been developed. However, there is evidence that earlier structures with an element of stratigraphic traps may have been present.

Syndepositional highs, especially subdued buried hills appears to have developed throughout much of the region of both the Zagros and the stable Arabian shelf, in areas which were later the sites of large structures (e.g., Masjid-e-Sulayman in Zagros, Ghawar, Burgan and Dukhan in the southern Persian Gulf region on the Arabian Shelf).

These source rocks which are not extraordinarily thick in the Persian Gulf region are all of marine origin. Because they were deposited over the entire Arabian platform at several levels and occasionally are thicker in the Cretaceous intrashelf basins, lateral migration was rarely a problem. A range of the marine environments in which organic rich source rocks are developed occurred during this time interval in the Persian Gulf region.

Considering the existence of high potential for petroleum in the Persian Gulf, it is a vital task to continue the exploration activities for discovery of new oil and gas fields in this region. The identification and detailed investigation of the source rocks within the stratigraphic succession as one of the primary steps of petroleum exploration is of great importance.

In summary, the Jurassic and Lower Cretaceous source rocks are currently within the oil generation window over much of the Persian Gulf region: it is apparently only over the north-south high of the Qatar-Gavbandi Arch that they are immature. The Middle Cretaceous is marginally mature over most of the Persian Gulf; in southwestern Iran however, the Kazhdumi Formation has reached peak generation and even the uppermost Cretaceous has locally generated oil.

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CHAPTER-5

RESERVOIR ROCKS IN PERSIAN GULF

INTRODUCTION

There is a wide stratigraphic range and a large variety of reservoirs in the Persian Gulf and neighboring region. These reservoir rocks range in age from the Middle Jurassic to the Oligo-Miocene. The simplified stratigraphy and petroleum system of the Persian Gulf is presented in Figure 5-1. Known giant gas reservoirs as old as Permian age also exist in the Persian Gulf district. The reservoirs are present in abundance and are widely distributed through the geologic sections with generally high porosities and permeabilities, enhanced by fracturing.

Considering the richest oil fields in the Persian Gulf region, carbonate rocks appear to have formed the overwhelming majority of reservoirs in the Zagros and the Persian Gulf oil fields. There is, however, some hydrocarbon production from sandstones and also from calcareous clastic tongues particularly, the Ahwaz Sandstone Member, within the Asmari Formation.

The carbonate reservoirs deposited before the main continental collision and the onset of the Zagros folding. As a result, the original fabric and reservoir characteristics and properties have been strongly modified by the later tectonism and appear to bear little relation to depositional facies.

One of the important points to note is that in the Persian Gulf region the maximum hydrocarbon abundance is in the Middle Cretaceous reservoirs (carbonate sequences and regressive sands) with the Upper Jurassic reservoirs coming a close second, followed by the Lower Cretaceous reservoirs. Proven reservoirs are widely developed in the Asmari Formation as well.

The vast oil reserves of the Persian Gulf region are mainly occurred in large structural (anticlines) traps in extensive porous and permeable limestone and more subordinately sandstones reservoirs with large drainage areas and under efficient seals. Although the whole volume of sediments present in the Persian Gulf synclinorium may not be a deciding factor in the great oil productivity, the reservoir volume may be of the utmost importance (Kamen-Kaye, 1970).

In general, reservoir pressures are high with abnormally high pressure zones being encountered at times. It is very rarely the case that reservoirs have to have their oil pumped to the surface because of the lack of pressure.

Oil and water (and free gas, if the oilfield is gas-saturated) are separated from each other by their different densities/buoyancies and their relative immiscibility into distinct zones with the denser fluid water at the bottom, oil in the middle and gas at the top and with sharp to diffused contacts between those zones.

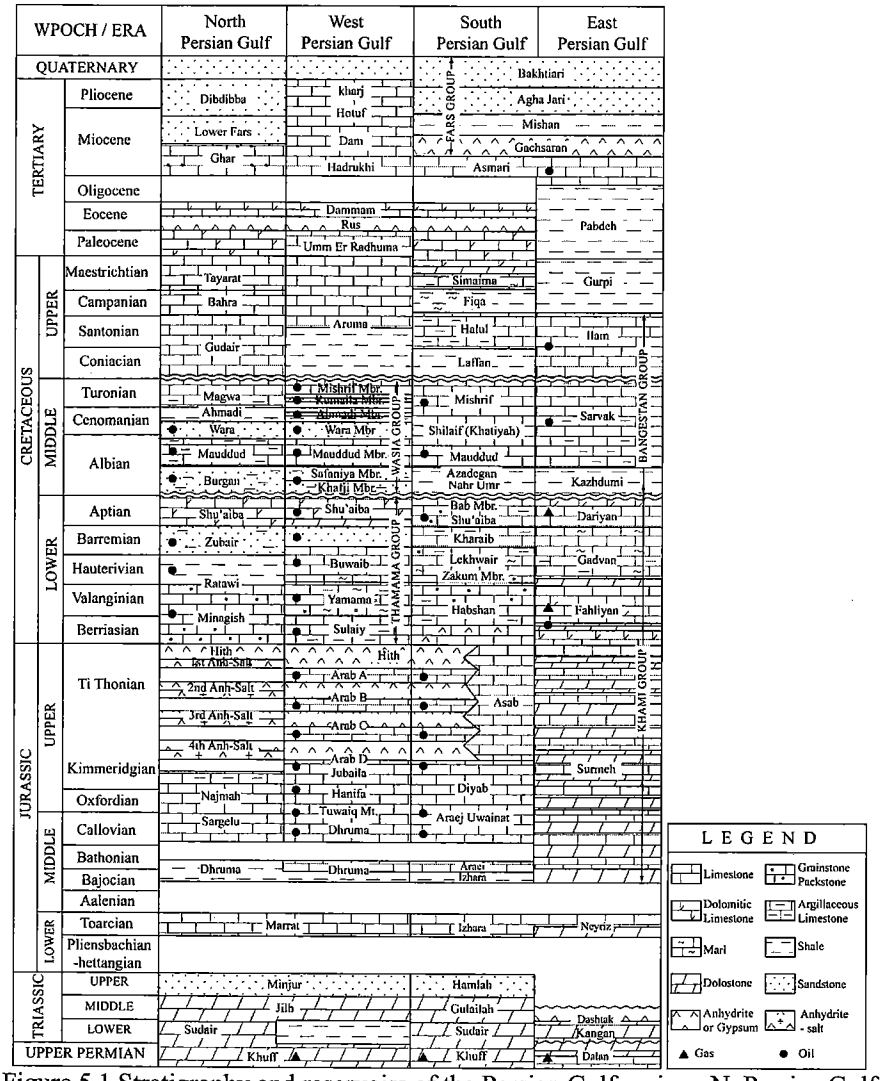

Figure 5.1 Stratigraphy and reservoirs of the Persian Gulf region. N. Persian Gulf corresponds to Kuwait and SE Iraq, W. Persian Gulf to Saudi Arabia, Bahrain, UAE and Qatar and East to Iran's offshore (modified from GeoArabia, 1998, v.3, p.438).

There are several important major plays in the Persian Gulf region. The first play is the Deh Ram Group which contains one of the world's richest gas-bearing sequences. The second play is the Jurassic platform carbonates of southern region of the Persian Gulf. The third play is the northern Persian Gulf mainly the Tertiary and Cretaceous fractured limestones. The fourth play is the Cretaceous regressive sandstone formation reservoirs around the head of the Persian Gulf, along with some deeper Jurassic and Cretaceous carbonate reservoirs. The fifth play is the rudistid mounds within Cretaceous carbonates

of the southern Persian Gulf. Iran's Sirri offshore fields are also part of this play (Pollustro, 1999).

PERSIAN GULF FRACTURED RESERVOIRS

Fractured petroleum reservoirs represent over 20% of the world's oil reserves. The natural fracture systems can have a striking impact on reservoir performance. They may act as highly permeable flow conduits or as baffles and seals. The complexity of the fracture network typically leads to an extremely heterogeneous and anisotropic permeability distribution within the reservoirs.

Production from the fractured hydrocarbon reservoirs has long been an oil industry target, but interest in this type of play has increased recently because of new concepts and technology, especially thanks to the horizontal drilling technology. Early petroleum exploration programs searched for fractured reservoirs from shale, tight sandstones, carbonates, or in anticline or fault traps, without particular attention to the source rocks.

Most of the Persian Gulf and also southwestern Iran's Cretaceous reservoirs are fractured and they frequently exhibit good primary porosity in the packstones and grainstone at the top of the regressive cycles. In fact, reservoir capacity and performance depend very strongly on fractures which are fold-related and understanding of the fracture distribution is the prime requirement of the production engineer (McQuillan, 1985). One of the excellent examples of productive hydrocarbon reservoirs includes the Asmari limestones.

In Iranian carbonate reservoirs such as Sarvak and Asmari in Persian Gulf, fractures play a major role in production. Although fractures have low porosity and their storage capacity are not considerable when compared to matrix, they provide the main path for production and high rates in fractured carbonates are due to high permeability of fractures.

Subsurface structures in the Persian Gulf which resulted from the salt movements and diapiric effect are also fractured and these fractures have also provided the route for the hydrocarbon movement and migration. Thus, the formation strength appears to dominate the stratigraphic distribution of potential reservoir rocks. In Salman field in the Iranian side of the Persian Gulf the fractures play important role reservoir enhancement.

An indication of the highly fractured nature of the Asmari carbonate reservoirs in the oil fields came at the turn of the century when oil was first discovered in Iran. Numerous 'gushers' were found and all the wells contained high production rates. By the year 1920, pressure measurements at Masjid-e-Sulayman field indicated that reservoir communication can only be explained by fracturing, an important observation that totally changed the field development strategy. Instead of drilling many closely-spaced wells, fewer, more widely spaced wells were put down. Without knowing it, the engineers were sowing the seeds of modern reservoir management.

Fractures are common in Lower Miocene carbonates in the Persian Gulf, particularly along the Zagros Fold Belt. In places where the carbonates have relatively low matrix porosity and permeability (e.g. the Asmari Limestone), fracturing has played a vital role in enhancing reservoir quality; variations in matrix porosity (e.g. moldic or intercrystalline) also influence production (McQuillan, 1985).

Rock fractures in the younger Asmari reservoirs also provide the route for fluid and pressure communication with the older and also deeper Cretaceous (Bangestan Group) rocks. This is one of the important reasons to explain why Cretaceous oils are found in the Asmari reservoir rocks. The fracture systems in many of these reservoirs are complex. However, recent study (Wibberley and Blanc, 2003) of a supergiant field, which lies further away from Zagros range, revealed an orderly fracture distribution. Most of the fracture occurrences are in the crestal portions of the carbonate layers and it is thought that the interlayered and highly porous reservoir sandstones have a dampening effect on the stresses in the anticline.

Fractures also play a significant role in both the porosity-permeability and migration pathways of Persian Gulf carbonate reservoirs. Fracture distribution in the folded carbonate reservoirs is controlled by tectonic evolution and also mechanical properties of layers (Wibberley and Blanc, 2003). The majority of the fractures are of tectonic origin. As would be expected, tectonic fractures are congregated along the crest and their orientations are either parallel or perpendicular to the axis. There is a systematic reduction in the fracture characteristics (aperture, width, density and length) from the crest to the flanks.

The distribution of fracture characteristics in the same field is neither uniform chaotic nor random. The orientations and spatial distributions of fracture sets around fractured and also faulted anticlines are correlated to deformation history, particularly with respect to folding mechanisms and the likely evolution of stresses during folding. Such genetic controls are considered to be important in estimating likely reservoir fracture geometries from large-scale, regional information such as tectonic deformation history and evolution of stress regime. Also vital in controlling fracture development during lithification and folding are the presence of pre-fold and syn-fold faults, whilst late or post-fold faulting commonly develops independent fracture clusters.

In a carbonate sequences such as the Sarvak or Asmari, the uppermost carbonate unit contains the most fractures. However, in lower layers, the fracture patterns does not conform a three dimensional fracture block network that is assumed during reservoir simulation and production analysis. Instead, they have a preferred orientation that rarely intersects. This means that they increase the vertical permeability of these tight rocks and provide a permeability anisotropy which runs parallel to the field's structural axis.

Fractures also provide the reservoir quality rocks in the Bangestan Group while diagenetic processes have created little secondary porosities. In many of

the oil fields fractures extends upward through the Upper Cretaceous and to the Asmari Formation in order to provide connection between the reservoirs.

Because of the Sarvak Formation's great thickness (more than 800 meters) and large structures in the Persian Gulf, tremendous volumes of hydrocarbons have been trapped in the Sarvak and associated Ilam reservoirs. Fractures have affected the Sarvak Formation porosity and reservoir characteristic. This is the case in oil fields such as Bahregansar and Handijan in the northern head of the Persian Gulf.

The relationship between lithofacies and fracture properties could be considered on a number of points of view. Firstly, strain partitioning along weak strata during folding may affect the vertical continuity of fractures. Secondly, fracture characteristics (e.g. density and aperture) depend on the mechanical properties of a given lithology. Thirdly, diagenetically altered units along key surfaces such as hardground surfaces or karstified units exert a geomechanical control affecting the development of later fracture arrays.

An important concern in fractured carbonate reservoirs is whether much of the fracture porosity has been destroyed or obliterated by later cementation. Nevertheless, microstructural observations show that even cemented fractures can reopen under certain stress conditions to act as conduits to fluid flow or as surface fissures held open during further burial by porous sediment infill. These types of diagenetic controls highlight the sensitivity of final fracture array properties to the burial and uplift history in relation to folding and fracture generation.

PERSIAN GULF RESERVOIR SEDIMENTARY CYCLICITY

The well-preserved sedimentary cyclicity of the majority of the formations is shared by most of the Persian Gulf hydrocarbon reservoirs (i.e., Permian-Triassic Dalan/Kangan, Jurassic Surmeh and Arab and Cretaceous reservoirs). In general three factors that are related to the depositional environment favor cyclo-stratigraphic analysis:

- Continuous and prolonged uninterrupted marine sedimentation;
- Uniform and comparable subsidence and sedimentation rate;
- High preservation potential with minimal reworking or erosion of sediments.

Most of the carbonate reservoir rocks of the Persian Gulf region meet these requirements and have the ideal settings for the preservation of the cyclicity of the sedimentary sequences.

The Persian Gulf region occupied equatorial and low latitudes during the Late Permian and Mesozoic that favored carbonate deposition. This resulted in long period of uninterrupted deposition in shallow marine environmental settings. As a broad continental shelf, the Arabian Plate subsided gently resulting in sufficient open space to accommodate most sedimentary input.

As a result of the weathering and erosion of the Arabian shield during sea level lowstands and under humid climatic conditions, large quantities of sediments were transported into the shallow-marine habitat during the Middle to Late Barremian (Kushk Sand member and Zubair sandstones), Albian (Azadegan and Burgan Sandstones), and Early Miocene (Ahwaz Sandstones). Consequently, these sedimentary successions deposited during these periods formed the main clastic reservoirs in the Persian Gulf region.

RESERVOIR DISTRIBUTION IN PERSIAN GULF

Considering the distribution of petroleum reservoirs laterally and stratigraphically within the great Persian Gulf region, numerous geological features and trends are evident (Figure 5-2). These characteristics are presented as follow;

Firstly, the oilfields are characteristically ellipsoidal to elongate in shape and they illustrate particular trends. Those in the northwestern region of the Persian Gulf and also in Saudi Arabia and Kuwait and to a lesser extent in the UAE geographic region are aligned in a north-south direction with fold axes coincides with positive gravity anomalies (Mina et al., 1967). The Nowrooz and Dorood anticlines also are following similar trend. The north-south orientation of major basement-involved structures, such as at Ghawar and the Safaynia fields in the offshore Persian Gulf, are easily identified on gravity maps where structural highs are generally associated with positive gravity anomalies (Wender et al., 1998).

A trend starting with the Safaniya-Khafji structure in the western Persian Gulf could simply be extended north-northeastward to the south, and also to the Nowrooz structural trends, and even as far north as the Bahregansar Field in the northern Persian Gulf. A similar trend could be traced along the Zuluf, the Esfandiyar and the Soroosh structure to IPAC "A" and possibly to the Tanb anomaly. The IPAC "F" structure and the Dorood-Kharg anticline also fall along similar trends. The same is true of the FPC, "B" structures in the Persian Gulf northern end and the IPAC"B" well (Mina et al., 1967). Thus, these structures were probably created by reactivation of deep basement or Mesozoic features producing doming in the overlying strata.

The oil fields to the north of the Persian Gulf and in southwestern Iran are trending in a northwest-southeast direction. Indeed some offshore prospective trends have been projected from onshore productive structural trends with seismic data and that could have led to development of viable prospects. The steep, long folds related to the late Tertiary Zagros orogeny, parallel the belt and are observed as far southwest as the Iranian coastline, and even in the Iranian offshore areas (Lavan Island gas field in the Persian Gulf). The wider, gentler folds of the peripheries of the Mobile Belt have affected the sediments as far as middle of the Persian Gulf. These broad folds have caused the originally connected north-south trending ridges or structural noses to be subdi-

vided into separate anomalies. The superposition of the northwest-southeast Tertiary folding over a pre-existing north-south structure is quite evident in the Dorood-Kharg anticline.

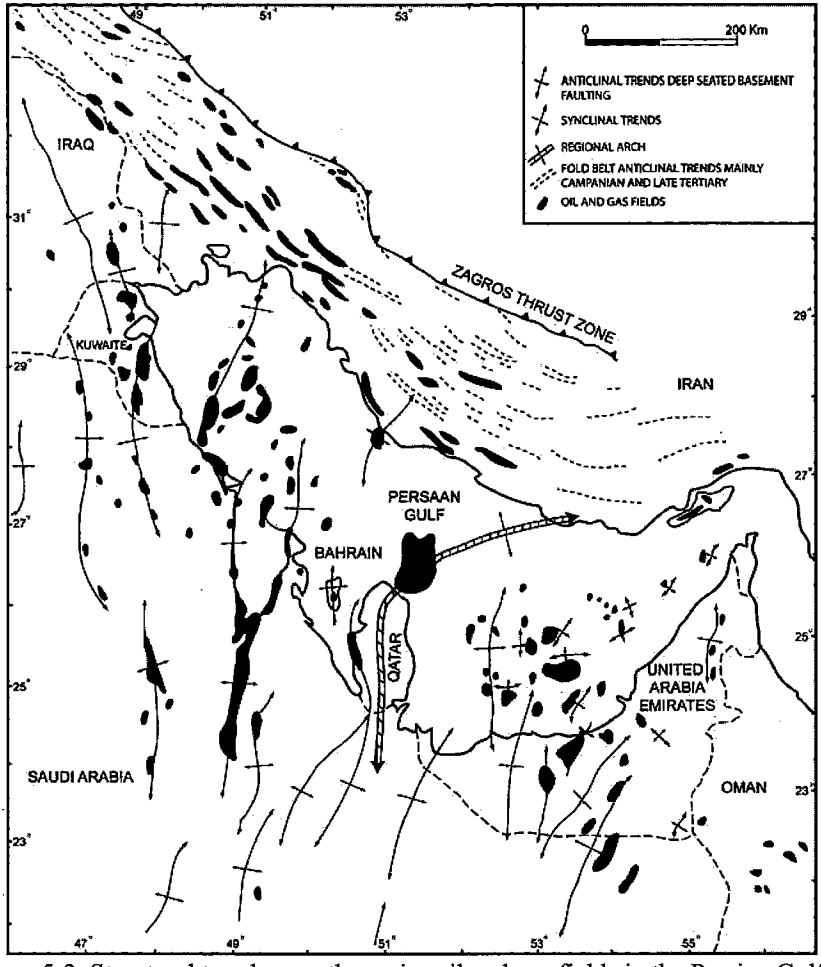

Figure 5-2. Structural trends over the major oil and gas fields in the Persian Gulf region (cited from Beydoun et al., 1992).

Secondly, the oil fields in the latter area tend to be more elongate and both aerially and volumetrically smaller than those lying on the platform, which have a simpler and less dramatic structural history. In general, folding intensity reduces southward toward the Persian Gulf. The gross thicknesses of the reservoirs are variable but are occasionally in the excess of 300 meters.

Thirdly, principal reservoirs become progressively younger from southwest to northeast. In Saudi Arabia, the principal reservoirs are Mesozoic in age while those in the Iranian territories are Tertiary in age. The reservoirs in

the main fields in Saudi Arabia, typified by the Ghawar oil Field are mainly Jurassic age. Slightly further north, in Kuwait region, the principal reservoirs, exemplified by Burgan (second only to Ghawar in size with 72 billion barrels), are Cretaceous in age. Likewise in the UAE the major reservoirs are the platform and reefal limestone of Cretaceous age. Further north again, in Iran, the reservoirs are typically of Oligocene to Miocene in age. The largest field illustrating these reservoirs is Ahwaz with 17.5 billion barrels of recoverable reserves.

Therefore, in the Persian Gulf basin, as described by Greig (1957), Jurassic fields lie along the lower foreland shelf, Cretaceous fields tend to follow next in order basinward, and Tertiary fields occur along the more strongly folded belt near the trough. One of the reasons for this arrangement is the manner in which basin subsidence and sedimentation commonly proceed. As a result, the major incidence of oil occurrence in a basin commonly lies within certain maximum and minimum depth ranges.

In the Persian Gulf, the area situated along the northern extension of Qatar-Gavbandi Arch is a gas field which occupies the major continental offshore structure. However, no significant oil was discovered in the area north of the Qatar Peninsula where sedimentation rate was relatively slow. Indeed some reservoir sections are absent due to both erosion and non-deposition.

It is important to point out that there are some fundamental differences between these two regions in the Persian Gulf. The eastern part of the Qatar-Gavbandi Arch was deeper and the contemporaneous sequences form greater thickness in this part. In addition, due to the presence of Hormuz salt deposits and its later mobility the Zagros folding have greatly influence the sequence. The main reservoir rocks in this area belong to the Middle Cretaceous carbonates of the Sarvak. According to Kamen-Kaye (1970), from the distribution of these fields, one may infer that a narrow swath of Cretaceous production may be found to occupy almost the whole length of the Persian Gulf. Oil fields of the Cretaceous age might be found to extend from Zubair in the northwest to Fahud in the southeast to a total distance of 1200 kilometers.

In the Hormuz Island region in eastern end of the Persian Gulf, the tectonic elements of the Musandam Peninsula and the Zagros thrust have acted on the region profoundly, placing the Jurassic sequences against Tertiary. In addition, the intrusion of the salt domes such as Hormuz and Larak Islands, have further complicated the structural feature of this part of Persian Gulf. Hydrocarbon accumulation has been indicated in the Sarvak and Dariyan Formations. However, these formations have been deeply effected by the erosional surfaces in the region.

PRECAMBRIAN RESERVOIRS

The oldest reservoir rocks in the Persian Gulf region were described by Riemens and De Jong (1985) which is a 50 meters-thick carbonate stringer in

the Precambrian Ara Salt of Oman. This signifies an episode of basin freshening when evaporite deposition terminated. Porosity distribution within the stringer ranges from zero to 20%.

In the South Oman Salt Basin, and possibly in the salt basins of northern Oman, an Early Cambrian carbonate play has reemerged. This is the Ara carbonate play, characterized by carbonate slabs, termed "carbonate stringers", encased and sealed in halokinetically deformed salt (i.e. halite) bodies. Even though the carbonate stringers are, at present, isolated within the remnant deformed salt bodies, seismic and well correlations suggest a cyclic stratigraphy and depositional evolution. The Ara stringers contain both oil and gas charge, which has likely migrated from deeper Huqf source rock (Shuster, 2003).

There is no additional deep drilling in the region to determine if any major hydrocarbon reservoir occurs beneath the Persian Gulf. No attempt has been made so far to explore deep stratigraphic horizons for oil and gas but the recognition that some of the Precambrian rocks contain hydrocarbons increases the possibility of such potential of coeval rocks.

PALEOZOIC RESERVOIR

The Paleozoic sedimentary sequences only turned out to be prospective during the early 1970's when the enormous Permian Dalan/Kangan gas reserves were delineated in the Persian Gulf region and Zagros Mountains, and also oil was discovered in southern part of the Persian Gulf particularly in the Oman region. A huge, non-associated gas discovery in 1972 in the Permian Kangan/Dalan in the Kangan No# 1 well in southwestern Iran increased gas reserves, which, with subsequent discoveries within the same sequence, have reached over 450 tcf (Beydoun, 1988).

Most of the Persian Gulf potential Paleozoic reservoir rocks are composed of continental clastics and signify highly sporadic and intermittent deposition. Further Paleozoic reservoirs include the Cambrian-Ordovician Saq Sandstone, shallow-marine sandstones of the Ordovician Qasim Formation (Senalp and Al-Duaiji, 1995), and Upper Ordovician glacial and periglacial clastics of the Zarqu and Sarah Formations (McGillivray and Husseini, 1992). Many of these Pre-basal Silurian clastics have had some hydrocarbon shows although they are poor-quality reservoirs owing to formation of silica cementation.

Paleozoic primary reservoirs of the southern Persian Gulf region include; shallow marine shelf Devonian Jauf Formations and eolian and fluvial sandstones of the Permian Unayzah Formation and in the Persian Gulf portion, basal transgressive marine sandstones and cyclic dolomitic shelf carbonates of the Late Permian Kangan/Dalan Formation. Potential reservoirs might also occur in fluvial and deltaic sandstones of the Cambro-Ordovician section.

Sourced by the basal hot shale, light sweet oils with high (44°-52°) API gravities are produced in southern Persian Gulf fields. Production is from alluvial and (or) fluvial sandstones of the Lower Permian Unayzah Formation

and shallow marine shelf sandstones of the Devonian Jauf Formation; some production is additionally from Ordovician sandstones. The primary regional seal combines basal shales, low permeability "tight" carbonates, and anhydrite of the Permian Khuff Formation. These oils migrated westward and updip from a more thermally mature eastern source area.

The Hercynian orogeny which is believed to have caused major uplift and significant erosion comprise sequence of clastics (late Carboniferous-early Permian). The deepest wells drilled in southern Persian Gulf reached Unayzah is in Hair Dalma which produces dry gas (Lutfi and El-Bishlawy, 1986).

DEVONIAN RESERVOIRS

One of the most important gas-bearing reservoirs is the Upper Devonian Zakeen Formation encountered in the Golshan Field in the Iranian waters of the Persian Gulf. The Zakeen Formation was penetrated in several wells such as Darang-1, Zarreh-1, Nura-1, Namak-1 and Finu-1 in Fars platform and Bandar Abbas hinterland accordingly. So far no reservoir seal has separated Zakeen reservoir from Ordovician Faraghan Formation. Therefore, the Zakeen Formation might be considered as a part of the Deh Ram play (Motiei, pers comm).

There are also other gas-bearing reservoirs in the Persian Gulf region. Gas in the Devonian Jauf sandstone was originally discovered in 1980 by a deeper pool test on the northern end of the Ghawar structure. Subsequent deep tests showed that the Devonian section was mostly eroded from the crest of the structure. The discovery in 1994 of Jauf gas in a combination of structural-stratigraphic trap along the flank of central Ghawar was a major exploration success, especially in light of poor seismic imaging of the sub-Khuff section (Wender et al., 1998).

Early to Middle Devonian shallow marine sandstones of the Jauf Formation are of good reservoir quality. Overlying the Jauf Formation is very fine grained to medium-grained, poor reservoir quality sandstones of the Middle to Upper Devonian Jubah Formation.

Devonian strata have turned out to be a prime exploration target because of the recognition of a quality, sweet-gas reservoir within the Lower to Middle Devonian Jauf Formation. The Jauf Formation is the main producing reservoir in the northern Ghawar area. It can be divided into two parts. In the upper part the good-quality reservoir well-sorted sandstone facies are interbedded with black, carbonaceous shales. The lower part of the formation, where the main reservoir occurs, consists of thick and continuous stacked coarsening-upward sandstone sequence. The thin, coralline limestone members of Jauf Formation could serve as a source as well as reservoir beds as these limestones thicken and are interbedded with shales and siltstones.

The shallow marine sandstones of the Devonian Jauf reservoir in Ghawar area are well developed and commonly display high (30%) porosities at a

depth of 4,260 meters. In the northern Ghawar area, the Jauf reservoir ranges in thickness from 89 to 145 meters. The giant gas-condensate discovery at the Hawiyah sub-structure field at Ghawar is in Jauf sandstones. The Jauf sandstones are fine to medium grained, are weakly cemented by authigenic illite clay, and lack the silica cement that is widespread and detrimental to reservoir quality of most other Pre-Dalan sandstones. The authigenic illite is considered to prevent quartz cementation and to sustain porosity. At Ghawar field, and at Abu Sa'fah field offshore in the Persian Gulf to the northeast of Ghawar, the Jauf reservoir is sealed by a distinct shale-silt layer that is referred to unofficially as the D3B zone (Wender et al., 1998).

PERMIAN RESERVOIRS

Permian Hydrocarbon discoveries in the carbonate rocks deposited at this period are common and well documented. Many of the reservoirs resemble modern shallow shelf tropical carbonates: oolite grainstones, dolomitic mudstones, reefal sequence, with evaporite seals. Potential zones generally consist of fractured dolostones and porous limestones. Large gas reserves have been discovered in the Permian successions of the Persian Gulf. Oil fields with significant Permian reservoir include North Dome and Pars fields in the Persian Gulf.

Reservoir rocks are commonly consists of the Upper Permian dolomitic limestones, dolostones, oolitic limestone or carbonates. For example, in Pars fields, there are multiple carbonate reservoirs such as the Dalan Formation (Permian), Kangan Formation (Triassic) and an argillaceous sandstone reservoir in Faraghan Formation (Lower Permian). All other fields produce from carbonates of the Dalan and Kangan Formations or from the Deh Ram Group.

Permian limestones and dolostones exposed in the Zagros Mountains (i.e., Kuh-e-Dinar, Kuh-e-Surmeh, Kuh-e-Gahkum, and Kuh-e-Faraghan) have a strong gasoline-like smell and sulfurous odor, especially where they are freshly exposed. Similar hydrocarbon shows have been reported from exposed Permian succession in the southern Persian Gulf and the Oman Mountains (Beydoun, 1991; Glennie, 1995; Beauchamp et al., 1995).

Faraghan Formation

The oldest rock sequence drilled in the Iranian side of the Persian Gulf is the Permian Dalan carbonates and the pre-Permian Formation. Transgressive Permian basal sandstones, is present not only in central and northwestern Iran (Berberian and King, 1981) but regionally southwestward to Iraq and into Saudi Arabia (Powers, 1968). The clastics of the Faraghan Formation have been recovered only in the deep well drilled on the Salman oil Field. Thus, the lithostratigraphy and thickness of the sediments between the Hormuz salt and Dalan/Kangan have not been recognized in the Persian Gulf (Hedayati, 2003).

The Faraghan and its stratigraphic equivalent Unayzah Formation are the most important reservoir in southern Persian Gulf and it lies unconformably on the Silurian Shale (i.e., Sarchahan), which is considered an important source rock in the region. However, this is not the case in Golshan Gas Field where the Faraghan Formation overlies the Zakeen Formation. In addition the Unayzah clastics show important stratigraphic trap potentials as they transgress over subcrops of older units. These clastics are important target where they overlie the Silurian shales and other potential source rocks.

The time equivalents of the Faraghan sandstones contain light oils in parts of central Arabia within the Greater Persian Gulf (McGillivray and Husseini, 1992). However, widespread reservoir quality variations occur in sandstone reservoirs owing to heterogeneous sedimentary facies and diagenetic history (Aktas and Cocker, 1995).

Depositional facies strongly influenced porosity evolution in these sands: both porosity and permeability generally decrease with cementation and silt and clay content and enhance with increasing grain size and dissolution of cement. The Faraghan and overlying Dalan Formation are separated by an unconformity. The cyclic nature of the Faraghan suggests a fluctuating sea level. The upper Unayzah unit is the principal reservoir averaging about 20% porosity.

Equivalent of basal Dalan succession also consists mostly of siliciclastics throughout southern Arabia. The "basal Khuff clastics" are shale, carbonaceous shale, limestone streaks, and incised channel-fill sandstones. Channel-fill sandstones of the basal Khuff clastics are as much as 18 meters in thickness and generally cut deeply into the Unayzah Formation. In Hazmiyah field of central Saudi Arabia, the reservoir occurs entirely within these channel sandstones in the basal Khuff (Al-Jallal, 1995; Senalp and Al-Duaiji, 1995).

Reservoir rocks are mainly alluvial, fluvial, and eolian sandstones of the Permian Faraghan Formation and the basal Dalan Formation. Oil and gas are produced from fluvial and eolian sandstones of the Permian Unayzah Formation and porous shallow marine sandstones of the Devonian Jauf Formation in the southern Persian Gulf. The hydrocarbons were generated from the Silurian shales in the eastern, more mature part of the basin, and migrated westward and updip into the wrench-faulted structures. Towards the northeast in the Persian Gulf portion of this petroleum system, basal transgressive marine sandstones and cyclic, dolomitic shelf carbonates of the Late Permian Dalan Formation produce gas and condensate; some sour gas and other non-hydrocarbon gases are also produced from these reservoirs. The reservoir layers are essentially traceable over wide distances by wire log signatures due to their contrasting lithologies.

In the south Ghawar area, the Unayzah is generally divided into two sandstone reservoir units separated by a siltstone member (Wender et al., 1998). Porosity in Unayzah sandstones is as high as 30% and permeabilities are as high as 4 Darcies. Traps range from stratigraphic and structural traps along

the margins of the basin to structural traps related to major basin-wide fault systems in the central part of the basin. Seals are mainly provided by the Nar anhydrites member of the Dalan Formation, but seal quality may degrade to the south along the basin margin. Permeability of several Darcy's is not uncommon; however, both porosity and permeability vary due to the presence of kaolinite and illite cements (McGillivray and Husseini, 1992).

In the Greater Ghawar area, the principal Pre-Dalan hydrocarbon reservoir in the southern area is the Unayzah Formation. Gas is produced from most of the Paleozoic reservoirs in this field; however, Qusaiba-sourced premium crude is produced from the Unayzah to the southeast. The Unayzah is missing in the north half of the field (McGillivray, 1994) but is present in the southern half of Ghawar, where it thickens from nil to greater than 152 meters to the southeast. Porosity of the upper Unayzah-A pay zone ranges from 5 to 25% (Wender et al., 1998).

UPPER PERMIAN

There are numerous hydrocarbon reserves in the subsurface strata of the Permian of the Persian Gulf region. A number of offshore wells in the eastern parts of the Persian Gulf have also encountered Permian sequence. These wells include Iminoco#1, Farsi as well as production wells in Pars Fields. In all these wells, fractured oolitic, detrital and dolomitic limestones of the Dalan were discovered to contain gas which is under considerable pressure (Edgell, 1977).

Important volumes of the Permian gas in Iran are now being produced in the Dalan and Kangan Formations in the coastal Fars and Boushehr area, largely at Kangan. The only appraised or partly evaluated discoveries within the Zagros Fold Belt are close to the coast at Kangan and Mand; the nearby offshore Pars accumulation in a halokinetically controlled structure beyond the folding is being developed at present.

Dalan Reservoirs

The Upper Permian Dalan limestone and dolostone form potential and also established gas reservoirs in a number of fields in the Persian Gulf region and beyond. The Dalan carbonate reservoirs (extending up into the lower Triassic Kangan Formation in northern Persian Gulf and southern Iran) form the most prolific gas reservoirs in fields such as South Pars, North Pars, Kangan, Nar, Agar, Golshan structure and other gas fields in southern Iran and in the offshore Persian Gulf.

The Dalan reservoirs consist mostly of cyclic grainstones and dolomitic shelf carbonate rocks, with production controlled mainly by distribution and amount of anhydrite present. The Dalan/Kangan and their time equivalent Khuff Formation contain extensive gas reservoirs in the Persian Gulf area

(e.g., Kish-1 and 2 wells in the Iranian waters of the Persian Gulf). The geologic conditions are similar in Kish-1 and 2 wells. In general, these formations are part of the Deh Ram Group which is one of the world's richest gas-bearing rocks in Iran and host giant gas fields.

Both the Dalan/Kangan reservoirs are sealed by the Triassic age Dashtak evaporitic sequence. These formations are treated at the same time because they seem to act as a single reservoir, especially where overlying Triassic evaporites serve as cap rock and in the overall region, it is often difficult to separate the Triassic from the Upper Permian succession.

The Kangan/Dalan reservoir is ranked as one of the largest reservoir of non-associated gas in the world with recoverable reserves anticipated at about 750 TCF. The reserves include the largest gas field in the world at North Dome Field, Qatar discovered in 1971; its total reserves are estimated at 500 TCF (Konert et al., 2001). The reservoirs produce primarily gas that probably formed by the cracking of oil (Bishop, 1995). Locally, the quality of gas depends upon the amounts of non-hydrocarbon gases, mainly H_2S, CO_2, and N_2. The quantity of H_2S increases with increasing temperature and depth, reflecting in place conversion of hydrocarbon gases into H_2S by the thermochemical reduction of anhydrite sulfate (Konert et al., 2001).

Although platform carbonates are found throughout the Persian Gulf and locally form gas reservoirs, nevertheless, the rock sequences are usually tight. In the southern Persian Gulf many of the Upper Permian fields are beneath the shallow oil fields, suggesting that the Hormoz salt has been mobile for some times and that the structures have been continually growing since at least prior to deposition. Gas production in this area is generally related to sedimentary facies, porosity variations, and varying diagenetic processes.

Dolostones, dolomitic limestones, and oolitic limestones reservoirs of the Dalan Formation exhibit good primary porosity and permeability in its oolitic to pelletoidal and grainstone facies, which accumulated in high energy depositional environments (Schlumberger, 1981). The Dalan Formation displays porosities reaching up to 11% at the Lavan Island area in the Persian Gulf. In contrast, low primary porosity is present in many places in tight dolomitic packstones associated with low-energy depositional environment. The hydrocarbon productive capacity of both the oolitic and dolomitic reservoir facies are strongly influenced by fracturing and by development of secondary porosity. According to Ehrenberg et al. (2007) most Dalan/Kangan (Khuff) reservoirs have average porosity of less than 12%.

Areas of high porosity in carbonate rocks of the Dalan Formation in most areas surrounding the Persian Gulf including Iran, Qatar, and Bahrain define a broad belt of shallow shelf breaks that once bordered a restricted evaporitic carbonate shelf. Good reservoir porosity in the Dalan of the southern Persian Gulf is attributed to the presence of basal sandstone unit.

Previously, it was believed that only carbonate units with secondary fracture porosity constitute potential reservoir rocks; it is now apparent that Upper

Permian strata may have the potential to produce hydrocarbons from their primary porosity, essentially in the south-southwest portion of the basin. Generally, the Dalan Formation is a thick formation consisting of cyclic anhydrite and carbonate rock that forms a regional seal for hydrocarbons.

Gas was discovered in carbonate rock reservoirs of the Upper Permian in the Awali Field domal structure of Bahrain in 1949. It is the predominantly carbonate units of Permian which constitute the most important actual and potential reservoir rocks in Persian Gulf area. In these carbonates permeability throughout the rock unit is generally low, but there are well-developed zones of secondary porosity, dolomitization and fracture porosity.

The Kangan/Dalan is locally a petroleum reservoir depending on the presence of dolostones and/or the ratio of carbonate and anhydrite. The evaporitic part of the section may act as an effective cap rock. But in recent discoveries in the south-southeast of the basin, shales may form an effective cap rock.

In the western Persian Gulf, Kangan/Dalan is divided into five units or members. However, throughout the Persian Gulf region they may comprise as many as seven designated units or members (Al-Jallal, 1995). Most of the Upper Permian carbonates are composed of limestones and evaporites; major siliciclastic facies increase towards the west. As many as four of the five units might be considered as reservoir units and correspond to four depositional carbonate-anhydrite cycles where transgressive carbonate rocks are capped by regressive anhydrite facies. The equivalent of the Kangan/Dalan in the southern Persian Gulf, i.e., Khuff, comprises four reservoirs, named K4 (i.e., the deepest) to K1, separated by impermeable non-reservoir layers.

Four main facies of the Kangan/Dalan are observed, open marine, oxic and highly fossiliferous, near shore, and restricted. The areas of interest in terms of petroleum occurrence correspond to the extension of the restricted facies only. This facies includes two layers of carbonates, 250 to 450 meters thick, separated by the massive bedded anhydrite of the Nar Member. Carbonates are made of thick layers of massive tight dolostones, and thin porous oolitic or pelletoids beds. Reservoir characteristics depend upon the relative thickness of the oolitic beds.

Generally, the best hydrocarbon reservoirs are in high-energy carbonate buildups consisting of oolitic grainstones and intertidal dolomitic mudstones formed during sea-level highstands at the shelf edge and along the shallow carbonate shelf; these were capped by impermeable anhydrite deposited during sea-level lowstands. The Khuff carbonate reservoirs at some of the southern Persian Gulf fields are the prime examples of such buildups. Wells producing from these reservoirs commonly contain considerable amounts of non-hydrocarbon gases, particularly H_2S. The quality of Upper Permian reservoirs is variable, and their porosity is highest where anhydrite percentage is the lowest.

Late Permian dolostones are major gas reservoirs, particularly along the offshore north and west of Qatar where Dashtak Formation and Nar evaporitic

member might act as a regional and local seals respectively. In contrast, the regionally extensive anhydrite, shale, and tight carbonates of the Dalan form the major regional seal for Pre-Dalan hydrocarbon accumulations in central and eastern Saudi Arabia (Al-Jallal, 1995; Wender et al., 1998).

Upper Permian reservoirs in offshore Abu Dhabi have proved the presence of large volumes of gas, composed primarily of methane with small volumes on nitrogen, carbon dioxide and C_2-C_5 gases. The onshore wells drilled through this interval were found to be dry. The reservoirs occur in thick sequences of dolostone, peloidal-oolitic packstone-grainstones and minor interbedded or nodular anhydrites. Porosities are mainly intraparticle, intercrystalline and fracture types. The main bulk of porosity ranges from 2-20% with an average of 10%. Permeabilities vary widely from less than one md to several tens of milli Darcy.

Porosity and permeability are generally low in these carbonates however secondary fracture porosity and pervasive dolomitization are widespread. Joint and fracture porosities are well developed where the thick carbonates have been folded; this is generally the case for most of the carbonates in the Zagros Basin. On the eastern part of the Qatar-Gavbandi Arch, no reservoirs were discovered in the Permo-Triassic Formations, and Kangan Formation is tight and argillaceous at Kuh-e Surmeh, and to the southeast, several wells found Kangan/Dalan Formations to be tight, Bavush-1, Khalafani-1, M-1, and 0-4BIS.

Carbonate units within Permian succession constitute potential reservoir rocks elsewhere in the Greater Persian Gulf area. These are:

- The Dalan Formation in southern Iran (Kashfi, 1992);
- The Khuff Formation in Saudi Arabia and Bahrain (Al-Laboun, 1987);
- The Chia Zairi Formation in Iraq (Sadooni, 1995).

The Permian sequence is generally fractured and bituminous in outcrop. Two sets of perpendicular joints and random fractures are often noticeable in outcrops of these massive carbonates. However, in the less-folded area of the foreland shelf of southwestern Persian Gulf, oolitic limestones with good primary porosities substitute the fractured and jointed carbonates which prevail in the northern parts of the Persian Gulf. Anticlines located inside the areas of pre-Zagros gas accumulations are potentially prospective, if several requirements are met;

- they should be located in areas of potentially good reservoirs,
- they should be covered by efficient Dashtak cap rocks,
- the structure should be large enough and relatively symmetrical with no tectonic disconformities expected at the Dashtak level,
- Top of Kangan should not be too deep, let say shallower than 5 kilometers.

The Dashtak Formation, made of a succession of thick massive anhydrite layers, and of tight primary dolomite, is an efficient cap rock.

MESOZOIC RESERVOIRS

Hydrocarbons have accumulated in carbonate and siliciclastic rocks of several ages, but Mesozoic carbonates contain most of the reservoir rocks. The primary petrophysical characteristics of these reservoirs are not favorable and production is obtained only when porosity and permeability have been enhanced by secondary processes such as leaching, dolomitization and fracturing.

Some of the most prolific petroleum reservoirs with high gravity oil in the world occur in the Upper Jurassic and Cretaceous carbonate sequences in the Persian Gulf. As a result, significant oil discoveries have also been made in Upper Jurassic and Cretaceous Formations providing excellent hydrocarbon reservoirs. The majority of the reservoirs are composed of pelletal, oolitic, or bioclastic grainstones and reefal limestones that have high primary porosity and permeability. These reservoirs are sealed either by shale, tight limestones, massive anhydrite, or by impermeable rocks. The seals are effective throughout most of the Persian Gulf and surrounding areas.

Abundant oil and gas reserves have been discovered in the Surmeh, Arab, Araej, and Diyab Formations of the Jurassic age. Cretaceous age, Fahliyan, Dariyan, and Sarvak Formations are also forming important reservoir in the Persian Gulf region. The best reservoirs are formed by regressive sands and high-energy ooidal grainstones terminating the carbonate cycles. Other favorable facies are the "rudist reef" and the algal boundstones along the shelf margins. Leaching and cementation processes are main factors in determining the ultimate and final reservoir quality of these carbonate rocks. Some porosity-creating diagenetic processes such as leaching is apparently related to the lowering of the sea level and subsequent subaerial exposure (Early Albian and Late Turonian) but there is also evidence for late leaching caused by acids in the formation water (Murris, 1980).

During the Late Jurassic and Cretaceous, a deep basin was centered in the Lurestan region in the northwestern Persian Gulf. This organic rich basin was the source of much of the hydrocarbon discovered in the Persian Gulf Jurassic and Cretaceous reservoirs. Surrounding this basin was a dolomitized reef and platform margin.

Jurassic and Cretaceous carbonate reservoirs are present along Persian Gulf northern borders. They are geologically related to the prolific carbonate reservoirs of the southern Persian Gulf. The Lower Cretaceous and the Upper Jurassic are by far the most important reservoir sequences in southern Persian Gulf. The Lower Cretaceous reservoirs contain more than 80% of the oil discovered, in addition to about 50% of the gas; while the Upper Jurassic reservoirs contain about 15% of oil and 30% of gas in southern Persian Gulf. The

hydrocarbon distribution in the Upper Jurassic reservoirs appears to have been influenced by the development of the intervening Hith Anhydrite.

TRIASSIC

In the northern Persian Gulf the dolomitic limestones, dolostones, oolitic limestone or carbonates reservoir rocks of Triassic age (i.e., Kangan Formation) were considered as a single unit within Upper Permian. For example, in the South and North Pars fields, there are multiple carbonate reservoirs such as the Dalan (Permian), Kangan (Triassic) and one argillaceous sandstone reservoir in the Faraghan Formation (Permian). All other fields produce from carbonates of the Dalan and Kangan Formations or the Deh Ram Group (Triassic). It appears that in the Persian Gulf, the Triassic contains gas which was probably generated from deeply buried source rocks (Kashfi, 1992).

Kangan Formation consists of limestones and dolostones with variable amount of clay and the presence of anhydrite layers throughout the formation. The porosity reaches up to 20% (i.e., in Lavan well #2 in the Persian Gulf). The porosity within the Kangan Formation observed in Salman field is mainly of vug, moldic, fenestral intracrystalline nature which is often packed with evaporite minerals (Abdi, 2004). Frequent fractures are observed resulting in the enhancement of the existing porosity.

Isolated Triassic reservoirs in the Persian Gulf are relatively insignificant and contain merely minor amounts of hydrocarbon. No hydrocarbon production has been reported from the Triassic sequence in the Persian Gulf however some gas shows occur in the southern Persian Gulf. Porosity is generally poor to fairly good (5-9%), with some reduction as a result of depth of burial and diagenesis. In spite of this, the Triassic strata have produced fair amounts of light oil, gas, and condensates from some fields in Iraq with a high potential of gas and condensate accumulations. Porous dolostones of Jilh Formation contain commercial quantities of gases in the Abqaiq and Ghawar Fields. The producing zone is better known as the Abqaiq gas zone (Mina et al., 1967; Sadooni and Al-Sharhan, 2004).

The Dashtak Formation is made up of a succession of thick massive anhydrite layers, and of tight primary dolostone, that could perform as an efficient cap rock. However, the Lower part of the Dashtak Formation has undergone pervasive dolomitization towards interior Fars in the Zagros Basin. As a result of this diagenetic modification secondary porosity have been developed forming reservoir characteristics. Initially, it was believed that the gas accumulation might have been the result of secondary migration from Kangan/Dalan through fracture network however detailed analysis has demonstrated major differences in the chemical composition of gas and reservoir pressure (Motiei, 2003). Dashtak Formation is replaced in the northeastern part of the Zagros Domain by bedded dolostones, sometimes oolitic and pelletoid of the Khaneh Kat Formation, which also forms a reservoir.

JURASSIC

The Jurassic rocks offer one the most attractive hydrocarbon potential in the Persian Gulf region. The main Jurassic reservoir target is the carbonates of Surmeh and its stratigraphic equivalent Arab Formation, sealed by the Hith and Gotnia evaporites and sourced by the Sargelu and Hanifa Formations.

In major parts of the Persian Gulf region, the Jurassic succession consists of a thick massive carbonates. It is known in the subsurface to be generally tight, but in spite of this, it could provide reservoirs where fracturing has vital role in enhancement of reservoir characteristics. In the northern Persian Gulf similar to southwestern Iran carbonates are forming the dominant reservoirs.

The Lower Jurassic of the entire Persian Gulf exhibits moderate reservoir characteristics, and oil fields containing light oils are uncommon. However, the Middle and Upper Jurassic rock sequences contain attractive hydrocarbon potential. This is indeed the case particularly in southern parts of the Persian Gulf. Therefore, the principal reservoir objectives in the Persian Gulf are in the Middle and Upper Jurassic, both occurring beneath excellent cap rocks. The seal over these reservoir rocks is the Hith Anhydrite immediately above the Surmeh and Arab grainstone reservoirs. It is a widespread and persistent seal which extends well into Iran.

The primary porosity is extensively preserved in grainstones and packestones of the Middle and Upper Jurassic and in the oolitic grainstones of the uppermost Jurassic Arab. The oolitic limestone reservoirs have high porosity and permeability, and have excellent source rock potentials, especially within the intrashelf basins. Some reduction in the water zones beneath oil accumulations suggests porosity preservation pending the arrival of the oil, suggesting that there was no movement of the formation waters for periods of some 100 million years.

MIDDLE JURASSIC RESERVOIR

In the southern Persian Gulf, the Araej Formation contains one of the most prospective parts of Middle Jurassic and economically important sequence; more than 20 structures were tested and produced hydrocarbons.

Since the Middle Jurassic was a tectonically stable period, the observed cyclic nature of the Araej Formation and the fluctuations in water depth were due in large part to high-frequency sea-level changes. These fluctuations caused lateral facies modifications which made meteoric diagenesis, and the resulting dissolution and dolomitization, possible. The dissolution processes were responsible for the creation of the vuggy, moldic and intercrystalline pores which make the Uwainat and Upper Araej good reservoir units (Sclumberger, 1981). Furthermore, these reservoirs are linked with halokinetically produced highs that became bathymetric shoals and focused wave energy,

which winnowed the sediments and so enhanced its reservoir quality (Schlumberger, 1981).

The reservoir properties of the Araej Formation are mainly controlled by the depositional fabric. The primary interparticle and intraparticle porosities were developed in the grainstones and packestones deposited on the shallow shelf.

The lower Araej Formation (=basal Surmeh) in the southwestern Persian Gulf shows very little reservoir development, with very low porosity (about 8%) and low permeability (less than 10md). This is due in a large part to extensive calcite cementation and the predominance of mud-supported textures. Secondary porosity is poorly developed in the form of rare interparticle and vuggy pores and, to a lesser extent, intraparticle and moldic pores.

The upper Araej Formation (=lower Surmeh) reservoir is characterized by moderate to good porosity (~16%) with good permeability (~100 mD). The grainstones and well-cemented packstones have porosity from 5 to 16% and permeability from less than 1 to 100 mD. The argillaceous lime mudstones and wackestones are characterized by lower porosity (ranging from 3 to 9%) and very low permeability (<1 mD). In bioclastic-peloidal grainstones the sediments are variably cemented by calcite and anhydrite, sometimes resulting in the total occlusion of porosity. The main porosity is interparticle because of the increase in grain-supported textures over the underlying members. Increased permeability within the upper Araej Formation is directly related to enhanced interparticle porosity and results in the creation of an excellent interconnected void network. Diagenetic processes were the primary factors responsible for the creation of porosity and permeability which make the Upper Araej Formation good reservoir.

Reservoirs in the upper Araej Formation, similar to the lower part are associated with bathymetric highs due to salt movement, producing shoals that were the site of grainstone deposition (Alsharhan and Kendall, 1986). These grainstones are thought to have accumulated in shallow, partly protected to high-energy depositional settings (Schlumberger, 1981) and possess good reservoir characteristics. The Dhrama Formation is an important hydrocarbon producer.

UPPER JURASSIC RESERVOIRS

Secondary hydrocarbon reservoirs of the southern Persian Gulf include the porous carbonate units within the Hanifa and Tuwaiq Mountain Formations. These porous carbonate units are referred to as the Hanifa reservoir facies and the Hadriya reservoir facies, respectively, and comprise large-scale upward-coarsening, shallowing-upward, platform carbonate sequences (McGuire et al., 1993).

The Upper Jurassic Hadriya and Hanifa carbonate grainstone reservoirs in Berri field situated partly offshore in northwestern part of the Persian Gulf

and contain large reserves of light crude oil. Both reservoirs have basinward-thinning wedge geometry. Bathymetry controls the distribution of carbonate lithofacies. The depositional setting of the Hanifa reservoir is similar to the underlying Hadriya. The Hanifa, however, is a much thicker sedimentary unit, exhibiting a steeper ramp profile than the Hadriya (McGuire et al., 1993).

The Upper Jurassic reservoirs such as Dhruma, Tuwaiq, Hanifa, Jubaila and Arab Formations generally composed of peletal, oolitic, and bioclastic shoal lime packstones sealed by tight lime mudstones or supratidal anhydrites. Hanifa reservoir facies consists of porous (5 to 30%, mostly microporosity), fine-grained, mud-supported limestones and subordinate dolostones with low matrix permeabilities. High-angle fractures are essential for production in these reservoirs. At Abqaiq field, the Hanifa is separated from the Arab D reservoir by more than 135 meters of fine-grained, impermeable carbonates of the Jubailah Formation. The Hanifa source facies is overlain by as much as 106 meters of the Hanifa reservoir facies, which is in pressure-fluid communication with the Arab D by means of a network of fractures through the Jubailah Formation (Grover, 1993).

The upper part of the Tuwaiq Mountain Formation contains a succession of carbonate grainstones, particularly at Berri field, in southern Persian Gulf, that is referred to as the Hadriya reservoir facies. The Hadriya reservoir facies consist of a basinward succession of coarse-grained, storm-related, skeletal and algal grainstone shoal deposits (Koepnick et al., 1995; Kompanick et al., 1995). The northsouth-oriented, wedge-shaped accumulation ranges from 15 to 70 meters in thickness and contains seven wedge-shaped, 5 to 9 meters upward-coarsening packages. Performance of Hadriya reservoirs is affected by depositional geometry and facies, by wide-spread preservation of the primary porosity and diagenetic processes. The Hadriya zone is composed of a porous limestone near the base of Jubaila Formation. The pay zone attains an average thickness of more than 30 meters in the Abu Hadriya Fields.

The reservoir structure is multilayered and internally heterogeneous owing to the Hadriya's sequence framework and depositional/diagenetic processes that created horizontal and vertical barriers to the fluid flow. Shallow burial, bed-parallel diagenesis produced cementation at the tops of parasequences impeding vertical cross-flow of fluids within the reservoir. In contrast, cross-cutting diagenetic alteration which includes some intragranular microporosity development and intergranular cementation resulted in a major reduction in permeability. The best producing horizons are algal grainstones that exhibit lesser depositional heterogeneity and greater preservation of primary porosity (Koepnick et al., 1995). Low permeability lime mudstones of the lower Hanifa Formation provide a good seal for the underlying Hadriya reservoir.

The upper Jurassic Diyab Formation, in addition to being the major source rock for the Jurassic and Lower Cretaceous reservoirs, forms a good reservoir unit in the oolitic-peloidal packestone-grainstone of the porous section. The

Najmeh-Sargelu Formation in the Minagish field in the Persian Gulf is a fractured reservoir in which fracture alignment controls oil production.

Surmeh and Arab Reservoirs

Late Jurassic (Tithonian) eustatic variations of the Arabian platform resulted in deposition of carbonate-anhydrite cycles that constitute the dominant reservoirs and cap rocks. It has long been known that the Upper Surmeh and the overlying Hith Formation form four main cycles of carbonates and evaporites, with the former being the prime oil reservoirs and the latter seals or cap rocks occasionally holding some minor oil reservoirs. Thus, the regionally extensive, Arab Formation cyclic carbonate rocks are the primary reservoirs of this geologic time interval.

In the northern part of the Persian Gulf, and sourced within the Jurassic Gotnia sub-basin, hydrocarbons accumulated in the Middle to Upper Jurassic, high-energy calcarenites and oolites of bar or shelf-margin origin. These reservoirs are cyclic and interbedded with organic-rich (2 to 5 w% TOC), muddy lime source rocks that were deposited under anoxic and dysoxic conditions in the restricted, intrashelf Gotnia sub-basin.

The Upper Surmeh reservoir and its stratigraphic equivalent the Arab reservoirs consists of alternated carbonates (mainly dolostones) and anhydrite and such sedimentary settings and conditions could impact the reservoir behavior during production. It has produced large amount of hydrocarbon in the Persian Gulf region which include the "Golshan" structure discovery, oil in the Foroozan and Reshadat fields and oil and gas in the Salman and Resalat fields respectively. Production is from Upper Surmeh (Arab zone) Formation with 32° API oil in the Salman offshore oil field in Persian Gulf. The Arab B and C are main reservoirs in the Reshadat and Resalat oilfield (Beydoun and Dunnington, 1975).

The Surmeh is one of the most important petroleum reservoir sections in the Persian Gulf region with porosities of up to 30% and permeabilities exceeding 100md. In the Persian Gulf area, the most common types of porosity in dolostones of the Surmeh and Arab Formations reservoirs are intercrystalline and vuggy, whereas in the limestones the porosity is typically intergranular and often is leached. Anhydrite cement influences porosity reduction in the upper reservoirs (Schlumberger, 1981).

The grainstone units of the upper Surmeh Formation comprise the most important petroleum reservoirs within the Persian Gulf basin. Based on drilling information the Surmeh attains its maximum thickness in Salman field (i.e., 150 meters) and the minimum thickness (66 meters) is encountered in the Sirri Field.

The Surmeh Formation in all the deep tests drilled in offshore Iran, with the exception of those in the northwest of the Persian Gulf, proved to possess excellent porosity and permeability. The Surmeh Formation constitutes the

main pay zones in the Salman structure (Mina et al., 1967). Commercial oil was also tested in the Surmeh Formation in the Dorood Field.

Upper Jurassic reservoirs consist of a series of thinly bedded dolostone and limestone streaks of variable reservoir quality interbedded with impermeable anhydrite layers (Arab-ABC) and a more uniform coarse-grained oolitic/bioclastic limestones unit below (upper Arab-D) (see figure 5-3).

In the central part of the Salman oilfield in Iranian side of the Persian Gulf, the Arab D makes the portion of the reservoir rocks with a thickness of 150 meters. Eastward, the thickness of the Arab decreases and the formation is very thin in the Sirri A and devoid of hydrocarbon. This is one of the main reasons that the exploration wells are not drilled passed Upper Cretaceous reservoirs in this field (Jahan-Mahin, 2002).

Arab D is by far the most developed and prolific horizon in some of the southern Persian Gulf oilfields. It is one of the largest oil-bearing carbonate reservoirs in the giant Ghawar field (Power et al., 1968; Mina et al., 1967; Cantrell et al., 2001). The greater part of the production is derived from grain-dominated limestones and although the dolostones in the Arab-D in general have rather poor reservoir characteristics, the presence of dolostones have a pronounced impact on reservoir quality in a number of ways. In some places, dolostones are responsible for producing permeability barriers, whereas in other places they are associated with zones of very high production (see, Cantrell et al., 2001). These zones of very high flow have been termed "super-k" zones and are defined as intervals that give a flow of oil or water of greater than 500 barrels per day per foot of vertical interval (Meyer et al., 2000).

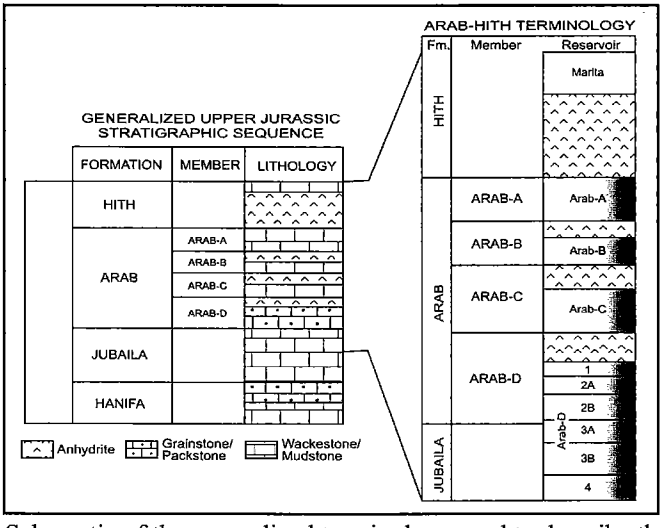

Figure 5-3. Schematic of the generalized terminology used to describe the Arab Formation (Cantrell et al., 2001).

Arab reservoirs consist of a series of thinly bedded dolomite and limestone streaks of variable reservoir quality interbeded with impermeable anhydrite layers (Arab A, B, C, D) and a more uniform coarse-grained oolitic/bioclastic limestones unit below (upper Arab-D). The primary reservoirs are commonly 10 to 30 meters thick, cyclic shallow-water, platform carbonate grainstones of the Upper Jurassic Arab Formation (Arab A, B, C, and D). Arab D is the primary reservoir with an average porosity of about 25%. Moreover, the Arab D reservoir accounts for most of the Upper Jurassic oil production in the Persian Gulf region, forming many supergiant and giant fields. A few reasons why the Arab D reservoir is a prolific producer of hydrocarbons are that it is in close stratigraphic position above the Tuwaiq Mountain and Hanifa source rocks and is sealed regionally by the Arab-D anhydrite.

The Arab D consists of several (at least four) major upward-shoaling cycles that were initiated in deeper water and shoaled to near sea level. Porosity and permeability in the reservoir are dependent on lithology, especially the type of dolomite present in the cycles, and microporosity, all of which play a major role in productivity (Bouroullec et al., 1995; Saner and Sahin, 1999; Cantrell et al., 2001).

From reservoir management perspective, it is important to understand the occurrence and distribution of dolomite in the reservoirs. At times, dolomite is responsible for producing zones of extremely high permeability and high fluid-flow (super-k) in the reservoir, while at other times these rocks act as permeability barrier or baffles. In fact in Reshadat field the Arab D has a lesser porosity (12 % on average) compared to the lower Cretaceous while the permeability is about 22 md (Jahan-Mahin, 2002). In addition, dolostone typically contains gas a higher grain density and acoustic velocity than limestones, which affects the response of most porosity wireline logging tools to dolostones. Dolostones also reacts more slowly to the presence of acids than does limestone, resulting in uneven responses to acidization treatments.

The Arab D reservoir is characterized by high primary porosity that was preserved because of early or pre-burial diagenesis. The porosity includes moldic, dissolution and vuggy types with intercrystalline porosity reported as being very good and the dominant type in the Reshadat and Salman Arab reservoirs especially Arab C. The thickness of Arab C is constantly measured 25 meters in the Reshadat field indicating a tectonic calm (Jahan-Mahin, 2002). According to Yousefpour (2004), the Arab C is the most porous unit and shows maximum porosity in the Reshadat field in the Persian Gulf. The mean calculated porosity from porosity logs in the Arab Formation ranges from 11 in Arab A to 16% in Arab C. Porosity preservation was not produced by early emplacement of hydrocarbons into an uncompacted reservoir (Purser, 1978; Ibrahim et al., 1981).

CRETACEOUS RESERVOIRS IN THE PERSIAN GULF

Cretaceous carbonate rocks have been extensively explored, drilled, and hydrocarbons have been produced from them since at least 1930. They contain about 16% of the world's hydrocarbon reserves (Klemme and Ulmishek, 1991) while Cretaceous subsurface buildups alone contain about 5% of the total known hydrocarbon reserves (Greenlee and Lehmann, 1993). Yet, the exploration potential is significant because of the vast extent of Cretaceous carbonates and because new play concepts are being developed. Even in the intensely explored Persian Gulf, new areas are available for further testing. The principal Cretaceous reservoirs lie in the Zagros Basin area encompassing parts of Iran, Kuwait Iraq and the Persian Gulf are present in Figure 5-4.

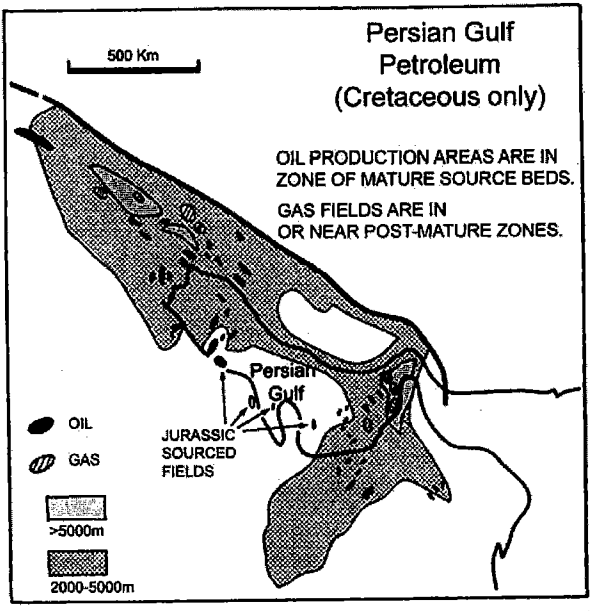

Figure 5-4. Some of the Cretaceous fields in the Persian Gulf region (modified from Murris, 1983).

In the Cretaceous sequences of the Persian Gulf, the primary reservoirs are rudist accumulations having enhanced porosity due to subaerial leaching resulted from relatively minor sea level rise. Primary reservoirs are the cyclic, shallow-water, platform and shelf carbonate grainstones and packstones of the Lower Cretaceous Fahliyan and Dariyan Formations.

Ascending in the geologic succession, it is noted that oil has accumulated at several horizons belonging to the Cretaceous era. Sandstones in the Middle Cretaceous mark an important development in general lithofacies. They form an eastward buldge into the head of the Persian Gulf at least as far as the Soroosh oil field, whereas farther south in the Persian Gulf, they bulge eastward

toward and possibly beyond the Qatar Peninsula. East of the area of sandstones concentrations, a lateral facies change to shale take place.

The deltaic deposits of the Lower Cretaceous of the Zubair and Middle Cretaceous Burgan Formations are the main reservoirs in many fields in northwestern Persian Gulf. For example, the second largest oil field in the world, Burgan, produces from the Cretaceous deltaic reservoirs, as do many surrounding giant oil fields in the southern side of the Persian Gulf.

LOWER CRETACEOUS

The Lower Cretaceous platform carbonate sequences are important reservoirs in the Persian Gulf area. The lower Cretaceous Khami Group marine carbonate reservoirs are sealed by Garau, Gadvan, and Kazhdumi Formations shales. These strata accumulated in one of the great epeiric seas (Murris, 1980) that bordered the Neo-Tethys in the area of the ancestral Indian and Pacific Ocean. Facies deposited at the passive margin of the Arabian platform and in the adjacent basin are encountered in the Persian Gulf region.

The Khami Group includes two relatively high energy limestone intervals (the Neocomian Fahliyan Formation and the Aptian Dariyan Formation) which are separated by a more argillaceous interval (Gadvan Formation). In the Dezful Embayment, the lowermost part of the Fahliyan is replaced by its tight, basinal time equivalent Garau facies. The reservoir characteristics of the Khami limestone are generally poor in the Dezful Embayment, with the exception of a brief lowstand period which led to the deposition of a 20 to 30 meters thick reservoir interval, the Khalij Member of the Gadvan Formation.

The geologic setting, sedimentologic nature, history and locations of the rudist-bearing formations in the Persian Gulf are one of the most important controlling factors relevant to hydrocarbon occurrences because they have high primary porosity. The Lower Cretaceous rudist reef trends in the eastern Persian Gulf Basin is now well established and contributes to the development of giant oil fields, such as Sirri fields.

In the northwestern Persian Gulf region, significant clastic deltaic systems prograded northeasterly from the Arabian Shield, forming major reservoirs in the Lower Cretaceous (Barremian-Aptian), that include Zubair Formation and the Middle Cretaceous (Albian) Burgan sandstone and Lower Azadegan sand. The coastal plain sandstones of the Zubair Formation contain major hydrocarbon reserves in several fields in the northwestern Persian Gulf.

By mid-Albian time the clastic regime had spread across the entire platform except for a narrow belt in the northeast. The Garau Basin was now at its smallest, and separated by a shallow mixed carbonate shelf from the Dezful Embayment sub-basin which was filled by shale deposited in form of the Burgan delta lobe. The coastal and alluvial sandstones of this interval (i.e., the Burgan Formation) are good reservoirs in the northwestern Persian Gulf. They

are sealed by interbedded shales, and have access to charge from the early Cretaceous euxinic deposits of the Garau Basin.

In the uppermost part of the stratigraphic section along the Persian Gulf, Middle Cretaceous clastic deposits are replaced by carbonates because of the sea level fluctuations in the Zagros foredeep as the Zagros Mountains rose. The platform was relatively stable tectonically throughout the Triassic to the Middle Cretaceous interval.

The deltaic deposits of the Lower Cretaceous Kushk Sand Member of the Gadvan (=Zubair) underlying Dariyan Formation with apparent conformity forms reservoir rocks in many fields in northwestern Persian Gulf. The sandstones are soft and clean and in the oil-bearing sections, display little secondary cementation and their primary porosity is well preserved with an average of 23% (Al-Rawi, 1981).

The Zubair Formation (i.e., Kushk Sand Member) of Early Cretaceous age is approximately 420 meters thick and consists of sands and sandstones intercalated with siltstones, shales, and few thin limestone beds (Al-Rawi, 1981). The highly porous unconsolidated Zubair sandstones have variable amounts of shales. There are three potentially productive zones in the northern end of the Persian Gulf with many sand pools separated by shales (Mina et al., 1967).

Cretaceous carbonate reservoirs tend to develop in both transgressive and highstand systems tracts controlled by relative fluctuations of the sea level. Cretaceous reservoirs also occur at the top of coarsening upward sequences and their deposition was often followed by a brief period of emergence. Karstification and leaching during emergence has greatly enhanced the porosities, and such accumulations are consequently prime oil exploration targets (Harris and Frost, 1984). Their significance in forming reservoir is limited by the paleogeographic conditions required for their development, as well as by the critical balance between sediment accumulation rates and subsidence rates in which water depths permitted extensive thick bodies to accumulate.

The Lower and Upper Cretaceous offshore reservoirs include oolite shoals and rudist patch reefs which lie over and/or around the depositional highs formed by salt structures, such as the Sirri fields in the east central Persian Gulf. The Middle Cretaceous sequence in the western part of the Persian Gulf also includes deltaic and coastal sandstone reservoirs which contain oil in Nowrooz, Bahregansar, Foroozan, Doroud, Binalud structures (formerly BB), Soroosh and Hendijan structures. The Early and Late Cretaceous, and Mid-Tertiary diapiric movements are the most effective processes on the reservoir characteristics and hydrocarbon entrapment.

Primary reservoirs are cyclic, shallow-water, platform and shelf carbonate grainstones and packstones of the Lower Cretaceous Dariyan Formation and bioclastic shoal buildups of the Middle Cretaceous Upper Sarvak Formation.

The final cycle of the Lower Cretaceous sequence is the most interesting because it contains a significant reservoir-bearing carbonates. Numerous significant reservoirs are developed in build-ups of caprinid rudists within the

Dariyan Formation. Shelf deposits are frequently bioturbated wackestones and packstones, with the caprinid rudist's build-ups occurring in belts of variable widths which partially rim intrashelf basins. Nearly all of the rudists buildups producing hydrocarbons do so from moldic porosity formed by fresh-water leaching of rudists and other skeletal fragments as a result of the middle Aptian unconformity. Although it is one of the main rudist-bearing reservoirs in onshore and offshore regions of northern Persian Gulf, the Dariyan Formation is not considered as a major reservoir in Mesopotamian Basin (Sadooni and Aqrawi, 2000).

The rudist-bearing carbonates of Dariyan, Sarvak, and Tarbur (=Simsima) Formations contain enormous reservoirs. The exposure of these shallow water bioherms apparently resulted from relative sea level fall. Partially aragonitic rudist shells were readily dissolved by meteoric water. The combination of high sediment production by rudists and their leaching during subaerial exposure affected the carbonate sequence and reservoirs. The basinal source rocks formed during the early part of the next ensuing transgressive cycle sealed the reservoirs.

The Cretaceous carbonate reservoirs tend to be the outcome of diagenetic processes within a facies framework, and traps commonly have both structural and stratigraphic components (see Alsharhan and Scott, 2000). During burial, recrystallization and cementation of calcite from intraformational brines tend to reduce interparticle porosity however subaerial exposure and introduction to undersaturated fresh water with respect to carbonates inclined to enhance porosity by selective carbonate dissolution.

The offshore Iran's Sirri Island with their associated oil fields and the offshore fields of the UAE are all Hormuz salt structures formed during the Late Cretaceous and Tertiary. These fields produced primarily from the Cretaceous reservoirs whereas in the southern Persian Gulf fields also produce from Jurassic and Permian reservoirs.

Significant hydrocarbon accumulations have been found in the Lower Lekhwair Formation (Lower Cretaceous in age). On the basis of sedimentary textures and sedimentary structures, reservoir and non-reservoir lithofacies have been identified (Al-Mansoori et al., 2004). The lithofacies range from open platform, middle ramp to restricted platform subtidal to intertidal environments. Bacinella/Lithocodium packstones to floatstones, floatstones to rudstones, and boundstones, dominate the reservoir zones. Good reservoir quality is developed within skeletal, peloidal packstones to grainstones and algal, skeletal rudstones. Intensively bioturbated carbonates, and interbedded argillaceous limestones characterize the dense units. Reservoir deterioration is also observed directly below the sequence boundary (erosive surface) on top of the reservoir. Diagenesis (cementation and compaction) is interpreted to play a major role in reservoir quality distribution (Al-Mansoori et al., 2004).

Fahliyan Reservoir

The Neocomian age Fahliyan Formation (its lateral equivalents are the Sulaiy, Minagish, Yamama and Lower Ratawi) is one of the oldest Cretaceous reservoir target. It is sealed by the Gadvan and sourced by the Garau and/or the Jurassic Sargelu Formations. In a number of oil fields such as Nowrooz and Darquain, the Khalij Member of the Gadvan constitutes the reservoir.

Regionally extensive carbonates of the Fahliyan Formation are the main productive units within an elongated anticline that partly underlies Kharg Island in the Iranian territorial waters of the Persian Gulf. Additionally, the Fahliyan porous calcarenites and oolitic limestones in the basal Lower Cretaceous are the main pay zone in the offshore Dorood field. This interval was discovered to be well-developed in the majority of the wildcats drilled in the Persian Gulf (Mina et al., 1967).

Fahliyan Formation also produced oil in the Foroozan field, oil and gas in the Dorood field, gas in the Suru field and "Golshan" and Ferdowsi structure discoveries. The thickness of the Fahliyan in the Salman field is more than 20 meters while the Surmeh forms the main reservoir with a gross thickness of about 115 meters. The Fahliyan Formation consists of shallow water massive limestone with a predominance of very thick-bedded strata of a general dark color. It is 61 to 122 meters in thickness and the section is even thicker toward the south of Foroozan oil field.

The Fahliyan limestones are forming gas reservoirs in Qeshm (i.e., Sallakh and Gavarzin) and Kharg Islands in the Persian Gulf. At these localities, the reservoirs are sealed by the Kazhdumi shales. The limestone and dolostones of Fahliyan Formation is considered to be capped by the compact micritic limestone from the Khami Group with poor to no reservoir quality, and ultimately by the micritic to shaly limestones from Lower Ratawi Formation.

The Fahliyan reservoir is a carbonate member composed of wackestone to packestone with shale interbeds. It contains reefal and additional bioclastic materials predominantly in a chalky and fine-grained matrix with large vugs. The carbonates were deposited in shallow water, high energy carbonate platform environment. Porosity consists of intergranular and vuggy components. Some fracture porosity is also present. The rock is firm and partly crystalline where it is developed as a mudstone. Some pyrites are also present.

Two members of the Fahliyan Formation form reservoir characteristics in the Persian Gulf (i.e., in Esfandiyar oil field) the Lower Ratawi carbonate and the Yamama carbonates. However, at the Binaloud C-1 Bushco, the Ratawi limestone is very tight and has low porosity and permeability. The Ratawi Formation also is forming reservoir rocks in Iraq oilfields. These reservoir units are created by partial leaching of oolitic and skeletal limestones. The formation has porosity ranging between 16 to 18%, improving significantly in the crestal parts of the oilfields such as Zubair and Rumaila (Sadooni and Aqrawi, 2000).

The Lower Cretaceous Ratawi Sand is a newly discovered reservoir. The Neocomian Ratawi Formation in the Partitioned Neutral Zone is divided into three sequences: (1) lower Ratawi Oolite; (2) middle Ratawi Limestone; and (3) upper Ratawi Shale. The South Umm Gudair field produces from a thick oil column of the Lower Cretaceous Valanginian Ratawi Oolite reservoir, following its discovery in 1966 (Al-Shaarawy and Barge, 2004).

The Azadegan sandstone member of the Kazhdumi Formation (Burgan "A" sand) and Fahliyan Formation form the main reservoir in Esfandiyar field. The clean limestone succession (Yamama Formation) is oil bearing in Bahregansar field, and forms the main Lower Cretaceous carbonate reservoir in southern Iraq. The formation produces from a combination of leached oolitic facies and slightly dolomitized horizons with porosity values of up to 22% and permeability of about 300 md (Sadooni and Aqrawi, 2000).

The Fahliyan oolitic Formation is also the primary reservoir in Kuwait (i.e., Minagish Field) where it contains 84% of the field's reserves and has contributed over 80% of the field's production. Permeability is good to excellent (200-2000 millidarcies and porosity ranges from 17 to 23 %.

Dariyan Reservoir

The limestone reservoir of the Aptian age which includes Dariyan and its equivalent Shuaiba is an important oil-producing carbonate unit in the Persian Gulf and surrounding regions. The limestone is often a rudist reef facies with calcareous algae and orbitolinids, forming major oil producing reservoirs in several fields in eastern Saudi Arabia, Abu Dhabi, Oman and offshore Iran and Qatar. The formation is almost entirely early Aptian in age.

According to the available information, regionally the rudist-bearing reefs are distributed along a sub-circular trend in eastern Persian Gulf (figure 5-5). The Dariyan Formation and its extension Shuaiba have been studied in great detail in the UAE, where it is an important hydrocarbon reservoir. According to Farzadi (2006) the geometries and sedimentary patterns of the Dariyan Formation in the SE Persian Gulf are not well documented.

Dariyan Formation has produced oil in the Alvand and Reshadat fields, and oil and gas in the Resalat Field. In addition to the Kazhdumi and Garau source rocks, the Dariyan is probably sourced by the shales of the underlying Gadvan Formation. The gross thickness of Dariyan in the Resalat and Reshadat oil fields are 10 and 28 meters respectively. The hydrocarbon production comes from structural closures at different reservoir horizons, these are:

At the top Dariyan reservoir the closure is 41meters and the aerial closure is 58 km^2 in the Resalat oilfield. Dariyan Formation which contains 32° API oil forms the main reservoirs in Resalat oilfield. In general, according to the well log information the porosity of the Dariyan Formation increases towards the Qatar-Gavbandi High. However, the porosity values decrease eastward towards the Strait of Hormuz.

Based on the petrographic and well log information, the porosity of the Dariyan Formation in most of the drilled well in the Persian Gulf proper is of microporosity nature. In the absence of major diagenetic effects and fracturing in order to create effective porosity, the formation lack substantial reservoir characteristics. The porosity trend is a function of the facies distribution and the middle ramp facies often display good porosity. According to the log records the porosity ranges from nil to 30% and shows an increasing trend from the Strait of Hormuz toward the Qatar-Gavbandi High. This also corresponds to the facies changes from inner to middle ramp facies. Near the Strait of Hormuz area, the inner ramp facies are represented by mud supported textures and that is the main factor in porosity reduction. Similar trend in porosity is observed toward the northwestern Persian Gulf (Moradi, 2002).

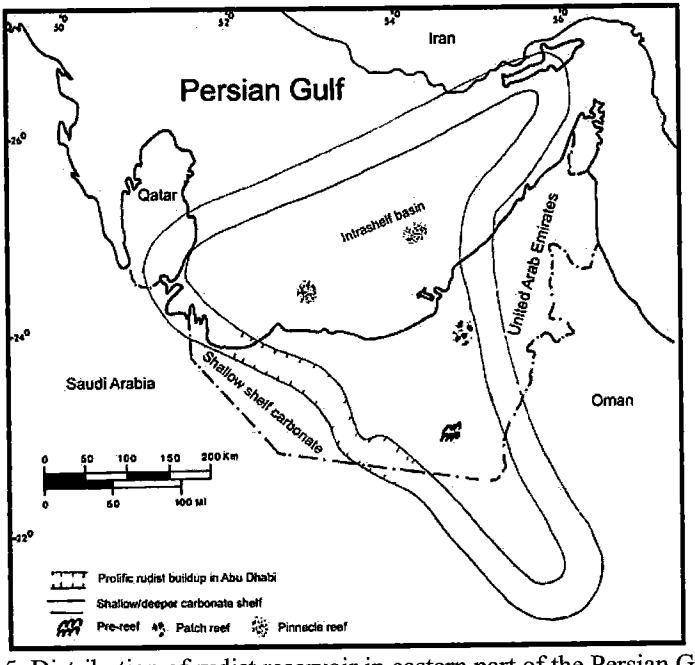

Figure 5-5. Distribution of rudist reservoir in eastern part of the Persian Gulf (after Frost et al., 1980).

There are three main sedimentary sections including; the restricted inner shelf, the open inner shelf, and the outer shelf. The presence of grainstones in the inner shelf is confined to the transgressive sequence, whereas the presence of rudist-bearing beds in the outer shelf is significant in regressive sequences (Moradi, 2002).

Dariyan Formation in the northwestern parts of the Persian Gulf shows an average of 13.4% porosity with average shale content of about 19.8%. The highest porosity has been reported from the Nowrooz oil fields and the lowest

observed porosity has been measured at the Mahshar field. Towards the east, average porosity is close to 24% and the shale content remains the same. As a result, towards the Qatar-Gavbandi Arch and neighboring area, the Dariyan carbonates show significant improvement and better reservoir characteristics (Moradi, 2002).

The Dariyan carbonates are forming reservoir rocks in Doroud and Kharg Island. In the southern Persian Gulf the Dariyan Formation forms a complex carbonate reservoir characterized by small-scale geological heterogeneity primarily related to rudist macrofauna. Additionally, it displays pronounced vertical and lateral lithologic variations produced by the development of rudist reef complex over an algal platform. The textural heterogeneity corresponds to extreme permeability variation that is the controlling factor in reservoir production. It comprises mostly of shallow-water limestones and argillaceous limestones and it forms the most geologically complex reservoir in the UAE, consisting of shallow-water shelf carbonates in the south and deeper water slope sedimentary rocks in the north.

Great variations in reservoir productivity result from differences in facies, texture and biota. In particular, four different biofacies are recognizable, dominated by rudists, corals, stromatoporoids, or algae. Nearly all the rudist buildups are producing hydrocarbons from moldic porosity formed by fresh water leaching of rudists and other skeletal fragments during the late Aptian unconformity and the subarerial exposure.

In many places, the upper part of the formation consists of rudist buildups, forming important reservoirs immediately beneath the sedimentary break. The reservoirs display preserved primary porosity and/or solution-enhanced and moldic porosity. The petrophysical characteristics (porosity and permeability) of the reservoir in the subsurface are primarily related to the depositional fabrics and relative abundance of the skeletal components, especially the rudists (Borgomano et al., 2002). The hardground and correlative sedimentary gap are attributed to different processes: emergence and erosion, non-deposition in a persistent marine environment, or polygenic evolution of marine hardground succeeded by subaerial exposure.

Some authors (e.g., Harris and Frost, 1984; Harris et al., 1985; Scott et al., 1988) attributed the porosity development to a short but pronounced late Aptian eustatic drop, during which subaerial exposure and dissolution by fresh water resulted in the leaching of the rudists and other bioclasts (Montenant et al., 2003). An alternative model attributes the development of porosity to the deposition of carbonates in seawater around the sequence boundary, without long-lasting emergence (Pratt and Smewing, 1993).

The potential of the rudist buildups as hydrocarbon exploration targets results from the interaction of three main factors;

- Development of an intraplatform basin by differential subsidence, establishing deep open-marine conditions on what had formerly

been a shallow carbonate platform and localizing a buildup-prone belt and around its rim;

- A rapid euststic rise in the early Aptian causing the buildups to grow vertically in contrast to the sheet-like biostromes of rudists or coral/algal communities which typify a low relief platform,
- Stratigraphic position of the buildups in the late Dariyan (perhaps resulting in part from the initiation of a sea-level drop at this time) positioning them favorably for subsequent fresh water leaching.

The best porosity resulted from leaching of mollusks and foraminifers and microporosity may also develop in the micritic matrix of packstones by complex secondary processes. For example, intercrystalline matrix microporosity is formed within microrhombic calcite matrix in Shuaiba Formation in the subsurface of Oman (Al-Awar and Humphrey, 2000). Meteoric diagenesis at subaerial exposure contacts stabilized matrix calcite resulted in microrhombic crystals and microporosity. Associated grain leaching has further enhanced porosity and permeability within the sequence. Traps commonly are sealed by thoroughly cemented fine-grained limestones, evaporites, or shales.

Moldic and vuggy porosity are important in Natih Formation reservoir in the UAE because subaerial exposure leached many bioclasts (Alsharhan and Scott, 2000). Likewise, the Shuaiba Formation in the UAE has porosity up to 32% and permeability between 1 and 160 md. (Alshrahan et al., 2000).

Bangestan Reservoirs

The Middle Cretaceous carbonates in the Persian Gulf region are among the most productive oil-bearing stratigraphic intervals in the world, containing numerous giant fields. As a consequence, the Middle Cretaceous sedimentary sequences are of primary importance in terms of carbonate petroleum systems in the Persian Gulf.

The Bangestan Group includes thick Sarvak limestone (300 to 1000 meters thick) and the thinner Ilam Formation (50 to 200 meters thick). These two reservoir intervals are separated in Lurestan by the Surgah marls but form a single reservoir in most of the Dezful Embayment.

Two depositional facies can be recognized in the Sarvak Formation. These are a high-energy, neritic facies with massive limestones, rich in gastropods, pelecypods, large foraminifera and rudist debris, often has good reservoir characteristics; and a basinal equivalent, tight, micritic, often argillaceous limestone, known as the "Oligostegina facies" (Motiei, 1993).

Cenomanian-Turonian carbonates of the Bangestan Group in the Persian Gulf region and in particular southwestern Iran form important reservoirs, where they are developed in neritic facies. This is primarily in the Dezful Embayment in the northern Persian Gulf, where they reach a thickness on the order of 1 kilometer with a considerable facies variation in a regional scale.

The Bangestan carbonates have experienced a complex diagenetic history, and the secondary porosities are very low and patchy. Again, it is the fractures that provide the reservoir characteristics. Indeed, in several Iranian oil fields the fractures extends upward through the argillaceous Upper Cretaceous and Lower Tertiary to the Asmari, to provide communication between the two reservoirs. As a result they can contribute significant hydrocarbons to the upper horizons.

Azadegan Sand Member

The primary reservoir in some of the oilfields in the Persian Gulf such as the Foroozan field is formed by the fluvio-deltaic sandstones of the Middle Cretaceous occupying the lower part of the Kazhdumi Formation (Azadegan Sand member or Burgan /Nahr Umr).

The Azadegan sandstone member (=Nahr Umr) is one of the main clastic hydrocarbon producers in the Cretaceous system. This formation is comprised of four clastic reservoir facies with intercalation of shale laminations. In many areas the upper zones are in communication with the Mauddud reservoir at faults through juxtaposition. Because of the high shale content, the Azadegan sandstone member is not a major oil reservoir in the northwestern part of the Persian Gulf, as its equivalent Burgan Formation is in Kuwait.

The Azadegan Sand member of the Kazhdumi Formation (i.e., Burgan member) in Foroozan field is divided into a lower massive sandstones unit (designated as Burgan-B) and also an upper shalier unit (designated as Burgan-A). The Azadegan sandstone member of the Kazhdumi (Nahr Umr) is also the oil producing reservoir in the Nowrooz field. Figure 5-6 shows the stratigraphic column in Nowrooz field with Azadegan Sand Member.

A rapid sea level fall in early Albian initiated the deposition of Azadegan clastic reservoirs over the Dariyan Carbonates in northwestern Persian Gulf. Therefore, the Azadegan sandstones form the main reservoirs and principal pay zone in northwestern Persian Gulf in Soroosh, Foroozan and Nowrooz oil fields. Oil has been tested in a number of other wildcats drilled in Persian Gulf as well (Mina et al., 1967).

The lower part of the Azadegan Sandstone (i.e., Burgan B) is the main reservoir in Soroosh field which ranges in thickness across the field from 52 to 73 meters. In this field, the lower part of the Azadegan Sandstone interval comprises well connected channel sands of 25-29% porosity and permeability in the range of 5-11 Darcy. The unit is very permeable, black sandstone, known locally as black caviar because of its coarse, black grains with high reservoir permeability (Denby et al., 2003).

Figure 5-7 illustrates the relationship between the Azadegan sandstone and the Kazhdumi lithofacies in the vicinity of Nowrooz. Some of Azadegan sand member cross the Nowrooz structure and are forming the reservoir for structural accumulations. It is likely that on the west flank of the Nowrooz field

additional sand bodies exists that shale out updip before they reach the crestal Nowrooz and Nowrooz NE wells. It is also possible that the Azadegan sand bodies near the top of Kazhdumi are truncated by the Turonian unconformity as indicated in figure 5-7. The overlying Gurpi shales and or Ilam argillaceous limestone should provide an adequate seal.

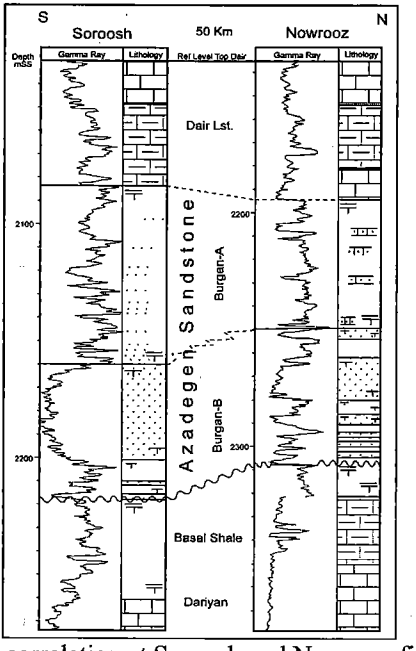

Figure 5-6. Reservoir correlation at Soroosh and Nowrooz fields (modified from (modified from Denby et al., 2003).

The Azadegan Sand member with good permeability is hydrocarbon-bearing in Bahregansar oil field. Since shale content of the Azadegan sandstone member is high, as a result it is not forming a major oil reservoir in Mesopotamian Basin in northwestern Persian Gulf, as its equivalent Burgan Formation is in Kuwait.

The Nahr Umr Formation is one of the main clastic hydrocarbon producers in the Cretaceous system. It is overlain by the Mauddud Formation with intervening shale and unconformably overlies by the carbonates of the Dariyan (Shuaiba) Formation. The basal contact is a regional unconformity having a complex history that in outcrop may span up to 2.2 million years or more (Scott et al., 1988). The widespread occurrence of clastic sediments of the Nahr Umr clearly manifests the prevalence of marginal marine deltaic regime with an easterly progradation in a north-south oriented depositional strike. Reservoir consists of fine-grain sandstone to siltstone, moderately well-sorted, rounded to subrounded, glauconitic, with thin beds of calcareous shale.

Burgan Sandstone

The Burgan Sandstone constitutes the main producing horizon in Kuwait fields. The Burgan is an accumulation of coarse-grained, unconsolidated and highly porous sandstones. The productive zones of the Burgan field occur within Middle Cretaceous sediments (Burgan and Mauddud) (Denby et al., 2003).

Burgan field is among the largest oil fields in the Persian Gulf region. The reservoir sands were formed by erosion of uplifted Paleozoic-early Mesozoic sandstones (Kamen-Kaye, 1970) where the halokinetic-basement horst block structures played an important role (Murris, 1980).

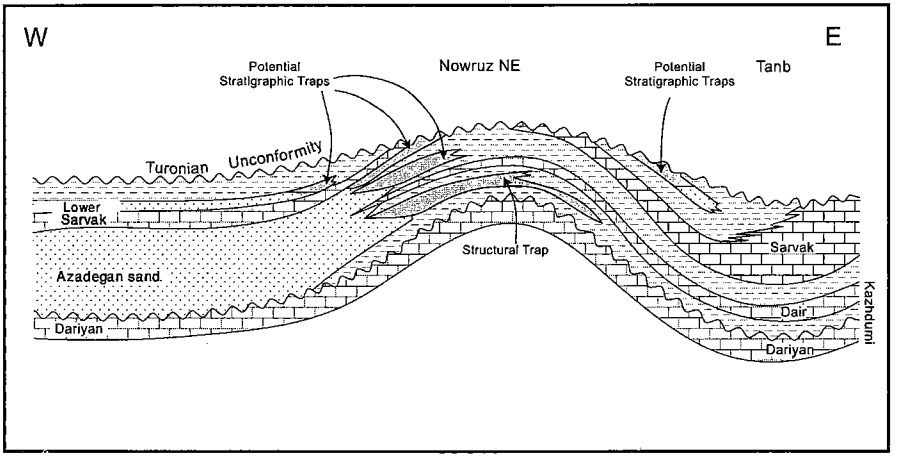

Figure 5-7. Stratigraphic play concepts of Kazhdumi and Ahmadi at the Nowrooz field.

The average reservoir thickness at Burgan may be 270 meters (Kamen-Kaye, 1970). These thick sandstones have retained almost all of their original porosity. The reservoir is overlain by a relatively insignificant cap of about 10 meters of shale, and underlain by thin but continuous shale which connects with a thicker shale body. However, despite the close relation of sandstone (reservoir) and shale (potential source), the shale appears to be essentially unpetroliferous.

Burgan Formation has been informally subdivided into Lower and Upper members, which are the most important oil-bearing units. The lower Burgan member (i.e., the B member) includes a very thick section of high quality reservoir sandstone and contains most of the reserves. The upper Burgan member (i.e., the A member), although smaller, is also considered as a giant reservoir interval.

The lower member is represented by massive sandstone reservoirs. High frequency sea level changes have resulted in deposition of shoreface sands

and extensive marine shales within an overall fluvial setting. The middle part Burgan was deposited in a transgressive systems tract (Hussain et al., 2003).

The upper part witnessed a relative sea level fall in a lowstand systems tract with deposition of sand prone facies in estuarine channels. Estuarine channel sand deposits govern the upper part of Burgan Formation. The clastic cycle was terminated by initiation of Mauddud carbonate sedimentations in transgressive systems tract. The amalgamated braided channel sands of the Lower Burgan Formation traps giant pools in Kuwait with active bottom water drive (Hussain et al., 2003).

Depositional history of the reservoir has been described under three broad categories. The lower Upper Burgan reservoir consists of cycles of shore face sands and marine shales. The marine shales are laterally extensive reflecting important high frequency sea-level changes. A low stand system tracts (LST) is interpreted in the middle upper Burgan and represents a time during which a complex pattern of stacked channels were deposited. The estuarine shales are discontinuous and act as local baffles. The upper Burgan was deposited during an overall transgressive event.

The oil reservoir in the Upper Burgan sandstone in the offshore Kuwait in the Persian Gulf has an average thickness of 50 meters, of which nearly 70% is permeable. Average porosity is 24% and average permeability is 1035md which is approximately similar to the lower Burgan reservoir. The Upper Burgan sandstone reservoir is underlain by a thick shale development that forms the seal for the deeper and larger oil accumulation in the lower sandstone of the Burgan Formation.

The Upper Burgan reservoir has a net-to-gross sand ratio ranging from 0.2 to 0.9. Due to the overall clay-rich nature and very fine-to fine-grain size, the ductile content is the fundamental control on reservoir quality. As a result, permeabilities are a function of lithotype. However, grain size is also critical to permeability, particularly within the cleaner and better-quality lithotypes. Diagenetic modification is of local importance (Al-Eidan et al., 2001).

Sarvak Reservoir

The Sarvak carbonates of the Persian Gulf region are proven exploration targets for hydrocarbon and form reservoirs of numerous oil fields in the Persian Gulf. The regional Turonian unconformity marks the upper boundary of this formation.

The Sarvak marine carbonate oil-producing reservoirs are sealed by Upper Cretaceous Ilam carbonates and the in some locality by the overlying Gurpi shales. Many of the oil fields including the Sirri fields in the Persian Gulf produce from the Sarvak Formation reservoirs.

In terms of reservoir characteristic and their potentials, two members of the platform limestones of the Sarvak Formation might be prime contender for accumulation of hydrocarbons these include; the Lower Sarvak (i.e., Maud-

dud) and the Upper Sarvak reefal limestone. The other two members of this formation (i.e., Khatiya and Ahmadi) comprise basinal and deeper shelf pelagic limestones.

Generally the porosity of the Sarvak Formation in the Persian Gulf area where the formation has been encountered is estimated to range from 4 to 20%. One of the Sarvak reservoir characteristics is that they vary laterally and vertically within the sedimentary succession. The Laffan shales marking the post-Cenomanian unconformity form the cap rocks. Cenomanian-Turonian subarerial exposure and associated karsts carved into rudist-rich limestones at the Upper Sarvak.

In addition to forming reservoirs in several Persian Gulf oil fields, Sarvak Formation forms the main reservoir rocks in Bahregansar. In this oilfield, the formation consists of dolostone and fractured calcareous dolostone. Important unconformities, affect the upper and lower parts of the Upper Cretaceous sediments. Due to the occurrence of these unconformity surfaces in different part of the area, the Sarvak Formation appears to be eroded away and in some areas it is completely missing. A regional unconformity capping Cretaceous lithologic sequence was formed in the Upper Maaestrichtian and marks the boundary between Cretaceous and Tertiary sequences. Porosity developed within these rock sequences is partly moldic, formed during this exposure.

In the Nowrooz oil field due to the high clay content (e.g., in well # 5), the reservoir characteristics of the Sarvak has been greatly diminished. Generally the Upper Sarvak has a low reservoir potential in northwestern Persian Gulf and this might be due to factors such as erosion, presence of clays in the formation, the existence of suitable reservoirs in stratigraphically lower horizons, and finally the lack of proper seal rocks.

Lithologically, most of the Sarvak Formation reported in the Hengam area is mainly packstone to mudstone. The formation consists predominantly of limestone with minor shale interbeds. These limestones are mainly dense shelf carbonates exhibiting poor primary porosity. Good permeability reported in the formation in the HE-E1 well is assumed to be due to reservoir fracturing. Fracturing is a common occurrence accounted for the storage of the hydrocarbons in large open fractures and in micro fractures.

Lower Sarvak Reservoir

The Lower Sarvak Formation (i.e., Mauddud member) is a shallow-water carbonate with extensive distribution in the subsurface of the Persian Gulf. This part of Sarvak Formation is an important rock unit in terms of regional distribution and thickness all over the Persian Gulf. It has produced huge quantities of oil since the 1940's, and it is promising that it may hold more oil in other potential areas.

The Lower Sarvak carbonates consist for the most part of Orbitolina-bearing limestone with local basin margin rudist buildups in the North field of

Qatar and South Pars Field in the Iranian waters of the Persian Gulf. A couple of factors strongly affected the porosity evolution and modification. First, the upper part of this part of formation is marked by the presence of an unconformity and as a result it may have been subjected to widespread meteoric diagenesis. Second, after its deposition, some portions of the lower Sarvak while depositing in the basin witnessed strong igneous activities, including ophiolite intrusion in Oman (Bolton, 1958, cited by Buday, 1980). The first factor created or possibly modified the regional porosity whereas the second factor may have been responsible for development of extensive interlocked and, at least, partially thermally induced dolomitization. Widespread dolomite formation, with wide variations in both extent and texture, has been reported from wells (Hajikazemi Ph.D in prep).

Porosity ranging from 10 to 35% and permeability of 10-110 md has been reported from different oil fields in the Persian Gulf for the Lower Sarvak. Such high porosity values could be attributed to combination of fracturing and diagenetic processes such as dolomitization and dissolution.

The formation has high oil potential in the northwestern Persian Gulf and the offshore areas of Qatar and Saudi Arabia as well as northern parts. Most of the oil fields that contain significant oil potential in the Lower Sarvak are located offshore in oil fields such as Marjan. From the facies and lithologic description, it appears that the Lower Sarvak in some of the fields such as Foroozan in Iranian waters of the Persian Gulf has many similarities with the offshore oil fields in Saudi Arabia and Qatar. In Kuwait, the relatively thin succession (5-10 meters) diminishes the importance of this formation as a major reservoir rock.

The Lower part of Sarvak thins out in eastern parts of the Persian Gulf; however, it shows porosity ranging from 4 to 28%. In the western parts, the porosity is about 9%. Considering the reservoir parameters and reasonable thickness, this horizon has a very good reservoir potential for hydrocarbons. However, the lack of hydrocarbon in the drilled wells such as in the Abouzar field might be due to unsuitable cap rocks and in other areas might be because the drilling has been performed off-structure (Motiei pers. commu).

The Lower Sarvak (i.e., Mauddud) limestone forms a giant oil reservoir in the Sabiriyah field of the northern Kuwait. Effective horizontal permeability is composed of matrix permeability, associated with secondary porosity and fracture permeability. Matrix permeability is mostly related to initial effective porosity whereas permeability associated with secondary porosity mainly takes the form of vuggy grainstone bodies. Fracture permeability is largely lithologically controlled. Low porosity, brittle cemented zones adjacent to more ductile and porous zones tend to be fractured preferentially.

Reservoir characteristics of the Lower Sarvak carbonates are also strongly affected by post-burial diagenetic processes. The high-energy grainstones and clean packstones preserve primary rock fabric. The mud-rich packstones and wackestones show high degree of degradation of reservoir properties due to

growth of carbonate concretionary cements. The early emplacement of hydrocarbons appeared to have detained the concretion growth, while in water leg the growth continued till the primary porosity is destroyed (Hussain et al., 2003). Thus, it appears that the reservoir characteristics of Mauddud member carbonates are strongly affected by post-burial diagenesis.

Upper Sarvak Reservoir

The Upper Sarvak (i.e., Mishrif Member) is an extensive carbonate succession in the Persian Gulf and surrounding regions. This member is a productive hydrocarbon reservoir and host a number of world class giant fields. It has been divided into a number of lithofacies in detailed by Schlumbereger (1981), Jordan et al. (1985) and Hajikazemi et al. (in prep).

These rudist-bearing carbonates are confirmed exploration targets and form the reservoirs in numerous oilfields in the Persian Gulf. Traps have a number of configurations and are mainly combination of stratigraphic and structural types, formed by truncation of reef, near-reef and forereef carbonates, but all are sealed by the regionally continuous basal marine shale of the overlying Laffan and in some of the oilfields by Gurpi and Fiqa Formations.

The Upper Sarvak is one of the unique successions in the entire Persian Gulf region. These carbonates are also the principal reservoir facies in the Mesopotamian basin in northwestern Persian Gulf (Sadooni and Aqrawi, 2000). Reservoirs are characterized by high porosities (20% average) and permeabilities (average of 200 md, but may reach up to >1d) (Sadooni and Aqrawi, 2000).

The Upper Sarvak possesses widespread good reservoir characteristics in different oil fields (see Table 5-1), particularly where it lies directly beneath the Turonian unconformity in the Persian Gulf. The traditional concept of widespread epeirogenic uplift and erosion at the end of the Sarvak producing the major unconformity is confirmed in many areas including the Sirri fields in Iranian side of the Persian Gulf.

In the Reshadat oil field in the Persian Gulf, the Upper part of the Sarvak has been divided into five different zones with the topmost zone showing great reservoir characteristics. The average porosity in the Upper Sarvak in the Reshadat field is 20.19%, indicating a high porosity. This zone consists of pure crystalline limestones whereas the lower zones are finer and the clay content increase downward. In addition to fracturing, diagenetic processes such as dolomitization, dissolution have been responsible for enhancement of the reservoir porosity and permeability. It is important to note that similar to the Nowrooz oil field, at the center of the Reshadat structure the topmost zone has been heavily eroded by an unconformity surface (Fathi, 2003).

Table 5-1 Data on selected Upper Cretaceous fields in Persian Gulf.

Field	Reservoir facies	Reservoir thickness	Porosity (%), and permeability (md)	Hydrocarbon Type	Approximate original OIP (whole Field)
Sirri C	Slope/shoal	10(m)	20-26%, 17-50	OIL/GAS	>200 MMbbl
Sirri D	Slope/shoal	30(m)	25-30%, 150-600	OIL/GAS	>100 MMbbl
Sirri E	Slope/shoal	35(m)	10%	OIL/GAS	>400 MMbbl
Fateh	Reef/shoal	81(m)	5-25%, 15-50md	OIL/GAS	3.5 Bbbl
Nosrat	Reefal Lst	45(m)	20-25% , --- ------	OIL/GAS	>100 MMbbl
SW Fateh	Reef/shoal	90(m)	5-25%, 5-50md	OIL/GAS	3 Bbbl
Falah	Reef/shoal (?)	45(m)	19%(ave), 5-12 md	Oil	>100 MMbbl
Mesopotamian	Rudist Lst.	---	20%(ave), 200md	Oil	----

Because of shoaling to the point of emergence, the Upper Cretaceous was subjected to truncation along positive relieves and axes, resulting in a major unconformity. The effects of this regional unconformity are severe is southern Kuwait, less so in northern Kuwait and southern Iraq (Owen and Nasr, 1958). The difference probably reflects simultaneous regional tilting towards north that caused Cretaceous succession to thicken in that direction and mitigating the effects of the erosion.

In the Sirri fields, the post-Turonian unconformity completely stripped the Upper Sarvak off the crest of the structures. Extensive dissolution during the subaerial exposure led to the development of biomoldic porosity. Reservoir is sealed by the overlying Laffan shale and sourced by Khatiya Formation (TOC of 1.5%).

In general, the unconformity above the Upper Sarvak is more distinct to the east than in the western part of the Persian Gulf, presumably in response to thrust loading in Oman Mountains. Thus, the truncation is probably an artifact of tectonic factors modified by sea-level variation.

The Upper Sarvak reservoir quality is facies dependent to a large extent, however it is particularly good quality where the carbonates were exposed to meteoric diagenesis and leaching at the Turonain-Cenomanian unconformity. This was first presented by the model put forward by Burchette and Britton (1985).

The Upper Sarvak carbonates accumulated as a progradational, low energy seaward margin in marginal slope, shoal-back shoal, and lagoonal setting, containing most of the oil in Middle Cretaceous rocks of the Persian Gulf and has the best potential reservoirs. It is a bioclastic carbonate that is locally

dominated by radiolitid rudists. Bioclastic shoal facies form major reservoirs for the southern Persian Gulf oilfields. These reservoirs are sealed by the overlying Coniacian Laffan shales in the Sirri and Fateh oil fields. In addition, the Laffan/Upper Sarvak contact shows a deeply weathered profile in the siliceous oil zones at the top of the limestone. Moreover, as the diapiric structures moved vertically, relatively minor part of the rudist core facies and the back reef lagoonal sediments was preserved (Jordan et al., 1985).

The erosion underneath the Laffan shale has removed reefal facies from the crest of the structures. Excellent reservoir porosities and permeabilities of the rudists core and fore reef debris apron results from remnant primary porosity being enhanced by fresh water leaching throughout the period of post-Cenomanian subaerial erosion.

As a result of depositional features and diagenetic processes, the reservoir facies are to some extent variable. Accordingly, the porosity and permeability distribution within the formation follows a complicated trend, mainly controlled by depositional facies distribution and later diagenetic processes. Based on the available information (see table 5-1), it can be stated that the Upper Sarvak porosity varies from less than 15% to 30% (Hedayati, 2003). It is also important to note that the porosities of the reef and near reef facies in the Upper Sarvak trend are 25-30% and permeability averages 50 millidarcy (Jordan et al., 1985).

According to Hedayati (2003) the main part of the Upper Sarvak reservoir interval that corresponds to forereef and reefal limestone in the Sirri Island area has porosity ranging from 25 to 30% and there appears to be no sharp lateral porosity change within the reservoir in the area. It is also important to point out that in the Reshadat and Resalat fields, the reservoir facies change abruptly laterally and vertically. Such a facies change could be attributed to the environment of deposition and to the back-reef facies depositional setting.

The molluscan packstone-grainstone facies that cap the shoaling upward successions (commonly localized by highs) contained a great deal aragonitic bioclastic material, mainly rudistid, allowing the formation of large volumes of moldic porosity (maximum value of 35%, but mostly 10-25%) during meteoric leaching. In many cases, partial formation of meteoric cements means that this facies commonly has a good to excellent permeabilities (maximum several Darcys, mostly 10-1000 md) (Harris and Frost, 1984; Burchette and Briton, 1985). Reservoir heterogeneity within this facies is generally rather low, although good rudist reefal facies have a fairly local distribution.

Where the Upper Sarvak consists of shoaling cycle reservoir attributes increases upward through the section so that finer grained slope facies (although significantly porous) contain much microporosity and generally exhibit low permeabilities (commonly just a few millidarcys). Hydrocarbon recovery may be complicated where this transition zone falls within the reservoir section. Several studies in the southern part of the Persian Gulf and adjacent to the

Iranian maritime borders (cited in Burchette, 1994) documented development strategies and production problems encountered in Upper Sarvak reservoirs.

Top of the Sarvak Formation in the Sirri oil fields in northern Persian Gulf are considered to have excellent reservoir quality and determined exploration targets for hydrocarbons. It provides the most reservoir characteristics and excellent quality in oil fields such as Sirri, Alvand and Alpha-1 (IMINOCO). On the Sirri C and D fields, the 3D seismic interpretation resulted in the accurate definition of structural geometry of the top of the Sarvak reservoir. This also illustrated clearly the presence of a crestal graben on both fields with structures developed largely as flexures over salt diapiris. In some of the large fields such as Sirri much of the Mesozoic stratigraphy produces oil or gas from such traps (Hedayati, 2003).

In western parts of the Persian Gulf, the porosity in the Upper Sarvak is more than 6%. Considering the thickness of this portion and its high shale content, in this area, the upper part of the formation can not be considered to develop good reservoirs. The main reason is the erosion of this formation due to the presence of the Turonian unconformity and its role in reservoir creation. However, in the eastern Persian Gulf the formation has good reservoir characteristics. The porosity of the Upper Sarvak ranges from 3 to 23% and good traces of hydrocarbon exist in this horizon which is covered by excellent cap rocks. This is in fact the case in oil fields such as Sirri, Nosrat, Reshadat and Resalat. At the top of Sarvak reservoir the closure is about 33 meters and the aerial closure is 18 km^2 in the Resalat oilfield. According to Hedayati (2003), combination and interaction of several different factors have contributed to the formation of excellent quality reservoir facies in the Upper Sarvak. These include;

- Formation of reefal and forereef depositional facies, bioclastic packstones to grainstone during deposition of the Upper Sarvak, providing excellent porosity and permeability,
- Occurrence of major unconformity at the top of the Sarvak with the accompanied laterally extensive subareial exposure,
- Meteoric diagenesis of Sarvak carbonates and fresh water leaching of unstable carbonates during the Turonian with the formation of secondary porosity (i.e., moldic and vuggy) and fracturing, locally enhancing and improving the permeability,
- Formation of several lithofacies with different sedimentologic and petrophysical properties.

The combined effects of all these factors resulted in formation of superb quality reservoir facies in some of the oilfields and the prospectiveness within the Persian Gulf area.

Khafji and Safaniya Reservoirs

Some of the world's largest oil fields occur in western offshore area of the Persian Gulf, primarily producing from fluvial-deltaic reservoirs. Safaniya Sandstone Member of Albian is one of the important hydrocarbon reservoirs of the Mid-Cretaceous in the northwestern Persian Gulf.

Khafji reservoir which is part of the Albian Khafji Member conformably overlie platform carbonate facies of the Dariyan (=Shuaiba) Formation and are conformably overlain by fluvial-deltaic facies of Safaniya Member.

Safaniya Sandstone Member is the stratigraphic equivalent of the upper part of the Azadegan and Burgan Sandstone in western Persian Gulf, and grades into shales of Kazhdumi Formation towards the northeast and east in the Khuzestan subbasin in the northern Persian Gulf (James and Wynd, 1965; Murris, 1980). Safaniya Member is underlain by the predominantly clastic, basal Khafji Member and overlain by the Mauddud limestone member. The Kazhdumi shales were deposited as prodelta/offshore shales in front of the Safaniya-Burgan delta lobe.

Near the Persian Gulf, the Safaniya is about 110 meters thick and consists mainly of sandstone with some shale and local limestone interbeds. Generally, the sandstone/shale ratio in Safaniya is about 12. These rocks were subjected to uplift during the Late Cretaceous. Therefore, after its initial cementation, the Safaniya was affected by meteoric water flushing and leaching from the paleocoast probably during the late Cretaceous uplift. Structural traps in this part of the Persian Gulf also started forming at this time, although structural growth continued during the Eocene, and additional structures developed in Plio-Pleistocene (Cagatay et al., 1996).

The precipitation of authigenic clays, silica and carbonate cements in the reservoirs have reduced the porosity of these rocks by an average of about 9% of their bulk rock proportion. Clay mineral formation as pore filling cement has also caused insignificant reduction in the permeability of these reservoirs. Porosity of these rocks range between 25 and 30%. About a quarter of this porosity is the result of calcite and feldspar dissolution (Cagatay et al., 1996).

Ilam (Halul) and Mansouri (Simsima)

The Ilam Formation and its equivalent Halul Formation are considered as reservoirs in some parts of the Persian Gulf. Except in the Qatar-Gavbandi Arch area, the Upper Cretaceous Ilam Formation (Santonian to Campanian) appears to have been deposited in central parts of the Persian Gulf. In the Sirri-A oil field, this formation mainly consists of dense shelf carbonates and exhibits fracture porosity and forms the main hydrocarbon reservoir. It is also important to note that in some areas, fractured Ilam carbonates are considered to be potential reservoirs.

The Ilam facies are shallow marine with the lowest thickness encountered around the Strait of Hormoz ranging from 11 to 27 meters. However, in the western part of the Persian Gulf its thickness increases from 55 to 100 meters. In general, the average thickness of the formation is about 100 meters with the upper portion showing an excellent geological and seismic marker in most part of the Persian Gulf (Hedayati, 2003).

Regionally, there is a considerable facies variation observed within the Ilam Formation. For example, in Lorestan, nearly the entire sequence consists of pelagic facies with slight possibility of the formation being considered as having reservoir potential. In addition, these carbonates in southwestern Iran have undergone a complex diagenetic history, and secondary porosities are very low and patchy. Yet again, it is rock fracturing that provides possible reservoir characteristics.

Regarding Ilam Formation in the Persian Gulf area, the highest porosity has been measured in Farzad oil field which is about 23% whereas the lowest porosity is at 7% observed in Bahman oilfield. The thickness and some reservoir parameters have been presented in Table-5-2.

Table 5.2. Thickness and some reservoir parameters in Ilam Formation, Persian Gulf

Well #	Thickness (m)	Porosity (Φ $\Delta\tau$)	Volume of shale
ARH#1	68	14.3	14.4
Dorood	24.4	13	8
ASK#1	68	8	14
FC#1	76	11	18
FB#1	46.1	23	23
FRB1	102	20	15
G#3	113	19	8
HE-E1	26	3	4
R#32	100.5	19	19
SIF-1	82	6	13
U#1	58	12	19
TUE#2	76	19	21
O#4BIS	64	23	20

The porosity of Ilam Formation is more than 11% in the northwestern Persian Gulf where the presence of the hydrocarbon appears to be directly related to the available porosity and also to the lower quantity of shale in the reservoir. However, the lack of hydrocarbon might be attributed either to the structural factors or to the lack of proper cap rock in the area. In oil fields such as Abouzar, the high shale content which often reaching up to about 14% might pose another important problem for the suitable accumulations of the hydrocarbon in the system (Rostami, 2002).

Ilam Formation in the eastern parts of the Persian Gulf displays porosity between 4 to 21%. In many of the drilled wells (SIE-1, SIE-3, 3H-1 FR-A1 and IMD-1) traces of hydrocarbons have been reported. Considering reservoir

parameters and the thickness of Ilam Formation, it appears that the formation has good reservoir potentials. Such trends seem to continue towards the Strait of Hormoz (Rostami, 2002). There are also a number of oil shows in the Ilam Formation in the offshore southern Persian Gulf area, primarily in the fracture porosity for examples at the Shah Field.

In the Ilam Formation and its lateral equivalent Halul Formation fracture, intercrystalline and vuggy porosity are occasionally present although they are frequently occluded by secondary carbonate cements. The limestones of the Halul Formation in southern Persian Gulf exhibit moderate porosity and low permeability (Al-Sharhan, 1989). Heavy oil accumulations are discovered in this formation.

Adjacent to the Sirri fields in the Iranian waters of the Persian Gulf, the Ilam Formation in the Fateh field contain hydrocarbon and is considered as a secondary reservoir while in the southwestern Fateh field it contain non-commercial hydrocarbon. The discovered hydrocarbon appears to be very similar to oil found in the Upper Sarvak reservoir. The hydrocarbon might have been migrated upwards from the Upper Sarvak along the fault zones or due to the lack of Laffan shale as cap rock (Bargrizan pers. commun).

Commercial hydrocarbon in the Upper Cretaceous of the Persian Gulf is not only confined to the Ilam but also is discovered in the Simsima Formation and these formations can be considered excellent exploration targets. The Shah oil field in the southern Persian Gulf is producing from Simsima (=Mansuri limestone of the Gurpi Formation), primarily from moldic and vuggy porosity. The porosity of the formation is 14-21% and the pay zone is more than 80 meters thick. The presence of significant matrix porosity and permeability in these carbonates, overlain by essentially non-permeable carbonates, makes this unit a potential target over much of the fore-deep area and adjacent shelf. In the northern Persian Gulf region no hydrocarbon has been reported in Tarbur Formation.

Rudist-Bearing Reservoirs in Persian Gulf

The rudists were specialized bivalve mollusks which formed reefal structures in the Cretaceous. Their distribution was related to an equatorial belt from 40°N to 20°S along the Tethyan Seaway through southern Europe and in the Middle East. They are significant constituents of reservoir rock in some of the largest oilfields in the world.

The rudist shoal-reefs are very common locally in the Lower and Middle Cretaceous limestone units which cover enormous areas of the Persian Gulf, attaining in some places a thickness of several hundreds of meters.

Most of the oil in various reef facies is found in reservoirs of Cretaceous age and also Tertiary in the Persian Gulf. Many giant oil fields in the Persian Gulf belonging to the Cretaceous period are made up of rudist reefs. Rudist reefs-bioherms are concentrated in three different formations: the Dariyan and

its equivalent Shuaiba, the Upper Sarvak, and the Maastrichtian Mansuri limestone Member of the Gurpi Formation (=Simsima). In each of these formations, the rudist reef-bioherms contain significant hydrocarbon reservoirs. The rudist reef extends in a subcircular pattern through the eastern Persian Gulf. It also includes many oil fields such as Sirri located offshore Iran (see figure 5-5). However, there are oil fields in the southern Iran which also produce oil from the rudist-bearing units.

Nearly all of the rudist buildups of the Dariyan produce hydrocarbons from moldic porosity formed by fresh-water leaching of rudists and other skeletal fragments. Leaching of aragonitic material has been widespread and of great importance wherever rudist materials is present, since the rudists are partly aragonitic. Moldic porosity is thus prevalent in reef, shoal and forereef facies. Fracture porosity is commonly developed as a result of compaction of the leached highly-porous rudist limestone prior to deep burial cementation.

Rudist reefs occur in the Sarvak Formation carbonates of the oil fields in the productive Bangestan Group. Large rudists, such as *Radiolites*, *Durania*, and *Sphaerulites* were also important reef builders in Cenomanian Bangestan Group of southern Iran.

The Middle Cretaceous also contains rudist reef reservoirs on the local structural highs of the offshore UAE. Rudistid reef carbonates interbedded with basinal limestones, offer significant potential in several regions in the Persian Gulf including Oman. Dariyan rudist buildups are different from the Upper Sarvak ones in that in the Dariyan the rudists develop on an algal platform.

Generally, the reservoir quality is high on rudist accumulations at the basin margin and around faults or above the salt domes. The rudist limestones in the Dariyan-Shuaiba, the Upper Sarvak, and Mansouri-Simsima that contain giant reservoirs have been progressively enhanced by meteoric leaching during subaerial exposure apparently resulted from relatively minor sea level fall (Jordan et al., 1985; Prat and Smewing 1993).

Interparticles and intraparticle porosity are found by the radiolitid rudist bioclasts. However, secondary porosity resulted from dissolution of the aragonitic bioclasts forms the major part of the porosity. Dissolution took place following deposition of the Upper Sarvak and subsequent salt movement that uplifted the Fateh Dome and exposed the carbonates to freshwater. Thus, the reservoir quality resulted from the interaction of depositional, diagenetic, and structural processes (Jordan et al., 1985).

In summary, shelf margin buildups, mainly rudist buildups form some of the major hydrocarbon reservoirs in the Persian Gulf region. The rudist buildups representing an exploration target result from interaction of three main factors (Frost et al., 1980). The first was the development of the intrashelf basin establishing deep, open marine conditions on what had formerly been a shallow carbonate platform and localized a buildup-prone belt around the basin. Secondly, the rising sea level provided a vertical component to the build-

ups that contrasted with sheet-like biostroms of rudists and/or coral algal communities. Thirdly, the stratigraphic position of the buildups favorably placed them for fresh water leaching and diagenesis of the rudists and other skeletal fragments during the subaerial exposure.

CENOZOIC RESERVOIRS

The principal Cenozoic reservoir rocks lie in the Zagros Basin encompassing parts of Iran, Kuwait Iraq and the Persian Gulf. Oligo-Miocene carbonate and clastic sequences are also locally productive in the oil fields of the Iranian side of the Persian Gulf (e.g., Abouzar, Bahregansar and Doroud fields) and also in southern part of the Persian Gulf (e.g., Ratga field, Kuwait). Generally, the Cenozoic carbonate pay zones are characterized often by poor primary reservoir properties, and as mentioned previously production is depending on fracturing.

Asmari Reservoir

An impressive gathering of giant fields, located in the 50,000 km^2 Dezful Embayment area in southwestern Iran, produces from the Asmari limestone of Oligo-Miocene age and also from the Cenomanian Sarvak limestone. They together contain some 400 billion barrels of oil-in-place, or 7% of the oil global reserves. The famous Asmari limestone was the first oil horizon to be discovered and developed in the region.

The Asmari and its Iraqi partial time-equivalent reservoir, the "Main Limestone" of the Kirkuk Group (Henson, 1950b; van Bellen, 1956), form by far the most important reservoir of both the Zagros foreland basin (*sensu stricto*) and the entire succession in the area. Foreland basins such as basinal setting that Persian Gulf is situated in are some of the best oil-generating and producing basins in the world because of their rich source rocks. They are accounted for production in numerous oil fields in reservoirs of equivalent age offshore in the Persian Gulf. It is estimated to provide at least 90% of the oil in the oil fields area of southwestern Iran (vicinity of the Dezful Embayment) and a lesser but still considerable percentage of the oil fields in the foothills belt of Iraq (Kirkuk Embayment).

The Asmari limestone and Ahwaz sandstone are the principal reservoirs in northern Persian Gulf and contribute to a large part of petroleum production. The Asmari carbonates deposited just before the closure of the Tethys Sea. Thus, the reefal limestones, dolostones, and sandstones associated with this formation are one of the most important hydrocarbon-producing reservoirs in the Persian Gulf. The thickness ranges from 100 to 800 meters and contains several siliciclastic layers with relatively high porosity and permeability. Some of the horizons within the early Miocene high energy Asmari limestone

are extremely porous almost everywhere with reservoirs sealed by the efficient Gachsaran evaporites which range in thickness from 600 to 1200 meters.

The Asmari reservoir characteristically is a fine to coarse-grained, hard, compact limestone with evidence of some recrystalization and dolomitization. Primary porosities of the limestones in its early depositional environment were generally poor, and dolomitization was sporadic. Thus, it could be stated that the formation generally had low porosity and permeability. In southwestern Iran and the Persian Gulf area, the Asmari is a massive, dense limestone with poor primary porosity, and its importance as a reservoir is due to fracture porosity and permeability resulting from subsequent fold movement.

The typical Asmari limestone has a matrix porosity of 5 to 14% on average in Iran, and an intrinsic permeability averaging about 10 md and range as high as approximately 30 md (Hull and Warman, 1970, p.431) but the formation is extensively fractured. The average matrix permeability in Asmari reservoir is 1.0 md and the pore type distribution in the reservoir is most important factor in reservoir characterization.

Fractures are noticeably open for the reason that some wells have high production rates on very small penetration of the reservoir, and production changes in one well are relatively rapidly detected in other wells at a great distance away in the same reservoir. Hall and Warman (1970) recognized that where sandstones are present, they appear to be unfractured. They also noted that there is a regional hydraulic gradient within the Asmari limestone from the Mountains to the Persian Gulf and oil/water contacts on the two flanks of same oil fields differ by as much as 150 meters.

Several types of porosities have been identified in the Asmari reservoir in southwestern Iran and northern Persian Gulf area. The most important types of porosities are intergranular, interparticle touching vugs and fractures, forming interconnected pore system. Non-touching vugs, moldic, channel and fenestral are other types of porosity identified in the Asmari reservoirs. Intergranular porosity is mainly found in grainstone and thinly bedded sandstone with high permeability and good porosity permeability relationship. Vuggy porosity is mainly found in dolostone and some of the wackestone while moldic type is mainly in carbonates (Keramati and Bahermandi, 2003).

With severe Tertiary tectonic compression and the resultant folding, the Asmari has been intensely fractured along axes of maximum folding. As a result the reservoirs are folded into elongated anticlines and are extremely fractured into a complex pattern of separate matrix blocks. Fold movements which created the anticline traps were responsible for the fracturing which not only made the Asmari a good reservoir but also provided migration pathways from the deeper source beds. It is the fracture and faults network that provides the paths of effective permeability, often more than several Darcies. The importance of fracturing is more evident in the Karanj oil field in the northern Persian Gulf where the Asmari and Pabdeh Formations are connected to each other by fracture system hence they are considered as one reservoir.

In brief, fracturing of the reservoir unit has been the most important factor considered for its characteristically high productivity. Fractures have also acted as the preferred passages for secondary mineralization throughout the Asmari reservoirs. The presence of secondary anhydrite and calcite is noted in fractures and matrix pore spaces of such reservoirs to the extent of complete sealing of fractures and faults in certain localities.

On this basis only the potential of the Asmari limestone away from Fold Belt and towards the Persian Gulf is less affected by fold movements and appears to be considerably reduced. Over large areas of the platform the Asmari limestone is not present, but this is compensated by its replacement by clastic deposits with greater porosities, such as the sandstones of the Ahwaz Delta. The more mobile post Asmari deposits with their evaporitic and marly content did not fracture to the same extent and sealed the ancient traps.

Andresen et al. (1963) have analyzed the Asmari reservoirs and their performance. During the depletion of a typical Asmari reservoir, the mechanisms of gas-cap drive, undersaturated oil expansion, solution-gas drive and gravity drainage are all in operation at various times.

Extensive fracture networks promote primary oil production in most reservoirs. However, faults and low porosity and permeability barriers resulting from diagenetic and facies changes often block intra-reservoir communication. Therefore, it is clear that production from such rocks as the Asmari is derived through fractures: wells have been tested at up to 10,080 m^3/day (120,000 BOPD) and sustained at 12,720 m^3/day (80,000 BOPD), with an estimated average for producing wells of 3180 to 3975 m^3/day (20,000-25,000 BOPD). Where wells have evidently failed to be drilled through fractures, they are essentially non-productive. A part of the gross porosity is required to be provided by the fractures themselves, but it would appear that there is slow subsurface drainage from the block matrix porosity into them; their productivity depends on the very large surface area of the fracturing contact with the oil-bearing matrix.

As the fold size frequency and amplitude decrease with increasing distance from the Zagros Fold Belt, the potential for discovering significant new fields in the Tertiary rocks of the Persian Gulf diminishes. Such fields as may be discovered are likely associated with diapiric movements or with hydrocarbon migration along faults, new or reactivated, penetrating the succession. On the optimistic side, the deficiency of the Tertiary rocks does not suggest that the resources of the underlying Mesozoic may still be unexploited.

Oil pools have been recognized in Asmari reservoirs in Bahregansar and Dorood oilfields in the Persian Gulf where Asmari thickness reaches about 115 meters and shows some oil bearing sandstone reservoir layers near its top, capped by the overlying anhydrite of the Gachsaran Formation. In Dorood field considering the total thickness of the Asmari, in spite of a greater thickness of formation in the northern part of the field, the reservoir potentials are higher and pay zones are thicker in the southern parts (Zeinali, 2002).

In Bahregansar and Handijan oil fields in the head of the Persian Gulf the Asmari reservoir consists of relatively fractured calcareous dolostones. Two oil pools have been identified in these fields separated by 1 to 2 meters thick layer of shale. The upper pool" A", with a thickness of 30-32 meters is water bearing whereas the underlying pool "B" is the most important. In the underlying pool "B" two zones with different permeability are observed, but from pressure measurements no vertical communication between the two zones seems to exist, probably because of presence of some anhydrite. Production behavior of Asmari "B" clearly reflects the complicated reservoir geometry.

In Bahregansar the Asmari is somewhat different from the typical formation prolific in the Iranian oilfields, which consists of massive limestone and compact dolomitic limestones where permeability is mostly due to the fractures. For this reason the permeability in the Bahregansar Asmari pool seems to have been more uniformly developed than in the well-known Iranian oil fields. The Asmari is about 150 meters thick and a substantial part of it is oil-bearing.

Further eastward in the Persian Gulf and around Kish and Farur Islands, the Asmari Formation consist of alternation of dolostone and limestone layers. It has a gas column of about 31 meters with good porosity and permeability in Farur. The sedimentary microfacies in the area include mudstone, bioclastic wackestone/packstones, peloidal wackestones and grainstone with anhydrite cements filling the intergranular porosity.

The Ahwaz field spans 420 km^2 in the Zagros area of southwest Iran with 400 meters thick Asmari Formation as the main oil-producing reservoir unit. Here, the Asmari formation consists of cyclic platform limestone, dolostones, sandstone, and shale. In this field, sandstone forms an appreciable part of the Asmari reservoirs. In Ahwaz the sandstone forms 50% of the total thickness of the Asmari but it thins markedly northeast and southeast. In most of the known Asmari fields, sandstone does not constitute a significant part of the reservoir. The Asmari formation is the only oil-containing formation in the Tertiary of Abu Dhabi, where hydrocarbon appears in the upper most part of the formation.

Ahwaz Sandstone Member

Ahwaz Sandstone forms an appreciable part of the Asmari reservoir and it is correlated with the upper part of the Asmari Formation. The Ahwaz sandstone, like some of the Mesozoic sandstone on the western side of the Persian Gulf, is an extensive sheet that spread out from the Arabian Shield. Ahwaz Sandstone Member (formerly Ahwaz Sand Member) forms reservoir rocks in the Abouzar and Soroosh oilfields in the Persian Gulf.

The reservoir thickness in these fields varies between 80 to 90 meters and has almost a constant thickness. The sands are fine to medium-grained with some shale and carbonate interbeds. Ahwaz Sandstone Member has excellent

reservoir properties in Abouzar and Soroosh oilfields, with porosity in the order of 30% and permeability of around 2 to 4 milli-Darcies. Ahwaz Sandstone Member contains sandstones of Darcy permeability with shaly layers. The sandstone is the youngest and shallowest oil-producing reservoir in the Persian Gulf area. In the Abouzar field, around 80 meters of the Ahwaz Sandstone Member reservoir directly overlies the lower Asmari limestone.

In parts of the Dezful Embayment and northwestern Persian Gulf, the quality of the Asmari reservoir is significantly enhanced by interbedded distal tongues of a spread of quartz sand (Ahwaz Sandstone Member) eastward from the vicinity of Kuwait. The sandstones die out eastward across the Iranian oilfields (see figure 5-8) but, in some of the oil fields, where they are believed to have been deposited in near shore, shoreline, and possibly eolian environments. They also form a significant proportion of the reservoir. The sands are clean and poorly cemented, and contain porosities of 20 to 30 %.

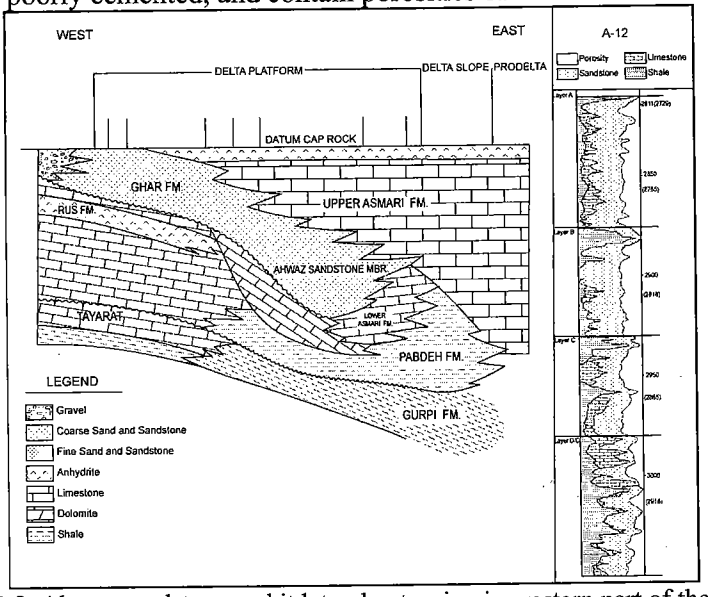

Figure 5-8. Ahwaz sandstone and it lateral extension in western part of the Persian Gulf.

The Formation produced oil in the Hendijan field, oil and gas in the Abouzar and Dorood fields and gas in the Bahregansar field in western part of the Persian Gulf. In Bahregansar oil field Ahwaz Sandstone Member could be divided in three zones with different characteristics: zone-1 (thickness 20-21 meters), mainly sandy dolostone with some interbedding of shale and anhydrite in the upper part. Some layers of clean sands are also present. Zone-2 with thickness of 30-35 meters consists of clean sand with some strikes of shales. This zone has the highest porosity and permeability. Zone-3 with a thickness ranging from 28 to 30 meters contains sandy dolomite and dolos-

tone with frequent interbedding of shale. Some layers of clean sand are also present.

Although the Asmari Formation in northern part of the Persian Gulf is one of the world's main oil reservoirs (see Beydoun et al., 1992; Jones and Racey, 1994), its potential on the Arabian Platform has received little attention. However, the discovery of heavy oil in Wafra field of Kuwait-Saudi Arabian Neutral zone, the conventional oils found in the Ahwaz Sandstone Member (i.e., Ghar Formation) in the Ratga and Bahrah Fields in northern Kuwait and the oil discovered in a thin Gachsaran dolomite and an Asmari reservoir in the Mandous Field as well as the oil in the Pabdeh section in the Hamidiyah Field in UAE suggest that the potential of the Asmari Formation in southern areas of the Persian Gulf necessitate further investigation.

OTHER RESERVOIRS

A number of additional proven and potential reservoirs are present in the Persian Gulf region, but they are inadequately explored and virtually undeveloped. The most important ones are the gas-bearing Neogene formations in the Bandar Abbas area in the far southeast.

The final noteworthy reservoir is the Guri limestone member of the basal Middle Miocene Mishan Formation, which contains developed gas in several discoveries near Bandar Abbas. The Guri Formation, at the southeast end of the Zagros foreland basin, varies in thickness from nil to about 1200 meters, but no information is available on its reservoir properties. In the region where it is present, it is the prime exploration objective, the Asmari Formation being thin and not persistent there.

Proven reservoirs are developed in Paleocene to Eocene carbonates of Jahrum Formation and the Umm Er Radhuma and Dammam Formations in the southern Persian Gulf.

CONCLUDING REMARKS

Mesozoic reservoirs are the most significant ones in the Persian Gulf and surrounding region. The principal producing horizons are considered to be found in the Middle Cretaceous, followed closely by the Upper Jurassic and then by the Lower Cretaceous and Middle Jurassic. The Lower Jurassic and Triassic reservoirs are relatively insignificant and production is normally confined to the other region outside of the Persian Gulf district.

There are two main levels of Mesozoic production that occur throughout the Persian Gulf region. The most prolific reservoirs are the shallow water carbonates of the Upper Jurassic, and the rudists and associated facies of the Dariyan, Fahliyan, and top of the Sarvak Formation being of prime significance where there is a fortuitous juxtaposition of source, reservoir and seal. The facies are laterally extensive and the structures broad and simple. Both

sequences occur beneath exceptional cap rocks. These are ultimate conditions for the formation of giant and supergiant fields.

In the Persian Gulf the excellent quality of the Late Jurassic, Lower and Middle Cretaceous reservoirs respectively is attributed in part to the effects of diapiric salt movement, whereby considerable secondary porosity developed as a consequence of exposures to the fresh water. In addition, erosion created better porous and permeable grainstone and packstone facies.

The most prolific oil-producing zones and principal Cenozoic reservoirs are the fractured carbonates of the Asmari of southwestern Iran and its equivalents (Oligo-Miocene) and its extension into Iraq and northwestern Persian Gulf.

Mansouri, Simsima and Tarbur (Aptian, Cenomanian and Maaestrichtian), the shallow water clastics of the Gadvan and Zubair and Azadegan Sandstone member of the Kazhdumi Formation (Burgan/Nahr Umr) in the northwestern Persian Gulf, southern Iraq and northeast offshore Saudi Arabia; the shallow shelf limestone and dolomitic limestone of the Dalan/Kangan; the carbonate and clastic sediments of the Huqf Group (Infracambrian-Early Cambrian) in Oman and the clastics of the Permian Faraghan (=Unayzah) are all the formations with potential reservoir characteristics.

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CHAPTER-6

CAP ROCKS AND SEALS IN PERSIAN GULF

INTRODUCTION

Modern petroleum geology dates from the recognition that the oil and gas accumulations require hydrocarbons to be generated from organic-rich source rocks, to be contained in porous and permeable reservoirs, and to be entrapped by a natural seal. Based on such a definition, the existence of petroleum play depends on the presence of an effective regional caprock or topseal.

Many authors who worked on the petroleum geology of the Persian Gulf and neighboring regions (e.g., Dunnington, 1967; Kamen-Kaye, 1970; Murris, 1980) have stressed on the importance of caprocks or seal rocks for petroleum accumulation. Among many favorable characteristics with which the Persian Gulf area has been exceptional is the presence of seals such as shales and more importantly evaporites at various horizons in the geologic succession.

Properties of reservoirs in which oil and gas are contained have been widely and intensively studied and enormous progress has also been made in the past years in techniques for identifying where and how oil and gas are generated and how they migrate, segregate, and transform. On the contrary, although seals are a key element of petroleum systems, surprisingly yet they have received limited systematic studies and little has been published on the recognition and evaluation of the properties of the physical boundaries or "seals" that allow for the entrapment of hydrocarbons. The reason for this is very obvious and that while exploring for oil cap rocks are drilled through rapidly and their geological and sedimentological characteristics are not of importance expect for providing a proper seal.

Seal rocks prevent the relatively buoyant hydrocarbons generated within a sedimentary succession from escaping to the surface. The best type of the seal rocks are evaporites (gypsum and anhydrite) such as sequences encountered in the Persian Gulf region. The depositional and environmental settings of these seals were most likely related to extensive ancient epeiric seas or evaporitic environments such as coastal sabkhas analogous to those now found along the shore of southern Persian Gulf (Purser, 1973) and also on the offshore islands in its northern waters. Moreover, many petroleum geologists have attributed the oil and gas abundance in the Persian Gulf basin to the presence of an evaporitic cap rock. However, in some of the oil fields in the Persian Gulf, the cap rocks preventing hydrocarbons from escaping to the surface are not made of evaporite rocks entirely. In this respect, Gaunau's (1987) result is of prime importance.

Gaunau (1987) collected considerable amount of information on the cap rock lithologies of the world's 25 largest oil and gas fields. Based on his in-

vestigation, there was a roughly equal split between shales cap rocks (13) and evaporites seals (12) for these oil fields. For the gas fields the situation was different and shales (16) prevailed over evaporites (9).

About 40% of the ultimately recoverable oil reserves from the world's giant oil fields are capped by evaporite rocks and 60% by shales (Grunau, 1987). For gas, the corresponding proportions are 34% for evaporite cap rocks and 66% for shales. It is important to note that the majority of giant oil fields with evaporite cap rocks are located in the Middle East and particularly the Persian Gulf.

Although evaporites are accountable for trapping more than 60% of the hydrocarbon reserves in the Persian Gulf and neighboring region (Edgell, 1996), yet worldwide, the role of evaproites in controlling regional accumulations of oil and gas has been largely overlooked but this is no longer the case. What can be said about the Persian Gulf region is that the association of carbonates, evaporites and hydrocarbon is unquestionable (Ala, 1974; Gill and Ala, 1972).

CAP ROCK PROPERTIES

Seal rock is a formation with extremely low porosity and permeability covering an oil or gas reservoir, and it constitutes a barrier against the volume flow of hydrocarbons into the upper layers. Although a seal rock can be considered as a seal to hydrocarbons, it is erroneous to view it as a completely impermeable layer. This is observed in some of the oil fields in Persian Gulf where seepage has occurred.

Two main mechanisms have been well recognized to be responsible for migration of hydrocarbon gases through seal rocks into adjacent upper layers (Krooss et al., 1992). One is molecular diffusion through the water-saturated pore space of the seal rock. The other is the compressible slow Darcy flow of a free gas phase. Molecular diffusion is a ubiquitous but slow process that is only considered significant in geological timescales. The second one, the slow Darcy flow, depends strongly on the geologic and hydrodynamic conditions of the system, including the reservoir, the seal rock, and the overburden formations, as well as the properties of the fluids in both the reservoir and the seal rock. Slow Darcy flow occurs when the pressure difference across the seal rock is sufficiently high to overcome the sealing capacity of the seal rock. In essence, the sealing capacity of a cap rock is provided by the capillary forces across the interface of the wetting phase (usually brine), which saturates the seal rock, and the non wetting phase (oil or gas), which is accumulating in the reservoir.

The quality of a seal, at a given time, is determined by many physical and chemical properties. Some of the most important factors in relation to the potential cap rock in the Persian Gulf are discussed here. Thus, the main factors

which are important in creation of effective cap rocks are briefly presented (Downey, 1984; 1993).

CAPILLARY PROPERTIES

The basic physical principles governing the effectiveness of petroleum cap rocks are the same as those controlling secondary migration of petroleum. A cap rock is effective if its capillary or displacement pressure exceeds the upward buoyancy pressure exerted by an underlying hydrocarbon column. Thus, the seal hold back fluid pressure caused by the buoyancy of the fluids. The buoyancy pressure is determined by the density of the hydrocarbons and the hydrocarbon column height. The capillary pressure of the cap rock is largely a function of its pore size which might be laterally very variable. The capillary pressure (sealing capacity) of the rock increases as; (1) the throat radius of the largest connected pores decreases, (2) the wettability decrease, and (3) as the hydrocarbon-water interfacial tension increases (Downey, 1993).

Capillary forces of a seal act to confine hydrocarbons within an accumulation. The buoyancy forces of the hydrocarbon column of a static accumulation are given by the product of the hydrocarbon column height and the differences in density between the hydrocarbon and the reservoir pore water. These hydrocarbon buoyancy forces must be matched or exceeded by capillary entry pressure that characterizes the pore structures of the seal. A cap rock of extremely small pore size is required to prevent the buoyancy rise of a tall underlying gas column. Hydrodynamics also affect cap rock effectiveness (see Downey, 1984; 1993; Grunau, 1987).

DIFFUSION LOSSES THROUGH SEALS

Loss of gas through cap rocks may take place through the process of diffusion. As a gross geologic simplification, diffusion of hydrocarbons through seals is depend on (1) hydrocarbon type, (2) the characteristics of the water-filled pore network of the contacting seals, and (3) time available for diffusion.

If the reservoired hydrocarbon is oil, little or no diffusive leakage through its seal is likely. On the other hand, if the reservoired hydrocarbon in methane, and is sealed by rock layers lacking connected pore water (salt, anhydrite, or gas hydrates) no diffusive loss should be expected. However, if methane is sealed by porous, water-bearing shale, substantial diffusive losses can occur over significant geologic time.

Evaporite seals are definitely more effective than shale seals, especially as diffusion losses through evaporite seals are considered to be minor or negligible. In view of diffusion losses, a thick shale seal is more effective than a thin one (Grunau, 1987).

To summarize, exploration uncertainties concerning effective loss of a hydrocarbon accumulation through a seal can be neglected except for exploration prospects where the expected hydrocarbon is methane, the seal has porous water-filled pore space, and long-term retention in the trap is required.

LITHOLOGY

The effectiveness of seals may be examined in term of their maintenance of stable lithology, ductility, thickness, lateral continuity, and burial depth. Any lithology could serve as a seal for a hydrocarbon accumulation. The only requirement is that minimum displacement pressure of the lithologic unit comprising the sealing surface be greater than the buoyancy pressure of the hydrocarbon column in the accumulation. A review of cap rocks indicates that the most effective caprock lithologies and overwhelming majority of them are evaporites, fine-grained siliciclastics, and organic rich rocks. Fine-grained lithologies are essential for good seals. Other lithologies such as argillaceous limestones, tight sandstones may also seal, but they are far less important. All these three types of lithologies have been encountered in the oil fields of the Persian Gulf region. These lithologies are commonly seen as seals because;

- They typically have high entry pressure,
- They are laterally continuous and maintain stability of lithology over large area,
- They are relatively ductile, and
- They are a significant portion of the fill of sedimentary basins (Grunau, 1987).

Nederlof and Mohler (1981) in a statistical analysis of reservoirs/seals have indicated that the cap rock lithology was of considerable importance in influencing seal capacity, correlating to a good seal, with thickness and depth to seal having positive, but lesser, correlation to hydrocarbon column.

DUCTILITY

Ductile lithologies such as salt and anhydrite, organic rich shales, are all observed in the Persian Gulf area and can generally increase the chance of hydrocarbon retention.

Folding and faulting that are tied in with the formation of many traps place significant strain on the sealing surfaces of accumulation. Brittle lithologies develop fractures, whereas ductile lithologies tend to flow plastically under deformation.

Ductility is an important requirement, particularly in tectonically disturbed areas. Salt and anhydrite are the most ductile, followed by organic-rich shales. Caprocks do not need to be thick to be effective, as long as they are laterally persistent. Similarly, depth of burial does not appear to be critical and as a result seals may be effective at all depths.

Ductile cap rock lithologies are less affected by faulting and fracturing than brittle lithologies. Caprocks are positioned under substantial stress during periods of structural deformation, including the deformation responsible for trap formation. During the formation of a simple anticline, for example, tensional fractures may occur in brittle caprocks in the crest of the fold. Ductility is, therefore, a particularly important requirement of caprocks in deformed areas such as Zagros Fold and Thrust Belt in the vicinity of the Persian Gulf (Grunau, 1987).

The most ductile lithologies among the sedimentary rocks are evaporites. This may explain the extraordinary success of evaporites as caprocks. High kerogen content appears to enhance the ductility of shale caprocks. That is one of the prime reasons for numerous source rocks to serve as seals. Highly organic-rich rocks are fine-grained containing deformable layers of kerogen; such rocks commonly have a plastic behavior during folding and the flowage of the soft kerogen layers makes for very high displacement pressures in the relict pores. Furthermore, ductility is a function of temperature and pressure. Evaporites may be brittle at shallow depths, but very ductile at depths over one kilometer (Grunau, 1987).

THICKNESS

A few centimeters of ordinary clay shales are in theory adequate to trap high column of hydrocarbons. A small thickness of fine-grained caprock may have sufficient displacement pressure to support a large hydrocarbon column. Thin caprocks, however, tend to be laterally uneven; thus a thick caprock considerably improves the chances of maintaining a seal over the entire prospect, or even over the entire play or basin. For example, the Ilam Formation in the Persian Gulf is a cap rock in some of the fields however it is not persistent in all the fields and as a result it does not form a pervasive cap rocks like the way Hith Anhydrites perform.

The benefits of a very thick seal are, providing many layers of contingent sealing beds and a higher probability that a sealing surface will actually be distributed over an entire prospect. A thick seal is important and beneficial, however does not linearly influence the amount of hydrocarbon column that can be held by a top seal. Wherever traps are created by fault offset of reservoirs, thickness of top seal can be very important. In such places, the top seal can be offset to become a lateral seal, and seal thickness can relate directly to column height of entrapped hydrocarbons.

Lees (1950) observed that at Burgan field in southern Persian Gulf, the oil was contained and preserved by as little as 100 feet of shale over the crest of the structure. This shows that one of the largest, if not the largest oil field in the world can be contained under a relatively insignificant cap. Moreover, the Burgan caprock is not an evaporite.

Typical cap rock thicknesses, irrespective of shale or evaporite lithology, vary form tens of meters to hundreds of meters (Grunau, 1987). Very large volumes of petroleum may be sealed by relatively modest thicknesses of cap rock. The Persian Gulf reservoir seals, without doubt, are very effective, but they are not unusually thick or abundant. For example, in Kuwait, the Ahmadi shales of Cenomanian age have a thickness of 30 meters over the crest of the Burgan structure, and seal approximately about 74 billion barrels of ultimately recoverable reserves in southern Persian Gulf. In Saudi Arabia, the upper Jurassic Arab C-D anhydrite, which seals the Arab-D Jubaila main reservoir of the Ghawar structure (approx 80 billion barrels) is about 33 meters thick, whereas the top seal, the Hith Anhydrite, is up to 150 meters thick. The giant Asmari oilfields in the Zagros in northern Persian Gulf are effectively sealed by the cap rocks anhydrite which is some 33 meters. Overlying evaporites and marls have varying thicknesses of up to 1200 meters, due to salt flow and compressional tectonic events. Thick seals could increase the probability that a sealing surface covers an entire trap of large dimension or large parts of a basin, as is the case for the Persian Gulf basin. In case of gas reservoirs, a thick caprock reduces the risk of substantial losses by diffusion.

The present burial depth of caprocks does not appear to be an important factor in influencing seal effectiveness. Grunau (1987) presented histograms showing the seal depths of the world's giant oil and gas field. Almost half of the ultimately recoverable reserves of oil occur in the one to two kilometers depth range, and 31% in the two to three kilometers range.

Progressive burial of geographically extensive source, reservoir, and seal rocks on a gentle structural setting would allow efficient horizontal migration that could drain large, mature petroleum-generating source areas into extraordinarily large gentle structural closures. In particular, deposition of thick and aerially extensive evaporite seals, combined with this gentle structural setting, permitted only minimal loss of hydrocarbons through fractures.

SEAL RETENTION

The term "retention" refers to the sealing process that prevents hydrocarbons from leaking out of a trap. In the quantification of the retention potential of a prospect, three types of potential leaks have to be considered:

- The seal could perform as an impervious lithologic unit, possibly affected by subseismic faulting and/or fracturing.
- Faults transecting an otherwise continuous seal (thickness greater than fault throw)
- Fault-induced discontinuities in the seal (thickness less than fault throw), requiring lateral sealing across the fault plane.

On the other hand, in order to form a reliable seal, a lithologic unit has to fulfill the following requirements:

- Low permeability to hinder the flow of hydrocarbons.

- Ductile behavior to minimize faulting and fracturing,
- Lithologic homogeneity to avoid lateral transition into non-sealing lithologies,
- Lateral continuity to ensure its physical presence over the entire field.

Based on the above criteria, some of the common lithologies which can be arranged into a sequence of decreasing retention potential are: salt, anhydrite, ductile cay, shale, kerogeneous rocks, brittle shale, marl, siltstone, dense sandstone, dense carbonate and chert (Downey 1984, 1993). In a review of the world's 176 giant gas fields, almost all appear to be sealed by evaporites (salt or anhydrite) and shales (Grunau 1981).

The above lithologic sequence reflects a combination of low permeability and ductility. Ductility increases with temperature and pressure and decreases with strain rate. Anhydrite is commonly regarded brittle down to a depth of approximately 3 km. However, it has a very low permeability, while faults and fractures may anneal rapidly by recrystallization.

Other predictable parameters that control the retention potential are: minimum thickness (lateral continuity), depositional environment of shales (lateral homogeneity and continuity), fault density (subseismic fracture density), and degree of overpressuring in shales (hydraulic fracturing). The seal continuity is a critical factor in cap rock evaluation.

In most petroleum provinces such as the Persian Gulf, there is excess charge and fields are filled to their structural spill point or to a fault-controlled leak point above the spill point (see Figure 6-1). Exceptions to this rule mostly have noticeable charge problems such as small and/or low-mature drainage areas or the presence of barriers to secondary migration. From the absence of underfilled traps in the many areas of excess charge, it can be concluded that, generally, seals are either perfect or a complete failure. In the first case fields are filled to their maximum capacity, whereas in the second case hydrocarbons are absent.

Figure 6-1 is a schematic cross section through one of the oil field in the Persian Gulf. The regional seal of the Hith Anhydrite in the Persian Gulf overlies Surmeh and the four Arab carbonate reservoirs, which are separated by thin layers of anhydrite. The reservoirs are charged from the stratigraphically deeper Hanifa source rock. From the residual oil found in the two wells, it is inferred that the structure was initially filled to its structural spill point and that at a later stage hydrocarbons leaked out, giving rise to the present contacts.

In this oil field the present anticline is cut by two faults systems: a system of normal faults which are precharge and a system of very young to recent strike-slip faults. Although the throw of the normal faults exceeds the thickness of the inter-Arab seals, they do not affect the hydrocarbon/water contacts and thus, do not form leak points. The strike-slip faults, on the other hand

control all hydrocarbon/water contacts and, although of minor vertical displacement, they clearly formed the paths for leakage. Part of the leaked oil is trapped at a shallower level below the regional Lower Kazhdumi (i.e., Nahr Umr shale) seal, but also here the strike-slip faults coincide with the water contact giving evidence of leakage.

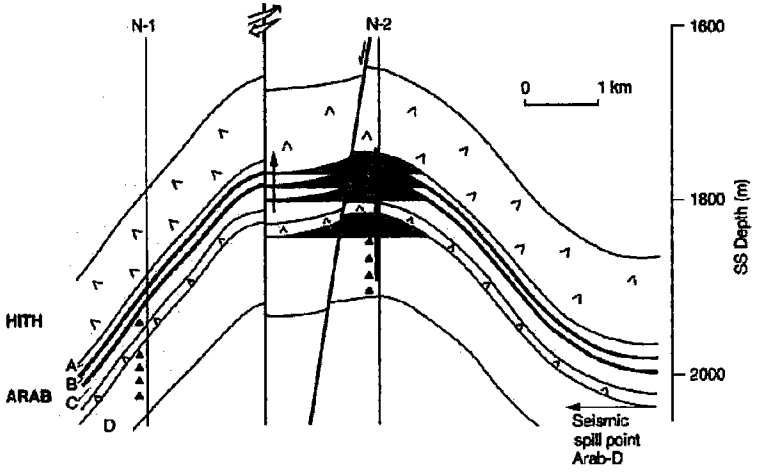

Figure 6-1, Leakage at four levels along Pliocene strike-slip fault: Cretaceous normal fault is precharge and has annealed. Note excess charge situation (black triangles indicate residual oil), Persian Gulf (cited from, Nijhuis, 1997).

Ductile faults are assumed not to leak unless the fault throw exceeds the seal thickness. In that case leakage may still be prevented by spreading of the ductile seal into the fault plane. This process is frequently observed in oil fields of Tertiary deltas, where rapid alternations of ductile clays and reservoir sands are deformed by slow, synsedimentary movements along normal faults (clay smearing; see Weber et al., 1978). The situation observed in the Persian Gulf within the Arab reservoirs could be explained by drag of the intra-Arab anhydrites (or their precursor gypsum) into the precharge fault plane combined with recrystallization (Nijhuis, 1997).

Brittle seals are assumed to break and leak upon faulting. In case the fault throw does not exceed the seal thickness, however, the fault planes are assumed to anneal upon stress release. It should be stated at this point that the rheologic behavior is not only a function of the seal lithology, but also of the depth of burial and the type of fault movements (strain rate). In the example of figure 6-1 regional seals of excellent quality behaved brittle under strike-slip movements at depths in excess of 2000 meters.

SIGNIFICANCE OF REGIONAL SEALS

Most sedimentary basins contain major widespread sealing layers. These regional seals are usually characterized by broad coverage, significant thickness, laterally stable character, and generally by relatively ductile lithologies. Where these seals are found above mature source rocks and reservoirs, they control, in large measure, the regional emplacement of hydrocarbons. The landmark publication on the geology of the oil fields of the Persian Gulf (Murris, 1980) provides excellent examples of this interdependence (see figure 6-2).

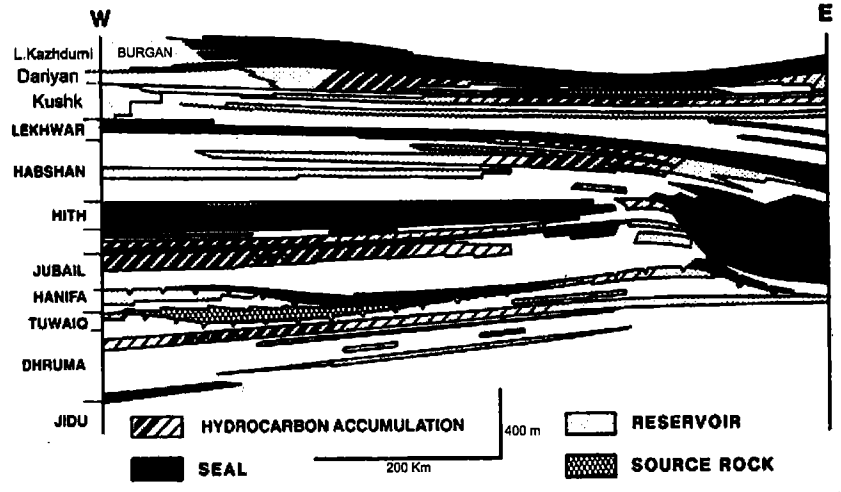

Figure 6-2 cross section of Middle Jurassic to Albian, central Persian Gulf area, showing distribution of hydrocarbons relative to seal rock (Adapted from Murris, 1980)

The cap rock requirements appear to be met in several formations in the Persian Gulf region, spotted through the stratigraphic sequence, which have wide regional distribution. Cap rocks occur at a number of stratigraphic horizons in the Jurassic and Tertiary, as well as in the Middle Cretaceous and the Cambrian sequences. Good examples of a regional cap rocks are the Upper Jurassic Hith Anhydrite, the Albian Kazhdumi shales and its stratigraphic equivalent Nahr Umr in the Persian Gulf area, which seal in excess of billions barrels of oil in the underlying reservoirs. They form excellent and widespread cap rocks and hydrocarbon accumulations are concentrated in reservoirs under these regional seals.

Where the seals are absent or disrupted by faulting, the hydrocarbons have migrated upward to be trapped by secondary seals. In order to provide good regional seal, cap rocks need to maintain stable lithological character (and hence capillary pressure and ductility characteristics) and thickness over broad area.

Most prolific petroleum provinces contain at least one regional seal. A megasequence with multiple seals, capped by an effective evaporite top-seal is the Miocene cap rock anhydrite of the Gachsaran in the Zagros Fold Belt of Iran which is considered to have been an excellent cap rock. Hydrocarbons migrating upwards through partly or completely leaking shales will eventually be retained by the most effective top-seals. A low measure of deformation and fracturing is excellent for retention. This could be one of the reasons that the Persian Gulf basin is one of the world's important largest oil provinces.

The search for petroleum in these basins may be focused on the base of the regional seal, rather than on any particular reservoir horizons. The lateral variability of the regional seal may be studied using wire line log information and seismostratigraphic analysis.

Cap rocks on the Arabian side of the Persian Gulf basin are adequate only because of the mildness of the folding in the southern side of the Persian Gulf. Upon approaching the Zagros foothills, where the rocks are strongly folded and fractured and where such poor cover would be ineffective, either salt or thick marls is present to seal the reservoirs. Lees (1950) pointed out that if it were not for the presence of salt, oil pools which have minimum cover or less than 330 meters might not have been preserved. Even with salt cover, there are numerous seepages from the foothills fields in the northern Persian Gulf region. Thus, the distribution of the various types of cap rocks is exactly what is required by the tectonics in different parts of the area.

CAP ROCKS DEPOSITIONAL SETTING OF PERSIAN GULF

As practically all lithologies can serve as cap-rocks, their environments of deposition vary from lacustrine to pelagic (open sea) and deep marine. Some depositional environments and basin settings are more appropriate for the establishment of thick and effective regional caprocks than others.

The conditions required for development of regionally extensive caprocks in association with reservoir rocks are frequently encountered in two particular depositional settings. One of these is where marine shales transgress over gently sloping siliciclastic shelves, such as Gadvan Formation in the Persian Gulf which serves as a seal for oil and gas in a lowermost Cretaceous limestone reservoir in the Dorood Field and for oil in the Foroozan Field. The other is where evaporites in regressive sabkha retreat over shallow marine carbonate reservoirs, as in the Hith anhydrite of the Persian Gulf.

Thick evaporite sequences developed as a result of arid climatic conditions during the Late Proterozoic with the deposition of the Hormoz salt; during the Triassic forming the Dashtak Formation; in the Late Jurassic with the extensive deposition of Gotnia and Hith Formation and towards the end of early Miocene which resulted in precipitation of the Gachsaran Formation.

A classic example of the importance of regional seals on the location of oil and gas is provided by Murris (1980) for the Persian Gulf region (see Figure-

6-2). There are two principal and major sealing formations, the Hith anhydrite and the Lower Kazhdumi shale; these are the main seals for the oil and gas accumulations in the underlying Surmeh-Arab Formations and Thamama Group, respectively. These seals to a very large extent control vertical migration of the hydrocarbon and hence oil and gas distribution.

A stratigraphic unit is not a caprock unless it seals an underlying reservoir; thus the ideal regional caprock maintains its sealing characteristics over wide area but also occurs in stratigraphic association with reservoirs. These sorts of conditions in the Persian Gulf region might have been liable to be encountered particularly in the evaporitic deposits on regressive supratidal sabkhas and in evaporitic interior basin.

In carbonate systems, extensive evaporitic sabkha may gently prograde across flat marine carbonate platform, providing extensive and quality seals. The Tithonian Hith anhydrite of the Persian Gulf is a good example (Murris, 1980). As the climate became arid in the Tithonian, the shallow carbonate platform in which the prolific Arab reservoirs were deposited was replaced by an extensive sabkha.

The Hith Anhydrite in Persian Gulf is interpreted by Murris (1980), as a sabkha deposits on the very shallow southern platform. The age-equivalent Gotnia Formation in the Lorestan basin consists of basinal salt, laminated anhydrite and shale.

At the end of deposition of the Asmari carbonates in the Zagros Basinal trough, the basin developed into progressively more saline leading to the deposition of gypsum, halite and potash salts. Salt deposited during this interval make up the all-important seal over the Asmari oil accumulations. Thus, the brittle Asmari producing reservoir which owes its prolific productivity to tectonically induced fracturing is overlain by the ductile evaporite caprocks of the Gachsaran Formation.

SEALS AND TRAPS IN THE PERSIAN GULF REGION

Excellent seals are provided by evaporites, particularly in the uppermost Jurassic, where caps are interbedded with high porosity reservoirs. Extensive evaporites of Gachsaran Formation similarly provide a near perfect seal to the Asmari reservoirs of Iran, Iraq and northwestern Persian Gulf. Elsewhere in the succession, shales and occasionally tight limestones perform as effective seals to reservoirs containing high oil and gas column.

In the Persian Gulf itself and on the Arabian side which have not been extensively affected by the late Tertiary Zagros folding, large and gentle traps are provided by non-compressional anticlines. They owe their origins to one of two causes: drape and compaction over nearly north-south, fault bounded highs (e.g., Ghawar); and to doming by the InfraCambrian salt. The large size of such structures gives rise to enormous accumulation.

In northern Persian Gulf, most of the hydrocarbon accumulations are in the large compressional anticlines of the Zagros Fold Belt, these are essentially concentric in form and most of them involve all the prospective sequences (Stoneley, 1990). Structural traps in petroleum provinces of Arabia-Eurasia collision zone commonly developed since approximately 5 Ma (Allen et al., 2005). A recent reported accumulation in a thin Albian sand north of Qatar is apparently hydrodynamically trapped.

Structures that trap hydrocarbons in these systems are mostly:

- large, gentle anticlines formed from reactivated basement fault blocks,
- salt domes that resulted from halokinesis, or
- structural traps resulting from a combination of these processes.

CAP ROCKS FOR PALEOZOIC RESERVOIRS

Many of the Ordovician sandstone reservoirs in the Persian Gulf are sealed by the overlying Silurian Shales. In addition, sandstone members showing reservoir potential are sealed by the intraformational shale members as well. For example, the Lower Ordovician, Saq reservoir unit is sealed by the lower Hanadir Member of the Qasim Formation. Although gas shows have been recorded in some sandstones of the Saq Formation, reservoirs are commonly of poor quality due to extensive silica cementation.

Sandstone reservoirs of the Devonian Jauf Formation are capped by a very distinctive shaly unit informally referred to as the "D3B" stratigraphic marker or zone. The D3B Zone lies directly on the Jauf sandstones at Ghawar and is recognized by high resistivities on electric logs, and high velocities on sonic logs (Wender et al., 1998). The D3B Zone is better developed to the northeast of Ghawar where it forms the seal for Jauf gas-condensate accumulations at Abu Sa'fah field, about 70 km north of Bahrain. The D3B Zone was probably deposited during a rise in sea level and may represent a condensed section (Wender et al., 1998).

Late Permian dolomites within the Dalan/Kangan are major gas reservoirs, particularly along the offshore north and west of Qatar in the Persian Gulf. In contrast, the regionally extensive Nar evaporites, shale, and low-permeability carbonates form the major regional seal for Pre-Dalan/Kangan (i.e., Khuff) hydrocarbon accumulations in central and eastern Saudi Arabia (Al-Jallal, 1995; Wender et al., 1998).

The Late Permian to Early Triassic Khuff Formation is a thick formation consisting of cyclic anhydrite and carbonate rock forming a regional seal for hydrocarbons. Gas is also produced in several fields in horst-block anticlines, particularly at Ghawar and surrounding structures. The primary regional seal for hydrocarbon accumulation in alluvial and fluvial sandstones of Unayzah Formation and shallow marine shelf sandstones of Devonian Jauf Formation

are basal shales, low permeability ("tight") carbonates, and anhydrite of the Khuff Formation (Wender et al., 1998).

Impermeable shales, evaporites and tight carbonate rocks at the base of Khuff Formation combine to form the primary seal for clastic reservoirs of the underlying Unayzah Formation. These impermeable rocks also make up the major regional seal; however, local intraformational seals within the Khuff are important for many of the Khuff reservoir units. Shales and tight carbonates of the basal Khuff were deposited over a widespread area during sea-level rise. The basal Khuff also forms the top seal of the Devonian Jauf reservoirs in unconformity-related traps at Ghawar. Hercynian faults are also important as lateral seals in controlling hydrocarbon accumulations in Ghawar area. It is likely that the reactivated Hercynian faults, such as those on the west flank of Ghawar, provided direct pathways for vertical migration into the Khuff from hydrocarbon kitchens in flanking basins (Konert et al., 2001).

Traps in Unayzah sandstones range from stratigraphic and structural traps along the margins of the basin to structural traps related to major basin-wide fault systems in the central part of the basin. Seals are mainly anhydrites of the Dalan/Kangan (Khuff) Formation, but its quality may degrade to the south along the basin margin.

CAP ROCKS FOR PERMIAN RESERVOIRS.

Permian carbonate reservoirs are, in general, suitably provided with overlying and interbedded impervious strata serving as a cap rocks. In the Persian Gulf region impervious cap rocks, for definite and potential Permian hydrocarbon reservoirs are present in several stratigraphic horizons. An exception to this is in northern Oman and on land in southeastern Iran, where thick Permian carbonates pass upwards into dolostones or thin-bedded limestones and dolostones of the Lower Triassic. In this case, the continuous Upper Permian-Lower Triassic carbonate sequence act as a single reservoir for which the first potential caprock would be the evaporites of Triassic Dashtak Formation.

The Permian Dalan reservoir which extends up into the lower Triassic Kangan reservoir in northern and along the axis of the Persian Gulf stretch into northern Oman contains immense reserves without impermeable layer between them. Thus, Dalan/Kangan reservoirs are mainly sealed by Triassic Dashtak evaporites. The characteristics of the Dalan/Kangan reservoirs, and the aerial extent of the Dashtak Formation, which seals the system, could be deduced from paleogeographic reconstructions, distribution of facies, and the isopach maps. Thus, the overlying evaporitic sequence which is known as the Dashtak Formation forms the cap rocks in these areas.

The Kangan/Dalan is also locally petroleum reservoirs depending on the presence of dolostones and /or the ratio of carbonate and anhydrite. Thus, the evaporitic part of the section may serve as an effective cap rock. However, in

recent discoveries in the northern Persian Gulf shales may form an effective cap rock.

Dalan and Kangan reservoirs form a single reservoir unit, especially where the overlying Triassic evaporites serve as cap rock and in some parts of the region, it is often difficult to identify the Triassic from the Upper Permian succession.

Cap rocks conformably overlying Permian rocks offer the most favorable conditions in the Persian Gulf area. Under such stratigraphic conditions argillaceous rocks of Triassic age immediately overlie the Permian carbonate sequences. Most of the Permian sections in the Zagros area are conformably overlain by Lower Triassic Marls. This is observed at Kuh-e Dinar where the thickness of Triassic marls is at least 150 meters, which also includes a few thin, intercalated, dolomitic limestones. In coastal Fars, the basal Dashtak shale member occurs together with Triassic evaporites capping Kangan and Dalan Formations.

In Kuh-e-Surmeh and Kuh-e-Dinar, the lower part of Dashtak Formation (cap rock) consists of anhydrite and minor shales with intercalated dolostones in the upper part. However, the Lower Dashtak Formation becomes a massive dolostone unit towards interior Fars.

In Saudi Arabia, a thick sequence of massive, impervious, overpressured shale, equivalent to the lower part of the Dashtak Formation known as the Sudair Formation, partly Triassic in age but it also extends into the Upper Permian conformably overlies the Permian-aged rocks supporting an extensive gas column. Throughout most of the areas underlain by Permian carbonates in Saudi Arabia there is also a conformable cover of massive shale with a thickness of up to about 125 meters.

The Sudair shale and argillaceous limestones and shales of the basal part of it act as an effective seal for the gas accumulation in the Khuff Formation. The thickness of the lower Sudair Formation is about 55 meters at its type locality in the southeastern part of the Rub' al Khali in the southern part of the Persian Gulf. It is believed to thin gradually towards the north-east (Grantham et al., 1988; Simmons et al., 2000).

There are a handful of minor cases where potential Permian reservoir rocks are overlain unconformably by considerably younger impervious strata. They are mostly marginal to the main areas of Permian sedimentation in southern Persian Gulf region particularly in Saudi Arabia. In general, the Middle Triassic, with younger Triassic evaporites, form an effective regional seal to major gas accumulations in the underlying Permian carbonates and lower Triassic clastic reservoirs. In northern Persian Gulf, the same Lower Triassic calcareous shales overlay the Permian carbonate reservoirs (i.e., Aghar Shale).

In southern Iran, the same Lower Triassic calcareous shales overlay the Permian carbonate reservoirs. Locally, thin beds of impermeable marls, shales, and evaporites within the Permian carbonates perform as permeability barriers. At Pul-e-Zarreh, there is a marl unit more than 40 meters in thickness

occurring in the middle of some 1 km of Permian limestones and dolostones (Edgell, 1977).

It appears that relatively impermeable zones within the Permian carbonate sequences are almost as important as overlying impervious cap rocks. Several zones have tested gas in the Permian rocks in Bahrain. These represent zones of dolomitization and secondary porosity within the reservoirs, separated by thin impermeable layers of dense limestone, anhydritic limestones and a few thin anhydrite layers behaving as barriers for fluid movement.

Evidently, Aramco have also recognized and named separate permeable zones within the Permian carbonates, as they refer to production of gas from the Dhahran Zone of the Khuff Formation in Dammam No.43. There are thin layers of gypsiferous clays in the upper half of the Khuff, probably acting as permeability barriers or cap rocks within the dominantly carbonate formation.

In general, it appears that the cap rocks which are conformably overlying the Permian reservoirs present the most favorable conditions for hydrocarbon accumulations in the Persian Gulf area. Under such stratigraphic positions argillaceous sediments of the Triassic age immediately overlie the Permian carbonate sequences.

MESOZOIC SEAL ROCKS

The most important Mesozoic cap rock and seals over the Persian Gulf oil fields include the Albian age Lower Kazhdumi (=Nahr Umr) shales and the Tithonian Hith Anhydrite, which are forming excellent regional cap rocks. The Hith anhydrite is the regional top seal to the prolific Surmeh and the Arab reservoirs sealing well in excess of 100 $x10^9$ (billion) barrels of recoverable oil reserves. Not only do prolific accumulations in the underlying Arab reservoirs demonstrate the effectiveness of the Hith anhydrite as a seal, but also does the general lack of accumulations in the overlying Lower Cretaceous where Hith is present. The Hith is occasionally breached by faulting, allowing upward migration of oil from the Arab reservoirs. Thus, in the Persian Gulf region the Hith anhydrite forms an excellent seal for the Surmeh and Arab Formations, preventing further upward movement of oil generated in Jurassic source rocks (Dunnington 1967; Murris, 1981; Ayers et al., 1982; Ziegler, 2001).

Hith Anhydrite Regional Topseal in Persian Gulf

The Late Jurassic (Tithonian) eustatic variations of the Arabian platform resulted in deposition of the carbonate-anhydrite cycles that constitute the dominant reservoirs and cap rocks. The depositional environment consisted of a restricted-shelf evaporitic environment resulted in the precipitation of the regionally extensive, massive Hith Formation evaporite.

The Hith Anhydrite cap rock sequence in the Persian Gulf area (Figure 6-3) forms the main regional seal over several Jurassic reservoirs charged with hydrocarbons from the underlying organic-rich intrashelf basinal shales. It is encountered in outcrops and in the subsurface of the oil fields of the region (Murris, 1980; Yousif and Nouman, 1997; Al-Husseini, 1997).

The Arab Formation is a prime case of a large inner shelf development due to successive sea level fluctuations. It consists of a thick sequence of shallow-marine limestones which are capped by Hith evaporites. The Arab and the overlying Hith Formations contain four major sedimentary cycles of carbonates and evaporites, the former being the prime oil reservoirs and the latter seals or cap rocks occasionally holding some minor oil reservoirs. The Hith anhydrite in addition to anhydrites which are interbedded within the Arab-ABC reservoir appears to have formed additional intraformational seals or aerially limited barrier to vertical hydrocarbon flow.

The evaporite cycles within the Arab Formation provide the seals for the B, C, and D reservoirs within the Arab Formation. The anhydrite units between each zone (zone A-D) in the Arab Formation act as intraformational seals in the same field, and the Hith Anhydrite has proved to be the ultimate regional seal for the oil and gas accumulation in southern Persian Gulf (Schlumberger, 1981).

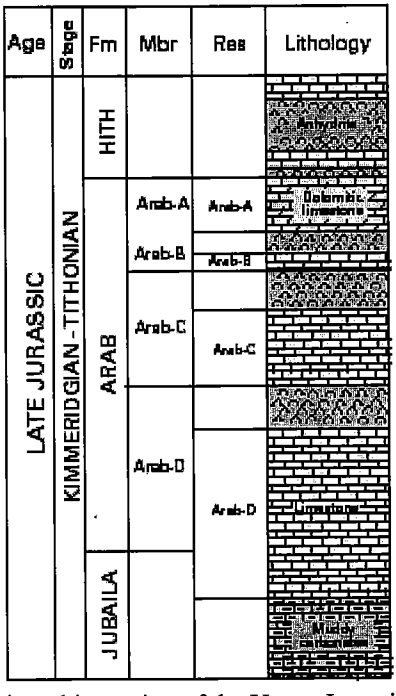

Figure 6-3. General stratigraphic section of the Upper Jurassic Arab Formation showing stratigraphic units, lithology, intraformational reservoirs and seals, overlying and underlying units (Modified from Hughes, 1996).

Upward seepage through the Hith anhydrite cap rocks is always rare and has occurred only as a result of major faulting over a structure or from lateral thinning or wedging out of these anhydrites. Wherever the Hith anhydrites are present over the Arab reservoir, the overlying Lower Cretaceous reservoirs are devoid of petroleum charge.

In general, seepage of hydrocarbons is practically absent when petroleum system is effectively sealed off in areas of weak tectonic deformation and minimal seal failure such as the system observed in the Persian Gulf region. Although anhydrite is accepted as one of the most effective hydrocarbon top-seals, however in low relief Arabian growth structures directly comparable to Burgan, the anhydrites that separate "giant" accumulations in stacked Arab Jurassic reservoirs are considered to have leaked, because this is necessary to satisfy the geochemical assumption that all the oil has been generated from the underlying formation (Ayers et al., 1982; Wilson, 1982).

On the shelf margin where Hith evaporite seals appear to be missing, hydrocarbons which have been generated in the Hanifa source rock could escape upward to be trapped in Lower Cretaceous reservoirs. Any significant loss of hydrocarbons generated within the Jurassic sequences seems to have been prevented by the regionally extensive, overlying evaporite seals; thus, only restricted upward vertical migration could have occurred.

During Late Jurassic, the Persian Gulf region was dominated by evaporites and shallow marine carbonate depositional environments. A vast platform covered the region at this time and produced the Hith Anhydrite and formed inland salt lakes in the western Rub 'al Khali Basin and intraplatform Gotnia sub-basin (Al-Husseini, 1997). The depositional setting was analogous to the present-day sabkha depositional setting that extends along most of the southern and southwestern coasts of the Persian Gulf.

Two evaporite inland salt lakes appear to have developed in the western Rub 'al Khali Basin and Jurassic Gotnia intraplatform sub-basin (Al-Husseini, 1997). Murris (1980) described Hith evaporite precipitation on a shallow platform in a sabkha environment due to an arid climatic condition, dominated the region. Alsharhan and Kendall (1986) suggested that the predominance of anhydrite and the precipitation of minor dolomite associated with the Hith Formation as marking a final regressive, prograding supratidal phase of Late Jurassic sedimentation. They interpreted the Upper Jurassic cycles of marine carbonates and anhydrites of the Arab and Hith Formations as a reflection of fluctuations and eustatic sea level changes caused by regional epeirogenic movements or by eustasy.

From northern Persian Gulf towards the southern part and to the Saudi Arabia, the Surmeh and Arab Formations are overlain by Hith Anhydrite Formation. From the coastal Fars toward the north, where the Hith Anhydrite is absence, the Surmeh Formation is covered by pelletic and oolitic carbonates of the Fahliyan Formation. Approaching the Strait of Hormuz in the eastern Persian Gulf the Hith anhydrite is missing from the stratigraphic column.

Based on information obtained from subsurface, in the Persian Gulf offshore wells the thickness of Hith Anhydrite is 47 meters in well # 0-4BIS, about 61 meters in U-1, 64 meters in R-32 (in Resalat oil fields), 96 meters in Reshadat, 76 meters in FRB-1 and 30 meters in Sirri A field. Locally, about 32 meters of the Hith Anhydrite have changed facies to dolomitic anhydrite and that is the case which is observed in well 3H-1. Eastward, approaching the Sirri field the Hith massive anhydrite facies changes to dolostones with anhydrite interbeds losing the caprock properties (Jahan-Mahin, 2002). This might be one of the main reasons for the lack of hydrocarbon in the Surmeh Formation in the Sirri field.

The thickness of the Hith encountered in wells drilled in Lavan and Kish Islands in the Iranian waters of the Persian Gulf ranges from 73 to 92 meters. However, in many localities in Iran the thickness of this formation ranges from 30 to 150 meters (Javadian, 1996) whereas it disappears or pinches out completely in the Bandar Abbas Area (Javadian, 1996).

Towards western and northwestern part of the Persian Gulf, the Hith is replaced by Gotnia anhydrite. The Hith anhydrite passes eastward to oolitic shoals and shelfal carbonates of the Asab Formation. De Matos (1994) shows the Asab Formation oolite is stratigraphically equivalent to the Hith and the Arab-A member.

In most of the area limestones of Fahliyan Formation rest unconformably either on carbonates of the Surmeh Formation or on the Hith evaporites. In most of the wells which were drilled through Fahliyan Formation, such as well U-1, the lower contact with the Hith is gradational and microfossil *Clypeina Jurassica* is identified at the base of Fahliyan.

In the southern Persian Gulf the Hith Formation consists of more than hundred meters of massive beds of anhydrite with subordinate interbeds of dolomites (Alsharhan and Kendall, 1994). The Hith anhydrite also acts as the ultimate seal for most of the oil fields of western Abu Dhabi.

At Ghawar field, the Hith anhydrite has a thickness of about 152 meters mainly consisting of anhydrite with subordinate fine-grained carbonates (Arabian American Oil Company, 1959). The anhydrite lithofacies of the Arab D in this field consists of nodular to massive anhydrite, commonly with chicken-wire texture (Cantrell et al., 2001). The Hith anhydrite is 128 to 287 meters in thickness; the anhydrites of the Arab B and C anhydrite sub-members are each about 21 meters in thickness and the Arab D is about 15 meters in Abqaiq field (Saner and Abdulghani, 1995).

In general there are two principal sealing formations in southern Persian Gulf, the Hith Anhydrite and Nahr Umr shales. The absence of oil in the Arab Formation in eastern offshore Abu Dhabi is also due to the absence of Hith Formation. The presence of Hith in contrast commonly prevents oil discharge into the overlying reservoirs as in western Abu Dhabi except where there is faulting.

OTHER MESOZOIC CAP ROCKS

Apart from the two main seals which are predominant in the Persian Gulf, there is other less widespread but still effective sealing strata in the region. Although the major seal rocks for the Jurassic reservoirs are anhydrites of Hith; secondary carbonate reservoirs of the Upper Jurassic such as Hanifa and Jubailah Formations are sealed by overlying fine-grained, impermeable carbonates or shales of adjacent formations. Thus, secondary seals and barriers exist in the stratigraphic sequence. For instance, the Hanifa source rock itself is capable of forming a good seal for the Dhruma or Tuwaiq reservoirs. Upper Jurassic argillaceous lime-mudstones hold modest oil columns in the Hanifa and Tuwaiq reservoirs in several oil fields (Murris, 1980).

The seals for Hanifa reservoirs are fine-crystalline carbonates which commonly leak due to the presence of fractures (Alsharhan and Nairn, 1997). For example, at some of the southern Persian Gulf oil fields the Hanifa reservoir is separated from the Arab D reservoir by more than 100 meters of fine-grained, impermeable carbonates of the Jubailah Formation, which appears to perform as a seal. However, these carbonates are in many places forming ineffective cap rocks due to microfracturing that causes the Hanifa and Arab D reservoirs to be in pressure fluid communication (Grover, 1993).

The low-permeability mudstones of the lower Hanifa Formation provide a seal for the underlying Hadriya reservoirs of the Tuwaiq Mountain Formation; this reservoir and seal relation is best developed in one of the oil field located in offshore Saudi Arabia in the Persian Gulf (McGuire et al., 1993). Oil and gas accumulation in the Araej Formation are sealed by argillaceous lime mudstones in the basal Diyab Formation (Lutfi and El-Bishlawy, 1986).

CRETACEOUS CAP ROCKS IN THE PERSIAN GULF

The ultimate top seal for Upper Jurassic sequence was previously thought to be the Hith Anhydrite, but in southern part of the Persian Gulf especially in the Abu Dhabi area it may rather be the tight limestones of basal Cretaceous Habshan Formation. The Habshan Formation rests unconformably on the top of the Hith anhydrite and towards the east, these anhydrite pass laterally into pellety intraclast grainstones with minor oolites called the Hith equivalent or Asab Formation.

The Lower Cretaceous marine carbonate reservoirs of the Dariyan in the Persian Gulf region are sealed by shales of Garau, Gadvan, and Kazhdumi Formations. The Lower Kazhdumi also is a major regional seal for Cretaceous reservoirs. The Nahr Umr Formation, a direct equivalent of the Kazhdumi Formation, acts as a regional seal for the Dariyan and also its stratigraphic equivalent Shuaiba reservoir in the southern Persian Gulf.

The Lower Cretaceous Fahliyan reservoir limestones in the Persian Gulf Islands such as Kharg are sealed by the lower Kazhdumi shales. These shales

were deposited during a relative sea level rise in low energy environments. The Kazhdumi shales are well known in the Persian Gulf area as a regional source of hydrocarbon mainly in the eastern part of the Persian Gulf and more importantly in southwestern Iran. These shales also appear to have acted as a regional cap rocks. In addition, they are providing the seal for the underlying Dariyan reservoir in Reshadat and Resalat oil fields in the Persian Gulf.

In general the Fahliyan reservoir is assumed to be capped by the compact micritic limestone of the Khami Group with reduced to no reservoir quality. The Lower Cretaceous Gadvan Formation consists of marl and shale, and associated pelecypod-bearing argillaceous limestone, resting gradationally upon Fahliyan Formation. The shale of Gadvan Formation serves as a partial seal for oil and gas in a Lowermost Cretaceous limestone reservoir in Dorood Field and also for the reservoired oil in Foroozan Field.

From the Strait of Hormoz towards the Sirri and Farur Islands to the west the sedimentary sequence of Gadvan Formation consists of alternation of micritic limestone and argillaceous limestones. However, further west and toward the Pars field the lithology of the formation has more resemblance to its type section on land. According to the acquired data from the drilled wells, both the lower and upper boundaries with Fahliyan and Dariyan are gradational in the Persian Gulf.

In Bahregansar area in the Persian Gulf, the limestones of upper part of the Fahliyan Formation are extremely argillaceous and their identification and division from the Gadvan Formation happen to be very difficult. However, the presence of the Khalij member is very helpful in the identification of Gadvan Formation in the Persian Gulf.

The dense limestones within the Thamama zones represents an intraformational seal for the Thamama reservoirs; while the shale of Nahr Umr represent the regional seal for the Shuaiba reservoir in the southern Persian Gulf. The highly bituminous lime mudstone of the Shilaif source rocks acts as a lateral seal for the stratigraphically-trapped Middle Cretaceous (i.e., Upper Sarvak) oil; whereas the Laffan shales form the regional top seal for the Upper Sarvak (i.e., Mishrif) hydrocarbon reservoirs in the southern Persian Gulf.

Regionally extensive and continuous basal marine shales of Laffan and Fiqa Formations have provided seals in several Persian Gulf oil fields. The Cretaceous rudist-bearing carbonates reservoirs in the Upper Sarvak and its stratigraphic equivalent Mishrif in the Persian Gulf form extensive reservoirs in oil fields with different configuration which are sealed by aerially extensive shale of the overlying Laffan and in a number of oil fields by Fiqa Formation.

Late Cretaceous deposition commenced with the Laffan shale, a prodeltaic sedimentary succession, followed by deposition of the shallow water carbonates of the Santonian Ilam Formation. Laffan shales grade upward into the regressive Ilam limestones which in turn is overlain by another transgressive the Aruma shale. The Ilam limestones appear to be thining or absent in the southern Persian Gulf, especially in the northern UAE. Ilam Formation and

its lateral equivalents consist of two Coniacian-Santonian facies: shelf limestone and platform-slope marl.

The Laffan shale deposited on the unconformity surface and performed as a very efficient regional seal for Sarvak Formation reservoir. This is observed in the majority of the wells drilled in the central portion of the Persian Gulf. For instance, the Laffan shale are encountered in wells D-2, G3, IMD2, U-1, FRB-1, SID-1, SIE-2 and IE1 which are drilled in central part of the Persian Gulf. However, approaching the Strait of Hormoz the Laffan Formation is thinned out.

The Upper Sarvak carbonates reservoirs which contain most of the hydrocarbons in the Middle Cretaceous rocks of the oil fields in the Persian Gulf such as Sirri, Reshadat and Fateh fields are sealed by the overlying Coniacian Laffan shale Formation. Locally, the Laffan shales can form a major seal over the hydrocarbon reservoirs in Resalat oil field in the Persian Gulf.

In the Sirri fields the thickness of the Laffan cap rock varies between 10 to 12 meters (Hedayati, 2003). For example, the thickness of the Laffan shale at Sirri reaches 4.5 meters whereas in the Fateh oil field the thickness of Laffan cap rocks reaches 30 meters. The discontinuous distribution of this seal makes it difficult to predict the location of traps in the Upper Sarvak Formation. Similarly, the Wasia Group in southern Persian Gulf contains reservoir rocks overlain by shale of the Laffan Formation however the oil fields in this region may be quite large (Fateh and Sirri fields). Westward, approaching the Qatar-Gavbandi Arch the thickness of Laffan shale is also decreased and pinches out completely towards the High.

Based on the drilling information, the thickness of Laffan shale is between 3 to 6 meters from eastern Persian Gulf near the Strait of Hormoz to the Sirri Island (Hedayati, 2003). However, the thickness of these shales increase in the Sirri field to 23 meters and ultimately it reaches a maximum of 41 meters at U-1 well. In some localities such as well 3H-1, the Laffan shale is absent and the Ilam limestone overlies the Sarvak Formation.

Unlike the Sirri fields a clear development of the Laffan shale acting as the main cap rocks has not been observed in the Hengam field. In this field the Gurpi shales form the seal as observed in the well correlation across Hengam. Thus, the Laffan shale in spite of a broad geographic distribution it is not always forming cap rocks in the Persian Gulf. In the deep wells drilled in the southern Persian Gulf region, the Laffan shales have been encountered in Bahrain, Qatar, and Abu Dhabi (Motiei, 2003).

In the Sirri and Mobarak oil fields, Ilam Formation has also revealed high potential as being reservoir rocks. However, its reservoir characteristics are remarkably lower than the Upper Sarvak. In Sirri-A, Ilam Formation exhibits fracture porosity forming the main reservoir unit and account for the storage of the hydrocarbons. In this field the Upper Sarvak Formation appears to be eroded away. The approved oil column found in the well is approximately

85.3 meters within the Ilam Formation (Hedayati, 2003). In these fields the Gurpi Formation also acts as a seal.

Thus, in the northern Persian Gulf, the Gurpi shale analogous to what is observed in the Dezful Embayment area can be considered as a regional seal or cap rock for the Ilam-Sarvak reservoirs. The Middle and Upper Cretaceous sediments of the Persian Gulf and Dezful Embayment form one of the richest petroleum systems in the region, with the presence of the Kazhdumi source rock, the Sarvak reservoirs and the sealing Gurpi shales.

In general, most of the Upper Cretaceous sediments deposited in the UAE form seals for the Middle Cretaceous and older reservoirs. The exceptions are the Ilam carbonates near the base of the Upper Cretaceous succession and the porous Simsima carbonates at the top which may be considered as attractive targets.

The Laffan shales interfinger with, and are overlain by the argillaceous limestones of the Halul Formation. This in turn is overlain by the Campanian Fiqa Formation composed of calcareous shales, marls, and argillaceous limestone with a deep marine fauna. It is followed by the Maastrichtian Simsima Formation composed of fossiliferous and shaley limestone and peloidal-bioclastic packstone and wackestone and dolomitic limestone with coral and rudist buildups (Schumann, 2000). The lower Laffan and Halul Formations form the first transgressive cycle, whereas the Fiqa-Simsima cycle is more directly related to tectonic events (Alsharhan and Nairn, 1997).

The seal of the reservoirs associated with Natih is a series of deep-marine shale of the Fiqa Formation. It overlies the Natih Formation in most parts of the northern Oman and is an excellent cap rocks in terms of thickness and also permeability properties.

The shales and argillaceous limestones of the basal Umm Er Rhahuma Formation (i.e., Pabdeh) act as an effective seal for the Simsima oil and possibly the Mansouri limestone. Anhydrite with minor dolomite and terrigenous clastics of the lower part of the Gachsaran Formation act as a seal for Asmari reservoirs, while the anhydrite and dolomitic limestone in the upper part act as a seal for this Formation.

CENOZOIC SEAL ROCKS

In Miocene time, similar to the late Jurassic period, thick sequence of evaporites formed in the Persian Gulf and surroundings regions subsequently acting as very efficient seals for the hydrocarbon accumulations.

An almost perfect seal is provided by the evaporites of Middle Miocene age in the region. The Gachsaran evaporites provide the all important seal for the prolific Asmari reservoir in the Iranian oil fields. Indeed Early Miocene hydrocarbon development along the northern Zagros foreland is to a large extent controlled by the distribution of evaporitic cap rocks of the Gachsaran Formation. A large part of petroleum production in the Persian Gulf is from

Asmari reservoirs which in most of the oil fields are sealed by these Miocene age evaporites, ranging in thickness from 600 to 1500 meters in the Iranian territory.

The Gachsaran Formation, formerly known as the "Lower Fars Series," is exposed extensively in the foothills of the Zagros Mountains and forms the cap rock in many important oil fields. These evaporites form a very effective seal for the Asmari Limestone and Ahwaz Sandstone member reservoirs of Khuzestan.

The Gachsaran Formation is one of the major evaporitic horizons in the geological column of the Persian Gulf region because it forms a thick cap rock in some of the major oilfields. Thus, this sequence plays an important role in sealing Asmari reservoirs within the Persian Gulf. The Gachsaran Formation conformably overlies the Asmari limestone except in Qeshm Island, in the eastern part of the Persian Gulf, where Pabdeh marl replaces the Asmari and directly underlies the evaporites (Gill and Ala, 1972). The thickness of the Gachsaran is estimated at 1200-1830 meters in the Persian Gulf and surrounding area (Edgell, 1996). The presence of such an adequate cover has led to the protection of potential reservoir rocks.

An almost complete seal is provided by the Gachsaran evaporites in the northern head of the Persian Gulf. Oil pools have been discovered in Asmari reservoirs in Kharg, Dorood, Nowrooz and Bahregansar oil fields. In Doroud field the Asmari reservoir is capped by anhydrite and fine dolomites of the Gachsaran Formation (well# D2). In Nowrooz field (well No#1) where the Asmari-Ahawaz sand member form the main reservoirs, 440 meters of the Gachsaran cap rock has been cored whereas in Abouzar oil field Gachsaran cap rock attains a thickness of 700 meters.

The Asmari Formation which shows some oil bearing sandstone reservoir layers near its top capped by the overlying anhydrite of the Gachsaran Formation around the Kharg Island and the thickness of Gachsaran cap rocks reaches at least 45 meters based on well data obtained from various boreholes. Kashfi (1980) has shown the distribution of the Gachsaran cap rock in the eastern part of the Persian Gulf (see Figure 6-4).

The Campanian-Oligocene marls and shales, which until then formed an effective seal to the Cretaceous reservoirs, were subjected to the tectonic forces. As a result, they were fractured and the accumulated hydrocarbons in them escaped upward into Asmari reservoirs and traps, which were effectively capped by highly efficient seal of the Gachsaran evaporites (Murris, 1980). Dunnington (1967) suggested that oils in the Persian Gulf and surrounding region were formed in Jurassic and Lower Cretaceous source rocks and accumulated in Lower and Middle Cretaceous structural traps.

It is believed that following the termination of Asmari Ahwaz member deposition the area of southern Iran, the northwestern Persian Gulf became a center of lagoonal-evaporitic environment. In terms of aerial distribution, the

all-important Miocene evaporitic facies of Iran and Iraq have been extended into the Persian Gulf.

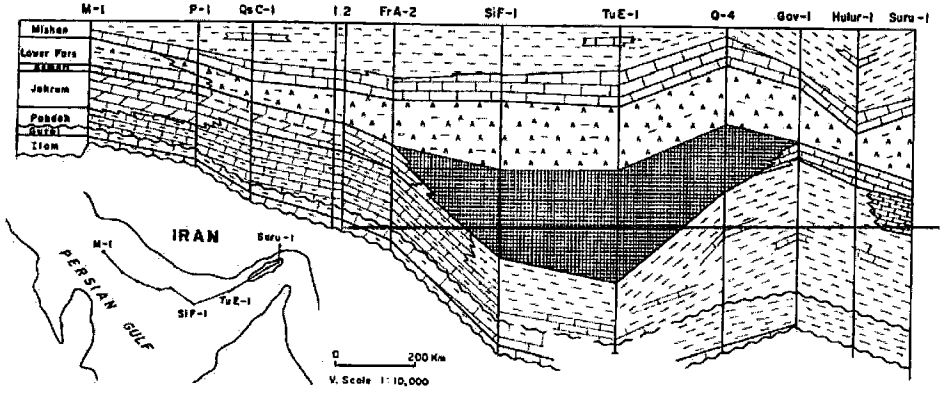

Figure 6-4. A cross section showing the east-west extension of the Gachsaran Formation cap rock in the eastern part of the Persian Gulf (cited from Kashfi, 1980).

The Gachsaran have formed by evaporation of large lagoons and embayment in a 'barred-basin model' with repeated marine incursions. Stromatolites and cryptalgal laminates formed in the limestone members of the Gachsaran Formation in northern Iraq (Shawkat and Tucker, 1978). This was the result of the trapping and binding of sediment particles by a surficial blue-green algal mat, and useful indicators of depositional environment.

The Gachsaran is an important formation in the Persian Gulf region for two different reasons. It is not only the cap rock to the major oil fields which lie beneath it, but it contains reserves of sulphur. Thus, from an economic perspective, these are important evaporite sequence.

The Gachsaran basin was elongated in a northwest-southeast direction, with a maximum width of 300 kilometers, stretching some 1500 to 2000 kilometers from northeast Syria across Iraq into Bandar Abbas region in Iran into the Persian Gulf (Stocklin, 1968).The area of Iranian oil fields and Zagros foothills appears to have been the center of the basinal subsidence. The basin where Gachsaran deposition occurred was asymmetric, with a steeper northeastern flank. A southern extension occupied the region between Qatar and Oman Peninsula.

There have been some investigations of the Gachsaran basin and all have interpreted the presence of evaporites and the cyclicity in terms of a barred-basin (i.e., evaporiting-dish) model. Lees (1938) considered evaporite formation to have occurred in an "immense gulf" while Dunnington (1958) invoked a "barred-basinal lagoonal" environment with intermittent connection to an open marine source. Van Bellen et al. (1959) also envisaged a 'semi-barred basin'.

Earlier works (Stöcklin, 1968b; Gill and Ala, 1972; Kashfi, 1980; Motiei, 1993) have pointed to the geologic requirement (s) for barriers to control seawater influx to the basin. However, the nature and distribution of such barriers are still unconstrained. Recently Bahroudi (2003) considering the geometry of the Zagros foreland and its evolution attempted to provide an explanation for the nature of such barriers.

Detailed stratigraphic investigations on the Gachsaran Formation suggest a rhythmic character in which each cycle was "capped" by a bed of continental eolian sediment (e.g. James and Wynd, 1965; Dunnington, 1968; Stöcklin, 1968b; Gill and Ala, 1972).

The identification of intertidal facies beneath nodular gypsum indicates that the cycles of marl, limestone, gypsum, developed through progradation of supratidal flats (sabkhas) over intertidal and subtidal facies (Shawkat and Tucker, 1978). Gachsaran sedimentation would have been analogous to that taking place today along the Trucial Coast of the Persian Gulf. The marls which occur at the bottom of the Lower Fats cycles are interpreted as deeper subtidal in origin and are comparable to sediments from the central part of the Persian Gulf. The evaporites and dense carbonates of the lower Miocene are recorded as a potential seal in some of the UAE oil fields.

CONCLUSION

One of the most important factors accountable for the large quantity of oil accumulations in the Persian Gulf region is the occurrence of efficient cap rocks. In general, it can be concluded that the predominance of evaporitic cap rocks of the Upper Jurassic (Hith Formation) and Miocene age (Gachsaran Formation) in the Persian Gulf area is extremely striking. These regional seals are often produced in the evaporitic sabkha environments. Nonetheless, there are transgressive and regressive shales within the Persian Gulf petroleum system which are acting as seal rocks as well. In the Persian Gulf, cap rocks appear to have been placed in the frame of a hydrocarbon habitat evolved through time.

The lower part of Kazhdumi and its equivalent Nahr Umr shale are major regional seals for the Cretaceous reservoirs; whereas, Eocene and Miocene evaporites are primary seals for Tertiary reservoirs. Significant loss of hydrocarbons, generated within these Petroleum systems was prevented by the regionally extensive, overlying evaporite seals; thus, only limited vertical migration occurred.

Typical cap rocks lithology such as Hith and Lower Kazhdumi often form part of a formation and are interstratified with non-cap rock lithologies such as carbonate and sandstones. However, carbonates, sandstones and other rock types have been locally also served as cap rocks when they are "tight".

It must also be understood that the vast hydrocarbon accumulation of the Persian Gulf region provide a outstanding example for the interdependence of

cap rock, reservoir and source trilogy as acknowledged by Murris (1980). The close association of source, reservoir and cap rocks is the most significant factor in the development of the great productivity of the Persian Gulf region (Kamen-Kaye, 1970).

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CHAPTER-7

TECTONICS OF THE PERSIAN GULF

INTRODCTION

The Zagros Mountains of SW Iran and Persian Gulf are one of the most prolific basins in the world. They contain 8.6% of oil and 15% of gas proven world reserves. The occurrences of the sediments and traps that generated and preserved hydrocarbons are linked to the history of the plate margin evolution. The thick sedimentary cover of the northeastern margin of Arabian plate records all the stages of evolution of a basin, from a passive continental shelf to a rift and finally through various stages of deformation associated with ophiolite obduction and plate collision.

The large-scale regional tectonic map suggests that Zagros Mountains and Persian Gulf are parts of the large Arabian continental plate (figure 7.1). The Arabian plate extends from the Red Sea to the Zagros and from the Gulf of Aden to the Taurus Mountains. It consists of Precambrian basement overlain by Tertiary and later volcanics in the west and marine and continental sediments in the east (Reches and Schubert, 1987). Its interior lacks any trace of intense late Tertiary deformation (Al Kadhi and Hancock, 1980). The Mesozoic-Cainozoic sediments in the eastern part of the plate are horizontal or slightly tilted, and they display subdued Late Cretaceous–Eocene structures (Hancock et al., 1984).

The Arabian plate boundaries embrace all types of plate boundary processes. They include rifting and sea floor spreading in the Red sea and Gulf of Aden, collision and subduction along the Zagros-Bitlis suture and Makran respectively and transform fault activity along the Dead sea and Owen-Sheba fracture zone. The Makran and Zagros convergence zones separate the Arabian plate from Lut block and Central Iran plate respectively (Beydoun 1993).

MORPHO-TECTONIC UNITS OF THE ZAGROS OROGENIC BELT AND PERSIAN GULF

Zagros belt occupy the southwestern part of Iran and portion of Iraq and extends from eastern Turkey to the Strait of Hormuz (figure 7.2). The Zagros Mountains gradually rise northwestward from an unfolded shelf, extend through a fold belt into a thrust belt and imbricated zone, and merge into the Sanandaj-Sirjan zone characterized by intrusive and metamorphic rocks (Berberian and King, 1981) (figure 7.2). The Persian Gulf and its north-western prolongation, Mesopotamian depression, are widely considered to occupy a downwarp in the Arabian plate which resulted from its tectonic loading by the Zagros Mountains (Uchupi et al., 1999).

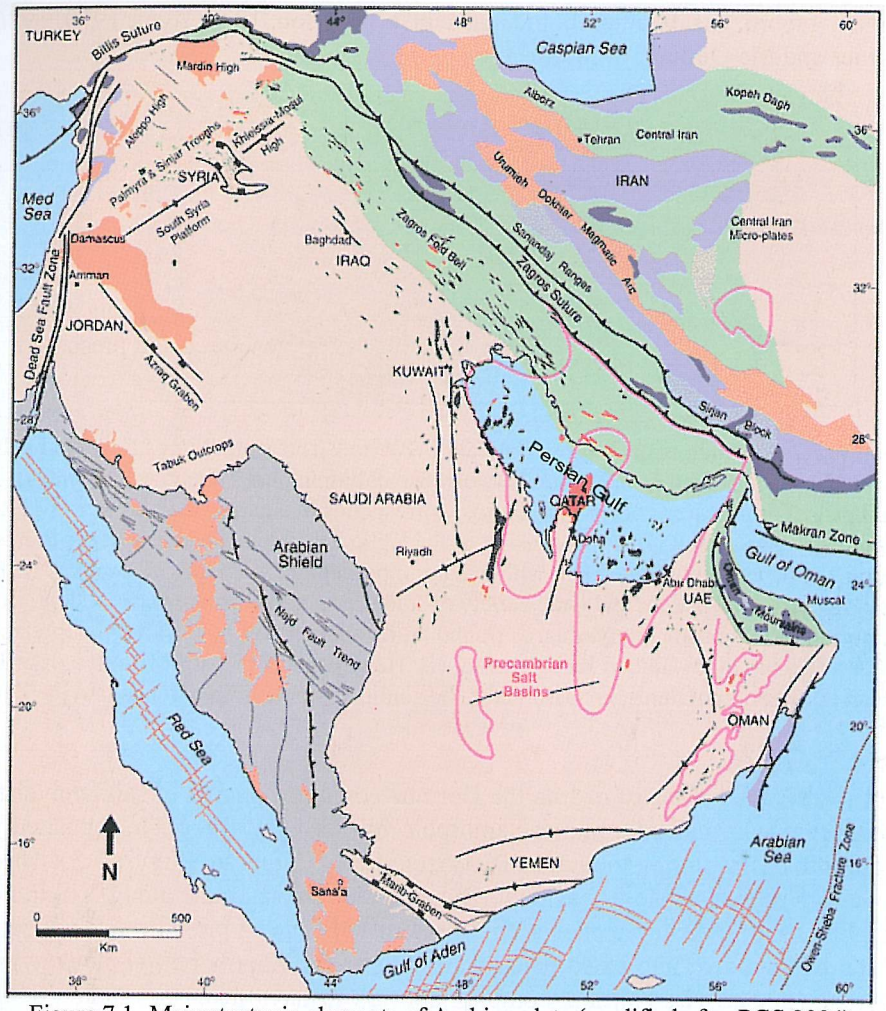


Figure 7.1- Major tectonic elements of Arabian plate (modified after PGS 2004)

TECTONO-STRATIGRAPHIC SETTING AND GEODYNAMIC EVOLUTION OF THE NE ARABIAN MARGIN

The oldest portions of the Arabian plate formed in the middle to late Proterozoic (800-650 Ma) when a series of island arcs and micro-continental fragments accreted against the northeastern margin of the African craton to form the Gondwana super-continent (Beydoun, 1991). The Precambrian basement of the Arabian plate is exposed in the west of the Arabian shield (Falcon, 1967; Husseini, 1988 and Konert, 2001) and is similar to the basement, which is exposed in Central Iran west of the Tabas block (Alavi, 1991). In Zagros its composition is just known based on few fragments brought to the surface by salt diapirs. It includes

granite, gabbro, basalt, amphibolite and schist (Harrison, 1930; Kent, 1970, 1986; Haynes and Mc Quillan, 1974).

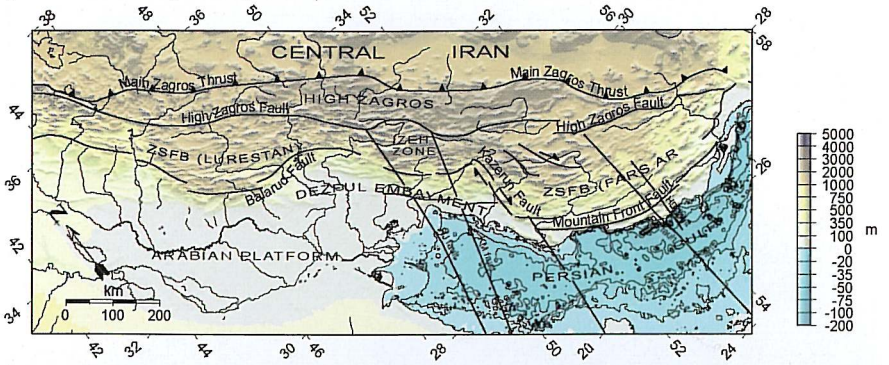


Figure 7.2- Location map, Zagros mountains, SW Iran. The Main Zagros Reverse Fault (MZRF) is considered as the suture between two colliding plates (Central Iran and Arabian plates). Imbricated zone (High Zagros) corresponds to a narrow belt between MZRF and High Zagros fault (HZF). It consists of the highest mountain and deepest exposures across the belt. Simply folded belt with a major topographical step located south of HZF. It shows less deformation and wide variety of folded structures with respect to their size, shape and tectonic complexity. Zagros frontal fault is border SW limit of Zagros foreland. N-S strike-slip faults, like as KZ: Kazerun, HJ: Hendijan, KM: Kharg-Mish, RZ: Razak and HD: Hendurabi faults, are assumed to be continuation of Arabic trends into the Zagros basement.

In south and southeast of Iran the Hormuz complex consists of salt, anhydrite, dolomite, shale, volcanic and metamorphic blocks (Ala, 1974). It deposited in evaporitic basins during the Latest Protrozoic-Early Cambrian (Figure 7.3). These basins are related to the extensional rifting of the Arabian plate along N-S trends (Edgell, 1996). Seismic evidence of Northern Fars shows pre-Hormuz salt sediments of unknown age exist at least in parts of the Zagros belt (Letouzey and Sherkati, 2004). The Hormuz complex appears to have taken advantage of the basement block faulting to produce domal structures (Letouzey and Sherkati, 2003). From the latest Proterozoic to the Late Paleozoic, Arabia with Turkey, Central and Northwest Iran formed part of the long and wide northern passive margin of Gondwana, bordering the Paleo-Tethys Ocean (Figure 7.4) (Beydoun, 1993 and Stampfli and Borel, 2004). The extent of the shelf changed in response to succeeding transgressions and regressions during the Paleozoic. During the Early Paleozoic shallow-marine, fluvial, sandstone, siltstone, and shale were deposited on the low-relief erosion surface formed on the Precambrian basement or Hormuz basin. During Late Silurian, the passive margin of Gondwana in Arabia became active as a consequence of the Hercynian orogeny. The large Carboniferous sedimentary gap (Figure 7.3) in Zagros is apparently the effect of epirogenic movements, which led to a regional regression and general emergence of the region. The regional shallow marine transgression during Permian time with basal

coastal clastics (Faraghan Formation), overlying the Ordovician, Silurian and Devonian rocks.

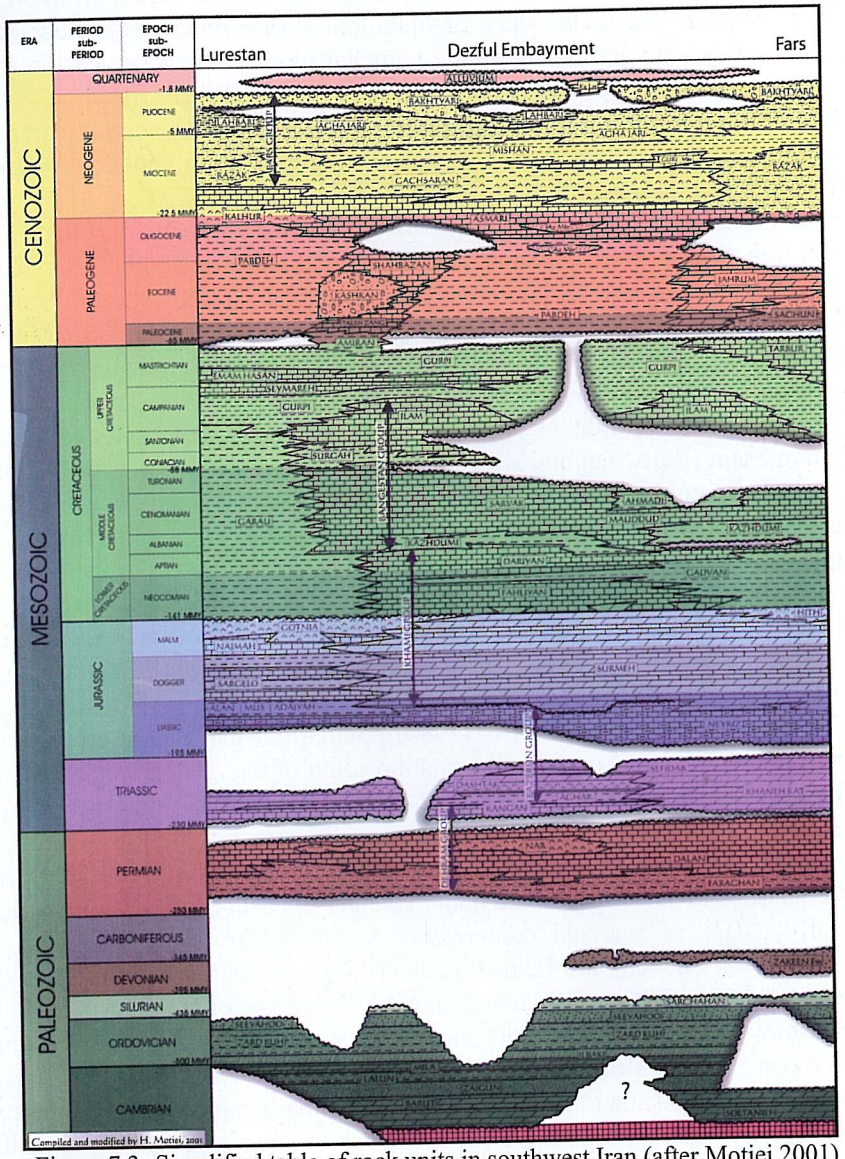


Figure 7.3- Simplified table of rock units in southwest Iran (after Motiei 2001)

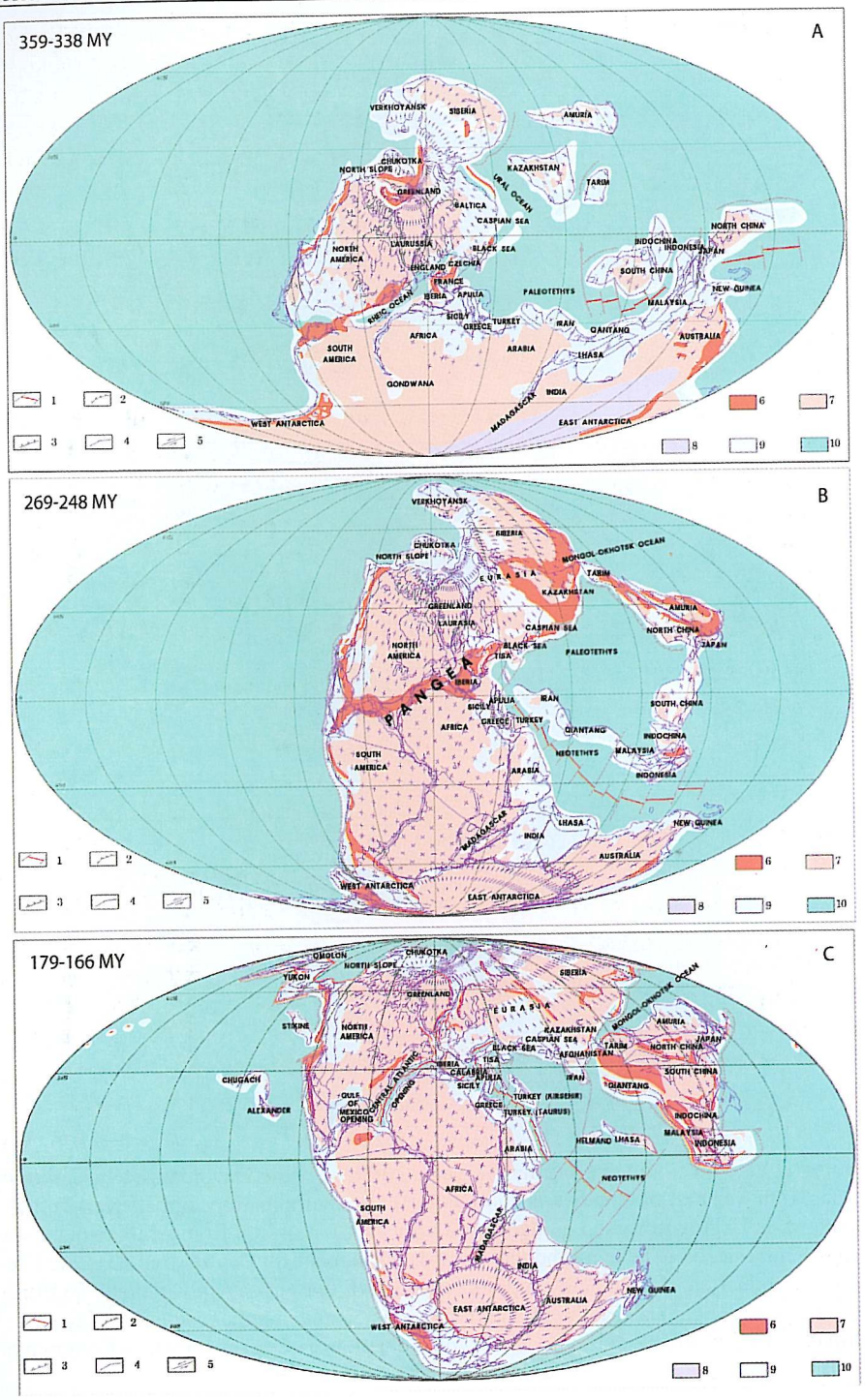
By Late Permian, an extensional phase with crustal stretching and rifting occurred. It led to Triassic separation of the Iranian plate from the rest of Gondwana along fractures parallel to the present "Main Zagros Reverse Fault" and to opening of the Neo-Tethys Ocean. Local strong unconformity between Jurassic and Permian sediments close to the Main Zagros reverse fault was attributed to the

early salt movements, which probably triggered by Neo-Tethys rifting (Motiei and Baghbani, personal comunication). The Iranian microplates broken away from Gondwana, probably docked with Eurasia during the Latest Permian-Early Triassic (Ruttner, 1993). Presence of ophiolotic rocks along large shear zones indicates that interior Iran is a mosaic of smaller blocks? The new ocean was referred to as the Neo-Tethys by Stocklin (1974) (Figure 7.4 and 7.6).

The Early Triassic period in Zagros was characterized by marine carbonate sedimentation (Figure 7.3), which deposited disconformably above the Permian sediments (Koop and Stoneley, 1982; Setudehnia, 1978).

Middle-Late Triassic history of Zagros was totally different from that of the Central Iran. Central Iran was folded and uplifted during the Middle Triassic epirogenic movements, whereas the Zagros was occupied by an evaporitic platform (Murris, 1980). Toward the High Zagros in the northern tip of the basin, the evaporites are replaced by dolomite suggesting a connection with the Tethys (Setudenia, 1978; Szabo and Kheradpir, 1978; Murris, 1980).

During Jurassic to Middle Cretaceous times, sediments deposited in a steadily subsiding basin (Berberian and King, 1981), in which subsidence was controlled by vertical movements and flexures along major basement faults (i.e. Hendijan-Bahregansar, Kharg-Mish, Kazeroun Razak and Hendurabi faults)(figure 7.2). Lateral facies changes from platform sediments in the SE Zagros to the predominantly basinal facies in NW are the significant characteristic of this time interval (Setudehnia, 1978). Mid-Cretaceous intra-shelf basins in Persian Gulf (Murris, 1980; Van Buchem et al. 1992) and Zagros onshore (Taati et al., 2005) are important sedimentological features, which controlled local source rock distribution in the folded belt (figure 7.6). Murris (1980) pointed out that the basement faults influenced the Early Mesozoic sedimentation south of the Arabian plate and central part of the Persian Gulf. These structures had periods of important activity alternating with intervals of relative quiescence. In particular they were most active from the Late Turonian to the Early Campanian (Sherkati and Letouzey, 2004). These periods correspond to major changes in basin configuration marking the early stages of regional compressive activity (Murris, 1980; Koop and Stoneley, 1982; Sherkati and Letouzey, 2004). Tectonic deformation of this long and very wide margin began in association with the onset of the ophiolites on the northeastern edge of Arabian plate during the Early Coniacian- late Santonian time (Ricou, 1971; Falcon 1974) (Figure 7.4 and 7.5). Thick accumulations of Campanian- Maastrishtian sediments (deep water marls, shales, marly limestone and turbidites) were deposited in front of the ophiloithic nappes (Sherkati andLetouzey 2004; Sepehr and Cosgrove 2004) (figure 7.6). Thickness and facies of the Late Cretaceous and Paleogene sediments are considerably affected by progressive deformation following the ophiolite obduction (Koop and Stoneley, 1982; Sherkati and Letouzey, 2004).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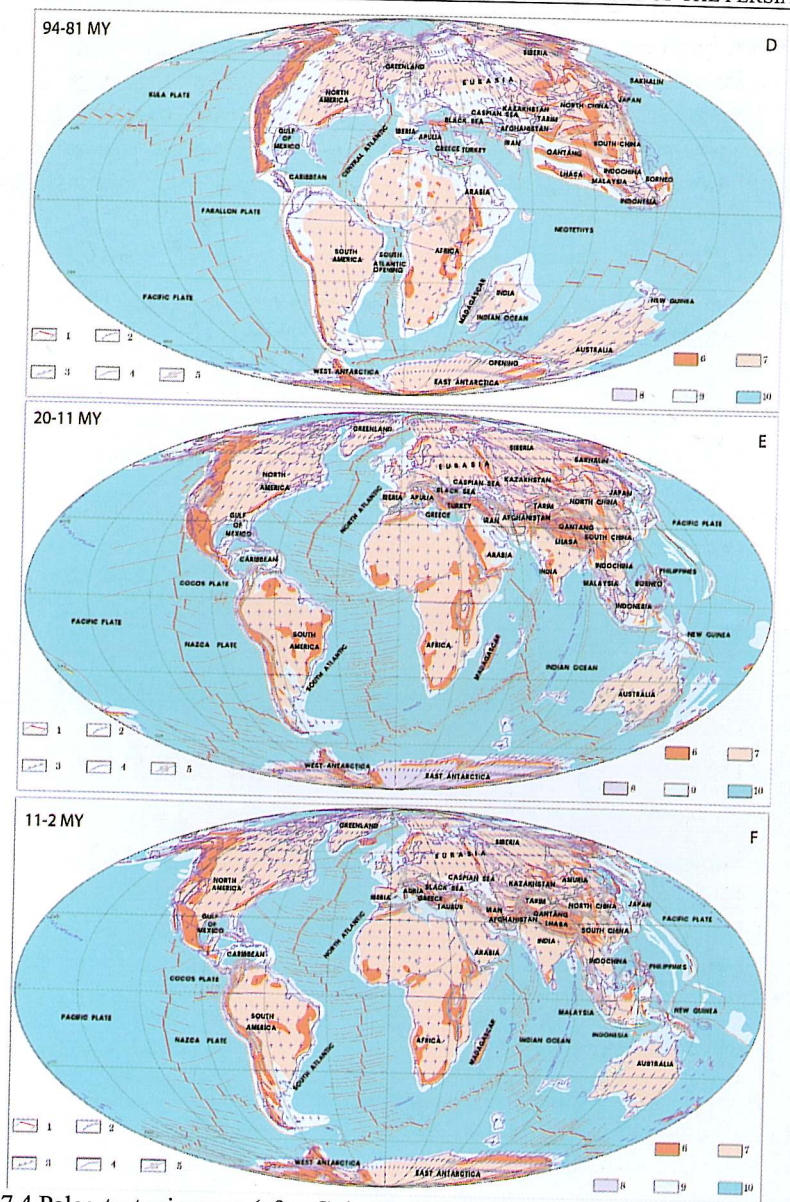

Figure 7.4 Paleo-tectonic maps (after Golonka, 2000). A) Late Devonian-Early Carboniferous, Iran was part of Gondwana continent. B) Late Permian, Opening of Neo-Tethys along Main Zagros Reverse Fault and separation of Central Iran from Arabian plate. C) Middle Jurassic, Neo-Tethys subducts towards north, beneath Central Iran. D) Late Cretaceous, Obduction of Neo-Tethys ophiolite along NE margin of Arabian plate. E) Burdigalian- Serravallian, Continent-continent collision and commencement of Zagros Orogeny. F) Tortonian- Gelasian, present day situation. 1- Oceanic crust, 2- Continental crust, 3- Volcanic belts.

The configuration of the NE margin of the Arabian platform changed abruptly with the Early Coniacian-Late Santonian ophiolite obduction (Ricou, 1971; Falcon, 1974; Berberian and King, 1981; Sherkati and Letouzey, 2004). Field surveys especially in the inner part of the belt provide information allowing a better understanding of this long period of convergence. Figure 7.9 presents the main sedimentary events from Late Cretaceous till Pleistocene time in northwest of Central Zagros.

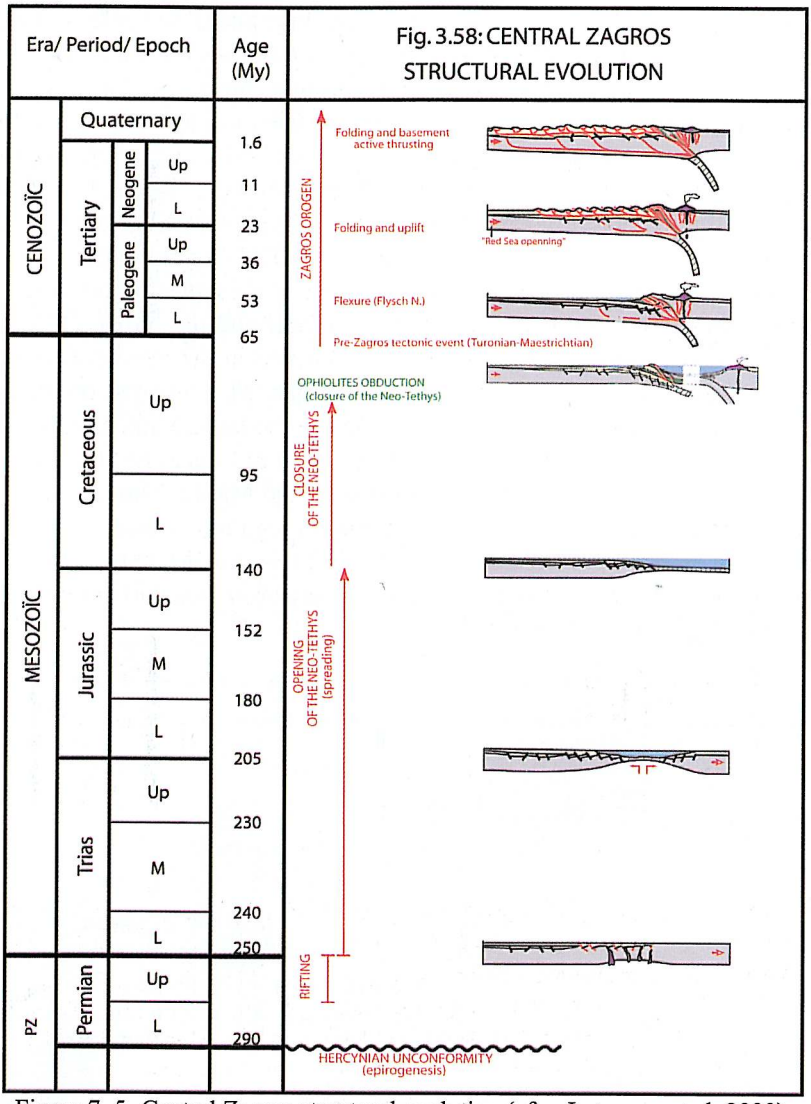

Figure 7. 5- Central Zagros structural evolution (after Letouzey et al, 2000).

North-east of the Arabian plate, a flexural basin has been formed due to the overloading of continental crust by ophiolite obduction in the late Cretaceous. This basin is marked by accumulation of Campanian flysch supporting radiolaritic nappes (Figure 7.8 A and B). The nappes emplacement was accompanied by an uplift, which provoked Paleocene erosion in the High Zagros Belt (Figure 7.8 C). Persian Gulf is divided to two sector by Qatar high (Gavbandi High, a paleo-high in central part of Persian Gulf, which is bordered by deep seated Arabic trends and was active at least since Paleozoic Era) (figure 7.9). Cinematic evolution of the southern sector has significant differences compare to the north Persian Gulf. Obduction of Oman ophiolite at Santonian- Coniacian time and uplift of Qatar high formed two separated depocenter during the Late Cretaceous (Campanian-Maastrishtian) (figure 7.9). These basins through time migrated towards each other and form one single trough in Bandar-Lengeh region. It marked by progradation of Eocene carbonate (Jahrom fm.) into the Eocene marl (Pabdeh Formation) (figure 7.9). Oligocene was the time of compression release due to the change in plate movement direction (Gonzalez, 2001). The compression and uplift of Oman Mountain during the Early Miocene time cause the closure of the eastern marine connection between the Persian Gulf and the Indian Ocean. This event probably explain the confining facies deposited in the Persian Gulf area at that time (Upper Asmari salt and Gachsaran Formation). Compression, uplift and erosion of the Oman Mountains took place before the large Middle Miocene marine transgression in the Persian Gulf domain. Onset of Zagros folding and thrusting affected the affected the Strait of Hormuz by the Middle Miocene time. This unconformity marks the beginning of a major regional marine transgression (Mishan Formation). Depocenter in front of the Zagros-Makran folding, with thickening towards the NE, show that this transgression was due to both flexural loading and sea level rise (figure 7.9).

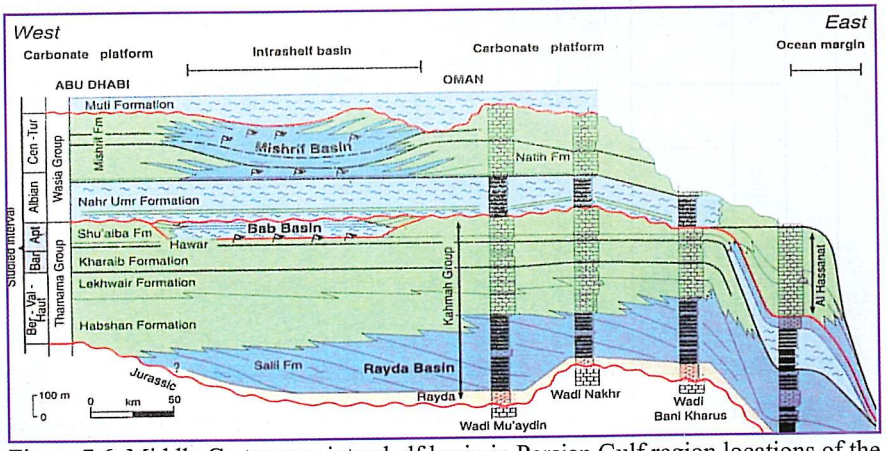

Figure 7.6. Middle Cretaceous intrashelf basin in Persian Gulf region locations of the source rock deposition (Van Buchem et al. 1992)

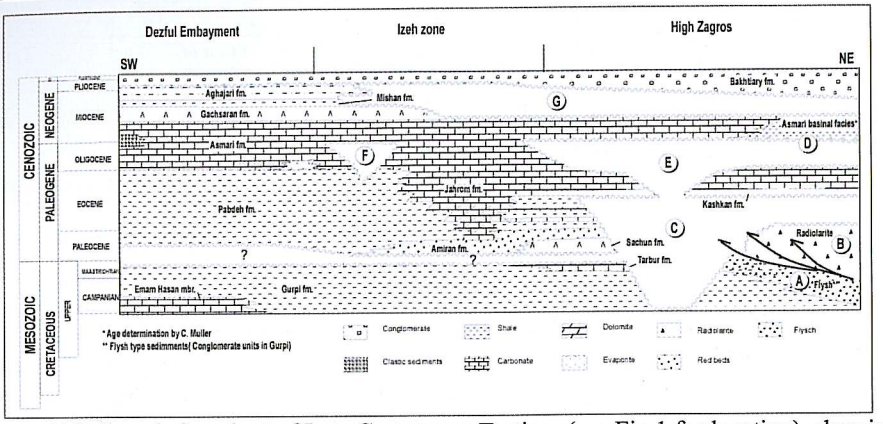

Figure 7.8: Correlation chart of Late Cretaceous-Tertiary (see Fig.1 for location), showing the main structural events that followed the ophiolite obduction. These events could be summarized as follow: (after Sherkati *et al.* in press). **(A)**. Deposition of the Campanian Flyschs in a flexural basin related to the ophiolite obduction over the northeastern margin of the Arabian plate. **(B)**. Emplacement of radiolaritic nappes coming from the Arabian margin and tectonically superimposed on the Campanian sediments. **(C)**. Erosion linked to a syn- to post-obduction uplift. **(D)**. Northward change of Oligo-Early Miocene Asmari Formation (limestone) to basinal facies resting unconformably on Eocene limestones. This formation has been dated by Muller (oral communication) as Aquitanian-Burdigalian. **(E)**. Erosion interpreted as the result of an uplift of the continental lithosphere (bulge geometry) related to the continent-continent collision that initiated likely during the late Oligocene-early Miocene. **(F)**. Erosion related to uplift along the Mountain Front Fault (basement fault reactivation?). **(G)**. Erosion related to the syn-folding Zagros uplift.

MECHANICAL STRATIGRAPHY OF THE PERSIAN GULF

The two major salt formations in the Persian Gulf and the Zagros fold belt are the deep seated Hormuz salts and Gachsaran Formation. They are both present in the Zagros fold zone and in foreland Persian Gulf. The Hormuz salts in the Zagros outcrop only as allochthonous salt plugs. Within the Persian Gulf, circular structures are thought to be draped over deep pillows of Hormuz salt (Edgell, -1996). The Hormuz series generally consists of salt, anhydrite, some dark dolomite, sandstone, siltstone, and marls (Figure 7.10). A Late Proterozoic to Early Cambrian age was attributed to this salts (Kent, 1958), and this age has been confirmed for the equivalent Ara Formation in Oman (Konert et al., 2001; Jeroen et al., 2003). The lower to middle Miocene Gachsaran Formation is composed of salt and anhydrite with some grey marls and thin limestone. In other parts of the Zagros, the time equivalent sediments consist of littoral clastic sandstone and marl (Motiei, 1995b). Most authors emphasize the role of the Hormuz salts and Gachsaran Formation in allowing décollement and disharmony in the Zagros folded belt.

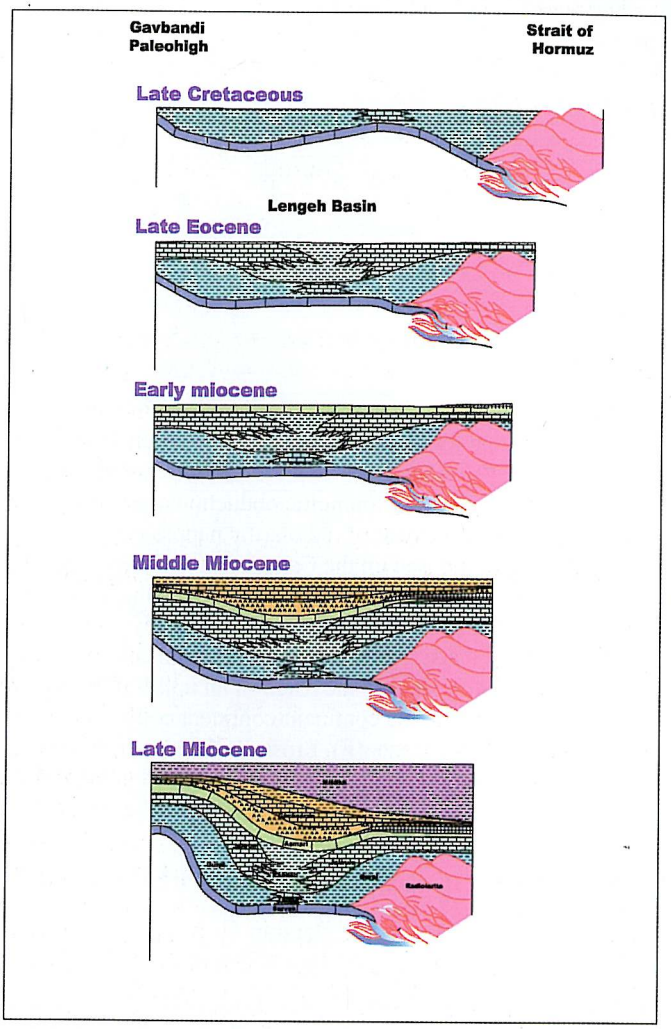

Figure 7.9 Schematic diagrams to show geodynamic evolution of Lengeh trough since Late Cretaceous.

SALT MOVEMENT AND STRUCTURAL STYLE IN ZAGROS AND PERSIAN GULF

The Hormuz layers are at about 10 km depth, south of the Zagros folded zone. But numerous salt plugs are exposed in it. In the Persian Gulf circular structures are draping over deep pillows of Hormuz salt, and only few diapirs are emergent (in islands). By contrast, most of the emergent salt diapirs are exposed within the folded zone. It suggest that squeezing of the salt domes during Zagros folding and erosion are the two main factors which control salt extrusion (Letouzey and Sherkati 2004)(figure 7.11).

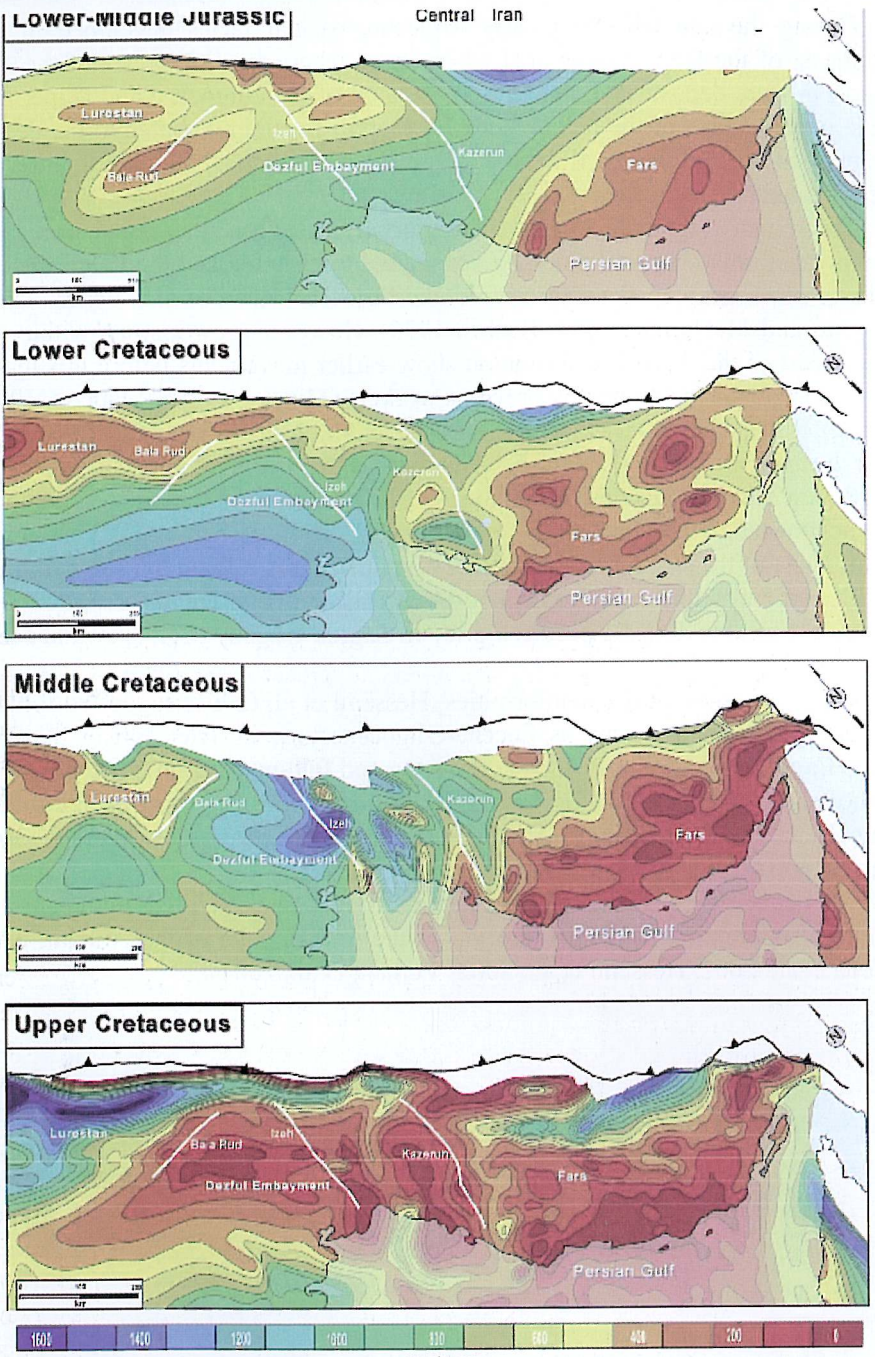

Figure 7.7 Aseries of Isopach maps illustrating the thickness variation in the Zagros basin between the Fars and Lurestan regions during the Jurassic–Cretaceous, The thickness variations suggest the possible activity and influenced of the Kazerun and Izeh Fault Zone on the sedimentation of the region (after Sepehr and Cosgrove 2004).

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During the late Oligocene-early Miocene, basinal facies developed in the northeast of the High Zagros area whereas elsewhere the limestones of the Asmari Fm were deposited (Figure 7.8D). Erosion of the Oligocene and Upper Eocene in some parts of the belt (Figure 7.8 E and F) could be related to the development of a lithospheric flexure (buldge geometry) and related activation of deep-seated basement faults.

The major regional angular unconformity between the Agha Jari and Bakhtyari formations was generally considered to have marked the Late Pliocene climax of orogeny in the Zagros fold-and-thrust belt (James and Wynd, 1965; Haynes and McQuillan, 1974; Kashfi, 1976). However growth strata within the upper part of the Agha Jari formation show earlier movements before this major unconformity as mentioned by previous workers (Mina et al, 1967; Falcon, 1974; Motiei, 1993; Homke et al., 2004; Sherkati et al., 2005). The base of the Agha Jari formation is dated at 8.1-7.2 Ma by magnetostratigraphic correlation in northwest Zagros (Lurestan) (Homke et al., 2004). Based on these considerations, we acknowledge that the Zagros folding covers the entire belt by the Early Pliocene. Most of the salt extrusions are coeval with Zagros folding but some of local pinch outs and sedimentary gaps in northern Fars and High Zagros area show that important salt movements occurred prior to Zagros orogeny (Letouzey and Sherkati 2004).

Based on some local unconformities, Hessami et al. (2001) suggested folding should be started as young as Eocene-Oligocene time in inner part of the Fars area. Based on surface geology, the thrusting and folding of Zagros belt represent a shortening of about 25% for western Zagros, including High Zagros and folded belt (Blanc, et al., 2003) and 22% for eastern part, Bandar Abbas region (Molinaro in press).

The convergence is still active at the present day, in a roughly N-S direction at a rate of approximately 25-30 mm yr^{-1} at the eastern edge of the Arabian plate (Sella et al., 2002; Hessami et al., 2002; Vernant et al., 2004).

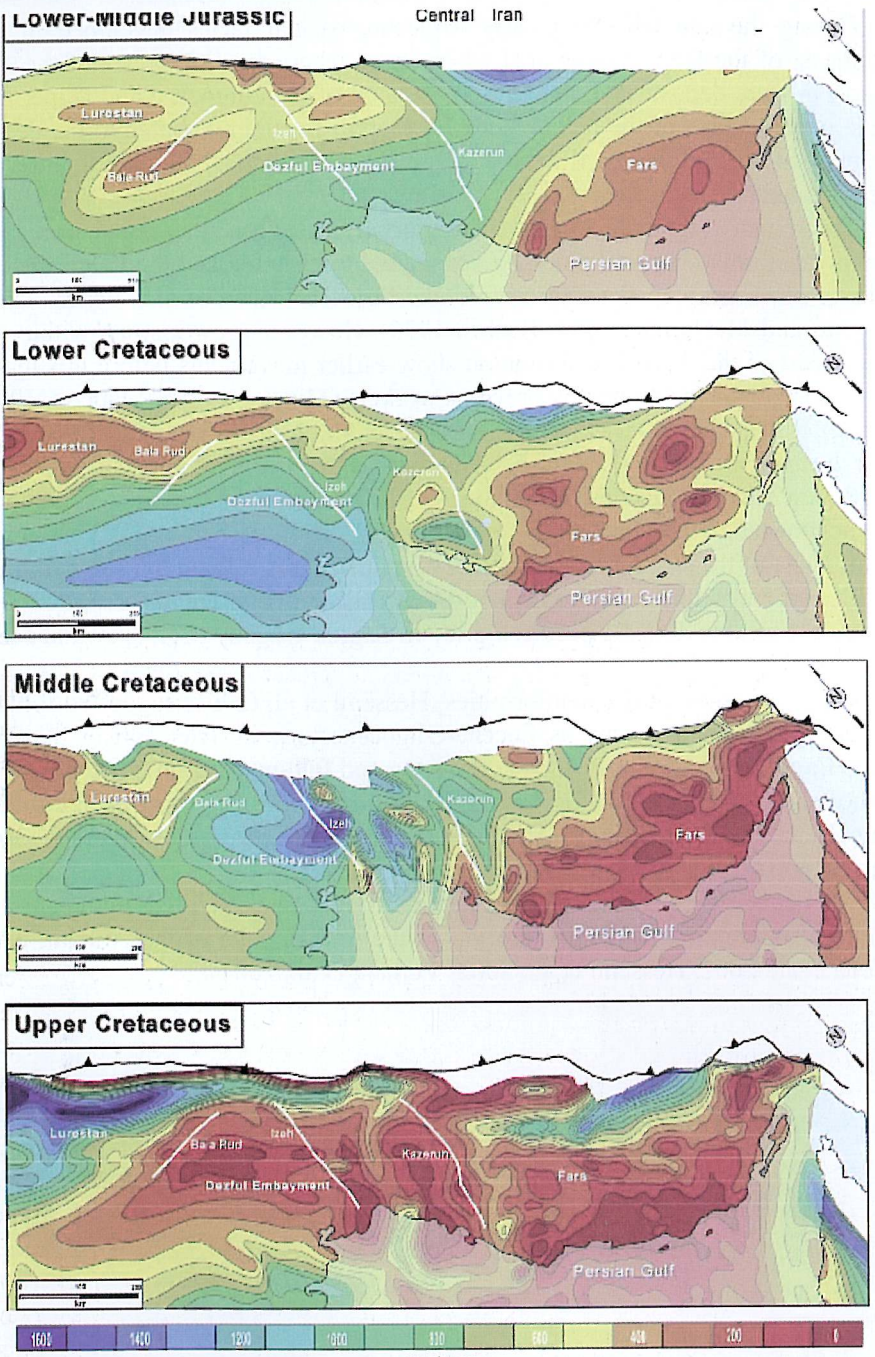

Figure 7.7 Aseries of Isopach maps illustrating the thickness variation in the Zagros basin between the Fars and Lurestan regions during the Jurassic–Cretaceous, The thickness variations suggest the possible activity and influenced of the Kazerun and Izeh Fault Zone on the sedimentation of the region (after Sepehr and Cosgrove 2004).

The mechanisms of diapirism in the Hormuz series have been a subject of interest for many years in the Iranian Zagros (Harrison, 1930; Eliassi et al., 1977; Kent, 1958 and 1979; Ala, 1974; Gansser, 1992; Talbot and Alavi, 1996; Edgell, 1996). Harrison (1930) and Kent (1958 and 1979) showed that most of the salt intrusions in the Fars region occurred during the Neogene Zagros folding. However, Kent (1958 and 1979) was the first to introduce the concept of pre-orogenic salt movements. He also noted that for numerous plugs, no final conclusion on the date of inception of movement is justified because of limited availability of seismic lines and the limited age range of the sediments that are in contact with salt plugs in outcrop. Based on new available data, Motiei (1995 a and b), showed that some salt movement began during Permian time. Talbot and Alavi (1996) attributed initiation of the salt structures to local manifestations of Jurassic and Cretaceous subduction of the Neo-Tethys before the Zagros orogeny.

Concerning the mechanisms of salt extrusion, O'Brien (1950) referred to the local predominance of igneous material in salt plugs and developed a theory of inception of plug movements by igneous activity. This theory was rejected by subsequent authors who demonstrated that there is no special relationship between salt plug extrusion and igneous intrusion (Kent, 1958). Kent (1958 and 1979), and most of the authors before the 1990's, believed that the Hormuz salt rose from great depth mainly under the influence of hydrostatic forces.

Infracambrian Hormuz salt and evaporite occurred in several subsiding rift basins in the Persian Gulf region, and also in Oman, Central Iran, Pakistan and northwest India (Stocklin, 1968; Edgell, 1996; Al-Husseini, 2000; Konert et al., 2001; Jeroen et al., 2003). The extent of the salt is not fully mapped, and it is not clear how far it extends into the Dezful region. This salt is believed to be absent along north-south-tending Arabian arches inherited from Pan-African structures. The Neogene salt and evaporites shown in yellow, are called the Gachsaran Formation, or the Lower Fars Group (Kashfi, 1980; Motiei, 1995b,). They are deposited in the flexural basin during the Zagros folding (Sherkati and Letouzey, 2004), (after Letouzey and Sherkati 2004)

However, a better understanding of the geometry and the continuation of Arabic trends into the fold belt, and the relationship between these deep-seated structures and some of salt plugs was mentioned by several workers (Harrison, 1930; Ala, 1974; Furst, 1990; McQuillan, 1991; Edgell, 1996). Understanding the significant role of extensional faulting in triggering salt diapirism (Jackson and Vendeville, 1994), caused Edgell (1996), and Talbot and Alavi (1996) to mention the probability of rapid salt extrusion in the southwest of Iran due to the local pull-apart structures which had been created as a result of the intersection of basement wrench faults and Zagros thrust fault trends.

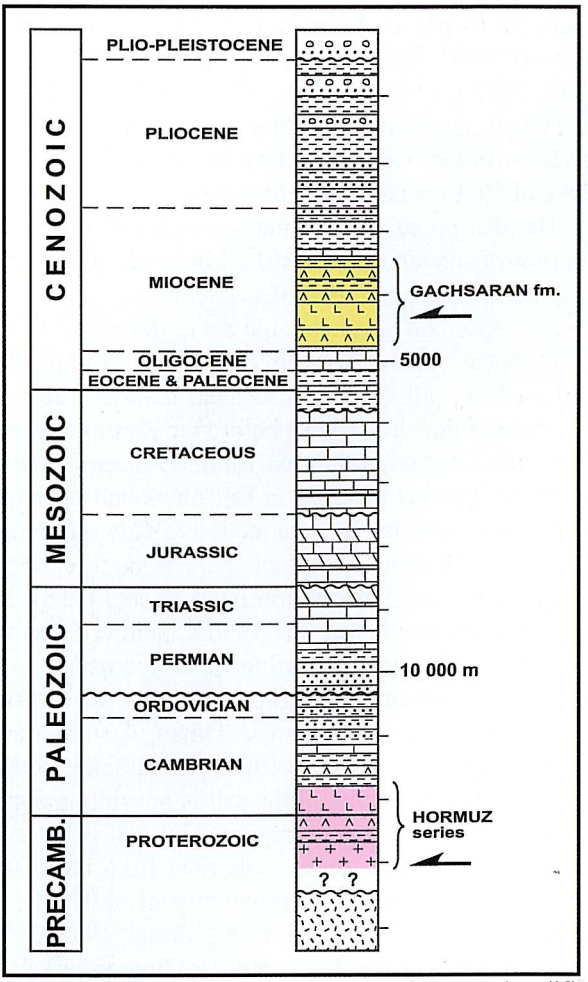

Figure 7.10. Schematic stratigraphic series of the Central Zagros (modified after O'Brien, 1950). Kent (1958) attributed a Proterozoic to earliest Cambrian age to the Hormuz series. The Paleozoic sediments are predominantly siliciclastic, whereas the Mesozoic is predominantly carbonates. The total thickness of the sedimentary column deposited above the Hormuz salt before the Neogene Zagros folding can reach over 8 to 10 km (Sherkati and Letouzey, 2004). The lower to middle Miocene Gachsaran Formation may have a salt layer at its base. From sub-surface data, we deduce that this evaporitic sequence could be up to 1600 meters thick in some areas (after Letouzey and Sherkati 2004).

Recent studies in the Central Zagros province show that Hormuz salt doming existed before the Neogene Zagros orogeny. Basement fault movements related to regional tectonic episodes could have initiated episodic growth of the salt diapirs. The Permian-Triassic Neo-Tethys rifting, and the Cretaceous-Paleogene obduction and compression events are two episodes of basement faulting with associated salt movements (Figure 7.11). However, in the absence of good quality, deep-penetrating seismic data in most of the Zagros fold belt, early Paleozoic

and Hercynian salt movements are not excluded. Squeezing of the pre-existing salt domes, erosion, or wrench fault deflection and pull-apart, could be possible mechanisms, which control the rise and extrusion of evaporites during an orogeny (Figure 7.12). Based on the results of analog experiments, and field observations (Sherkati and Letouzey, 2004), it is deduced that thrust fault location in this region is often controlled by the presence of pre-existing salt domes. Furthermore, emergent diapirs could occur either above pre-existing domes, or locally in wrench fault deflection (pull-apart or push up zones).

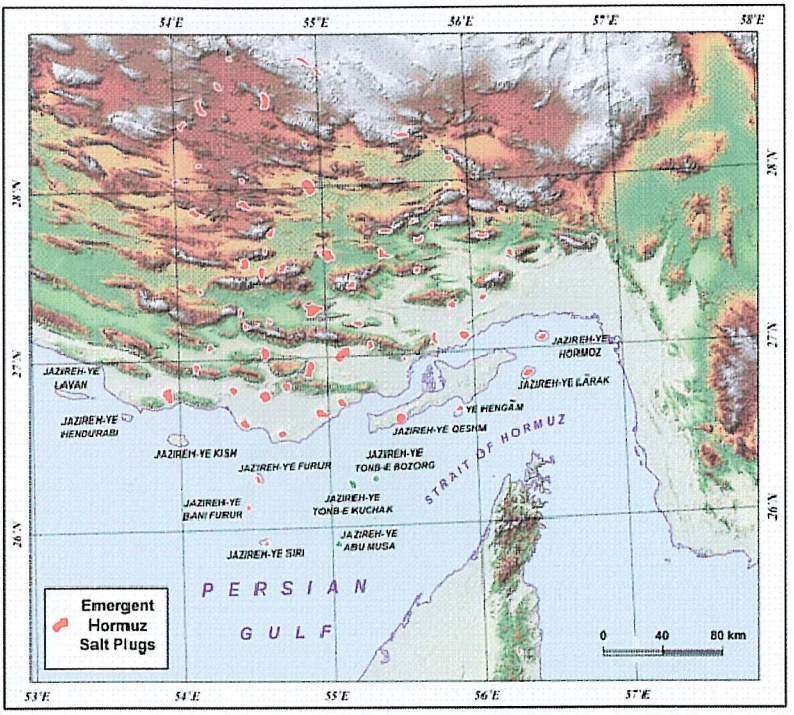

Figure 7.11- Topographic map of southern Zagros. Differences in distribution of salt plugs in Persian Gulf and Zagros onshore suggests that squeezing of the salt domes during Zagros folding and erosion are the two main factors which control salt extrusion (Letouzey and Sherkati, 2004).

During the Neogene-age Zagros folding, thrust and wrench fault location was influenced by pre-existing salt domes. The Hormuz salt played the role of low-friction, basal décollement level, at least in the Fars and High Zagros areas, and influenced fold style by allowing the free development of fore-thrusts and back-thrusts without any preferred vergence. Large competency contrasts within the sedimentary pile favored the development of "fish tail" structures, and caused a shift of anticlinal axes from surface to depth.

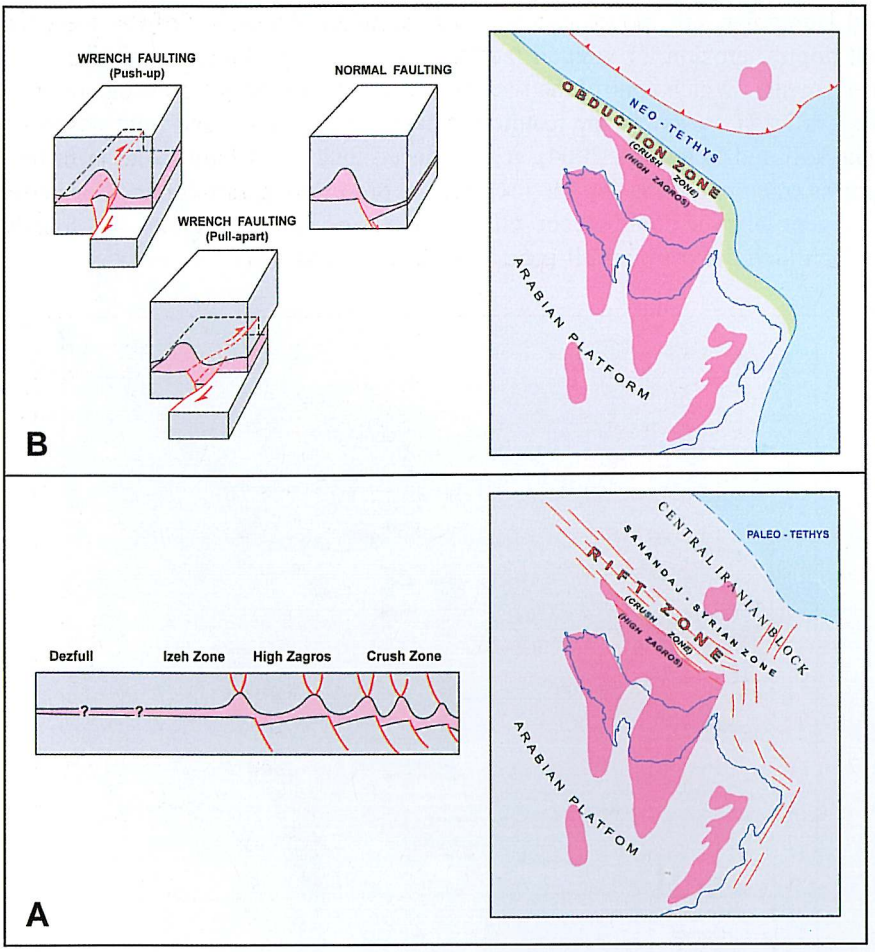

Figure 7.12. The distribution of Hormuz salt plugs in the Central Zagros, and the interpretation of analog models, suggest that salt doming could predate the Neogene-age Zagros folding (after Letouzey and Sherkati 2004). The most likely tectonic candidate for inducing salt pillows and domes is the activation or reactivation of basement blocks (Kent, 1958; Vendeville and Jackson, 1992; Jackson and Vendeville, 1994; Talbot and Alavi, 1996). In Oman, salt pillows and domes appear to have been active since the Lower Paleozoic (Jeroen *et al.*, 2003). In the Zagros domain, we assume that tectonic events, erosion, and basement faulting triggered episodes of salt doming. (A) The Permo-Triassic rifting event has played an important role in the mechanism of salt doming, especially in the High Zagros and "Crush Zone" areas. (B) During the Late Cretaceous-Paleogene, movement occurred along north-south trending faults in the Zagros basement (Sherkati and Letouzey, 2004).

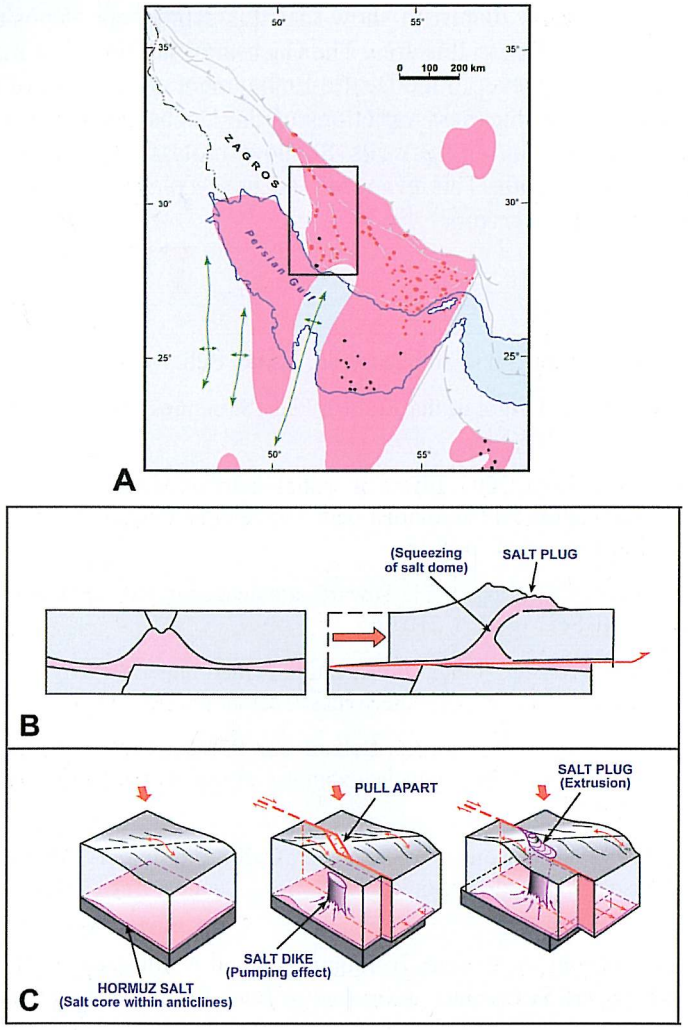

Figure 7.13. (A) In the Persian Gulf, circular or elongated structures are thought to be draped over deep pillows of Hormuz Salt (Edgell, 1996). However, in the Zagros folded zone, salt plugs are emergent. In the studied area in the Central Zagros, these plugs are located as discontinuous masses along faults and thrusts. (B) Salt reaches the surface during the Neogene-age Zagros folding. Analog modelling suggests that the location of thrust and wrench faults was influenced by pre-existing salt domes. Squeezing of pre-existing salt domes and erosion are major mechanism for the rise and extrusion of salt. (C) Salt can also be extruded along tear faults, wrench-fault deflection, and pull-apart zones (Letouzey *et al.*, 1995; Talbot and Alavi, 1996), (after Letouzey and Sherkati 2004).

The Neogene sedimentary sequence began with the deposition of the evaporitic Gachsaran Formation above the Asmari limestone reservoir. The extent of this facies is restricted to the Dezful zone, marking the evolution of the Central Zagros area towards a fold belt and its associated flexural basin. Thick-

ness variations and early diapirism show that this syntectonic deposit was contemporaneous with folding in this area. The Gachsaran salt level is a major décollement and disharmony level in the Dezful Embayment zone, south of the Mountain Front Fault. Large thickness variations of the Gachsaran Formation are observed on seismic lines and in the wells. Shallow, molassic synclines often overlie anticlinal axes at depth. This evaporitic sequence plays an important role in the sealing of Asmari reservoirs.

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In this chapter a review is presented in order to provide the required background for understanding the evolution of salt structures formed within the Zagros basin.

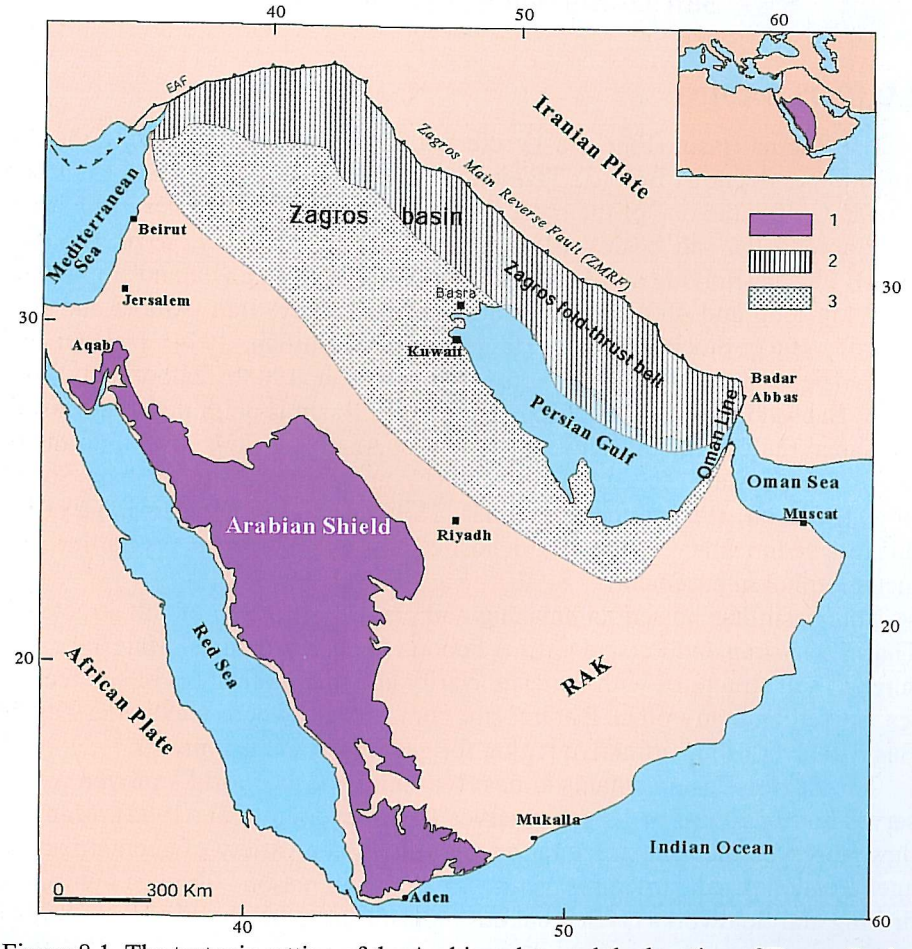

Figure 8.1. The tectonic setting of the Arabian plate and the location of Zagros Basin as 1) the Zagros fold-thrust belt, 2) Mesopotamian foredeep and Persian Gulf, 3) Arabian Shield.

EVOLUTION OF THE ZAGROS BASIN

Geological literature of the Zagros basin has been continuously extended by contributions of many petroleum geologists, since the earliest oil and gas fields discovered in the basin by Darcy (1908), for example, around the Masjed Sulyman oil field within the ZFTB about a century ago.

Generally, the Zagros stratigraphy is divided into three main parts based on various tectonic settings which they developed in. They are: a) epicontinetal platform sediments, b) extensional and subsequent passive margin se-

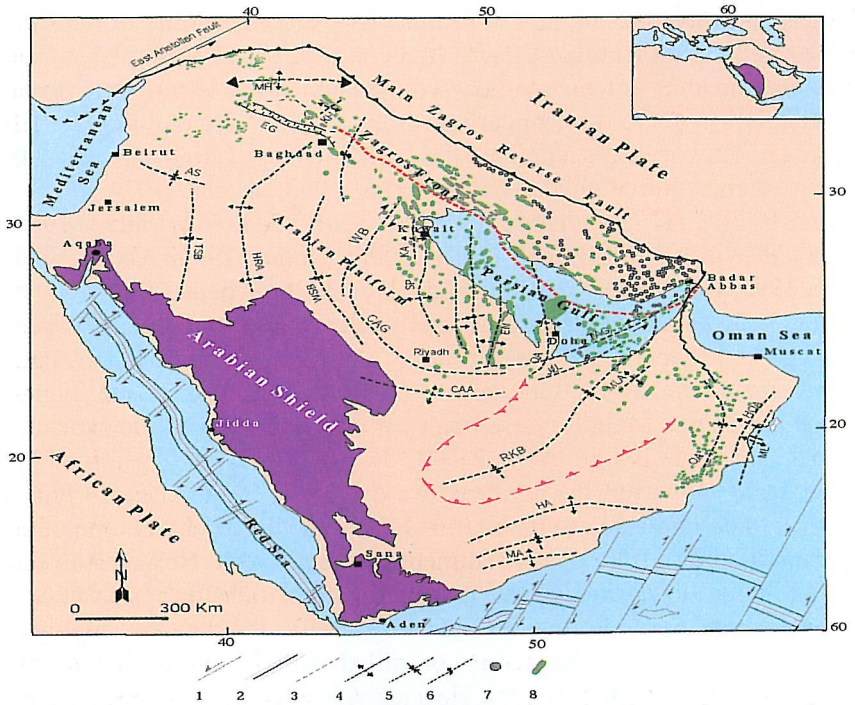

Figure 8. 2. The structural map of the Arabian plate showing main exposed structural elements inside the plate including 1) Transform Fault, 2) Normal Fault, 3) Spreading Axis, 4-6) Basement lineaments (Anticline/Arch, Syncline/Basin, and Flexure) **AS**: Azarq Sirahan Basin, **BF**: Barazjan Fault, **CAA**: Central Arabian Arch, **CAG**: Central Arabain Graben, **EAF**: Eastern Anatolian Fault, **EG**: Euphrates Anah Graben, **EN**: En Nala Safaniya Trend, **HA**: Hadhramout Arch, **HQA**: Huqf Arch, **JL**: Jaub lineament, **HRA**: Hail Rutbah Arch, **KA**: Kuwait Arch, **KBF**: Kar Bas Fault Zone, **KF**: Kazeron Fault Zone, **KH**: Khleissia High, **MA**: Mukalla Arch, **MH**: Mardin High, **ML**: Masirah Line, **MLA**: Mender Lekhwair High, **OA**: Oman Basin, **OL**: Oman Line, **QA**: Qatar Arch, **RKB**: Rub Al Khali Basin, **SBF**: Sabz Pushan Fault Zone, **SF**: Savastan Fault Zone, **SG**: Sadah Graben; **SP**: Summan Platform, **TAG**: Trans-Arabian Gulf fault, **TSB**: Tabuk Basin, **WB**: Wadi Al-Batin, **MAW**: Makran Accretionary Wadge, **WSB**: Widyan Basin; 7) extruded Hormuz salt structures; Oil-gas fields (complied from: Berberian, 1995; Alsharhan and Nairn, 1997; Weijermars, 1998).

The Amar collision was followed by extensional collapse event (620-530 Ma) of the Nubian-Arabian-Zagros shield during the late Precambrian-Early Cambrian (e.g. Husseini, 2000). It seems that post-collisional collapse of the Amar orogeny culminated in the development of the NW-trending Najd-Zagros fault system and the reactivation of other older basement grains with NE trend. Subsequent displacement along these fault systems resulted in development of some rifted/pull-apart basins e.g. Dibba, Oman, Punjab and Jordan rifts. Talbot and Alavi (1996) followed Kinsman's theory of a proto-ocean that failed to form for the development of those rifted basins in the re-

quence of Neo-Tethys Ocean, and c) sedimentary succession due to the Closure of Neo-Tethys and Arabian-Central Iran continental collision.

The entire thickness of the Zagros sedimentary cover is not well documented. That is why there is a wondering variety in suggested numbers for the total thickness. However, it seems that the total thickness varies between 5 to 20 km (e.g., James and Wynd, 1965; Stöcklin, 1968; Falcon, 1974; Player, 1969; Kent, 1979, 1987; Setudehnia, 1972; NIOC, 1975, 1976a; Murris, 1980; Berberian and King, 1981; Edgell, 1991, 1996; Motiei, 1993; Alavi, 1994; Berberian, 1995; Bushra, 1995; Talbot and Alavi, 1996; Sepehr, 2000).

Figure 8.3 shows a contour map of total thickness of the Zagros stratigraphy. This gives a general picture for slope of the top surface of the Pan-African basement beneath the sedimentary cover that dips toward the Zagros suture zone (or Zagros Main Reverse Fault). It may explain why the exposure of the oldest sequence is rare to the ZFTB, despite vertical expansion of the sedimentary pile. However, the northeast-ward increase in thickness of Phanerozoic succession implies very long-term slop for the basement. On the other hand, the distribution of the oldest sediments, especially the Hormuz salt derived the geologists to assume an active tectonically margin for northeast corner of the Arabian plate. Probably, Husseini (1989) was the first geologist who suggested some pull-apart basins controlled by north and NW-trending basement faults for deposition of the Hormuz salt (figure 8.3). Later almost the same model was proposed by Talbot and Alavi (1996) in a larger scale. These models suggested that the boundary between Arabian and Central Iran should be an old suture which reactivated several times in different periods, for example Neoproterozoic-Cambrian when the Hormuz salt deposited (e.g. Stocklin, 1986; Talbot, 1998).

NEOPROTEROZOIC- MIDDLE PALEOZOIC

Stoseser and Camp (1985) suggested a tectonic model for Precambrian Amar collisional tectonics (640-620 Ma) of the Arabian Shield. In this model, the Afif terrane in the west collided to the Ar Rayn microplate to the east along the N-S Al Amar-Idsas suture zone. This collision resulted in the most significant structural trends with different direction within the Nubian-Arabian-Zagros basement. E-W compression formed probably not only the N-S trends (figure 8.2) such as the Summan, Khurais-Burgan, En Nala-Ghawar and Qatar-Kazerun structures but also generated NW-SE (e.g. Najd and Zagros fault systems) or reactivated NE-SW trends, for examples the South Oman basin and Dibba fault (Husseini, 2000; Bahroudi and Talbot, 2003).

gion. One of the main consequences of the post-collisional extension was the development of the extensive Alkalic-peralkalic intrusions and volcanism consisting of alkalic granites and ryholites and other extrusions in Arabian shield has been interpreted as post-orogenic magmatism that developed in rift basins (Stern and Hedge, 1985; Brown et al., 1989; Blasband et al., 2000; Genna et al., 2000; Husseini, 2000).

Early paleonotological evidence and many stratigraphic correlations have confirmed the late Precambrian to Middle Cambrian age for the Hormuz salt (see chapter 3). The lithologies of the exotic blocks in the Hormuz Salt do not confirm either an Arabian or an Indian origin. Although some inclusions were dated by Player (1969) to 590-443 Ma, the question of their age have not been fully resolved until more potential basement inclusions from in and around emergent diapirs of Hormuz salt in Lurestan are dated (Gansser, 1992).

However, the Hormuz salt and its time-equivalents deposited in Iran, Pakistan, Oman and Australia are considered as syn-rift sequences. These syn-rift sequences comprise a great variety of sedimentary and igneous rocks. The most important components of sedimentary part are halite, anhydrite which formed more than 200 salt diapirs in the Zagros basin. Other sedimentary components are dolostones with/without stromatolite, fetid laminated limestones, and sandstones, siltstones partly rich in hematite/magnetite grains, dark trilobite-bearing limestones and shales. The salt provinces are separated by non-evaporitic terranes (Stocklin, 1986). The common igneous components are altered dolorite, rhyolites, splilitic flows, pillow lavas, ignimbrites and tuffs. The sedimentary and igneous components of the Hormuz salt appear to have been formed contemporaneously (Kent, 1970; Berberian and King, 1981; Talbot and Alavi, 1996). The association of shallow/evaporitic deposits with igneous succession implies that Hormoz salt and its time equivalents formed in intra-continental basins (Husseini, 2000).

Instead of Proto-Tethys opening as a palaeo-ocean where the Persian Gulf is now located, huge volumes of mid Ordovician to mid Devonian mafic to intermediate igneous rocks opened Paleo-Tethys to the north, in what is now the high Zagros (or Zagros imbricate zone), central Iran and the Alborz Mountains (Stampfli et al., 1991; Sengör and Burke, 1978). These igneous rocks were fed by dikes but are still neither metamorphosed nor deformed by subduction or orogeny. Continental magmatism in the Sanandaj-Sirjan zone was accompanied by the accumulation of Silurian, Devonian and Carboniferous siliciclastic redbeds (Alavi, 1991) in new sedimentary basins that Sengör (1990) has suggested originated as back-arc basins.

Meanwhile, the basement keys that had played gently along the still-born Proto-Tethys were buried beneath volcanic-free Upper Cambrian to Lower Ordovician carbonates and clastic sediments. The passive northeastern margin of Gondwana stabilized into a vast shallow marine shelf 2000-3000 km wide until late Paleozoic (Stocklin, 1968). Outcrops of Paleozoic rocks are rare beneath thick younger sequences in the Zagros (Fig 8.2).

Husseini (1990) divided Cambrian-Ordovician terrestrial clastic deposits into different facies that extended from West Arabia and Turkey through Iran to Oman with thickness between 600 to 3000 meters. About 250 meters of Ordovician marine clastic rocks in western Arabia thicken to about 500-1000 meters in Turkey, the Zagros and Oman. In the Zagros Basin, the early Cambrian-Ordovician sequence includes the Zaigun, Lalun, Mila and Ilbeyke Formations. The second sequence consists of alternations of shale and sandstone of the Zard-Kuh Formation. Migration of this margin from tropical through temperate to polar latitudes resulted in some glaciations and deglaciations across the Ordovician-Silurian boundary on the Arabian plate as well as further south nearer the pole in Gondwana (Hussein, 1991).

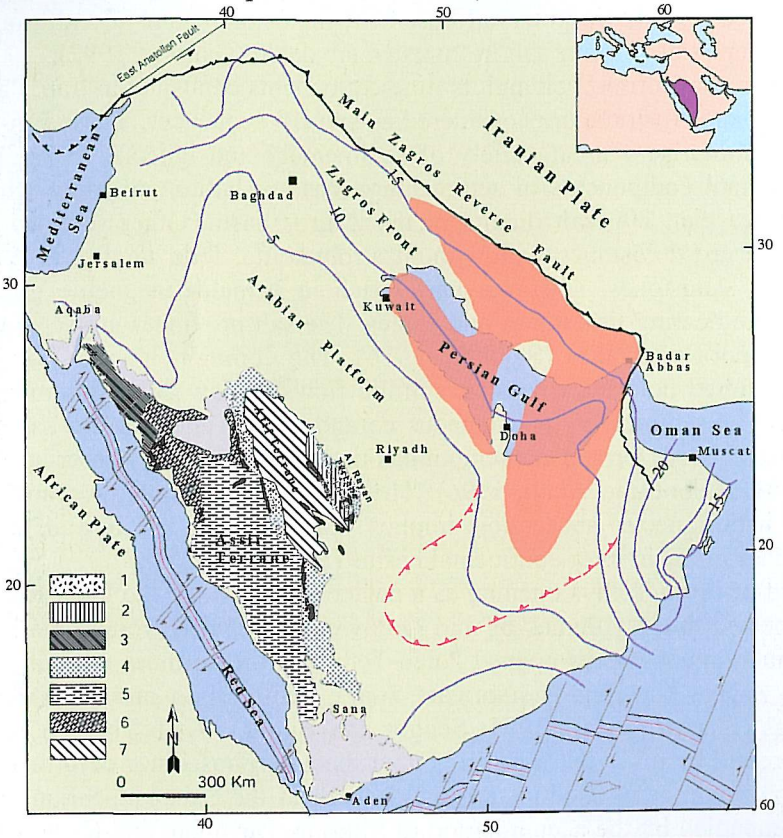

Figure 8. 3. The tectonic setting of the Arabian plate and distribution of Hormuz salt (in yellow) within the Zagros basin and the Oman basin with general thickness of the sedimentary cover in thousand feet. The Arabian Shield consists of 1) Al Ryan terrane, 2) Al Amar-Idsas zone, 3) Midyan terrane, 4) Nabitah terrane, 5) Asir terrane, 6) Hijaz terrane, 7) Afif terrane.

Lower Silurian sediments consist mainly of carbonate, sandstone and shales deposited as Paleo-Tethys rapidly transgressed over the northern edge

of Gondwana. North of Bandar Abbas region, more than 680 meters of lower Silurian organic rich shale Gahkum Formation (Setudehnia, 1972) probably records the southern edge of large thicknesses of mud rocks deposited on the slope and in the basin to the north. These organic rich shales probably sourced the extraordinary hydrocarbon riches that migrated into the shelf that became a remarkably productive hydrocarbon kitchen that brewed in and around the current Persian Gulf.

UPPER PALEOZOIC-EARLY MESOZOIC

Hercynian movements during middle to late Devonian times converted the deposition of carbonates over of the Arabian plate to clastic facies. Further, most of lower Devonian deposits were lost to subsequent erosion so that, in the Zagros Basin, the Silurian Sarchahan shale is conformably overlain by Permian Faraghan sandstone.

Widespread transgression dominated Permian and carbonate deposition returned to most of the Arabian plate and adjacent continental fragments. In the Zagros Basin, the Faraghan sandstone and the carbonate of Dalan Formations are about 1055 meters in thickness. The total thickness of the Paleozoic sequence in the Zagros Basin is about 3500 meters (Setudehnia, 1972, 1975; Szabo and Kheradpir, 1978).

Late Permian rifting and Upper Triassic drifting (e.g. Berberian and King, 1981) further shredded the margin of Gondwana when Tethys (Stamfli et al., 1991) opened westward along normal and transfer faults in the basement (Jackson, 1980, 1984; Berberian, 1995) along what is now the high Zagros (Talbot and Alavi, 1996). Deposition in this temporary NW-SE trending Persian Gulf was characterized by red and evaporitic beds intercalated with dolostones: the early-middle Triassic Khaneh Kat Formation and its equivalents (James and Wynd, 1965; Murris, 1980; Berberian and King, 1981).

OPENING OF NEO-TETHYS OCEAN

Comparison of the Paleozoic stratigraphies of Arabia and Iran on either side of the Main Zagros reverse fault reveals comprehensive correlation. This similarity is explained by paleomagnetic and paleogeographic data indicating that Central Iran, Pakistan, Central Afghanistan, Arabia, and Turkey are all characterized by similar epicontinental platform sediments deposited on a passive margin along the northern shores of Gondwana from late Precambrian to upper Paleozoic times (e.g. Stocklin, 1968, 1974; Berberian and King, 1981; Koop and Stoneley, 1982; Scotese and McKerrow, 1990). The opening of paleo-Tethys in lower Paleozoic time separated this passive margin from a north-dipping subduction zone along the active margin of Paleo-Eurasian. This subduction eventually led to Gondwana meeting Eurasian along a suture recorded by relicts of Paleo-Tethys ophiolites together with metamorphic and

magmatic rocks along, the Caucasus and Alborz Mountains. Subsequent convergence produced a multi-stage late Paleozoic (Hercynian) orogeny from Turkey through the Caucasus and Alborz and northern Afghanistan to northern China (Berberian and King, 1981; Alavi, 1991; Stampfli et al., 1991).

There is controversy over the number of continental break-up events along the northern margin of Gondwana. While Paleo-Tethys closed along the Alborz Mountains, the passive margin of Gondwana further south appears to have been still rifting. Convincing evidence indicates that Turkey, Central Iran, Arabia, India, and north-western Australian rifted away from Gondwana diachronously and episodically during Permo-Triassic times (e.g. Stocklin, 1974; Cherven, 1986; Stampfli et al., 1991; Alavi, 1994; Ricou, 1994). Onset of rifting along northern to northeastern Arabia and Iran is demonstrated by differentiation in sedimentary facies and rift-related magmatic activity on either side of the Main Zagros Reverse Fault (MZRF). A phase of Permian-Triassic extension along the active margin of Neo-Tethys along the Sanandj-Sirjan zone is marked by andesitic-basaltic volcanic activity associated with shallow lagoonal deposits with rapid facies variation due to block faulting (e.g. Stocklin, 1974; Berberian and King, 1981; Stampfli et al., 1991). By contrast, isopach and facies maps of the Upper Paleozoic-Mesozoic carbonates and shales in the Zagros (figs. 4 to 9 in Koop and Stoneley, 1982) simply parallel a likely continental margin along the MZRF (Stocklin, 1974; Morris, 1980; Berberian and King, 1981).

Talbot and Alavi (1996) compared the Permo-Triassic opening and Cretaceous closure of the southern passive margin of Neo-Tethys in Arabia to a zip fastener with basement keys defined by N-S and NW-striking Pan-African faults in the basement. By contrast, the active margin of Neo-Tethys was the straight NW-SE trending MZRF.

Abrupt variations in the nature of the sedimentary rocks, magmatism, and paleogeographies across the NW striking MZRF since the Upper Paleozoic record the opening and closure of Neo-Tethys between Arabia and Iran along a structure which is generally agreed to have reactivated a Pan-African basement structure with the trend of the Najd faults (e.g. Falcon, 1967; Stoneley, 1974; Stocklin, 1974; Koop and Stoneley, 1982).

Ophiolitic complexes associated with deep-water radiolarites exposed in Kermanshah and Nyriz further southeastward along the MZRF are attributed to Mesozoic sea-floor spreading which was followed by subsequent subduction and ophiolite obduction in the upper Cretaceous-Paleocene (Berberian and King, 1981; Cherven, 1986).

As Neo-Tethys closed in Iran, the same N-S and NW-SE trending Pan-African tectonic grains in the Precambrian basement that controlled the opened and closed of various versions of Tethys appear also to have influenced how and where the lithosphere pinched and rifted between Africa and Arabia on the way to opening the Red Sea in Tertiary times (Dixon et al., 1987; Ghebreab and Talbot 2000). The same tectonic grain built into the con-

tinental lithosphere by Pan-African crustal growth and deformation therefore influenced the opening and closure of Proto-, Paleo-, and Neo-Tethys from Neoproterozoic to Cretaceous, and the Tertiary to current opening of the Red Sea.

MIDDLE MESOZOIC-CENOZOIC

Opening of Neo-Tethys probably ceased in Middle Cretaceous when the stable abrupt intensive reactivation of basement faults jostled the previously stable platform. This activity led to uplifting and subsequent erosion and triggering of structures in the Hormuz salt. Local unconformities trend in N-S between the eastern and western segments of the Zagros basin. Map patterns of isopachs and facies distributions of Cretaceous sediments are more complex that for any the other period probably as a result of intense salt activity and reactivation of basement faults (e.g., Koop and Stoneley, 1982, see later).

Obduction of the Oman ophiolite in Late Cretaceous, together with complex facies changes within the Zagros Basin, heralded the onset of compressional tectonics and subduction of Neo-Tethys beneath Asia leading to eventual closure of Arabia and Iran with many different models having been proposed (Haynes and McQuillan, 1974; Beydoun et al., 1992; Berberian, 1981). The final closure of Neo-Tethys along the Zagros suture between the magmatic arc and the Sanandaj-Sirjan zone was diachronous-like a zip-fastener is pulled eastward (Talbot and Alavi, 1996).

The Cenozoic history of the Zagros Sedimentary Basin opened with an extensive transgression from the north which replaced pelagic by neritic sediments (e.g. Beydoun, 1991). Together with marine deposits, the evaporitic sediments were deposited in Fars region, west of Bandar Abbas (James and Wynd, 1965). During the Paleocene to Early Eocene, the Zagros Basin still connected with Neo-Tethys and evaporites were deposited in the northern shallows. Convergence narrowed the seaway to the north in late Eocene with Oligocene closure resulting in the propagation of evaporitic beds alternating with carbonate and clastic sediments (see Koop and Stoneley, 1982). This change was simultaneous with the onset of north-eastward movement from a stationary Africa which opened the Red sea.

BASEMENT CONFIGURATION OF THE ZAGROS BASIN

No basement rocks are exposed within the Zagros Basin, and it is generally assumed that the Zagros basement is a northeastward continuation of the Precambrian shield exposed in Arabia (Falcon, 1967, 1969; Berberian and King, 1981; Husseini, 1988) which is similar to the basement exposed west of the Tabas block in central Iran. However, recent maps of Gondwana show that the basement beneath Iran comprises not only Pan-African (900-600 Ma) rocks

therefore extrapolated the east and west boundaries of the East Arabian Block northwards to the Main Zagros Reverse Fault. Since their model implied that the ZFTB lies on a northern continuation of the East Arabian Block, they used the new term "East Arabian-Zagros Block" to include both areas. This model suggests that although most of the deformation in the sedimentary cover is confined to the 200-350 km wide Zagros fold-thrust belt and its foreland basin, the existence of the East Arabian-Zagros Block implies that part of the continental collision may already have been transferred into the Arabian platform by the reactivation of basement faults. Weijermars (1998) presented geological evidence from the East Arabian Block which indicates significant deformation since the Pliocene. Some Zagros deformation may have propagated forward of the currently-recognised Zagros front in (at least the eastern) East Arabian-Zagros Block. Recent tectonic activity around the margins of the East Arabian-Zagros Block raises the possibilities of aseismic deformation in the basement, with or without cryptic shortening in the cover. A significant characteristic of the East Arabian-Zagros Block is the development of transpressional zones within NW and NE corners (indicated by shaded blocks in Fig. 8.4) of the EAZB and along its SW arcuate front. Weijermars (1998) described the Mughran-Al-Kharj transpressional zone between latitudes 47° and 48° in the SW corner of the East Arabian-Zagros Block. Similar transpressional zones are developed at two syntaxes at the NE and NW corners, where the Main Zagros Reverse Fault departs from the general NW-SE trend which characterises the portion of the Zagros belt on the East Arabian-Zagros Block between the two syntaxes.

Zagros Fold - Thrust Belt

Geologic evidence indicates that the ZFTB is being shortened and thickened by folding and thrust faulting. These processes result in uplifting of alluvial terraces, beaches above the anticlines., subsiding of areas (Lees and Falcon, 1952), and development of deep river valley (Orberlander, 1965) cutting down the anticlines nearly perpendicular to their axe. To calculate the rate of shortening, various methods were used for examples morphology, seismicity, and GPS-survyings by different workers (e.g. Berberian, 1995; Hessami, 2002).

Study of the fossil shorelines in the coastal plains indicated 29 mm/yr of shortening and 1.8-6.6 mm/yr of uplifting since Holocene, whereas the Holocene deformation of coastal folds showed about 20 mm/yr at 061° (Vita-Finizi, 1978, 2001). Jackson and McKenzie (1984) estimated the movement rate of the Arabian plate relative to the central Iran as 0.95°/Ma which results in 10 mm/yr in northwest relative to the Kazerun fault and 26mm/yr for the SE Zagros.

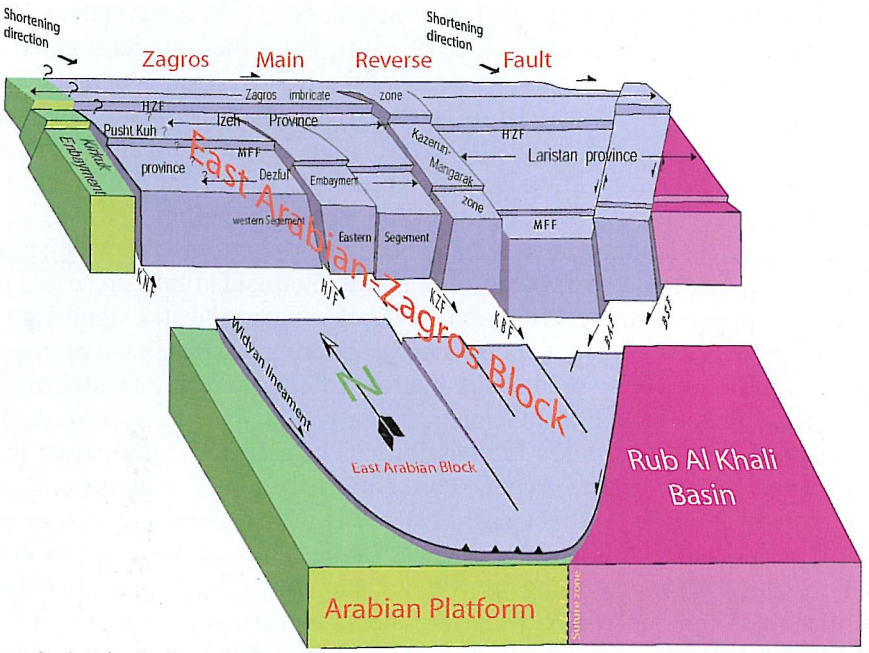

Figure 8. 4. Block diagram showing proposed basement configuration of the Zagros basin by Bahroudi and Talbot (2003). Main basement faults and lineaments within the Zagros basin are: DA, Dibba fault; RKB, Rub Al Khali Basin; BSF, Bostaneh fault; BAF, Bastak fault; TAL Trans Arabian Lineament; KF, Kazerun Fault Zone; QA, Qatar Arch; MFF, Mountain Front fault; KHF, Khanqin fault; HRA, Hail Ga'ara Arch; TSB, Tabuk Basin; MH, Mardin High; CAG, Central Arabian Graben; MLA, Mender Lekhwair High; MLA, Masirah Line; HA, Hadhramout Arch; MA, Mukalla Arch; SG, Sadah Graben.

Geophysical data also indicate that the ZFTB is currently active and is being shortened at rate of 20-30 mm/y (Vita Finzi, 1978, 2001; Jackson and McKenzie, 1984; Berberian, 1995). Earthquakes of 5.5-6 Mb are common in the current seismicity which, in the Zagros Fold- Thrust Belt, occurs in a zone ≈200-300 Km wide (Jackson, 1980; Baker et al., 1993; Chandra, 1994; Berberian, 1995). All this seismic activity is confined to depths of less than 40 kilometers so there is no evidence for subduction continuing beneath the Zagros Fold-Thrust Belt (Jackson et al., 1981; Jackson, 1980; Dehghani and Makris, 1984). A study of 16 large earthquakes indicated that they originated at depths between 8-14 kilometers (Baker et al., 1993) without any sign of deepening toward the Zagros Suture/Main Zagros reverse fault (Ni and Barzangi, 1986). Furthemore, seismicity appears to be lower in the northern Zagros (Haghipour, 1992; Ameen, 1992). Large earthquakes in the Zagros are not precisely located by teleseismic data (Jackson and Fitch, 1981; Asudeh, 1983; Berberian and Papastamtiou, 1978; Berberian, 1995; Koyi et al., 2000). However, most have hypocentres about 10-20 kilometers deep and their focal

plane solutions indicate blind reverse faults with dips between 30° and 60° with NW-SE strikes (Berberian, 1995; Jackson et al., 1981; Jackson and McKenzie, 1984). These are steeper than in other parts of the Alpine-Himalaya orogen, such as, the Hellenic trench, the Makran and Eastern Himalaya. McKenzie (1984) estimated the movement rate of the Arabian plate relative to the central Iran as 0.95°/Ma which results in 10 mm/yr in northwest relative to the Kazerun fault and 26mm/yr for the SE Zagros. Nevertheless, seismic moment calculation of earthquakes occurred in the Zagros showing up to 10-15% of shortening (about 1-2.7 mm/yr) release by the earthquake.

It should be remembered that only about 10% of the current Zagros deformation results in seismic activity (Jackson and McKenzie, 1984, 1988; Jackson et al., 1995) and 90% is aseismic and cryptic.

Very significant is that most workers interpret the seismic activity as involving the basement (Ameen, 1992) so that the Hormuz salt does not appear to completely decouple the cover from its basement. Steep reverse earthquakes along faults with NW-SE trends are almost certainly along faults that had originated in the basement as late Pan-African Najd faults (Fig. 8.2; e.g. Hussini, 1990, 2000). These had probably been reactivated as thick-skinned normal faults during the opening of Neo-Tethys, and inverted to steep reverse faults with dextral offsets during convergence (e.g. Jackson, 1980, 1984; Berberian, 1995). Similarly, other fault plane solutions indicate subvertical strike-slip faults with N-S trends such as along the Kazerun, Kareh Bas and Sabz Pushan faults (Jackson, 1980; Berberian, 1995; Koyi et al., 2000). These are almost certainly along faults inherited from the N-S trends of Pan-African sutures.

HORMUZ SALT

Zagros Basin is one of the world's largest salt provinces and many of oil-gas pools of the region are trapped by a variety of salt structures in the Phanerozoic cover above old faults in the Precambrian crystalline basement. For further information on the geology of Hormuz salt see chapter 3 in this book.

In this section, after reviewing the stratigraphy of the Hormuz series, current distribution and previous work on when and why it's salt moved, the current shapes of the emergent salt structures will be considered.

Stratigraphy of Hormuz Salt

Although no salt survives in an autochthonous equivalent succession on the Iranian plateau (Stöcklin, 1968) but the older Hormuz sequence is exposed in most emergent diapirs in Iran and Oman (Kent, 1970, 1979; Stocklin, 1986). This sequence is cyclic (Kent, 1979) and consists of thick beds of multicoloured salt and anhydrite interbedded with dark foetid dolomites, and thin red, purple, or greenish sandstones, siltstones or marls with local yellow-

brown orthoquartzites (Stocklin, 1986; Talbot and Alavi 1996). Stromatolites and algal mats common in the dolostones indicate Neoproterozoic (Infracambrian) supertidal facies (Kent, 1987). Abundant hematite, sulphur and local concentrations of base-metals indicate that the early-Hormuz sequence accumulated in reducing conditions. These lithologies indicate the deposition of an unknown number of early Hormuz cycles of salt, anhydrite and carbonate over large shallow marine areas that emerged locally and temporarily.

The early syn-rift cyclic Hormuz sequence accumulated in two broad half graben trending NW along the northern margin of Gondwana. Their smooth NW-trending boundaries (Fig. 8.5) are where NW trending Najd faults acted as breakaways along the northern margins of Proto-Tethys (Alsharhan 1989; Husseini and Husseini 1990; Talbot and Alavi 1996). Such master faults defined basement keys boards that dipped northward under most of the Zagros but in which individual basement keys may have dipped southward beneath the Qatar arch, the Fars platform and the Zagros west of the Kazaroun line (Figure 8.5).

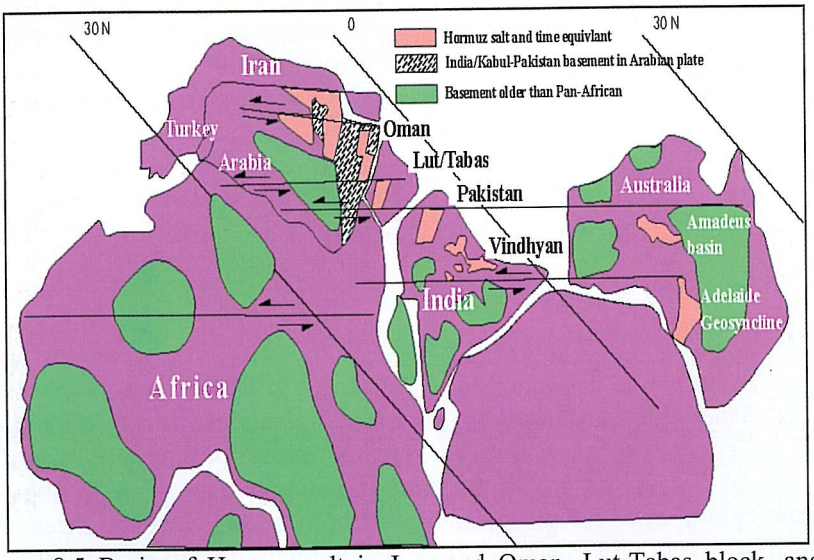

Figure 8.5 Basin of Hormuz salt in Iran and Oman, Lut-Tabas block, and time-equivlant sequences in Pakistan, the Vidhyan basin of India, and Australia. 1) Hormuz salt and time equivlant, 2) India/Kaboul-Pakistan basement for Arabian plate, 3) Basement older than Pan-African (modified from: Talbot and Alavi, 1996; de Wit et al., 1999).

By contrast to the repetitive cycles of the older shallow marine salt, the younger Hormuz salt consists of thick beds of a comparatively pure uniform grey or buff anhydritic salt rich in inclusions of igneous rocks interrupted by occasional red beds containing trilobites up to mid-Cambrian in age (Lees,

1924 in deBockh et al., 1929). Such pure salt sequences are likely to accumulate rapidly in marine lagoons and embayments.

Abrupt Hormuz lithofacies changes that now trend N-S and NE-SW bound basement keys inherited from the 900-600 Ma terrane-accretion fabric in the Pan-African basement (Stocklin, 1968b; Hussieni, 1988, 2000; Alsharhan 1989; Husseini and Husseini, 1990; Beydoun et al., 1992; Edgell, 1996). Pointing to the Mangarak trough as an example (Fig.8.6), Talbot and Alavi (1996) argued that the clean Cambrian salt and associated igneous rocks were confined to a salt of long (≈200 km), narrow (12 km) and deep (1.5 km) half-graben pulled-apart at releasing bends along faults in the basement-like the Dead Sea in Miocene times. The early NW trending basin of Proto-Tethys was therefore segmented by reactivation of cross-marginal faults that could have controlled the location of transforms had Proto-Tethys opened. Cambrian Hormuz salt and associated volcanic rocks accumulated in troughs above basement keys that sagged down to the north (Fig. 8.6).

Hormuz salt was either never deposited or was removed from some basement keys that did not subside- such as the Qatar-Gavbandi Arch and Fars platform and a long margin to the NW of the Kazerun fault zone (Fig. 8.6). These basement keys may have been strips of Pan-African basement that accreted with distinctive characters; however, the presence of igneous rocks on the same keys is also significant.

EXOTIC ROCKS

Igneous inclusions are common in the pure Cambrian salt in diapirs emergent between the Kazerun fault zone and the Oman line. Inclusions of intrusive diabase in diapirs in central Iran, in the Hormuz-type sequences near Kerman (Stöcklin, 1968a, 1986), and inland Lorestan (Fig. 8.6) give way southward to extrusive vesicular mafic pillows and agglomerates and tuffs along the gulf coast of Laristan (Kent, 1958). Rhyolites, trachytes and porphyries are ubiquitous in the diapirs emergent in the Persian Gulf islands (Fig. 8.7) and in the southern most diapir emergent in Oman. Silicic and mafic rocks occur together along the Iranian coast east of the Kazerun fault zone (Kent, 1979, 1987).

Possible samples of basement rocks have surfaced as inclusions in diapirs of Hormuz Salt in Laristan. Most inclusions in the salt are of igneous and sedimentary rock of the same age. However, a few inclusions comprise metamorphic rocks which are assumed to be basement blocks that fell into the accumulating salt from fault scarps (Kent, 1979).

No igneous rocks of equivalent age are known to the NW or east but it is not clear whether signs of igneous activity are confined to only one segment of Iran because that is the only segment where salt diapirs emerge. For instance igneous inclusions re-appear in the next diapir to the NW of the Kazrerun fault zone, a solitary salt diapir near the Iraq-Kuwait border (Kent, 1970 p.

83). However, igneous intrusions are also missing from the Salt Range Formation exposed in Pakistan (Butler et al., 1987) but reappear in northern India. If we accept that lack of evidence implies lack of igneous activity then the Cambrian igneous rocks developed on basement keys that sagged to the north, and are missing from keys that did not sink. This is contrary to findings of a recent study of seismic volcano-stratigraphy constrained by potential field measurements associated with the Early Tertiary break-up of the north Atlantic. As in the Zagros, pre-break-up rifting of the north Atlantic was concentrated along a few margin-parallel extension axes. Subsidence is usually assumed to depend upon crustal thinning by stretching and therefore to depend mainly upon distance from the break-up axis. However, this was fairly uniform within 50 kilometers of the break-up axis area and therefore had little effect on local subsidence. Subsidence instead relates to the volume of break-up magmatism because crust thickened by magma does not sink isostatically.

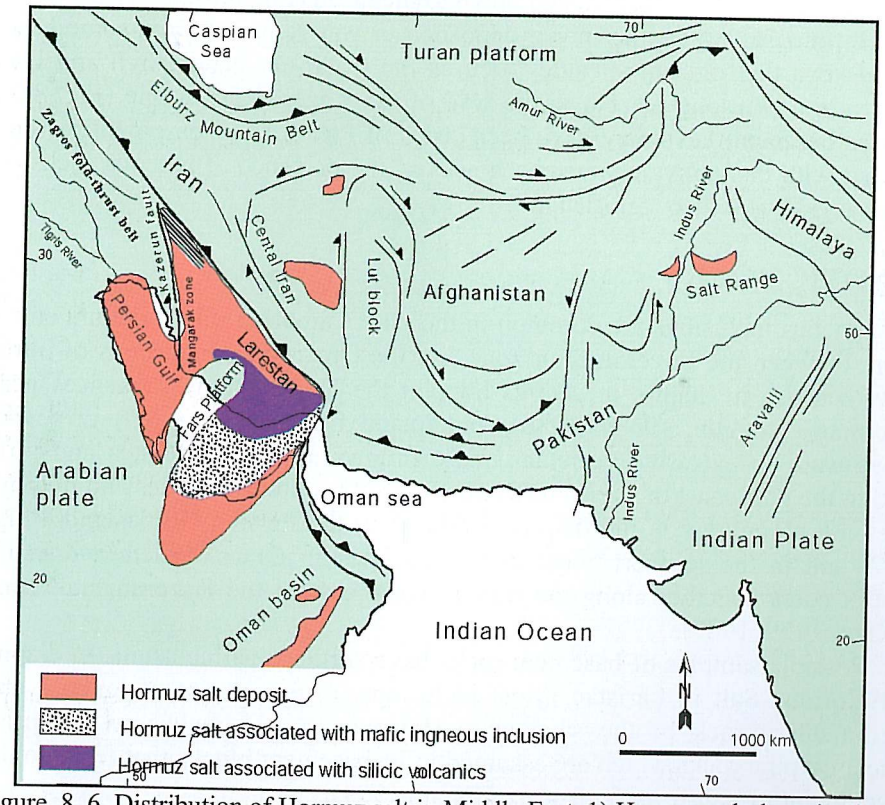

Figure 8. 6. Distribution of Hormuz salt in Middle East, 1) Hormuz salt deposit, 2) Hormuz salt associated with mafic ingneous inclusion, 3) Hormuz salt associated with silicic volcanics (after Stocklin, 1986; Talbot and Alavi, 1996).

The volcanics were subaerial where the crust underwent least isostatic subsidence because it was thickened most by volcanic rocks- and submarine

extending northward from East Africa (e.g. Haffman, 1999), but also older rocks (>1,000 Ma) extending westward from India (e.g. de Wit et al., 1999).

Broad gentle anticlines and narrower synclinal basins (Beydoun, 1991) or graben with a variety of trends affect the thickness of the cover surrounding the Arabian Shield (Al Laboun, 1986). Such structures are referred to as lineaments, blind or hidden basement faults (Berberian, 1995), geo-flexures (Falcon, 1974), geowarps (Ameen, 1991, 1992) periclines (Alsharhan, 1989), drape folds (Edgell, 1991) or forced folds (Fig 8.2, Sattarzadeh et al., 2000). Most have had long histories of activity that began before the Late Paleozoic.

Several of the structures in the Arabian Shield obviously continued northwards into the Zagros Basin before they were reactivated and deformed by the Zagros orogeny during the Cenozoic (Berberian, 1976, 1981, 1995; Talbot and Alavi, 1996; Hessami et al., 2001). This effect is recorded in the pattern of oil- and gas-fields. The many giant (and few supergiant) oil- and gasfields in the Zagros foreland occur in gentle and essentially unbroken periclines in Tertiary sediments with flank dips of <5° (Kent 1979), and define the N-S and NNE-SSW lineaments (Fig 8.2). Approaching the Zagros front, the oilfields are first elongated N-S and then become circular, decreasing in areal extent as the flank dips increase; they then become elongate with the NW-SE trend of the superimposed Zagros structure (fig.3 in Talbot and Alavi, 1996).

Previous models suggested for the basement configuration in the southeast of the Zagros area (e.g. Barzegar, 1994) invoked either complicated interrelationships between transverse and reverse faults in the basement (Berberian, 1995) or transverse left- and right-lateral faults (Hessami et al., 2001). In the extreme SE of the Zagros Mountains, displacement along NE-SW trending, left-lateral strike-slip faults truncates surface anticlines (see Furst, 1990). Minor uplifts of basement along these faults' hanging walls indicate minor dip-slip components.

Bahroudi and Talbot (2003) suggested a new model involved the same basement faults (Fig. 8.4) with the same trends recognised by previous workers, but only applies to those faults which are confirmed by the various data sets. The kinematics of these faults relates to their trends in the Zagros strain field with shortening along a N40°E axis (Berberian, 1976). Kinematic data come from surface offsets (e.g. Hessami et al., 2001), earthquake fault-plane solutions (e.g. Baker et al., 1993), and/or different velocity vectors for groups of GPS stations on each block (Hessami, 2002). Previous workers have distinguished an "East Arabian Block" bound by reactivated Precambrian faults (Hancock and Al-Kadhi, 1978; Hancock, 1984; Weijermars, 1998). This block is bound to the SW by the Central Arabian Graben and to the east by the 450 km long, left-lateral Nisah-Sahba strike-slip fault (Weijermars, 1998; Fig.4). Bahroudi and Talbot (2003) suggested that the Trans-Arabian Gulf fault (TAG in Fig. 8.2; see also Weijermars, 1998), a gulfward extrapolation of the Nisah-Sahba fault, passes north of Qeshm Island to join the left-lateral strike-slip Bastak and Bostaneh faults in Iran, just west of Bandar Abbas

where magmatic thickening was least and it subsided earlier. Volumes of marine volcanics and magmatic crustal thickening generally decreased along the break-up margin away from the Icelandic plume. However, this trend, clear in adjacent rifted margins, was interrupted by much smaller volumes of submarine volcanics on and beside a transform margin. Subdued volcanism near this transform margin was attributed to cooling of the magmatic source region by lateral transport of heat into adjacent cool continental crust.

The Kazerun fault zone in the Zagros is an obvious analogue of the future transform along the North Atlantic margin, (and working backwards, that transform may have developed by reactivation of an old basement structure or fabric). However, whereas the North Atlantic was opened by the Icelandic plume in high latitudes there was no plume beneath Iran to open Proto-Tethys which was in low latitudes. Early subsidence along the Kazerun fault zone was marked by thick accumulations of clean marine salt in addition to submarine volcanics.

Talbot and Alavi (1996) attributed mafic inclusions in the Cambrian Hormuz salt to intraplating of the deepest northward-dipping Arabian footwall by mafic sills of mantle melts. Local melting of the deep Pan-African basement by these sills led to silicic melts erupting to the south. The order in which rifting of Proto-Tethys was followed by early Hormuz salt deposition and then uplift and volcanism along late Hormuz insert basins implies passive rather than active rifting of the Proto-Tethys half-graben.

However, there is no paleomagnetic evidence for any significant ocean basin near the Persian gulf in Hormuz times (Scotese, and McKerrow 1990). Kinsman (1970) wrote of the Hormuz sequence and its associated igneous rocks as accumulating in a proto-ocean that failed to open (Stamfli et al., 1991). Talbot and Alavi (1996) called this aborted ocean Proto-Tethys and attributed the mid-Cambrian cessation of its slow extensional rifting to the asthenosphere having bulged passively beneath the hanging wall and intruding sills (which are efficient at melting continental crust but not at disrupting the lithosphere) rather than dykes (which are more efficient at opening new oceans).

Hormuz Salt Structures: A Historical Background

The first descriptive catalogue of plugs of Hormuz salt (deBöckh et al., 1929) described and numbered 63 individual plugs on a topographic map of the southeastern Zagros Mountains. Episodes of salt extrusion from the Oligocene to Pliocene were recognised on the basis of the oldest exposed rock unit containing the distinctive bright coloured debris reworked from the Hormuz salt exposed at the time, a method used by most subsequent workers.

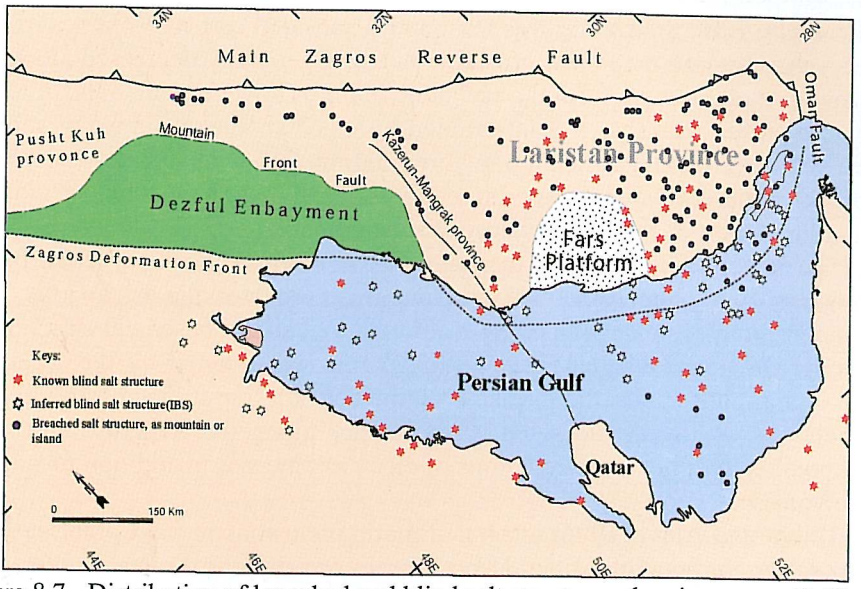

Figure 8.7. Distribution of breached and blind salt structures showing area with Hormuz salt and the Fars platform with thin or no Hormuz salt (complied from: N.I.O.C., 1975; Kent, 1987; Beydoun, 1991).

Harrison (1930, 1931) mapped and named 34 new salt plugs and assigned the first diapiric salt activity to Upper Cretaceous due to basement fault reactivation (at Kuh-e- Shamilo plug). He pointed out that some of the 130 salt plugs found by then probably first surfaced as islands in the proto-Persian Gulf in the Zagros foreland of the Miocene. Their upper levels were therefore down-built in soft muds rather than pierce the more general limestones. Later studies indicated that some salt dome islands probably extruded even before the deposition of the lower Miocene Fars Group (Schroeder, 1946; Wolf, 1959; Gansser, 1969).

British Petroleum (1956) published the first structural sections across the Zagros region with geological maps showing the locations and regional settings of most of the salt plugs known then.

Kent (1958) published the first list of some of salt plugs around which field studies showed pre-Zagros activity. He also adapted the "stopping theory" to account for the existence of huge rafts of sedimentary and igneous rocks in emergent salt plugs, even though the rafts are Hormuz in age.

Player (1969) assigned the activity of Hormuz salt in the Zagros Mountains to Permo-Triassic reactivations of NW-SE trending faults in the basement. He mapped and listed the onset of extrusion and subsequent repeated extrusion of several more plugs both before and during Zagros deformation. He also pointed to some blind salt diapirs still hidden beneath the sedimentary cover of the Zagros.

Jackson and Vendeville (1994) answered as to why diapirism in some salt basins such as Zagros Basin was delayed for few hundreds million years and represented a comprehensive temporal relationship between the onset of diapirism of the Hormuz salt and regional extension.

Bosak et al. (1998) used remote sensing to study 68 salt plugs emergent in the southeastern Zagros and listed such characteristics as the stratigraphy, hydrology and morphology on and around each plug. Although Bosak et al. (1998) added to former descriptions of the plugs in their catalogue, they also assigned names and numbers that bear little relationship to the names and numbers in older lists.

Talbot (1979) described the deformation structures and fabric with a salt glacier of Kuh-e-Namak Dashti in details. Field measurements were made using artificial or natural markers on flankes of slat glaciers to determine not only the variation in flow rates during dry and rainy seasons but also to estimate the rate of salt extrusion and loss (Talbot and Rogers, 1980; Talbot and Jarvis, 1984; Talbot et al., 2000). Talbot (1998) showed that the profiles of Hormuz salt extrusions could be compared with the profiles of extrusive viscous fluids. Using field observations on various shapes of the Hormuz salt extrusions, their internal fabrics and flow rates; the evolution of current salt extrusions and also the extrusion of metamorphic core complexes could be understood.

Timing of Activity of Hormuz Salt Structures

General understanding of salt tectonics has advanced considerably during the 1950s and 1960s while oil geologists carried out most of the fieldwork in the Zagros Basin (e.g. Kent, 1958, 1970; Player, 1969). They probably thought in term of diapirs of buoyant salt actively upbuilding (rising) through denser and ductile overburdens.

Many of these advances were inspired by contrasting the histories of salt structures being found in new basins offshore with those already known onshore in places like the Zagros Basin. Thus, some of the salt in offshore basins mobilized soon after deposition beneath remarkably thin overburdens. Here, the crests of passive salt structures stayed near the depositional surface as the surrounding salt was buried ever deeper by downbuilding of its overburden. By contrast, there was no sign of the Hormuz salt having moved for 350 Ma despite an overburden about 3 kilometers thick. Vendeville and Jackson (1992) cited the Hormuz salt as an example of buoyant salt being constrained by a stiff overburden until differential loading drove reactive diapirs when and where the stiff overburden had been thinned and weakened by faulting. Based on the authror's opinion, salt moving into conformable low amplitude pillows above faults reactivating in the underlying basement (Harrison, 1930; Bruderer, 1960; Player, 1969; Furst, 1976; Kent, 1979; Stöcklin and Nabavi, 1975; N.I.O.C., 1977) as well as reactive diapirs rising along different types of faults

at different times and then surfacing and either undergoing repeated episodes of extrusion on land, or being downbuilt by marine sediments offshore (Player, 1969; Furst, 1990; Harding and Lowell, 1975; Edgell, 1987, 1996; Vendeville and Jackson, 1992; Talbot and Alavi, 1996; Jackson and Vendeville, 1994).

In summary, Hormuz salt structures in the Zagros Basin have been divided into three different generations, pre-, syn-, and post-Zagros salt structures (e.g. Colman-Sadd, 1978; Koyi 1988; Talbot, 1998). However, there is a difficulty in terminology in this simplification.

PRE-ZAGROS SALT STRUCTURES

The only rocks available for studying past salt activity around most salt diapirs in the Zagros are Cretaceous or younger. Evidence for earlier salt activity may come from comparing current salt structures with isopachs of different age, an approach advocated by Kent (1979), before appropriate isopach maps were published for early Mesozoic to Tertiary sequences by Koop and Stoneley (1982). In principal, regional isopachs show local effects around salt structures undergoing syn-sedimentary growth and no such deflections over inactive salt structures.

Most salt diapirs now in the Zagros appear to have begun to rise; some had even surfaced, long before the ZFTB began propagating in Miocene. The first movements beneath some areas may have been as early as Triassic times (Player, 1969; Ala, 1974). Certainly much of the Hormuz salt was on the move by late Jurassic or early Cretaceous (e.g. Ala, 1974; Kent, 1979, 1987; Beydoun et al., 1992). However, Motiei (1995) suggested the onset of the Hormouz salt movement as early as Permain based on some operational evidence from some internal reports of Iranian National oil company.

The remarkably low density of salt deposits means that columns of salt with increasing thickness increase in buoyancy. In some circumstances, buoyancy forces can act without the imposition of lateral forces. Salt layers buried by ductile overburden can develop sufficient buoyancy to rise in conformable salt pillows, which mature to diapirs, either actively, by lifting existing overburdens or passively, as their overburdens are down-built around them. However, neither of these cases applies to the Hormuz salt.

The Pre-Jurassic clastic and carbonate overburden that buried the Hormuz salt in Arabia and the Zagros Basin to a depth of about 3 km would have rendered the Hormuz salt buoyant. However, there are no signs of salt movement from Cambrian to at least Triassic times so the overburden must have been sufficiently strong to resist buoyant salt uplift for about 300 Ma.

The locations of the buoyant salt structures depend on such factors as the thickness of the salt and the relief on its top and bottom contacts, and the thickness, density and strength of its overburden. Because of the obvious cor-

relation between early structures in the Arabian cover and old faults in the basement, early studies focussed on how thick-skinned reactivations of the basement faults localized the early salt pillows and later diapirs. However, Jackson and Vendeville (1994) made a great advance when they recognised that overburdens as strong as those to the Hormuz salt have to be broken and thinned before differential loading can drive salt rise in reactive diapirs.

Pre-Zagros triggering of salt structures has been attributed to a variety of events. Kashfi (1976) blamed the beginning of the closure of Neo-Tethys in Jurassic. Alsharhan (1989) suggested opening or closure of the NE trending Oman basin with a foreedeep parallel to the Oman line.

Jackson and Vendeville (1994, p. 64) advocated the rifting and drifting of Neo-Tethys at some time between Permian and earliest Cretaceous. They attributed the earliest pillowing, piercement and most vigorous venting of the Hormuz salt to weakening and thinning of its overburden on a north-dipping shelf by normal faults during thick-skinned opening of Neo-Tethys. However, most drape folds forced in the Arabian cover, both with and without cores of Hormuz salt, developed above basement faults with N-S trends. Jackson and Vendeville (1994) did not explain how salt pillows with N-S trends relate to N-S extension. Kent (1987, p.31) considered the alignment of the early salt structures at high angles to what later became the Zagros suture to demand an origin invoking tear rather than tension faults.

Talbot and Alavi (1996) considered both the closure of Paleo-Tethys in the Alborz Mountains and the Early to Late Triassic opening of Neo-Tethys along what is now the Sanandaj-Sirjan imbricate zone to have been diachronous. However, they recognised no sign of either event in the tectonics of the Hormuz salt. Instead, they considered the most likely tectonic candidate for starting movement of this salt to have been the reactivation of basement keys along the margin of Gondwana that accompanied Jurassic subduction of ocean floor beneath Asia. This could have been before the diachronous closure of Neo-Tethys along the Zagros suture in early Cretaceous.

Drape folds were forced in the cover above old faults reactivating in the basement where the Hormuz salt was absent, and where it was present, salt rose in pillows where the overburden was distored near releasing bends along N-S trending strike-slip transfer faults in the cover. Many of the conformable pillows of Hormuz salt beneath the drape folds that still exist in Arabia and the Persian Gulf spawned intrusive diapirs some of which surfaced before they were modified by the Zagros orogen covered in the next section.

While using analogue tectonic models to argue that the pre- syn- or post-Zagros shortening these diapirs are recognizable in planform, Koyi (1988) explained why diapirs of Hormuz salt do not relate neatly to Zagros structures. Pre-Zagros diapirs evacuated the surrounding deep salt to high-friction primary welds between the cover and its basement. This pinned the basal decollement locally so that many of the pre-Zagros diapirs ended up squeezed to Zagros trends either in Zagros synclines or near the ends of anticlines (Kent

1958, 1979). By contrast, syn-Zagros diapirs are larger and rounded in the crests of Zagros anticlines or rose up rhomboid pull-apart cavities along the N-S trending transverse faults (Talbot and Alavi, 1996; Talbot, 1998).

SYN-ZAGROS SALT STRUCTURES

Stratigraphic evidence indicates that increasing numbers of salt plugs were beginning to reach the surface in the ZFTB during and after the Cretaceous (e.g. Harrison, 1930, 1931; Kent, 1958, 1970; 1979; Player, 1969; Murris, 1980; Bosak et al., 1998).

Of the 136 emergent structures of Hormuz salt in and around of the Persian Gulf, about 130 have surfaced along the Kazerun fault and to the east (Kent, 1970, 1979, 1987; Ala, 1974; Talbot and Alavi, 1996). Although, most the exposed salt diapirs are now behind the Zagros deformation front, the majority began growing before the ZFTB began to develop (Kent, 1979; Koyi, 1988). Most of these reactivated when the Zagros front arrived but some diapirs formed for the first time as the Zagros front reached a particular location.

Along the deep pre-Zagros pillows aligned along N-S transverse faults, the pillows deflate in local salt withdrawal basins infilled by syn-orogenic sediments in association with pull-apart offsets in the cover along the strike-slip offsets along the fault zones (e.g. Talbot, 1998).

To the north of the Zagros deformation front, the collisional compression has resulted in squeezing and thickening laterally both the sedimentary cover and its underlying Hormuz salt. Although, this process increases the strength of overburden by folding and thrust faulting, but the lateral shortening, for instance, has led to buckling in the cover sediments, bulging of Hormuz salt in the core of anticlines, and in contrast, thinning of the Hormuz salt at the bottom of synclines. However, at least two different categories of syn-Zagros salt structures can be distinguished: a) salt cores or fold-related salt and b) fault-related salt structures.

Depending on the style of folding, the first group can be subdivided into different subgroups, including: 1) salt-cored fold, 2) liftoff fold, 3) pop-up structures (Hudec, 2000). This type of salt structures shows low- amplitude geometry in concordant contact with its overlying cover associated with or without secondary thrust faulting on the fold limbs.

The second group of Syn-Zagros salt structures can be also subdivided into: 1) shortened diapir, 2) overthrust diapirs, 3) thrusted salt.

POST-ZAGROS SALT STRUCTURES

The stratigraphic implications of inclusions in emergent Hormuz salt have already been discussed, but here it is pointed to recent resolution of a long-standing mechanical puzzle. The inclusions include rafts of Hormuz volcanics

and rocks denser than salt up to 3 km across and hundreds of meters thick (Player, 1969; Kent, 1979; Bosak et al., 1998). More recent work (Koyi, 2001) has pointed out that when the salt ceases to rise, inclusions not extruded above supporting country rocks can sink back down the diapir, a factor that may be very significant for storage of nuclear waste in salt diapirs.

Model by Koyi (2001) uses very conservative rates of rise for salt diapirs. Salt pillows rise slowly for long times (0.01 mm/y for 100 m.y.; Edgell 1996) blind diapirs upbuilding through their overburden accelerate as they amplify (e.g. to 3 mm/y in Player, 1969) but, quite apart from any lateral forces involved, the buoyancy forces are strongest just as the salt begins to extrude.

Young active diapirs of Hormuz salt rise as high as two kilometres above sea level, about 1000 m above their country rock orifices before they flow over the surrounding scenery at measured rates that can reach 10 m/y (Talbot et al., 2000). Modelling such rates of surface flow imply that the salt must extrude out of its orifice at >1 m/y (Talbot, 1998; Talbot et al., 2000).

Rows of post-Zagros diapirs now active behind the Zagros front lie along traces of the reactivating basement faults, either along the Mangarak fault zone or faults trending ENE north and west of Bandar Abbas (Furst, 1990; Talbot and Alavi 1996).

Current Distribution of Hormuz Salt Structures

More than 200 salt structures (including blind and extrusions) of the Hormuz salt have been recognised in the north-eastern Arabian platform (Kent, 1979; Jackson and Talbot, 1986; Edgell, 1996; Talbot and Alavi, 1996). The distribution of emergent and buried salt diapirs shows that most of the extruded diapirs are located within different domains in the Zagros folded belt (Fig. 8.7). Husseini (1988) attributed the "irregular" distribution of Hormuz salt to Late Precambrian faults. The experiments described in the next section were designed to investigate the conditions that may have controlled the structural pattern in the ZFTB.

A new catalogue of the 140 emergent salt plugs, of which 124 are on-shore in Iran and 16 form islands in the Persian Gulf (Kent, 1987) is produced. The onshore diapirs can be divided into two groups, one of 32 plugs extruded along the north-trending Kazeroun strike-slip fault and where its northern continuation has been distorted NW along the Izeh zone in the High Zagros. The other group consists of 92 plugs to the north and east of the Fars platform (on which Hormuz salt appears to be missing).

KAZERUN-MANGARAK ZONE

N-S rows of emergent plugs (e.g. like those along the Kazerun-Mangarak fault zone) probably began (between Triassic and Jurassic) as pillows

squeezed above reactivating faults in the basement-like those still preserved in Arabia. Talbot (1998) has been followed and referring to salt diapirs spawned from pre-Zagros salt walls when the Zagros deformation reached them as a third category of syn-Zagros salt structures .These plugs increase in maturity and age northward (Talbot, 1998), the Kuh-e-Gach plug at the southern end through the vigorous salt fountain (Kuh-e- Jahani plug), the Kuh-e-namak Firuzabad droplet, the degrading droplets at Kuh-e-Dadanjan plug and Roxana plug to breccia pipes at the north end (Talbot and Alavi, 1996.) This northward increase in maturity and age records the generally southward advance of the Zagros deformation front along a pre-Zagros pillow trending N-S at depth.

During this advance, successive frontal synclines squeezed Hormuz salt from very local withdrawal basins into the frontal anticline. Because the deformation front was slightly oblique to the axis of the pillow it was squeezing to the surface, releasing bends tended to develop in transfer faults linking successive imbricate thrusts. Plugs that emerged in N-S rows therefore probably also surfaced as reactive diapers, but instead of rising along normal faults they rose at releasing bends pulled apart between Zagros thrust anticlines along N-S transfer faults (Talbot and Alavi 1996; Talbot, 1998).

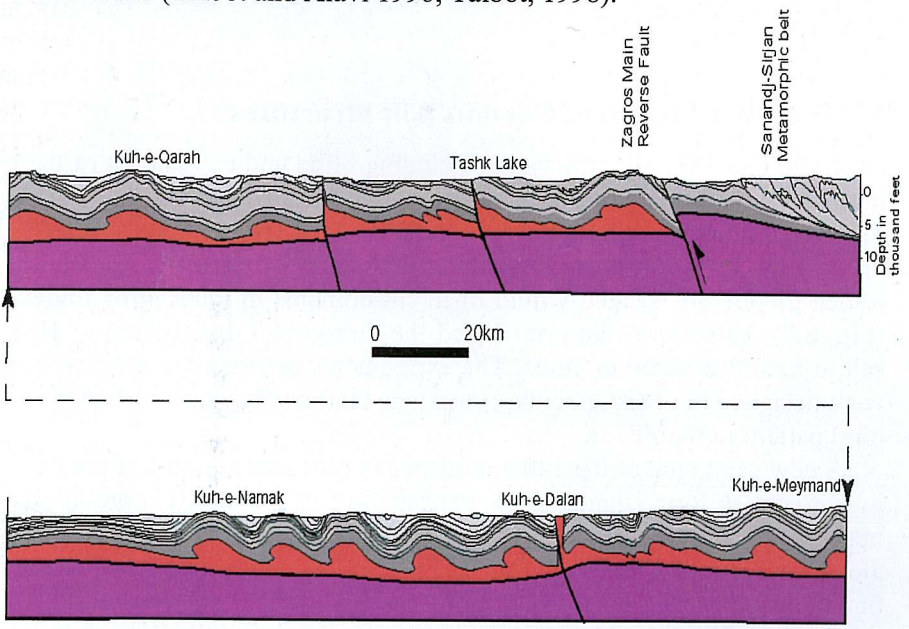

Figure 8.8. Geological cross section of the Zagros fold and thrust belt showing deformation of sedimentary cover above the Hormuz salt (black) which is involved with reactivated basement faults as reverse faults to develop folding in the cover (modified from: N.I.O.C., 1975).

SHAPING OF HORMUZ SALT STRUCTURES

Early workers (e.g. Harrison, 1930; O'Brien, 1957; Kent, 1958; Player, 1969; Trusheim, 1974; N.I.O.C., 1976) assumed that salt diapirs in the Zagros fold-thrust belt are smooth vertical pipes. But, the changes in sediment accumulation rate indicated by the many regressions and transgressions recorded in the regional stratigraphic column (see figs. 9, 12, 13, 19 and 20 in Murris, 1980) imply that emergent diapirs that were subsequently downbuilt offshore are likely to have irregular molded contacts (Fig 8.9; see fig.3 in Talbot, 1995). Partial or complete overhanging flanges flare outward upward when sedimentary downbuilding was slow and taper inward upward when surrounding downbuilding was rapid relative to salt extrusion that might have been accelerated by lateral shortening (Koyi moulding). Abrupt changes of sediment thickness around many of the high amplitude discordant salt structures now in the Zagros confirm that they were temporarily dominant offshore morphological features (see also Jackson and Talbot, 1986). Plugs that surfaced offshore in earlier versions of the Zagros foreland basin were downbuilt by comparatively weak marine sediments (Paleocene-Eocene shales of the Pabdeh formation and, anhydrite, salt, marls of the Fars group (James and Wynd, 1965; Motiei, 1993). Hormuz salt structures in this region display a wide variety of shapes (Figs. 8.9, 8.10, and 8.11). Emergent salt structures onshore in this region of low rainfall evolve through surface morphologies that have been categorized in slightly different ways (Harrison, 1930; Player, 1969; Walther, 1972; Ala, 1974; Fürst, 1976, 1990; Talbot, 1998; Bosak et al., 1998). The most basic divisions distinguish only pre-breaching, post-breaching and collapsing extrusions (Player, 1969). Fürst (1976) divided active extrusions marked by topographic salt domes from dying extrusions marked by negative surface morphologies. This led to the active, passive and ruined categories of Bosak et al. (1998). Harrison (1930) recognised other subdivisions such as salt-hills that developed one or more salt glaciers and decayed through erosion craters to salt marshes.

Here, current salt structures are classified into 3 numbered main groups subdivided into lettered subgroups (see Figure 8.9) that it will be used when it is resumed reviewing the regional history of Hormuz salt activity. The main classes are: a) group1 with blind salt structures consisting of salt pillows, salt ridges, cuspate salt mullions and unbreached salt diapirs; b) group 2 with active salt extrusions including salt fountains and salt mushroom, and c) group 3 with inactive salt extrusions including degrading salt structures and breccia chimney.

BLIND SALT STRUCTURES

Salt structures are traditionally assumed to evolve from low amplitude structures having concordant contact with its overburden to hight amplitude

stocks (with discordant contact to the cover) and eventually they may extrude to surface. The former structures are non-diapiric and immature including salt pillows, salt ridges or welt and salt rollers (Jackson and Talbot, 1986). Salt pillows have a gentle and symmetrical periclinal form in profile and circular to elliptical pattern on plan view (Fig.8.9 and 8.10). Whereas, salt rollers are asymmetric in cross section, and have a long and gentle limb (in a concordant contact with the cover) and short steeper slope (being in normal fault contact with the cover). The formation of salt pillows is assigned to response of faulted blocks to subduction of Neotethys in northen margin of Gondowana beaneath Central Iran (Talbot and Alavi, 1996). They were triggered to form and evolve from pillow to diapiric structures above basement grain by the re-activation of N-S basement faults. In the Zagros basin, some broad and closely-spaced gentle structures arranged along N-S basement faults are suggested as salt pillows (e.g. Edgell, 1987; Talbot and Alvai, 1996). By the onset of the Zagros shortening, the Hormuz salt was probably ruked up in the core of anticlinal buckles to form salt welt or cuspate salt mullions (Talbot et al., 1988). Blind salt structures can subdivided into Pre-Zagros salt pillows and syn-Zagros salt welts, blind growing diapirs (subgroup 1b) and blind inactive diapirs.

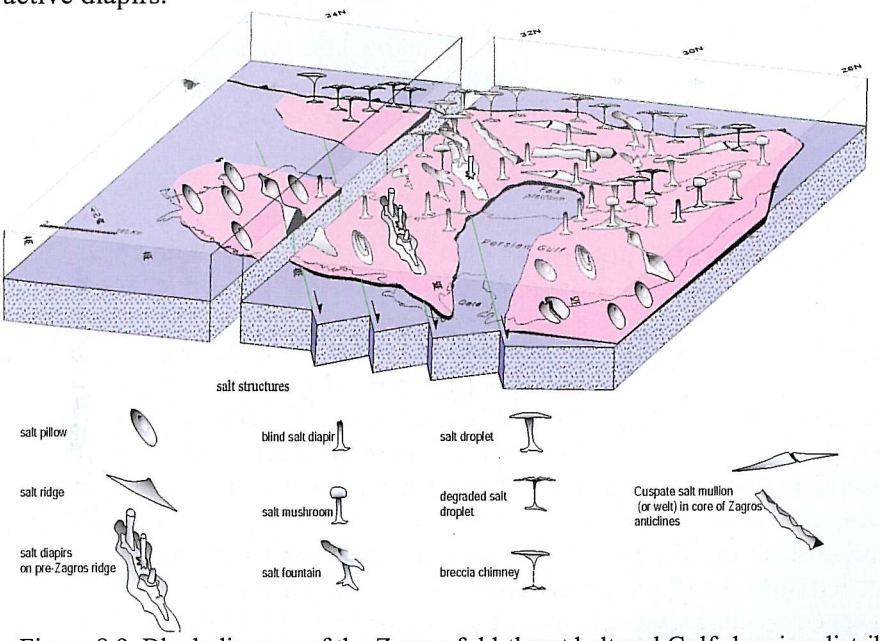

Figure 8.9. Block diagram of the Zagros fold-thrust belt and Gulf showing distribution of Hormuz salt (in white) and shapes of structures in it. The main shapes shown are: 1-3) Pre-Zagros salt structures: 1) salt pillow, 2) salt ridge, 3) Salt diapirs on pre-Zagros ridge. 4) blind salt diapir, 5-8) emergent salt structures: 5) salt mushroom, 6) salt fountain, 7) salt droplet, 8) degraded salt droplet, 9) Breccia chimney, 10) cuspate salt mullion (or welt) in core of Zagros anticline. See text for more details.

When the salt is piercing and rising through its sedimentary overburden, it forms a diapiric structure or intrusion which can result in salt wall, salt stock, or salt bulb etc. It may extrude to surface or stop in any level through the cover. Therefore, it is important to draw a conclusion that all non-diapiric and some of diapiric salt structures can be unbreached or blind within the Zagros basin.

In the most case, non-diapiric blind salt structures are indirecly recognized using subsurface studies and the arrangement of hydrocarbon fields (for examples Khafji, Jana, Bahrain, Bu Hasa, Dammam) or morphological features formed above them (Edgell, 1996; Wirjermars, 1999). Blind salt structures may deflect overlying beds and the drainage pattern by bulging (Figure 8.10).

The exact numbers of blind and emergent salt structures is still unknown. It is likely that more detailed studies will discover more both offshore and onshore, particularly old eroded examples along Zagros thrusts. Recent remote sensing study integrated with morphology led to recognition of 12 new hidden salt diapirs in land (Liaghat et al., 2002). At least 66 diapirs of Hormuz salt are concealed (blind) beneath the Zagros Mountains and the Persian Gulf (Figure 8.7 Kent, 1987; Liaghat et al., 2002).

Most of the 26 onshore blind diapirs are not far beneath circular domes in their overburden. Twelve of these occur along the boundary between areas with and without Hormuz salt around the Fars platform. About 20 of the islands have been known in Persian Gulf that those form about the exposed and blind Hormuz salt structures (Kent, 1987). The below section will indicate a possible further 49 salt diapirs concealed beneath the Persian Gulf.

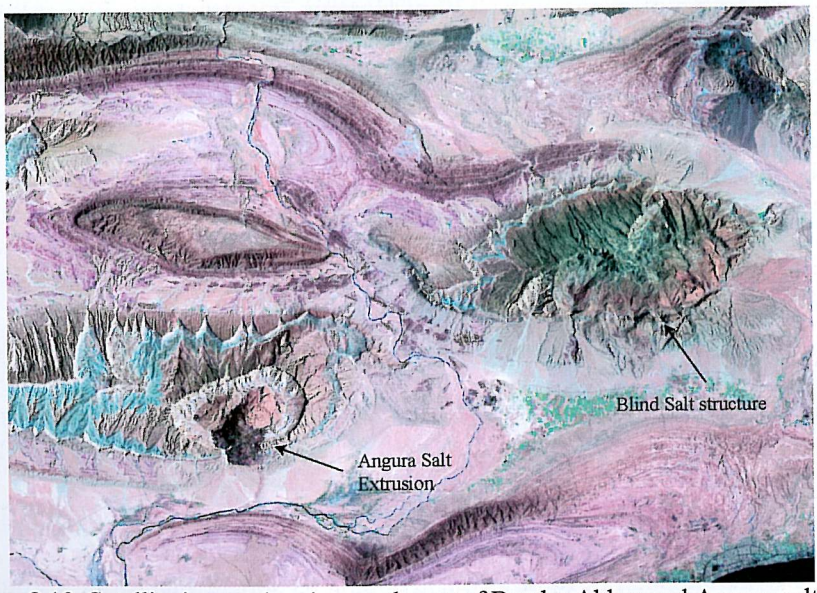

Figure 8.10. Satellite image showing northwest of Bandar Abbas and Angura salt plug as active salt extrusion and blind salt structure to the east.

INFERRED BLIND HORMUZ SALT STRUCTURES

All blind structures known in the Persian Gulf are associated with small circular to sub-circular closures in structural contours drawn on the top Jurassic (Figure 7; N.I.O.C. 1976), with some of the remaining sub-circular contours to previously unknown or Inferred Blind salt Structures (IBS: open stars on Figure 8.7). Tentative assignments display the same positive morphologies on bathymetric maps of the floor of the Persian Gulf as those above known blind salt structures. IBS decrease in number northward from Qatar to the Fars platform and follow similar trends to already known salt structures. Southeast of Qeshm Island, many IBS have been affected by the Zagros deformation and generally trend parallel to Zagros Folds in this area. A few IBHS occur behind the Zagros deformation front in the west, while others also occur along north-south trends in the Mesopotamian region. As existing seismic profiles are not in the public domain, it has been unable to divide blind salt structures into conformable and diapiric examples.

ACTIVE SALT EXTRUSIONS

deBockh et al. (1929) and Richardson (1929) were the first geologists who described 63 of salt extrustions and their glaciers in south Persian Gulf (Fig. 8.9, 8.11). Harrison (1930, 1931) mapped other salt extrusions in southen part of Zagros Mountains. Since then, Kent (1956, 1970, 1979, 1987) studied and reported many of on- and off-shore salt structures in different parts of the Zagros basin.

By observing of many of the 130 of Hormuz salt structures, Player (1969) suggested that salt can flow downslope as ice does in glacier. Talbot (1979) described deformation structures and fabric within the flowing glacier of Kuh-e- Namak Dashti salt plug (as one of the most active salt extrusion) in detail (Figure 8.11).

The field measurements of Tabot and Roger (1980) and Talbot et al. (2000) demonstrated that some of the salt extrusions are still flowing at the surface under room temperature in Zagros basin. Despite of many studied made on Zagros salt diapirs, the exact number of active and inactive extrusions are unknown.

Known active salt extrusions in the Zagros may fall into two groups (Figures. 8.9, 8.11, 8.12). The first subgroup of active extrusions is the least mature: topographic salt domes; examples are Kuh-e-Shur plug which rises to 2.2 kilomteres above sea level, about 900 meters above a Zagros anticline, and Kuh-e-Gach plug that rises 900 meters above the surrounding plain. Salt extruding this high cannot support its own weight and so gravity spreads to the profile of a viscous fountain (Talbot, 1998).

The dynamic summit domes of salt fountains spread flanges or aprons of allochthonous salt over their surroundings. Two examples of the 12 vigorous

salt fountains are Angoru plug (Figure 8.10) with one salt glacier (Harrison, 1930) or namakier (Talbot and Jarvis, 1984; Talbot, 1998), and Kuh-e-namak, Dashti plug with two (Figure 8.11 Talbot, 1979).

SALT GLACIER OR NAMAKIER

Salt glaciers or namakier are one of the most outstanding phenomenon which has interested geoscientists since the commencement of plug search. The first assessment was by Lees (1927) who introduced the term salt glacier. Talbot and Jarvis (1984) proposed the term "namakier" is composed of Farsi name for salt (i.e., namak) and glacier. Salt glaciers can be distinguished into (Trusheim, 1974): (1) hanging glaciers (on slopes of anticlines), and (2) tongue-like to areal foothill glaciers intervening synclines.

The circumstances of their derivation have been compared with the origin of ice glaciers. Only O'Brien (1957) assumed that the initiation of the diapirism and following glacier origin is caused by magmatic intrusion. This explanation was basically rejected. The origin of salt glaciers has been also described by a salt extrusion below a layer of unconsolidated bottom sediments, which requires specific unusual conditions to survive as stated by Jenyon (1986).

Although, salt glacier was elucidated for the first time by Lees (1927) and Harrison (1930), but detailed works and field measurements made by Uppsala University and Geological Survey of Iran showed that some of salt glaciers are still flowing at a rate of half a metre per day during rainy seasons.

The occurrence of salt glaciers is influenced by numerous factors. Air and rock temperatures in the region are important. The water content is important to keep the viscosity of salt intruded on the surface in low temperatures. Experiments (see Jenyon 1986) proved that the introduction of brine leads to an immediate and large acceleration in creep rate, while the temperature effect acts over much a longer period to produce a comparable increase in the creep rate. The presence or absence of free water is important, perhaps the most important - factor governing the deformation behavior of salt. Temperature gradient took part in broader context, too. Temperature and precipitation on the surface are very important factors widely influencing the viscosity of intruded material.

Extrusive salt generally flows slowly when it is dry, and rapidly when it is wet (Talbot and Rogers, 1980) or exposed in very high and steep river cliffs (Talbot et al., 2000). Modelling such measurements indicates that salt in one of the largest salt fountains, plug 135 (Jahani) extrudes out of its vent at over 1 m/y, a rate that is likely to exhaust its local deep source layer in something like 56,000 years (Talbot et al., 2000). However, salt glaciers seem to be shrinked when they dry and episodically expand and contract during 24 hours due to variation in surface temperatures. Measurments came out from a

marker installed on salt glacier of Kuh-e-Namak (Dashti) plug about 20 years ago by Talbot and Rogers, 1980) suggested the rate of 15 cm a^{-1} for salt flow.

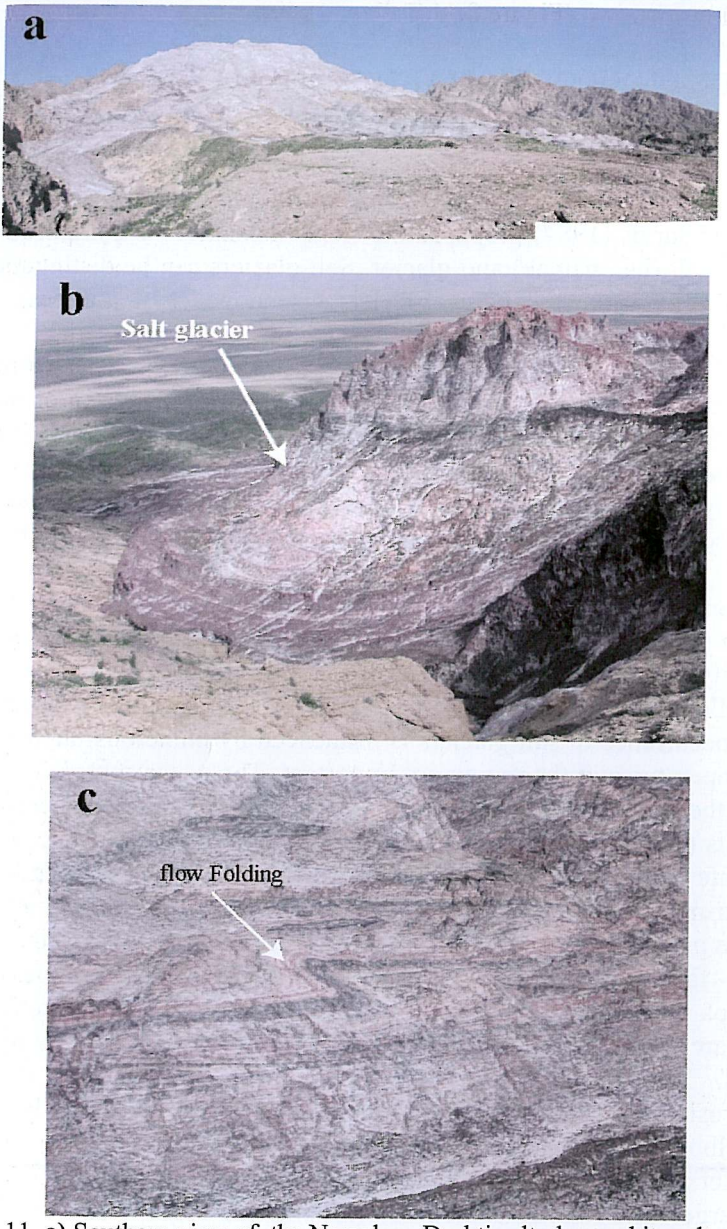

Figure 8.11. **a)** Southern view of the Namak-e- Dashti salt plug and its salt glacier located in the north of Boushehr, **b)** salt glacier of north limb of the plug flowing down into surrounding plain to the north **c)** a close view of salt glacier with flow folding in multiple- colour salt.

INACTIVE SALT EXTRUSIONS

As its deep salt source layer closes to a primary weld, the rate of gravity spreading of the extruded salt eventually exceeds its rate of supply from below (Figure 8.12). In such inactive plugs the summit dome rapidly spreads into the allochthonous salt apron to form the smooth parabolic profile known in fluid mechanics as a salt droplet (Figure 8.9), examples are Kuh-e-Namak, Firuzubad plug and Puhal plug. When the salt dissolution rate exceeds the supply of new salt, salt droplets dissolve beneath thickening caps of insoluble blocks dispersed among residual soils of Hormuz salt (Figure 8.9); an example of such a ruin is Chah Benu plug. Dissolution melanges start as badlands of conical hills that become rounded as they retreat to a hollow or crater above a breccia pipe or chimney. Such ghost diapirs are usually elongate along fault zones, particularly thrusts in the high Zagros.

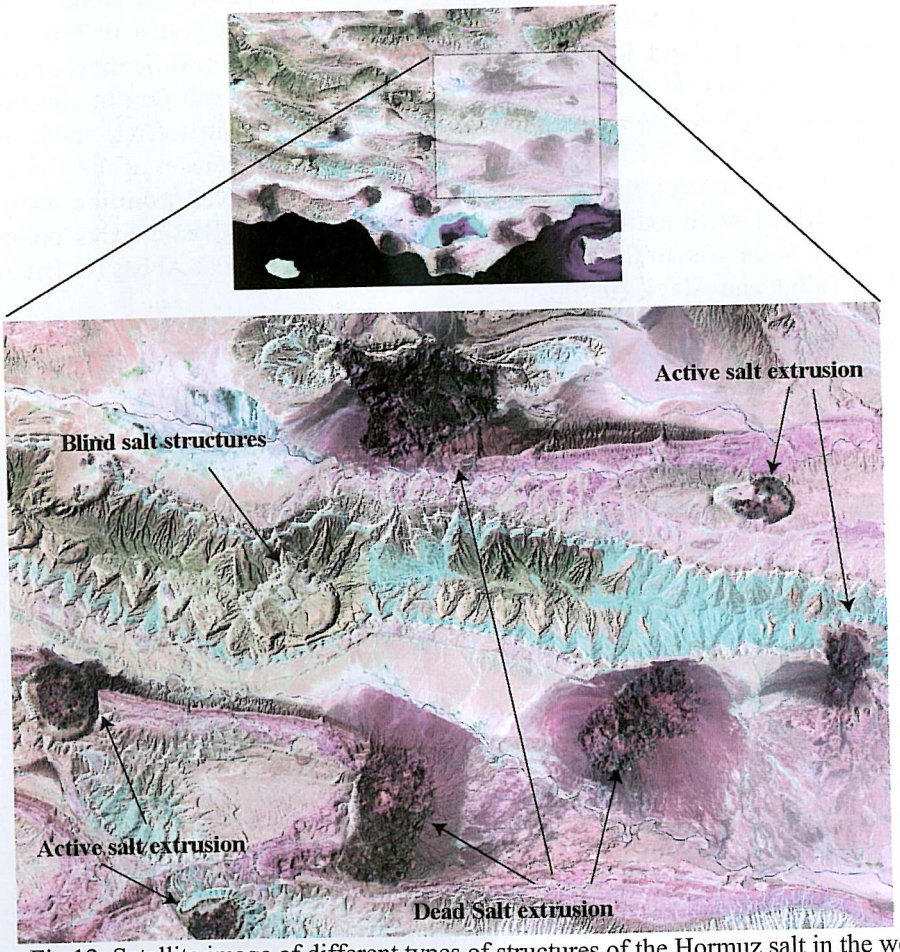

Fig.12. Satellite image of different types of structures of the Hormuz salt in the west of Bandar Abbas within the Larestan province.

GACHSARAN SALT IN THE ZAGROS BASIN

Gachsaran Formation is one of the most important seals for hydrocarbon reservoirs (especially in the Asmari Limestone) in one of the richest habitats for hydrocarbon in the world (O'Brein, 1957; James and Wynd, 1965; Dunnington, 1968; Stocklin, 1968; Colman-sad, 1978; Murris, 1980; Beydoun, 1991; Beydoun et al., 1992; Motiei, 1993; Edgell, 1996). Leakage of oil-gas from areas where this seal was absent or removed, fuelled the "holly eternal Fires" in the Zagros belt (e.g. Beydoun, 1991).

The Gachsaran formation varies in age, facies and thickness and extends for over 1200 km along the Zagros fold-thrust belt between the East Anatolian Fault and the Oman fault zone (O'Brien, 1957; fig. 2 in Stocklin, 1968; Motiei, 1995).

In Farsi, "Gach" covers anhydrite, gypsum and salt and although the Gachsaran Formation consists mainly of salt it also contains marls, limestones, and shales. Most of the calcareous rocks and muds were developed in NW-SE trending basins behind the advancing Zagros mountain front while most of the salt was deposited to the south, beyond it, in the Kirkuk and Dezful embayments west of the Kazerun fault zone and around Qeshm Island, south of Bandar Abbas (Fig. 8.13). It is probable that a large proportion of the Gachsaran salt was reprecipitated Hormuz salt that was dissolved from the many diapirs which were extruding among the carbonate and clastic rocks being deposited to the east of the Kazerun fault and north of Bandar Abbas (O'Brien 1957; Talbot and Alavi, 1996).

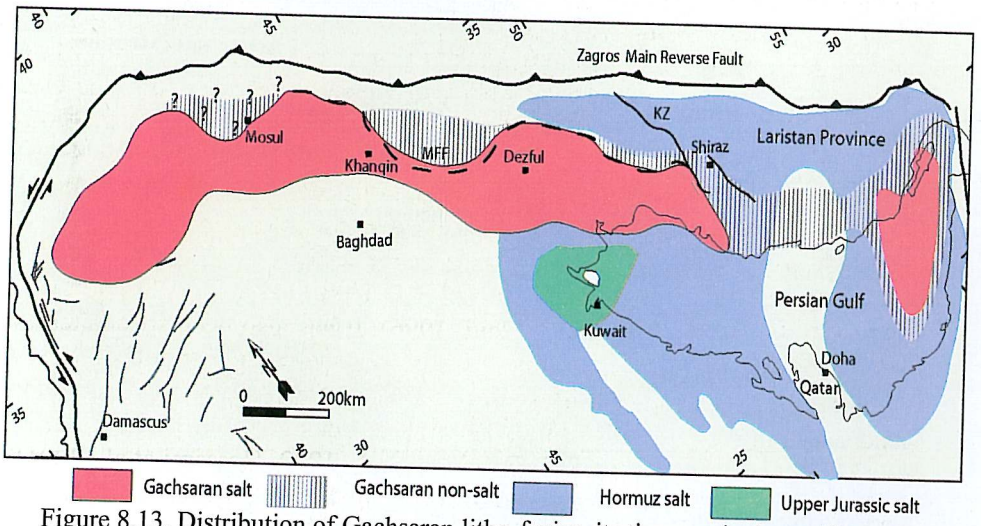

Figure 8.13. Distribution of Gachsaran litho-facies, its time-equivalents, Upper Jurassic salt and the Hormuz salt along the Zagros basin.

Although generally considered as lower Miocene, the basal parts of the Gachsaran Formation drilled on Qeshm Island, are Oligocene or even older, probably Eocene, so that it may young to the north (Motiei, 1993). A detailed lithofacies map of the Lower Fars deposit by Motiei (1993) indicates that the main facies changes in the Gachsaran Formation were influenced by major reverse faults reactivated in the basement. An example is the Zagros mountain front fault where the Gachsaran formation passes laterally into the marls and calcareous silts of the Razak formation (see Fig. 8.13).

The convergence between Arabia and Asia that began in Cenozoic is still transferring platform sediments from the foreland in Arabia to the Zagros fold-thrust belt in Asia. This transferring due to continental collision across the Zagros front involves folding and thrusting which shortens and thickens the 6 km thick undeformed platform sequence on the Arabian foreland to a deformed sequence about 14 km thick in the Zagros. Such thickening results in the High Zagros about 5000 m height (Kuh-e-Dinar) above sea level (Kent, 1979). Late Miocene-Pliocene evaporitic and clastic sediments were deposited in some of the enclosed synclinal Zagros basins trending NW-SE (Koop and Stoneley, 1982; Berbrian and King, 1981). Erosion of the rising Zagros mountains has built up the clastic, non-marine molasse deposits of the Bhaktyari since the Neogene (Alsharhan and Nairn, 1997).

The 2000 m thick thickness of the Gachsaran salt requires three fundamental elements: 1) evaporation exceeding the supply of seawater, 2) arid climate, and 3) near isolation of the salt basins. Most of the literature about the Gachsaran Formation discusses its stratigraphy, sedimentology and how its mechanical led to disharmonic Zagros structures (Fig. .14 O' Brien, 1950, 1957; Dunnington, 1968; Stöcklin, 1968; Gill and Ala, 1972; Kashfi, 1980; Motiei, 1993). Litho-facies maps of the Gachsaran Formation indicate that the Gachsaran salt was deposited in a narrow (about 150 km wide) and continuous basin 2000 km long between Oligocene to Miocene times (Fig. 8.14; Stöcklin, 1968; Gill and Ala, 1972; Kashfi, 1980; Motiei, 1993). It has been suggested that a large proportion of the Gachsaran salt was reprecipitated from Hormuz salt that was dissolved from the many diapirs which were extruding among the carbonate and clastic rocks east of the Kazerun fault (O'Brien 1957; Kent, 1979; Motiei, 1985; Talbot and Alavi, 1996). It has also been speculated that the Gachsaran formation was a syn-tectonic sediment deposited in NW-trending synclinal troughs (during active folding) that divided the Zagros foreland basin into sub-basins with poor water circulation (Berberian and King, 1981; Koop and Stoneley, 1982; Beydoun et al., 1992; Hessami et al., 2001).

Talbot and Alavi (1996) distinguished two thin-skinned tectonic wedges on either side of the Kazarun fault zone. These wedges differed in taper angle, styles of Zagros deformation, width and propagation rate. To the northwest of the Kazarun fault zone, where Gachsaran salt (deposited after Zagros folding began) detaches only an upper competent sequence (Fig. 8.14). The thrust-cored anticlines in this fold-thrust wedge with a high friction sole are charac-

teristically long (87 km in average), tight (7 km wide in average) and straight. The longest anticlines, the Pasan and Kabir-Kuh folds, are 310 and 200 km long, respectively. Most folds are asymmetric in profile and verge southwest with steep southwestern limbs (Colman-Sadd, 1978; Motiei, 1995; Talbot and Alavi, 1996).

In contrast to the Hormuz salt east of the Kazerun fault zone, the lower Miocene Gachsaran salt lies high in the cover sequences west of the Kazerun fault zone (Fig. 14). Where the Gachsaran salt was present when the Zagros front arrived, it is responsible for strong disharmony between structures it detached in over- and underlying competent groups. The weak salt was squeezed from high pressure areas above anticlines developing in the underlying competent group to low pressure areas above synclines (Fig. 8.14 O'Brien, 1957). Hundreds of cubic kilometres of salt migrated into salt bulges, which are just southwest of the main anticlines. As a result, the Gachsaran formation varies in thickness from several hundred up to 2000 metres over short distances (O'Brien, 1957; James and Wynd, 1965; Stocklin, 1968; Murris, 1980; Edgell, 1996). Gravity tectonics associated with near surface Gachsaran salt is distinctive and in places (e.g. the Masjid-e-Sulaiman and Haft Kal areas) allochthonous sheets of Gachsaran salt extrude over younger sediments in synclines (O'Brien, 1957).

SALT DIAPIRISM AND HYDROCARBON

The Paleozoic-Middle Miocene sedimentary sequence of Arabia and the Zagros is one of the richest hydrocarbon habitatas known and, at one stage, contain 66.7% of the proven recoverable oil and 31.5 % of proven gas reserves of the world (Murris, 1980; Beydoun, 1991). The Zagros fold-thrust belt and its foreland (referred to here as the Zagros basin) house 98.7% of this oil and 97.2% of the gas (Beydoun et al., 1992; 1991 Edgell, 1996). This huge hydrocarbon potential has been attributed to the climate and oceanic circulation affecting the passive margin of Arabia when the various versions of Tethys were open. Murris (1980) argued that the pre-Zagros source-rocks, reservoirs and seals are so extensive because the basin was wider and longer than other basins.

In front of the Zagros deformation front, all the hydrocarbons have been trapped in structures which formed by north striking basement faults lineaments only some of which have associated cores of Hormuz salt. The larger oil-gas fields are in the middle of the Zagros belt and its foreland basin in Iran, Iraq and Arabia (Fig. 8.2). Behind the Zagros deformation front, the larger hydrocarbon fields are in the Dezful and Kirkuk embayments. These fields are commonly sealed in the thick cover of the embayments by Gachsaran evaporites in NW-SE trending Zagros anticlines (Fig. 8.14). In Lorestan in the northeast of the Dezful embayment, oil and gas pools are few and confined to NW-SE trending post-Miocene asymmetric anticlines away from thrust faults.

In front of the Zagros deformation front, the most important source-rocks are considered to be shales in the Mid-Cretaceous Kazhdumi, the lower Cretaceous Garau, the upper Cretaceous Gurpi and the Paleocene-Eocene Pabdeh formations (Bordenave and Burwood, 1990; Beydoun et al., 1992). Geochemical analyses indicate that the majority of hydrocarbon pools were generated during middle Mesozoic to early Tertiary (e.g. Motiei, 1995). Variations in maturity and productivity of potential sources in the Kazhdumi and Pabdeh formations relate to facies changes almost certainly influenced by reactivation of basement faults. For instance, shales in the Kazhdumi Formation appear to be the only likely source for the giant oil fields in the Dezful embayment and change to barren facies eastward across the North-striking basement faults (Bordenave and Burwood, 1990, 1994; Motiei, 1995). Other potential source-rocks in Pusht Kuh, such as the Lower Cretaceous Garau and Upper Cretaceous Gurpi formations, are only productive south of the Mountain front fault thought to be the result of reactivation of yet another Pan-African Najd-type fault in the basement (Ala et al., 1980; Berberian, 1995; Motiei, 1995).

The organic maturity of potential source-rocks depends on temperature and thus burial depth and heat flow. There is close relationship between maps of geothermal gradient and basement fault distribution in the Zagros (Bahroudi and Talbot, 2003). Thus the Kazerun fault separates the relatively high geothermal gradients in the Dezful embayment from lower gradients in Fars province to the east. These differences reflect the differences in thickness and facies of the cover rocks deposited (and/or retained) on each block. By controlling the facies and thickness of the cover sequence, the reactivation of basement faults thus affected the location (facies) of source-rocks as well as their maturity.

The horizontal or lateral up-dip migration of hydrocarbons from their source rocks to higher level reservoirs in the Zagros has usually been attributed principally to post-Cretaceous Zagros collision tectonics responsible for both the folds and the reactivation of old faults in the basement (Beydoun, 1991; Motiei, 1995). However, there is both field and laboratory evidence that at least some of the hydrocarbons were already mature and migrating by middle Cretaceous times. Thus, Player (1969) reported two distinct levels of stratified bitumen within Cenomanian sediments pierced by the Khormuj salt diapir. Fluid inclusion studies from the United Emirates also confirm source maturity in Turonian to Campanian times (Beydoun et al., 1992). It is therefore clear that at least some of the hydrocarbons existed and were already migrating before Zagros shortening began.

This is why the shapes of hydrocarbon pools differ on either side of the Zagros deformation front (see fig. 3 in Talbot and Alavi, 1996). On the Arabian platform not yet reached by the Zagros deformation front, oil and gas fields, which include a few super giant and many giants, are elongate along N-S or NNE-SSW trending basement lineaments only some of which have associated cores of Hormuz salt (Fig. 8.2 Murris, 1980; Ameen, 1992). Super gi-

Most of the smaller oil-gas fields are at the two ends of the Zagros orogen, in Oman in the southeast and in Turkey and Syria in the Northwest. Most hydrocarbon fields in Oman relate to structures from which the Hormuz salt has already been lost in front of the Zagros deformation front (Ameen, 1991, 1992). Many oil and gas fields in southern Turkey are close to, but south of, the Zagros mountain front fault. Most of these trend W-E-to WSW -ENE and are controlled by folds related to old normal faults in the basement rejuvenated as reverse faults during Zagros compression.

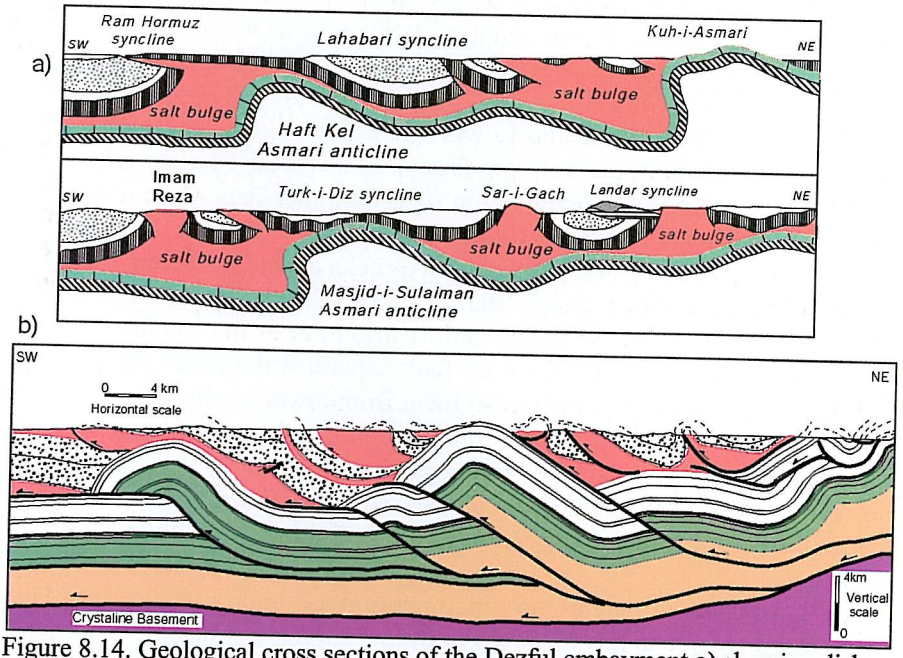

Figure 8.14. Geological cross sections of the Dezful embayment **a)** showing disharmonic structures due to mechanical behaviour of Gachsaran salt (after O'Brien, 1957) response to **b)** differential stress imposed by folding and faulting in underlying units (after Motiei, 1995).

Hydrocarbon source rocks vary in age and distribution throughout the Zagros basin. Potential source-rocks are generally rare in late Paleozoic-Tertiary strata. Only the Ordovician-Silurian mud rocks (i.e., Seeyahoo and Sarchahan Formations, in the region show signs of having been sufficiently organic rich to source hydrocarbons. Motiei (1995) argued convincingly that the organic rich shales of the gas-prone Silurian Sarchahan Formation (tectonised outcrops of which occur in a Zagros anticline north of Bandar Abbas; Setudehnia, 1972) sourced the Dehram and Kazerun groups gas reservoirs in the Zagros. Similar shales crop out in the core of the Surmeh anticline near Feroozabad.

ant fields lying above faults without intervening salt suggest that the reactivation of faults in the basement was more important than movement of salt. Air photos and satellite images of the highly productive oil fields show an excellent correlation between the production pattern and NNE lineaments (McQuillan, 1991) or longitudinal N-S trends (Edgell, 1996). High oil production comes from secondary permeability and porosity fractured in the sediments (e.g. Asmari limestone) by episodic activity along the underlying basement faults (McQuillan, 1991).

Northward, in the Persian Gulf, such oil pools become circular where they are influenced by the shallow foredeep pushed in front of the low-taper Zagros wedge advancing southward over Hormuz salt. Behind the Zagros deformation front, oil and gas fields are elongate with the superposed trend of Zagros thrusts anticlines. Many traps behind the deformation front probably developed as a result of Zagros reversed dip-slip reactivations of normal faults in the basement formed or reactivated during the opening of Tethys (Ameen, 1991, 1992).

The Zagros front advanced through a cover sequence in which hydrocarbons were already trapped in pools with N-S trends in reservoirs like the Bangestan limestone as still seen in Arabia. As the Zagros deformation front reached each pre-existing trap, the oil and gas either escaped or re-migrated into new NW-SE anticlinal traps of Asmari limestones sealed by the Gachsaran salt (e.g. Dunnington, 1967; Beydoun et al., 1992; Motiei, 1995).

Most of the reservoirs in the Zagros Mountains and its foreland basin consist of carbonate rocks although a few are of sandstone or conglomerates. The most important carbonate reservoirs are the Asmari Formation and Bangestan Group and their time-equivalents. The low intrinsic porosities and permabilities usual in these formations have been greatly enhanced by Zagros fractures and allow high productivity from reservoirs created above reactivated basement faults (Edgell, 1996). Pools in the Asmari Formation, one of the world most prolific reservoirs, typically provide high quality oil from shallow productive zones (McQuillan, 1973, 1991; Motiei, 1995).

Less important oil and gas reservoirs in the region are the Jurassic Surmeh and the Lower Cretaceous Fahliyan Formation in the southeastern Zagros. The oldest reservoirs are the Permian-Triassic Dalan and Kangan Formations which still host hydrocarbons sourced by Silurian rocks in the Pars, Kangan, Nar, Aghar and Kuh-e-Mond fields (Motiei, 1995; Beydoun et al., 1992).

Despite some of the super giant fields not being associated with salt, 60% of the recoverable oil in the Persian Gulf region has been assigned to salt-induced structures (Edgell, 1996). Most Iranian hydrocarbon fields in the Persian Gulf have been formed by breached or unbreached diapirs of Hormuz salt.

The distribution of oil-gas fields in the Zagros foreland indicate control by anticlinal structures forced over the deep basement faults and draped over

deep salt pillows (Alsharhan, 1989; Kassler, 1973; Colman-Sadd, 1978; De-Jong, 1982; Kent, 1987; Beydoun et al., 1992).

Salt tectonics played both constructive and destructive roles in the development of hydrocarbon pools in northeastern Arabia and the Zagros. In its constructive role, the early rise of structures of Hormuz salt trapped hydrocarbons in stratigraphic pinchouts due to onlap (e.g. the Sarkhun gas field) and in faults and domes above pillows and diapirs (e.g. the Resalat, Reshadat and Pars oil-gas fields) as well as deep turtle-back structures. Similarly, the correlation between the oil-gas pools in the Zagros Mountains and the Gachsaran salt attests to the remarkable capacity of that salt to seal hydrocarbons that migrated into new traps in the Asmari formation as it deformed (Dunnington, 1967).

By contrast, salt tectonics also has a dark side for diapirs may reduce the thickness of seals and source rocks as well as the deep geothermal gradient required for hydrocarbon maturation. The general lack of hydrocarbon reserves beside diapirs of Hormuz salt behind the Zagros front east of the Kazerun fault zone (Motiei, 1995) implies that these diapirs induced local leakage of all or part of the pre-existing hydrocarbons (e.g. in the Namak-Kangan, Khormuj and Chah Pir anticlines in Fars province). The bitumen layers beside the Khormuj salt diapir are all that remain of perhaps 200 barrels of oil that escaped in Cenomanian time (Player, 1969).

CONCLUSIONS

The Zagros basin contains not only almost 60% of the world's proven oil reserves but also hosts world's largest salt provinces. Many of hydrocarbon fields of the basin have been formed above a variety of salt structures and reactivated basement faults in the sedimentary cover above. All those fascinating characteristics have been evolved by interaction between two basic elements, basement fabric and salt deposits.

Although, Precambrian crystalline basement has no exposure within the Zagros basin, but salt structures carried up to surface possible samples of basement rocks as exotic rocks. Most exotics suggest that the basement consists of igneous, metamorphic and partly sedimentary rocks. Within the basin, long and linear topographic anomalies and structures with a variety of trends referred to as lineaments provide a possible basement configuration. In this context, the new structural model of the Precambrian basement successfully can explain the presence of two blocks, active and passive.

Despite of significant variety of salt deposits within the Zagros basin, the Hormuz salt or lying at the base of sedimentary sequence and Gachsaran Formation at uppermost part of the sequence are the thickest and the most widespread salt deposits in the basin.

In the absence of any complete undisturbed sequence of Hormuz salt exposed in the Zagros Basin, the extent and stratigraphy of the Hormuz salt have

been reconstructed and inferred from indirect observation such as distribution of blind, breached salt structures, etc. It is possible to assume a significant proportion of the Gachsaran salt resulted from reprecipitation and dissolution of extruded structures of Hormuz salt.

The distribution of emergent and buried salt diapirs shows that most of the extruded diapirs are located within three domains. As the tectonic activity of Zagros basin has been divided into three major phases: 1) lateral extension and 2) approximately N-S compression and 3) Post-Cretaceous continental convergence, structures of the Hormuz salt also can be categorized into classes as pre- syn- and post Zagros salt structures.

By adding salt welts in the cores of Zagros anticlines onshore to the >200 breached and blind salt structures already recognised, and adding another 49 blind salt structures beneath the gulf and Mesopotamia, this study indicates over 300 structures of Hormuz salt in the Zagros basin. A new catalogue lists the number, name, surface morphology for only the 139 emergent structures of Hormuz salt in Iran.

Both Gachsaran and Hormuz salt play important and similar role as viscous decollement in different levels through the whole Phanerozoic sequence. But, Gachsaran Formation also provides the most important seals for hydrocarbon reservoirs in the region whereas Hormuz salt appears to play two contrasting roles constructive and disconstructive.

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CHAPTER-9

HYDROCARBON FIELDS OF PERSIAN GULF

INTRODUCTION

Since 1957 National Iranian Oil Company has singed contracts with many European and American companies for exploration, extraction, production and development of the offshore oil in the Persian Gulf outside consortium agreement area of the Zagros foothills and Fold Belt. A number of discoveries were made several of them were quickly put into production while some remained under lineated and undeveloped. This type of agreement, known as 75%, 25% was followed by the negotiation of service contract agreements in 1966 with various non-US firms and several discoveries here were also made such as oil, extra-heavy oil, gas and gas condensate.

The first offshore oil discovery in the Iranian side of the Persian Gulf was the Bahregansar field in 1960. The field started producing one year later. This was followed by the discovery of the giant Doroud field in 1961. Oil was again found offshore in Nowrooz in 1965 and in Hendijan (1968). From these three fields a total production of 120,000 b/d was obtained.

By 1979 four joint ventures operating offshore had brought ten fields into production. After the Revolution the state took the control of almost all Iran's economic activity and NIOC took total responsibility for the oil and gas projects.

Among foreign companies active in Iranian oil industry in the years before the Revolution, Sirib, Ipac, Iminiuko and Sufiran succeeded to discover oil resources. After 1979, activities of foreign oil companies working in the country were considered contradictory to the principle of nationalization of oil industry in Iran and on May 30, 1980, the contracts were cancelled.

In August 27, 1980, the Iranian Continental Shelf Oil Company was formed to conduct research and launch operations for exploration, extraction, development and exploitation of oil, natural gas and other hydrocarbons in coastal waters belonging to Iran. Therefore, all offshore oil-related activities in Iran were concentrated within the framework of responsibilities charted for the company.

The first offshore buyback project was the development of the Sirri A and E oil fields by TotalFinaElf, signed in 1995 and completed in 2000. Since then four other offshore oil projects have begun. The Balal field development was completed in 2001 also by Total and it came on stream in January 2003. In late 2004 it was producing 40,000 Bbls per day.

The other main offshore areas where work is being carried out to increase oil production capacity are the heavy oil of the Soroosh and Nowrooz fields

by Shell and the Doroud field by Total. The two oil fields in the Persian Gulf contain about 1 billion barrels of heavy oil. Shell purchased the producing rights and planed to bring production on over 200,000 b/d by 2004. Four platforms have been installed on the Soroosh and Nowrooz fields, producing around 50,000 bbls per day in 2003, their production capacity increased to 190,000 Bbls per day at the end of 2004.

In July 1998 the first exploration bid round was held and five blocks were offered offshore (East Kish, Farsi, Hormuz, Qeshm and West Kish) but none were licensed. To assist in marketing the estate in 2000 NIOC commissioned a seismic survey of the entire Iranian Persian Gulf continental shelf, known as "Persian Carpet". The Farsi offshore block, which has two oil discovery wells in water depths ranging from 20 meters to 90 meters, has been offered as an exploration service contract to a consortium of Indian public sector oil companies. However, due to continued poor take-up Iran's new five year economic development plan is expected to enable companies to develop fields as well as explore for them and to loosen the restrictive buy-back agreements.

Many commercially significant oil and gas fields have been discovered in the Persian Gulf region since the beginning of the 20th Century. Most of the hydrocarbons in the Persian Gulf oilfields are generated and produced from Jurassic carbonates; however, Cretaceous, Paleozoic, and Infracambrian Petroleum systems account for production in numerous giant oil fields in reservoirs of equivalent age. In the present chapter attempt has been made to cover the geology and reservoir parameters of some of the oil fields in the Iranian side of the Persian Gulf region.

Crude Oil Reserves of Continental Shelf in Persian Gulf

The vast majority of Iran's crude oil reserves are located in giant onshore fields in the southwestern region and also in the Persian Gulf. According to the latest published accounts, Iran has 40 producing oil fields, of which 27 are onshore and 13 offshore.

According to the Oil and Gas Journal (January 2004), Iran holds 125.8 billion barrels of proven oil reserves, roughly 10% of the world's total, up from 90 billion barrels in 2003. The vast majority of Iran's crude oil reserves are located in giant onshore fields in the southwestern Khuzestan region near the Iraqi border and the Persian Gulf.

Major offshore fields include the following: Doroud (130,000 bbl/d); Salman (130,000 bbl/d); Abouzar (125,000 bbl/d); Sirri A and E (95,000 bbl/d); and Soroosh and Nowrooz (60,000 bbl/d). Iran's crude oil is generally medium in sulfur, with gravities mainly in the 28°-35° API range. Some of the physicochemical characteristics of the oil in some of the oil fields of the Persian Gulf are presented in Table 9-1.

Table 9-1. physico-chemical properties of some crude oils from the Persian Gulf (from HPI Consult, 1987)

Crude oil type	Specific gravity API	Total S (%)	Total N (%)	H_2S (mg/ml)	Ni (µg/ml)	V (µg/ml)
Abouzar (Iran)	0.8927	2.48	0.160	18.30	71.00	
Bahrgansar (Iran)	0.8916	2.45	0.260	20.40	72.00	7.90
Dorood (Iran)	0.8565	2.35	0.054	5.65	23.00	5.00
Foroozan (Iran)	0.8686	2.50	0.067		36.00	6.50
Iranian Heavy (Iran)	0.8707	1.73	0.230	9.40	116.00	5.25
Iranian Light (Iran)	0.8554	1.35	0.170	6.40	35.00	3.50
Rostam (Iran)	0.8447	1.55	0.070	3.30	16.50	2.84
Salmon (Iran)	0.8549	1.91	0.087	5.60	11.60	4.10
Soroosh (Iran)	0.9452	3.30	0.260		101.00	12.00
Al Bu Khoosh (UAE)	0.8670	2.00		6.70	12.00	4.3
Murban (UAE)	0.8223	0.78	0.047	2.70	1.00	1.35
Umm Shaif (UAE)	0.8372	1.51	0.061	3.60	3.00	2.20
Zakum, lower (UAE)	0.8216	1.05	0.050	2.90	0.36	1.56
Zakum, upper (UAE)	0.8591	2.00	0.097		8.77	4.42
Mubarek (UAE)	0.8392	0.62		3.20	1.23	
Basrah Heavy (Iraq)	0.9052	3.5		4.00	90.00	9.73
Basrah Light (Iraq)	0.8559	1.95	0.095	6.5	18.00	4.18
Basrah Medium	0.8696	2.58		12.60	50.00	5.40
Kuwait Export	0.8680	2.52	0.120	9.78	30.00	5.30
Burgan (Kuwait)	0.9134	3.37		42.2	34.00	7.70
Rataawi (Kuwait)	0.9094	4.24	0.240	80.00		39.00
Wafra (Kuwait/SA)	0.9420	4.55		315.00	59.20	8.90
Hout (Saudi Arabia)	0.8606	1.91		6.03	28.00	5.01
Khafji (Kuwait/SA)	0.8838	2.85		17.50	55.00	8.04
Ratwai (Kuwait/SA)	0.9123	4.07		36.50	55.00	9.50
Dukhan (Qatar)	0.8203	1.27		5.28	2.26	1.70
Qatar Marine (Qatar)	0.8442	1.42		5.93	7.00	2.72
Arab Light (Saudi A)	0.8575	1.79	0.098	6.25	20.50	3.58
Arab Extra Light	0.8352	1.19	0.042	3.86	1.10	1.83
Arab Medium- (SA)	0.8712	2.40	0.137	9.41	22.00	5.44
Arab Medium-Zulf	0.8696	2.48		11.01	43.00	5.05
Arab Heavy (SA)	0.8871	2.85	0.137	19.00	57.00	7.9
Mubarek (UAE)	0.8392	0.62	0.168	3.20	1.23	

OIL AND GAS RESERVES, PRODUCTION, CAPACITY

In 2003, the Persian Gulf contained almost 715 billion barrels of proven oil reserves, representing over half (57%) of the world's oil reserves, and 2,462 trillion cubic feet of natural gas reserves (45% of the world total). Also, at the end of 2003, Persian Gulf countries maintained around 22.9 million bbl/d of oil production capacity, or 32% of the world's total. Perhaps even more significant, the Persian Gulf countries normally maintain nearly all of the world's excess oil production capacity.

According to the Energy Information Administration's International Energy Outlook (2003), Persian Gulf oil production is expected to reach about 26 million bbl/d by the year 2010 and 35 million bbl/d by 2020, compared to about 21.7 million bbl/d in 2000. This would increase Persian Gulf oil production capacity to 33% of the world total by 2020, up from 28% in 2000.

In 2003, Persian Gulf countries had estimated net oil exports of 17.2 million bbl/d of oil. Saudi Arabia exported the most oil of any Persian Gulf country in 2003, with an estimated 8.40 million bbl/d (49% of the total). Also, Iran had estimated net exports of about 2.6 million bbl/d (15%), followed by the UAE (2.4 million bbl/d- 14%), Kuwait (2.0 million bbl/d- 12%), Iraq (0.9 million bbl/d-9%), Qatar (0.9 million bbl/d-5%), and Bahrain (0.01 million bbl/d-0.1%).

OFFSHORE PERSIAN GULF

Oil Development

Major offshore Persian Gulf oil fields include Khafji and Hout, which are both connected to the Saudi Arabia's Safaniya, the world's largest offshore oilfield (with estimated reserves of 35 billion barrels). Saudi's offshore Persian Gulf production includes Arab Medium crude from the Zuluf (over 500,000 bbl/d capacity) and Marjan (270,000 bbl/d capacity) fields and Arab Heavy crude from the Safaniya field. Iran's national oil company (NIOC) has expressed interest in developing five oil and gas fields in the Hormuz region (Hengam A (HA), HB, HC, HD, and HE), according to NIOC, they hold an estimated 400 million barrels of oil and have production potential of 80,000 bbl/d.

As of August 2000, Iran was producing about 620,000 bbl/d of crude oil from its offshore fields. Doroud 1 and 2, Salman, Abouzar, Foroozan, and Sirri fields comprised the bulk of Iran's offshore output, all of which is exported. Iran plans extensive development of existing offshore fields and hopes to raise its offshore production capacity of about 1 million bbl/d from about 675,000 bbl/d currently.

In October 2003, Iran relaunched a tender for eight exploration blocks in the Persian Gulf after receiving little interest from a January 2003 announcement. One of the areas considered to have hydrocarbon potential is located near the Strait of Hormuz. Another interesting area is offshore near Boushehr, where Iran claimed in July 2003 to have discovered three fields with as much as 38 billion barrels of oil reserves.

In late 2001 and early 2002, Shell brought part of $800 million Soroosh-Nowrooz development online, with production of around 60,000 bbl/d. The two fields are located offshore, about 65 kilometers west of Kharg Island, and contain estimated recoverable reserves of around 1 billion barrels of mainly

heavy oil. Although Soroosh was shut down briefly in March of 1983 at the outset of war with Iraq, output from the field expected to reach 190,000 bbl/d.

Natural Gas Development

Besides oil, the Persian Gulf region also contains huge reserves of natural gas (2,462 Tcf). Iran, Qatar, Saudi Arabia, and the UAE are holding the world's second, third, fourth, and fifth-largest reserves (after Russia), respectively. This likely will become increasingly important in the future as both domestic gas consumption and gas exports increase.

Most of Saudi Arabia's currently proven natural gas reserves consist of associated gas, including the offshore Safaniya and Zuluf field. Safaniya field, has estimated reserves of 19 billion barrels (Energy Information Administration, 2000). A huge (13-Tcf) natural gas field, called Dorra is located offshore near the Khafji oil field in the Saudi-Kuwaiti Neutral Zone and may be developed by Japan's AOC. Dorra development is controversial, however, because part of it is also claimed by Iran (which is called the Arash field). Currently, Iran is resisting any moves by Kuwait and Saudi Arabia to develop the field on their own. Iran and Kuwait have been discussing their offshore boundary since 2000.

Iran's largest non-associated natural gas field is the South Pars, which is geologically an extension of Qatar's North Field. Current estimates are that South Pars contains 280 Tcf or more and some estimates go as high as 500 Tcf of natural gas, of which a large fraction will be recoverable and over 17 billion barrels of liquids.

Based on estimates, Iran's offshore oil reserves in the Persian Gulf, including the operating and undeveloped reserves, totally amount to about 11.7 billion barrels comprising 5.9 billion barrels from the operating reserves and 5.7 billion from undeveloped reserves.

NIOC is also inclined to develop five oil and natural gas fields in the Hormuz region: Hengam A (known as West Bukha by Oman; the two countries are discussing possible joint development); the A field near Lavan Island; the Esfandiyar field near Kharg Island; and two structures near the South Pars natural gas field. According to NIOC, five Hengam fields hold an estimated 400 million barrels of oil and have a potential production of 80,000 bbl/d. Other Iranian oil fields scheduled for increases include Doroud, Nosrat, Farzam, and Salman.

In March 1999, France's Elf Aquitaine and Italy's Eni/Agip were awarded a $1 billion contract for a secondary recovery program at the offshore, 1.5-billion-barrel Doroud oil and natural gas field located near Kharg Island. The program is intended to boost production from around ~136,000 bbl/d to as high as 205,000 bbl/d. Total is operator of the project, with a 55% share, while Eni holds the other 45%.

In April of 1999, Iran awarded TotalFinaElf (46.75% share), along with Canada's Bow Valley Energy (15% share), a buyback contract to develop the offshore Balal field. Eni is also involved, with a 38.25% stake. The field, which contains some 80 million barrels of reserves, started producing at a 20,000-bbl/d rate in early 2003, and reportedly reached 40,000 bbl/d in February of 2004.

NATURAL GAS

Iran contains an estimated 940 Trillion Cubic Feet (TCF) in proven natural gas reserves the world's second largest and surpassed only by those found in Russia. Around 62% of Iranian natural gas reserves are located in non-associated fields, and have not been developed, meaning that Iran has huge potential for gas development. Major non-associated gas fields include: South Pars (280-500 TCF of gas reserves), North Pars (50 TCF), Kangan (29 TCF), Nar (13 TCF), and several others.

In 2002, Iran produced about 2.7 Tcf of natural gas. Around 10% of this was flared, and approximately 30% reinjected in part for enhanced oil recovery efforts. In March 2004, Iran signed a $1.2 billion contract with a consortium of two foreign and two domestic companies gathering associated gas, previously flared or re-injected, from the Nowrooz, Soroosh, Hendijan and Behregansar fields.

Oil Field Districts in the Persian Gulf

The geographical district belonging to Iran in the Persian Gulf has been divided into four regions: Behregan, Kharg, Sirri and Lavan. All of these four regions contain oil fields. There are 17 oil fields in the regions, with several wells dug in each of them.

Bahregan region: It includes Behregansar, Nowrooz and Hendijan oil fields. Formerly, Iran's Oil Company and Italy were active in the region.

Kharg region: It includes Abouzar, Doroud, Soroosh and Foroozan oil fields. Formerly in this region Iran's Oil Company and Amoco were active.

Sirri region: Active oil fields in Sirri are Sirri C and Sirri D. Iranian Oil Company and French company Arap were active there in the past.

Lavan region: the oil fields in this region include Resalat, Reshadat and Salman fields. In this region two active old oil companies and three foreign companies under the title of International Oil Company of Iran were operating.

Pool Size Distribution in the Persian Gulf

Most petroleum exploration companies wish to have a view on how much petroleum remains to be found in a particular area prior to committing significant spending. On the basis of a "yet to find" study, a company can decide to

enter a new basin or license to exit from the same. The two key products of such a study are the number of petroleum pools that are expected to be found and their size (volume) distribution.

The Iranian sector of the Persian Gulf is a fine example of where pools seem to be missing from the pool size distribution. The data are shown in figure 9-1 from which it is clear that there is a large gap between the size of the largest fields (>2500 mmbbl boe, where "boe" means "barrels of oil equivalent") and the upper size limit of the smaller fields (250 mmbbl boe). It is possible to speculate that fields in the size range 250-2500 mmbbl boe remain to be found.

From this figure it can be deduced that there is no progression from many middle-sized fields to a few very large ones. This leads the exploration geoscientists to suspect that fields in the reserves range 250-2500 mmbbl may yet be found. Moreover, when the data used to compile this graph were examined further, only one field was recorded as a stratigraphic trap. Thus, even before necessary examination of geologic data, the geoscientist is likely to suspect that there are opportunities to discover more stratigraphically trapped petroleum within the Iranian side of the Persian Gulf.

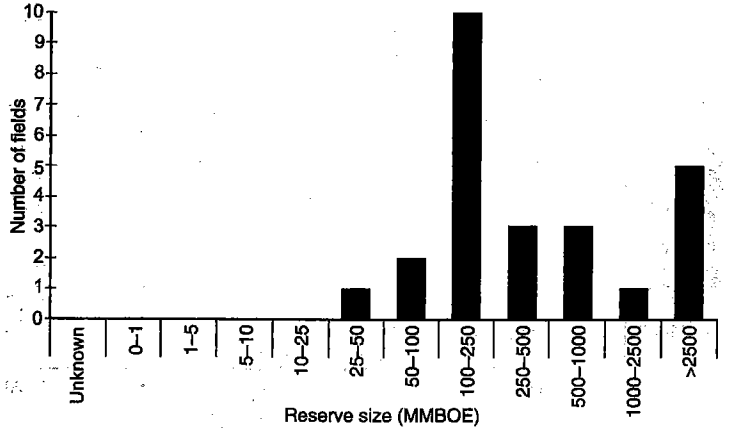

Figure 9-1. The reserves size distribution for Iranian petroleum fields in the Persian Gulf.

Persian Gulf Oil Fields

There are 151 giant oil fields in this region (Figure-9-1). These fields are concentrated in a large Persian Gulf foreland basin formed during the Late Cenozoic collision of the Arabian Plate with Eurasia. Source, reservoir, and seal rocks of great geographic extent characterize the productive hydrocarbon-producing systems of the Persian Gulf.

Downward flexure of the Arabian Plate underneath the Zagros Mountains was caused by the northeastward consumption of the Tethys Ocean at the Za-

gros Suture zone. Additional causes of this flexure were the eventual Cretaceous to Recent convergence and collision of the Arabian plate against the Eurasian plate. This protracted convergent event has created the Persian Gulf and Mesopotamian lowlands as a sag in the foreland basin, as well as formation of the Zagros Mountains, with a culmination of fold-thrust deformation in Miocene and Pliocene time. However, other than minor tilting, large areas of the foreland appear completely undisturbed by the Zagros-related convergent deformation, as manifested in the variety of giant-field shapes. For that reason, formation of elongate giants parallel to folds and thrusts in the Zagros Mountain and foreland basin was classified as a continental collision margin, while those giants to the southwest were counted as continental rifts and overlying steer's head the sag basins.

Basal stratigraphic succession underlying today's foreland basin was deposited along a Cambrian-Permian passive-margin setting along the southern Tethys margin. Deeply buried salt, possibly deposited in a rifted basin was activated by small-displacement basement faults during Permian to Jurassic time. These gave rise to salt ridges and diapirs, forcing folds in the overlying sedimentary section, which include some of the largest giant fields, such as South Pars, in the Persian Gulf. These folds are at a high angle to later folds and thrusts related to the Zagros convergence. The source rocks in this basin include Cambrian-to-Permian units, with the main reservoir in the Permian.

Second hydrocarbon formation period occurred from the Triassic through Tertiary, with Middle Jurassic and Cretaceous source rocks and the Upper Jurassic, Middle Cretaceous and Oligo-Miocene reservoirs. Migration was primarily upward from underlying source rocks in giant fields that were removed from the Zagros deformation. Structural traps produced in the area adjacent to the Zagros fold belt and relate to early collisional effects in the Eocene and younger time.

Abouzar (Formerly Ardeshir)

This field is located in the northern part of the Persian Gulf about 100 km to the SW of Kharg Island close to Median Line. It was discovered in October 1959 by IPAC (the Amoco-NIOC partnership) by exploration well A-1. The Abouzar field came into production in 1976. The water depth over this field is about 30 meters. Producing formation is mainly Ahwaz sandstone member of Asmari Formation. The Oligo-Miocene Ahwaz sand reservoir has almost a constant thickness in the Abouzar Oilfield.

The field is a NW-SE trending anticline, dipping by 1-1.5° measuring at approximately 24 by 8 kilometers and filled to spill point by a hydrocarbon column of about 62 meters. The structure is an elongated and very gently deformed NW-SE symmetrical anticline which is parallel to the direction of the Zagros Mountains. Thus, it appears that the Abouzar field owes its present structural configuration to the superposition of NW-SE trending fold of the

late Tertiary Zagros orogenic movements over the earlier north-south folding movements.

The reservoir is capped by a few meters of anhydrite that form the base of the Upper Asmari. The structural evaluation analysis of the Abouzar anticline illustrated that the Abouzar anticline was formed in Late Tertiary. The hydrocarbon accumulation within the Ahwaz Sandstone reservoir is considered to have migrated during the Zagros folding. The reservoir at the crest of the structure is at a depth of 815 meters with a hydrocarbon column of about 62 meters of which the gas column is 18 meters and oil column is 44 meters. The structural closure of the Abouzar field at top of the Ahwaz sand reservoir is about 60 meters and the aerial closure is 86 km^2.

The reservoir has almost a constant thickness, consist of fine to medium-grained sand with some shale and carbonate interbeds. The reservoir thickness varies between 80 to 90 meters. In this oilfield, the Ahwaz sandstone contains excellent reservoir properties, with porosity of about 30% and permeability of about 2 to 4 Darcies. The Ahwaz sand reservoir is the youngest and also the shallowest oil-producing reservoir within the Persian Gulf area.

In the Abouzar field, the Ahwaz reservoir is at a shallow depth (700 m) and at this depth the seismic data is of excellent quality (Hedayati, 2003). The structure at the top of Ahwaz sand is a very gentle elongated anticline with very continuous seismic horizons.

Oil gravity is 27° API. In 1980 the field averaged 36.5 MBD oil and by mid 1980 had produced 79.9 MM Bbls of oil. Ultimately the remaining recoverable reserves are estimated at 50MMB. Undeveloped Asmari carbonate reservoir zones contain 20-25° API oil with in place of 900 MMB and Azadegan sandstone member of Kazhdumi Formation (Burgan-Nahr Umr) with in place of 110 MMB, 28° API oil shall be considered.

Alvand- Alpha-1 (Iminoco)

This field is situated about 30 kilometers northeast of the Resalat and about 25 kilometers from Reshadat fields. Alvand was explored in 1970 by IMINOCO. Discovery well was tested 1.8 MMD of Surmeh Formation, member-C and some of the gas was discovered from Surmeh Formation member-A. The oldest rocks drilled in the Alvand (Alpha-1) belong to the basal Surmah Formation. The well was terminated at a depth of 2788 meters.

The structure contains some interesting reefal developments and also it represents good closure in Upper Sarvak, Dariyan and reaches the maximum areal extension and vertical closure in the Surmah Formation. Lithology of the Dariyan Formation in this well is mainly consists of rudist limestone. Based on the well log information, the porosities of Dariyan Formation range from 15 to 30%. The porosity is mainly of primary nature.

Baneh, Former Beta-1 (Iminoco) or Behrooz

The structure is located 25 kilometer from north of Resalat (i.e., Formerly Rostam) oil field. This is a NW-SE elongated structure which includes two culminations and the vertical closures are varying from 20-33 meters in the Sarvak to Surmeh Formations accordingly. Small amount of hydrocarbon was reported from Sarvak, Dariyan and Surmeh Formations. Discovery well was completed in 1972 at depth of 2316.5 meters in the Surmeh Formation as a dry hole. Based on well log information, the porosity of Dariyan Formation in this well is of primary nature and reached 10% whereas the total porosity is in the order of 10 to 35%.

Bahman (IPAC, B-1)

This is an abandoned exploration well which was drilled by IPAC in 1961 in order to prospect the Cretaceous sequence but no commercial hydrocarbons were discovered. The well was mainly drilled based on the geophysical information. It is highly probable that the stratigraphic thinning of the Asmari and Cretaceous formations to the south provide a favorable area for possible stratigraphic trap accumulation. Total depth of the well is 3261 meters in the Surmeh Formation.

Binalud (BA-1 Bushco, BA-1)

The structure is located in southeast of Foroozan (Fereydoun) oil field about 15 kilometers southeast of well F-5, the well was reached to a total depth of 3068.2 meters in the Surmeh Formation in 1973 and extra heavy oil was recovered from Fahliyan and Surmeh Formations.

Top of the Azadegan sandstone member of Kazhdumi Formation (Burgan) is at 2282.8 meters. The stratigraphic column penetrated in BA-1 well down to the Upper Jurassic Surmeh Formation (i.e., Arab D). This well was known as a dry one, but it requires further detailed studies.

Bahregansar

This was the first discovery in the Iranian offshore which was made in 1960 by SIRIP (The AGIP-NIOC Partnership). Oil production commenced in January 1961, from well No#1 completed as an Asmari "B" producer. The main production comes from the Sarvak Formation but some oil and gas is also present in Ahwaz Sandstone member of the Asmari Formation and some oil and gas also reported from Jahrum, Kazhdumi, Dariyan and Fahliyan Formations. The Sarvak oil is 25° API and Asmari oil is 31° API.

There are five hydrocarbon reservoirs within the Bahregansar field. These include, Ahwaz Sandstone Member, Asmari carbonates, Sarvak, Kazhdumi and Fahliyan. The deepest well (Bs#10) has been drilled to a depth of 4253

meters reaching the Gotnia Formation. Similar to the Asmari carbonates, the Sarvak Formation has also been largely affected by fracturing and consequently porosity creation.

Ahwaz Sandstone Member can be divided in three zones with different characteristics: Zone-1, mainly sandy dolomite with some interbedding of shale and anhydrite in the upper part. Some layers of clean sand are present. Zone-2 consists of clean sand with some strikes of shales. This zone has the highest porosity and permeability. Zone-3 contains sandy dolomite and dolostones with frequent interbedding of shale. Some clean sand layers are also present. The gas-water contact of the gas pool which is quite clear from the well logs was fixed at 2073 meters s.s.l.

In this oil field, the Asmari Formation consists of carbonate and calcareous dolostones which is more or less fractured. Nodules of anhydrite are often present. Two oil pools have been recognized in the Asmari Formation in Bahregansar fields which are separated by a layer of shale 1-2 meters thick. The upper one named, pool "A", that is water bearing in Hendijan field and is the least important in terms of OOIP. On the contrary, the underlying "B" is the most important.

Pool "A" with a thickness of 30-32 meters seems to be quite homogeneous in terms of reservoir characteristics. The original oil-water contact has been assumed at the average depth of 2097 meters below the sea level. No original gas cap is present in this pool.

In Asmari "B" two main zones with different permeabilities are observed, but from pressure measurements point of view, no vertical communication between the two zones seems to exist. This is probably due to the presence of some anhydrite. Production behavior of Asmari "B" clearly reflects the complicated reservoir geometry.

Sarvak pool consists of dolostones and fractured calcareous dolostones. Due to the erosional surface which exists on top of the Sarvak Formation, the morphologic culmination, parallel to the overlying formation (Gurpi, Pabdeh, Jahrum, Asmari, Ahwaz sandstone member), is shifted towards SE with respect to the older structures and parallel to the underlying formations (i.e., Azadegan sandstone, Dariyan etc.). Erosion was deeper on top of the old structural culmination, reaching the maximum indicating that the Sarvak Formation is missing. The original oil water contact was assumed at the average depth of 2752 meters s.s.l. Based on the production data, the Sarvak reservoir has been divided into four zones in Bahregansar oil fields with thicknesses reaching up to 78 meters.

Due to the presence of these unconformities the Sarvak Formation seems to be eroded and often is completely missing. Such erosional surface on Sarvak is also evidence on other oil fields in the Persian Gulf such as Sirri. In addition to this, the sediments of the Azadegan Sandstones of the Kazhdumi Formation are also reduced in thickness to about 95 meters. Such a deduction

is based on the comparison of the sedimentary column in others wells of the Nowrooz structure.

The Lower Azadegan sand (Burgan) with good permeability is commonly hydrocarbon-bearing. The clean limestone section (i.e., Fahliyan Formation) is oil bearing from DST performed in open and ceased hole API 40.6°. The possible oil water contact could be established around 3642.5 meters.

The field went on production in 1962 and 1980. It averaged 12.334 MBD and at the end of 1979 had produced 120.94 MMB through nine development wells. Primary ultimate recoverable reserves were 180 MMB but in 1977 it was evaluated to 150 MMB.

Balal (Formerly Bahram or 3W-Structure)

The Balal offshore oil field is located in the middle part of the Persian Gulf, 98 kilometers southwest of Lavan Island near Iran's maritime border with Qatar. The field is located between Resalat and south Pars fields. The development scheme here involves setting up two platforms (wellhead and production) and drilling ten wells, divided between production and water injection. Start-up was achieved in early 2003 and production quickly reached 40,000 barrels per day.

One hundred and five million barrels Balal field discovered in 1967 by LAPCO with the Sarvak and Surmeh Formations as the oil-producing reservoirs. The reserves are estimated at 15 MMMB at 41° API oil. The Balal field was never developed even though an oil pipeline connecting the field to the Lavan Island export terminal was laid.

The discovery well (3W-1) was completed at total depth of 2318 meters in the Surmeh Formation. Other wells such as 3W-2 and 3W-3 were drilled to appraise the field. The four wells drilled on the structure found a stratigraphic sedimentary sequence and series consistent with the regional data. Existence of oil in the Surmeh and Sarvak Formation was approved by drilling of these wells.

In general three main reservoirs levels were identified: Sarvak, Dariyan, and the Upper Surmah. Studies showed that on the spot oil reserves and the final capacity of the above reservoirs were 555 and 138 million barrels, respectively. Development of the field and its exploitation was being planned according to the capacity of the above reservoirs. The optimum target was 40,000 barrels of oil per day which equaled the maximum production rate of the oil field and the duration regarding the production ceiling is 3 to 4 years. The expected production period is 14-15 years.

The Upper Surmeh reservoir consists of alternated carbonates (mainly dolostones) and anhydrite. Thus, such lithological association and conditions could impact the reservoir behavior during production. Its deepest reservoir is situated in the depth of 2667 meters from the surface. The Upper Surmeh reservoir holds about 84% of the total reserves and is being considered as the

main reservoir of the field. The degree of oil gravity in this reservoir is 4.16° API and the ratio of oil to its liquid gas is 412 cubic feet per barrel. The gravity degree is an indication of the superb quality of the oil in Balal field.

Production is from the Upper Surmeh (RD=3500ft, 27°≤Gr≤28°, Original Recoverable Reserve, ORR=17mn brls) and Surmeh (RD=5500ft, Gr=31°, ORR=118mn brls).

Balal offshore oil field had reached a production level of 40,000 barrels of crude per day by January 2003 and NIOC has taken operatorship of the production and is exported from the offshore platform using sub sea pipeline and processing facilities on Lavan Island.

The field was developed under a buy-back contract signed with the NIOC and a partnership made up of Total with a 46.75% interest, Eni 38.25%, and Bow Valley 15%. Dehram reservoir of the Balal field was explored in 2004 and proved to contain 7.9 TSCF gas in place and 182 MMB of recoverable condensate. Also there are some strong indications that the Dehram Group in the Balal oil field is apart of and/or extension of South Pars giant gas field (Motiei, in press).

Binalud-B (Former Bushco-B or BB)

This field is located in the southeast of the Foroozan field in the Persian Gulf. This is an offshore three-well discovery. The exploratory well BB-1 was drilled by BUSHCO (the Amerada-Hese-NIOC partnership) in 1972 and discovered 14.2° API oil at rate of 3.3 MBD. Producing zone is in Azadegan Sandstone of Kazhdumi Formation (i.e., Burgan sands). BB-1 was penetrated to a depth of 3024.5 meters. Total of three exploration and delineation wells were penetrated but the field evaluated as non-commercial.

The main targets of this location were the Azadegan Sandstone of the Kazhdumi, Fahliyan and Surmeh Formations. Although oil shows were observed in the Asmari, Ilam, Dariyan and Gadvan Formation, electrical logs indicated these horizons to be water bearing (Motiei, in press).

Binalud-C (Former BC-1 Bushco, or BC)

The structure is located 40 kilometers south-southwest of port of Bushehr and 58 kilometers ENE of well BB-1. The main objective of this abandoned well was to evaluate Khami Group but extra heavy oil of 3.3° API was recovered from the Surmeh Formation (i.e., Arab D).

No hydrocarbon was found by DST from Asmari, Ilam, Sarvak Formations and the Azadegan sandstone member. The Fahliyan limestones are also very tight and display low porosity and permeability. The well was completed in the year 1972 at total depth of 3505 meters in the Surmeh Formation.

Doroud (Formerly Kharg-Darius)

The Doroud field is located in the northern part of the Persian Gulf, offshore Iran. This field has been producing for approximately thirty years and it is partly underlies the Kharg Island. It is also the offshore extension of the Kharg field.

Doroud is a single N-NE to S-SW elongated anticline structure and its size is approximately 25 kilometers long by 5 kilometers wide. The 2002 development was done from offshore platforms (26 wells from 14 Platforms) and from onshore clusters (26 wells from 14 clusters).

The field was discovered in 1961 with the IPAC exploration well #D-1 drilled offshore. Doroud went on production in 1964 with averaged 12 MBD and to 1980 cumulative production exceeded to 650MMB.

The field was worked under two different agreements; northern portion called Kharg (including Kharg Island) was under the control of OSCO (Oil Service Company of Iran) and southern portion called Darius was with IPAC. The southern part was explored in 1961 and northern part was delineated in 1962. The production started in 1964. Before starting of the drilling operation by ELF Petroleum Iran, the Doroud field counted 52 wells.

According to Mina et al. (1967), in the area of the Doroud oil field, the fold belt structural trend had been superimposed on the platform trend. A similar superposition of structural trends may be present at the Bahregansar oil field at the head of the Persian Gulf. A third superposition of structural trends is also possible in the eastern part of the Persian Gulf near the small island of Lavan, north of the Salman oil field.

The Fahliyan Formation of Lower Cretaceous is the main proven pay zone of the structure (33 producers). There are minor but strikingly important variations in the Fahliyan pay zone. These differences are generally due to changes in porosity and permeability of the reservoir rocks. Oil water contact within Fahliyan is placed between 3651.3 to 3632.4 meters.

The limestone and dolostones of the Fahliyan Formation is thought to be capped by the compact micritic limestone from the Khami Group with poor to no reservoir quality, and ultimately by the micritic to shaly limestones from Lower Ratawi Formation. The respective average thicknesses are 65 meters for the Khami, 250 meters for the Upper Fahliyan and 50 to 60 meters for Lower Fahliyan. There is no production from Surmeh in the Doroud field. Additionally, the Dalan/Kangan has not been drilled so far in this field. Table 9-2 shows the stratigraphic results obtained from the Doroud field.

Table 9-2. Stratigraphic Results (Fahliyan reservoirs) in Doroud Field

Interval	Top (meter)	Bottom	Gross thickness
Khami	3512.0	3583.0	71
Upper Fahliyan	3583	3684.5	101.5
Middle Fahliyan	3684.5	3856	171.5
Lower Fahliyan	3856	3905	49

The other known pay zone of the structure is the Asmari Formation (dolomitic mudstones of Oligo-Miocene), which shows some oil-bearing sandstone reservoir layers near its top that are capped by the overlying anhydrite of the Gachsaran. The Asmari Formation here contains relatively heavy oil whereas Fahliyan accommodates light crude.

In Doroud # 2 well the thickness of Asmari is variable and ranges between 82 to 199 meters. Therefore the pay zones of the field are Ahwaz sandstone member with 21° API oil with 3.5% H_2S and ultimate recoverable reserve of 200 MMB, Fahliyan Formation with 32.35° API oil and ultimate recoverable reserves of 0.975 MMMB oil and 6 TCF gas.

The new development project, which was aimed at boosting production by about 85,000 barrels per day by 2004, involved drilling 29 additional new wells, five of these offshore and building new onshore facilities. These facilities have now been connected to two offshore wells which were brought into production in May 2002.

IM-D-1 IMINICO

This abandoned well was drilled by IMINICO in 1965 in order to prospect Khami and Kazeroun Groups to a total depth of 3942.5 meters in Aghar shale member of Dashtak Formation. The main goal of drilling for well # D-1 was to obtain stratigraphic data and correlate the beds with the corresponding hydrocarbon bearing levels in the adjacent wells. No significant commercial hydrocarbons were discovered but some extra-heavy oil was recovered from Fahliyan and Surmeh Formations.

Esfandiyar

The Esfandiar Field is located in the Persian Gulf 95 kilometers southwest of the Kharg Island and 30 kilometers northwest of Foroozan Field in a water depth of 45.7 meters. The field is the northeast extension of the Lulu field in the Kuwaiti-Saudi Arabian Partitioned Neutral Zone, about 18 kilometers south of the Soroosh oil field. The locations of all the fields mentioned here are presented in figure 9-2.

The Esfandiar Field was discovered with the drilling of Esfandiar-1A by the Iran Pan American Oil Company (IPAC) in July 19, 1965. The well is reached a total depth of 4007.9 meters in the Lower part of the Lower Jurassic Surmeh Formation. The well tested oil at a rate of 4060 to 4200b/D with 31.5 API gravity on ½" choke from the Lower Fahliyan carbonate over the interval 2734.5 to 2750.7 meters. A delineation well was drilled in 1966 and later in 1992 another well was drilled and 2D seismic acquired. Preliminary studies indicate that OOIP is between 220 to 491 bbls the Fahliyan (RD=8865ft, Θ=21%) with potential in Kazhdumi and Surmeh reservoirs.

Producing horizons are Kazhdumi's Azadegan Sandstone member (Burgan "A" sand) and Fahliyan Formation (Lower Cretaceous). The first well showed potential of 3MMD of 30° API oil but two other delineation wells have not proved the same results. Fahliyan limestone (and the Lower Cretaceous Ratawi) is also oil producing with 30° API.

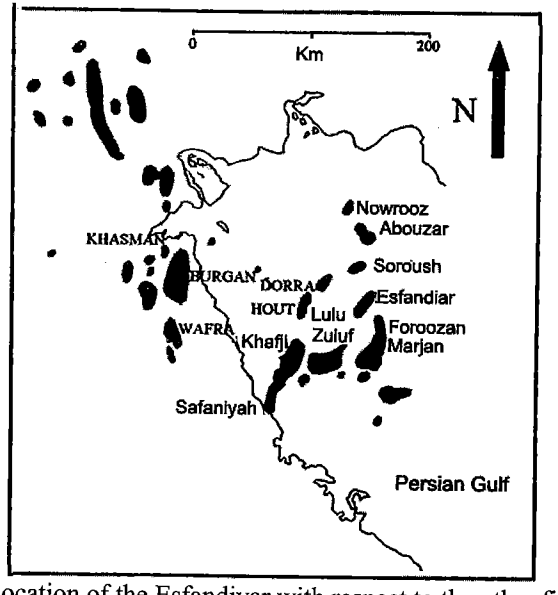

Figure 9-2. The location of the Esfandiyar with respect to the other fields in the Persian Gulf.

The Esfandiar structure is an anticline feature associated with the Foroozan and Doroud trend. This is a generally north-south trending elongated closure with four-way dipping feature covering an area of about 340 km^2. However, the proven reservoir is only distributed around Esfandiar-1A in the current trap configuration covering approximately 4.5 by 2.5 kilometers.

Lulu-1 well is located 16 kilometers southwest of Esfandiar-1A well in Saudi Arabia (see Figure 9-2). It was drilled by ARAMCO on February 15, 1967 to a depth of 2861 meters in Yamama Formation. No clear information is available about this well but it is reported that the Yamama carbonate has 23.5 meters oil column with OWC at -2763 meters. Lulu-1 flowed at a rate of 2000-3000 BD of oil on test.

Esfandiar-2 well was drilled to total depth of 3000 meters. The well was drilled to a total depth of 3192.6 meters in the Gotnia Formation (Hith Formation). It yielded only 5-10 bbls of oil with 18.5° API gravity from the Azadegan sand and also 469 meters of oil mixed with water (32.2° API) from the Fahliyan reservoir. A test of the Lower Fahliyan member indicated that the equivalent reservoir is tight. The well was subsequently plugged back and abandoned.

There are two members of Fahliyan Formation forming reservoir rocks in Esfandiyar field which are the Lower Fahliyan (Zone-1) and Upper Fahliyan (Zone-2). Zone-1 of Fahliyan reservoir is a carbonate unit composed of wackestone to Packestone. It is interbedded with thin shales and seems to have been deposited in shallow waters and high energy carbonate platform environment. Porosity consists of both intergranular and vuggy components. This member is approximately 16.5 meters thick in Esfandiyar-1A but thins drastically to the south of the Esfandiyar-2 and 3 wells where only shaly carbonates with poor reservoir properties are developed. As a result, it appears that there is an up-dip pinch-out of reservoir somewhere between Esfandiyar-1 A and E-3.

The Fahliyan Zone-2 is the other reservoir present in Esfandiyar field. It is approximately 61 to 122 meters thick. The section becomes even thicker toward the south of Foroozan field. The lithology of this zone consists of wackestone to packestone with reefal and other bioclastic materials predominantly in a chalky and fine-grained matrix with large vugs. Some fracture porosity is also evident.

The most upper part of the Fahliyan Formation is generally saturated with oil but it is very tight. Drill stem test (DST) across Fahliyan Formation (zone I and II) and Azadegan sand of lower Kazhdumi were carried out and indicated non-commercial oil for both of the mentioned reservoirs.

An Esfandiyar pilot project was expected to produce 6,000 b/d through two wells tied back to the nearby Foroozan platform. Further development was anticipated, with a target output level of 60,000-70,000 b/d to be directed via Foroozan processing facilities.

Farzad-A (Former Farsi A or FA)

The structure is located 13 km north of Farsi Island. This is an asymmetric growth anticline with axial direction of east-west with steep dipping south flank. Well # FA-1 located some 115 km southwest of Bushehr and 125 km south of Kharg Island proved the presence of heavy oil in Jahrum Formation and extra-heavy oil in the Gurpi and Ilam Formations.

Well # FA-1 was the discovery well drilled by FPC in 1966. Stratigraphic horizons encountered in this well include Fahliyan, Hith, Surmeh Formations (i.e., Mond member). The aerial and vertical closures on Hith Formation are 300 km^2 and 500 meters respectively.

Farzad-B (Former Farsi-B-1 or FB-1)

The structure is located about 124 km southwest of Bousher and 136 km south of Kharg Island, discovered in 1966 by Farsi Petroleum Company. Farsi-B is an elongated anticline with north-south axial direction with growth origin, with a Turonian age. It has emerged out of water and caused truncation

of part of the Sarvak Formation and an angular unconformity between lower and upper Cretaceous sequences.

The aerial and vertical closures of the faulted zone at Hith anhydrite level are 15 km and 30 meters respectively and 400 km^2 and 870 meters were calculated for the original structures.

FB-1 was drilled under the seabed and in 55 meters of water down to a depth of 3158.8 meters in Triassic Kangan Formation where gas was recovered, extra heavy oil discovered from sea floor down to the Sarvak Formation, semi solidified grading to solid bitumen was reported from top to the base of Dariyan Formation. Dariyan shows a thickness of about 123 meters in this structure. In addition, only some asphaltic material was recovered in Asmari, Jahrum, Gurpi, Mauddud and Kazhdumi Formations. In Farzad-B, Deh Ram reservoir contains approximately 12.5 TCF gas and 256 MMb of condensate in place.

Farsi-C-1 (FC-1)

The well is located at about 78 km southwest of Bousher and 36 km northeast of Farsi Island. This geophysical structure is located NNE of Farsi Island. FC-1 was drilled in 1971 by FPC to a depth of 3091.5 meters and recovered small amount 31° API oil from Ilam Formation. The thickness of the Ilam and Laffan Formations were measured at 76 and 12.5 meters respectively.

The presence of extra heavy oil and asphalt were indicated from Jahrum, Dariyan and Fahliyan Formations, but Surmeh was water bearing. Total depth was 3091.5 meters in the Surmeh. The thickness of Dariyan Formation was about 131 meters whereas Asmari Formation shows 30 meters thickness.

Fateh Field

Since Fatah field has many similarities with the Persian Gulf's Sirri A, B, C fields in the Iranian waters, here the general description of the field has been presented. The field has 2.5 billion barrels total original oil in place produced from the Upper Sarvak Formation. The Upper Sarvak has almost 70% of the total original oil in place (Videtich et al., 1988).

Fateh is a giant oil field located in the southern Persian Gulf in offshore Dubai with ultimate reserves of 2.3 billion barrel of oil. Discovered in 1966 and went on stream in 1969 by Dubai Petroleum Company. Fateh-1 well was drilled to 3694 meters, in water depth of 39.6 meters, and tested 2,524 bopd.

Most of the production is from the Upper Sarvak (i.e., Mishrif member), which consists of a large rudist reef complex that grew on a gently dipping ramp and from the Upper Cretaceous (Santonian) Ilam Limestone. Fateh field is a domed structure caused by salt movement during the Cretaceous. The superior quality of Upper Sarvak reservoir is attributed to the effects of post-Cenomanian diapiric salt movement.

Ferdowsi Heavy Oilfield (Formerly F)

The Ferdowsi structure is located in the central part of the Persian Gulf (Iranian sector) approximately 88.5 km offshore of Iran and 193 km SSE from Busherh port. This domed structure is located in southern gentle slope of the Persian Gulf Basin west of south Pars, south-southwest of North Pars.

Discovered in 1965 by IRAPCO, well # F-1 was penetrated down to the Surmeh Formation to a depth of 2319 meters. Well # F-2 was also completed in the Dehram Group. Because of the lack of complete production tests and PVT results, there is no exact data about the chemical constituents, well behavior and also reservoir conditions. This is proven by 61 DST tests that there is a huge amount of heavy oil reserves in the encountered Formations.

The pay zones are the Fahliyan Formation with 8-10° API oil and the Upper Surmeh with 6-16° API. The Lower Cretaceous with 770 meters of oil column, 366 km^2 areal closure, 20% porosity and 40% water saturation is expected to be one of the largest extra heavy oil reserves of Iran. Approximately 10 TCF of gas in place and related condensate were expected from Deh Ram Group.

The first marine seismic survey started in 1963 and completed in 1964. The principal horizons identified as follows; 1) Lower Miocene, 2) Eocene, 3) Middle Cretaceous, and 4) Jurassic. The second 2D seismic survey carried out in 1989 through 1990 and as a result four horizons had been interpreted and mapped in the area; 1) Top of the Jahrum, 2) Top of the Turonian Unconformity, 3) Top of the Surmeh and 4) Top of the Dehram Group. There are five layers from Khami group in Ferdowsi offshore field with their basic reservoir engineering (see Table 9-3).

Table 9-3. Reservoir engineering of different layers of the Khami Group encountered in Ferdowsi offshore field, Persian Gulf.

Formation	Ferdowsi #1	Ferdowsi#2	Bulk volume	OIIP
	Subsea (m)	Subsea(m)	(MMBBL)	(MMSTB)
Dariyan	1299.6	1192.6	55719.96	222.96
Gadvan	1452.6	1343.5	23293.1	0
Fahliyan	1549.5	1427.3	126928.09	1783
Surmeh	1753.1	1633	58441.53	125.82
Jubaila	1953.7	1840.3	---	---

Foroozan (Formerly Fereydoun)

Foroozan oil field lies in the Persian Gulf 100 km southwest of Kharg Island straddling the sea boundary with Saudi Arabia. This field is an extension of Saudi Arabia's Marjan field (see figure 9-2). It has been in production since 1974. Discovery was made in 1966 by IPAC. Reservoirs include Ahwaz sandstone member with 22° API oil and Fahliyan and Surmeh Formations with 30° API oil.

The field lies on the northeastern flank of a very large domal anticline. The anticline straddles the offshore border between Iran and Saudi Arabia. The Iranian portion of the field is named Foroozan (formerly Fereydoun), whilst the Saudi Arabian part of the field is called Marjan. Thus, the Foroozan and Marjan oil fields are of one large structure which appears to share original gas-oil and oil-water contacts. Marjan oilfield began oil production in the mid 1970's.

In 1980, Foroozan oil field average production was 54 MBD. By the end of 1980 the field had cumulative production of 170 MMB. The estimated recoverable oil reserves are 4 MMMb and with Marjan probably reach to 10 MMMB. Production in 1998 amounted to 50,000 b/d. Reserves were also estimated at 890 million bbl. According to NIOC, producing reservoirs could be developed further, while some reservoirs had not been developed and could yield an additional combined 40,000 b/d. Reservoir studies indicate that production from the Dariyan and Fahliyan can be optimized while other horizons such as the Surmeh and the large gas cap remain undeveloped (Motiei, in press).

In common and comparing with other large domal anticlines in the Persian Gulf region, Foroozan structure was formed by halokinesis of the underlying Hormoz salt during the early Tertiary. Salt movement created very gentle anticlines with intervening salt withdrawal and fault collapsed synclines. The primary reservoir in the Foroozan field consists of fluvio-deltaic sandstones of the Late Cretaceous, Lower Kazhdumi (Azadegan Sandstone member). The Azadegan Member (i.e., Burgan member) in Foroozan field is divided into a lower massive sandstones unit designated Burgan-B equivalent and an upper shaly unit designated Burgan- A equivalent.

Foroozan produces from 3 reservoirs: Kazhdumi (Azadegan sand member, RD=2043 m, Θ=24%, GOR=650 cf/brls, sweet oil with Gr= 29.4°), Dariyan (RD=2149m, Θ=18.5%, GOR=590 cf/brls, sweet oil with Gr= 29.4°) and Fahliyan (RD=2438m, Θ=12.4%, GOR=600 cf/brls, sour oil with Gr= 34°). Kaveh et al. (1971) described some of the stratigraphic complications encountered in the Kazhdumi and Surmeh (Gr=30°).

A pilot well was drilled to establish the fluid contact levels in Azadegan sandstone Member and lower Dariyan reservoirs. The Azadegan sandstones showed essentially no oil column and approximately 30 meters of oil column found in Lower Dariyan reservoir.

Additional reservoirs in Foroozan field include the sandstone belonging to the Upper Azadegan Member and also carbonates of lower Sarvak, Dariyan, Fahliyan and Surmeh.

Forooz B (Former Farur B-1 or FRB-1)

The well FRB-1 is located some 55 km southeast of Kish Island and 40 km west-southwest of Farur Island and drilled in 1968 by FPC down to total

depth of 3162 meters. The oldest Formation encountered in this well is the Surmeh Formation. The Asmari-Jahrum Formation and all the other carbonate horizons including those of Bangestan and Khami are containing water. Table 9-4 shows the formation drilled in this well with their respected thickness and lithology.

Asmari Formation consisting of alternation of dolostone and limestone layers which is encountered at depths between 899 to 1192 meters. Microfacies reported in the well include mudstone, bioclastic wackestone/packstones, peloidal wackestones and gainstone with anhydrite cements filling the intergranular porosity. The well was abandoned as a dry hole.

Table 9-4 Formation and lithologies in FRB-1 well in the Persian Gulf

Formation	Lithology	Thickness (m)
Asmari	Micritic ls, with Globigerina, Tricolina	291
Jahrum	Micritic ls	171
Pabdeh	Argillaceous ls., with shale and marlstones	327
Gurpi	Shales and calcareous shales	83
Ilam	Micritic limestones with Rotalia	104
Laffan	Shales with Ostracodes	16
Sarvak	Mauddud and Ahmadi Mmbs are present	144
Khazdumi	Shales with traces of orbitolina	49
Dariyan	Micritic , mudstone to wackestone, orbitolina ls.	139
Gadvan	Argillaceous ls. Khalij Mmb present	43
Fahliyan	Dolostone, dolomitic limestone to micrtitc ls.	424
Hith	Anhydrite	39
Surmeh	Micritic limestones with Pfenderina	444

Well FR-A1 is located on the western flank and very close to the crest of the seismically defined FR-A structure some 26 km east-northeast of FRB-1. Drilling in this area established gas and oil in the structures. The FR-A anticline is a domal structure and seems to be related to the PreCambrian salt movements. The Asmari Formation has a gas column of about 31 meters with good porosity and permeability. Its gas/water contact is at 1202 meters.

Golshan (Former DOPCO or G-Structure)

The field is located 50 km west of South Pars and 180 km southeast of Port city of Bushehr. The well G-1 was drilled by DOPCO in 1966 down to where the Surmeh Formation was encountered. Well G-2 which is located 6 km from G-1 was drilled in the same year. Tar and extra heavy oil were reported from Jahrum down to Surmeh Formation alternatively.

G-Structure and B-Structure in the northern Persian Gulf offshore portion of Iran produce gas from the Kangan/Dalan reservoirs. B-Structure gas field has an estimated recoverable reserve of 50 TCF of gas (8.3 BBOE); median field size calculated from the two fields is 17.0 TCF.

Well # G3 and G4 were drilled by NIOC after additional geophysical data were available. These wells penetrated the Silurian shales and other reservoir layers in the Kangan/Dalan and Faraghan Formations were discovered. They are gas bearing with original gas in place of 40 TCF and condensate in place of 0.7 MMMB. Table 9-5, shows the thickness of some of the Formations covered in G#3 well.

Table 9-5, Thickness (in meters) of the Formations in G#3 well.

Well	Ilam	Laffan	Upper Sarvak	Middle Sarvak	Lower Sarvak
G#3	113	37	23	43	36

Haman (Former H-Structure or IPAC-H-1)

The structure is located 50 km NW of Kharg Island. Exploration well No # H-1 was completed by IPAC in 1969 at total depth of 174 meters in the Fahliyan Formation. The "H" structure has a domal shape uplifted by a deep-seated salt flow (Bashari, 1988). Evaluation of different seismic horizons indicated thinning of the beds over the structure. This is based on the assumption that uplifting began in the Triassic and continued through Cretaceous and Tertiary. The 3H exploratory well was drilled to evaluate possible hydrocarbon in the "H" structure. According to Bashari (1988) the primary objectives were:

- Lower Cretaceous limestones of Dariyan and Fahliyan;
- Upper Jurassic limestones and dolostones of Surmeh Formation;
- Middle Jurassic limestone;
- Triassic and Permian porous section.

Secondary objectives were limestones of the Asmari and Sarvak Formations. No commercial hydrocarbon was recovered.

Hamoon (Former LAPCO, 3H- Structure)

This structure is located in the east of South Pars gas field and north of Balal field. The structure is a roughly domed shaped growth structure with a slight elongation in a northwest-southeast direction proved by geophysical prospecting. The structure seems to have been the result of salt intrusion. The structure on the upper Jurassic horizon is approximately 12.87 km long and 9.66 km wide.

Discovered in 1967 by LAPCO in the exploration 3H-1, 18° API oil from the base of Asmari, 20° API oil from Lower Sarvak, heavy and extra heavy oil from Dariyan Formation were discovered. In addition minor amount of extra heavy oil was reported from Jahrum and Gurpi Formations. Wells No # 3H-2 and 3H-3 were also drilled in the structure. The sedimentary sequence drill in this area contains rock from Recent to Dalan Formation. The stratigraphy of the 3H-1 well is presented in Table-9-6.

Table 9-6.The stratigraphy of the 3H-1 well in the Persian Gulf.

Formation	Lithology	Thickness (m)
Asmari (middle and upper parts)	Packstone, grainstones, oolitic/pelletic biomicrtite and biospirites	85
Jahrum	Siliceous Dolostones, Glauconite at contact with Sarvak	536
Sarvak	Micritic ls. With Gluaconite on top.	126
Khazdumi	Shales with glauconite with no fossils	47
Dariyan	Micritic ls, mudstone to wackestone, orbitolina ls.	98
Gadvan	Argillaceous and Micritic ls. With Khalij Mmb presence	50
Fahliyan	Dolostone, dolomitic limestone to micrtitc ls.	195
Hith	Anhydrite	32
Surmeh	Dolostone with Lithiotis at base, Pfenderina trochoidea	610
Neyriz	Dolostone with shale interbeds. Lithiotis on top.	17
Dashtak	All the members from Aghar shale to evaporite D present	346
Kangan	Dolostone with anhydrite on top	170
Dalan	Nar Mmb and upper carbonate, *Staffellidae*, *Globivalvulina* sp. are present	354

Hengam (HE-E1)

This structure is situated some 50 km south of the Qeshm Island in the eastern part of the Persian Gulf. This elongated anticline with north-south trend parallel to the Arabian trends has been affected by high throw fault along its eastern flank. The Hengam hydrocarbon accumulation within the Sarvak Formation was discovered in the year 1975. The well # HE-E1 which was drill to a depth of -3786 meters encountered gas/condensate and the test produced 2,906 BCDF of 43.3° API. The GOR was 4600 SCF/BBL. The Hengam structure straddles the Persian Gulf Median line between Iran and Oman. Subsequent wells drilled in the Omani side had produced disappointing results.

HE-E1 tested 3 MBD 41° API oil and 13.5 MMSCFD gas with 60 ppm H_2S from the Sarvak Formation. The isopach of the Ilam-Sarvak ranges in thickness from about 250 meters to just below 100 meters. At HE-E1 the combine thickness is 229 meters. The Ilam-Sarvak reservoirs display some porosity and excellent permeability in HE-E1. The reservoir in the Hengam area comprises fine-grained low porosity limestones with low matrix porosity, while good permeability in the HE-E1 is believed to be due to reservoir fracturing.

Despite poor porosity of the Ilam-Sarvak reservoir observed in HE-E1 which is located on the horst part of the structure, a high oil and gas productivity during DST had been indicated. This demonstrates that the reservoir is highly fractured in the horstal part of the structure. At Hengam HE-E1 well, the structural configuration is clearly a horst shape and poor seismic data is caused by the intensity of faulting and fracturing of the Ilam-Sarvak reservoir.

One must bear in mind that the Ilam Formation can not be distinguished from the Sarvak Formation since the Laffan shale that would separate the two Formations is extremely thin in Hengam area and often is only less than two meters thick or even may not be present.

It is of importance mentioning that the uppermost member of the Sarvak Formation correlates with the Mishrif limestones seen in the Sirri fields. However, unlike the Sirri fields a clear development of the Laffan shale which serves as the main seal or cap rocks has not been observed in Hengam field. In this field the Gurpi shales form the seal as observed in the well correlation across Hengam area. In the HE-E1 well the lithology beneath the top of the Dariyan is composed of tight limestone with very low primary porosity. The porosity in Dariyan Formation is mainly secondary and it reaches 10%.

The structural evolution analysis of the Hengam field was performed by Fugro-Jason (2003) using cross sectional restoration and analysis of isopach maps of numerous intervals. The result of the structural analysis demonstrates that at the time of Upper Cretaceous deposition, Hengam structure had rather graben geometry with thicker Upper Cretaceous Gurpi deposition within the graben. The Tertiary compressional movement has produced an inversion of the graben and produced Hengam field with thick Gurpi Formation at the crest of the structure.

The Hengam structure appears to be faulted and seem to consist of a series of normal faults that have been reactivated during the compressional tectonic phase related to the Oman uplift commencing in the Late Cretaceous. Thus, it appears that faulting has played a key role in controlling the structural spill point but most importantly it has major significance for the Hengam structure where the Ilam-Sarvak reservoir can be highly fractured.

The abrupt thickness variations around Hengam HE-E1 discovery could be due to the tectonic activity. In addition, the thickness variations of the Ilam-Sarvak limestone between bounding faults and the shoulder of the graben could be either related to the depositional setting resulting in thicker sediments in the graben or differential erosion.

HA-Structure

The HA structure had the highest priority in the former HOPECO exploration area; however it was drilled after the HD well due to technical difficulties. The field is located on the crest of an elongated domal high which has suffered only minor faulting at its crestal part.

The seismic environment appears to be good, because the H-A structure is only slightly faulted and the sea floor is soft. The latest available depth map was calculated from the seismic 2-way time map using laterally and vertically varying velocity functions based on the seismic stacking velocity data base. The accuracy of the velocities has suffered due to seismic noise from the northeastern salt body.

HOPECO tested the Sarvak Formation with well HA-1 in 1975 and it was proved the formation to be hydrocarbon-bearing. The rock formations in this well aging from Recent to Dariyan. The Sarvak and Dariyan Formations have good reservoir quality at HA-1. About 73 meters of *orbitolina* limestones of Dariyan Formation have been drilled in this well. In addition the thickness of Kazhdumi is about 110 meters.

The areal extent of the HA-Structure is some 9 km by 14 km. Vertical closure is 173 meters. The Sarvak Formation at this location consists of light colored soft chalky limestone which becomes more argillaceous, darker and harder towards the base. Mud losses and lost circulation during drilling may be attributed to the softness of the drilled rocks or due to fracturing. There was no observed visible porosity.

The results of structural analysis demonstrate that during the Upper Cretaceous time deposition the Hengam structure was rather had graben geometry with thicker Upper Cretaceous Gurpi deposition within the graben. It is believed that most of the present Hengam structure originated during upper Miocene compression. Thus, the Tertiary compressional movement has produced an inversion of the graben and produced Hengam field with thick Gurpi Formation at the crest of the structure.

In this area Gurpi shales with an approximate thickness of 340 meters form the seal as seen in the well correlation across the Hengam area. It is important mentioning that the separation of Gurpi shales from Tarbur is not possible in this area. A mixture of the Pabdeh and Jahrum facies are drilled in this area in the eastern part of the Persian Gulf. The sediments are separated by an unconformity surface from the underlying Gurpi and Tarbur Formations. Asmari carbonates have also been deposited locally in this area.

From the porosity logs it appears that the average porosity for the Sarvak Formation is reaching 6%. Thus, it can be regarded as a potential reservoir, especially if the lateral and vertical communication within the reservoir is enhanced with an acid treatment.

Based on the information from the seismic lines, it appears that the Ilam Formation pinches out on the flanks of the structure. However, the Dariyan Formation seems to be completely untested and may be offering some further potential.

A seismic velocity survey shows that a pronounced lowering of velocities below the depth of 1828 meters indicating the need for an accurate velocity model in order to avoid errors while converting maps from time to depth.

Hormoz-A (Former HOPECO, HA)

Hormoz-A structure is located in the southeast-east of Hengam Island near the median line of Iran-Oman. Discovery well HA-1 was completed in 1976 by HOPECO. The recovered 49° API oil (4256-4436MDD) at a rate of 700 b/d and gas at a rate of 4 MMSCFD are both from the Sarvak Formation

(4256-4436meters). In addition some gas and gas condensate was recovered from Dariyan Formation (4561.4-4635 meters).

Two main bounding fault systems could have compartmentalized the Ilam-Sarvak reservoir observed in the Hengam structure. The important variation in the permeability of the Ilam-Sarvak reservoir is due to fracturing of the reservoir. Thus, fracturing has played an important role in the Sarvak reservoir characterization and enhancement of porosity and permeability. The fracturing of the reservoir is related to the structural style of the deformation at the reservoir level.

Hormoz-B (Former HOPECO, HB-prospect)

The HB-structure is located to the southeast of the Larak Island in the eastern part of the Persian Gulf. It follows the Oman Mountain structural trend. Gravity modeling has shown that Hormuz B prospect is not a basement structure. The thick underlying sedimentary successions include the Devonian and Silurian clastics; the Permian-Early Cretaceous section is thought to be more than 3000 m thick.

A depth map of the unconformity level at 3000 meters indicates that the HB-structure is an elongated closure bounded by a reverse fault on its western flank. The structure covers 29,000 acres. As mapped, the structure's potential can be taken to be high with several hundred million barrel reserves.

The prospect's liability is the erosion which is thought to increase regionally towards the east, and could affect prospect B more than the prospects already drilled.

Seismic data is of excellent quality down to the "green horizon", but the reflections from the possibly underlying reservoir rocks are distorted by diffractions originating at the unconformity.

Hormoz-D and F (Former HOPECO HD and HF Structures)

The Larak salt complex consists of two central diapiric stems, on the east and western shores of Larak Island, and a shallow widespread salt overhang extending to a distance of 20 to 50 km offshore around the Island. Prospects HD and HF are located on the northeast and southwestern corners of the salt overhangs. It is not certain how far the fields extend underneath the salt overhang, because of lack of seismic resolution to solve the reflections from the salt body and the underlying reservoir rocks, and possible lateral variation of seismic velocities.

The well HD-1 tested the northern part of the mapped HD-structure. The youngest drilled sediments are Recent age while the oldest rocks encountered in the well belong to the Fahliyan Formation with a thickness of 430 meters. Argillaceous limestones of the Gadvan Formation cover 90 meters of the rock sequence. The Khalij member is also encountered in this well similar to the

Kharg Island. In this general area the Sarvak Formation is represented by its Lower part (i.e., Mauddud member).

The well found that the Dariyan Formation as being hydrocarbon bearing and was subsequently tested resulting in modest oil flows with some water. The thickness of the Dariyan Formation is 110 meters here and consists of micritic limestone, mudstone and wackestone. Well log evaluation indicates that the maximum secondary porosity is about 6% whereas the total porosity reaches 12%.

After drilling the HD-1 well, based on the information obtained, the HD-structure could further be divided into two separate closures. The northern one, which was tested, appears to have a fairly thin and apparently contains uneconomic accumulation of oil. Reserve estimates for this accumulation are of the order of 6 MMBO.

The HD-south structure, which plunges underneath the salt overhang, might offer some sizeable reserves providing that the clean carbonates of the Dariyan Formation increases in thickness basinward, and lateral and vertical reservoir parameters enhance at the same time. Currently, there is very little information to support such as assumption. Consequently, the recoverable reserves of this structure might vary from nil to almost 300 MMBO depending on the parameters used. Therefore, the structure remains as a high risk wildcat play the best at this time.

The HF-Structure is located on the southwest side of Larak Island. It remains untested to date. The areal closure as mapped is 12100 acres, but if the same oil water contact as seen in HD-1 wells is used, then the closure diminishes to 3600 acres. Furthermore, there still remains concern about the validity of the closure under the salt overhang.

The HF-Structure still offers another high risk exploration target for the Dariyan Formation. Recoverable reserves, as currently mapped, may be in the order of 50-75 MMBO.

Hengam E Field (HEE)

The central part of the field lies in what was then designated block K. The field straddles the boundary, and the Iranian sector was explored by Sofiran. The Hengam field is the shallowest Lower Cretaceous structure in the area. The heavily faulted anticline shows a well pronounced elongation along the Oman uplift trend (approximately north-south). The surrounding synclines, and a crestal graben in the southern part of the structure, support the theory that the structure was induced by a deep salt ridge.

Seismic mapping of the central part of the Hengam structure is mainly based on a 48-fold seismic conducted in 1974. The main structural features at the top of the Sarvak Formation were interpreted to be similar to the underlying Dariyan Formation, supporting the notion that the Sarvak Formation is not eroded. Post-drilling findings of the fault pattern have changed the previous

interpretation and seems to indicate a lack of seismic resolution; however, more seismic sections should be inspected for quality.

The discovery well HeE-1 was drilled in a crestal horst block. In addition hydrocarbon-water contacts could vary in the fault that separated field blocks. The structure was tested (2,096 bopd, Gr =41°), by well HeE-1 in 1974 and found to be hydrocarbon bearing in Sarvak Formation. The average porosity of the Sarvak and Ilam Formations is ranging from 1 to 3%, whereas Dariyan, Gadvan and Fahliyan Formations are very tight and average porosity varies between 2 to 3% and salt water-bearing.

The discovery well was not drilled on the crest but on the NE-flank of the structure as later indicated by the dipmeter logs (15° dip due NE). However, there are some concerns about the true structural dip because of the structure's heavily faulted nature.

Assuming the reservoir to be filled to spill, the OOIP could be in the order of 1200-1300 MMB of condensate, which approximately two thirds is in the Iranian waters. Recoverable reserves are estimated to be 80-120 MMB of condensate and 3.5-4.0 TCF of gas.

The upper most part (10-15 meters) of the Dariyan Formation might also have reservoir quality. Also on the well logs, it appears to be hydrocarbon saturated, but rather tight. However, there were some mud losses while drilling suggesting some porosity and permeability development. No tests were run in this formation.

Hendijan

This is an offshore field is located 35 kilometers south of Hendijan town and about 10 kilometers southeast of Kaparha village and north of Bahregansar offshore field at the head of the Persian Gulf. The most northern portion of the field is located in the marshland and coastal area. Hendijan oil field produced 8,000 b/d of oil, with output delivered to nearby Bahregansar field for export.

The Hendijan structure is a small anticline with a north-south trending axis. It lies on the same trend as Nowrooz-Bahregansar and 10 km north of Bahregansar structure. Due to its proximity to the Bahregansar structure no facies changes are expected.

Production from four reservoir areas follows: Ahwaz (RD=2330 meters, Θ=18.5%, Gr=30°, GOR=876 cf/brl); Asmari (RD=2450 meters, Θ=11.6%, Gr=28°, GOR=799 cf/brl); Sarvak (RD=2970 meters, Θ=9.6%, Gr=27°, GOR=392 cf/brl) and lower part of the Kazhdumi Formation (RD=3270 meters, Θ=16.5%, Gr=32°, GOR=1013 cf/brl). In the case of Sarvak Formation, fracturing has greatly attributed to the porosity creation.

Discovery was taken place in 1968 by SIRIP. Pay zones are Ahwaz sandstone member of the Asmari Formation with 31° API oil and Sarvak Formation with 25° API oil. The field went on production stream in 1971 and to

1980 averaged 7.7 MBD through 5 out of 10 drilled wells. The cumulative production in the same year was in the order of 50 MMB and ultimate recoverable reserve was estimated at 75MMB. NIOC aimed to appraise and develop the northern part of the reservoir with a view to raising output to 25,000 b/d.

Javan (Former IPAC, J-Structure)

The J-Structure is seismically defined and it is located about 10 km WSW of the Doroud oil field. Well J-1 was drilled in 1968 by IPAC in order to evaluate geological significance and hydrocarbon possibilities. The well was completed at total depth of 4016 meters about 5 meters in the Hith Formation. Water-oil contact discovered to be at 3758 meters in the Fahliyan Formation, visible hydrocarbon from Fahliyan were extra heavy oil to dead oil. The field was found non commercial.

According to the present data, the "Javan" structure might be a piercement type salt dome and uplift of this structure did not take place until late Tertiary. Thus, it can be concluded that this is a young feature with little oil showing.

Javdan (Fromer LAPCO, 3J)

The structure is situated about 10 km NW of Balal field (3W-2). 3J-1 well was drilled by LAPCO in 1968 in order to evaluate Jahrum Formation, also Bangestan and Khami Groups. The drilled sequences showed increased thicknesses comparing to Balal field.

It is thought that 3J is a salt core structure which might have occurred in the late Tertiary. This means that the structural forming has happened after oil migration period. Therefore, for this reason they contain only minor showing of hydrocarbons. The 3J-1 was abandoned as a dry hole.

Kish Structure

Kish Structure was defined by marine seismic work at the top of Asmari. Areal closure is about 32 by 25.5 kilometers and vertical closure is about 487.6 meters. Kish-1 is situated near the center of Kish Island on the crest of structure. Kish-1 was drilled in 1968 by IOC and PC (consortium) in order to appraise Tertiary, Cretaceous and Jurassic sedimentary sequence. The well was penetrated down to total depth of 2621 meters in the Surmeh Formation but no commercial hydrocarbons were found. Thus, it was abandoned as a dry hole.

Oil-staining was noted in carbonates of the Gachsaran, Asmari, Ilam, Hith and Surmeh Formations. However, the results of Schlumberger logs indicate that all these formations are water-bearing. Kish-2 was drilled in 2005 and large column of gas was found in Dehram Group.

Lalleh (Former IPAC, L)

The proposed well L-1 is situated about 11 km NE of Foroozan-8. The structural anomaly has been described as a closed prominent structural nose which plunges N-NE and raises southward to join Foroozan, however L-1 is structurally lower than Foroozan-8. The L-1 was drilled to total depth of 3065 meters in the Surmeh Formation. A column of about 18 meters of gas was distinguished in the Fahliyan and the presence of oil and gas in the Lower member of Sarvak Formation were recognized by electrical logs but due to some mechanical problems the interval was not tested. Ultimately, the well was temporarily abandoned.

Lavan-1

Lavan-1 is located on the crest of Sheikh Shueyb structure in Lavan Island. Lavan-1 was operated by IOE and PC and completed in 1961. The well was drilled to a total depth of 3184 meters in Dashtak Formation. Hot salt water flow was encountered with a surface temperature of 115° C, nevertheless a fish was left with top at 2861 meters (16 m inside 9 5/6" csg) and owing to unsuccessful fishing operation the well was plugged and abandoned.

Based on the information from this well, the Dehram Group of Lavan is gas-bearing. Estimated gas in place is about 5 TCF. In the year 2002 LN-1 was worked over and deepened to Dehram by NIOC exploration. Some specification of the Lavan well is presented in Table-9-7 and 8.

Table 9.7. Specifications of Lavan-1 Well.

Well No.	Well Name	Longitude (Φ)	Latitude (λ)	KB Elevation (m)	TD (m)	BHT (°C)	WD (m)	BMT (m)	Well Type
41	Lavan-1	53.2	26.82	42	3184	102.4	-34	8965	Suspended

1E-1

The structure is located between South Pars, North Pars and Kangan gas fields and the Lavan structure (including Lavan Island) with NW-SE axial trend. Well # 1E1 was drilled down to a depth of 2075 meters in Dashtak Formation in 1966 by LAPCO and completed as a dry hole.

Bitumen and dead oil stains were present in the Upper Jurassic and Lower Cretaceous carbonate successions but no significant shows of gas or oil were discovered. This structure possibly is the result of deep seated salt dome activity and surrounded by Kangan, North Pars and South Pars giant fields. Thus, exploration of the Dehram Group seems to be extremely promising and more geophysical prospecting is required.

Table 9.8. Formations characteristics in the Lavan-1 Well.

Stratigraphic Unit/Event	Depth to Top of Unit (Relative to KB)	Age (Ma)	Lithology Data
Kish Limestone	8	0	100% Limestone
Agha Jari	44	1.5	100% Sandstone
Mishan	547	10	100% Shale
Guri Mbr.	667	12	100% Limestone
Asmari	689	28.4	100% Limestone
Hiatus	795	32	—
Jahrum	795	41	100% Limestone
Pabdeh	934	57.8	90% Shale, 10% Limestone
Hiatus	1374	65.4	—
Gurpi	1374	68	95% Shale, 5% Limestone
Ilam	1397	82	100% Limestone
Hiatus	1461	86.5	—
Laffan	1461	87.5	100% Shale
Hiatus	1499	88.5	—
Sarvak	1499	90	78% Limestone, 22% Shale
Kazhdumi	1570	98	90% Shale, 10% Limestone
Hiatus	1613.8	112	—
Dariyan	1613.8	114.8	100% Limestone
Gadvan	1738.7	119	67% Shale, 33% Limestone
Fahliyan	1785.4	124	100% Limestone
Hiatus	2057.3	133	—
Hith	2057.3	146	100% Anhydrite
Surmeh	2148.7	150	91% Limestone,5% Shale, 4% Anhydrite
Neyriz	2772	190	85% Limestone, 10% Shale, 5% Anhydrite
Hiatus	2822	206.6	—
Dashtak	2822	210	80% Anhydrite, 20% Limestone
TD	3184	221	80% Anhydrite, 20% Limestone

M-1 (PEGOPCO)

The domal shaped M structure is located about 35 km south of Lavan Island. Well M-1 was completed in 1967 by PEGOPCO. The DST results showed that the Dariyan, Gadvan, Surmeh, Kangan, Dalan Formations were salt water bearing against presence of good porosities in the cited rock units except Kangan and Dalan which interpreted from electrical logs but in later formations porosity was reported to be less than 5%.

Extra heavy oil was reported from cuttings and cores of Asmari-Jahrum and also minor amount of gas was detected by gas chromatographer up to 520,000 ppm while drilling and tripping in the Dehram Group. The well was plugged back and abandoned.

Nowrooz Field

Nowrooz field lies in the northern Persian Gulf, 95 km southwest of Behregansar oil field and about 50 km north of Soroosh. This is the most southerly of the SIRIP discoveries near the head of the Persian Gulf. Agip, the former operator, discovered the field in 1967 and developed it in 1970 and till 2001 fifteen wells had been drilled.

The field is a NNE-SSW trending, elongated anticline structure, and with an areal extent of 62 km^2 and the crest of the structure is at 2230 mss with the estimated oil water contact at around 2337 mss. The structure is heavily faulted along the crest of the field. The largest fault displacement observed from the wells is 60 meters in well NR-11. A seismic map of the field has been presented in Figure 9-4

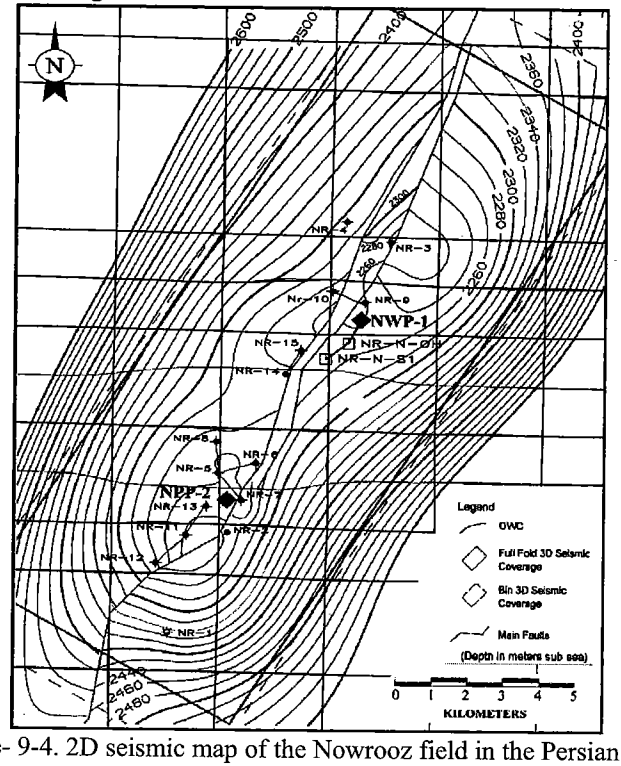

Figure- 9-4. 2D seismic map of the Nowrooz field in the Persian Gulf.

The producing reservoir is the Azadegan sandstone of the Kazhdumi Formation (RD=2286 meters, Θ=22.5%, GOR=508cf/brl, 20°$\leq$Gr$\leq$21°, S=3.6%),

and also the Khalij Member of the Gadvan Formation (RD=2560 meters, Θ=15%, GOR=560cf/brl, Gr=18° API oil. The amount of sulfur in this field's crude is 3.6 % with high density. The cases evaluated as non-commercial are in Dariyan and Fahliyan Formations. The field went on stream in 1971. Fifteen wells have been drilled on the Nowrooz structure producing 100 MMbbl between 1970 to 1980 with a maximum offtake of around 35000 bopd.

Palinowrooz-1 was a dry hole drilled in 1965 by SIRIP. The total depth was 4512 meters in the Butmeh Formation. The well is located in the NNE of Nowrooz oil field. However it was found off structure. In Palinowrooz and Nowrooz due to the presence of the paleohigh, the Sarvak Formation has been totally wiped out by erosion.

Nowrooz oil field was brought on stream in 1970 but damaged during the Iran-Iraq war. It was scheduled for renovation and further development. NIOC envisaged renovation of facilities and expansion to produce up to 90,000 b/d.; estimated of remaining reserves were 606 million bbl of oil. Ultimate recoverable oil reserves are estimated about 410 MMB. In 1988, all the productions were obtained from 14 wells through 4 platforms.

The field is estimated to contain 1.7 billion barrels, roughly 705 million barrels of which can be exploited. So far about 112 million barrels of it have been exploited. The field experienced considerable damage during the imposed war to the effect that its installations have been recognized as nearly useless with no possibility of undergoing repair. The project is aimed to develop the field to exploit 90,000 barrels of oil per day. Some of the reservoir specifications are presented in Table 9-9.

Table 9-9. Nowrooz Field, Kazhdumi (Burgan B) Reservoir Parameters

Original OWC in Meter Subsea	2337 to
Average Net Thickness(Feet)	180
Formation Volume Factor (RB/STB)	1.32
Initial Solution Gas-Oil Ratio (SCF/Bbl.)	515
Oil Gravity (Degrees API)	20-21°
Oil Viscosity at Reservoir Conditions (Centipoises)	0.73
Sulfur Content, by Weight	1.91%
Average Porosity	23%
Average Permeability (Millidarcies)	220
Water Saturation (Original)	11%
Average Productivity Index (BOPD/PSI)	92

In terms of reservoir description, the interpretation of depositional setting is relatively poorly understood in both Nowrooz and Soroosh fields with the Azadegan Sandstone being described in the literature as deposited in a range of environments, i.e. fluvial, estuarine, deltaic, shoreface and even turbiditic. In the absence of actual core and with limited core description information

there remains much uncertainty when modeling depositional trends and in the definition of lithofacies types.

Mobarak

The field is located 20 km east of Abu Mosa Island discovered in 1972 by SOFIRAN. The exploration well produced 14 MBD oil and 30 MMSCF gas from four producing zones in the Ilam and Sarvak Formations. But in well No# A-1 and B-1 the amount of production were reported 50 MBD and 32 MBD respectively. The Ilam oil is in the order of 35-36° API whereas the Sarvak oil is 45° API and H_2S content of both oil were reported as trace which could be ignored.

The field went on production in the year 1972 averaged 54-60 MBD which later was reduced to 13.5MBD in 1977, 6.4 MBD in 1983, and 5.9 MBD in 1985. Up to 1986 cumulative production was estimated at about 77 MMB and the remaining ultimate recoverable oil is estimated at about 10 MMB. At the end of 1980s some gas and gas condensate were discovered in the Fahliyan Formation.

"O" Structure

The O-structure is situated at about 45 km SSW of Lavan Island. This elongated north-south trending anticline is sliced through the central portion by few longitudinal faults forming graben complex and its growth nature could be recognized by increased dips proportion to the depth increase. Overall, the dip angle in the post Sarvak sequence is increased in the order of 5-8°, in the Sarvak to Neyriz 8-10° and in the Dehram Group 12-35°.

Well O#-4 BIS was drilled to a total depth of 3820 meters about 211 meters in the Faraghan Formation in 1974 but no hydrocarbon was discovered.

South Pars

In total, there were 14 giant gas fields discovered in the Middle East and Asia during 1990's, including four of the five largest discoveries of all regions, three of which are in Iran, the other being in Azerbaijan. The largest one, South Pars field of Iran, it is indeed the across-border extension of the supergiant North Field of Qatar in the Persian Gulf.

The South Pars gas field in the Persian Gulf is one of the largest known fields in the world, with reserves estimated at more than 7,000 billion cubic meters and 3 billion barrels of condensates. Gas reserves of the field have been estimated at 14 trillion cubic meters, 8% of the world proven gas reserves and 50% of Iran's gas reserves. In addition to the above-mentioned reserves, it is estimated that about 17 billion gas liquids and 5 billion barrels of condensate could be obtained from the field.

The South Pars field lies about 100 km off the south-west coast of Iran. The areal closure on top Kangan Formation is about 2200 km^2. This major gas field was discovered in 1970s, after determining that Qatar's North field extended into Iranian waters. Although it was discovered in the 1970s, this gas "giant" extending over 8,000 km^2 was only brought into production in 1991. It covers an area of 1,300 km^2 in a water depth of 65 meters. In Qatar, the Dome's Dalan/Kangan reservoir covers more than 6000 km^2 with the Qatari reserves of about 240 TCF of the structure's total 340TCF (AOG, 1998).

North Qatar Dome was officially discovered in 1971, but in fact several of the earlier offshore tests drilled by Shell to the Dehram Group which found gas, predate the official discovery date and are now taken to be part of this supergiant field rather than separate structure, e.g., Matbakh, Umm Al Irshan. However, the first well in the Iranian portion was drilled in 1991 by NIOC. Of course it was a delineation well referring to the North Dome and was an exploration well in the Iranian site.

South Pars gas in place was announced to be 108.24 TCF and recovery factor of 68% with amount of 35 Bbls of condensate per million gas production. Up until middle of the 1997 the total numbers of the wells were four and each well is able to produce 100 MMSCF/d.

Two small oil discoveries have been made on separate traps within the overall major structure of North Qatar Dome. There are:

1) Qatar marine B structure which is located on the NW flank of North Dome. The first was able to produce 1.4 MBD oil from Surmeh Formation but, appraisal wells were disappointing;

2) the KNA/NWD wells on the northeast flanks of North Dome. The extension of those pools in the Iranian part is not known.

Iran's largest non-associated natural gas field is South Pars, geologically is an extension of Qatar's 380-Tcf North Field, most likely the largest non-associated gas field in the world. The Dome is a structural culmination along the prominent, north-northeast trending basement controlled Qatar-Gavbandi Arch which divides the greater Hormuz salt basin into northern and southern basin. South Pars was first identified in 1988 and originally appraised at 128 Tcf in the early 1990s. Current estimates show that South Pars contains 280 Tcf or more (some estimates go as high as 500 Tcf) of natural gas, of which a large fraction will be recoverable, and over 17 billion barrels of liquids.

The South Pars field comprises the Dalan (Late Permian) and Kangan (early Triassic) geological strata, more than 3,000 meters under the sea floor and in 65 meters of water. The well SP#1 was drilled to a depth of 3522 meters down to the top of the Faraghan Formation. The Dalan and Kangan Formations attain a thickness of over 400 meters in the South Pars field forming a very extensive carbonate reservoir in the Persian Gulf. The Kangan/Dalan (Reservoir Depth (RD) = 2636 meters, $10.2\% \leq (\Theta) \leq 12.6\%$) permeability thickness is 1200 to 1800 meters, gas saturation = 60 to 80% and condensate yield=33 to 42 brls/mn cfg.

Dariyan Formation covers a large interval in this well and its thickness is about 110 meters, mainly consisting of wackestone. The porosity ranges from 20 to 35%. In spite of the fact that the total porosity is high but the maximum secondary porosity does not exceed 10%. According to the cross-plot of neutron and sonic logs the limestones of Dariyan are clean and the porosities are very high. The Asmari consisting of argillaceous limestone was encountered at a 376 to 426 meter depth.

Pervasive dolomitization has deeply influenced Kangan/Dalan reservoirs and their characteristics. Porosity and permeability shows substantial increase when large dolomite crystals are formed.

The Kangan/Dalan Formation (known as Khuff on the southern side of the Persian Gulf) comprises four reservoirs, named K4 (the deepest) to K1, separated by impermeable non-reservoir layers. According to Lotfpour and Adabi (2002) the reservoir characteristic and their distribution are facies controlled. There are distinctive diagenetic features and varied reservoir characteristics in the Lower Kangan unit.

North Pars

The near-shore North Pars gas field lies 120 km southeast of the port of Bushehr and 10 km northwest of Kangan port in the Persian Gulf. The field was discovered in 1965, and after South Pars, it contains the second largest gas reserves in Iran. A total of 17 appraisal wells were drilled (10m ≤water depth (WD) ≤30m), between 1973 and 1976 to delineate the Kangan/Dalan (Kangan Θ=10.6%, Upper Dalan Θ=11.3%). The field is elliptical with dimensions of 25 by 20 km. Original gas-in-place and recoverable gas are 59 and 47 TCF. The gas is lean (4brl/mn cfg) and contains H_2S (0.61 mol%) and CO_2 (4.96%).

The North Pars is a domal shape seismic structure under the flat sea floor beneath 20 meters of water. It was discovered in 1967 by DOPCO, but further development was carried out by OSCO till the year 1970. Production comes from Dehram Group. The ultimate recoverable gas estimated at more than 50 TCF.

The North Pars has estimated reserves of 1.4 Tcm of gas. In addition to South Pars, Iran's long-term natural gas development plans may involve: the 48-Tcf North Pars field (a separate structure from South Pars); the 6.4-Tcf, non-associated Dalan reservoir of the Salman oil field (which straddles Iran's maritime border with Abu Dhabi, where it is known as the Abu Koosh field); the 800-Bcf Zireh field in Bushehr province; the 4-Tcf Homa field in southern Fars province; the 14-Tcf Tabnak natural gas field located in southern Iran; the onshore Nar-Kangan fields, the 13-Tcf Aghar and Dalan fields in Fars province, and the Sarkhoun and Mand fields. The North Pars field could ultimately produce 40 Bcm per year.

"P" Pegopco Structure

"P" Structure is located 67 km southeast of Lavan Island and 60 km to the southwest of Kish Island. This NE-SW trending structure was defined by seismic in 1965. The most prominent tectonic features are effective graben on the crest of structure and limiting faults in the east and west of the structure. Gravimetric survey showed that there is no salt intrusion younger than Triassic.

Well No# P-1 was drilled by PEGOPCO in 1966 to a total depth of 2438 meters in the Mond member of Surmeh Formation. Unfortunately no tests were carried out due to log interpretation and the well was abandoned as a dry hole.

"Q" Structure

"Q" structure is located 70 kilometers south of Lavan Island and 80 km south of the Kish Island. This domal shaped anticline comprises an area of about 110 km^2 and 1000 m of vertical closures on the top of the Asmari Formation. Well No# Q-1 located on the southwestern flank and was drilled in 1967 by PEGOPCO. Normal sedimentary sequences were drilled down to a total depth at 2743 meters in the Mond member of Surmeh Formation but the upper part of the Sarvak was missing due to Turonian unconformity.

Formation dips from top of Sarvak down to Surmeh are constant and were measured at 15° S and 16°W. It has been suggested that a salt plug might have been intruded up to the Turonian unconformity below Laffan shale but there are no scientific significance to prove such a concept.

No commercial hydrocarbons were discovered through the tests and the well was abandoned as a dry hole. In the Q structure, the Kangan and Dalan Formation show the presence of gas.

"QSC" Structure (Sofiran)

"QSC" structure is located 25 km southeast of PEGOPCO P-1 and 50 km southwest of Kish Island, areal closure of 40 km^2 and vertical closure of 100 meters on the top of Bangestan were determined by seismic.

QSC-1 was drilled in 1975 by SOFIRAN in order to evaluate Bangestan and Khami Groups. The well was penetrated down to a total depth of 2861 meters in the Surmeh Formation. Traces of gas were discovered in the Asmari and Ilam whereas similar traces of oil and dead oil found in the Dariyan and Fahliyan accordingly. It is worth mentioning that extra heavy oil was reported in Hith. The well was abandoned as dry hole. The interpretation of petrophysical logs was not an indication of any significant hydrocarbon.

Resalat

The Resalat field is located some 25 km E-NE of Reshadat oil field, 90-95 km S-SE of Lavan Island, and 100-105 km SW of Kish Island (see figure 9-5). The structure was defined by seismic in 1965. Discovery well drilled by IMINICO (the Agip, Phillips and hydrocarbon India partnership with NIOC) in 1969 by exploration well ARK-1 drilled near the crest of the structure. Because most of the anticline folds are asymmetric, the drilled wells often missed the crest of the structure.

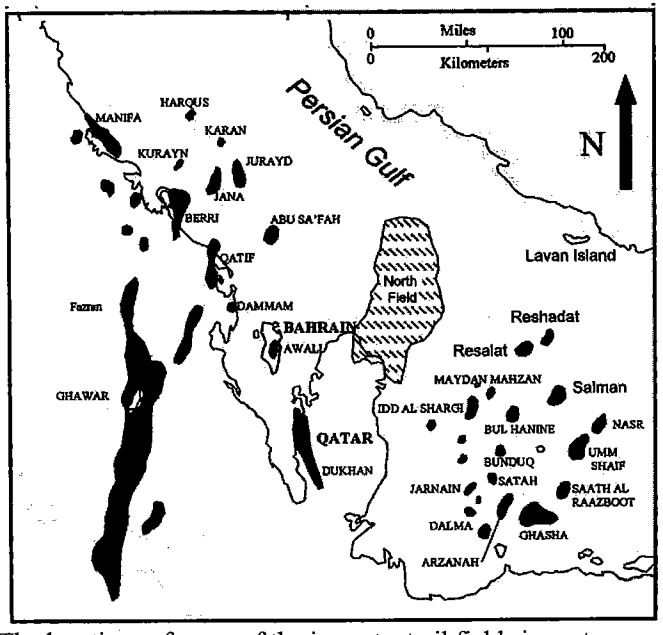

Figure 9-5. The locations of some of the important oil fields in eastern part of the Persian Gulf.

The field was appraised by a further seven wells and developed through eleven wells drilled from a single platform. Oil production from Resalat field commenced in 1971 and recovered 26° API oil in Dariyan and 34° API oil in Surmeh Formations.

By 1979 this oil field was averaging 20.744 MBD oil and by the end of 1980 it had produced total of 85.6 MMb from 17 wells and one platform. Recent information shows that only 14 wells are producing ones and 3 wells are abandoned. Ultimate recoverable reserves were estimated between 200 and 230 MMM. The remaining prospect for exploration is Dehram Group.

The structure of the Resalat field is defined by a set of perpendicular NW-SE and NE-SW trending synclines superimposed on a gentle anticline plunging to the east. In this oilfield the hydrocarbon production comes from the structural closures, at three different reservoir horizons which are:

- At the top Sarvak reservoir the closure is 33 meters and the areal closure is 18 km^2
- At the top Dariyan reservoir the closure is 41meters and the areal closure is 58km^2
- At the top Surmeh reservoir the closure is 70 meters and the areal closure is 106km^2.

Reshadat

This field was discovered by IMINICO (Agip, Phillips and Hydrocarbon India partnership with NIOC) in 1966 by exploration well #IM-R3 drilled on the crest of the structure. It is located in southeastern part of the Persian Gulf close to the median line with Qatar, 100-105 km SSW of Lavan Island and 130 km SW of Kish Island.

The oil production commenced from the Reshadat field in 1969. This was mainly from the Upper Sarvak, Dariyan and Surmeh reservoirs. The Upper Surmeh reservoirs were brought on stream in 1971 and 1972. Hydrocarbon productions from the reservoirs ceased in 1985.

On the Reshadat anticline structure, two NW-SE trending faults define a crestal graben. The structure is 22 km in length and 8 km in width with vertical closure of 40 meters for the Lower Sarvak Formation and Kazhdumi Formations.

Production principally comes from Dariyan Formation which contains 32° API oil and Surmeh with 37° API, but 26° API oil was found in the Upper Sarvak Formation. The average porosity of the Upper Sarvak is 20.19%. Deh ram gas reservoir was also found in 1974. Well #23 was drilled to a depth of 3635 meters reaching the Dalan/Kangan reservoirs. On the Reshadat field, deep exploration well R-32 drilled in 1974, discovered gas within the Dalan Formation. Asmari Formation consisting of coarse crystalline limestones with large dolomite crystals encountered at depth between 396 and 472 meters. Table-9-9 represents the Reshadat oil field stratigraphy at well R-32.

Total numbers of drilled wells were 32 while 5 of these wells were abandoned; two operating platforms are fulfilling average production of 11.211 MBD. By the end of 1980 fields production was at a total of 100.9 MMB. The ultimate reserves are estimated at 15.2 MMB to 3.25 BBbls.

Structural closures of Reshadat field at different reservoir horizons are as follow:

- At the top of the Sarvak reservoir the closure is 50 meters and the areal closure is about 76 km^2;
- At the top of the Dariyan reservoir the vertical closure is 85 meters and the areal closure is 113 km^2;
- At the top Surmeh reservoir the vertical closure is 112 meters and the areal closure is 145km^2.

- Finally at the top of the Dalan reservoir the vertical closure is 120 meters and the areal closure is 150km^2.

Salt diapirism has played a very important role in the formation of the trap and structure in this field.

Table 9-9. Representing the stratigraphy of the Reshadat oil field in the Persian Gulf based on the information form well R-32.

Formation	Lithology	Thickness (m)
Asmari	Coarse crystalline dolostones with *Elphidium sp.*	75
Jahrum	Dolostones with traces of anhydrite	605
Gurpi	Shales and calcareous shales with *heterohelix*	46
Ilam	Micritic limestones shale with Rotalia skourensis	100
Laffan	Shales with continental facies.	24
Sarvak	Mauddud at base, clean limestone with rudists on top.	187
Khazdumi	Shales with glauconite with Orbitolina	65
Dariyan	Micritic ls, mudstone to wackestone, orbitolina ls.	137
Gadvan	Argillaceous Micritic ls., with Khalij Mmb.	49
Fahliyan	Dolostone, dolomitic limestone with echinoids	352
Hith	Anhydrite	74
Surmeh	Limestone with Lithiotis fragments at the base, *Posidonia Pfenderina trocholina,* Upper part is Arab zone	744
Neyriz	Shale with dolostone and limestone interbeds.	17
Dashtak	Aghar shale and evaporite Arab B and part of C present	346
Kangan	Dolostone with shale on top and no fossils present	170
Dalan	Calcareous dolostone with a basal anhydrite, Hemigordius renzi evolutus, Globivalvulina, Gymnocodium	354

Salman (Formerly Sassan or Lavan 2S-1)

Salman oil field lies 150 km south-southwest of Lavan Island and 135 km southwest of Kish Island in the Persian Gulf. Discovery well No# 2S-1 was drilled by LAPCO (Atlantic Richfield, Murfy, Sum and Union as partner with NIOC) in 1965 on the crest of domal shaped structure 2S which was defined by reflection seismic survey in May 1964 and came on stream in 1968. The structure is mapped on phantom horizon of Jurassic with aerial and vertical closure of about 725 km^2 and 175 meters respectively.

This field is a domal anticline (i.e., isocline) with a northerly axis which follows the direction of the basement fault which acted as a conduit for the salt movement through the upper strata. This structure appears to have a length of 14.5 km and width of 12.5 km. The limbs of the structure have a dip of about 10°. In this field there are two normal faults dipping 35° to the southeast with a N50°W direction. Considering the field data, the Salman anticline appears to have formed due to the salt intrusion and this is confirmed by the seismic profiles.

The Salman field is an extension of Abu Dhabi's Abu Al-Buskoosh and they form a common field and may have a production potential of 5 Bcm per year whilst the 40 Bcm Hengam's field which is an extension of Oman's Bukha gas/condensate field, might also be developed to produce 2 Bcm per year, to be sold to Oman.

In addition to South Pars, Iran aims to develop the 6.4-Tcf, non-associated Dalan reservoir of the Salman oil field, which straddles Iran's maritime border with Abu Dhabi, where it is known as the Abol bo khosh field. NIOC is seeking to develop Kangan/Dalan reservoir, which could lead to the production of 500 Mmcf/d of non-associated gas, along with the 120,000 bbl/d of crude oil that is now being produced from a shallower reservoir.

Two transversal faults made a horst which is the location of all the 28 producing and 10 injection wells. The field went on stream in 1968 and in 1978 the production averaged 194 MBD and by the end of 1980 the field had produced a total of 580 MMB. Ultimate recoverable reserves are estimated at 1.5 MMMB. The remaining objective for further exploration is the Dehram Group. In 1998 the field delivered 100,000 b/d. NIOC envisaged infill drilling, production plant optimization, and water injection. Estimated remaining reserves amounted to 430 million bbl.

Based on the available log data Kangan Formation attains a thickness of 160 meters in this field whereas the Dalan Formation reached a thickness of 640 meters consisting of the basal carbonates, Nar evaporites and the upper carbonates (Tabatabaie, 2003).

Table 9-10 shows some reservoir index for the Salman field in the Persian Gulf.

Table 9-10. Reservoir index in Salman oil fields.

Reservoir rock	Reservoir Depth (m)	porosity (Θ)	Gas to oil ratio(cf/brl)	oil Gravity in API	RR (mn brls)
Fahliyan	1920	23.4%,	477	35.4	130
U. Surmeh	2377	11	663	35.4	130
L. Surmeh	2415	19.8	240	31	200

Sirri Field

The location of the Sirri field in the Persian Gulf is shown in the location map in figure 9-6.

The first major project under the buyback investment scheme became operational in October 1998, when the offshore Sirri A oil field (operated by Total and Malaysia's Petronas) began production at 7,000 bbl/d (i.e., Sirri A currently is producing about 20,000 bbl/d). The neighboring Sirri E field began production in February 1999, with production at the two fields expected to reach approximately 120,000 bbl/d.

The Upper part of the Sarvak Formation provides the most suitable reservoir characteristics and excellent quality and proven exploration targets for hydrocarbons in this region of the Persian Gulf. On the Sirri C and D fields,

the 3D seismic interpretation has resulted in accurate definition of structural geometry of the top of Upper part of the Sarvak reservoir. This illustrated clearly the presence of a crestal graben on both fields (Hedayati, 2003). The hydrocarbon fields involving the Upper Sarvak as the main reservoirs in the eastern part of the Persian Gulf developed largely as flexures over salt diapirs. In some of the large fields such as Sirri much of the Mesozoic strata produce oil or gas from such traps.

Figure 9-6. The locations of Sirri oil fields and other fields in eastern part of the Persian Gulf.

The Sirri C and D structures are the results of deep-seated salt tectonics formed prior to Permian sediment deposition. The present structural deformation at the top of the Sarvak reservoir level and upper horizons are due to continued salt growth and movements. The Sirri C and D offshore oil fields have total reserves of 1.2 billion bbl oil in place. The main producing interval is Upper Sarvak Formation (RD=2400 meters in Sirri C, and 2430 meters in Sirri D; Θ=23%, Gr=31° in C and 30° in D). Original oil-in-place (OOIP) and cumulative production (in mn brls) is 486 and 51 in Sirri C, and 693 and 103 in Sirri D. Both fields require artificial lift and pressure maintenance.

The Sarvak Formation has estimated porosity of more than 20% with the reservoir characteristics vary laterally and vertically within the sedimentary succession. Laffan shales form the cap rocks for the reservoir.

Sirri C and D oil fields were each producing 14,000 b/d, but NIOC planned to maximize output to a combined 70,000 b/d with electric submersible pumps, water injection, and infill drilling. Combined remaining reserves were estimated at more than one billion bbl. Seismic interpretations have illustrated clearly the presence of a crestal graben on both fields. The isopach map of Upper Sarvak reservoir shows the thickness variation of the reservoir.

Sirri-A (Alvand)

This field is located 85 km SSE of Kish Island and 95 km SE of Resalat oil field near the median line with Dubai (figure 9-6). Well SIA-1 was drilled by SOFIRAN in 1968 down to a total depth of 3474.5 meters in the Surmeh Formation and discovered 85.3 meters oil column within Ilam Formation. By the end of 1988 the total numbers of wells were two. Nine tests were carried out over Ilam Formation, indicating moderate productivity.

Between 1968 and 1975, five exploration/delineation vertical wells were drilled by Sofiran on Sirri A field and as a result, it was concluded that the Ilam reservoir could not be commercially developed with the technology available at the time. As part of the Sirri buyback contract which also includes the development of the Upper Sarvak reservoir in the neighboring field Sirri E with the target production plateau of 100,000 bopd, TOTAL Sirri was requested to consider this conclusion.

Sirri A corresponds to a north-south elongated anticline of 14 km by 7 km with a maximum vertical closure of around 150 meters. In Sirri A, the Ilam Formation exhibits fracture porosity forming the main reservoir unit and account for the storage of the hydrocarbons.

In Ilam Formation oil was encountered with relatively good productivity. Such good result has been explained by the combination of the proximity to the fault and also the presence of a "detrital" limestone at the top of reservoir. However, this reservoir is very heterogenous and show low reservoir potential. Ilam oil is in the order of 31° API. The approved oil column found in the well is approximately 85.3 meters within the Ilam Formation.

Sirri-C Structure (Sivand)

This small field is situated about 10 km east of Sirri-A. Discovery well SIC-1 was drilled by SOFIRAN in 1973 down to total depth of 2770.5 meters in the Gadvan Formation. The well encountered 50 meters of Upper Sarvak reservoir but no oil water contact was recognized. The development wells on Sirri-C fields demonstrate the presence of a tilted OWC within the Upper Sarvak reservoir dipping northward (Fig-9-7). The tilt of OWC was estimated approximately to be the same as Sirri D. In this well 27 meters of Laffan shales were encountered.

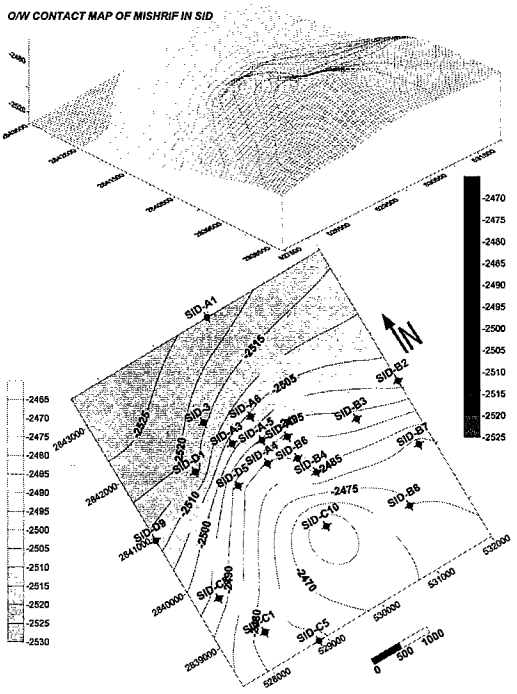

Figure 9-7 Oil water contact at the Sirri Field in the Persian Gulf (Hajikazemi et al., 2003).

The Sirri-C structure appears to be a domal anticline, with a length of 15.7 and width of 6 km and an areal extent of 20.5 km^2. The main pay zone of Sarvak has hydrocarbon column of 39 meters with porosity of 25-30%, permeability of 40-100 MD and with 30-31° API oil. The Upper Sarvak reservoir after acidification produces between 4134 BOPD under choke 5/8" with a flowing wellhead pressure of 625 psi.

The permeability of the Ilam reservoir is very low. In the Sirri-C oil field the structural closure at the top of reservoir is about 50 meters and the area corresponding to this closure is 24 km^2. Both Sirri-C and D oil fields are deep seated salt related structures. The Upper Sarvak reservoir at the crest of the Sirri C field is at depth of 2360 meters.

The Formation enabled to produce 4.138 MBD 31°API oil. Dariyan is also impregnated with hydrocarbon but unable to produce due to either low permeability or high viscosity of the oil. The field briefly produced through 18 drilled wells to the end of 1980. In the early 2003 the daily production rate was about 29,000bbls/d.

Sirri-D (Dena)

This structure is located some 20 km southeast of Sirri-A and about 20 km northwest of Fateh oil field. Discovered by SOFIRAN in 1972, by exploration

well No# SID-1 drilled on the northwest flank of the structure. The formations identified from top to bottom of the well include; Recent sediments to the Dariyan Formation. The thickness of Dariyan is 83 meters whereas Kazhdumi shale reached a thickness of 66 meters. The total thickness of Sarvak was 199 meters including 90 meters of Upper Sarvak reservoir with an oil water contact. Generally the Upper Sarvak Formation attains its highest thickness in this field.

The wells were drilled to a total depth of 2823 meters in Dariyan Formation, where the reservoirs are Ilam with 33°API and Upper Sarvak (i.e., Mishrif) with 31°API oil, hydrocarbon column in the later is 62.8 meters and reservoir rock contains 25 to 30 % porosity with 150-600 md permeability. The Upper Sarvak reservoir at the crest of the Sirri D field is at depth of 2400 meters. The Sirri D structure appears to have an aerial extension of 25km^2.

The Main Reservoir in this field is Upper Sarvak that contains mollusk fragments, bioclastic packstones to grainstones, and rudists mixed with wackestone lithoclasts. The top of the Upper Sarvak consists of packstone gradually changing into wackestone facies with an increase in depth. Permeability and porosity parameters have a very good correlation coefficient, and this relationship is used in estimation of reservoir permeability (Bashari and Zaree, 2003).

On the Sirri D structure, fault pattern illustrates the presence of a crestal graben in NW-SE direction. This type of crestal graben or collapsed zone is a typical feature seen on salt domes or anticline structures. These faults appear to have been generated during structural growth and reactivation during the Turonian uplift. The Laffan shale and Ilam horizon appear to be only slightly affected by these faults. On the Sirri C and D structures Hurmoz salt seems to have pierced the pre- Permian strata.

The Laffan shales are calcareous in this locality and attain a thickness of about 22 meters. Ilam, the youngest formation of the Bangestan Group which consists mainly of packstone, grainstones and pelletic biosparites to biomicrites and mudstone to wackestone from the depth to its upper part reach a thickness of 98 meters. Gurpi and Pabdeh Formations are 209 and 457 meters thick respectively.

At depth of 1124.5 down to 1688.5 meters Asmari Formation has been encountered containing micritic limestone at the base, argillaceous limestone with micritic interbeds, and finally the upper parts consists of 30 meters of micritic limestone, mudstone to silty wackestone and sand.

The field ultimate recoverable reserves were estimated at 300 MMB. Total numbers of drilled wells by the end of 1988 were 33 including water injection wells. The development wells have demonstrated the presence of a tilted OWC dipping northward. The tilt of OWC was estimated at approximately 12 meters per km or about one degree. Tilting or folding of subsurface structures have been proposed to explain the tilted oil water contact. Porosity reduction by the diagenetic processes in the reservoir combined with tectonic tilting

may create tilted OWC. Figure 9-8 shows the stratigraphic column at the Sirri field in the eastern Persian Gulf.

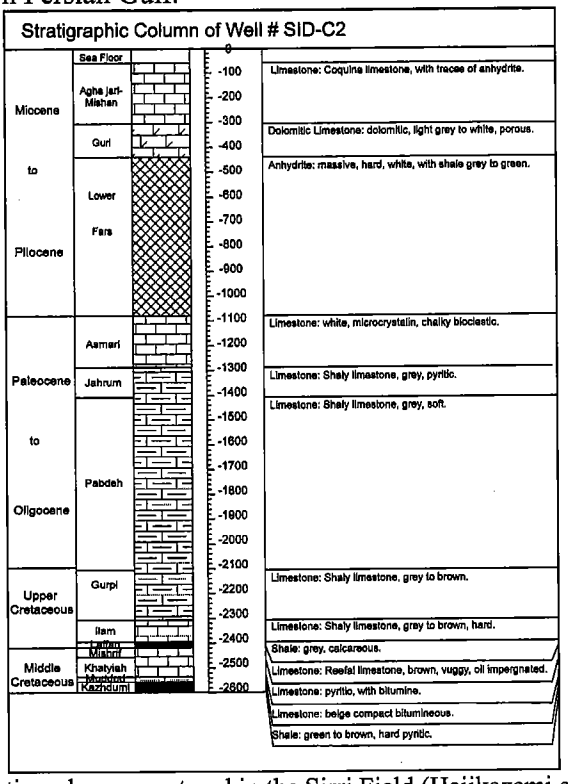

Figure 9-8. Stratigraphy encountered in the Sirri Field (Hajikazemi et al., 2002).

Nosrat (Formerly Sirri-E)

This structure is located 35 km southwest of Abu Musa Island and 50 to 55 km SE of Farur Island in the eastern part of the Persian Gulf.

This structure is an NNE-SSW trending anticline where the flanks are steeper due to the effect of three major and one minor fault. The aerial and vertical closures are in the order of 80 km^2 and 70 meters on the top of the Bangestan Group. Discovery well No# SIE-1 was drilled in 1971 by Sofiran down to a total depth of 3468.7 meters in the Fahliyan Formation. It recovered 33° API oil in the Upper Sarvak. The reservoir rock is a reefal limestone about 45 meters thick and average porosity of 20-22%, ultimate recoverable reserves estimated at 154 MMB. Oil water level was at 2942 meters which interpreted from electrical logs. Well No#SIE-3 was drilled as delineation and proved the presence of gas in the poor reservoir rock of Dariyan Formation.

Sirri-F Structure

This structure is situated 24 km northeast of Sirri Island and about 30 km southeast of Farur Island. Sirri-F was seismically defined in 1966 by CGG. Sirri-F-1 which located on the shot point No 2470 on the seismic line No 15 was drilled by Sofiran in 1970 down to total depth of 3630 meters about 200 meters in the Fahliyan Formation, but electrical logs showed that all porous interval were water bearing. Very small traces of gas were as recovered while drilling in the Dariyan, Gadvan and Fahliyan Formation. Ultimately, the well was abandoned as a dry hole.

The thickness of Fahliyan Formation here is about 205 meters whereas the Gadvan reaches a thickness of 40 meters including Khalij member. Dariyan attains a thickness of 145 meters containing *Orbitolina* sp *Trocholina* sp and *Dictyoconus* sp. In addition, Kazhdumi is represented by a 78 meters long column of shales with limestone partings. In well SIF-1 the thickness of the Upper Sarvak and Ilam are 107 and 88 meters respectively. Laffan shale is completely missing in this well. Asmari Formation is absence in this well and there is a continuous deposition of Pabdeh Formation shales and calcareous shales with argillaceous interbeds up to Oligocene time.

Sirri-L Structure

The Sirri L-structure is located about 52 km southeast of Kish Island and 36 km southwest of Farur Island. Well No# SIL-1 was drilled by SOFIRAN in 1969 to total depth of 2988.5 meters in Fahliyan Formation. About 18 meters of 24° API oil column discovered in the upper part of Sarvak Formation but it was evaluated as non-commercial. In this well the thickness of Upper Sarvak is about 65 meters. Ilam, Laffan and Gurpi Formations encountered in this well have thicknesses of 94, 15 and 96 meters respectively. Therefore, no further production tests were carried out and the well was abandoned.

The Lower Cretaceous rudist reef trends in the eastern Persian Gulf Basin is well established in this part of the Persian Gulf and often contributes to the development of giant oil fields, such as Sirri (offshore Iran).

Soroosh Field

Soroosh (formerly Cyrus) is in the northwest of the Persian Gulf, 50 km south of Nowrooz. This oil field is a domal structure located some 80 km WSW of Kharg Island about 130-140 km west of port city of Bushehr. Both fields are in 30-40 meters of water depth. Past and present planned development has been based on the Middle Cretaceous Azadegan Sandstone (Burgan B Formation) which is the main reservoir interval ranging in thickness across the field from 52 to 73 meters.

The main reservoir zones of Azadegan Sand (RD=2133 meters, Θ=18%) and Burgan B (RD=2164 meters, Θ=25%) with common GOR=100cf/brl and

$14° \leq Gr \leq 19°$. The Burgan-C contains heavy immobile oil. Estimated OOIP and RR are 9.1 and 0.414 bbrls in the lower Kazhdumi. Kaveh et al. (1971) mapped the Burgan A and B structure and the isopach and net sand isopach in this field is shown in figure 9-9.

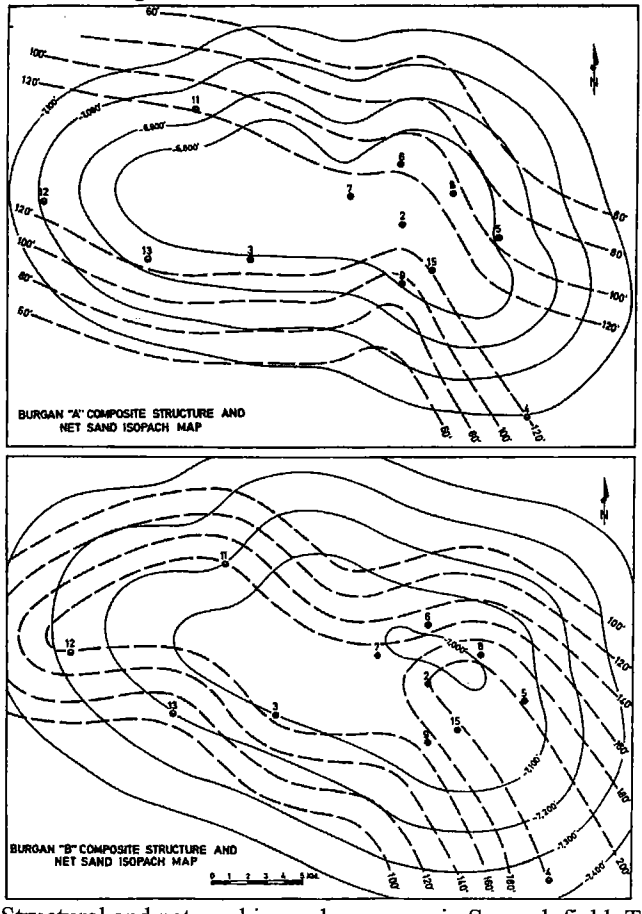

Figure 9-9. Structural and net sand isopachous maps in Soroosh field: Top- Burgan "A", Bottom- Burgan "B" (modified from Kaveh et al., 1971).

Oil comes from the Middle Cretaceous sandstones specially Burgan sandstones. Some reservoir parameters of the lower Cretaceous successions are presented in Table 9-7.

The Burgan-B reservoir has a closure of some 212 km^2 containing oil with estimated STOIIP of some 8.6 billion bbl between 2131 mss and 2272 mss. The top of the structure map does not show the presence of faults off-setting the Burgan B reservoir. Faults of an undeterminable orientation are recognized on the 2D seismic data.

The Burgan Formation is underlain by the basal shale (also referred to as "Unnamed Clastics") and the low permeability carbonates of the Dariyan

Formation and as a result only a flank aquifer is expected. Regional correlations suggest that the Burgan B reservoir is very extensive and that a volumetrically large flank aquifer exists.

The other reservoir in this field is Ahwaz Sand Member. It has always been assumed that the Ahwaz reservoir was only gas bearing but it has been established in recently logged well that the Ahwaz is also likely to contain a thin oil rim. Thus, Ahwaz is partly hydrocarbon-bearing with a hydrocarbon-water contact just below 613 mss.

The anhydrite, claystones and limestones at ca.540 mss of the Lower Ghachsaran form the ultimate top seal of the Ahwaz accumulation. Fluid properties for Ahwaz have been estimated as follows; API surface oil gravity 27°. The Ratawi, Gadvan, Dariyan, Kazhdumi and Ilam Formations are all dry. The Ahwaz reservoir in Soroosh field contains sands of Darcy permeability with shaly layers and located in a relatively unfaulted anticline structure at a depth of around 600 meters. The reservoir is believed to be analogous to the Abouzar Ahwaz oil rim reservoir.

The Soroosh oil field was discovered in 1962 by IPAC, the former operator and till 2001 fourteen wells had been drilled. Production from this field started in 1967 and continued until 1979. Production and export of crude from the field are carried out fully in marine installations which were almost ruined in 1983 during the imposed war with no chance of undergoing repair.

The Soroosh oil field was brought into production in 1967, and in 1980 was averaging 1.787 MBD oil. The drilled wells on the Soroosh structures producing a total of 86 MMB between 1967 and 1979 with a maximum production of around 30,000 bopd. The cumulative production in 1979, when the field was shut-in totaled just over 86 million bbl from the Burgan B, mainly from the crest with two wells showing signs of water breakthrough.

Rehabilitation was under way by an Iranian contractor to give output capacity of 60,000 b/d, but NIOC expected to develop the field further and to introduce enhanced recovery to raise output as high as 150,000 b/d by mid 1988 total number of wells were 14 of which 6 were abandoned. Ultimate recoverable reserves are variously estimated at 140-320 MMB.

Crude analysis suggests the presence of a density gradient over the oil column in the main Burgan B reservoir at depths of 2131 mss down to an oil-water-contact at 2272 mss. High viscosities over the base of the oil column possibly reduce aquifer support. Definition of fluid property distribution and prediction of the oil-water displacement process present the main challenges.

Soroosh had estimated reserves of 500 million bbl of oil. Shell intended to raise production from Soroosh to 100,000. The field's crude oil reserves are estimated at about nine billion barrels lying on the two layers of A and B. About 5 to 7% of the crude can be exploited.

Table 9-12. Reservoir Parameters of the Kazhdumi (Azadegan sandstones= Burgan B) in Soroosh field in the Persian Gulf.

Original OWC in Meter Subsea	2272
Thickness (Meter)	54-73
Formation Volume Factor (RB/STB)	
Initial Solution Gas-Oil Ratio (SCF/Bbl.)	
Oil Gravity (Degrees API)	20-15°
Oil Viscosity at Reservoir Conditions (Centipoises)	
Sulfur Content, by Weight	3.2
Average Porosity	22-29%
Permeability (Darcy)	5-11
Water Saturation (Original)	%
Average Productivity Index (BOPD/PSI)	92

In one of the wells, oil sour gas and extremely high pressure, super saturated salt water was encountered in the Upper Jurassic Hith-Surmeh Formation nevertheless 32° API oil was reported from Surmeh in Soroosh-2. Fahliyan also is oil bearing but lack of porosity and permeability unables to account the reservoir as commercial. However, the producing reservoir is Burgan B sandstone member of Kazhdumi Formation.

Fluid properties of the Soroosh crude in the reservoir vary with 20° API degrading to 15° API oil over the Upper 50 m of the reservoir, and heavy oil and tar observed towards the OWC at 2272mss.

Tondar (Former IMINOCO "T") Structure

Tondar structure geographically is located approximately 25 km SE of Lavan Island and about 20 km SW of Hendorabi Island. The structure is mainly dominated by a "salt plug" and its tectonic effects. Well no # IM-T-1 was drilled in 1967 by IMINOCO down to total depth of 2918.3 meters in the Surmeh. The Asmari Formation is fairly well-developed and sedimentation appeared to be continuous between the Asmari and Jahrum Formations. Drilling in the area encountered gas in the Asmari of the "tondar" structure.

A major unconformity is recognized between Pabdeh and Khalij member. The interval of 919 to 937 meters of Asmari Formation was confirmed to be gas-bearing. Calculated gas flow at a rate of 4189 MSCFD but gas column calculated to be minor. The Upper porous Surmeh (i.e. Arab D) and Dariyan Formations were confirmed by electrical logs. Other formations were evaluated as water bearing. Overall 2 wells were drilled in "Thunder" structure.

Taban (Former Sirip T-Tanb)

The structure is situated 45 km southwest of Deylam and 70 km northwest of Genaveh and some 25-30 km SSE of Bahregansar No#1. According to the old documents it was called "Tanbsar". This seismically defined structure is

trending NNW-SSE which might be considered as an average between Zagros and Arabian trend.

The dimensions of the structure are 10.5 km by 5.5 km. Tanb-1 was drilled by SIRIP in 1962 through normal sequences of sediments down to total depth of 4378.5 meters in the Fahliyan Formation. During the drilling operation, many oil and tar shows were prominent. This was the case, for example, from 3814-3864 and 4014-4130 meters in the Burgan and Gadvan accordingly but those were not confirmed to be commercial by drill stem testing. Analysis of oil tar of Burgan resulted in; 56.9% oil, 21.6% resins and 18.3 asphaltenes. The well was finally abandoned as a dry well.

Tousan

One of the areas considered to have potential hydrocarbon accumulation in the Persian Gulf is located near the Strait of Hormuz. Another interesting area is offshore near Bushehr, where Iran claimed in July 2003 to have discovered three fields with potentially huge, 38 billion barrels oil reserves. In May 2004, Brazil's Petrobras signed a deal to develop the Tousan field in the Persian Gulf.

The block sought by Petrobras is known as Tousan. This block covers an area of about 8000 km^2 between Sirri Island in the southern Persian Gulf and Qeshm Island, near the Strait of Hormuz.

Youish (Former PEGOPCO "U" Structure)

This flat and seismically defined structure is located some 32 km east of Resalat oil field, 100 km southeast of Lavan Island and 100 km west of Sirri Island, trending northeast-southwest.

Exploration well No# U-1 was drilled by PEGOPCO in 1966 a year after the seismological investigation was carried out. Normal sequences of rock units were penetrated down to a total depth at 3586 meters in the Dashtak Formation. The well was drilled in order to investigate the expected reservoirs of Dariyan, Gadvan and Surmeh Formations for hydrocarbons. Only minor shows of heavy oil trapped in vugs and fractures was encountered in the tight part of the reservoir rocks whereas the porous part discovered to be free of hydrocarbons. The formations and the lithologies encountered in the well are presented in Table 9-13.

In spite of minor to medium heavy oil to tar shows in the cores and cuttings from the Kazhdumi, top of Dariyan, Hith and Surmeh, drill stem testing proved those to be water bearing. However, the well was abandoned as a dry hole.

Table 9-13. Formation lithology and thicknesses found in Youash Structure.

Formation	Lithology	Thickness (m)
Asmari	Micritic ls,	40
Jahrum	Micritic ls with Somalina sp., Discocyclina.	687
Pabdeh	Argillaceous ls., with Globorolatia velascoensis	82
Gurpi	Shales and calcareous shales	50
Ilam	Micritic limestones with Rotalia skourensis	55
Laffan	Shales with Ostracodes	41
Sarvak	Mauddud and Ahmadi Mmbs are present	210
Kazhdumi	Shales with traces of orbitolina	69
Dariyan	Micritic ls, mudstone to wackestone, orbitolina ls.	146
Gadvan	Argillaceous ls. Khalij Mmb present	55
Fahliyan	Dolostone, dolomitic limestone to micrtitc ls.	383
Hith	Anhydrite	61
Surmeh	Micritic limestones with Pfenderina	768
Neyriz	Bottom to top: dolostone, silty shales, argillaceous ls	19
Dashtak	All members from Aghar shale to evaporate D present	270

'IM-V' Structure (IMINOCO)

The 'V' structure is situated 60 km southwest of the Lavan Island, about 75 km NNE of Reshadat oil field and about 35 km NNW of Balal oil field.

Well No# IM-V-1 was drilled in 1968 by IMINOCO in order to evaluate the Cretaceous and Jurassic hydrocarbon potentials. Normal sequences of formations were drilled down to total depth of 2743 meters in the Surmah (Lower Surmeh Shale member). Traces of dead oil heavy and extra heavy oil and residual bitumen were reported during drilling from the Mishan, Pabdeh, Dariyan, Fahliyan and Surmeh Formations but no major amount of oil or gas was recovered. Through drill stem testing it was proved that both primary and secondary objectives were water bearing. Finally the wells were abandoned as dry hole.

'X' Structure

The 'X' seismic anomaly is located 10 km north of the Salman oil field. Well No# 2X-1 was drilled in 1967 by LAPCO in order to evaluate Lower Cretaceous and Upper Jurassic hydrocarbon potential. Normal sequences of Formation were drilled down to total depth at 2714 meters in the Surmeh. The stratigraphic sequence encountered is very similar to that of the Salman field, but comparing with Salman, the formations were thickened. The slight thickening of the section might suggest that the well is an off structure well.

Drill stem tests showed that objectives were salt water bearing. It was also concluded that there is no closure associated with seismic 'X' anomaly.

'Y' Structure (IMINOCO)

The 'Y' structure is located near the median line with Arabia, about 160 km south of Bushehr port and some 130 km SW of Kangan port. This seismically defined structure is trending north-south with a small closure along the crestal area.

IM-Y-1 exploration well was drilled in 1968 by IMINOCO to evaluate the Khami Group. It was penetrated down to Surmeh Formation (Lower Surmeh Shale member) at total depth of 2986 meters. Extra heavy oil reported while drilling in the Surmeh but all drill stem tests through perforation found that the objective to be salt water bearing. Dehram prospect is awaiting further exploration.

Yalda (Former LAPCO-'3 Y' Structure)

Yalda or 3Y structure is a seismically defined elongated E-W trending anomaly which geographically situated about 20-30 km north of Balal oil field. Well No#3Y-1 was drilled by LAPCO in 1972 with primary objective of Khami Group and secondary Asmari, Jahrum and Lower Sarvak Formations. The well was penetrated through normal sequences of rock units down to total depth of 2048 meters in the Surmeh Formation, nevertheless no hydrocarbons were found. Thus, the well was abandoned as a dry hole. Dehram prospect is pending for further exploration.

Hydrocarbon Migration to the Oil Fields of Persian Gulf

In geological terms, the eastern flank of the Persian Gulf basin extends into the Iranian territory both onshore and offshore. The great onshore fields lie in the classic setting of the Zagros foothills, where huge anticlinal structures have formed above a glide-plane provided by a layer of salt. They are in part gravity structures as sediments slipped off from the rising mountains.

The prime source-rocks are deeply buried Jurassic shales, which in southern Iran have been depressed into the gas-generating window, but there are also leaner, yet still prolific, source-rocks in the Upper Cretaceous and Eocene sequences. The main reservoirs are found in fractured limestones of the Miocene Asmari Formation. Pliocene evaporites provide effective seals to the reservoirs, which as a result have exceptionally long oil columns, commonly with substantial gas caps, possibly being partly recharged from depth. These are not easy reservoirs to manage being prone to high-pressure gas invasion.

Primary migration plays a very important role in the formation of giant oil and gas reserves. Continuous subsidence and sedimentation from the close of the Paleozoic to Late Tertiary has deposited over 10,000 meters of sediments on the northern side of the Persian Gulf. Isopach maps of different geologic periods of this vast area show the thinnest sedimentary deposits on the Arabian Platform situated on the southern side of the basin.

The Cretaceous isopach map of the region shows the least thickness in the area of Kangan. Epirogeny together with salt diapirism persisted in the region from Late Jurassic to early Cretaceous times resulting in geologic structures and the rising of salt plugs. These structures with over one kilometers thickness of the Permian limestone and dolostones with the anhydride seal have resulted in the prolific accumulation of hydrocarbons.

To date the commercial gas reserves form exploratory drilling has been discovered on the northern side of the basin. Giant gas fields on the Iranian platform in the area of Kangan, Persian Gulf and part of northern Arabia have been discovered. This is attributed to the huge sedimentary thickness and the resultant overburden pressure on the source rocks on the northern and south eastern side of the basin. Organic material was transformed into hydrocarbons and the excessive pressure forced the generated oil to migrate into the present paleogeographic high structures on the southern side (platform area).

In the case of gas, however, it migrated towards the Kangan high at the end of the Cretaceous to early Tertiary. Primary migration of hydrocarbons entered the porous limestones and sandstones. According to Dunnington the primary migration was responsible for filling all the available pore spaces of the reservoir rocks by the hydrocarbons before compaction and has preserved the primary porosity. Consequently, this primary porosity has resisted later digenesis and associated pressures from the overlaying sedimentary cover. This is one of the main reasons for the creation of giant oil fields due to the primary migration.

The Silurian carbonaceous shales can be a very good source rock for the Permian reservoirs with limestones and dolostones of the Dalan Formation being marly towards the northwest of the region can itself be good source rock. The generated hydrocarbons from these source rocks can be migrated into limestone, dolostone and the sandstone reservoirs of the paleogeographic structures to the southern part of the region. Likewise, the Kazhdumi, Gadvan and Garau shales and marls can be the source rocks for the Azadegan sandstone, the Bangestan and the Khami Formations respectively. Thus, it seems to be clear that primary migration has played a vital role in forming of the Permian gas reserves in the Persian Gulf region, the Jurassic oil reserves of Arabia and the Cretaceous oil of Kuwait, southern Iraq and offshore Persian Gulf. The huge oil reserves located in the Persian Gulf region are the result of not any single factor but of the coincidence of all the conditions favourable for the formation, accumulation, and preservation of hydrocarbons. The most important of these conditions were the following;

- Deposition of a very large volumes of marine sediments some which deposited under the stagnant reducing conditions, excellent reservoirs rocks and consequent high recovery factors,
- The association of reservoir rocks and source rocks through a very extensive shelf area.,

- Reefs and reefal structures are common and thick deltaic sands also occur.
- The availability of structural and stratigraphic traps during migration of oil.

The predominance of carbonate rocks in the Persian Gulf basin may have been of critical importance in retaining oil.

Concluding Remarks

Conditions responsible for the abundance of oil and gas accumulations in the Persian Gulf region include the presence of a great volume of Mesozoic and Tertiary marine sediments, many of which were deposited under reducing conditions favoring the generation of petroleum hydrocarbons, the close association of source and reservoir beds throughout an extensive shelf area, the widespread distribution of large anticlinal structures, the availability of the structural and stratigraphic traps during the initial migration of oil, and the presence of effective cap rocks.

In the Persian Gulf region extremely large oil reserves resulted from a combination of ideal conditions necessary for hydrocarbon migration, entrapment and preservation. The Persian Gulf is rich in petroleum since it comprised an aerially extensive depositional platform along pre-Mesozoic passive margin of Gondwana. Subsequent development of intraplatform basins, extensive source-rock deposition within these basins, and multiple tectonic stages of compression and extension, produced large subtle structural closures coincident with peak oil generation and migration.

Due to the remarkable horizontal extent of the Persian Gulf sedimentary basins, horizontal hydrocarbon migration was generally very efficient (Murris, 1980) but cases of vertical migration have also been reported. Progressive burial of extensive source, reservoir, and seal rocks on a gentle structural setting allowed for efficient horizontal migration that could drain large, mature petroleum-generating source areas into extraordinarily large gentle structural closures.

Structures within the petroleum systems of the Persian Gulf are unusually large, gentle anticlines and, mostly in the offshore, salt domes that were formed from reactivated basement fault blocks, halokinesis, or a combination of the two processes. Most of these structures were initially formed during the Hercynian tectonic event, where Arabian Plate underwent multiple phases of compression from the Late Devonian to the Early Carboniferous.

Three post-Jurassic tectonic events are responsible for the formation and modification of structures and traps that consequently created oil and gas fields of such great magnitude: (1) Early Zagros rifting during the Early Triassic; (2) the First Alpine Orogeny during the Late Cretaceous; (3) the Second Alpine Orogeny in the Middle to Late Tertiary. Despite all these favorable aspects, there is a significant difference between the sizes of individual fields.

The thickness of the Kazhdumi and Sarvak Formation is variable in the drilled wells in the Persian Gulf. Such a variation appears to be due to the tectonic activity that commenced in Cenomanian with its peak at Turonian Epoch resulting in a regional unconformity surface in the Persian Gulf. Extreme facies variations within the Sarvak Formation might be attributed to these tectonic movements that are well beyond the influence of the Qatar-Gavbandi Arch.

A salt diapir is at least twice as thermally conductive than other sedimentary rocks. This phenomenon causes a substantial positive temperature anomaly in the overlying sediments, leading to higher hydrocarbon maturity than in surrounding environments. Concurrently, sediments under the diapir lose heat faster than sediments farther away, leading to under-maturity of hydrocarbon source rocks. A region with diapirs can therefore yield oil at depths where in salt-free basins only gas remains, because all the oil has been cracked. Condensate may occur under diapirs where only gas is expected. Therefore, a better understanding of the emplacement mechanisms, geometry and thermal history of salt structures is needed to reduce risk.

Maximum oil abundance is in Middle Cretaceous reservoirs with Upper Jurassic reservoirs coming a close second, followed by Lower Cretaceous reservoirs. Thus, the principal reservoirs are of Middle Jurassic to Tertiary age. Yet the source rocks in the Persian Gulf are limited to the Middle Jurassic to Upper Cretaceous sequences, with the Middle Cretaceous confirmed as the major source rocks for the prolific Oligocene-Miocene reservoirs.

The most prolific hydrocarbon-producing sequences are the reefal and fractured carbonates such as the Cretaceous limestones and the Asmari Formation and their stratigraphically equivalent formations. They are accounted for hydrocarbon production in numerous oil fields in reservoirs of equivalent age offshore in the Persian Gulf region. Trapping was possible by multiple tectonic stages and the halokinesis of thick underlying salt that resulted in reactivation or continued growth of primary anticline and domal structures.

In summary, the sequence stratigraphic, diagenetic, and tectonic histories of the Persian Gulf have produced an exceptional combination of geologic elements and conditions favorable for petroleum formation, migration, and accumulation. The exceptional elements and conditions include (1) extensive geographic distribution of rich, mature source rocks, high-quality reservoir rocks, and highly efficient seal rocks and (2) the formation of large structural traps during or subsequent to peak oil and gas generation.

The vast lateral continuity of the platform which existed in the region during most of its evolution gave rise to significant lateral continuity of the stratigraphic horizons, with relatively gentle and broad tectonic effects. These are ideal conditions for the formation of the most prolific hydrocarbon-producing areas in the world.

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CHAPTER-10

GEOPHYSICAL SURVEY OF THE PERSIAN GULF

INTRODUCTION

Approximately 30% of the world oil reserve lies in Persian Gulf area, hence, presenting a very important area potentially crucial for hydrocarbon exploration. In spite of the vast hydrocarbon reserves, it is difficult to unravel prospects and often ambiguous to appraise and develop fields.

What is explored so far, are oil and gas fields of different sizes. Traps are mostly structural with reservoirs of diverse nature, with play of both stratigraphic-structural within structural frame.

The South Pars field the extension of North Dome of Qatar, is an example that displays structural complication and ambiguity. Although, this field is considered as one of the largest structure in the Persian Gulf region, but it is subtle in nature and in fact difficult to define to some extent. At the beginning, its extension in Iranian side was not evident and its existence was owed to initial guess. However, based on the seismic data, it was proved that it is indeed extended to the Iranian territory in the Persian Gulf. On the other hand, its proper structural size and eventual reservoirs were another issues required utilization of advanced geophysical exploration methods.

So far, reservoirs encountered in the Persian Gulf are commonly made up of stratigraphic and structural play, which are still to be explored even in the known oilfields. Reservoir studies including reservoir characterization and field development is another challenge and worth to investigate in detail. Based on that, it would be realizable with the help of three or four dimensional seismic data, seismic attribute and inversion techniques, and evidently, summon other disciplines such as geology, reservoir and production engineering.

Brief Review of Geophysical Survey in the Persian Gulf

Geophysical investigation of the Iranian sides of the Persian Gulf began on January the 6th, 1958. However, it was not until the beginning of later decade that the major work commenced. During the 1963 and 1964 a large part of the Persian Gulf was shot for 200 percent stack seismic reflection reconnaissance survey which was followed by more detailed seismic reflection work. By the end of that decade, most of the Persian Gulf had been covered by seismic reflection surveys accompanied locally by gravity and very minor refraction work.

It is important to mention that the original seismic reflection data had some shortcomings and mainly lacked continuity. The data did not provide clear-cut results of the deeper and important part of the section in the Persian Gulf.

Based on the acquired data, there appeared to be two noticeable and well defined structural trends. The first one oriented approximately along a younger northwest/southeast direction whereas the second one was in a north/south direction. The former trend typified the structures in the southwestern Iranian mainland where most of the hydrocarbon production came from Tertiary sequences and horizons. In addition, it was discovered that oil in large and commercial quantities had also been discovered in the Mesozoic sequences (i.e., Cretaceous age). The latter trend followed the structures on the Arabian Plate where Mesozoic sequence (i.e., Cretaceous and Jurassic) were the main prolific hydrocarbon producers in the region.

As a result of the geophysical investigations, it became increasingly critical to distinguish the variations in structural trends between the Tertiary horizons and the older sequences below the regional Upper Cretaceous unconformity. In effect, methods to overcome the near-surface reverberations and multiple reflections and the lack of energy returns had to be employed to obtain reliable data in order to define and delineate the anomalies below this regional unconformity.

Increasing utilization had been made of multiple coverage recordings in analog form. Lengths of seismic cable, reaching ten thousand meters were effectively employed in some seismic reflection surveys. A higher degree of dip resolution and multiple attenuations were attained by the use of lone cable and six fold stacking technique.

A further improvement in seismic reflection data was also made by the application of digital recording and processing devices. As a result of all these development, encouraging results were obtained in "no data area" even though previously shot for 600 per cent stacking: so much so, that some of the older stacked data were also digitized to provide additional control.

The structural configuration of the Tertiary horizons can usually be followed without major difficulty. As the result of the application of more advanced seismic reflection techniques, usually two, and in some cases locally more horizons with fairly good reliability can be followed over large areas in the Mesozoic. Some deep, but scattered data could also be observed which were coming from deeper Mesozoic and Paleozoic or even from the basement. Therefore, it was possible not only to define and delineate the anomalies, but also to relate the structural events and piece together a tentative geological history and palegeography of the Persian Gulf region.

The deepest seismic data, in itself highly questionable might correspond to the Lower Mesozoic or the Permian age sequence. With these seismic data at least some continuity was maintained throughout the Persian Gulf area, and the structural history of the Persian Gulf could, to some extent, be studied through the isopachous mapping of the sedimentary packages. The isopach of

the Upper Sarvak reservoir for example is well-defined and the seismic inversion has led to the definition of facies and porosity variation with the reservoir on Sirri fields (Hedayati, 2003).

Marine gravity surveys carried out in some parts of the Iranian sector of the Persian Gulf were conducted to assess the part played by possible salt dome (or plug) activity in some features and areas which the seismic data suggested. In some areas the gravity surveys proved to be of little value and even provided conflicting evidence which did not correlate with seismic anomalies. In other areas conformity to the seismic interpretation had been found.

By surveying the geophysical activity in the Persian Gulf, it was evident that for many decades two-dimensional seismic data was the only tool and available method that resulted in discovering prospects for further exploration activities. This was fulfilled within separated blocks or concessions during periods of 1950s to 1990s. Later, the Persian Gulf was considered for seismic data vintage, under "Persian Carpet-2000 Project", where some 100,000 km^2 of 2D seismic geophysical data from period 2000-2004 was acquired. This was still insufficient, due to problems encountered during exploration or development steps.

Based on the exploration and development concept, the Persian Gulf region has been divided into different blocks, within which a number of oilfields exist (Mina et al., 1967). The first geophysical method which has been used in the region was Torsion Balance in 1923. The first 2D reflection seismic was carried out on Abouzar field in the late 1958. However, in later years 3D seismic was performed on this field which provided a better definition of the structural configuration and fault pattern and more accurate definition of the reservoir isopach and better understanding of reservoir facies distribution.

Magnetic method firstly has been used on northern part of the Persian Gulf in the Iranian territory in 1972. However, the first major 2D seismic, between 1988 and 1992 was carried out in nearly 15000 kilometer area. Although most of the productive oil fields in Persian Gulf area were explored by 2D seismic between 1958 and 1975. The first 3D seismic in the Persian Gulf region was carried out on the South Pars in area of about 100km^2 in 1990.

Geophysical Surveys are employed by NIOC in southern Iran and the Persian Gulf area to assess whether subsurface strata are attractive for the accumulation of hydrocarbons and furthermore to determine the size and structure of the known oil and gas reservoirs.

Seismic projects normally comprise various activities related to planning, collecting, processing and interpretation of seismic data. Such data are usually based on computer- generated graphic 2D or 3D images.

2D seismic data is collected with a wide distance (less than 500meters) between the seismic lines, while 3D seismic data is collected with relative narrow distance (25 to 100 meters) separating the seismic lines. The narrow line

distance makes it possible to create a three dimensional picture of the location through data processing.

The Persian Carpet- 2000 project was a seismologic and geophysical survey undertaken through the entire Iranian part of the Persian Gulf with a uniform carpet of seismic lines according to the terms of the contract between NIOC and a Joint Venture of MJF (Mostazafan and Janbazan Foundation) Energy Group and the Norex Group- Norway.

The Persian carpet survey has been with almost 106,000 km^2 of high quality 2D seismic data. It covers the Iranian part of the Persian Gulf and the Oman Sea. The dense grid of 2 by 2 km seismic lines would serve as a basis for all oil companies who will apply for offshore petroleum licenses at the Iranian side of the Persian Gulf and the Oman Sea.

The Persian Carpet-2000 data also facilitates exploration in the agreement area which has also strong indications for having large petroleum potentials. Tentative schedule for collection, processing and quality control of the project was as follows:

Estimated 110,000 km lines 2 by 2 km grid in the Persian Gulf, 2 by 4 km in the western Oman Sea and 4 by 8 km in the eastern Oman Sea by following cations: Lavan, Assaluyeh, and Bushehr. Kharg, Qeshm, Oman Sea, Transition Zones (TZ's), Northern Persian Gulf, Inner Qeshm.

Data collection subdivided into three zones which included; 1) Deep Marine, 2) Shallow Marine and 3) Transition Zone. Crew, equipment and teamwork which needed for the operation included; 6 Boats and Transition zone crew were deployed in the project. Different processing companies were active in processing the data.

The Persian Carpet-2000 covers the heart of the most prospective and oil rich basins in the world. It was collected based on an important exclusivity agreement, made at a historic point in time when Iran was starting to open up for foreign investment into its oil industry. Very limited framework was in place for the actual exploration and production activity in the region. The Iranians had developed a concept called the buy-back contract that was designed to permit foreign companies to invest in the reconstruction of war-damaged and run-down oil fields as a service contractor for the National Iranian Oil Company.

In 2002, the Iranian Offshore Company carried out a program of 3D seismic surveys in the Persian Gulf totaling 1472 km^2 in order to delineate in detail the structural and stratigraphical aspects of some of the major oil fields in the Persian Gulf including Sirri C and D, Resalat, Reshadat and Abouzar oilfields. Thus, the main 3D seismic activity started from 2002 on five major productive fields to overcome the production problems.

GENERALITIES AND DATA INTERPRETATION

In order to review the geophysical and exploration activities in the Persian Gulf, specific areas from northwest to southeastern parts were selected based on the availability of data and also spatial distribution representing basin characteristics. Owing to the application of conventional methods, complication and contradiction in exploration in search of hydrocarbon were overcome by making the use of new approach and technology. This resulted in a better understanding of the historical evolution of the Persian Gulf Basin and also allowed exploration of new horizons and also stratigraphic events, suggesting and pointing out the reservoirs which were not evident before.

As mention before, for many decades exploration in the Persian Gulf was limited to two-dimensional seismic data, as evidently in offshore area this was an undeniable tool. The main aim of such geophysical operation was to indicate prospects and to some extent suggesting the well locations with limited information concerning tectonic elements, faults, sedimentary features, or depth of entry for horizons. Even within these limitations, there would be places for misinterpretation or contradiction during prospect evaluation, reservoir characterization or development stage.

Abouzar

The morphological setting of the Abouzar field was discovered in the late 1959s by exploration well# A-1. In the year 2002, a 3D survey was carried out in this field in the northern Persian Gulf and subsequently the fields were introduced. Most of the seismic horizons had been picked and mapped with high degree of confidence. The purpose of the 3D seismic interpretation was to define a better characterization of the structural configuration of the Upper Ahwaz Sand Member of Asmari reservoir and deeper formations and better definition of the deep fault pattern.

On the Abouzar oil field the Ahwaz Sand Member is at shallow depth and sufficiently thick to be resolved seismically and the seismic data is of excellent quality (Hedayati, 2003). It is therefore an excellent case for seismic inversion studies. The Ahwaz Sandstone reservoir is characterized by low acoustic impedance through the entire section. The gas-bearing interval is characterized by low acoustic impedance. The carbonate or carbonate cemented sand interbeds are defined by higher acoustic impedances. Direct hydrocarbon indication has been seen very clearly on the seismic data on the acoustic impedance derived from the seismic inversion.

The seismic structural interpretation in addition to a structural evolution analysis and 3D seismic inversion seemed to have provided a much better understanding of the Ghar reservoir facies in the Abouzar field. Further it has shed some light regarding the timing of the hydrocarbon migration into the Ghar reservoir (Hedayati, 2003).

Resalat and Reshadat Fields

The Resalat field was discovered in 1969 by exploration well ARK-1, while the Reshadat field had been already discovered in 1966 by exploration well IM-R3. Both of these fields were discovered by drilling on the crest of the structures. Following 2D seismic data acquisition in 1966 and subsequent drilling of the exploration wells and proving hydrocarbon-bearing zones later led to the development phase by drilling a number of wells over the fields.

In 2002, IOOC carried out a 3D seismic survey to delineate the structural and stratigraphical aspects of these two oilfields which are located in central part of the Persian Gulf. The interpretation of the 3D seismic data resulted in delineating the details of the Resalat and Reshadat oilfields covering an area approximately 1050 km^2.

The seismic interpretation revealed noticeably that at least the Reshadat structure is a deep-seated salt dome structure. The amplitude of the structure increasingly decreases from the Permian to the Cretaceous. The seismic interpretation indicates that the top Laffan and Gadvan seismic horizons are the most characteristics seismic horizons for structural and fault definition. Additionally, based on these data, on the Reshadat field, the presence of crestal faults, which has produced a small crestal graben, has also been demonstrated and such a graben could produce compartmentalization of the reservoirs with the Resalat and Reshadat oil fields (Hedayati, 2003).

Both fields produce hydrocarbons from more than one reservoir. In Reshadat field, the main producing intervals are the upper part of the Sarvak and Dariyan Formations of the Middle and Lower Cretaceous. Additionally, hydrocarbons have also been produced from the Jurassic Surmeh Formation.

The seismic inversion has revealed evidently the lateral facies variation of the Upper Sarvak reservoir. A comparison of the well log correlation and seismic inversion demonstrates that the confidence of the acoustic impedance derived from seismic inversion.

In Resalat field, the main producing intervals are the Dariyan and Surmeh Formations. Minor amount of hydrocarbons have also been produced from the Upper Sarvak and Surmeh Formations. Figure 10-1 is the geoseismic cross section through both structures illustrating the geological interpretation of the seismic section.

The structural interpretation and mapping in connection with reservoir facies through seismic inversion and well data provided the foundation for the creation of the 3D geologic model of Ahwaz Sand Member, volumetric calculation and reservoir model for flow simulation analysis.

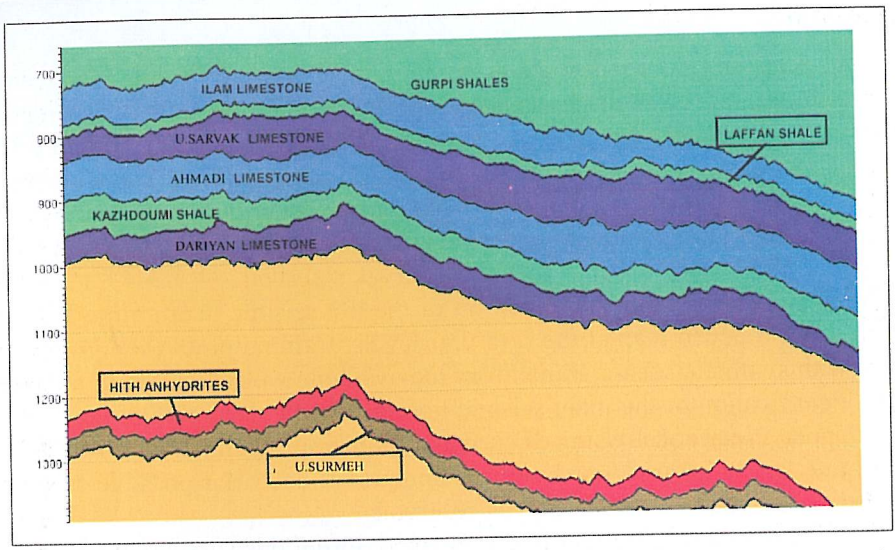

Figure 10-1. Seismic cross section showing the impedance of various formations in Resalat and Reshadat fields in the Persian Gulf (After Memarzia, 2005).

Sirri Field

Sirri C and Sirri D are two geological structures that were discovered in 1974 and 1972 respectively by exploration wells following 2D seismic data acquisition and subsequent drilling exploration wells and proved to be hydrocarbon-bearing leading to the development phase by drilling a number of wells over these fields.

Also in 2002, IOOC carried out a program of 3D marine seismic surveys in the Persian Gulf, of which 256 km^2 is acquired over these two fields. Interpretation of the 3D seismic data resulted in discovering eight horizons to be mapped with associated isopach and isochron maps.

The isopach of the Upper Sarvak reservoir is well defined and the seismic inversion has led to the definition of facies and porosity variation within the reservoir. The seismic inversion has also demonstrated that the Upper Sarvak reservoir in the Sirri C and D is a relatively homogenous facies.

The results of structural evolution analysis performed using cross-sectional restoration and analysis of isopach maps shows that the salt tectonics played a major role in the structural growth of Sirri C and D and also Resalat and Reshadat fields. On Sirri C and D, salt movements were more significant and occurred at an early stage of pre-Permian depositional successions. The definition of the fault pattern and the crestal graben indicates that there is some compartmentalization of these fields. The structural growth continued during the Permian Jurassic.

Hengam

The Hengam gas/condensate accumulation within the Middle Cretaceous Sarvak Formation was discovered in 1975 by exploration well following 2D seismic data acquisition in 1974. In the year 2002 the Iranian Offshore Oil Company (IOOC) carried out a program of 3D marine seismic in Hengam, in the eastern part of the Persian Gulf. The purpose of the investigation was to detail the structural geometry of the Hengam field and to establish the isopach map and facies variation with the upper Sarvak reservoir.

A detailed structural interpretation of the 3D seismic data on the Hengan field area produced map at the reservoir levels. Calibration of the 3D seismic data with synthetic seismograms from the available wells resulted in an accurate identification of the main seismic horizons particularly within the middle and Upper Cretaceous. Using 3D seismic modeling, in combination with key attributes and advanced processing techniques it has been possible to study the seismic response of Ilam-Sarvak reservoir.

One of the most important maps obtained during this survey was the Ilam-Sarvak isopach map. This map was derived from the Top Ilam-Sarvak and Top Kazhdumi depth maps and it may be related in part to the thickness of the reservoir section where a reservoir facies may exhibit significant fracturing. It must be mentioned that it is extremely difficult to distinguish Ilam Formation from Sarvak because the Laffan shale that would separate the two Formations is very thin or even absent. The result of structural analysis through flattening seismic horizons and analysis of the isopach maps demonstrates that at the time of Upper Cretaceous deposition of the Hengam structure was rather graben geometry with thicker upper Cretaceous Gurpi deposition within the graben.

The main difficulty with the seismic interpretation over Hengam areas stems from the fact that this has been a difficult area to document good quality seismic data, especially over the crestal part of the structure. Additionally, due to poor porosity of the reservoir, acoustic impedance can not be used with confidence for the definition of lateral and vertical reservoir facies variation of definition of average porosity of the reservoir (Fugro-Jason, 2003). There are a number of factors that are controlling the quality of the final processed results, but the geology and structural complexity of the area play a major role. This gives rise to severe multiple and poor imaging of the seismic data.

Based on the detailed investigation completed by Fugro-Jason (2003), it could be concluded that most of the hydrocarbon reserves is possibly located within the northern part of the horst structure where the intense deformation produced highly fractured reservoir.

Seismic Data Quality: Signal and Noise

It is important to point out that the seismic data quality varies over the entire Persian Gulf. However, the 3D seismic data quality is relatively good in some of the intervals on the Resalat and Reshadat fields (Lower and Middle Cretaceous), Sirri C and D fields (Middle and Upper Cretaceous). In the Abouzar field (Oligo-Miocene) the data had excellent quality. Therefore, it could be stated that the majority of the key seismic horizon can be picked and mapped with high degree of confidence.

On the Abouzar oil field the presence of a gas cap within Ghar reservoir has some impact on the attenuation of the seismic energy over the crestal part of the structure. Figure 10-2 shows a line across the Abouzar structure. It demonstrate clearly that the Abouzar structure at the top of Ghar sand reservoir is almost horizontal meaning that during the deposition of the overlying formations Abouzar had no structural expression at the Top Ghar.

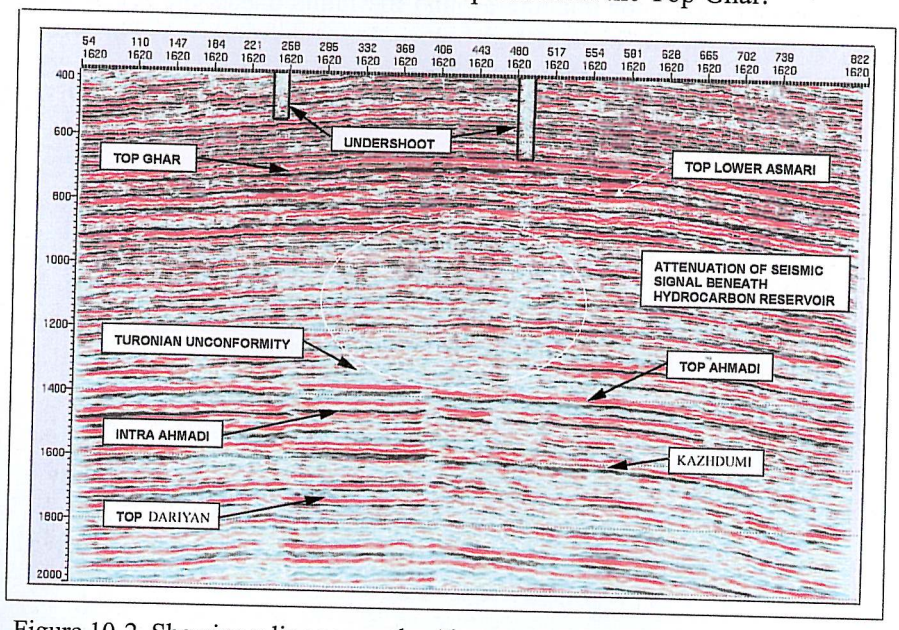

Figure 10-2. Showing a line across the Abouzar structure. Due to the very gentle structural deformation and low dipping horizon at the Top Ghar reservoir, the synthetic seismograms have been correlated to the nearest data outside the undershoot area.

The seismic data quality in Hengam varies over the area. The near surface down to the Top Pabdeh is of good to excellent quality and is high frequency data. Underneath this, the data is much lower in amplitude and shows a range of data qualities. Towards the HA-1 well the data quality is good, whereas in the core priority area it is fairly poor.

Figure 10-3 shows a traverse through the vertical wells across Sirri C and D structures. Note the areas underneath platforms, marked as undershoot. The change in data quality is caused by the absence of near traces due to the surface obstacles. Fold is maintained at target level by undershooting with a two boat operation. Even so, the data quality in these areas is poor compared to the normal acquisition, continuity is degraded, and vertical resolution is lower. The undershoots occur beneath the platforms and the ties to two of the six vertical wells in Abouzar and four of the five in Sirri C and D are affected by poor quality data there.

The seismic data quality and continuity of the seismic horizons degrades on the Sirri D field, which grant further investigation. Some deterioration and discontinuity of the reflection at the reservoir level on the eastern part of the Sirri D can be observed. This has been attributed to interference with long period of multiples. Significant amount of random noise and multiple interferences, together with poor imaging around the faults makes the seismic interpretation extremely difficult at and below the reservoir level (Fugro-Jason, 2003).

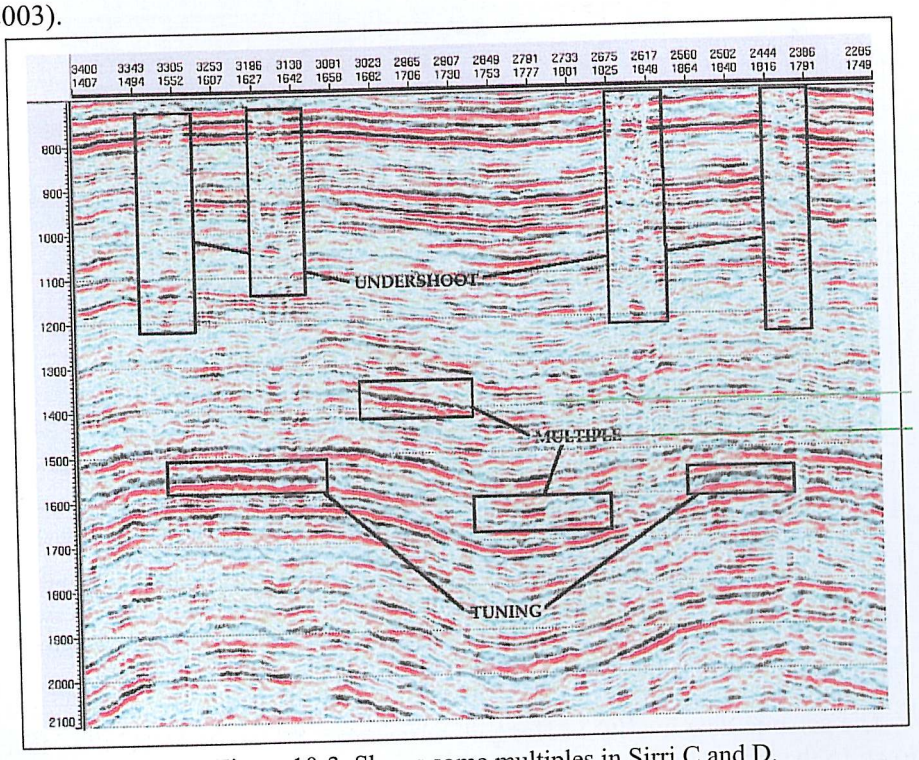

Figure 10-3. Shows some multiples in Sirri C and D.

Velocity Distribution

Considering the subject that there is no correlation between the total drilling depth in wells and the geological boundary, the velocity-depth or time-depth logs were used to derive a velocity table for geological boundary.

To generate the iso-velocity maps for main and better known geological and continuous horizons like Upper Cretaceous unconformity, Turonian unconformity, Azadegan sand member of Kazhdumi and Upper Ahwaz Sand member of the Asmari Formation, has been picked on related reflectors. Figure 10-4 shows the seismic velocity at Reshadat structure.

Comparing the average iso-velocity and the depth map of the Upper Cretaceous unconformity, Persian Gulf area can be divided into three part; north and northwest, central and eastern parts.

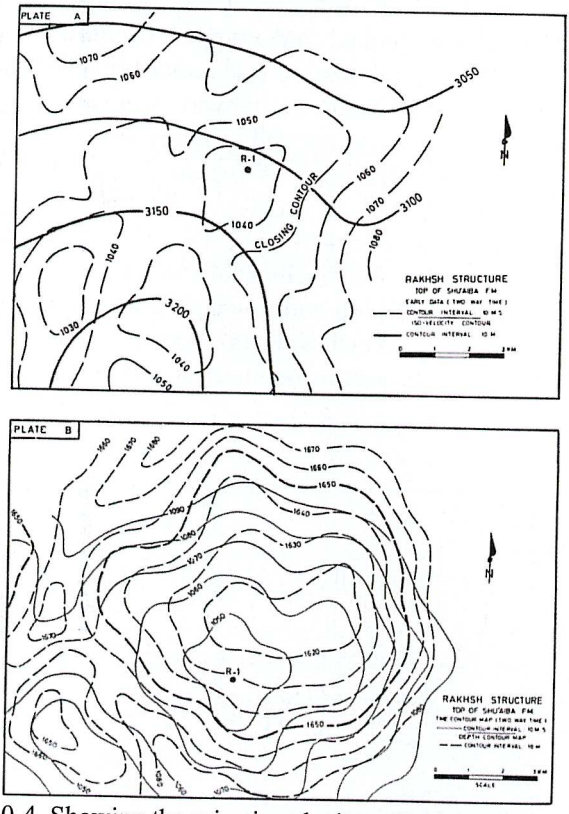

Figure 10-4. Showing the seismic velocity at Reshadat structure. Plate A showing early data, Plate B shows time contour map (two ways time) for the Top of Dariyan.

The existing maps show that, since the depth of the interested horizon in N-NW part is too deep (>2000m/s), the average velocity is high (>2900m/s) and is a function of increasing depth toward north. The maximum velocity corresponds to the Binak depression, north or Kharg Island.

In the central part, the depth decrease (about 2 km) and the average velocity in the western part of this area is corresponding to the depth and will decrease down to 2800m/s. But in the east part of the central Persian Gulf (south of Lavan Island) although the depth is not too high, the velocity act as local anomaly and increase up to 3100m/s. This velocity increase is due to the existence of salt and evaporite deposits in the Hormuz Formation.

In the eastern part of the Persian Gulf, up to the Strait of Hormuz, depth maps show an increasing magnitude in depth for the basin (up to 3.6 km), but the velocity shows a decreasing trend toward the east.

NORTHERN PERSIAN GULF (ABOUZAR FIELD)

Aghajari-Mishan-Top Gachsaran

The Gachsaran horizons were picked and mapped to show the shallow structure pattern and to be used in the geological model for inversion. In the case of the Aghajari horizons, an accurate tie between well logs and seismic was not possible as there were no well tops and in many cases no impedance data. The horizons were purely identified as regionally consistent, strong seismic events. The top of the Gachsaran event was similarly identified as a strong regionally consistent seismic event.

On the acoustic impedance logs, the Gachsaran is shown by thin interbedded layers of anhydrite and shale of high and low acoustic impedance. On the Abouzar field the thickness of the Gachsaran is about 250 meters and at a depth of 500 meters. The top Gachsaran is identified in many of the wells (see figure 10-5).

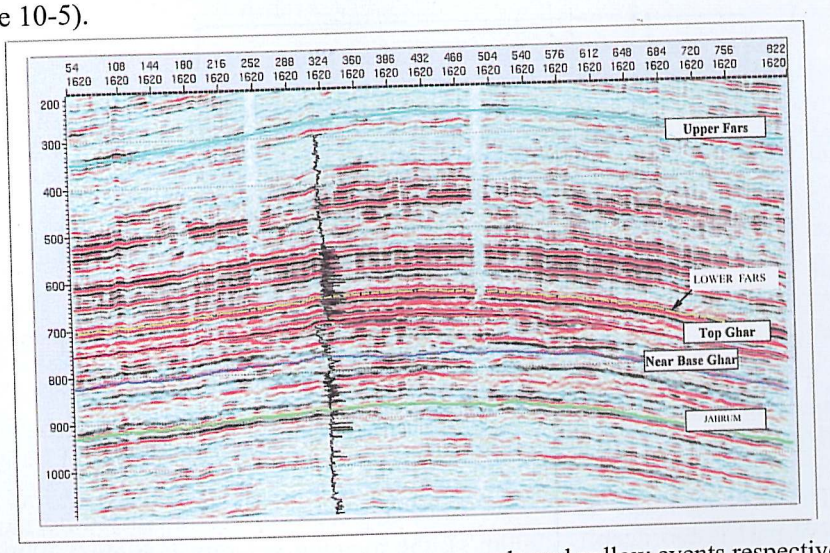

Figure 10-5. Picks can be seen in as the cyan, purple and yellow events respectively.

Dariyan. The top Laffan shale and top of the Dariyan reservoir are the most prominent seismic horizons that have been picked and mapped with high degree of confidence.

After years of extensive exploration a complete 3D picture of the Persian Gulf still is not available. The transition zones yet to be completed and more importantly the structural complexity near the Strait of Hormoz remains a major obstacle for exploration program. In general seismic stratigraphy has been little performed. In spite of this great deal of studies that have been performed in the Persian Gulf region and great achievement, some major objectives and future investigations undoubtedly will add more to the existing knowledge.

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Top Upper Ahwaz Sand Member

The Top Upper Ahwaz Sand Member shows a clear, negative strong impedance contrast with the harder limestone and anhydrite deposit above. This consistency of character of Top Upper Ahwaz Sand Member is a clear and strong peak on all the synthetic seismograms. On the 3D seismic data the Top reflection is characteristics and has picked with high degree of confidence. The Top Upper Ahwaz Sand Member event proved to be straightforward to pick on the seismic data and is good quality across the survey area except within the zones of undershoots. In brief, the seismic interpretation has illustrated that the Top Ghar seismic horizon is the most characteristic seismic horizon for the structural definition of the reservoir horizon (see figure 10-6).

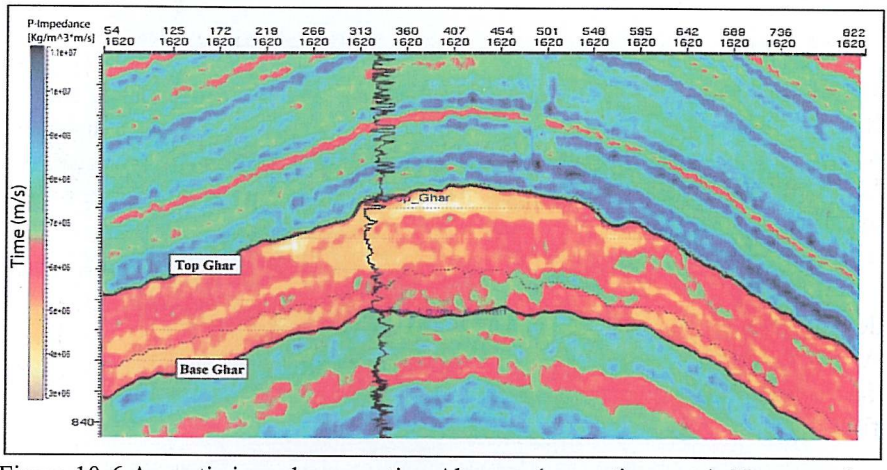

Figure 10-6 Acoustic impedance section Abouzar (upper time gate). Note very low acoustic impedance in the gas cap and low acoustic impedance within oil zone in the Ghar reservoir. Hydrocarbon within Ghar reservoir produces horizon push down below accumulation.

Due to occurrence of a gas cap within the Ghar with its exceptional porosity, some velocity anomalies push down the deeper horizons and degraded the quality of the seismic data. The existence of a gas cap in an unconsolidated porous sand reservoir creates a stronger acoustic contrast with the overlying Gachsaran Formation.

Top Lower Asmari / Near Base Ahwaz Sand Member

The Top of the Lower Asmari limestone also displays a clear and strong impedance contrast with the soft Upper Ahwaz Sand Member above. Top Lower Asmari is a relatively clear trough on the synthetic sections. On the 3D seismic data, the horizon has been picked with some degree of confidence. The Top Lower Asmari event proved straightforward to pick on the seismic

data across most of the survey area. However, the presence of gas creates a low velocity anomaly pushing the horizon down in time. In addition, the gas absorbs the p-wave seismic energy leading to a degradation of the seismic signal.

Lower Pabdeh

The Lower Pabdeh event represents a transition from low to high impedance and corresponds to a regional trough on the seismic data. The importance of this event lies in its use as a constraint horizon in the inversion of the upper time gate. The continuity of this event was good throughout the survey and proved relatively easy to pick accurately.

Upper Gurpi

The Upper Gurpi horizon represents the base of a high impedance interval within the limestone and dolomite sequences and corresponds to a strong regional significant peak on the seismic data. The picked horizon was useful as a constraint horizon in the inversion of the lower time gate. The Upper Gurpi is shown figure 10-7.

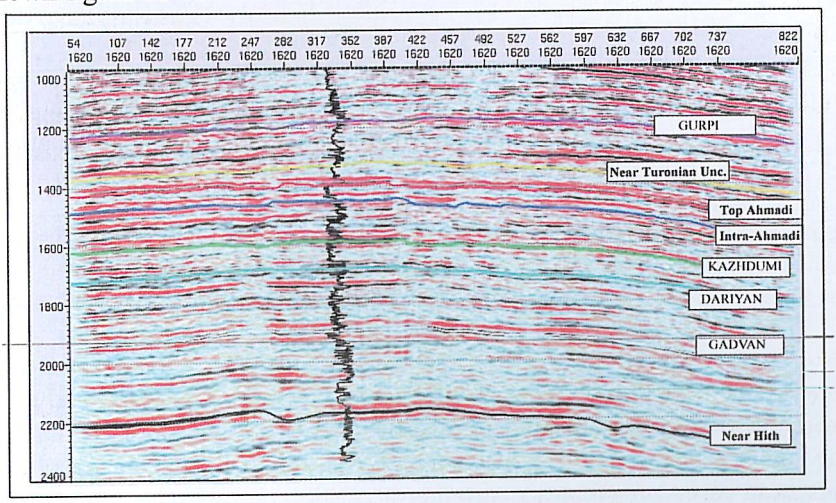

Figure 10-7. Picks can be seen in as the cyan, purple and yellow events respectively.

Turonian Unconformity

The Turonian Unconformity is identified by a decrease in impedance. This event corresponds to a positive peak on the 3D seismic data. However, because the formation above overlies this event disconformably, the magnitude of the impedance contrast is variable across the survey leading to a variation in the strength of the seismic reflection. The quality of the event is variable

and picking is relatively easy. In some areas, a review of the log information in combination with the results from the inversion of the lower time gate led to a revision of the interpretation and the selection of a deeper. In figure 10-7 the original event referred to as "near Turonian Unconformity" is shown as the distinct picks.

During the Turonian uplift, further salt movement produced structures at the Upper Sarvak on Sirri C and D. The crestal parts of the structures were severely eroded by the Turonian Unconformity. The deposition of a relatively constant thickness of the Laffan shale above the eroded Upper Sarvak suggests that the peneplained surface was created prior to Laffan shale deposition.

Kazhdumi

The Azadegan member of the Kazhdumi Formation and Top Ahmadi are events marked by a very large decrease in impedance representing a change in lithology. In the case of Azadegan the change is from interbedded shales and limestone to sand and silt while for Ahmadi is from limestone to sandstone and siltstone interbedded with limestone. These correspond to a very strong, regionally consistent black peak on the 3D seismic data. The Azadegan (i.e., Nahr Umr) event proved straightforward to pick on the seismic data and is good quality across the survey area. Also the Intra- Ahmadi marks a large decrease in impedance within the Ahmadi Formation. The Top and the Intra Ahmadi events proved straight forward to pick on the seismic data and are good quality across the survey area. In figure 10-7, Top Ahmadi is shown with a distinct picks.

Top Dariyan

The Top Dariyan marks the base of the Azadegan and represents a sharp increase in impedance caused by a transition from shale to limestone. This corresponds to a trough on the 3D seismic data. The quality of the Top Dariyan event was variable and picking was difficult in some areas. A review of the log information in combination with the results from the inversion of the lower time gate led to a revision of the interpretation and the selection of a slightly deeper and stronger event in the north western portion of the survey area.

Gadvan

The Gadvan approximates to the Top of the Lower Gadvan limestones and marks a slight decrease in impedance which corresponds to a regionally consistent peak on the 3D seismic data. This synthetic event corresponds to a shaly interval within the Kharaib Formation as well. This layer has been correlated through the well log. The Gadvan event proved straightforward to pick

on the seismic data and is fairly good quality. On the 3D seiesmic data the intra-Kharaib reflection is very consistent and can be picked with high degree of confidence within the region.

Near Hith

The Near Hith approximates to the top of the Hith anhydrites and marks a very large increase in impedance corresponding to a regionally consistent peak on the 3D seismic data and has been picked with high degree of confidence. The Top Hith horizon has been used to produce map at the Arab and Surmeh reservoir level. However it was found to be much easier to pick the corresponding very strong black peak approximately 20 meters below, as this was better quality across the survey.

CENTRAL PART OF THE PERSIAN GULF

Top Asmari Seismic Event

The Asmari limestone in Sirri C and D fields was picked and mapped to show the shallow structural pattern. An accurate tie between the well logs and seismic was not possible for top of the Asmari, since there is no significant impedance change. Instead a pick was made at the base of the high-energy reflections around 800 ms. This pick is shown in figure 10-8 and is approximately near the top of the Asmari level.

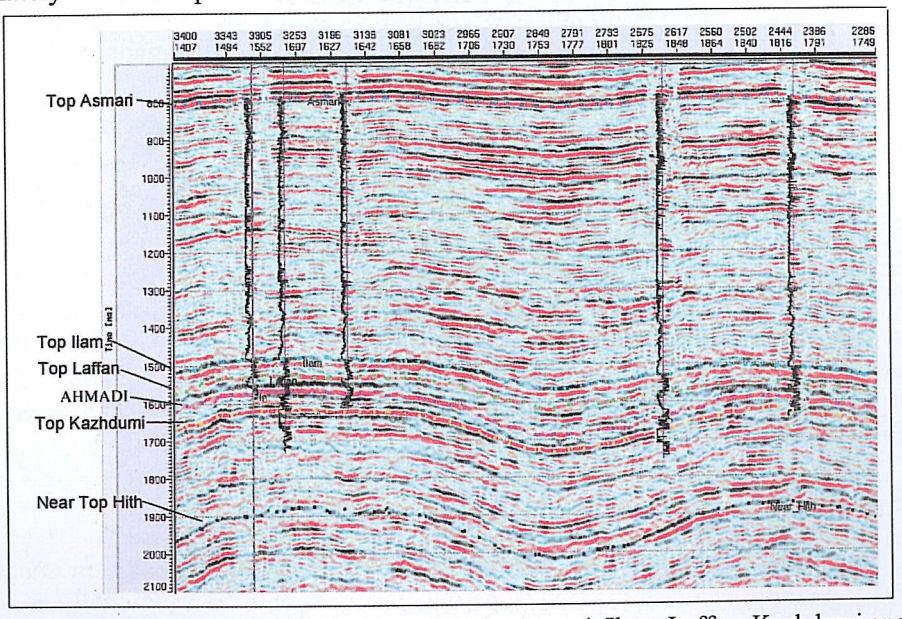

Figure 10-8. Top of main horizons including the Asmari, Ilam, Laffan, Kazhdumi and Hith.

Upper Jahrum Seismic Event

A strong event close to the top of the Upper Jahrum Formation in Resalat and Reshadat was picked and mapped showing the shallow structural pattern. An accurate tie between the well logs and seismic was not possible for Upper Jahrum itself, since there is no significant impedance change. Instead a pick was made at the base of the high energy reflections between 300-500ms.

Top Ilam Seismic Event

The top of the Ilam limestone in Resalat, Reshadat, Sirri C and D shows a clear and strong impedance contrast with the softer overlying marine sediments (see for example figure 10-9).

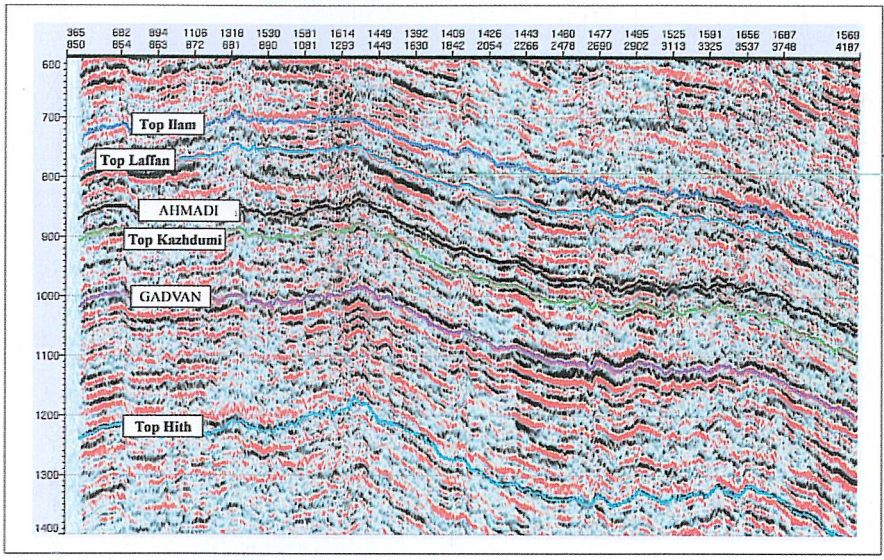

Figure 10-9. This is a random seismic line from 3D data and illustrates a very broad and gentle anticlinal structures at the middle Cretaceous reservoir horizon in Reshadat.

Top Laffan Seismic Event (Resalat, Reshadat, Sirri C and D)

In Resalat, Reshadat, Sirri C and D fields, the Laffan shales form the top seal for the Upper Sarvak reservoir and are therefore important to map accurately. The Top Laffan on the acoustic impedance log corresponds to a sharp negative deflection, on the synthetic seismogram represented by a strong trough event. Over the 3D seismic data area, the horizon is very continuous.

The quality of the pick is very good over most of the data set as this is probably the strongest event in the section. In the Sirri fields there is also evi-

dence of significant multiple interference in the Laffan shale reflection, which makes interpretation more difficult compared to Ilam.

In Resalat and Reshadat, Laffan overlying the Upper Sarvak reservoir and the top Laffan is almost parallel to the Top Upper Sarvak reservoir, picking and mapping therefore has been performed with high degree of confidence. The thickness of the Laffan varies between 30 to 40 meters on these fields.

Upper Sarvak Reservoir

The Upper Sarvak reservoir in Resalat, Reshadat, Sirri C and D fields does not produce a clear seismic event and it was not directly picked from the seismic data. In this region of the Persian Gulf, the Upper Sarvak limestone has no impedance contrast with the overlying Laffan shales and as a result no seismic event is associated with the Upper Sarvak reservoir. The only exception here is where the Upper Sarvak has low porosity and produces a clear seismic response as a clear black peak.

Concerning the Sarvak Formation and its associated members, the Intra-Khatiyah seismic event is also important event. The top Khatiyah limestone in Resalat, Reshadat, and Sirri C and D fields is not characterized by a clear seismic response as no impedance contrast exists between the lower part of the Upper Sarvak and Khatiyah member. A strong negative reflection below the Upper Sarvak reservoir was picked as an intra Khatiyah seismic event. This event is very consistent on the synthetic seismogram. On the 3D seismic data the reflection is also very consistent and has been picked with high degree of confidence. It could be considered as one of the best seismic horizons within the Resalat and Reshadat fields (Hedayati, 2003).

Top Kazhdumi, Top Dariyan Seismic Events

The Top Kazhdumi unit in Resalat, Reshadat, and Sirri C and D fields has a sharp negative reflection seismically. The quality of this event is good across the whole survey area, with little evidence of multiple interferences.

A strong and consistent trough event is present on the all synthetic seismograms within the Gadvan Formation corresponding to a shaly interval. On the 3D seismic data the intra-Kharaib (Gadvan) reflection is very consistent and can be picked with high degree of confidence within the area. The Top Gadvan in Resalat and Reshadat fields is characterized by a marked decrease in impedance resulting in a strong negative trough in the synthetic seismograms. At this level, a clear strong regional trough is present on the 3D seismic data. The quality of the pick is good throughout the survey.

The seismic response of the Top Dariyan reservoir in Resalat and Reshadat fields corresponds to a weak positive event as the Al at the top of the reservoir is only marginally higher than the Al in the overlying Kazhdumi shale. On the seismic data, the event corresponds to the Top Dariyan reservoir is often ill-

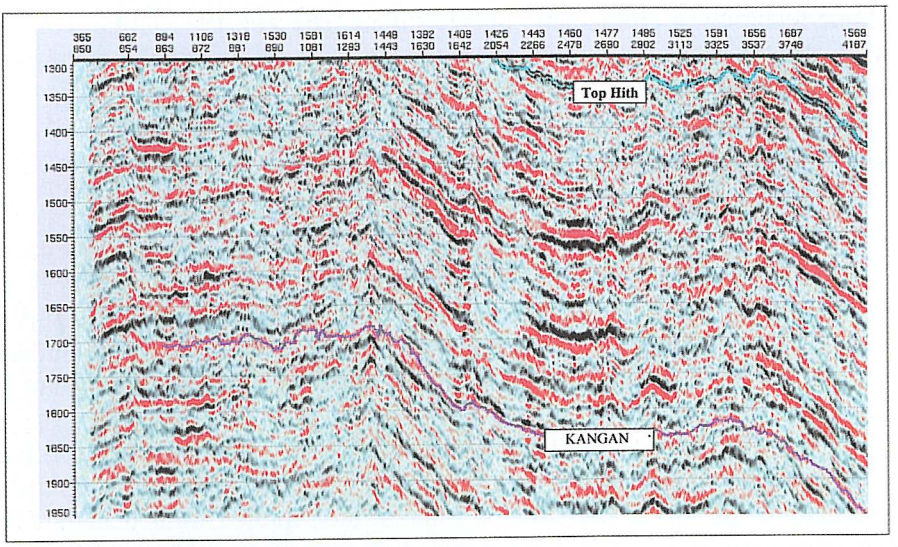

Figure 10-10. Seismic section showing a laterally continuous event close to the top of the Kangan-Dalan picked and mapped to demonstrate that the deep structural pattern on the Reshadat structure.

MIOCENE UNCONFORMITY

The Miocene Unconformity was picked and mapped in order to demonstrate shallow structure. An accurate tie between the well logs and seismic was possible for top Gachsaran evaporites, since there is a significant impedance change at the top of the evaporites below the Guri Limestone. Gachsaran evaporits were mapped as a trough at around 800 meters. The pick is displayed as dotted lines that representing the top of the Gachsaran (Fig. 10-11).

Top Cretaceous and Top Gurpi Shale

The Top Cretaceous displays a weak positive impedance contrast compared to the overlying softer Pabdeh shale. The Top Cretaceous is a peak on the synthetic sections and corresponds to a peak on the 3D seismic data. The Gurpi shale forms the seal for the Ilam-Sarvak reservoir. According to the synthetic seismograms, the Gurpi shales and marls have low acoustic impedance relative to part of the Gurpi marls.

At the Top Gurpi and Top Cretaceous the structure is expressed by a simple anticline. This change in geometry from horst and tilted fault blocks to anticline geometry could be attributed to depositional conditions and the thickness variations within the Gurpi Formation.

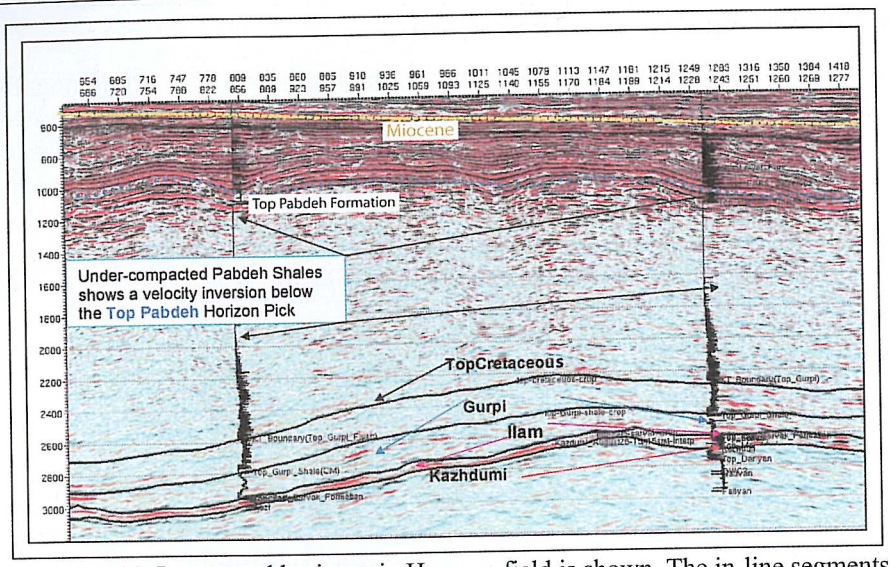

Figure 10-11. Interpreted horizons in Hengam field is shown. The in-line segments shown demonstrate good quality near surface image, and the much more lowe amplitude at depth.

Ilam-Sarvak Reservoir

The top Ilam-Sarvak reservoir has a strong positive impedance contrast with the overlying Gurpi shale in this area in the Persian Gulf. There is a distinct seismic event associated with the top of Ilam in the wells but Ilam Formation is only separated from the underlying Sarvak Formation by very thin shales of the Laffan Formation with a thickness of about less than one or two meters. Hence it is referred to the seismic pick as the Top Ilam-Sarvak which has been mapped as a positive peak on the 3D seismic.

In summary the seismic structural interpretation and mapping demonstrates that the Hengam structure at the Top Ilam-Sarvak reservoir is a complex horst shape structural feature in the north of median line and becomes a tilted fault block in the south. The two main bounding faults could have compartmentalized the Ilam-Sarvak reservoir seen in the Hengam structure. The internal faults within the horst-like feature have smaller throws and have played an important role in the fracturing of the Ilam-Sarvak reservoir. Reservoir quality may be also related to sub-seismic faults. Based on the geophysical observations, it can be concluded that most of the hydrocarbon reserves is within the half northern part of the horst structure where the intense deformation produced highly fractured reservoir.

defined resulting in problematic interpretation. The Top Dariyan horizon has therefore been picked on the inverted impedance, keeping the Top Kazhdumi event as guide event.

Top and Near Top Hith

The Hith anhydrites in Resalat and Reshadat fields are characterized by higher impedance than the overlying sediments. Top Hith is a clear and strong peak on the synthetic sections and corresponds to a strong regional peak on the 3D seismic data. The quality of the pick is fair over most of the survey area. The Top Hith horizon has been used to produce the map at the Surmeh and Arab reservoir level. The reservoir due to its limited thickness cannot be resolved seismically.

The Top Hith horizon has been used as guide event for defining the Top of Surmeh events which show a poorly defined seismic response on synthetic seismograms. In Sirri C and D fields, none of the supplied wells penetrate the Hith evaporites.

Kangan-Dalan

In the Resalat and Reshadat fields, a laterally continuous event close to the top of the Kangan-Dalan Formation was picked and mapped to show the deep structural pattern. An accurate tie between the well logs and seismic was not possible for the Top Kangan-Dalan itself since there is no significant impedance change. Instead a pick was made at the base of the high-energy reflections around 1700ms on the Reshadat structure. This pick is shown in figure 10-10 as the thick event and is approximately 30ms above the top of the Kangan-Dalan level.

EASTERN PERSIAN GULF (HENGAM)

The main seismic events were identified from the synthetic seismograms. Comparison of the synthetics with the seismic data enabled selection of suitable seismic event for the first stage of the interpretation. In general, regular grids of in-lines and cross lines were picked for each event. Accurate calibration of the seismic horizons has allowed identification of the main seismic horizons within the Cretaceous interval.

Kazhdumi and Dariyan Formations

In the eastern part of the Persian Gulf, the Kazhdumi is a strong negative reflection on seismic. This event is below the Ilam-Sarvak reservoir and corresponds to a low impedance layer often associated with a high gamma-ray response on the electric logs. Meanwhile the Top Dariyan Formation pick is generally very poor in the area and has been tied to a black positive peak on seismic representing a strong increase in acoustic impedance. Based on the seismic interpretation, the Top Dariyan appears to be the deepest horizon mapped.

MAIN SEISMIC EVENT

Structural Aspects

The seismic inversion has been used for the structural interpretation and better definition of the fault patterns. However, due to poor quality of the seismic horizons at the crestal part of structure and furthermore, the poor quality of reservoir, acoustic impedance could not be used with confidence for the definition of lateral and vertical reservoir facies variations or definition of average porosity of the reservoir.

From tectonics view point in the Persian Gulf, various structural styles ranging from simple to very complex could be observed on the seismic sections. These events include anticline, syncline, faults, horsts, grabens, unconformities, diapirs etc. Some of the very typical seismic sections which demonstrate these events and phenomena from different part of the Persian Gulf region are presented in figure 10-12.

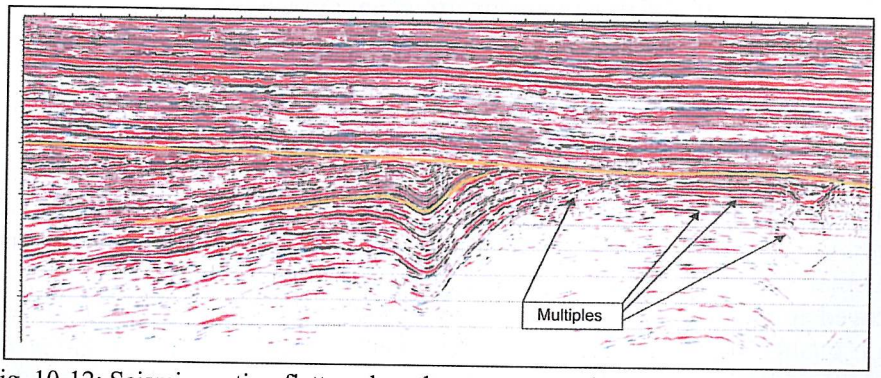

Fig. 10-12: Seismic section flattened on the near top marker suggesting earlier structural development.Miocene angular Unconformity near the Strait of Hormoz (Memarzia, 2005).

Salt Diapirism

The Resalat and Reshadat anticlinal structures are believed to be of salt tectonic origin and the available seismic data seem to suggest that the salt structures are deep seated. Thus, these fields are clearly deep-seated salt domes and the closure and amplitude of the structures decreases progressively from Permian to the Cretaceous time period (see figure 10-13 and 10-14).

The crestal faults on Sirri C and D fields are predominantly NW-SE and their origin is related to salt tectonism and the Turonian uplift. The Resalat and Reshadat are clearly deep-seated salt dome features.

Based on the result of the structural evolution analysis of the Resalat and Reshadat fields, it has been demonstrated that during the pre-Permian, the Hurmoz salt had the highest growth activity and this growth decreased considerably during the Cretaceous period. During Mid-Cretaceous depositional period, these fields had no structural expression and facies were deposited on the flat sea floor (Hedayati, 2003).

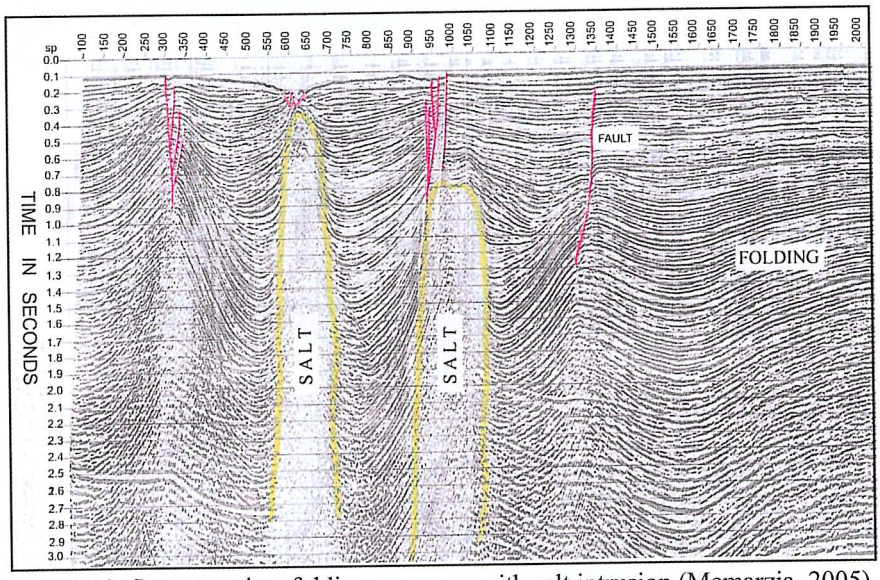

Fig.10-13. Structures in a folding sequence with salt intrusion (Memarzia, 2005).

FAULT AND FOLD DEVELOPMENT

Most of the faults over Sirri C and Sirri D appear to be extensional mainly with a small throw in the order of 5 m (in the Upper Sarvak). The faults form a distinctive pattern over the crests of the domal structures. The faults show a typical crestal graben and the bounding faults of the graben have opposing dip and take up the bulk of the throw (figure 10-15). Some small secondary faults, both synthetic and antithetic, have been interpreted within the crestal graben. Only one of the faults appears to join across both structures.

CHAPTER-11

PERSIAN GULF ENVIRONMENTAL GEOLOGY

INTRODUCTION

The Persian Gulf petroleum resources are fundamental to regional prosperity and development and are of global significance. It is significant that the Persian Gulf is a naturally stressed environment, and at the same time have been subjected to unprecedented development pressures over the past three or four decades.

Discovery of oil in the Persian Gulf during the 1930s and 1940s led to a massive increase in shipping, and has been principally responsible for the immense economic wealth and geopolitical importance of the region today.

The present chapter is on the environmental geology of the Persian Gulf and it is mainly consists of the recent geologic history and coastal morphology and environmental changes imposed on the Persian Gulf.

The environmental stress imposed on the marine life and it consequences are going to be discussed. The marine geology and pollution are highly regarded as the main subjects, which are to be tackled in this chapter. This chapter also addresses impacts of the Persian Gulf crisis on marine and terrestrial environments. .

THE PERSIAN GULF ENVIRONMENT

Climate

The Persian Gulf is arid by any definition, and being largely landlocked, suffers a continental climate with marked seasonality. In the north, the local climate is influenced by orography. The Taurus and Pontic Mountains of Turkey, the Caucaus Mountains of Iran, and the Hejaz Mountains of the Arabian Peninsula together with the Tigris-Euphrates Valley, from a northwest-southeast axis that strongly influences the tracks of extra-tropical storms to the southeast direction.

Generally, the Persian Gulf exhibits extremely complicated meteorology, with variable sea surface temperatures, enormous latent heat fluxes, abrupt topography and strong circulation.

The climate in the Persian Gulf is markedly different than the climate in the neighboring Gulf of Oman. While the Persian Gulf is affected mainly by the extra-tropical weather systems from the northwest, the Gulf of Oman is at the northern edge of the tropical weather systems in the Arabian Sea and Indian Ocean. The monsoon circulation produces southerly winds in the sum-

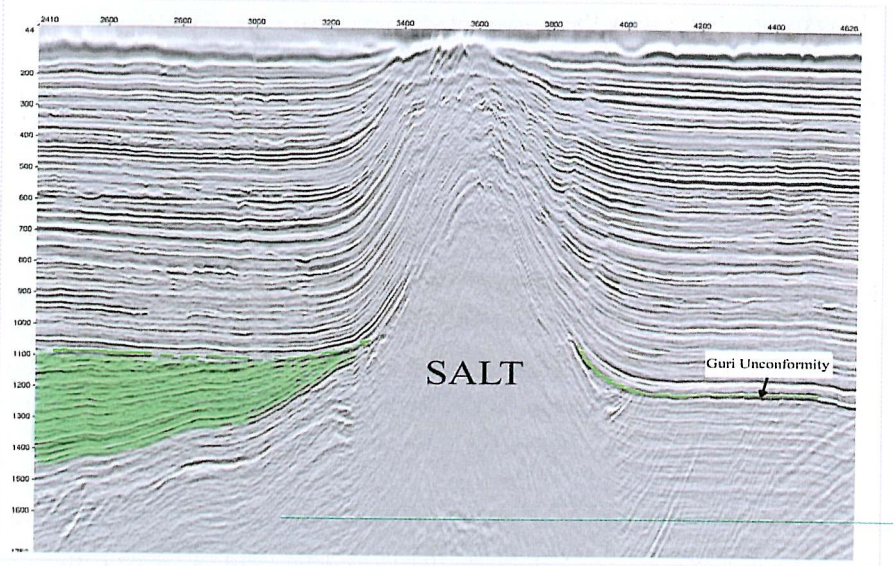

Fig.10-14. Salt Diapirism. Salt intrusion into the overlying strata and formation of a trap belw the Guri unconformity (After Memarzia, 2005).

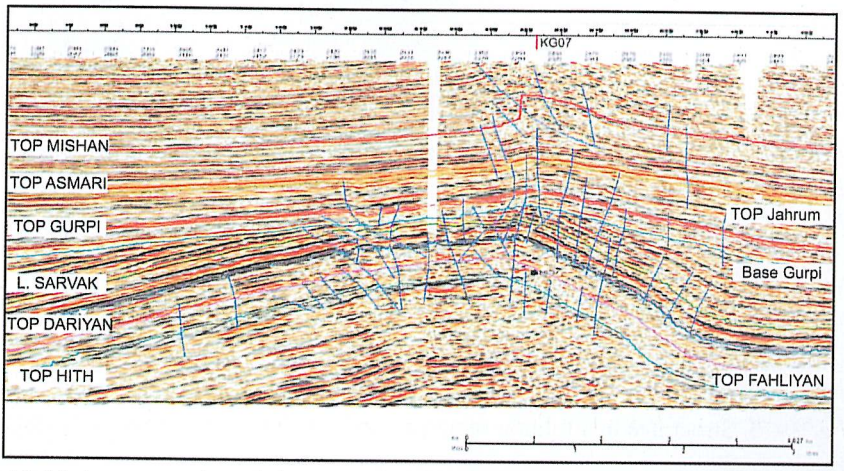

Fig.10-15 Across section of the upper part of the 3D seismic data on one of the fields showing an anticline and unconformity (After Memarzia, 2005).

The faults in the area can be fully described as being linear, planar extensional faults, caused by flexure within the surrounding rocks and the setting up of a tensional stress regime around the crests of the folding. Once failure occurred, the typical extensional graben system formed, typical of the fault patterns seen on the crestal areas of dome-shaped features. Figure 10.16 show

a series of inlines over the structures zoomed in on the reservoir zone. This figure also shows how the faulted graben develops over the field.

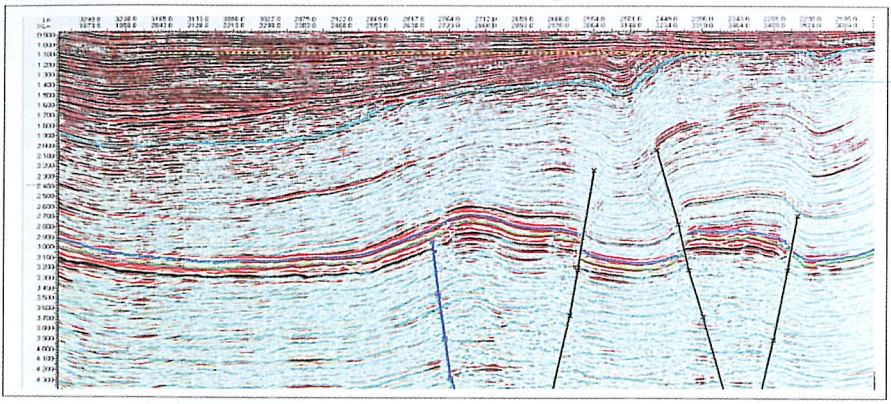

Fig 10-16: Faults creating a horst and graben system in the Persian Gulf (After Memarzia, 2005)

There are four main fault trends in the Persian Gulf. The majority of these faults in the area are extensional faults, usually parallel to one another. These extensional faults have developed in an area of compressional tectonics in reaction to the folding of sedimentary strata and the stress regime that was imposed on the rocks.

Two fold patterns could be observed across the Persian Gulf area which appears to be separated by the Turonian unconformity. Pre-Turonian unconformity folding was much less elongate, suggesting that the compression on two axes, but it could also be noted that the dominant trend in this early folding stage runs NNW-SSE. During the post Turonian, folding became much more elongate and rotated compared to the earlier deformation. This may have been due to either; a new stress regime or the rotation of the older pre-Turonian stress vectors, it is important to note that the second stage of folding trends appears to be in a NW-SE direction.

Figure 10-17 shows a cross section of the upper part of the 3D seismic data on one of the Western fields, illustrating the NE-SW folding and absence of major faulting. Note how the structural deformation extends almost to the sea floor.

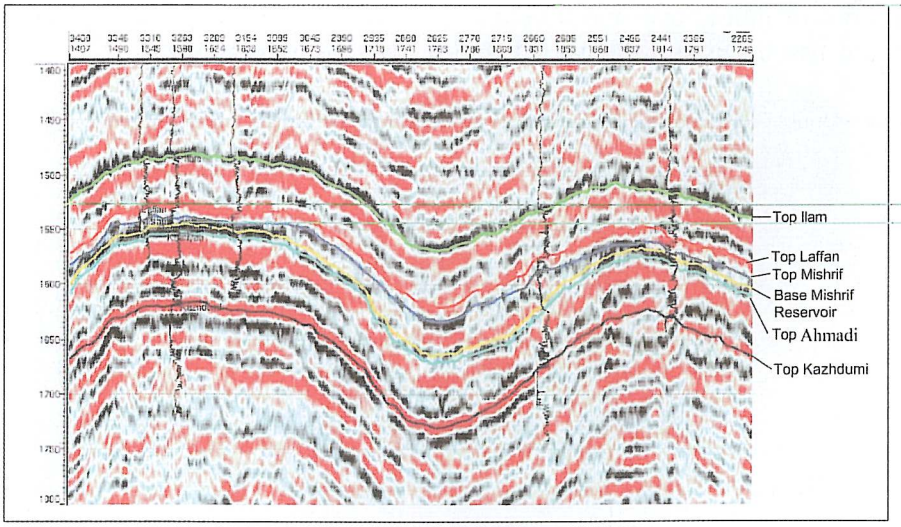

Fig.10-17. Anticlines and a syncline occurring in a homogenous beds of different formation in Sirri Field in Persian Gulf (After Memarzia, 2005). The figure is a random seismic line from 3D data and illustrates clearly both structures over the reservoir interval.

STRATIGRAPHY

Reefs

Seismic stratigraphic modeling has been performed extensively to illustrate better understanding of the seismic resolution at the reservoir level. A positive event close to the sea bottom reflection was picked to map the extent of recent and present age carbonate reefs (see figure 10-18)

The reservoir facies derived from the seismic inversion suggests a complex back-reef-reef facies, which requires further sedimentological and well log correlations over a greater area of the structures.

In the geophysical investigation within the Persian Gulf, 2D and 3D seismic profiles have been routinely obtained. These profiles have demonstrated the platform morphology and displayed their confuguration. Carbonte reefs, bamks and mud mounds can be identified on the profiles. Such modelings have shown that the stratigraphic traps associated with them are mainly hydrocarbon-bearing.

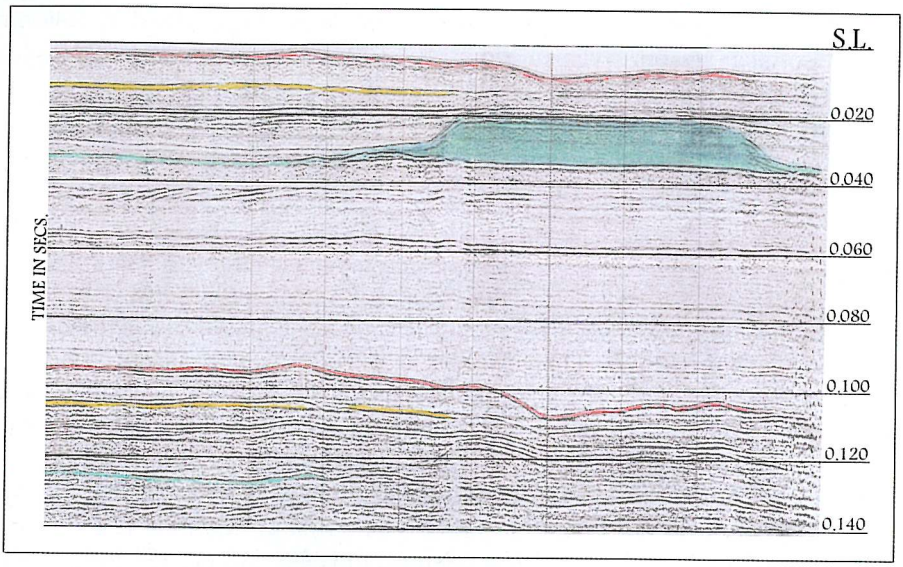

Figure 10-18. Shallow reefs

Facies Changes

The regional thickness and facies variations of the Cretaceous horizons could be exclusively due to the regional depositional setting. However, local thickness variations on the structures as mentioned in various part of this book correspond to the major erosional event and mainly the occurrence of the Turonian unconformity. For example the Upper Sarvak reservoir facies on the Resalat and Reshadat fields is more heterogeneous than the Upper Sarvak reservoir on the Sirri field. The sporadic lateral facies changes of the Sarvak Formation in Resalat and Reshadat oil fields are not yet understood and require detailed investigation.

Reservoir Characterization

The computed acoustic impedance cube represents a real rock property and can be used for reservoir characterization. A quantitative reservoir characterization requires calibration of the acoustic impedance with key reservoir properties such as porosity using well data.

Unfortunately the Resalat and Reshadat well databases do not include any porosity logs. Well data from nearby Sirri C and D fields show that a strong inverse linear relationship exists between impedance and porosity in the Upper Sarvak reservoir. The best porosity conditions in the reservoir are associated with the lowest acoustic impedance values. Assuming that an analogous porosity-impedance relationship exists in the Upper Sarvak and Dariyan carbonate reservoirs in the Resalat and Reshadat fields, a qualitative characterization of the reservoirs can be made in terms of acoustic impedance.

In the Reshadat field, the best reservoir conditions, highlighted by low impedance values, are observed in the north and west, characterized by higher impedance values and probably lower porosities.

In the Resalat field, the lowest impedance values and best porosity conditions are observed in the western part of the structural high. In Reshadat, the best porosity conditions highlighted by the lowest impedance values are observed in the northern part of the field. The highest values of impedance are observed at the western edge of the field, indicating the poorest porosities. In Resalat, impedance values are distinctively lower within the area approximately corresponding to the OWC indicating higher porosities in the oil bearing Shuaiba carbonates. Within the area corresponding to the OWC, only minor differences are observed in the acoustic impedance values, possibly suggesting the best reservoir porosities in the north and relatively poorer porosities in the southwest.

The seismic interpretation resulted in good understanding of the Upper Sarvak reservoir in Sirri C and D fields. The structural definition and thickness estimation of the reservoir has been established and crestal graben over both fields has been defined. The crestal graben could create compartmentalization within both fields at the reservoir. The deep seated faulting has been identifyied and mapped and an improved definition of porosity variations within the reservoir has been developed.

Isopach maps of a number of horizons have been produced resulting in a better structural analysis to determine the structural evolution of the Sirri fields from Top Hith to late Tertiary.

CONCLUSIONS

The 3D seismic interpretations performed within some of the oil field mentioned here have resulted in an accurate definition of the structural geometry, the reservoir thickness and to some extent the reservoir facies variation within these fields in the Persian Gulf.

The detailed investigation has also made possible the integration of the available geologic and well data into 3D seismic interpretation. The results and knowledge obtained from these 3D seismic structural and startigraphic interpretations provide information in order to establish the 3D geological and reservoir model.

The integration of structural geometry, reservoir thickness variation, depositional model and facies variation of the reservoirs together with well data, have provided the basis for the establishment of a 3D geologic model. The experience and knowledge obtained from these 3D seismic interpretations may be applied to nearby fields and prospects within the Iranian offshore of the Persian Gulf.

In the Reshadat and Resalat fields, the seismic interpretation has provided relatively accurate structural map at the top of the Upper Sarvak and top of

mer and strong northerly in the winter. The Strait of Hormoz and its surrounding area in the Persian Gulf approximates a boundary between the two systems.

Temperatures are high, but winters are quite cool particularly at the head of the Persian Gulf. Air temperature reach 45-50°C in summer and fall to 10°C or even lower in winter; sea water temperatures are less extreme, 20-32°C in open waters, but in nearshore areas ranging from 15°C or even less to values in excess of 35°C.

The climate of northern Mesopotamia is characteristically semiarid, with strong seasonality in both precipitation and temperature. Winters are cool and wet with precipitation ranging form 100 to 300mm/yr. The temperature may drop to 7° C in January, whereas summers are hot, very dry, and marked by a persistent northwest wind known locally as the Shamal. Temperatures during summer reach 45° C on most days in June and July. In the winter months of December to February air temperature descends to almost 0°C. At this time of the year, there are strong winds; rain and thunderstorms are characteristic. High temperatures, lack of rain and strong northwest Shamal winds, characterize the summer months.

Rainfall is scanty and begins in October and ends in May. December and January are the rainiest months of the year. The mean annual amount of precipitation is about 115 mm. Winter precipitation results from the eastward penetration of Atlantic and Mediterranean rain-bearing cyclones embedded within the mid latitude westerly flow.

The rainfall is very slight and infrequent and is slightly higher in the northeast. It falls mainly as a few brief downpours from November to April. The relative humidity is high. Cloud cover is small but greater in winter than summer. The occasional flash floods may also transport vast amount of unstablized surface materials.

Relative humidity in the Persian Gulf and along the shoreline areas is generally rather high (>60%) but may fall inland to very low values. Nighttime dew is often heavy and is the main source of water for many desert plants. Thunderstorms and fogs are rare in the Persian Gulf region. Dust storms and haze occur frequently in summer time. The most common and strongest shamal wind, blows from between north-northwest and west-northwest (see Figure 2-3 in chapter-2).

A general lack of rainfall ensures that most of the southern Persian Gulf is a desert. Summer temperatures can approach 50°C on the coast of the UAE, where relative humidity averages between 50 and 60%. Inland, however, temperatures can exceed 50°C and relative humidity is less than 20%. Over the western lowlands of the UAE, annual rainfall is mostly less than 40 mm.

Surface seawater temperatures vary markedly between approximately 12°C to 35°C; however, in the coastal areas under certain conditions, they can reach nearly 40°C. Normal seawater salinity usually ranges between 30 to 35 parts per thousand; however, because of high rate of evaporation in the Per-

sian Gulf region, salinity often exceed 40 parts per thousand in the northwestern portion and can surpass 70 parts per thousands in various shallow, intertidal lagoons on the Arabian side of the Persian Gulf. Such extremes pose enormous environmental stress on many coastal marine species against which might additional impact from pollution must be gauged.

The western Persian Gulf environment is extreme in both salinity and temperature variation. Water temperature in the Persian Gulf generally ranges between 15°C to 35°C, however, temperature below 10°C to as high as 38°C have been reported in the literature (e.g., Pursur, 1973).

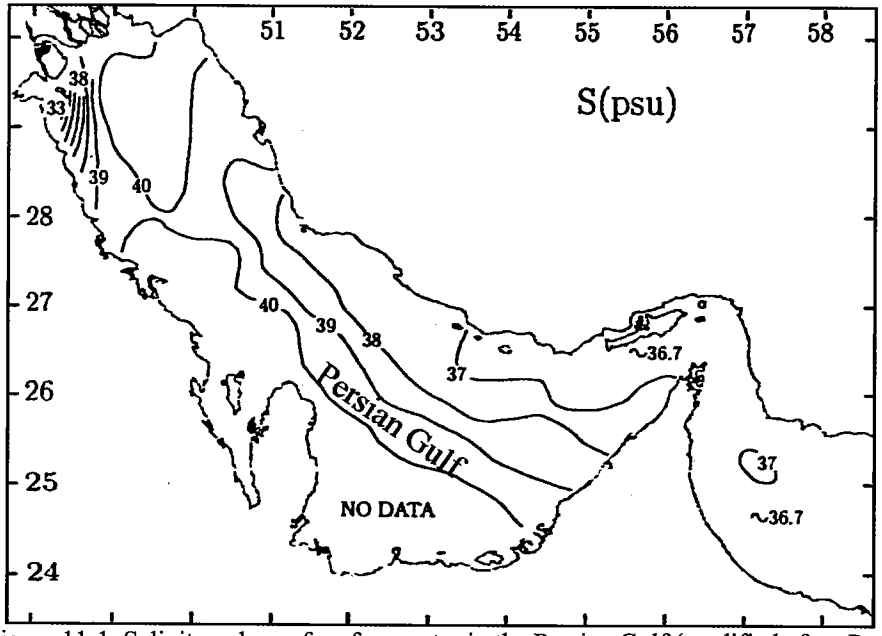

Figure 11-1. Salinity values of surface water in the Persian Gulf (modified after, Pursur, 1973).

WINDS

The Persian Gulf is located between latitudes 24-30°N in which most of the Earth's deserts are situated. The region marks the boundary between tropical circulation (Hadley Cell) and the synoptic weather systems of mid-latitude. Descending dry air in these latitudes produces clear skies and arid conditions.

Regional winds are westerly at the head of the Persian Gulf, swinging to north-northwest in the southeastern Persian Gulf. The area experiences gales but not hurricanes, and thus storm deposits are poorly developed in comparison. The constancy of the regional wind and wave direction is responsible for the formation of extensive sand bodies in the islands and shoals throughout much of the Persian Gulf (Purser, 1973). Orientation of lagoon barriers and

many other sedimentary features along the southern shore of the Persian Gulf are related to the wave approach direction (Purser 1973). Sand dunes orientation, source area for sand, and sand movement directions are also controlled by the regional wind direction.

The most well known, and notorious, weather phenomenon in the Persian Gulf is the Shamal, a NW wind which occurs year round. Shamal is a Farsi word meaning north. The winter Shamal is a wind that sets in with great abruptness and force, and is related to synoptic weather system to the northwest. It seldom exceeds 10 ms^{-1} (<5% frequency) but lasts several days. The summer shamal is practically continuous from early June through July. It is associated with the relative strengths of the Indian and Arabian thermal lows.

The winter Shamal brings some of the strongest winds and highest seas to the Persian Gulf. Winds in the area ahead of an approaching cold front blow from the southeast. The winds called Kaus in Arabic or Shakki in Arabian, slowly increase in intensity as the front approaches. They may reach gale force before the passage of the front and the onset of the Shamal. Due to the channeling of the low-level airflow by the Zagros Mountains of western Iran, the strongest of the southerly winds occur on the eastern seaboard. The Shamal usually occurs first in the northwest and then spreads south.

Prevailing winds blow from the northwest at an average intensity of approximately 1-4 ms^{-1}. These winds tend to generate a consistent surface drift toward the southeast in the central Persian Gulf with speed ranging from 0.2 to 0.7 knots (Linden et al., 1990).

A strong sea breeze occurs along the entire coastline, especially along the Arabian Peninsula. Driven by the intense temperature difference between the land and water surfaces, the sea breeze circulation adds a landward component to all winds. The effect of these winds is to drive surface pollutants to the beaches much faster than they would move otherwise.

Dust phenomena are characteristic features of the climate in the Persian Gulf area. Dust may occur in any month of the year, but it is more frequent and severe in summer, particularly in June and July. Depending on the particle size and wind velocity, dust may take one of the following forms: suspended dust, rising dust, and dust storm.

HYDROGRAPHY

The Persian Gulf is extremely shallow with an average water depth of only about 35 meters (Linden et al., 1990). The entire Persian Gulf marginal sea lies on the continental shelf whose margin and slope occur in the Gulf of Oman. In the western parts of the Persian Gulf the average depth is considerably less with estimates of less than 15 meters; bottom sediment in the subtidal zone of the shallow western Persian Gulf consists primarily of sands or silty sand.

The land surrounding the Persian Gulf is dry so that there is strong excess evaporation over the Persian Gulf. Evaporation (-350 km^3/yr) exceeds freshwater input (precipitation 24 km^3/yr and runoff km^3/yr), creating a net loss of 321 km^3/yr (Linden et al, 1990). This results in a surface inflow of relatively fresh water and an outflow of deeper, more saline water at the Strait of Hormoz. The evaporation also causes a circulation pattern, which is typical for epicontinental seas within the arid climate region (Purser and Seibold, 1973; Reynolds, 1993). Evaporation studies undertaken during the Mt Mitchell research cruise indicated that winter evaporation in the Persian Gulf could be double the rate in the summer.

The annual water evaporation rate in the Persian Gulf ranges from 150 to 400 cm. This is a high rate compared to other marine areas such as the Mediterranean Sea. Moreover, the salinity of the water intensifies from the Strait of Hormoz to the northwestern parts, measuring 38 units per thousand in the Strait to between 60 to 70 units per thousand in Khour Musa. Surface salinities during the winter vary from 37 parts per thousand at the Strait of Hormoz and 40.5 near the head of the Persian Gulf coast to over 70 in the southern Persian Gulf. This water loss is made up by the inflow of seawater through the Strait of Hormoz. Salinity in the northwestern portion of the Persian Gulf is influenced by runoff from the Tigris-Euphrates River. The permanent Tigris and Euphrates Rivers are fed by the drainage of large and distant mountain areas, which have more humid climate. These types of rivers are found only in the Mesopotamian Plain. Among the main rivers of local origin, only the Karoon is strictly permanent.

General circulation in the Persian Gulf is counter clockwise. Indian ocean-Arabian sea surface water enters the Persian Gulf via the Straight of Hormoz while higher salinity water exits along the bottom. Water flows into the Persian Gulf moves north along the Iranian coasts, then south along the southern coasts. Tidal range is 3.5 to 4 meters in Kuwait to one meter in southern Saudi Arabia.

Surface water flows in from the Indian Ocean and sinks to the bottom of the Persian Gulf mainly in the northern part and continuously refreshing the bottom out flow water (Hartmann et al., 1971). The input of surface water from the Indian Ocean also supplies the Persian Gulf with organic matter and nutrients. Circulation in and out of the Strait of Hormoz has not yet been clearly ascertained. However, in recent years great contribution to understanding of the circulation pattern in the Persian Gulf have been made (see Swift and Bower, 2002).

Estimates of the turnover time vary between 2.4-5.5 years (Brewer and Dyrssen, 1985), and perhaps even longer due to the effects of vertical mixing and other turbulent processes (Sheppard, 1993). As such pollutants are likely to remain in deeper parts of the Persian Gulf for long periods of time.

PERSIAN GULF COASTAL MORPHOLOGY

Northern Shore

Persian Gulf, is the arm of the Arabian Sea, situated between the Arabian Peninsula on the southwest and Iran on the northeast. The Persian Gulf extends northwest from the Strait of Hormoz to Arvand Rood, a river formed by the confluence of the Tigris and Euphrates Rivers. The Strait of Hormoz and the Gulf of Oman connect the Persian Gulf to the Arabian Sea.

The boundaries of the Persian Gulf are made by mountainous coasts of Iran on the east and north and the low-lying Arabian coast on its western side. The continental region could be classified as hilly to mountainous. In addition to that the Iranian coastal region is irregular in outline and backed by the northwest southeast trending Zagros Mountains. The relief is very young and the highs represent huge folds which are the product of the Miocene to Plio-Pleistocene Zagros orogeny.

The kidney-shaped Persian Gulf in general, is formed to a great extent by a fold system, which causes its deepest depression to run along its northern side (see Figure 11-2). Thus, the geological and geomorphologic evolution of the Persian Gulf is generally influenced by the tectonic movements and geomorphic processes that took place during the late-Pliocene-Pleistocene age (Kassler, 1973).

In general, the geologic structure, lithology and tectonic strongly control landscape morphology. As a result, the main morphologic features are of tectonic origin with climate and rock types playing only secondary roles. The relief is very young, the principal folding is only of Middle Pliocene to Pleistocene in age, and the movement has been continuing up to the present time with relatively high intensity. The uplift in the region has been continuing up to the present time with relatively high intensity. Vita-Finzi (1979) calculated 1.9 mm of annual uplift in Gachin and Qeshm area near the town of Bandar Abass.

The deep-water axis of the Persian Gulf lies close against the Iranian shore and the basin in cross section is markedly asymmetrical. This asymmetry reflects the very different structural characteristics of the Iranian and Arabian hinterlands of the basin. Most of the topographic features within the basin itself and of its hinterlands are directly controlled by these rather youthful structural elements, only slightly modified by erosion or sedimentation.

Tectonically, Arabian Plate has rotated anticlockwise by 7° causing the movement of the Musandam Mountain bordering the Strait of Hormoz towards Iran. The crumbling which results from this location has led to both the fjordic nature of this entrance and to the narrowness of the Strait itself which is only 56 kilomteres wide at its narrowest point with consequent restriction in water exchange with Gulf of Oman.

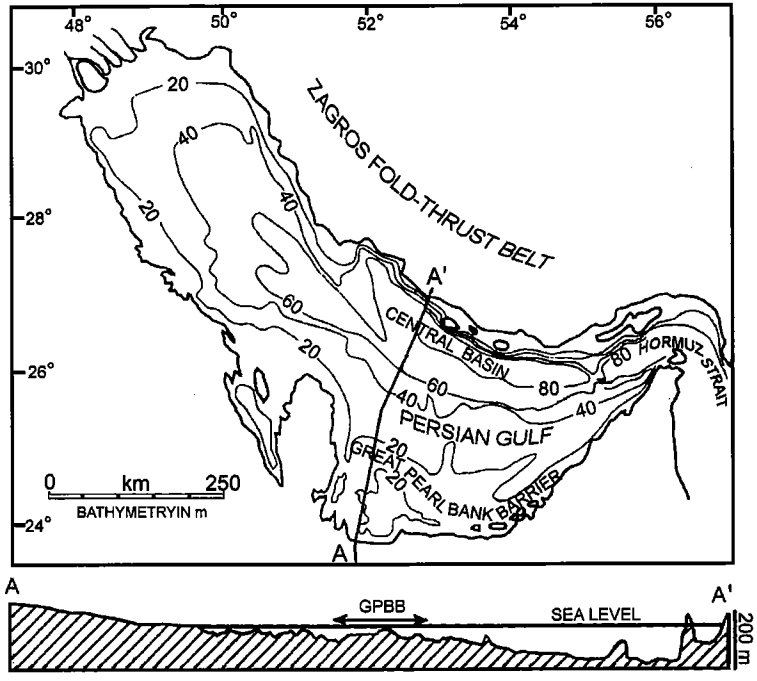

Figure 11.2 Map of the Persian Gulf showing the deepest depression along its northern side and cross section of the basin.

The northwestern Persian Gulf coastline comprises a number of estuaries, extensive tidal flats and salt marshes, mangroves and sand dunes. The eastern half is mainly rocky with limestone cliffs near the Strait of Hormoz. The chief islands in the Persian Gulf are Qeshm and Bahrain.

The majority of Iranian coastlines tend to be mountainous and fringed with rocky cliffs, while sandy beaches border the Arabian shore, broken by many small islands and lagoons. Large banks of pearl-producing molluscs are found on the Arabian shore. Spectacular cliffs rise from the shore around the Musandam Peninsula near the Strait of Hormoz. The Tigris, Euphrates, and Karoon rivers deposit large amounts of silt as they empty into the Persian Gulf in the northwest.

The southwestern littoral of the Persian Gulf from Kuwait to Musandam Peninsula is strikingly different from the northern littoral in terrain. Instead of a narrow strip of lowland or terraces pressed against or even into the sea by mountains, the Arabian littoral consists of a broad plain, dipping gently into the sea from the far interior: the lowest part of the down tilted slope of the great Arabian block. An elevation of 200 meters above sea level is not attained until 45 to 75 km inland in most of the littoral; several hundred kilometers at the northern and southern ends. Across the plains no streams, even in-

termittent ones, reach the Persian Gulf, although there are some long inconspicuous, sandy beds of Wadis leading across the interior.

With the exception of Musandam peninsula and north central Oman Mountains, the southern part of the Persian Gulf occupies a broad strip of land flanking the southern shores of the Persian Gulf between the Qatar peninsula and the Gulf of Oman. Much of that land consists of relatively low-lying rolling dunes and inter-dune areas forming the northeastern limit of the Rub al-Khali, which reach 150 m above sea level.

In the northern UAE, the dunes extend up to the Oman Mountains. To the southeast, however, the eastern limit of the dunes coincides approximately with the Oman border, where they overlie the deflated (wind eroded) surface of sub-horizontal fluvial sediments that had earlier been transported westward from the mountains.

One of the most morphologically pronounced areas in the southern part of the Persian Gulf is Qatar Peninsula. Qatar forms an exposed part of the Arabian shelf between the Arabian shield and the mobile belt of Iran. Topographically, Qatar has a low relief landscape with a maximum elevation of about 110 meters above sea level. Structurally, Qatar is an elliptical anticline arch with a north-south axis. Karstic landscape is widespread on the Qatar peninsula, including depressions, sinkholes, caves and solution hallows (Sadiq and Nasir, 2002).

The sharp difference between the two coasts of the Persian Gulf, a flat stable, carbonate-dominated cratonic plain and an active Iranian mountain range reflects the collision of the Arabian and Eurasian plates. The compressional regime also resulted in the formation of a broad structural depression, about 2000 kilometers long which extended from Strait of Hormoz to Syria, and which eventually became the extensive sedimentary basin, including the Metsopotamain Plain and the Persian Gulf. The structural asymmetry of this foreland basin strongly affects modern sedimentation (Purser, 1973), notably in the distribution and rates of clastic sedimentation.

The Zagros Mountains represent the deforming part of the Arabian platform as attested by the active seismicity and the folded upper layer of sediments. The Persian Gulf has not been deformed as much as Zagros Mountains and this is consistent with the lack of seismicity.

Topographically, the Zagros Mountains can be divided into three zones: a 50 km wide coastal foreland consisting of elongated, symmetrical folds; a 225 kilometers wide belt, northeast of the coastal foreland where the sediments are deformed into larger and tighter folds than those in the foreland; and a 50 kilometers wide region of overthrusts (Zagos Crush zone) where the rocks are extensively deformed and the sedimentary sequence down to the Paleozoic is exposed.

Folding of the Zagros during the Miocene to Plio-Pleistocene may have been discontinuous, becoming younger to the southwest. Locally, some of the coastal hills are cut by terraces and flanked on the seaward side by the sand

flats and salt marshes. A similar type of coast north of the Strait of Hormoz is fronted by a narrow belt of mangrove swamps.

Planation surfaces are developed only at a small scale. Both river and marine terraces systems document the cyclic nature of the uplift which occurred in the Persian Gulf region and the sea level changes. Relics of abrasion and accumulation of the marine terraces are visible along the coastal areas and also on many of the small islands in the Persian Gulf. The best examples of coastal terrace are developed between Puhal and Lashtegan, comparable with abrasion terraces at +15 meters on Hormoz Island (cf. Gansser, 1960). Higher terraces at +25 to +30 meters above sea level have also been observed on the Hormoz Island. Quaternary conglomerate and beach sand can be found even as high as at +100 meter above sea level in islands and on some of coastal plugs (Gansser, 1960). Such geomorphic features provide evidence for younger vertical movements of the area and an uplift of salt plugs (cf. Kent 1958) in the Persian Gulf region.

Many salt diapiric structures are present throughout the Persian Gulf region, both onshore and offshore. These diapiric highs have exerted a considerable control over sedimentary facies distribution (Purser, 1973). Numerous islands and shoals are present and some of them represent crests of folds or salt plugs and others merely depositional features composed of unconsolidated and partially consolidated Quaternary deposits.

The salt plugs of the southern part of Iran near the northern shore of Persian Gulf have a special morphology, forming highly positive or negative forms of relief, reflecting the plug activity. About 200 salt plugs (Kent, 1970) have been known in the area of the Persian Gulf. Salt plugs (diapirs, domes) are still morphologically active (e.g., Furst 1970; Talbot and Jarvis, 1984). They have different diameters, and a conical shape with clear evidence of mushrooming near the surface (Kent, 1958). They contain "exotic blocks" with diameters up to 2 km. The salt plugs expose abundant fragments of igneous rocks, dolomite and anhydrite, which are concentrated in alluvial fan sediments deposited in the vicinity of the diapirs. Salt diapirs are common in the Makran coast of Iran and in the Persian Gulf, but are absent from the Mesopotamian Basin (Edgell, 1996).

SOUTHERN SHORE

Tucked in the southernmost corner of the Persian Gulf is a chain of eight or more barrier islands. They line almost about 75 km section of the Abu Dhabi coast, better known as the Trucial Coast. These are the hottest, driest barrier islands in the world. Accompanying the very low rainfall are the high temperatures of the Arabian Desert, the warm near shore sea waters with high salinities of the Persian Gulf waters. Normal oceanic salinity is around 35–36 parts per thousand, in contrast to open Persian Gulf salinities of 42–45 parts per thousand and 55–65 parts per thousand in the lagoons behind the barrier

islands. Shamal wind comes mainly from the northwest, essentially perpendicular to the barrier island shorelines. The Abu Dhabi barrier island sand grains are all calcium carbonate.

Abu Dhabi Barrier Island system is clearly the intertidal area with barrier islands lined one after the other in west-east direction. The tidal amplitude is 1-2 meters. In the Abu Dhabi barrier island system the key property is the broad transition from the sabkha to the intertidal zone, which means a very flat gradient from absent to rich productivity.

The barrier island chain formed atop a rocky offshore ridge almost parallel to the shoreline called the Great Pearl Bank. The bank was the primary site of the pearl industry before the coming of oil. Between the Great Pearl Bank and the mainland is a low trough occupied by the Kor al Bazm Lagoon.

These islands nucleated around ancient coral reef islands that once grew in a higher sea level, three thousand or four thousand years ago. Sand was pushed ashore from the nearby shallow waters and then carried laterally by longshore currents to lengthen the islands. Outcrops of the corals, originally responsible for the location of the islands, are still visible on some islands, but there are lots of other rock outcrops that are not of coral origin. These are beachrocks and play an important role in island evolution. Beachrock forms a long, narrow band, few meters wide and less than one meter thick, down the length of a beach between the high and low tide lines. The rock is beach sand, cemented in place by calcium carbonate precipitated out of seawater. It has the same layering that is in the beach, the glass fragments, may be cemented in the rock.

The extensive beachrock outcrops on the Islands are responsible for the blocky shapes, the sharp corners, and the straight lines in the island outlines. Normally, the outlines of barrier islands are smooth and rounded. In several instances in the Islands, beachrock that originally formed along the margins of an inlet now extends offshore like a jetty, left there by the retreat of the ocean shoreline, which exposed the beachrock that once lined the inlet.

The triangle shape of the Abu Dhabi barrier Islands is unique. The bases of the triangles, which face toward the sea, consist of the dunes (some as high as 10 meters) and overwash fans typical of barrier islands everywhere. The landward pointing tip of the triangles is a mud and sand flat extending into the lagoon from the island. The flat was formed by wind-blown sand taken from the island by the dominant northwestern winds as well as by mud-and-sand-bearing floods during storms and spring tides.

The sediment tails forming the triangles behind the islands are slowly expanding, so eventually the shallow lagoons behind the Abu Dhabi islands will fill in (as will all lagoons everywhere if sea level will hold still).

MESOPOTAMIA PLAIN

The head of the Persian Gulf in the north is bordered for 200 kilometers by the extensive composite delta of Metsopotamia. "Mesopotamia" originally referred to the land between the Tigris and Euphrates Rivers, but the term has been extended to the entire alluvial plain that extends inland about 750 kilometers from the shores of the Persian Gulf. The area is a deltaic landform formed by sedimentation and floodplains of the Tigris, Euphrates, and Karoon Rivers. The Karoon River, rising in the Iranian Zagros, joins the Arvand Rud at Khorramshahr.

The rivers of Mesopotamia are significant as creators of the landform. They are also resources for water supply and transportation. The main arteries of the plain are the Tigris and Euphrates, heading in the mountains of Turkey and flowing through Mesopotamia, and finally joining to form a single river.

The Iranian portion of the Mesopotamia includes all lower courses of the Karoon River and of its tributary the Jarrahi. Much of the water of the Jarrahi is lost in the extensive coastal marshes through which it meanders. The principal stream in Iranian Mesopotamia not connected with the central system is the Hindijan or Zuhreh River. It leaves the mountains near the southeastern corner of the plain and winds through the alluvial lowlands before emptying into the Persian Gulf at the eastern edge of the coastal marshes.

The alluvial plains of Iraq occupy a structural trough, known as the Mesopotamian Basin (Figure 11-3), which is linked to active subduction-related orogenic processes in the Zagros Mountains (Jassim and Buday, 2004). The Mesopotamian Basin is part of the larger Zagros foreland basin associated with the closure of the Neotethys and the collision of the Arabian passive margin and Eurasian plate (Beydoun et al., 1992; Bahroudi and Talbot, 2003). Convergence in the Zagros collision zone is still going on, and the region is currently tectonically active (Berberian, 1995).

The Mesopotamian Basin is floored by crystalline basement rocks of the Arabian shield (Bahroudi and Talbot, 2003). Overlying the basement is a thick pile of sedimentary rocks consisting of: 1) an attenuated Paleozoic succession; (2) a well-developed Mesozoic succession; and (3) a Cenozoic succession of Eocene to Pliocene rocks, overlain by Pleistocene to Holocene alluvium (Beydoun et al., 1992). The alluvium, consisting of clay, silt, sand and gravel, is related to the floodplain of the Euphrates and Tigris rivers and associated swamps, as well as to marine incursions.

The discovery of the remains of a 9000 year-old boat far inland in the Kuwaiti desert points to a former rise in Holocene sea level (Lawler, 2002). Larsen and Evans (1978) estimated that the recent sediments of the Tigris-Euphrates plains were deposited in the last 5000 years, during which about 130-150 km of seaward progradation has taken place.

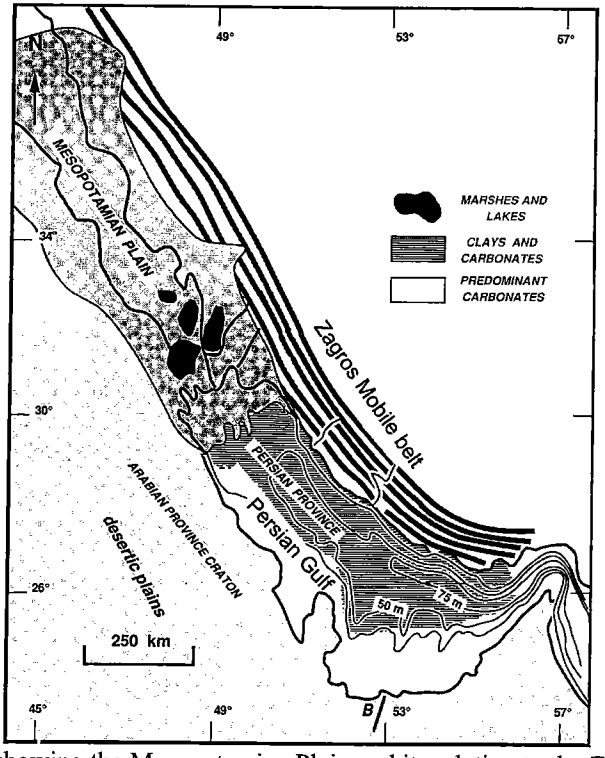

Figure 11-3. showing the Mesopotamian Plain and its relation to the Zagros and its extension into the Persian Gulf.

The geological and geographical history of the Tigris-Euphrates-Karoon delta region and the head of the Persian Gulf have been debated since the 1830s. It has been argued from historical evidence that the former head of the Persian Gulf was situated much farther inland in Mesopotamia (Larsen and Evans, 1978; Hansman, 1978). In addition, many authors presented evidence for the presence of recent marine or estuarine fauna far inland from the current head of the Persian Gulf, especially in the vicinity of Basra (Mitchell, 1958a; Dance and Eames, 1966).

De Morgan (1900) was the first to reconstruct palaeogeography of the Mesopotamian delta. However, Lees and Evans (1952) questioned his model of a simple outbuilding delta, and presented evidence for a more complex interplay of tectonically-induced subsidence and fluvial-aeolian aggradations in the delta region supported by later observations (see Mitchell, 1958a, b; Hansman, 1978).

The siltation and saltiness of Mesopotamian watercourses, ascribed to poor agricultural practices are thought to have arisen partly as a result of climatic changes and increased aridity (Weiss et al., 1993; Issar, 1995). The shifting watercourses of the Mesopotamian floodplain represents a dynamic system in

which there is an interplay of natural processes, including neotectonic subsidence, fluvial-aeolian aggradations, eustatic marine incursions, and human-induced canalization, draining and dredging (Nicholson and Clark, 2002).

Mineralogical study of the sediments of the Tigris and Euphrates Rivers, the Arvand Rud, and some older terraces, shows similar source areas with the main light mineral fraction made up of quartz, cryptocrystalline silica, carbonates, biotite, muscovite, chlorite, plagioclase feldspars and heavy minerals (Philip, 1968). The suspended loads of the Tigris and Euphrates show marked differences, with the Euphrates richer in both chlorite and expandable lattice clays (Berry et al., 1970).

Clay minerals from the oil field west of Basra, and found mainly mixed-layer illite-smectite clays and chlorite, suggesting a marine depositional environment. Such evidence was explained as the result of marine incursions due to tectonic subsidence (Lees and Falcon, 1952; Mitchell, 1957). However, Larsen and Evans (1978) invoked eustatic sea-level changes, and attributed the marine sediments to transgressions during Holocene highstands. This is supported by radiocarbon dating of marine terraces in Kuwait, which are dated at between 4570 ± 70 years B.P. and 3250 ± 80 years B.P. (Al-Asfour, 1978).

The rivers are subject to floods during winter rainstorms and particularly during the melting of mountain snow in the spring. The Tigris, on the mountainside of the valley with large tributaries, has more severe floods that the Euphrates, on the desert side of the valley. Thus, the Tigris River seems to be the main source for floods causing a great deal of environmental changes in the area. The sediments of the Mesopotamian plain are undeformed, while their substrate is only very gently folded (Lees and Falcon, 1952; Lees, 1955).

ISLANDS MORPHOLOGY

The offshore islands in the eastern Iranian part of the Persian Gulf extending from Lavan to Larak Islands are rocky with substantial coral reef development, particularly in the east. Some of the offshore islands such as Larak and Hormoz are mainly salt plugs, partly fringed by the coral reefs and marine terraces. They are small with more or less oval to circular shape and built by salt domes and some sedimentary rims with relatively low morphology and abrasional shore formations.

Qeshm Island follows the shoreline in the Iranian waters is the largest Island in the Persian Gulf, situated in the western part of the Strait of Hormoz. It is 120 km long and up to 30 km wide and close to the mainland (see figure 11-4).

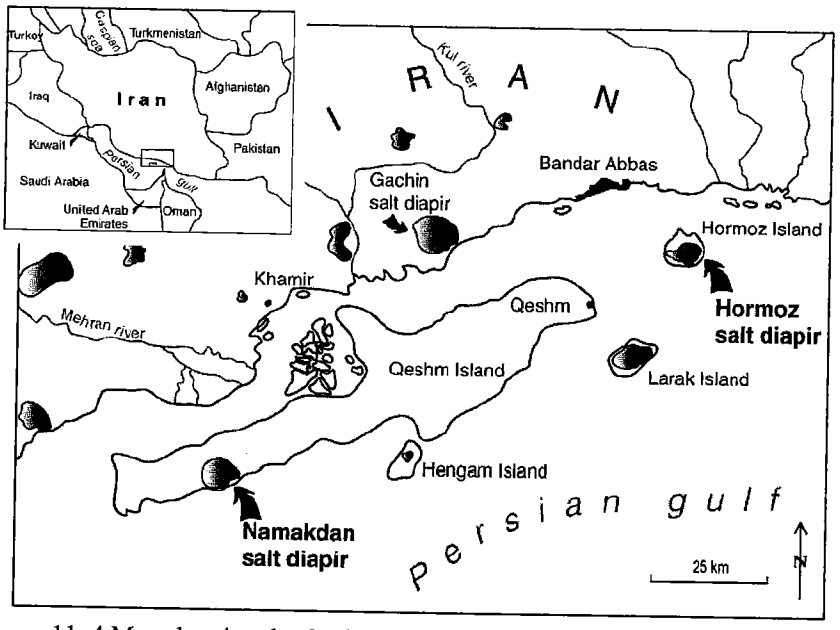

Figure. 11. 4 Map showing the Qeshm, Larak and Hormoz Islands and surrounding areas in the Persian Gulf

Qeshm Island has many different intertidal zones, sandy, mixed, and muddy. Sandy flats are found along the relatively well exposed southern shoreline. Intertidal flats attain a width of more than 2 km and in the west and north and exhibit numbers of macrobenthic individuals, mainly mud skippers and large crabs. Cyanobacterial mats cover the lower supratidal zone around mangrooves. The tidal amplitude is in the range of 2.5 meters. Intertidal flats extent mainly along the northern coastline. The most important feature is the "Hara", which is by far the largest mangrove area of the Persian Gulf, covering approximately 20 km by 20 km, dissected by a net of tidal channels, and continued on the opposite mainland (see Figure. 11-5).

The discovery of the world's largest salt cave called Namakdan (see figure 11-4) in Qeshm Island was reported in 2006 by a joint team of geologists from Iran and Czeck Academy of Science. Caves and cave systems with salt speleothems are abundant in Qeshm Isalnds. Numerous large depressions of the uvala or polje type have been reported (Bosak et al., 1999). Caves are often developed within in several levels.

Karst landforms are also developed on the Hormoz complex. Distinct karst features have resulted from the differential salt solution in Hormoz and Qeshm Islands and karst forms represent a distinct part of the surface morphology in these Islands (Bosak et al., 1999). There are numerous elongated to irregular solution and collapse dolines, large uvala-like depressions, elon-

gated asymmetric dolines with ponors in Hormoz Island where several caves were found and karstic forms have been identified.

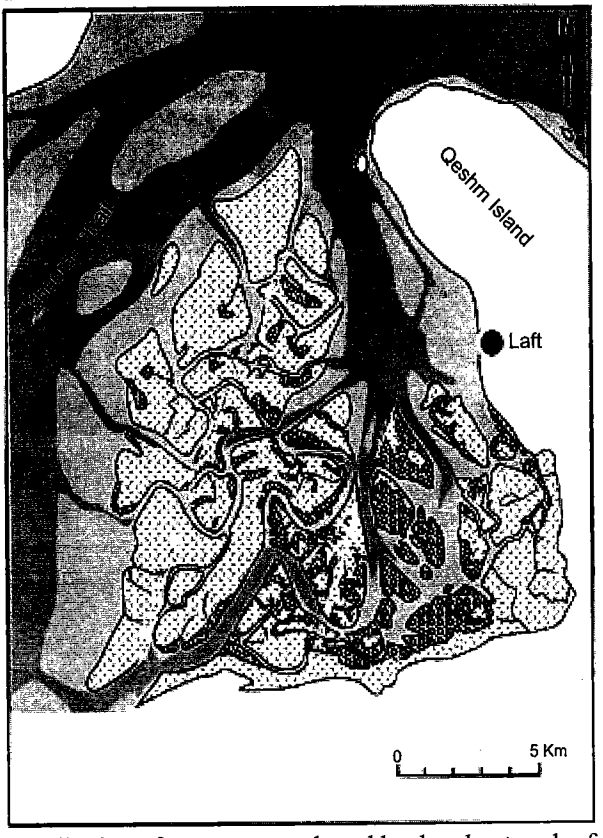

Figure 11-5. Distribution of mangrove and mud bankand network of channels and associated tidal channel in the northern shore of the Qeshm Island in Persian Gulf.

PERSIAN GULF MARINE HABITATS

Very extensive coastlines of the Persian Gulf present variable environments which include different types of ecological sensitive area and this is followed by the existing biodiversity seen along the shorelines.

The Persian Gulf is represented by at least four critical marine habitats, which include; 1) coral reefs, 2) mangroves, 3) coastal marshes and mudflats and 4) seagrass beds. The adjacent lands also support a number of key terrestrial habitats, including riverine marshes and undisturbed desert biotopes.

Elevation and depth contours in western and southern Persian Gulf are generally extremely gradual, leading to a sedimentary environment, encouraging growth of seagrass and algal beds. While soft substrate habitats dominate in terms of area, hard substrate habitat is important, particularly away from the coasts. These include coral reefs and carbonate platforms with substantial algal growth.

Coral Reefs

The Persian Gulf represents one of the most extreme environments in which coral reefs are found. The high salinity, water turbidity, extreme of temperatures and high evaporation rate prevent the development of extensive coral reef systems. The best developed reefs are restricted to offshore island areas.

The Persian Gulf is at the northerly limit of coral reef distribution and due to fluctuations in temperature and salinity it forms a highly stressful environment for corals. The low winter temperatures are probably ecologically a limiting factor for corals development in this environment.

Few coral species can survive in highly saline waters (i.e., 40–70 ppt) of the Persian Gulf. The reefs that do exist and grow in the Persian Gulf are of interest for the very reason that they do survive in such harsh saline environment. Corals in the Persian Gulf can withstand temperatures much higher than corals from other reefs in the world and, therefore, are of scientific interest in studies of the impact of increased sea temperatures and global warming on coral reefs. Reefs surviving under such conditions could be particularly vulnerable to additional environmental pressures such as oil pollution; alternatively, they could be much more resilient, with an ability to adapt to difficult conditions.

In terms of biodiversity, reefs in the Persian Gulf are relatively impoverished and the coral diversity is low compared to truly tropical areas. The most extensive coral reef communities are found in the western part of the Persian Gulf. Extreme fluctuations in water temperature and high salinities affect coral species diversity and many species live near their maximum tolerances.

Corals are rarely found below 15m in the Persian Gulf and the most extensive developments occur at depths of less than 10m. Coral cover drops from 75% to 40% below 10 meters, and decreases to 10% below 15 meters. Where suitable substrates occur, there are communities of scattered corals with live coral cover approaching 10% in places. The major stresses are dramatic temperature fluctuations (ranging from 18°C to 34°C, with a mean of 27°C, and daily fluctuations of 8–10°C during summer). Others include infrequent episodic rain, coral bleaching and cancer, black and white diseases, and oil pollution. The near shore reefs of the Persian Gulf were severely damaged by coral bleaching in 1996 and 1998, while offshore reefs were less affected. However major coral bleaching occurred in the year 2000. Coral bleaching was observed in *Acropora* and some brain corals.

Many similarities exist between coral communities in different part of the Persian Gulf. *Acropora clathrata* dominates the communities and have been described from Kharg Island in the Iranian waters (Shinn, 1976), Kuwait and Saudi Arabia (Fadlallah et al., 1993).

Coral reefs in the Persian Gulf occur mainly as numerous patch reefs. However, fringing reefs are found around offshore islands. They consist of

shallow fringing reefs influenced by runoff from the land, but experience large variations in salinity and temperature. Coral reefs fringe the offshore islands and numerous small patch reefs are present near shore. The best fringing reefs are developed around Larak and Hengam Islands. Large areas of the subtidal zone consist of consolidated sandstones covered by a thin layer of sand with scattered patches of hard substrate. Coral communities and patch reefs are found off the southern coasts of Persian Gulf.

The Iranian coast of the Persian Gulf has limited coral reef development, except around the offshore islands at the eastern end. The Persian Gulf's best reef system is located around Kharg Island, which is situated relatively close to (180 kilometers) the Arvand Rood delta. Larak and Qeshm Islands are fringed with reefs. The other main reef area is in the Strait of Hormoz. Thus, a few reefal communities that occur on the 2000 kilometers coastlines of Iran, around the islands near the Straits of Hormoz. At the entrance of the Persian Gulf reef community is dominated by *Porites* and *Acropora.*

Most of the Persian Gulf floor has soft sediments and the coasts have gentle slopes with vast shallow areas of sandy and muddy bottoms, thus there are few reefal developments. Huge expanses of sandy substrate, essentially devoid of any hard substrate or macrophyates, cover the majority of the shallow subtidal zone.

Off Iranian coast at 29° 15'N, 50° E, at a depth of 28-35 meters the undulating terrain is a reef complex with an area of 350 km^2 (Graf, 1993). Also on the outer shelf of Qeshm Island is a cluster of pinnacles which are the result of reefal growth; such constructional features are common in a platform that is characterized by high amplitude flooding.

Coral reefs grow in the offshore, clear waters near Kuwait and Saudi Arabia in the Persian Gulf. Some fringing reefs have developed at a few sites near shore, but they are not well developed due to extreme variations in temperature and light. The rest of the area consists of mud or sand, with some dense seagrass beds. A ribbon of coral reef extends from the Saudi Arabian border to the mouth of the Gulf of Bahrain. Evidence suggests that western Persian Gulf organisms are extremely tolerant (Sheppard and Price, 1993). Reef development and diversity decline with increasing salinity and sedimentation in the south. Coral reefs of this area are exposed to a greater annual temperature range than that found in the world. The principal inshore reef building coral, *Porites compressa*, and various faviid corals survived lengthy exposure (four days) below 11.5° C, a period longer than reported elsewhere (Coles and Fadlallah, 1991). Big boulders of *Porites* coral often make up the main bulk of the reef.

Kuwait has very limited reef growth, not exceeding 4 km^2. The Kuwaiti offshore coral islands are renowned for its coral reefs and sandy beaches. The Kuwaiti reefs are the most northerly in the Persian Gulf; although there are isolated outcrops on the mainland, the best developed reefs are around the

offshore islands. All are in shallow water (mainly less than 15m) and have rather low coral diversity.

Isolated corals grow on rocky outcrops, and there are some reefs around offshore cays. Oil pollution and sedimentation cause the largest impacts, and many reefs were impacted during the Gulf War, with some long-term effects of oil pollution. Sewage, outbreaks of sea-urchins, and damage from anchors are other problems. Immediate impacts from oil spills during the Persian Gulf War were less than generally expected, indicating a high resilience among reef communities.

The marine environment of Bahrain is highly stressful for reefs; coral communities are found only off the north and east coasts, and there is evidence that most of these are not true, actively growing reefs. The slopes are gentle with loosely attached corals and little true reef growth. Coral cover is generally less than 10%. The main human impacts arise from the dumping of dredged sediments, land reclamation, and from oil pollution. Areas of sparse *Porites lutea* growth have been reported from Bahrain (Sheppard and Price, 1993).

Qatar has shallow reefs of low diversity, the best-developed being on the eastern coast. The western coast of Qatar and the Trucial Coast of the UAE supports a mosaic of coral reefs, seagrass beds and saltmarsh.

A long ribbon of coral reef extends from Bahrain, down the east coast of Qatar and along the UAE coast. The Trucial Coast is low-lying with extensive tidal flats, lagoons and sand dunes. The shallow water is subject to extremes of temperature which breaks up the ribbon of coral reef into discontinuous sections. The numerous offshore islands and banks support coral and seagrass with sandy beaches.

High salinity, temperature extremes, and shallow waters limit reef growth around the 560 km long Qatar peninsular in the Persian Gulf. Reefs are best developed in the east, but are shallow and low in diversity. The major threats are oil, solid waste and sewage pollution, and impacts from coastal developments.

MANGROVES

Mangroves are salt-tolerant trees usually found in mudflats. In the Persian Gulf they occur along the upper intertidal zone in bays and mudflats, although they tend to be poorly developed and patchily distributed.

Mangroves of the Persian Gulf are primarily comprised of *euryhaline* and *eurythermal* species *Avicennia marina* which occurs naturally due to the extremes of salinities and temperature characteristics of the Persian Gulf. *Avicennia marina* (Farsi name for this tree is Hara) and *Rhizophora mucronata* trees are amongst the mangrove trees of Iran (DOE, 2004a). *Avicennia marina* is found in all of the habitats and is the most tolerant of mangrove species with respect to temperature fluctuations and salinity levels. Due to

their high biological productivity, Mangroves act as critical marine habitats for various marine lives. Hara biosphere contains the largest stand of mangrove along the Persian Gulf coast shoreline and is also of major importance to breeding, wintering and migrant birds.

The mangrove forest in the Persian Gulf, which is a continuation of the forests in Southeast Asia and the Indian Ocean, are also very important from the ecological viewpoint. The occurrence of only one species in the Persian Gulf contrasts strongly with the much higher diversities found on contiguous shorelines of northern India, and with the Red Sea where *Avicennia* occurs with three additional genera. In the Persian Gulf proper trees are poorly developed and reach 2 to 3 meters tall.

Mangroves are more abundant along the Iranian coasts but they also occur in southern parts of the Persian Gulf and the densest stands are in the Strait of Hormoz. The Iranian coast and northern shore of the island also has an estimated 8,900 ha of mangrove stands, although some have recently been felled. The largest stand is in the Khooran Straits within the Hara Protected Area. The largest mangrove forest of the Persian Gulf occur in many intertidal flats in the inflow of the sea water into the Persian Gulf particularly in the northern part of the Qeshm Island (figure. 11-4). Thus, the Iranian shores of the Persian Gulf contain most of the mangroves in the region. Mangroves are absent from Iraq and Kuwait, perhaps due to climatic effects of latitude or because of intensive human use in the past. In Saudi Arabia and Bahrain, mangroves have limited extent.

In the Persian Gulf, the extent of mangroves has been declining due to the impacts of unplanned coastal development, with only about 125-130 km^2 remaining (90 km^2 off Iran, 10 km^2 off the Persian Gulf coast of Saudi Arabia and Bahrain, remainder along the UAE coast).

The roots of mangrove tree trap fine-grained sediment to form a nutrient rich substrate for the development of a complex, productive community of organisms. Mangrove and seagrasses can cause bioturbation and their decayed roots forming channels and cavities in the sediments.

Mangrove roots and litters produce an organic-rich layer which decays under the action of microorganism. This organic matter is preserved in the form of small tubes and plant fibers. Moreover, the byproducts of organic decay create and maintain a slightly acid environment in which fine carbonates dissolve. This dissolution seems to be confirmed by the quartz concentration, which is significantly higher in the fossil mangrove soils. The abundant quartz fraction could be due to aolian transport. But the dissolution of shells in sediments rich in organic matter is observable, and the calcium content of the interstitial waters of the mangrove palaeosol are higher than that of neighboring sediments, whereas the salinity remains similar (Baltzer et al., 1990).

Mangroves-associated mudflats are probably richest wader (shorebirds) feeding habitat in the Persian Gulf. The trees provide shelter and cover from predators and the fine-grain substrate provides an abundance of organisms for

food. Mangroves, particularly their root system, could be very sensitive to changes in coastal water quality; especially from the impacts of large petroleum spills.

Seagrass Beds

Seagrasses are one of the primary producers in the food chain and are usually found in tidal and subtidal areas. Seagrass typically grows in the form of submarine "pastures" in shallow inshore waters. These pastures are vital feeding areas and form the basis for many food chains.

Seagrasses or underwater meadows are plentiful near shores. They occur principally in shallow (< 10 meters) coastal areas. The most extensive areas of seagrass bed development occur in the western part of the Persian Gulf, since it is the largest area of shallow sea beds. Seagrass ecosystems represent one of the most critical marine habitats in the Persian Gulf and provide food or shelter for more than 500 species of plants and animals.

The dominant seagrass species known in the Persian Gulf is *Halodule uninervis*, a eurthermal species particularly tolerant to high salinity. Living *Halodule uninervis* occur immediately below the lower limit of intertidal zone. Seagrasses are also characterized by high biological productivity, represented by the species *Halophila ovalis, H. stipilacea* and *Halodule uninervis*, located in subtidal shallows from 0.5-6 metres. They occur along the coasts from Iran, through Iraq and Kuwait to beyond Bahrain and UAE. The coast of UAE is low lying and mostly swampy. Offshore, the water is very shallow and rich in seagrass, and while it is generally muddy and unsuitable for most corals, there are numerous patch reefs. The distribution in Kuwait is limited whereas in Saudi Arabia, the greatest concentrations are between Safaniya and Manifa, in Musallamiyah and the south of Abu Ali, and in the Bay of Bahrain.

Seagrasses are prone to physical and physiological damage as a result of oil pollution, and certain species are known to be affected adversely by dispersants commonly used to combat oil spills.

Extensive algal flats and seagrass beds cover a substantial portion of the bottom in the relatively shallow waters and they account for a major portion of the net production. Coral reefs are considered more productive than seagrass beds even though they cover a relatively small portion of the subtidal zone.

Mudflats and Salt Marshes

Along the Iranian coasts of the Persian Gulf there are extensive mudflat areas with total extension of 7234 km^2. Most of the mudflats are composed of mud and fine-grained sediments.

At the head of the Persian Gulf, the extensive Shadegan Marshes and tidal mudflats of Khor-al Amaya and Khor Musa are designated as a Wetland of International Important under the Ramsar Convention. This area of some 190,000 ha comprises the alluvial delta plain of the Karoon and five other rivers. The mudflats are barren of vegetation except for some characteristic salt marsh species.

Khowr-e-Mussa consists of a basin surrounded by a corona of numerous tidal creeks of varying length and width, linking to the Persian Gulf by a 50 kilometers long estuary-like channel. The salt marshes and mudflats provide rich habitats.

The deltas of Rud-e-Shur, Rud-e-Shirin and Rud-e-Minab form a continuous strip of coastal wetlands extending for some 55 kilometers along the northern shore of the Strait of Hormoz. It is a large area of intertidal mudflats, mangrove swamps and sandy beaches in the contiguous deltas of three rivers. The wetlands of these deltas are good representative examples of the mudflat and mangrove ecosystem characteristic of the coasts of the Persian Gulf. This wetland includes extensive intertidal mudflats of over one kilometer wide at low tide. The sediments consist of alluvial deposits, silt, sand and mud.

There are about 300 ha of mangroves at the river mouths and along adjacent creeks, and there are long sandy beaches, low sandbars and sand spits. Two large shallow bays, Khor Tab and Khor Kolahy, occur near the mouth of the Rud-e-Minab. The rivers are dry for most of the year, flowing only after heavy rainfall in the interior (usually in winter). The waters of the Rud-e-Minab and Rud-e-Shirin are fresh, but that of the Rud-e-Shur is somewhat brackish. Arid, sandy plains with open thorn woodland stretch inland from the coast.

One of the most important areas in the Persian Gulf in terms of mudflat development is the Bay of Kuwait which is about 30 kilometers wide and about 45 kilometers long. The mean tidal amplitude is in the range of 2 meters and about two thirds of the bay is dry during low water. Intertidal flats of a width of up to several kilometers stretch mainly along the northern coast. The muddy character is extreme, and there are mudflats in the inner part, which are virtually inaccessible. The Bay of Kuwait is a huge area and seems to serve as a trap for receiving exclusively finest grained sediments from the Arvand Rud.

Sandy Coastlines and Tidal Flats

Sheltered and exposed tidal flats exist along the Persian Gulf coastline. Many sheltered flats are associated with salt marshes and their sediment is largely very soft silt. Exposed tidal flat tend to have larger-grained sediments than their sheltered counterparts, but some fine-grained flats occur along the open Persian Gulf coast.

Exposed sandy beaches are of low biological productivity and are dominated by gastropods and ghost crabs (*Ocypode* spp.) They are well distributed throughout the Persian Gulf. For example some 350 kilometers of the Saudi Arabian shoreline comprises sandy beaches.

Intertidal areas exposed to the open waters consist primarily of sandy beaches with an occasional wide tidal flat. Extensive tidal flats have developed in the sheltered water of the numerous embayments along the coast of Saudi Arabia. The intertidal zone within these embayments is conductive to the development of salt marsh and mangrove communities. Seagrass beds and algal-covered rubble are commonly found within these embayments. Intertidal areas of the Persian Gulf are generally or at least potentially hypersaline. In some areas, salinity reaches 45 psu and saturation could be observed. As a contrast, in the intertidal zone of Qeshm, salinities are only around 39 to 42 with single top values of 45 psu, independently of tide and seasons.

Tidal deposits are broadly developed, between the deltas and Qeshm Island in the northern shore of the Persian Gulf. In this region, there is a system of typical tidal marches, sandy-muddy flat islands separated by shallow tidal channels. Some of the islands are covered by mangrove. The tidal zone proper is also relatively broad due to the gently sloping shore; it is covered by fine-grained sediments. In places, short sandy beaches are also present with distinctly developed backshore sand bars.

Saudi Arabian coasts consist of sea-influenced sabkhas, dunes and salt marshes. In the intertidal zone, cyanobacterial mats, crab colonies, beachrock flats, mud and sand flats are represented. In the subtidal zone, macroalgal beds, seagrass meadows, coral reefs and mobile sand bottoms are typical. Thus, the most characteristics of the area include biotope diversity, covering special biotopes such as beachrock flats, cyanobacterial mats and mangrove.

Sabkhas

One of the features of the physical landscape, particularly evident throughout the Persian Gulf seaboard, is the sabkha. Sabkha is an Arabic word for a salt-flat that has come into general use in sedimentology following classic research in the Persian Gulf during the 1960s and later. It is used in the sedimentologic literature for a supratidal flat in an arid climate.

The sabkhas are hostile for constructions, because of excessive settlement under normal loading, corrosive ground water and flooding risk. Its salt-encrusted surface often look deceptively firm. Beneath the thin crust of the coastal sabkha the algal mat and underlying mush of gypsum crystals and clay-size carbonate has little bearing strength.

Sabkhas are flat and very saline areas of sediments lying just above the water table and often containing soft nodules and enterolithic veins of gypsum or anhydrite. A thin crust of halite and gypsum may be present. Many ancient evaporite successions show sedimentary feature of sabkhas, such as gypsum

nodules. They can be considered as saltpans, which are found around the coast and inland where the sea has once transgressed. Essentially, the sabkha are formed by the action of the sun or seawater held in shallow pools on the surface of the desert. The water evaporates as a consequence of the sun's heat and salt-encrusted layer is formed, the salt being drawn up, as it were, to the surface by the effects of evaporation.

Sabkhas are flat areas of sand, silt or clay that are covered by a crust of salt (halite) for at least a part of the year. These hypersaline wetlands are particularly distributed along the north and western Persian Gulf and cover some 1,000 km^2 in Saudi Arabia and also found in the north east of Bahrain, as well as much of the Qatar and UAE coastline. Many of the sabkha are relatively recent in origin. An age of approximately 4,000 years before present has been obtaind for the infamous sabkhas of Abu Dhabi coastal area by Carbon-14.

Radiocarbon dating has indicated that these coastal sabkha was formed within the past 7000 years (Evans, 1969). Transgression began in this area about 7000 years ago and reached an apparent high about one meter above its present level somewhat prior to 4000 years B.P. Since then, progradation has taken place meaning that the land area is presently expanding seaward. It can be expected that the lagoonal areas to eventually dry out and the islands to coalesce.

There are two types of sabkha, coastal and continental. They have developed where hard rock lies below the groundwater table, allowing water to remain close to the surface and susceptible to evaporation. Coastal sabkhas may be flooded by the sea during storm and spring high tides, whereas the continental variety has no direct marine influence but derives its moisture from rare rainfall and the proximity of the water table at shallow depth, within capillary reach of the surface. The flatness is controlled by the content of capillary moisture from the water-table, which is close to the surface, keeping the sediments damp and firm and preventing it from being blown away.

Continental sabkhas tend to be lacustraine in origin and some are relics of the marine transgression. They are commonly found many kilometers inland. Inland sabkhas in the eastern part of Arabia, are remnants of coastal sabkhas of Pleistocene and late Pliocene sea-levels.

Coastal sabkhas are flat; featureless surfaces without vegetation that occasionally flood by storm surges and spring tides. When saltwater flooding occurs in this hot, dry climate, evaporites precipitated out of seawater. Water evaporates from the damp surface, during the hot summer months, which becomes saturated with halite that crystallizes to form a hard crust. Beneath the surface, calcium sulphate also becomes concentrated and forms a mush of gypsum crystals.

At ground temperatures greater than about 42°C, the water of crystallization is driven from the gypsum crystal lattice to create anhydrite. The temperature of the sediment surface may increase under insolation to 60°C and more even if the sediment is moist, and salinity may increase until salt crystal-

lizes. In the temperate climate, moving from the land over the intertidal zone into the subtidal area does not mean finding spectacular jumps in productivity.

Continental sabkhas differ from the coastal variety in having no direct marine influence on their development. Their supply of water comes from rainfall and the presence of a water table within capillary reach of the surface; a balance is achieved between evaporation and deflation at the surface and the supply of water from below which can trap wind-blown sediment, both being affected seasonally. Algae may be present, but extensive algal mats are not well developed; like coastal sabkhas, gypsum crystals form a layer below the surface.

In many part of the area adjacent to the Persian Gulf and some of the Islands, extensive inland sabkhas are found. These areas include: 1) at the landward margins of the coastal sabkhas beyond the reach of storm tides and extending into some adjacent interdune areas; 2) in the large broad interdune areas between the huge dunes.

In the southern Persian Gulf, the coastal areas includes several small shoals, islands, protected lagoons, channels and deltas, an inner zone of intertidal flats and broad areas of supratidal sabkha. The most characteristic feature of a coastal sabkha is a widespread mat of thin, black, algae. Most of the time, this algal mat is dry, and commonly cracked and curled up at the edges like flakes of mud in a dried-out pond. During high spring tides, or when storm winds drive seawater over the horizontal sabkha surface, the algae spring to life.

Coastal sabkhas cover the surfaces of much of the extensive system of low islands in the Persian Gulf. Along the coasts, however, the development of longshore bars has resulted in the creation of a series of shallow lagoons, which have tidally formed deltas at their mouths.

The sabkha area runs approximately parallel to the coast and in some places is up to 16 km wide. It has a slope that averages 1:3000 and lies above the level of present-day high tide. Extensive flooding occurs when offshore winds combine with high spring tides and during sporadic torrential rainfall. After the floods, the pools on the sabkha evaporate and leave salt-crusts. The crusts are dissolved when the surface is flooded or washed by rain. Cross section of a sabkha in the Persian Gulf is presented in Figure 11-6.

The temperature of the sabkha surface can reach 60°C or more in summer. As a consequence, evaporation is intensive and the salinity of the open Persian Gulf waters ranges from 40% to 45% while the lagoons can reach a high of 70% in their nearshore areas. In such a depositional environment with strong evaporation, the pore waters become highly concentrated and are drawn towards the surface, causing the precipitation of evaporites with some authigenic carbonates. The distribution or occurrence of the typical minerals of the sabkha can be summarized as follows:

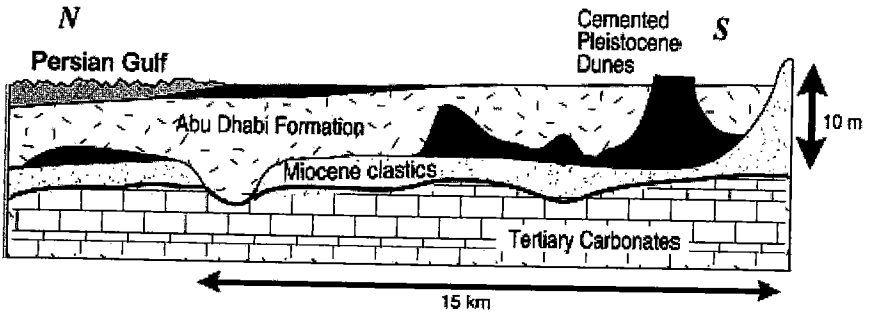

Figure 11-6. General geologic cross section of the coastal sabkha-aquifer system of Southern Persian Gulf (Modified from Wood et al., 2002)

Gypsum is commonly associated with the algal mats. The algal mats are well developed in the intertidal flats and are composed of blue-green algae. The mats stabilize the muddy sediment and in depth produce a characteristic laminated structure. Gypsum can make up more than 50% of the sediment. Gypsum crystals are mostly discoidal and flattened and oriented with their plane in a vertical position. Some crystals are clear while others contain calcium carbonate inclusions, even whole gastropods that usually turn out to be Cerithium.

Anhydrite is characteristic of the evaporites. There are two kinds of anhydrite; one, with a cottage cheese texture, considered to be secondary replacement of gypsum. The other occurs more inland and appears as nodules and contorted layers, and is of primary origin.

Dolomite first appears at the junction between the algal mats and the sabkha and increases in amount inland. By about 10 km inland the whole of the top meter of sediment may be replaced by fine-grained (2 to 3mm) calcium-rich, disordered dolomite. Peritidal dolomite is typically associated with sabkha conditions (Shin, 1973; Butler, 1969).

DOLOMITIZATION

In recent years, the two environments most frequently mentioned, as modern analogues for ancient dolomitization sites are the coastal fresh water-seawater mixing zone and more importantly coastal sabkhas.

Modern dolomite was found forming in the sabkha environment on the Trucial Coast of the Persian Gulf (Butler, 1969; Illing et al., 1965). In sabkhas, evaporation provides both the concentrated brines involved in dolomite formation and the driving force required to displace significant amounts of reactants through sediments. A series of hydrocirculation models were proposed for evaporitic dolomitization including seepage refluxion, concentration of capillary rise from the water table, and evaporative pumping. However,

controversy continues to surround the sabkha model and its ability to produce massive dolomites.

The modern studies leave no doubt that the coastal sabkhas of the Persian Gulf are effective sites of dolomitization, but controversy surrounding the sabkha model still remains. Because evaporitive pumping occurs in response to intensive evaporation at sediment surface, it must require extremely arid climatic conditions, as in southern Persian Gulf and not every modern sabkha will experience evaporative pumping or produce dolomite. Thus, sabkha type dolomitization in the geologic records is probably a reflection of extreme aridity. The limited extent and magnitude of the modern sabkha complex in contrast to that of ancient dolomite deposits is frequently cited as an inadequacy of the sabkha model and the scale is still an issue.

SEDIMENTS OF THE PERSIAN GULF

The Quaternary period imposed large worldwide, sea-level changes, which have been the primary reason for the observed sedimentary package in the Persian Gulf. The sea level was higher than at present during some of the interglacial, whereas it was considerably lower during the glacial periods (Glennie, 1996). Colder global climates during glacial periods gave rise to stronger wind systems as the ice caps squeezed air-pressure zones towards the equator and increase global wind velocity (Glennie et al., 1994). Winds were certainly stronger than in today's intergalcial climate. Therefore, the aeolian processes were more significant during the lower sea-level stands. However, the rock records indicates that wind circulation was essentially similar to current prevailing winds, which are dominated by the northwesterly Shamal, especially during the winter and spring.

NATURE OF THE SEDIMENTS

According to Baltzer and Purser (1990), the Persian Gulf contains classical carbonate and evaporite deposits which have been studied extensively in the southern part, giving the erroneous impression that the sediments of the Persian Gulf are essentially calcareous in nature. Studies of the Iranian coastal region and Iraq have shown, however, that the Quaternary to Recent sediments are largely of terrigenous nature and a significant fraction of them are detrital carbonates. Thus, the Persian Gulf is essentially a domain of active terrigenous sediment accumulation (see Figure 11-7).

The paradox is understood when the altitude of the Zagros Mountains and the flash floods, typical of many arid regions, which increase the terrigenous input along both permanent and ephemeral drainage systems are taken into consideration.

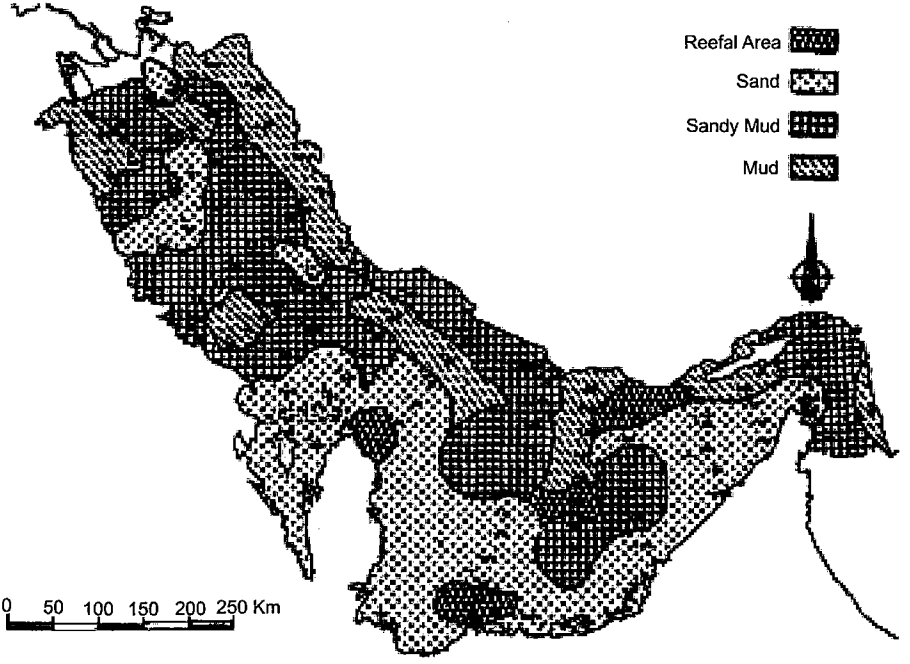

Figure 11-7. Nature of the sediments in the Persian Gulf (Modified from Baltzer and Purser, 1990)

During the Pleistocene there were periods of strong biogenic limestone formation and carbonate sedimentation. As a consequence of the gradual topography of the Persian Gulf and the favorable conditions for carbonate producing biota, today the Persian Gulf is a strongly sedimentary province. Its dominant substrate is soft sediments, relieved only where active reefs grow, or where older limestone is moved upwards by the activities of salt domes. In general, the shallow-marine and continental sediments consist of sabkha deposits, sand dunes, and calcareous sands.

Much of the Persian Gulf floor is covered by biogenic sediment, produced mainly from microorganisms such as Foraminifera. There is a wide range of older limestone producing fauna and flora such as corals and some calcareous algae. Most of the sand-size particles of these sediment tails are shell fragments. Much of the mud is derived from the dust storms so famous in the Persian Gulf region, and the rest is carbonate mud precipitated by algae and other organisms.

During the AtlantisII cruise 1993, Wisconsin age sediments were only sampled in the central basin and at the head of the Persian Gulf off Iran. Underlying the modern sediments, there are extensive layers of terrigenous sediments, entered the Persian Gulf basin as a result of increased rainfall. These sediments mingled with growing reefs, smothering many, and resulting in the present pattern of fossil or sub-fossil reefs, which are seen inland from

the present shorelines, and leading to very gradually sloping shorelines. Sublittorally, even when there are vast layers of hard limestone substrate in the shallow waters, these tend to suffer severe abrasion from the mobile sediments.

The Persian Gulf dried up during the last ice age, about 12,000 years ago. Later, when it was flooded, substantial reef growth occurred on the shallow platform. Heavy rainfall during these periods might have eroded the developing reefs with accompanied karst erosion and alluvial abrasion. Uplift of many of these reefal areas occurred and further, the diapirism of Hormoz salt beds underlying the carbonate platform partly forced the overlying sequences including reefal units.

It has been suggested that the river-bore sediments of the Tigris-Euphrates and the wind-bore dust and sand, transported from the surrounding lands, are major contributors to the total sediment budget of the northern part of the Persian Gulf (Sugden, 1963). Other general sediment sources that have an impact on the Persian Gulf are direct precipitation from Persian Gulf water, submerged estuarine mud of the ancient delta, and material eroded from the coastal ridges and raised beaches of Persian Gulf shores.

There is a strong terrigenous influence near the Arvand Rud affecting Kuwait and Iraq. On the Iranian side these are mixed with a greater proportion of terriginous sediments from the wind and numerous small riverine inputs from the Zagros Mountains.

The marked seasonally of Mesopotamian rainfall and wind makes this region a rich source of mineral dust to the atmosphere, with many regions. Analysis of satellite imagery and marine sediments (Al Ghadban 1990; Sirocko and Sarnthein, 1989) indicates that mineral dusts are transported by the Shamal wind to the Persian Gulf and Gulf of Oman with an estimated mass flux of $100x10^6$ tons/yr (Pye, 1987). Metsopotamian dust has characteristically high concentrations of detrital dolomite, calcite, and quartz (Sirocko and Sarnthein, 1989).

The contribution of dust fallout to the bottom sediments of the Persian Gulf has been reported in a number of studies. Sugden (1963) estimated that one third of all Persian Gulf sediment is eolian in origin and wind-transported sediment is a major contributor to sediments deposited in the Persian Gulf. Emery (1956) stated that thr Persian Gulf dust fallout is composed mainly of calcareous silt, rich in dolomite. On the other hand, the greater part of the Tigris-Euphrates suspended material is deposited in Iraq and only about 10% of the material that passes Baghdad can reach the Persian Gulf (Wilson, 1952). These statements and the climatic data strongly suggest that the dust and dust storms, which are commonly derived from prevailing winds which pass over southern Iraq and Kuwait, are far more important than the Tigris-Euphrates as a source of detrital sediments in the Persian Gulf.

Marl forms the primary sediments as a soft cover substrate, particularly on the Iranian side (Purser and Seibold, 1973; Seibold et al., 1973) which has a

sand fraction consisting mainly of molluscs, foraminifera, ostracods, echinoids and coral debris and carbonate content of greater than 50% (Stoffers and Ross, 1979; Uchupi et al., 1999).

According to Sarnthein and Walger (1973) the ridges exposed in the central part of the Persian Gulf in water depth greater than 40 meters consists of quartzose sand with some feldspar and an equal percentage of ooids. The terrigeneous grains tend to have diameters of 0.12 to 0.20 mm; many grains are encased in aragonitic oolitic shells. Some of the grains are inbedded in aragonite mud, which are partially lithified into clumps to form a minero-oomicrites.

Aeolian dunes cover most of the southern Persian Gulf and a large part of the eastern Arabian Peninsula. Although these sands, as well as older aeolianites, are largely composed of quartz, there is a high percentage of detrital carbonate in them south of the Persian Gulf for more than 40 kilometers; this percentage decreases inland. The carbonate grains consist mainly of marine bioclastic fragments and calcareous ooids, were derived from the floor of the Persian Gulf, which was exposed during low sea level of the last glacial period.

Throughout Arabia and UAE coastal areas, carbonate sands predominant strongly. Among the major constituents of the sediment of the southern Persian Gulf islands are oolites, almost perfectly spherical sand grains of calcium carbonate (aragonite), precipitated out of seawater. The ebb tidal delta shoals, which continually feed the beaches and adjacent islands, are production sites for this sand. Oolites are responsible for the bright white color of the ebb tidal deltas. Such grains are found in warm, shallow, and wave-agitated waters in many areas of the world. The southern Persian Gulf barrier islands are among the few with the capability of producing their own sand.

MAJOR ALLUVIAL ACCUMULATION

Mesopotamia alluvial plains have filled the northern half of the former Persian Gulf with sediments transported from remote mountains. The Lower Mesopotamian Plain includes 10,000 km^2 of marshes associated with very shallow lakes, whose peripheries evolve in accordance with pluriannual changes in the river discharge. This delta extends for about 100 kilometers seaward from the river mouth, covering most of the northern offshore area.

Towards the east and between Bandar Abbas and Khamir, small ephemeral wadis have built a series of alluvial fans about 1 km in width, which impinge on the seashore as minor fan deltas. These fans composed of angular rock fragments include finer peripheral sediments which are reworked and sorted by the sea, forming arcuate beach deposits contouring the fan. A series of probably wave cut terraces at several meters above HWM; suggest both limited sedimentary supply and rapid uplift of the coast (Baltzer and Purser, 1990).

Deltas of Rud-e-Shur, Rud-e-Shirin and Rud-e-Minab are located on the northern shores of the Strait of Hormoz, stretching from 10 to 70 kilometers east of Bandar Abbas. They reach from the region of Bandar Abbas in the west to Khor Kolahy in the east. The city of Bandar Abbas was built west of the deltaic plain, at a point where the interior hills approach the coast and provide solid footing.

The Mehran River has developed a marine alluvial-fan delta (Nemec and Steel, 1988) near the southeastern extremity of the Iranian coast of the Persian Gulf. Mehran delta has the overall morphology of an alluvial-fan delta and it receives the lateral output of several tributary fans. This delta progrades into the Khooran Strait situated between Qeshm Island and the Iranian mainland. Immediately in front of the Mehran River delta, in the strait, an extensive mud bank complex occupies a large embayment of the Qeshm Island coastline.

FLUVIAL SEDIMENTS

When there is sufficient rainfall, fluvial gravels and sands are transported down the mountainsides and across the valley floors within the mountains into the Persian Gulf. This is specially the case in some of the Islands in the Iranian side where the salt domes are intruded into the sedimentary sequence and weathering products are transported to the Persian Gulf forming braided channel deposits and alluvial plains. The river transported material seems to be important in the northern and western region of the Persian Gulf. Between these the materials carried by flash floods from rivers draining Zagros Mountains in Iran, appears to be more significant than that from the Arvand Rud system. The absence of rivers on the Arabian side of the Persian Gulf leads to carbonate rich sediments.

There are broad sheets of fluvial sands and gravels that spread for a considerable distance beneath the present cover of dune sands in the southern Persian Gulf region. There is also the same spread of alluvial fans reaches as much as 200 km south of the Oman Mountains; in the north, and they may extend beneath the floor of the Persian Gulf.

The time of deposition of some of the younger gravels now exposed in incised wadi banks have been dated at around 30 and 70 ka BP, while others, coincided with the Climatic Optimum (Sanlaville, 1992). The fans have been subjected to repeated deflation, however, and near-surface sediment has been dated at over 400 ka, while the degree of alteration of some ophiolite-rich fluvial sediment suggests deposition up to a million or more years ago. The extent of these sediments, and the size of the pebbles and boulders found in them, indicate that at the time of their deposition there was much more rainfall over the area than is experienced today. The surfaces of such alluvial fans are exposed between some of the large linear dunes of the eastern emirates.

Quaternary fluvial sediments are rarely exposed between the dune cover of most of the southern Persian Gulf. Along the western limit of Abu Dhabi, an-

other sequence of fluvial gravels is exposed at the surface. Goodell (1995) documented evidence for significant fluvial activity in sabkhas during Pleistocene time when major rivers flowed eastwards from the Arabian Shield. The attitude of the bedding laminae indicates that there, an ancient river flowed towards the north or northeast. The types of rock (e.g. limestone, volcanic lava) represented by the pebble content of the gravel point, in this case, to a source in the southwestern highlands of Saudi Arabia. The time of their deposition has been dated at over 200 ka BP (Goodall, 1995), which obviously was another period of higher rainfall than now.

PLEISTOCENE SEDIMENTOLOGY

Throughout Pleistocene to Recent the Persian Gulf basin has subjected to the interaction between three different depositional systems which include; the Mesopotamian fluviodeltaic system, the Persian Gulf marine carbonate system, and the Arabian continental aeolian system. The Arabian continental aeolian system is the vast repository of dune sands forming the sand sea of the Arabian interior.

The Mesopotamian fluviodeltaic system is restricted to Tigris-Euphrates valley and an extension along the northern edge of the Persian Gulf to include Karoon and numerous smaller distributaries that extend directly away from the Zagros front (Baltzer and Purser, 1990). The most obvious features today are the Tigris-Euphrates delta at the northern end of the Persian Gulf and the numerous alluvial fans along the Zagros front itself.

The present-day distribution of fluviodeltaic clastic deposits reflects the location of the Zagros front and its related drainage systems. These clastic deposits influence the marine basin more than is generally realized (e.g., Uchupi et al., 1996). Baltzer and Purser (1990) showed that more than half of the present Persian Gulf area is affected by clastic input. The high proportion of this clastic sediment is in the form of detrital carbonates. This is derived primarily from erosion of tectonically uplifted carbonates but some may also be derived from the reworking of palustrine carbonates within the fluviodeltaic systems. This has given a false impression of the extent of recent carbonate production in the Persian Gulf area. Baltzer and Purser, (1990, p.175) stated that "the present-day Persian Gulf is essentially a domain of active terrigeneous accumulation". Therefore, there seem to be an overestimation of the role of biogenic and primary carbonates in overall sedimentary regime of the Persian Gulf.

EOLIAN SEDIMENTATION

Southward flowing rivers of the Persian Gulf area extended further basinward than today during periods of lower relative sea levels and formed alluvial plains that were a major source of aeolian siliciclastic sediments, which

was later blown southwards by the Pleistocene wind. The present-day dune fields of the southern Persian Gulf were active during these times but they are now largely out of phase with the more subdued wind system (Glennie, 1994).

Most of the land surface on the southern Persian Gulf is dominated by the presence of sand dunes. Dunes migrate in the direction of the sand- transporting wind. Where the supply of sand is limited, crescent-shaped barchans are formed.

The effects of changing sea level in the Persian Gulf have modified the broad pattern of large dunes. When sea level rose at the end of the last glaciation, the supply of aeolian sand from the north was ceased. Although the wind still blew, its direction was out of equilibrium with the geometry of the existing dunes, so their shape became modified; these modifying winds apparently were not as strong as formerly, so the new resulting dune forms were smaller than the pre-existing large dunes.

Every time the sea flooded the Persian Gulf, shallow-marine organisms flourished and eventually died, leaving the evidence of their former existence on the sea floor in the form of calcareous shells and their fragments. When the Persian Gulf floor was exposed to the wind during sub-polar glaciations, the smaller size shells was transported southward to the southern Persian Gulf where they formed carbonate dunes.

It is clear that the dune systems of the southern Persian Gulf have been controlled not only by global shifts in wind direction, but also by glacially controlled changes in exposure of the Persian Gulf floor, which in turn have controlled the distribution of both coastal and inland sabkhas. Those dunes and sabkhas are still reacting to today's climate and associated wind directions.

CARBONATE EOLIANITES

During Late-Pliocene-Mid Pleistocene time the sea flooded the Persian Gulf and as a result, marine carbonates were deposited but later they were exposed to eolian deflation during subsequent regression (Hadley et al., 1998). Carbonate sediments were blown southwards by the paleo-wind during the periods of lower sea levels. The color variation of the Pleistocene dune is striking (Kirkham, 1998). They become whiter as the marine carbonate contents increased, especially nearer to coastline where this color variation is enhanced by the veneer of Holocene aeolian carbonate sands. The Pleistocene carbonate dunes are cemented by calcium carbonates wherever they are exposed.

Carbonate eolianites of Pleistocene age occur extensively in the Persian Gulf region. These deposits have accumulated through eolian reworking of marine sediments. They have been reported from Saudi Arabia and crop out along the eastern coast (Holm, 1960), and scattered around the coast in Qatar (Holail, 1999), large part of UAE (Hadley et al., 1998; Kirkham, 1998), with

less extensive deposits in Kuwait (Khalaf. 1988) and Iran (Haeri-Ardakani, 1998). In Qeshm Island they are at least 5 to 10 meter thick and are well exposed in vertical cliffs, and much of the surface highland of the Island is formed of carbonate eolianite, and these sediments unconformably overlie rocks of Miocene age (i.e., Mishan Formation).

The carbonate aeolianites were originally called "miliolite" because of their high content of miliolid Foraminifera. These deposits formed through eolian reworking of Persian Gulf marine sediments, which have been admixed locally with eolian siliciclastic sediments. Semi-lithified carbonate eolian sand deposits are common in the southern Persian Gulf. They underlie the modern coastal sabkha and believed to be Wisconsin-Holocene in age. This is based on the occurrence of abundant reworked grains, elevated siliciclastic content, and planar truncation by overlying Holocene marine deposits.

Modern carbonate dune accumulation is rare in the southern Persian Gulf and the Iranian Islands such as Qeshm. This appears to be largely a result of the present day coastal geomorphology and high sea level. Deposition of the carbonate eolianites was initially linked to fluctuation of sea level and climatic changes. Sea level controlled the amount and the nature of sediment available for eolian deposition, whereas paleoclimate has been the main factor influencing the size, distribution and accumulation of the carbonate eolianites.

The geographic setting, sedimentary architecture, and sedimentary composition of the coastal dunes in the southern Persian Gulf are consistent with their deposition during falling sea level and they provide a good example of regressive Carbonate eolianites.

NEOGENE SEDIMENTS IN THE PERSIAN GULF

Neogene sediments in the Persian Gulf comprise a northeast-thickening wedge of clastics shed from the uplifted Zagros Mountains in Iran. It is revealed that there is an unconformity dating to the Last Glacial Maximum and a sequence of deltas along the northern Iranian margin of the Persian Gulf (Uchupi et al., 1996, 1998). Radiocarbon ages performed by these authors suggested that the basin was subsiding in apparent contradiction to previous interpretations of seafloor topography.

Swift and Ross (2002) have compiled, edited, and mapped the primary seafloor structures in water depths greater than ~30 meters in the Persian Gulf. Their most surprising result is the apparent lack of Holocene sediment over most areas deeper than 30 m which is confirmed by the sediment cores. Sediment cores in regions with 0-2 meters of Holocene sediments identifiable in the acoustic records often penetrate 10-50 cm of Holocene marl into reddish-brown Pleistocene sediment.

Holocene accumulation is constrained to the margins of the basin off rivers draining the Zagros Mountains and to a narrow strip of carbonate deposition in 40-50 m of southern Persian Gulf. The Tigris-Euphrates delta in the head of

the Persian Gulf is problematic. Although, the delta is interpreted as a Holocene feature, Holocene material could not be identified acoustically. Sediment cores in the proximity of this delta recovered a layer of marl less than 1 m thick above cross-bedded reddish-brown sand. Surface textures of quartz grains suggest aeolian processes were responsible for the deposition of the sand. These sediments have not been dated, and as a result the accuracy of the seismic interpretations at the head of the Persian Gulf is not confirmed.

SEDIMENTATION RATE

Since the Persian Gulf basin has experienced interplay between various depositional systems, it is very difficult to conclude with certainty a unique sedimentation rate which could be applied to the entire system. Thus, it is more reasonable to assume that different part of the basin is subjected to different sedimentation rate.

Based on lead-isotope investigation, the minimum sedimentation rate in the Persian Gulf is around 1.95 mm/year from the core sediments taken from the Strait of Hurmoz between Larak and Hormoz Islands. However this rate is much higher in the northwestern part of the Persian Gulf and it is about 10.13 mm/year for the Karoon River mouth.

UPLIFT IN THE PERSIAN GULF REGION

The coastal area of northern Persian Gulf is part of the southern Zagros geological structure which has been tectonically active since the Tertiary and still remains active. Regional uplift during the Pleistocene is indicated by the presence of raised marine terraces and sediments. These consist of reef and beach deposits from near shore or shallow water depositional environments. From the altitude and age of the raised sediments the uplift rate of a specific area such as the surrounding regions or Islands can be reconstructed.

Little (1970) reported the first set of ^{14}C ages for corals from raised beaches along the Iranian coast of the Persian Gulf. Further dates which are mainly older than 20 ka resulted in calculation of uplift rates as high as 3 mm per year for the Makran coastal region (Vita-Finzi, 1981) and up to 2.6 mm per year for Qeshm Island (Haghipour and Fontugne, 1993). Comparing the ^{14}C and $^{230}Th/^{234}U$ dates indicated that $^{the\ 14}C$ ages older than 20 ka could be considered as minimum ages (Page et al., 1979). The $^{230}Th/^{234}U$ determination resulted in a much smaller uplift rate of about 0.2 mm per year for the Makran coast and Persian Gulf region.

Kish is an island of about 77 km^2 in the southeastern Persian Gulf, a few km south of the Iranian mainland. Corals from this Island in the Persian Gulf have dated by various methods. Electron Spin Resonance (ESR) dating of raised coral reefs exposed on the Kish Island in Persian Gulf indicated that average uplift rates for Kish Island are between ~0.13 and ~0.24 mm per year

(Preusser et al., 2003). This is consistent with previous estimates based on $^{230}Th/^{234}U$ dating of raised marine deposits from the nearby Iranian mainland and Qeshm Island, Strait of Hormoz, but contrary to results based on ^{14}C dating that predicted uplift rates as high as 3 mm/ year in that area.

ESR ages determined for raised coral reefs from the Island demonstrated two distinct clusters of ages indicating formation of coral reefs on Kish Island during sea level highs. Coral growth appears to have been interrupted by clastic sedimentation, indicating that reef development on Kish Island was at least dicyclic. Corals grew on the slowly emerging remains of a pre-existing older reef. The presence of old corals at low elevation is interpreted to represent the lower part of that older paleo-reef. The hypothesis of at least dicyclic reef growth on Kish Island is supported by identifying coral of different age at the same elevation on two sites.

Thus, corals in the Kish Island display a 0.2 mm/yr uplift rate as calculated for nearby mainland Iran (Haleh, Jazeh) and Qeshm Island, Strait of Hormoz. These uplift rates are based on $^{230}Th/^{234}U$ dating (Fontugne et al., 1997; Reyss et al., 1998). The findings are significantly lower than predicted average uplift rates of ~3 mm/yr for the nearby Makran coast and Qeshm Island (Vita-Finzi, 1980; Haghipour and Fontugne, 1993).

Inclined Holocene marine terraces on Hormoz and Namakdan salt diapirs in the Persian Gulf studied by Bruthans et al. (2006), showed that the uplift rate is not constant and changes from 2mm/yr (sea shore) to 5–6mm/yr (diapir interior) on Hormoz and 1–3mm/yr to 3–5mm/yr on Namakdan salt dome in Qeshm Island. The uplift rate is even higher in central part of Namakdan.

THE PERSIAN GULF SEA LEVEL FLUCTUATION

Extensive sea level fluctuations that occurred globally, mostly causing contemporary sea level to vary between 30 to 80 meters below present sea level. During the past million years or more, one event has repeatedly affected global climate. With a cyclicity of around 100 ka, Scandinavia, the northern half of North America and Greenland, suffered a repeated slow build-up of an ice cover up to two or three km thick, which then melted very rapidly (Shackleton 1987; Boulton 1993).

During each of these glaciations the Persian Gulf became a very large fertile valley through which meandered the Tigris-Euphrates River which extended a thousand km farther. Its delta was not near present-day Basra but out in what today is known as the Gulf of Oman, nearly a hundred km beyond the Strait of Hormoz.

Since the global temperatures were lower during glaciations, many highland areas became the sites of mountain glaciers, whereas the ice cap over Antarctica, which had been a permanent feature of the Southern Hemisphere from at least the Miocene onward, only, expanded and contracted in size.

Apart from lowering global temperatures, these glaciations affected climate in two other ways:

• Because the ice caps became the centers of very large areas of high atmospheric pressure, all other air-pressure belts around the globe were squeezed towards the low-pressure equatorial area. With isobars much closer together than is the case today, global winds would have been much stronger and more persistent than what we now experience.

• So much water went into building the ice caps that global sea level at the last glacial maximum, about 20 ka BP, the sea level was some 120 or 130 meters lower than today's.

The last interglacial period, which occurred at about 125 ka, represents the last time global sea levels were at or near modern levels, and by inference, the last time ice volumes and global climatic conditions were similar to present day.

The Persian Gulf investigations are of interest in order to understand the evolution of the morphology and sedimentary record, including the evolution of the Tigris-Euphrates Delta. The results also provide a framework for discussing human movements and settlements in Late Paleolithic and Neolithic times. The geographic reconstruction also provides new insights into the interpretation of the environmental and human record from Paleolithic times onwards.

Since the floor of the Persian Gulf is everywhere less than 120 meters deep, its shallow depth has made it extremely susceptible to the effect of sea level changes. During glacial maxima the exposed floor of the Persian Gulf would have been the site of sand dunes migrating southward under the influence of the northern wind. The only sign of water in the Persian Gulf would have been in the combined Tigris-Euphrates River, which derived its water from the wetter Anatolian highlands and reached the open sea south of the Straits of Hormoz.

The high-latitude glaciations took some 80 to 100ka to reach their maximum extent; the last glaciation melted within little more than 10 ka to produce a global sea level similar to the present one by about 6ka BP; thus sea level rose at an average rate of about 1 cm per year but possibly exceeded 4 cm/year for short periods (Boulton 1993).

The sea level of the Persian Gulf appears to have risen and fallen fairly sharply over the past 100,000 years. There is considerable evidence that between 110,000 and 10,000 years ago the sea receded, leaving the sandy floor of the Persian Gulf exposed. A brief transgression occurred between 105,000 and 80,000 years before present, followed by the major Late Pleistocene regression with sea level again steadily dropping toward a Pleistocene record low stand of 120 meters below the present level at 17,000 years before present. It would then have been broad plain receiving water probably by an extension of the Arvand Rud, which may have reached the shelf margin of the Gulf of Oman, representing a fall of some 110 meters below the present level.

Before the onset of a major regression, the early Pleistocene was marked by a high sea level of +120 to 150 meters, which covered much of the Eastern part of the southern Persian Gulf.

During the middle and late Pleistocene, from about 80,000 years ago, the level of the waters in the Persian Gulf fluctuated, as indeed was the case globally. In many places along the western shore of the Persian Gulf it is possible to see old shorelines from times when the sea level was a few meters higher than today; others have also been detected underwater in the Persian Gulf. Such changes in the sea levels were the consequence of the advance and retreat of the glaciers during the succession of glaciations and interglacial. The formation of these ice-sheets locked up vast quantities of water, leading to lowering of the sea level globally.

Wisconsin-Holocene sedimentation in the Persian Gulf was controlled by glacially induced changes in sea level and climate. The glacially induced Wisconsin regression, which began about 125ka years ago, reached its lowest stand about 21ka to 20 ka years ago when sea level dropped to -120 to -130 meters. The most marked regression of the Persian Gulf waters happened between 70 ka and 17 to 18 ka years ago: then the sea withdrew beyond the Strait of Hurmoz. The lowest sea level occurred about 20 ka years ago, leaving a channel in the Gulf of Oman extending towards the present Strait of Hormoz along the Iranian shore. This presumably would have been contiguous with the outflowing channel of the Tigris and Euphrates. Apart from the latter watercourse, the present Persian Gulf floor was dry, so that when sea level rose to present levels during the Holocene transgression, the biota of the Persian Gulf was completely reset. The sea began to return around 17 ka years ago. It has been debates whether or not sea level rose to 1-2 meters higher before settling to present level. Vertical movements of limestone and vertical build up of sediments since that time have greatly exceeded this amount, both in magnitude and importance.

With retreat of the glaciers the sea level began to rise reaching its present level about 5000 years ago. During the latest cold peak in the last Ice Age, 18 ka years ago, the sea level fell to 110 meters below todays. In only a small area inside the Strait of Hurmoz was the sea present. The exposed seabed consisted of a pattern of Wadis and sand dunes much like Arabia today. The Tigris and Euphrates rivers, which today empty into the Persian Gulf, may not have reached the sea but have run into sands.

The glacio-eustatic sea level rise during the last 18 ka years is marked by two major glacial melt water discharges at 12 ka and 9500 years ago when the rate of sea level rise was at its maximum (from 18,000 to 12,000 years ago sea level rose from -120 to -100 meters; from 12 ka to 11500 it rose from -100 to 70 meters, and from 9500 to 8500 sea level rose from -50 to about -28 meters Fairbanks, 1989).

From the peak of the glaciation until about 14 ka years BP the Persian Gulf was free from marine influence out to the edge of the Biaban Shelf but the

potential existed for extensive shallow lakes and swamps on the Persian Gulf floor along the ancient bed of the Euphrates-Tigris river system throughout Late Glacial time.

The Late Pleistocene regression was followed by the Holocene or Flandrian transgression when the sea level slowly rose to its present level. By about 12,500 years ago the marine incursion into the Central Basin had started and the western Basin was flooded about 1000 years later. Much of the southern and northern sides of the Persian Gulf remained dry until about 9000 years ago.

Acceleration in the process took place about 11 ka years ago, perhaps by as much as 2 to 4 cm per year. The sea level rose to -20 meters at about 10,000 years ago. At this time the Island of Bahrain became separated from the mainland between 6 ka to 7 ka years ago; previously it had simply been a dome-shaped prominence inland. The available data suggest that the sea level dropped substantially during the Wisconsian time (Felter et al., 1978; Potts, 1990).

Sea level variations in the Persian Gulf during the last 9000 years ranged from <-1 to >+1 meter. By about 1000 years ago the Persian Gulf attained its present level as a result of tectonism and aggradations along the Arabian-Iranian flanks and sedimentation at the head of the Mesopotamian lowland.

The postglacial rise in sea level rapidly reflooded the floor of the Persian Gulf, cutting off the source for these aeolian sediments from the basin. Nevertheless, between 12 and 6 ka, the sea transgressed more than one thousand kilometers inundating the extended route of the Tigris and Euphrates Rivers. Because of the varying rate of eustatic sea level rise, these waters at times flooded across the flat floor of the Persian Gulf at more than a kilometer per year.

The present Persian Gulf shorelines was reached shortly before 6 ka years ago and exceeded as relative sea level rose between 1 to 2 meters above its present level. This was primarily in response to the hydro-isostatic adjustment of the Earth, inundating the very low areas of lower Mesopotamia. Whilst there is evidence of marked changes in the sea levels in the Persian Gulf, such changes are far less dynamic in the Persian Gulf sister the Red Sea.

The sea level reached its maximum transgression (i.e., its highest level) between 7,000 to 4,000 years before the present. Thus, he Flandrian transgression attained its highest point about 4,000 years ago. Then it was perhaps some 2 meters higher that it is today, before falling to the present day level (Felber et al., 1987). Along the low coastline, which characterizes so much of the Arabian littoral of the Persian Gulf even so relatively small, a rise in sea level would result in the flooding of large areas. Unfortunately, the database for the Persian Gulf is inadequate to determine the magnitude of this difference.

It is likely that tectonism caused the Wisconsin regression and Holocene transgression trend in the Persian Gulf region to depart from the global one.

The latest regression is unlikely to reflect purely local tectonic uplift rather than eustatic sea-level changes (Vita-Finzi and McClure, 1991). Raised beach deposits of the Middle Holocene reaching up to approximately 2 meters above present sea level also occur on the southern coast of the Persian Gulf (Evans et al., 1969; Kapel, 1969; Kirkham, 1997).

About 3,750 years ago the sea level first fell rapidly by one meter and then more gradually regressed to the present level about 1,000 years ago. In contrast, the Iranian shore, subjected to the Zagros folding of the Fars platform, has locally undergone as much as 25 meters tectonic uplift during the last 6,000 years (Vita-Finzi, 1980).

RECENT SEA -LEVEL CHANGES AND ITS IMPACT

Relative mean sea level has been steadily rising in the Persian Gulf and the Oman Sea at a rate of about 4 centimeters in the past decade. Changes in sea level for the northern side of the Persian Gulf have not been recorded for a long period and relevant data has been collected only for the last 40 years. The only available data are based on the records obtained from three stations at Bandar Abbas and Bushehr in the northern Persian Gulf (Sharifi et al., 2003).

Climate change and consequently sea level rise effectively influences the natural condition of the coastal area and the resources. Changes in water salinity causes fish migration and decrease food resources and commercial fishing activities.

Saltwater intrusion due to sea level rise may diminish the water resources for drinking and agricultural use. In this respect the effect of underground halocline changing due to deep well drilling should be taken into account. Such condition is occurring in Khuzestan coastal region and water quality has been affected in cities like Abadan.

Further consequence of salt-water intrusion is land salinization which limits the agricultural activities. Flooding will affect many urban areas in the coastal plains especially in Khuzestan province and erosion severely damaged the infrastructures made along the coastline especially in islands and the shoreline.

Mud flats and coastal plains, especially in Khuzestan Province and Iranian Islands of the Persian Gulf, are subjected to flooding and inundation, followed by salt-water intrusion to the Bahmanshir and Arvand Rud estuaries.

Coral reefs, a critical global resource from both biologically and socio-economic points of view are one of the first victims of the global warming. Climate change and increasing sea surface temperature considered as a main reason for the coral mass bleaching. Most coral bleaching occurs in the top few meters of the water column due to the temperatures being highest at the surface

Mangrove forests are also subjected to change with the sea level rise. This includes and changes in concentration of mangrove species. Species change and also migration occurred in marine habitats- especially fish, due to the salinity changes and estuaries will the first affected environments in this regard.

In a regional or local scale, certain corals have adapted to warmer and/or more variable temperature regimes. These include some of the same species, which have been observed to be highly sensitive to temperature variations in other areas. Such adaptation is clearly observed in the reefal community of the Persian Gulf, where temperatures fluctuate over relatively wide extremes every year. All reef development is the result of coral growth out-pacing natural processes of erosion, from bioeroding organisms and also physical processes such as storms. Slower coral growth rates and weaker skeletal structures may shift the balance of many reefs from that of gradually accreting structures to that of gradually eroding structures. This change will be further compounded by increasing rates of sea-level rise (Sharifi et al., 2003).

Sharifi et al. (2003) have indicated those coral genera with fast growth rates and high metabolic rates, such as *Acropora* spp., are the most susceptible to changes. They showed that *Acropora* spp. recovered to lesser extent if at all, compared to complete recovery of *Porites* spp. This suggests that mass bleaching has the potential to change the structure of coral communities, that is, tolerant genera or species may temporarily dominate. In the Persian Gulf corals exist in relatively high temperatures that average up to about 34°C in summer. This is 4°C higher than the average maximum summer temperatures normally experienced on the central Great Barrier Reef.

PERSIAN GULF PALEOCLIMATIC CONDITIONS

Persian Gulf past acute climatic variation was of crucial importance in influencing the course of human settlements and the development of the societies which lay around its shore and islands. This was generally known as the 'Neolithic Wet (or Moist) Phase which occurred between 6 ka to 10 ka years ago.

Over the past 36 ka years or thereabouts the climate of the Persian Gulf region has veered between relatively moist periods, in which there was a notable increase in precipitation, and periods of aridity, some of which, like the one which persists today, were of considerable ferocity. As mentioned before, although the current arid conditions began to prevail in the Persian Gulf region near the end of the Middle Pleistocene, two important minor wet (pluvial) episodes can be distinguished; 1) Between 36 ka years and 17 ka years; and 2) during the "Neolithic wet phase" from 9 ka to 6 ka years (McClure, 1988). The following table presents the moist and arid periods in the Persian Gulf region.

Table-11-1. Periods of moist and arid phased in the Persian Gulf region

Moist	36,000-17,000
Arid	17,000-15,000 BC
Moist	15,000-11500 BC
Arid	11500- 9000 BC
Moist	9000-6000 BC
Arid	6000-5000 BC
Moist	5000-4000 BC
Arid	4000-2800 BC
Moist	2800 –800
Arid	800

The period 7000-4000 BC saw the emergence of active springs and formation of shallow lakes with slight increase in rainfall. Even the most minor variations permitted or prevented settlement and the raising of crops and herds. During this period there was evidence in eastern Arabia of the creation of small, probably seasonal, settlements of people who may have been the fore runners of the Persian Gulf of harvesting pearls.

Paleoclimatic records from the Persian Gulf region have shown shifts to more arid climate beginning about 4000-4200BP. In the Lake Van in eastern Turkey, the headwaters of the Tigris and Euphrates Rivers, oxygen isotopic and geochemical analyses of lake sediments were used to estimate that lake-level fell between 30 and 60 meters beginning around 4190 B.P. (Lemcke and Sturm, 1997).

Many desert areas had a higher rainfall between about 10 and 6 ka BP. Flooding of the Persian Gulf had a great effect on the southern parts. The supply of wind-driven sand was progressively cut off by the increasing extent of seawater. The wind continued to blow, however, so that in areas close to the expanding sea, sand was removed by wind action down to the level of the rising water table, due to the rising sea level. The resulting moist surface developed into sabkhas.

Widespread climate variations in the past were larger and more rapid than those occurred during more recent historical times. For instance, the cooling of the climate leading into the last "ice age," the peak of which occurred around 21 ka years ago, and the subsequent climate transition to a warmer, more modern world were punctuated by abrupt climate changes that were one-third to one-half as large as the change from an "ice age" to a warm climate (i.e., the roughly 6-7°C) transition from an "ice-age" to a warm climate, globally.

Paleoclimate records also indicate that during the abrupt shifts many aspects of the climate in the regions changed suddenly in the time span of a few years or even a single year. The current warm period since the peak of the last ice age (21 ka years ago) thought to be very stable with no large climate shifts that characterized "ice ages". However, evidence from deep-sea sediments

and ice cores shows that this warm period was interrupted by a series of abrupt cooling events, each lasting several hundred years.

One of the most prominent of these events occurred approximately 12,800 years ago, after Greenland warmed to near-present conditions. As the climate was warming following the Earth's last glacial maximum ("ice age"), an abrupt transition to cold conditions occurred, during which the surface temperature of the Northern Hemisphere dropped precipitously (nearly 15°C) in Greenland. For example, in a series of abrupt, decade scale jumps, some of which involved temperature changes on the order of 3°C.

Once the abrupt transition to a colder climate had occurred, the Northern Hemisphere, especially Europe and Greenland experienced considerably colder conditions lasting about 1,300 years. Other parts of the world were affected as well. This abrupt climate cooling is known as the "Younger Dryas" event. Between 11,000 and 10,500 years BP, during the younger Dryas, sea level only rose from -70 to -60 meters below present level (Uchupi et al., 1996).

The termination of this cold event around 11,500 years ago occurred as an even more abrupt warming; most of which took place in a single 5-year period. The entire transition to a warmer, more modern climate took no more than 40 years. During this transition, snow accumulation in Greenland doubled in a single 3-year period, with 90% of that increase occurring in a single year. This abrupt transition to a warmer world led to a three-fold drop in wind-blown sea salt, a seven-fold drop in wind-blown dust, and a climate warming of 5-10°C in Greenland, all in less than a decade.

Within 30 years following this transition to a warmer climate, atmospheric methane (another greenhouse gas) levels increased, as a result of the creation of more wetlands globally. Conversely, the climate cooling associated with the onset of the "Younger Dryas" event resulted in a loss of wetlands worldwide, and a drop in the concentration of atmospheric methane. Numerous climate records from other parts of the world confirm these abrupt climate events recorded in the Greenland ice cores, and extend the signature of these events to other regions of the globe.

Another smaller but significant abrupt cooling event occurred roughly 8,200 years ago when temperatures in Greenland were slightly above present-day temperatures. These abrupt cooling events have been detected from various part of the world. One such notable event about 4,200 years ago (2200 BC) is shown to be synchronous with the collapse of the Acadian empire in Mesopotamia in the northern end of the Persian Gulf.

CLIMATE AND HUMAN CIVILIZATION

Historical social consequences of abrupt climate changes can also be assessed from the archeological record. Archeologists had long known of a large social disruption in Mesopotamia approximately 2200 BC (4,200 years ago)

when the world's first known united empire led by Sargon-I of Akkad abruptly collapsed and splintered after reigning from Turkey to the Persian Gulf for several hundred years. This event seems to have been contemporaneous with one of the sharp cooling events detected in the North Atlantic and off Africa. Archeological investigation from excavation site in northeast Syria have suggested that a major environmental changes associated with Akkadian collapse occurred near 4200 BP (Cullen et al., 2000).

Analysis of sediments core from Persian Gulf indicates that the supply of dust from the Mesopotamian region to the adjacent Gulf of Oman, at roughly 2200 BC (4,200 years ago) was five times the amount of dust supplied to the ocean in recent time. Around 1900 BC (3,900 years ago), the supply of dust delivered to the oceans sharply decreased, similar to modern concentrations. Geochemical analyses of a thin volcanic ash layer found at both the archeological sites, and in the deep-sea sediment core, indicate that this abrupt drying event coincided in time with the collapse of certain historic civilizations (Cullen et al., 2000).

The region at the head of the present Persian Gulf and Mesopotamia was settled by the early Sumerians during the fourth millennium BC but the origin of this civilization has raised many questions. As previously mentioned during Paleolithic (before about 8000 years BC) and Mesolithic and Neolithic (from 8000 to about 5000 years BC) times much of the Persian Gulf floor would have been exposed and the broad river valley with lakes and marshes in the flatter regions, would have formed a natural route for people moving westwards from east of Iran.

There is evidence of a flooding event at about 4000-3000 BC and it is tempting to associate the Sumerian `Flood' legend with the peak of the Holocene transgression during the flooding of the low-lying delta region when sea levels raised perhaps a few meters above present between about 6000 and 3000 years BP.

While it has been recognized that abrupt climate changes were limited to glacial climates of the distant past, these and other results now document the occurrence of abrupt shifts in climate during the present, modern warm period. This interval encompasses the emergence of agriculture, the growth and collapse of civilizations, and the current exponential expansion of human population. These findings may have implications regarding any human-induced future climate warming.

ENVIRONMENTAL POLLUTION IN PERSIAN GULF

Oil, domestic, urban and industrial pollutants are a problem in several parts of the Persian Gulf. Additionally, the coastal zones of the Persian Gulf are fast becoming the repository for solid waste disposal. As a result, major ecological problems have arisen from loss and degradation of productive coastal habitats, caused by landfill, dredging, and sedimentation.

The Persian Gulf and the surrounding areas contain about 68% of the world's proven reserves of petroleum and about 34% of total natural gas reserves (year 2000 estimate), and new reserves are still being found, both on land and offshore. Large amounts of oil are refined in the area, and oil tankers carry oil from marine terminals to different parts of the world. In the year 2000 the Persian Gulf states produced almost 28% of the world's oil.

Despite the heavy presence of oil industry and their related activity in the Persian Gulf, the response of marine ecosystem to extensive oil pollution is still not well understood. Beach oil is widespread, often in high concentration throughout much of the Persian Gulf.

Widespread man-made pollution of the sea that can be detected by current spaceborne systems is concentrated in the Persian Gulf and the Gulf of Oman. Obviously, there is some pollution wherever ships discharge oil and other material into the sea that is foreign to the marine environment. These events are short-lived, however, and cannot be located and tracked from space observations.

Large amount of petroleum products ends up in the Persian Gulf. Seagoing tankers carry 60% of all oil extracted. The marine environmental pollution is caused when these ships flush their tanks with seawater. A smaller portion comes from passenger ships and freighters draining ballast water from their fuel tanks.

Rivers carry the greatest volume of petroleum products dumped into the Persian Gulf. It represents more than triple the quantity coming from all tankers and other ships. Oil and other petroleum products are discharged into rivers and the marine environment by many industrial enterprises, including oil refineries and oil storage installations. The quantity of petroleum products dumped each year into the sewage network by gasoline stations twice exceeds the amount resulting from ship disasters.

Locally, especially in coastal regions, a sudden spill of oil into the sea can have catastrophic consequences that are usually short-lived with long term effects. In the case of the Kharg Island spill in the Persian Gulf, the flow into the sea has been nearly continuous since 1982. As a result, an entire fishing industry has been destroyed, complete populations of some fish species are now extinct, and desalination plants have become inoperative. It is unlikely that the Persian Gulf waters will return to normal in this century.

EFFECTS OF REGIONAL CONFLICTS

In addition to the growing pollution caused by oil extraction in the Persian Gulf as well as the inherent characteristics which give rise to environmental difficulties, the Persian Gulf has likewise witnessed the fiercest military confrontations during the last two decades.

Major oil spills in 1983, during the Iraqi-Imposed war, and in 1991, during the Gulf War, have adversely affected the Persian Gulf environment, as has oil pollution from routine tanker operations.

The eight-year Iraqi-imposed war against Iran and Iraq's war with Kuwait inflicted serious damage on the Persian Gulf and its biological resources. The Iraqi-imposed war resulted in a total oil spillage of about two million barrels. This caused relatively modest ecological damage and this was indeed ignored by the world's press.

During the Iraqi-imposed war the Shadegan wetland with an estimated area of 269,000 hectares on the frontier between Iran and Iraq was reported to be severely polluted by chemicals as a result of military action. Shadegan wildlife refuge is part of the largest lowland wetlands in Iran (3.8 million hectares). It consists of brackish sedge marshes, giving way to saltmarsh vegetation along with mudflats, sandbars and muddy islands on the coast.

The oil spillage in the Persian Gulf has been heralded as one of the worst ecological catastrophes in history. The Gulf war oil spill released up to 11 million barrels of oil into the Persian Gulf from the period of January 20, 1991 through May 1991. There is no doubt that this is the largest oil spill recorded. The third largest spill also in the Persian Gulf occurred in the Nowrooz oil field during the Iraqi-imposed war. The Nowrooz spill came to 2 million barrels, and was also an Iraqi military creation.

After the terrible oil spill of 1990-91, the Persian Gulf suddenly became a worldwide disputed sea area. A rush of examination and research works was triggered, of which the best general idea is presented in a special volume of the Marine Pollution Bulletin which published in 1993 (Price et al., 1993).

The above-mentioned conflicts not only resulted in the spillage of large quantity of oil in the Persian Gulf but also severely damaged the littoral areas in the southern and northern regions of the Persian Gulf, even affecting their soil and air. Because of the unique geographical and biological features of the Persian Gulf, it was likely to become the worst ever man-induced oil-related marine disaster. The waters of the Persian Gulf are particularly fertile with a wide diversity of species and habitats, making it one of the most productive marine environments in the world. This biological richness and the sensitive ecosystem were threatened.

Consequent to these military conflicts, the United Nations and the World Environment Organization initiated extensive programs to alleviate the destructive impacts of the wars and planned special projects to control the expanding oil leaks in this important water body. These actions, however, failed to render any outstanding results in protecting the marine environment.

There were in fact two major sources of oil slicks: The main slick originates from the deliberate discharge of oil from the Mina Al-Ahmadi terminal in Kuwait about 30 kilometers south of Kuwait City. The valves at this terminal were open for 4 days. The second slick originated from the Al Khafji oil storage tanks some 15 kilometers south of the Kuwait and Saudi Arabia

border. The anticlockwise circulation of the Persian Gulf spread the oil down the Saudi coast towards Bahrain and Qatar.

The infamous oil released into the marine environment of the Persian Gulf amounted to between 6 to 8 million barrels. After evaporation, natural decay, and weathering perhaps 45% of that (i.e., 2.7 to 3.6 million barrels) beached along the northern Saudi Arabian coast (Evans, 1992). The Saudi intertidal areas, largely composed of sand and mud flats, are extremely shallow. Their linear extent between high tide and low-tide marks ranges up to 5 kilometers, with an average gradient of 35cm/km (Evans, 1992).

Winds from the southwest are also common. These winds were responsible for float beached oil which then was swept southward by the water current and then redeposited further south along the northern Saudi coast as the wind changed back to its northerly direction. Thus, it was clear from the beginning that the oil's effects would be localized. Indeed, there was no damage from marine pollution along the southern Persian Gulf coast, nor on Bahrain, Qatar, the UAE, Iran, or Iraq, and even of Kuwait's shoreline 95% remained oil-free.

Oil percolation into the sediment would depend on sand-grain coarseness, suffocating or poisoning burrowing animals such as ghost crabs, bivalves, and polychaete worms. Indeed, for most of the sampled sites in southern Persian Gulf, a Greenpeace research team found "no sign of surviving marine life on the shore and the first signs of life start appearing well out below (the low-tide mark)" (Bloom, et al., 1994). Hayes et al. (1993) arrive at a similar conclusion. One year after the war all the halophytes were dead and there was no sign of living epibiota in the mid to upper intertidal areas.

The Persian Gulf islands were virtually unaffected by the oil spills. However, upon examination of the islands several researchers noted that many islands show pollution by industrial debris.

Regarding coral reefs, researchers agree that there was no damage due to the Gulf War (Bloom, et al., 1994). However, it was found that Bahrainian reefs were completely dead along dredging channels presumably dug to make way for oil tankers.

Saudi mangrove stands had already been substantially depleted along the southern coast of the Persian Gulf, and there were only two remaining areas hosting mangroves. The smaller one, comprising about 10 hectares, is the bay west of Abu Ali; the larger one consists of 8 acres around Tarut Bay. This second area was unaffected by the oil spill. The former showed patches were mangroves were badly affected but also patch where mangroves were almost unaffected (Böer, 1996). Most damage to mangrove stands derives from peacetime land reclamation efforts, particularly in the unoiled Tarut Bay (Evans, 1992).

Experience from the oil-discharges from Kharg Island and the Nowrooz oil loading platform during the Iraqi-imposed war shows how difficult it is to predict the longer-term pattern of oil dispersal. As the slick degrades, it will break up into small patches, begin to emulsify and finally sink. However, the

high salinity of the Persian Gulf waters mean it is likely to float for longer unless mixed up by the continued action of the strong winds and waves.

Faith of Oil in Persian Gulf

Immediately after a spill, oil spreads out on the sea surface at a rate which is determined by the prevailing wind speed. Having lower surface tension than seawater, oil will spread much faster than flow of seawater underneath it. The lighter fraction of oil will evaporate during the first day immediately after a spill.

Photo-oxidation by solar Ultra Violet radiation will account for a maximum of 1% per day of the total volume spilled. Oil-degrading bacteria, naturally occurring in the seawater will break down the heavier fraction. A part of the oil will also be oxidized by the dissolved oxygen at the rate of 1 mg oil/ mg O_2 (Gerlach, 1981).

Barely 1% of the spilled oil may be dispersed, suspended or dissolved in water. All these processes precede quit fast in warm water. Thus, it might be optimistically presumed that in warm tropical waters roughly half of the spilled oil will disappear during the first 24 hours after the oil spill. This amount will vary with the varying density of the oil at its source.

After the first day, owing to the marine conditions and sea state and high temperature, water-in-oil mousse may be formed due to the prevailing wind which will adsorbed onto the surface of any suspended particle to form tar balls. Some of the tars balls may sink to the seabeds or depending on their density become suspended in an intermediate watermass and flow-out. The remaining tar balls will, ultimately, be washed ashore on nearby beaches. One such example could be observed on the Islands near the Strait of Hormoz.

Therefore oil originating from spills in the Persian Gulf may leave the region in dissolved or dispersed form in deeper outflowing water, perhaps with drifting tar balls through the Strait of Hormoz. Ultimately any oil would find its own density level in the water mass at 200-350 meters depth. Floating tarballs are unlikely to leave at the surface, being confined inside the Persian Gulf by circulating counter-clockwise gyre.

Effects of Oil Pollution

The Persian Gulf constitutes an almost entirely closed body of shallow water and it is one of the most productive plankton water bodies in the world. In addition, it is regarded as being one of the most fragile and vulnerable marine ecosystems. Its low tidal displacement means that it has little discharge of its water into the Gulf of Oman and as a result little opportunity to flush out pollutants.

The Persian Gulf is one of the most oil-polluted marine areas in the world. Its ecology is at risk from the discharging of ballast water, bilges and slop oil.

Many sites show various stages of oil-induced degradation and it is no longer a pristine environment.

The major human impacts come mostly from the oil and tourism industries, although increasing urban development on the coasts is damaging reefs through dredging and pollution. There is little active coral reef management in the region, although several large projects are developing national management capacity, and targeting particularly valuable tracts of reefs.

There are few major natural stresses on the reefs. Many of the human threats to Persian Gulf reefs are shared throughout the region, but are at different levels of intensity, depending on the growth of coastal populations: pollution from towns and industries; oil exploitation and transport; mining and quarrying; and huge power and desalination plants. Increasing quantities of solid waste are being dumped from ships and the land.

Following the Nowrooz oil spill, there was an increase in algal cover on coral reefs, which led to an apparent reduction in invertebrate frequency. A secondary impact was increased sedimentation as a cause of oiling resulting in complete or partial smothering of the coral polyps, killing the coral. Heavy oiling on beaches of offshore islands following the Nowrooz oil spill is still impeding the breeding activities of turtles and birds.

Oil pollution had detrimental effects on seagrass beds if it smothers the leaves and stems, or alternatively it may damage the grass bed by destabilizing the sediments. The oil have also caused glutinous conglomerates with the sediment, forming balls which, with their increased buoyancy, are more susceptible to wave action, so that eventually the seagrass becomes uprooted.

Petroleum hydrocarbons have numerous detrimental effects on coral, including reduced reproduction, larval development and settling, growth rate, photosynthesis, cell structure, feeding and behavioral responses. Such effects are probably the result of hydrocarbon fractions being incorporated into the water column; hence these problems can be exacerbated by the use of dispersants. A major threat also comes from the smothering of corals by crude oil during particularly low tides. This is known to cause massive mortality, and can result in toxins entering the food chain through coral feeding fishes.

The Persian Gulf reefs can provide increasing economic benefits to the people of the region, which can be sustainable, if successfully managed. However, systematic and coordinated efforts to manage these resources are being hampered by the complex politics in this region, weak legal and environmental policy capacity, weak administrations, poor organization, and limited skilled human resources.

Reef tourism is expanding with damage from curio collecting and anchors in marine protected areas. Oil pollution, from operational spills and discharge of dirty ballast water, is a continuing threat in the Persian Gulf.

The islands of southern Persian Gulf have well developed coral reefs, although these have already been degraded by oil spills from the Iraqi-imposed war.

Oil covers the leaves and clogs the aerial roots, preventing salt diffusion and suffocating the plant. Mangroves act as oil traps, and together with salt marshes are considered to be the most vulnerable shoreline habitat. If it is left to its own natural abilities, recovery may take a minimum of twenty years, dependent on the type of impact involved. Large scale erosion of the substrate may follow the death of mangroves, which postpones recovery indefinitely.

Avicennia media is acutely threatened in Saudi Arabia and Bahrain. Mangroves of Iran are threatened by intensive human use. Mangroves act as oil traps and are the most vulnerable shoreline habitat to oil spills. The effects of oiling may not be apparent immediately after a spill.

Foraminefers from various localities in the northern Persian Gulf show high concentrations of Ni and V especially in Bushehr Port up to the Arvand Rud waterway area at the head of the Persian Gulf. Less pollution is indicated in the northeastern Persian Gulf region from Kangan to Qeshm Islands. The enrichment Factor for Ni and V which are oil pollution indicators reveals that the sampling stations in northwestern Persian Gulf are most affected by oil pollution.

INDUSTRIAL POLLUTION

In many coastal areas of the Persian Gulf, the disposal of untreated or slightly treated sewage and industrial wastewaters is a common practice. ROPME (1986) estimated that the current sewage treatment facilities in the Persian Gulf coastal region were sufficient to treat only 58% of this waste. In addition to having a reputation as the most heavily oil polluted body of water in the world, the Persian Gulf is receiving a considerable quantity of untreated sewage and industrial waste water.

Numerous sources contribute to wastewater pollution in the Persian Gulf region. Of domestic and urban sources, untreated sewage and solid and liquid wastes are discharged at several localities. For example, in Saudi Arabia inputs of raw sewage into the Persian Gulf may be as high as 40,000 m^3 (IUCN, 1976). Effects include unsightly solids and grease mats, local eutrophication, increasing BOD and algal blooms. Sewage treatment plants are helping to alleviate some of these problems.

A variety of factors have all combined to threaten the Persian Gulf marine and coastal environment and its specific ecological characteristics. Among them are its higher rate of water evaporation than fresh water supply, and most significantly, the extended drilling and oil extraction projects that take place here, enabling lucrative exports for the littoral states.

Mainly rivers in the northwestern part of the Persian Gulf are supplying fresh water to the system. However, the amount of fresh water inflow is insufficient and does not compensate for the evaporation. One of the most vital factors in maintaining the ecological balance in this water body is the circulation of water. This process, as well, is relative and takes place every three to

five years. Given the above-mentioned conditions, the United Nations Environmental Program (UNEP) has declared the Persian Gulf as special areas and promulgated specific regulations for their preservation.

Another particular characteristic of the Persian Gulf marine environment is the presence of coral reef colonies and plant species that thrive in areas which mark tidal movements. Anchor damage to coral reefs is a problem in many localities. Fishing pressure is intensive in some areas.

The mangrove forest of the Persian Gulf is very important from the ecological viewpoint. Hara biosphere contains the largest stand of mangrove along the Persian Gulf coast shoreline. This site is also of major importance to breeding, wintering and migrant waterfowl. Their protection is of prime importance to the ecosystem of the Persian Gulf.

The coral reefs are crucial in controlling the water flow and they harbor various kinds of fish, especially the smaller species. The mangrove and *Avecina Marina* plant, which is particular to the Persian Gulf is among the sea resources that provide ideal living environments for crustaceans such as shrimps and also for other marine life.

The coral reefs and mangroves, together with an array of other plant colonies are among the marine life forms that are threatened by petroleum and other hydrocarbon-based pollutants in the area. The total area covered by mangroves in the Persian Gulf and the Gulf of Oman, where there is ebb and flow, exceed more than 20,000m^2.

Equally as significant are the colonies of plants living on the seabed near the shore, which also play a significant role in the area's marine life cycles. The vegetation that results is the prominent food source that sustains the many sea species thriving in the region. These include shrimp, which is among the species that generate revenue for the littoral states and other marine mammals such as Dugongs and Turtles.

Landfilling has eliminated large areas of shallow intertidal and subtidal habitat in the region of Saudi Arabia. Material for landfill of intertidal areas often comes from suction dredging of nearby subtidal areas associated with the creation of shipping lanes, harbors and marinas. When mangroves, intertidal flats, saltmarshes and seagrass beds are dredged and/or covered with landfill, they are destroyed and lost forever to the marine ecosystem and the process is irreversible. More than 100 km^2 of coastal habitat has been buried and destroyed under landfill in the last 20 years along the southern Persian Gulf shore. A much larger area of surrounding habitat has been affected by changes in water quality and shifting substrates due to landfill.

TYPES OF POLLUTANTS IN THE PERSIAN GULF

The environmental issues concerning the Persian Gulf, such as the presence of polluting substances have been examined in this part. The marine environment in the Persian Gulf has been exposed to various destructive con-

taminants in recent years. The extraction of oil from coastal areas and the continental shelf of the Persian Gulf, coupled with its export and the passage of oil tankers along the waterway, have had an increasingly destructive impact on marine ecosystems. At present, an estimated 100 ships enter and leave the Persian Gulf every day. This indicates that 40% of the world's total oil transportation passes through the region.

Therefore, it is only natural that such an extensive transit volume will have negative repercussions on the marine environment. The oil sludge, released by the aggregate of tankers traversing the Persian Gulf, is estimated to be around 8 million metric tons per year. This kind of pollution represents some 60% of the pollution plaguing the Persian Gulf. Studies conducted in recent years have shown that the major part of the pollution is caused by ships sailing from the Strait of Hormoz to oil terminals in regional countries.

The seabed along this route is often covered with oil sludge, which brings with it a particularly foul environment. The contaminants are discharged from the oil tankers when they release ballasts, since most are not equipped with oil and water tank separators, referred to as segregated ballast tanks (SBT). For as long as there are no regulations enacted to limit the passage of these ill-equipped vessels through the waters of the Persian Gulf, this problem will continue to the detriment of the Persian Gulf region.

Upon closer look, the dependence of the states in the southern Persian Gulf region on the marine environment becomes obvious. Among the necessities provided for these states through the resources of the Persian Gulf is the desalination of water for sanitary purposes as well as irrigation. In fact, over 60% of the world's desalinating facilities, with a capacity of over four billion cubic meters, can be found in this part of the world (Saudi Arabia alone processes about three million cubic meters of saline water for its daily consumption). There is also the continuing exploration and extraction of oil from the Persian Gulf's continental shelf. Moreover, marine resources in the Persian Gulf serve as the main food source of the inhabitants of the littoral areas.

Among the industrial wastewater inputs are desalination effluents, wastewater from fertilizer plants and refinery and other industrial effluents containing heavy metals. Elevated concentrations of lead, mercury and copper in bivalves and fish have been reported around some of the ports and industrial areas. High levels of cadmium, zinc and vanadium have been found in sediments (Linden et al., 1990).

Aggravating the pollution from tankers are the wastes that are released by industrial townships into rivers that pour into the Persian Gulf. These pollutants come mostly from the northern and northwestern areas. The conclusion calls for a collective effort by the littoral states to collectively prevent further pollution.

PERSIAN GULF SHORELINE SENSITIVITIES

Marine shorelines and environments have a wide range of sensitivities to oil and clean-up activities. The National Oceanic and Atmospheric Administration and the American Petroleum Institute have developed the Environmental Sensitivity Index (ESI) to classify shoreline types for spill response (NOAA, 1992). This classification scheme (Table 11-2) has been used in oil spill contingency planning and spill response operations (Hayes et al., 1999).

Major factors considered in ranking habitat sensitivity include shoreline type (substrate, grain size and tidal elevation), exposure to wave and tidal energy, biological productivity and sensitivity, and ease of cleanup. All of the shoreline types presented in table-11-2 can be seen along the northern coastline of the Persian Gulf. The new ESI rank has been added to the NOAA indexes regarding the special coastal substrates and morphology in the northern coastline (Iranian side) of the Persian Gulf (Sharifi and Haeri-Ardakani, 2004).

Table 11-2. Shoreline ESI ranking for habitats in marine shorelines (where 1 is least sensitive and 10 is most sensitive to oil and clean up actions)

Environmental Sensitivity Index (ESI)	Shoreline Type
1	Exposed rocky shores Sea walls and piers
2	Exposed wave-cut platforms
3	Fine-grained sand beaches
4	Coarse-grained sand beaches
5	Mixed sand and gravel beaches
6	Gravel beaches and riprap
7	Exposed tidal flats
8	Sheltered rocky shores
9	Sheltered tidal flats
10	Salt marshes and Mangroves

PROTECTION OF THE PERSIAN GULF ENVIRONMENT

The destructive consequences of the two wars, the special ecological conditions of the Persian Gulf, the dire consequences of abnormal extraction of marine resources, as well as the implementation of development projects and the pollution resulting from the extraction, drilling, refining and export of oil, if continued, could all lead to unpleasant impacts in the long run.

Predictions about the further destruction of the marine environment motivated the Persian Gulf states to join hands and commence regional cooperation programs to preserve the vulnerable Persian Gulf ecosystem. Toward this end, in April 1978, eight Persian Gulf states, together with UNEP, signed an agreement prepared by a conference of special regional representatives in

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