ISSN 0024-4902, Lithology and Mineral Resources, 2006, Vol. 41, No. 4, pp. 344–361. © Pleiades Publishing, Inc., 2006.
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The Persian Gulf Basin: Geological History, Sedimentary Formations, and Petroleum Potential

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Received October 19, 2005

Abstract—The Persian Gulf Basin is the richest region of the World in terms of hydrocarbon resources. According to different estimates, the basin contains 55–68% of recoverable oil reserves and more than 40% of gas reserves. The basin is located at the junction of the Arabian Shield and Iranian continental block that belong to two different (Arabian and Eurasian) lithospheric plates. Collision of these plates at the Mesozoic/Cenozoic boundary produced the Zagros Fold Belt and the large Mesopotamian Foredeep, which is a member of the Persian Gulf Basin. During the most part of the Phanerozoic, this basin belonged to an ancient passive margin of Gondwana, which was opened toward the Paleotethys Ocean in the Paleozoic and toward the Neotethys in the Mesozoic. Stable subsidence and the unique landscape–climatic conditions favored the accumulation of a very thick sedimentary lens of carbonate rocks and evaporites (up to 12–13 km and more). Carbonate rocks with excellent reservoir properties are widespread, while the evaporites play the role of regional fluid seals. Organic-rich rocks, which can generate liquid and gaseous hydrocarbons (HC), are present at different levels in the rock sequence.

DOI: 10.1134/S0024490206040055

PRINCIPAL STRUCTURAL ELEMENTS AND STAGES OF GEOLOGICAL EVOLUTION OF THE REGION

The Persian Gulf Basin is situated in the Arabian Peninsula between the Arabian Shield in the west, Taurus Mountains in the north, and Zagros Orogen in the east and northeast. In addition to the plains of Arabia, this basin also includes water areas of the Persian and Oman gulfs. At the end of the Paleozoic, this basin witnessed the origin of several structural elements, including the following three large troughs: Gotnia Trough in the north (Iraq and Syria), Arabian Trough in the central part of the basin (Saudi Arabia, northern branch of the Persian Gulf and Bahrain), and Rub-Al-Khali in the United Arabian Emirates, U.A.E.). The second and third troughs were separated by the Qatar Arch and its extension in the form of the Fars Block (Iran), while the Arabian and Gotnia troughs were separated by a group of small horst-type elevations, e.g., the Kuwait and Rimthan arches. Small grabens and semigrabens situated between them were elongated in the meridional direction in accordance with a deep fault system (Fig. 1) that was inherited from the time of consolidation of the Arabian–Nubian Shield approximately 1000 Ma ago. The large Ghawar High, which appeared in the Paleozoic in the eastern Arabian Basin, is bounded by a deep fault system of the same trend (Edgell, 1992).

The most ancient (900 Ma) magmatic complexes of the study region are represented by diorites, quartz diorites, and trondhjemites in plutons related to a volcanic island arc that existed here 920–680 Ma ago. Magmatism of that time was related to the Hidjaz tectonic cycle that was also manifested in Africa. This tectonic process was terminated by amalgamation of the Arabian Block with Gondwana.

Basement rocks in the majority of regions of the Arabian Plate are overlain by different age sandstones, which overlie salts and limestones in some areas. The age of these salts known as the Hormuz Salt is defined by different authors as Late Precambrian or Early Cambrian (Sharland et al., 2001). During the most part of the Paleozoic, the Persian Gulf Basin was a zone of stable subsidence. The Paleotethys Ocean was situated to the north of the Central Iranian Massif. In the Paleozoic, together with the Arabian–Nubian Shield, the Central Iranian Massif belonged to Gondwana as a member of the passive margin of this continent.

At the end of the Ordovician, Gondwana was subjected to glaciation. Fast retreat of glaciers at the initial Llandoverian led to a drastic rise of the World Ocean level and marine transgression on continental margins, resulting in the formation of graptolite shales enriched in OM (C_{org} 4–12%) and radioactive components. Due to high radioactive background, the basal Silurian layers are well traced by gamma well logging. In Saudi Arabia, they are known as “hot shales” or Kusaiba Formation (Luning et al., 2000).

Uplift of a significant part of Arabia in the Carboniferous due to the Hercynian tectogenesis is reflected in

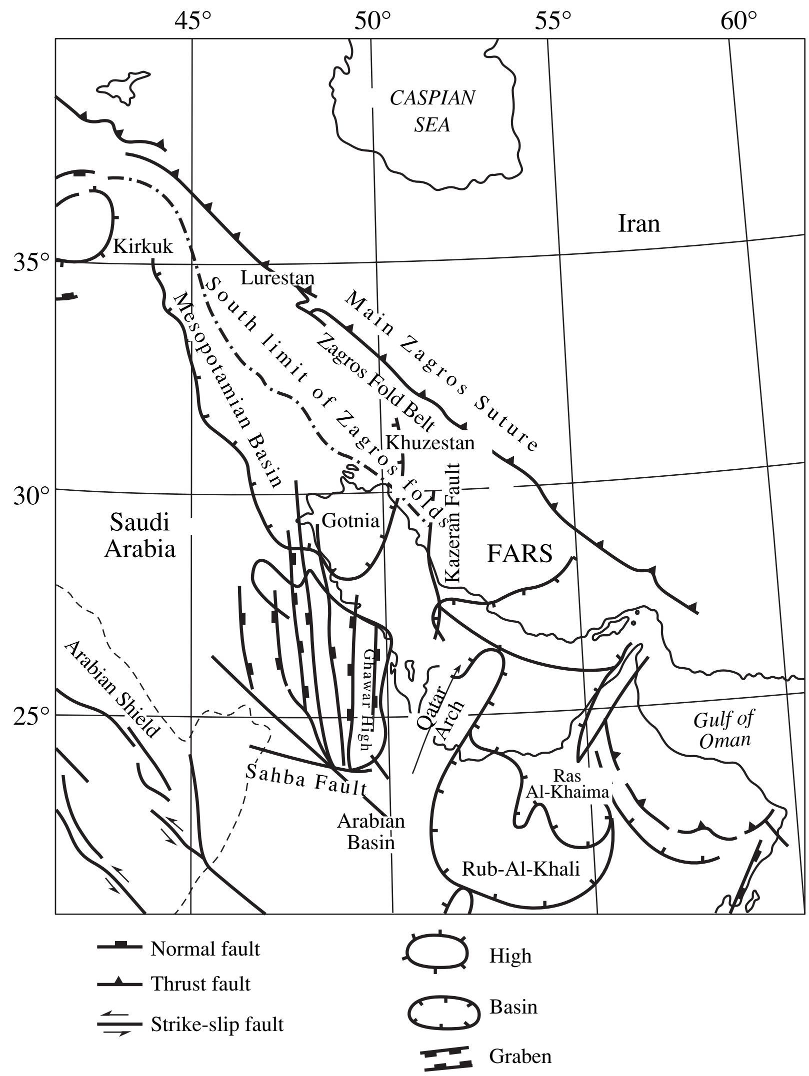

Fig. 1. Tectonic scheme of the Persian Gulf region. Compiled after (Ziegler, 2001).

the large hiatus and unconformity recorded in the majority of Paleozoic sequences of this region. This event is known as the Main Hercynian unconformity. At the Zagros foothills, Devonian and Carboniferous rocks are absent at all as a result of the erosion of as much as 1000 m of rocks. In the central part of the Fars Platform, the Permian sequence with basal conglomerates overlies Ordovician clays with angular unconformity (10°). The new phase of glaciation of Gondwana at the Carboniferous/Permian boundary was successively followed by fast thawing of glaciers and peneplanation of relief. At the Paleozoic/Mesozoic boundary, the Persian Gulf Basin represented a relict of the ancient passive margin. At the same time, the surface of the Arabian Plate gently dipped in northeastern and eastern directions.

The new ocean (Neotethys) was opened in the Middle Triassic simultaneously with the Gondwana breakup into the western and eastern parts (Ziegler, 2001). These events are known as the Triassic phase of extension. The related movements along deep faults renovated the relief and enhanced the supply of terrigenous material. The end of the Triassic was marked by a new phase of intense extension in the Neotethys, which was accompanied by subsidence of the northeastern margin of the Arabian Plate (Stampfli et al., 1991). In contrast, large domains in southern areas were drained. Judging from the absence of Rhaetian and Hettangian rocks in many sections, the hiatus was quite prolonged. A large area of the Gotnia Trough was also involved in the tectonic reactivation, and the subsidence trend was only retained in its eastern half, which became isolated as the Zagros Basin.

In Jurassic and Cretaceous, vast epicontinental seas, which largely accumulated carbonate sediments, were located in the northern and eastern peripheral parts of the Arabian Plate. The Turonian marked the onset of processes leading to the closure of the Tethys Ocean at the Mesozoic/Cenozoic boundary (Ziegler, 2001). These events initiated the origin of the Mesopotamian Foredeep that includes, in addition to the Zagros Basin (Lurestan, Dezful, and Khuzestan provinces in Iran and the adjoining areas in Iraq), the Fars Block (Fars Platform) in the southwest of Iran, the northern slope of the Qatar Arch and the most part of the Persian Gulf area, including the Rub-Al-Khali Basin (U.A.E.). Carbonate flysch was deposited in the central area of the Rub- Al-Khali Basin, while reef buildups were developed on its southern flank. This basin disappeared at the end of the Eocene. In the Zagros Basin, the Paleocene and Early Eocene were also marked by the deposition of flyschlike sediments (>1000 m) mainly related to the erosion of Cretaceous radiolarites. Here, the flysch deposits are overlain by molasse-type redrocks up to 330 m thick.

Ophiolitic packages, flysch members, and radiolarite units in the mountains of Zagros and Oman testify to the collision of the Arabian Plate with the Central Iran Block at the Mesozoic/Cenozoic boundary. The westward advance of the collision front was accompanied by washout of Turonian–Santonian sediments on tops of a number of anticlinal uplifts. Meanwhile, shallow-water conditions gave way to deep-water ones in eastern areas of the previously passive margin. Turbidites and other gravity deposits started to accumulate in some troughs. At the later stage of collision (at the end of the Early Miocene), the Zagros allochthon was thrust over the eastern edge of the Arabian autochthon. The sedimentary cover was partially detached from the basement and transported along the surface of the Hormuz Salt or younger evaporites (Bahroudi, 2003), resulting in the appearance of numerous diapirs in the Persian Gulf area beyond the Fars Block (Fig. 2).

Diapirs are not developed in land areas of the Mesopotamian Foredeep. Movements along faults in the basement were the major factor dictating the tectonics of the region, including the formation of the extended belt of anticlinal folds. This belt extends from the southeastern areas of Turkey across the eastern area of Syria and Iraq to southern Iran and abruptly comes to the end eastward of Bandar Abbas. Here, the sedimentary cover includes rocks of the whole >12000-m-thick Phanerozoic sequence in the south and is reduced two times in the north at the boundary of Iraq and Syria. The largest symmetrical folds are confined to the axial part and internal flank of the Mesopotamian Foredeep characterized by sharp gravity gradients.

Thus, four large tectonic stages can be distinguished in the evolution of the Persian Gulf Basin. The final stage of Gondwana formation was marked by its amalgamation with the Arabian–Nubian continental block and the subsequent accumulation of Hormuz Salt. During the whole Paleozoic, the region was situated in the rear zone of the passive Gondwana margin of the ancient Paleotethys Ocean. The onset of the Mesozoic Era was marked by destruction of the Pangea Supercontinent and opening of the Neotethys Ocean in the Triassic. The northeastern part of the Arabian Plate formed the core of the new passive margin that existed until the middle Late Cretaceous. Finally, collision of the African–Arabian continent with the Central Iranian continental block at the Mesozoic/Cenozoic boundary initiated the formation of the Zagros Thrust-Fold Belt and Mesopotamian Foredeep. The foredeep continues to develop at present.

During all stages listed above, the Persian Gulf remained a region of predominant sedimentation. This is expressed in the formation of very thick sequences including diverse rocks ranging from tillites to evaporites with the leading role of carbonate rocks and relatively modest participation of terrigenous sediments (sandstones, siltstones, and clays including organic-rich varieties). Such prolonged and continuous accumulation of sediments, which could generate, enclose, and screen hydrocarbon accumulations, created conditions favorable for the transformation of the Persian Gulf region into a unique oil-and-gas (hereafter petroleum) basin with enormous hydrocarbon resources.

LITHOLOGICAL COMPOSITION OF PETROLIFEROUS COMPLEXES OF THE PERSIAN GULF BASIN

One of the most prominent events for the recent years in the region under consideration was the discovery of rich gas pools in carbonate rocks of Permian–Triassic age, which are widespread in the southern part of the Mesopotamian Basin (Fars Platform) and the adjoining water area of the Persian Gulf. The productive sequence (250–450 m) of this region includes the Kangan and Dalan formations divided by the massive Nahr anhydrite bed. The Permian–Triassic sequence consists of thick layers of dense massive dolomites alternating with oolitic and pelletal limestones containing abundant small pores. Reservoir properties of these rocks are defined by the thickness of the oolitic limstones. The caprock for them is represented by massive anhydrites and dolomites of the Dashtak Formation, which are replaced in the northwestern Zagros area by layered dolomites with interlayers of oolitic limestones of the Kaneh Kat Formation. Thus, the dolomites are transformed into reservoir rocks. The absence of impermeable rocks makes this part of the basin less promising in terms of petroleum potential, although the Dalan and Kangan carbonate rocks with excellent reservoir properties are widespread (Maleki, 2004).

Many researchers consider Early Silurian graptolite shales as the principal source rocks that generated hydrocarbons in the Permian–Triassic complex. At the Zagros foothill, Silurian rocks are only exposed in two sites (north of Bandar Abass and in Kuh-i-Faragan). These rocks are observed as black layered clays (C_{org} content up to 4.1%, thickness 40–70 m) with a high degree of maturity (T_{max} 457°C, hydrogen index 50–

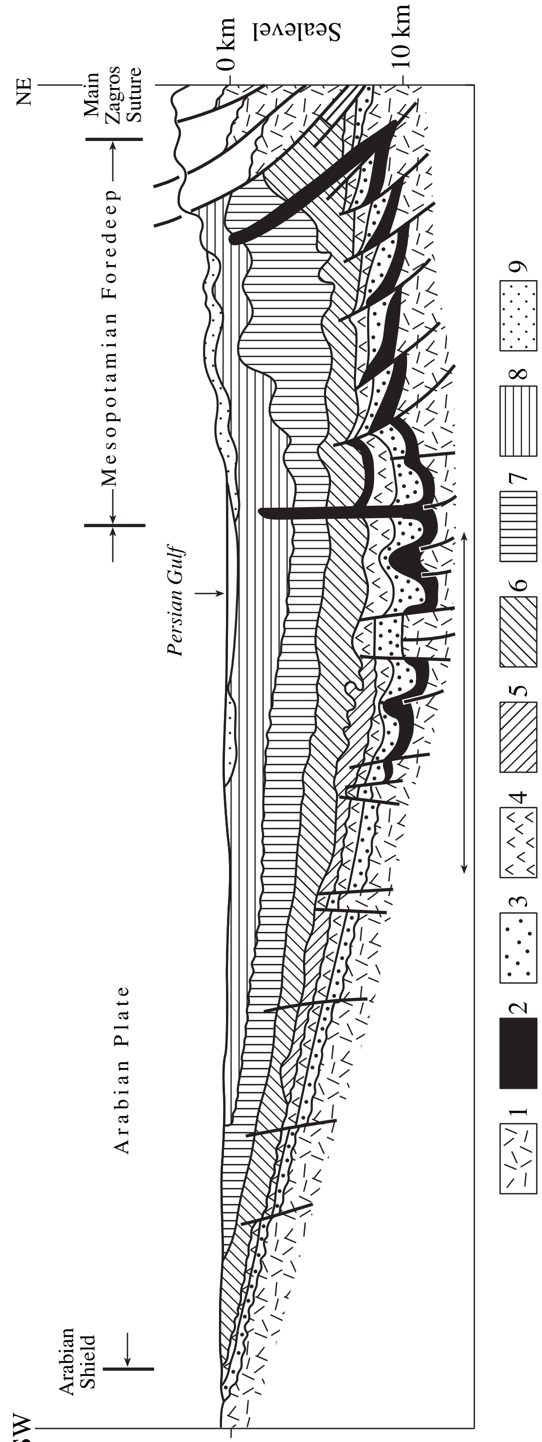

Fig. 2. Structure of the sedimentary cover in the central Persian Gulf Basin including the Arabian Plate and Zagros Orogenic Belt. Compiled after (Beydoun, 1998). (1) Precambrian basement; (2) Cambrian salt; (3–9) sedimentary rocks: (3) Lower and Middle Paleozoic, (4) Permian, (5) Triassic; (6) Jurassic; (7) Cretaceous; (8) Tertiary; (9) Quaternary.

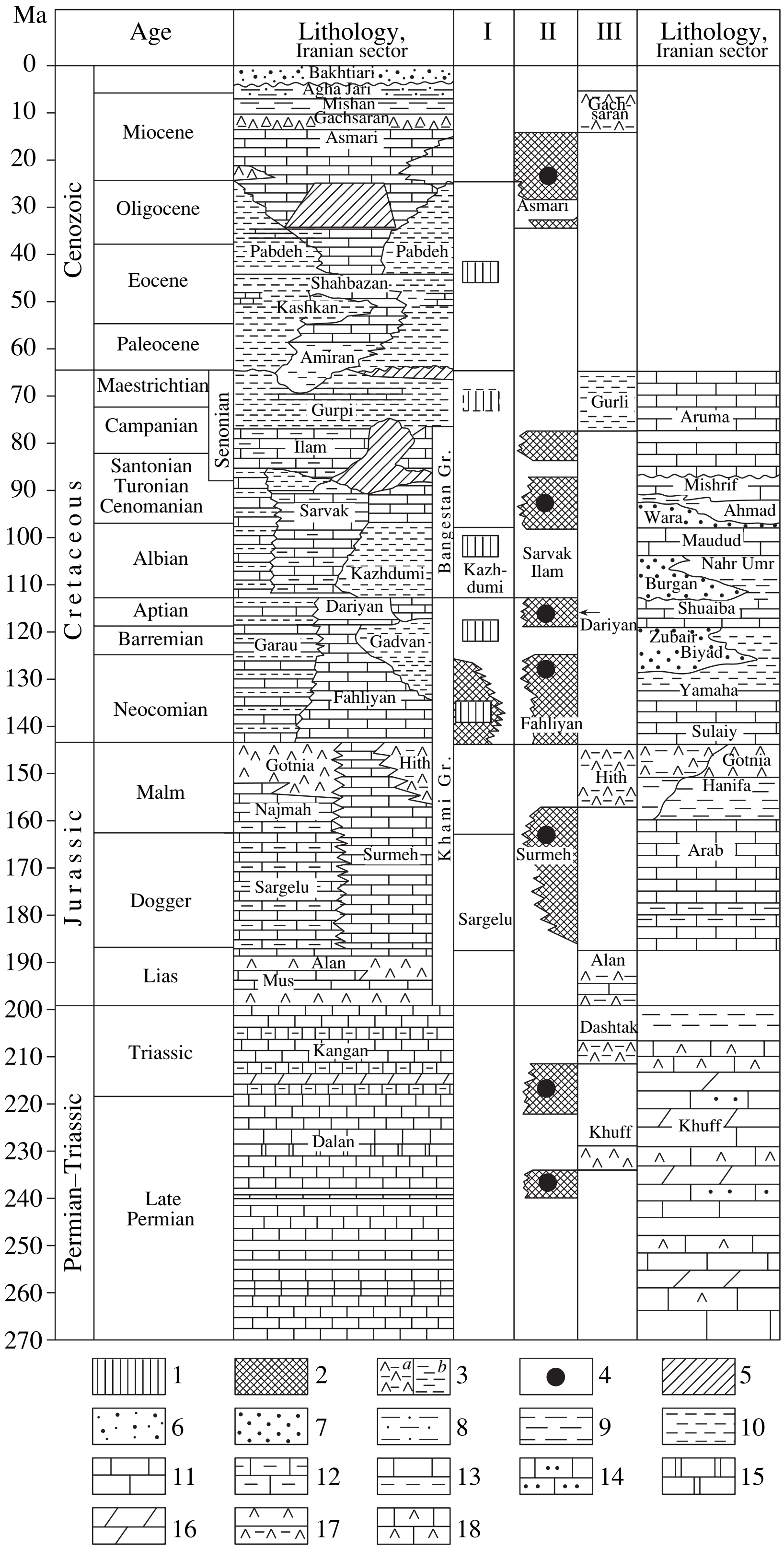

Fig. 3. Lithological composition and principal petroliferous complexes in the internal and external parts of the Mesopotamian Foredeep. After (Bordenave, 2002b). (I) Rocks capable of hydrocarbon generation; (II) rocks containing petroleum pools; (III) rock units and horizons sealing petroleum pools. (1) petroleum-producing rocks; (2) reservoir rocks; (3) impermeable rocks: salts (*a*), clay (*b*); (4) petroleum pools; (5) washout zones; (6–18) rock types: (6) conglomerates and gritstones; (7) sandstones; (8) alternation of sandstones and siltstones; (9) alternation of siltstones and clays; (10) clays and mudstones; (11) limestones; (12) clayey limestones; (13) alternation of limestones and clays; (14) sandy limestones; (15) dolomites; (16) marls; (17) gypsum and anhydrite; (18) alternation of limestones and anhydrite.

200 g H/C kg C, $\delta^{13}C = 30.8‰$). In the course of the Mesopotamian Basin formation, the Silurian black clays were first buried to a depth of 6000 m (Bordenave, 2002a) and then exhumed as a result of orogenesis in the Zagros zone.

It should be noted that the Fars sequence lacks sediments with a high petroleum-generating potential, except for Lower Silurian rocks. At the same time, the Fars Platform incorporates numerous petroleum seeps and sulfur accumulations related to bacterial decomposition of sulfates due to the emission of hydrocarbon gases (Bordenave, 2002a).

The Dalan Formation (southern Iran) can be divided into three units. The lower unit consists of limestones (160 m). The middle unit includes anhydrites and dolomites (300 m). The upper unit is composed of limestones and dolomites (~180 m). The thickness of the Dalan Formation sharply increases (up to 1075 m) in mountain areas of Zagros. The rocks make up a band (up to 2000 km long and 75 km wide) extending from Kuh al Gahkum to Kermansheih (Fig. 3) and the Iran/Iraq border. The Dalan sequence includes coastal-reefal rocks represented by algal concretions and fusulinid shells. The limestones have excellent reservoir properties. They include significant gas pools in the Kangan, Ach Har, Nar, Varavi, Mand, and Dalan fields.

Massive carbonates of the Kangan Formation (up to 160 m thick) are also a natural reservoir. Pelecypods found in clays at the base of this formation indicate Early Triassic age of the host rocks.

The Dalan and Kangan carbonates are frequently included in the Kuff Formation. They contain more than 50% of gas reserves discovered at present in the Persian Gulf Basin (Sadooni and Alsharhan, 2004).

The Jurassic petroliferous complex includes the Callovian–Kimmeridgian Surmeh limestones, which are reservoir rocks, and the overlying (Kimmeridgian–Tithonian) Gotnia evaporates (Fig. 3). The bituminous limestones and clays of the Sargelu Formation are considered source rocks for this complex (Bordenave, 2002b). At the Zagros foothills and in the plain part of the Mesopotamian Foredeep, the Jurassic complex is a compositionally homogeneous sequence from 250 to 500 m thick. The thickness decreases to 160–220 m in the southwestern areas of Iran.

Black bituminous limestones alternating with foliated clays lie in the lower part of the Sargelu section. Upward the sequence, dolomitic limestones with lenses of black flints start to play a more important role. Calcareous sediments probably accumulated on a relatively deep shelf in anoxic media with weak marine water circulation. Some layers include abundant organic remnants allowing us to define the age of the Sargelu Formation as Middle Jurassic (Aalenian–Bathonian). However, one cannot exclude that the boundary between the underlying rocks and Sargelu limestones is diachronous. For example, their age range is narrower (Bajocian–Bathonian) in Kuwait, where the Sargelu sequence is mainly composed of clayey limestones alternating with calcareous clays. The thickness of these rocks varies from 34 to 76 m. Some horizons are characterized by the presence of terrestrial organic remnants. The presence of interlayers of oolitic limestones at the base and top of this sequence indicates a coastal accumulation environment. These rocks accumulated in the course of gradual intensification of marine regression, since the clayey limestones are replaced upsection by pelloid varieties (packstones) accumulated on tidal flats and salt marshes.

In southern areas of the Persian Gulf, the black bituminous shales are present in the overlying Callovian–Oxfordian Najmah Formation mainly composed of clayey limestones (24–104 m). These limestones are frequently saturated with organic matter resembling kerogen. The enrichment of these rocks in ammonite and radiolarian remnants testifies to their accumulation on the outer shelf, where euxinic environments predominated. In areas adjoining the Persian Gulf water area, the Najmah limestones and clays together with the Sargelu clays are considered source rocks for the entire Jurassic section. In zones with fractured rocks, small oil pools have been detected in the limestones.

In the Iranian part of the Mesopotamian Foredeep, the Najmah Formation is mostly represented by shallow-water pelletal and algal limestones (up to 20 m). They are unconformably sandwiched between the underlying Sargelu clays and the Gotnia anhydrites. The anhydrites (~140 m) alternate with dolomites and dark gray clays. In the northwestern, Iraqi part of the Mesopotamian Foredeep, the anhydrites include black bituminous clays and oolitic and recrystallized limestones. These sediments accumulated in lagoons with hypersaline waters. This is indicated by the presence of rock salt in the Najmah sequence recovered by deep wells in southeastern areas of Iraq.

In the Bahrain Island, one can see a dolomitic limestone bed (87 m thick) with abundant coral fragments. At the base of the limestone sequence known as the Callovian–Oxfordian Tuwaiq Mountains Formation, black carbonate clays occur with interlayers of bedded microporous limestones. In Saudi Arabia, this sequence is 200–215 m thick and contains biomicritic limestones with abundant calcite spicules in its lower section and coral and algal fragments in the upper one.

In the Late Jurassic, the Qatar Peninsula area incorporated an intrashelf depression, which accumulated layered bituminous clays and marls of the Hanifa Formation. In the southern part of the Persian Gulf, these rocks are considered the principal hydrocarbon source for the oil pools found in Upper Jurassic and Cretaceous complexes. Organic matter in them (C_{org} 1–6%) has a sapropel composition, although it was partially decayed due to bacterial activity. Correlation between oils and bitumens extracted from the Hanifa marls and clays confirms that they served as the principal oil source sequence in the vast region.

The Jurassic part of the sequence is crowned in many areas of the Persian Gulf Basin by massive Tithonian anhydrites of the Hith Formation that are usually impermeable (Fig. 3). In many places, they alternate with dolomites and micritic limestones. Their top is composed of oolitic and stromatolitic limestones, which can contain sufficient hydrocarbon accumulations (e.g., the Manifa Member). The thickness of anhydrites is 40–72 m.

The best carbonate reservoirs in the region are represented by Upper Jurassic oolitic limestones of the Arab Formation. They are developed in Saudi Arabia, Qatar, Bahrain and the territorial waters of the United Arabian Emirates (U.A.E.). Horizons of coarse-grained oolitic and bioclastic limestones commonly terminate the sedimentary cycles (cyclites) of the Jurassic and Cretaceous Arab and other formations. Fast lithification of granular carbonate sediments favored the preservation of the initial high porosity. The consequent dissolution and dolomitization significantly increased the size of pores.

In the Qatar region, precisely the Arab limestones enclose the currently known largest oil pools of the world. Unit Arab IV includes four types of carbonate reservoirs composed of sugarlike dolomites (porosity 10–30%, permeability 10–100 mD or more). Approximately the same reservoir properties are recorded for pelloid packstones and grainstones. Reservoir properties of the oolitic limestones positively correlate with the size of oolitic grains characterized by rounded shape and excellent sorting. The porosity is commonly >30%. The permeability is 100–5000 mD or more (Alsharhan and Nairn, 1997).

Dolomitic bioclastic limestones are present at the base of the overlying Unit Arab III. Dissolution of the major portion of clasts and grains in them led to a drastic increase of porosity and permeability. These rocks form the main natural reservoir in the Northern Dome and Idd El Shargi oil fields. The top of this unit includes algal boundstones and pelloid and oolitic limestones with traces of leaching in some places and cementation with calcite in others. Therefore, their permeability varies within a very wide range from 1 to 1000 mD. Upper members of units Arab I and II are dominated by algal concretions with interlayers of oolitic limestones that are also affected by leaching. Their porosity varies from 7 to 30%, while the permeability varies from 1 to 800 mD.

The Qatar area and Neutral Zone are mainly composed of Early and Middle Cretaceous reservoirs represented by the Zubair and Burgan sandstones and the Shuaiba limestones. The thickness of Hauterivian–Early Aptian Zubair Formation increases from 280 m in the south to 427 m in the north. At the same time, the massive sandstones are replaced by alternation of sandstones with siltstones and clays. These rocks related to marine regression include sediments of shallow shelf, prodelta, land part of delta, bogs, and salt marshes. In southern Iraq, the Zubair section includes five units. The lower (first), middle (third), and upper (fifth) units are mainly composed of clays, whereas the second and fourth units are composed of sandstones. Oil pools were discovered not only in the thick massive horizons, but also in the lenslike interlayers of predominantly clay composition.

Within the framework of the platform flank of the Mesopotamian Foredeep, which includes the Persian Gulf area, coastal region of Qatar, and U.A.E. in the south, Aptian limestones of the Shu'aiba Formation represent the principal Cretaceous reservoir. In most areas, they are composed of fragments of reef-building organisms: rudists, corals, stromatoporoids, and algae. They commonly form thick, complex bodies (biostromes), whose composition changes both along the strike and in the vertical sequence (Edgell, 1997). Specific features described above are responsible for the instability of reservoir properties of these limestones and sharp variations of oil yield in wells. If the porosity varies from 7 to 30%, the permeability of limestones is usually more than 15 mD, but it can increase in some horizons up to 100 or even 1000 mD. The most dramatic variations are recorded in rocks, whose composition is dominated by fragments of rudists and algal concretions. Buildups composed of rudists usually grew on algal "pillows" and used the algal material as a hard substratum. In the Bu Hasa oilfield (U.A.E.), a significant clay admixture is present at lower horizons of the Bu Hasa Formation and dolomite cement appears at upper horizons.

In Qatar, basal layers of the Shuaiba Formation consist of algal limestones formed in lagoons or tidal areas. They grade upsection into the actively bioturbated fine-dispersed varieties. The middle part of section is composed of microporous clayey well-cemented limestones containing pelagic fauna. They are overlain by bioturbated fine-grained carbonates with remnants of sea-urchins and foraminifers. They belong to deposits of the open marine basin with low hydrodynamic activity. Finally, reefal limestones appear at the top of the sequence. They include rudist fragments, algal concretions, and gastropod shells. The thickness of the Shuaiba limestones varies from 100 to 145 m.

The Burgan Formation is composed of Albian sandstones represented by excellently sorted coarse- and medium-grained varieties that grade into the alternation of fine-grained sandstones and siltstones toward the top of the sequence. This section contains several interlayers of brown coal, amber, and glauconite (Alsharhan and Nairn, 1997). Hydrocarbon pools are most frequently associated with the so-called "Member III" (an equivalent of the Safania Formation) that represents an intercalation of glauconite sandstones and dark gray clays. Its middle section usually includes a layer of pure quartz sands, up to 110 m thick, containing lenslike interlayers of brown coals. The sands are characterized by high porosity (20%, on the average) and permeability (380–605 mD). Sandstones in the basal member (Member IV) also show good reservoir properties (porosity 23%, permeability 4 mD). The thickness of these coarse- to medium-grained quartz sandstones rarely exceeds 210 m. It is supposed that the rocks accumulated in the littoral zone at the front of a large river delta. Estuarine clays occupy no less than 10% of the sequence. They contain abundant remains of terrestrial plants and amber fragments. The Burgan sandstones and clays accumulated in the course of sea transgression. Limestones are present at the top of both members III and IV.

In the Kuwait Arch area, which incorporates three large (Burgan, Magwa, and Ahmadi) oil fields, the Burgan sandstones are overlain by the Ahmadi clays that serve as a reliable seal for petroleum pools.

In the eastern Persian Gulf area, as well as the central and northern areas of Iraq, sandy sediments (Nahr Umr Formation) are also widespread. Within the Northern Dome of Qatar, they make up sequences of well-sorted friable sands, 3–5 m thick, alternating with quartz sandstones cemented by calcite, siderite, and quartz. The porosity of these sediments is ~21%. The permeability varies within a wide range (from 3 to 1000 mD). Layers of clays appear at the top of this sedimentary sequence. In a number of fields, they play the role of impermeable caprocks that seal oil pools, for example, in the Nahr Umr sandstones and Shu'aiba limestones. The Bahrain Island section (219 m) is mainly composed of black clays alternating with sandstones and siltstones. The rocks contain lenses of brown coal and small pieces of amber. The sequence also includes horizons of glauconite sandstones and sandy limestones with the shallow-water fauna. In the eastern area (U.A.E. territory), the black shales are replaced by variegated clay sediments with interlayers of limestones, marls, and sandstones, sometimes with phosphorite concretions. These rocks overlie the Shu'aiba limestones with washout (the Late Aptian nonconformity). In Iraq and Kuwait, littoral and neritic limestones appear in the sequence. The most part of the sequence is composed of deltaic deposits with interlayers of continental sediments.

Many researchers consider Neocomian–Valangian clays and limestones in the lower part of the Garau Formation as potentially petroleum source rocks (Bordenave, 2002b). These rocks mainly occur on the internal wall of the Mesopotamian Basin and make up eight units. The basal units consist of black carbonate clays with concretions and interlayers of gray fine-bedded limestones (305 m thick). They are overlain by gray and brown clays (256 m thick) with lenticular limestone interlayers (units 3 and 4). The next overlying unit (263 m thick) includes light and dark gray fine-bedded limestones containing siliceous concretions with sandy and glauconite clays. The sediments described above are overlain by rocks of the Sarvak Formation, which is one of the major productive complexes in the internal (foredeep) part of the Mesopotamian Basin (primarily, in the Iran territory and adjoining areas of Iraq).

The Sarvak Formation includes three carbonate units with the total thickness of 832 m. Their age ranges from Late Albian to Turonian. The lower part of the sequence (255 m thick) consists of dark gray granular clayey limestones with lenticular bedding, ammonite fauna, and dark marls. The middle part of the sequence (535 m) includes massive microporous limestones with siliceous concretions and rudist fragments. The oblique (cross) bedding is evident in a number of horizons. The top of the sequence (42 m) includes a unit of weathered brecciated ferruginous limestones. In the Fars and Khuzestan provinces, rocks of the Sarvak sequence overlie the Kazhdumi marl. In the northwestern areas of Iran and in Iraq, they are replaced by rocks of the Garau Formation. On the northern coast of the Persian Gulf, the thickness of the Sarvak Formation decreases to 91–180 m. The lower part of the sequence is composed of gray to brown fine-bedded limestones containing orbitolinids, whereas the upper parts consist of grayish green clays with interlayers of limestones. It is possible that only the lower part of the Sarvak Formation is preserved here, and its upper part is destroyed by the post-Turonian erosion.

The Albian–Cenomanian rudist buildups incorporate excellent natural reservoirs in the Mishrif Formation that enclose large hydrocarbon pools along a wide zone extending from southern areas of Iraq to U.A.E. and Oman. The Mishrif sequence is dominated by bioclastic limestones composed of fragments of corals, rudists, and algae. The sequence also includes buried bioherm structures with large oil pools. In Qatar, the Mishrif Formation (up to 58 m) is composed of crystalline limestones with thin clay interlayers. Reservoir properties of limestones in this area are not very good. Correspondingly, the productivity of these rocks is not also high. The largest pool confined to the Mishrif sequence was discovered in the Minagish oil field.

Rocks of the Kazhdumi Formation are considered the most important ones in terms of oil production. They lie at a depth of 3000–5000 m in the Main Oil Field situated in the central part of the Mesopotamian Basin and include several giant oil fields. The Kazhdumi sequence is composed of alternating dark gray marls and clayey limestones. Planktonic globigerinas and radiolarians in this sequence are of the Albian–Cenomanian age. In the southwestern areas of Iran, the Kazhdumi sequence consists of black bituminous clays with minor interlayers of dark clayey limestones. Glauconite is common in the lower part of the sequence. The thickness of the Kazhdumi marls varies from 210 to 300 m. These rocks accumulated in a relatively deep shelf depression located between the Bala Rud carbonate platform and the Fars submerged bock. In the Darius area of the Persian Gulf, the Kazhdumi sequence is composed of alternation of clays with marls and limestones deposited in the neritic environment. Thin sandstone interlayers also occur here. The role of sandstones significantly increases toward the next Sirus area. Here, sandstones make up a member up to 40 m thick in the middle part of the sequence. The Kazhdumi clays are traced over the entire water area of the Persian Gulf up to the Oman coast, where their thickness decreases to 130 m.

The Kazhdumi Formation is considered the principal oil-generating sequence, i.e. the richest hydrocarbon source in the region. This is testified by the SPI index exceeding 25 t/m^2 (Bordenave, 2002b). The organic matter of this sequence is enriched in sulfur (5–7%). Together with bitumens, a part of this sulfur was delivered to pools of the Main Productive Field. Therefore, oils of this field are enriched in sulfur.

The hydrocarbon system of Tertiary rocks includes Miocene limestones of the Asmari Formation, which represent the principal reservoir in the study region, overlying salts of the Gachasaran Formation, as well as Eocene–Oligocene clays of the Pabdeh Formation that generated some bitumoids. However, clays and marls of the Kazhdumi Formation were the principal source of liquid hydrocarbons. The formation of the majority of oil (partially, gas) pools in the Iranian part of the Mesopotamian Basin is attributed to these sediments (Bordenave and Burwood, 1995).

Outcrops of the Pabdeh Formation are known in different areas of Zagros. Wells drilled in the large Lali oil field area recovered 870-m-thick rock sequence that can be divided into the following five units (from bottom to top). The lower unit (140 m thick) is composed of blue and orange marls with interlayers of clayey limestones. They are overlain by gray clays with lens-like interlayers of the same limestones (74.7 m), passing upsection into fine-bedded limestones with siliceous concretions (42.6 m). The clayey limestones are overlain by dark clays containing rare limestone interlayers (82.3 m). Finally, the upper part of the sequence (more than 450 m thick) consists of alternation of limestones and clays. According to the paleontological data, the Pabdeh rocks has mainly Paleogene age, although Early Miocene fauna was encountered in upper parts of the sequence in the Khuzestan Province. In some sequences of the Fars Province, the lower unit of purple clays is absent, and the basal horizon consists of siliceous limestones, including glauconite, shark teeth, and coarse gravel. Contact with the overlying Asmari limestones is conformable.

The Asmari Formation (up to 400 m thick) in the Iranian area of the Mesopotamian Foredeep is divided into numerous cyclites (0.5–5 m thick), in which fine-bedded dolomites and limestones are associated with anhydrite microconcretions. Anhydrite developed after gypsum that precipitated from brines in sebkhas during the late diagenesis. Commonly, fine-grained dolomites with a significant microporosity and very low permeability lie at the top of the cyclites. Biomorphic-detrital limestones accumulated under sublittoral conditions near the shoreline are frequently found at their base. Data on stable ^{18}O and ^{13}C isotopes testify to high water salinity in the sedimentary basin. The accumulation rate of Asmari carbonate sediments decreased from 41–93 m/Ma in the Late Oligocene to 14–28 m/Ma in the Early Miocene. Dolomitization of limestones during their burial significantly improved their reservoir properties (in particular, permeability). Petroleum pools in the Asmari limestones were preserved due to their sealing by evaporites of the Gachsaran Formation over wide areas.

In Kurdistan, Oligocene carbonate rocks are represented by algal and reefal limestones (Kirkuk Formation). These rocks with good reservoir properties contain abundant hydrocarbon reserves. The principal oil reservoir in the giant Kirkuk Field known as the Main Limestone is composed of reefogenic limestones that can be subdivided into the front reef, main reef, and back reef. The main reef body is dominated by shells of large foraminifers and miliolids, whereas the front reef contains remnants of nummulites and lepidocyclins. The large Oligocene coral reef, about 44 m high, serves as oil reservoir in the Bu Hasa field in Iraq.

SEDIMENTATION CONDITIONS AND FACIES ZONATION

The terminal Paleozoic (Late Permian) time was marked by the intense accumulation of carbonate sediments in very different circumstances ranging from lagoon and coastal zones to offshore areas of the open shelf. They also accumulated in sebkhas and salt lakes on the coastal plain. This is indicated by the abundance of evaporites (mainly, gypsum and anhydrite) at the top of the Upper Permian sequence and at the bottom of Triassic sequences. Terrigenous sediments (mainly, sands) accumulated only along the periphery of uplifts in the central and western parts of the Arabian Plate. Sands accumulated in sebkhas contained gypsum and anhydrite. However, the large-scale accumulation of sands was probably confined to lagoons and peripheral parts of bays that deeply cut into shores. A large lagoon or a chain of lagoons was situated in the central part of the basin (central areas of Saudi Arabia and Kuwait). According to (Ziegler, 2001), the thickness of anhydrites in the Khuff Formation in these areas varies from 60 to 100 m or more (Fig. 4). At the periphery of the lagoon, anhydrites alternate with dolomites, which are gradually replaced by limestones (mainly, dolomitic, oolitic, and bioclastic varieties) off the coast. The bioclastic and oolitic limestones alternate with clayey dolomites and anhydrites in southern areas of the Persian Gulf and with oolitic and micritic varieties (frequently, silicified limestones) in the north (Iraq and Iran). Biohermal buildups were developed in the

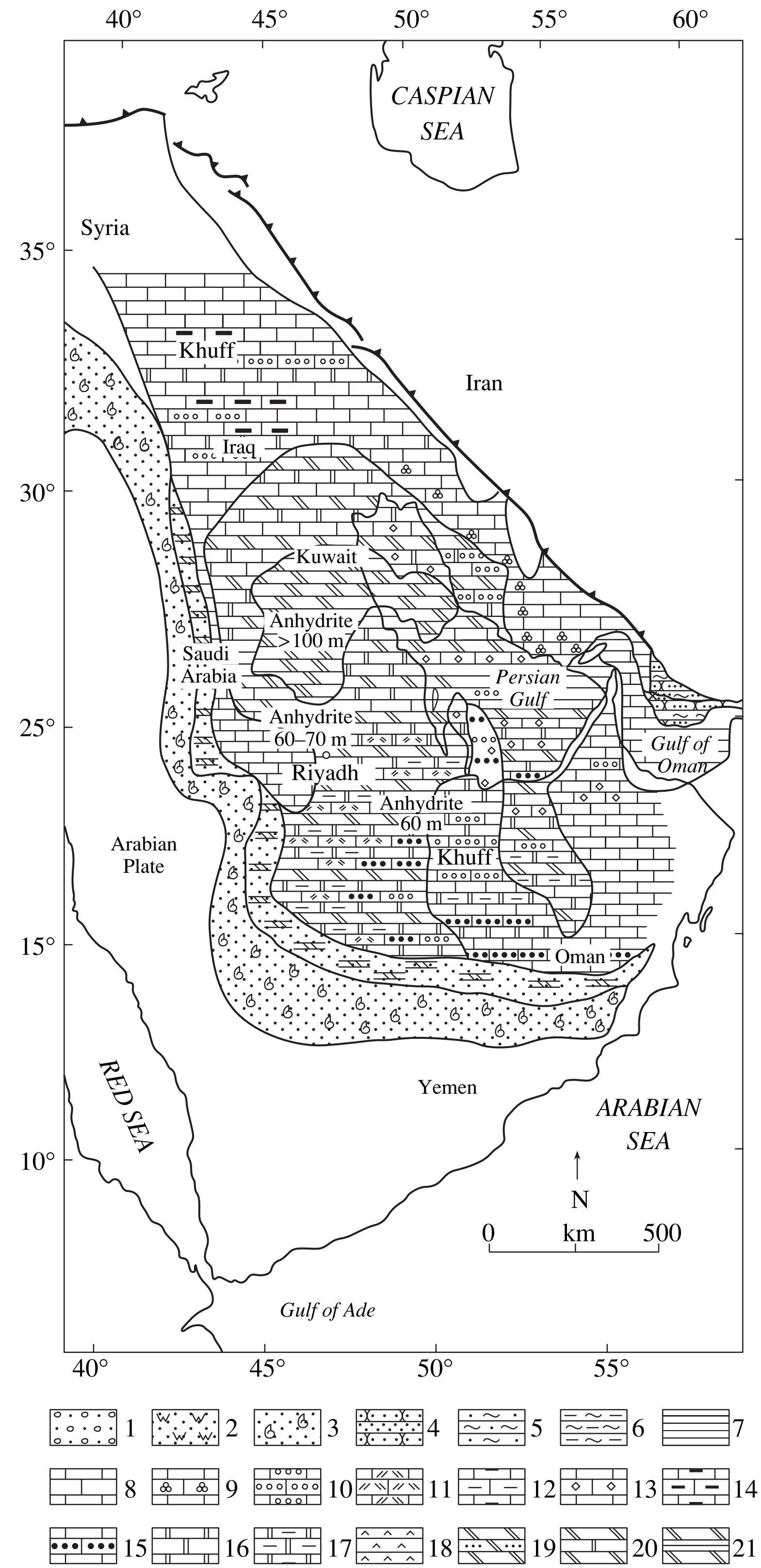

Fig. 4. Lithofacies scheme of location of different types of Late Permian rocks (Kazanian and Tatarian) in the Persian Gulf Basin. (1–7) Terrigenous rocks: (1) continental terrigenous, (2) lacustrine, (3) sands and sandstones, (4) silty sandstones, (5) siltstones, (6) clayey siltstones, (7) clays and clayey rocks; (8–16) carbonate rocks: (8–15) limestones: (8) micritic, (9) reefal and/or algal, (10) oolitic and pelletal, (11) bioclastic, (12) clayey, (13) dolomitic, (14) with concretions of phosphorites and small amber fragments, (15) silicified; (16) dolomites; (17) clayey dolomites; (18–21) evaporites: (18) rock salt; (19) anhydrites and sandy anhydrites; (20) alternation of anhydrites and dolomites; (21) alternation of anhydrites and clays.

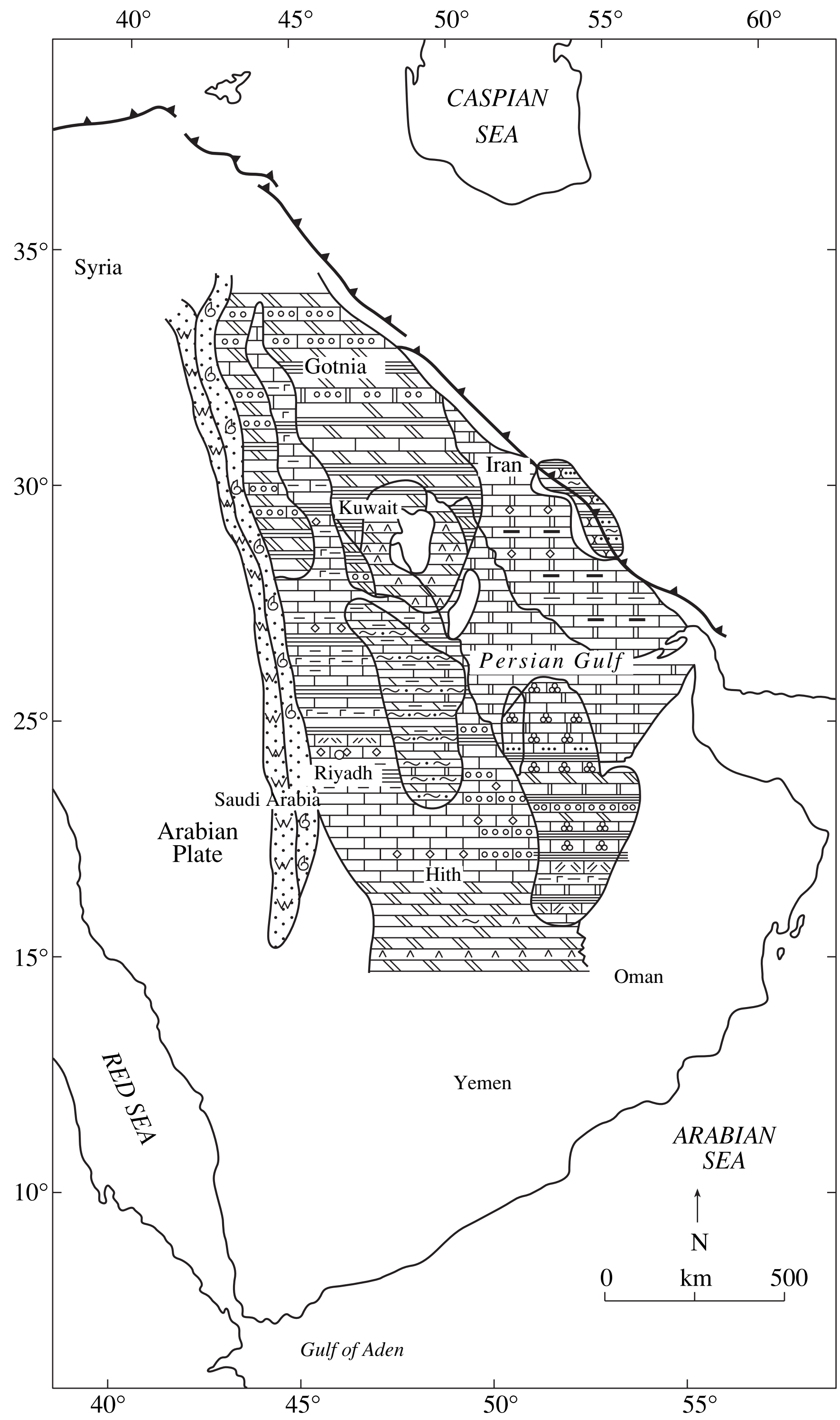

Fig. 5. Lithofacies scheme of location of different types of Upper Jurassic (Oxfordian–Kimmeridgian) rocks in the Persian Gulf Basin. See Fig. 4 for the legend.

Zagros Basin (Alsharhan and Nairn, 1997). During some periods, they defended the lagoon (or lagoons) from the action of storm waves. Similar conditions of sedimentation also dominated in the Early Triassic that terminated with the accumulation of evaporites of the Dashtak Formation. During the Triassic and the most part of the Jurassic, primarily carbonate sediments were accumulated in the Persian Gulf Basin. However, their domain gradually shifted to the east toward the Zagros Basin.

In the Middle Triassic, carbonate sediments frequently alternated with terrigenous sediments due to tectonic activation within the Arabian Shield, and evaporites formed in association with clays and clayey–silty sediments. Continental rocks of the terminal Triassic are dominated by variegated gypsum-bearing clays. It is interesting that evaporites continued to accumulate in the Kuwait area and northern part of the present-day Persian Gulf. Subsequently, the evaporites gradually gave way to dolomitic and silty sediments and fine-grained sands as a result of the significant sealevel drop in the Carnian 223 Ma ago.

At the beginning of the Jurassic, the facies zonation generally retained the Late Permian evolution trend. Terrigenous sediments continued to accumulate in the near-shore environment. They were replaced by carbonate sediments in the open part of the shelf. The evaporites also continued to accumulate mainly at the periphery of the Zagros Basin. Here, the evaporites alternate with clays and clayey limestones.

At the Middle/Late Jurassic boundary, coral–algal bioherms and bioclastic sediments of sand dimension formed on the widespread ramps and submarine carbonate shoals. At the end of the Jurassic, dolomites, anhydrites, and sometimes rock salt started to accumulate on tidal flats, sebkhas, and lagoons extending along the coast (Fig. 5). The salts occupied slopes of paleouplifts, in arches of which Kimmeridgian and Tithonian rocks are absent. One of these uplifts was situated at the extension of the Ghawar High in the western part of the Persian Gulf, while the other uplift was located at its top in the offshore zone of Kuwait. These structures can be named the Marjan and Burgan paleouplifts, respectively, after the names of large oil fields located on their slopes. The third (Rimthan) Arch is situated on the western side in the southwestern part of Iraq. The majority of evaporites of the Gotnia Formation were accumulated north of the paleouplifts separated by a meridional marine gulf. The Upper Jurassic sequence of this area consists of alternation of clays, anhydrites, and limestones, including oolitic ones. In the eastern Zagros Basin, these sediments are replaced by clayey and siliceous limestones with dolomite interlayers. Finally, Upper Jurassic rocks are represented by sandstones, siltstones, and clays accumulated on submarine slopes in the Zagros thrust zone.

The Rub' Al-Khali halogenic basin was confined to evaporites of the Hith Formation in southern areas of Saudi Arabia. The halogenic basins were separated by an uplift, where evaporites were replaced by dark-colored (frequently, gypsum-bearing) clays with interlayers of clayey, oolitic, and dolomitic limestones (more rarely, anhydrites). In the Ghawar High area, dolomites and anhydrites are present in the Upper Jurassic sequence of dark-colored organic-rich marls and siltstones. Another field of organic-rich sediments was located in southern regions of the Persian Gulf on eastern and southeastern sides of the Qatar Arch (U.A.E.), where the sediments alternate with anhydrites, dolomites, and oolitic limestones.

The areas mentioned above are separated by a narrow zone of Upper Jurassic rocks represented by the alternation of oolitic, micritic, and dolomitized limestones with rare clay interlayers. Probably, this zone incorporated a large gulf characterized by accumulation of carbonate sediments in its subsiding part and organic-rich fine-grained sediments on coastal salty lagoons and tidal flats in the peripheral areas.

It should be noted that the disposition pattern of different facies types of Upper Jurassic sediments is similar in many aspects to that of the Late Permian Epoch (Konyuhov and Maleki, 2005). For example, an area of the predominant evaporitic accumulation was located in the northern part of the present-day Persian Gulf and the Kuwait territory, i.e., almost in the same terminal Paleozoic places. However, in addition to anhydrites and dolomites, rock salt also precipitated here in the Late Jurassic. Moreover, a gulf deeply penetrating the land mass also existed to the south of the Qatar Arch. Thus, the facies zonation developed by the second half of the Jurassic in the Persian Gulf Basin partially repeats the Paleozoic/Mesozoic boundary pattern. Consequently, one can assume a definitely inherited character of sedimentary processes in this region over a period of more than 110 Ma.

Some signs of the inherited nature of evolution are also retained in the Cretaceous. For example, Early Cretaceous sediments are lacking or washed out on the arches of the Marjan and Rimthan paleouplifts (the Late Valanginian unconformity). Meanwhile, evaporites completely disappeared from the sedimentary sequences and they gave way to shallow-marine carbonate sediments with interlayers of terrigenous sands and silts on slopes of the paleouplifts. In the eastern Arabian Plate, Zagros Basin, and adjoining areas, black carbonate clays and clayey limestones of the Garau Formation accumulated over a long time. Abundance of remnants of radiolarians and plankton foraminifers in these sediments indicates proximity to the open ocean. The western areas represented vast carbonate shoals dominated by the accumulation of oolitic and pelletal carbonate sediments.

Marine transgression reached its maximum at the end of the Albian and coincided with the renovation of topography in the western Arabian Plate. These processes fostered a significant increase in the riverine transport of terrigenous material and accumulation of sandy sediments in river deltas, which advanced northeastward along paleorelief depressions that separated the Burgan and Marjan uplifts. Thick sandy sequences (Zubair and Burgan formations) deposited in this area playing a crucial role as petroleum reservoirs in eastern Saudi Arabia and Kuwait. Reefal buildups (e.g., Shuaiba and Mishrif formations) developed in areas lacking

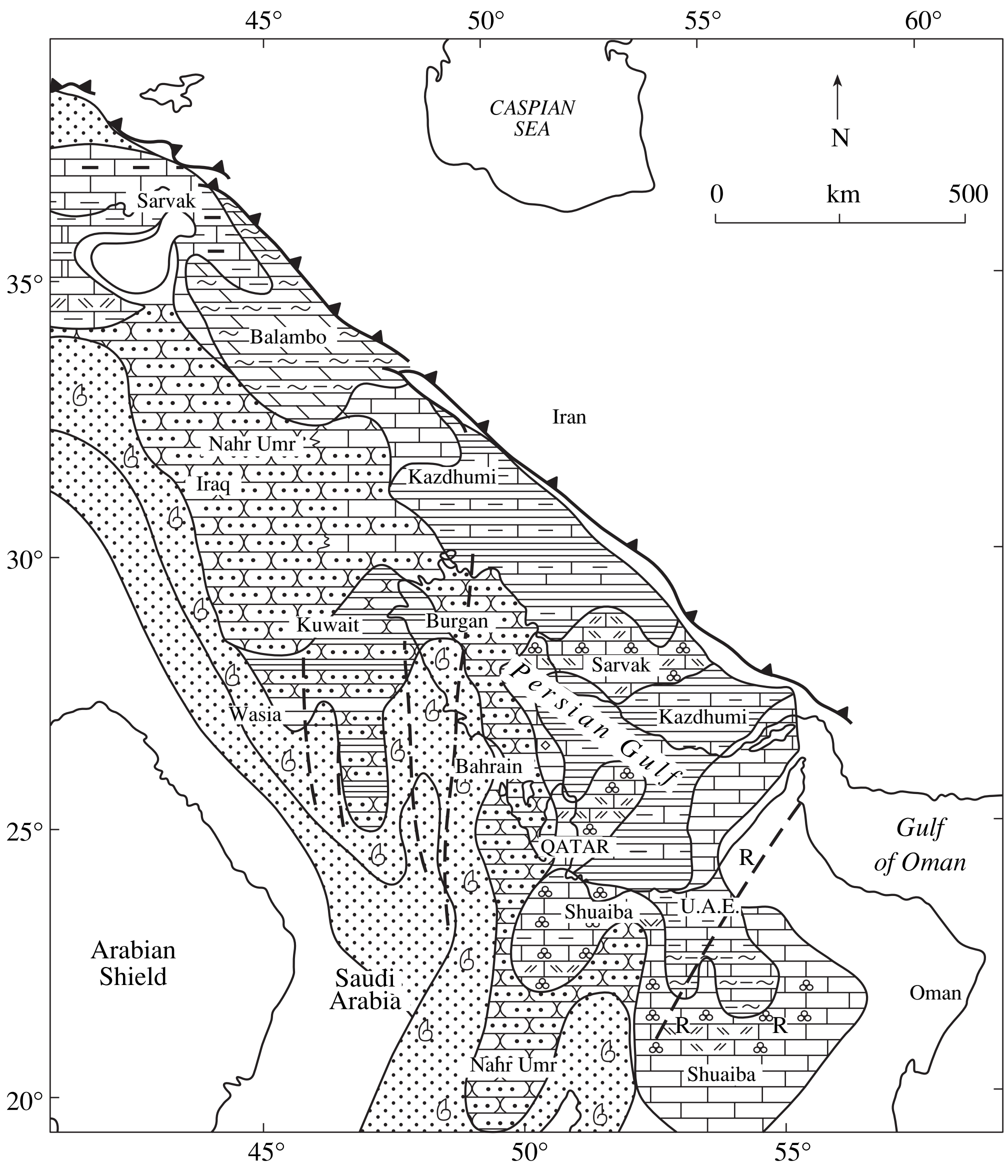

Fig. 6. Lithofacies scheme of location of different types of Lower Cretaceous (Aptian–Albian) rocks in the Persian Gulf Basin. See Fig. 4 for the legend.

the input of terrigenous material, e.g., at the estuary of the extended marine gulf situated east and southeast of the Qatar Arch, as well as at the base of the shelf near the U.A.E. coast. Fine-dispersed clayey–carbonate sediments accumulated beyond the coastal shelf zone (mainly, in the Zagros Basin) (Fig. 6). They were frequently enriched in organic matter (Kazhdumi Formation).

Dark gray marls of the Pabdeh Formation started to accumulate in small depressions of the Mesopotamian Foredeep after its transformation at the Cretaceous/Paleogene boundary (Bordenave, 2002b). Isopachs of these sediments are elongated along the axial zone of this trough, while isopachs of older sediments are oriented across the basin. In the Cretaceous, the sedimentary material was mainly delivered from the Arabian Shield. In the Paleogene, the material was predominantly transported from the Zagros orogenic system. In addition, sediments delivered by sea currents settled along submarine slopes.

In the Late Oligocene and Miocene, the organic-rich siliceous–clayey sediments gave way to carbonates of the Asmari Formation (Fig. 7). Massive limestones were mainly deposited on tidal flats. The lower part of this formation shows the alternation of limestones with clays and marls, whereas the upper part demonstrates the prevalence of pure limestone varieties. The external platformal flank of the basin (southeastern areas of Iraq and Kuwait) was marked by the accumulation of terrigenous sediments (Ghar and Ahvaz sandstones) derived

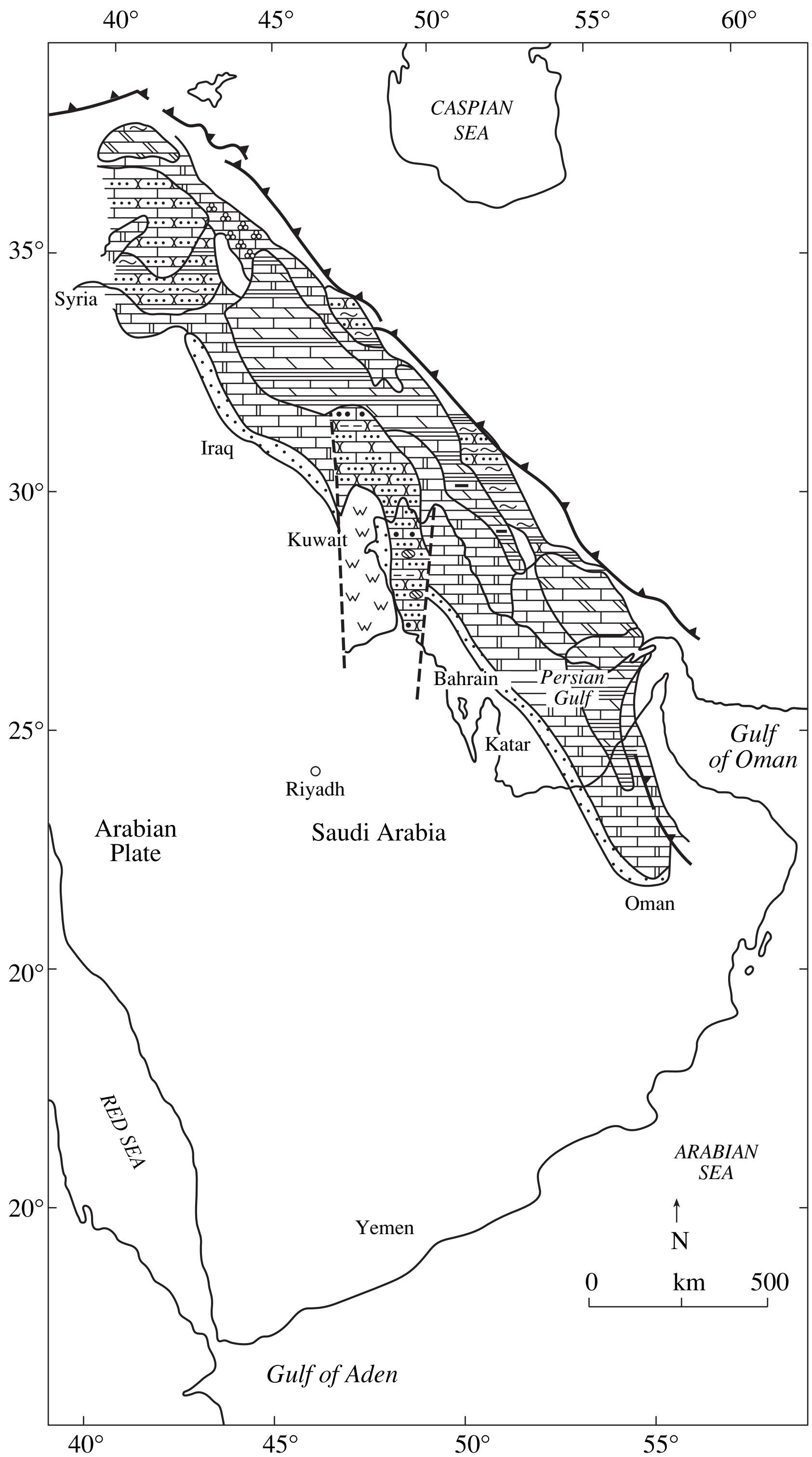

Fig. 7. Lithofacies scheme of location of Oligocene–Lower Miocene rocks in the Persian Gulf Basin. See Fig. 4 for the legend. Figs. 4–7 are compiled by the authors based on (Alsharhan and Nairn, 1997; Bordenave, 2002); Edgell, 1997; Ziegler, 2001; and others).

from the Arabian Shield. In some sections of southwestern areas of Iran, one can see the replacement of the Asmari limestones by the Ahvaz sandstones. In other sequences, both limestones and sandstones are widespread, as well as mixed varieties of sediments. Sands from the lower part of the sequence were locally deposited during the lowstand, possibly, by ephemeral flows (wadis) that are very similar to the present-day ones. Sandy sediments of the middle and upper members accumulated near the shelf break. This is indicated by their mixed (terrigenous–carbonate) composition. Closer to the provenance, the sands contain anhydrite admixture and give way to continental varieties in the western direction. The influence of marine transgression decreased as a result of uplift of the Zagros orogen. Subsequently, the foredeep was transformed into a system of lagoons with the accumulation of salts (Gachsaran Formation). At the final stage of the foredeep evolution, the salts were replaced by the molasse-type terrigenous sediments.

SPECIFIC FEATURES OF THE DISTRIBUTION OF PETROLEUM RESERVES IN THE REGION

Recoverable hydrocarbon reserves (as of the beginning of 1998) discovered in the Persian Gulf Basin account for 66.4% of oil and 33.9% of gas in the total world reserves (Beydoun, 1998). They make up almost 90 Gt of oil and 49.3 tln m^3 of gas. About 98% of them are included in rocks located at the northeastern margin of the Arabian Plate, which extends from northern areas of Iraq to Oman. This region is 3000 km long and approximately 2000 km wide. The main hydrocarbon fields are located in the eastern part of Saudi Arabia, Kuwait, Iraq, southwestern areas of Iran, and Abu Dhabi. No more than 2.94% of oil reserves of the region are located in other countries of the Persian Gulf. More than 65% of gas reserves are concentrated in Qatar and southwestern Iran as a result of the discovery of the Northern Dome supergiant field in the offshore zone of Qatar and several giant deposits in offshore areas of Iran. Oil reserves of Saudi Arabia account for no less than 25.4% of the global recoverable oil reserves. Among 40 supergiant fields discovered in the world at present, 27 fields are situated in the Middle East.

According to (Alsharhan and Nairn, 1997), up to 80% of oil reserves are contained in carbonate rocks and only 20% of oil reserves are confined to sandstones. As for gas, up to 95% of its volume is concentrated in limestones and dolomites; the rest, in sandstones. Moreover, up to 51% of the recoverable reserves of liquid hydrocarbons are located in Cretaceous rocks, whereas gaseous hydrocarbons (more than 50%) were discovered in Paleozoic and Early Mesozoic rocks. It should be noted that carbonate rocks dominate almost everywhere in the sedimentary cover in both marginal parts of the Arabian Shield and the Zagros zone. Clastic rocks compete with carbonates only in areas bordering the uplifted part of the Arabian–Nubian Shield. Carbonate rocks are primarily composed of two (coastal and coastal-marine) types of sediments. Sediments of the second type (the so-called carbonate ramp) mainly accumulated in the open shelf (neritic) environment. Due to the high hydrodynamic activity of water medium, the near-shore facies are usually composed of the primary grained material (biomorphic, biomorphic-detrital, detrital, oolitic, and pelletal limestones) that initially had a relatively high porosity. Its volume significantly increased as a result of secondary processes of dissolution and dolomitization. Therefore, carbonate reservoirs with high porosity and permeability are most widespread in western and southern areas of the Persian Gulf (Geodekyan et al., 1993), which represented the areas of “struggle” between land and sea during different periods of the Late Paleozoic and Mesozoic. These areas are marked by the cyclic structure of sedimentary sequences reflected in the alternation of limestones, clays, and marls at transgressive–regressive stages related to the advance of shoreline and supply of terrigenous material from elevated areas of the Arabian–Nubian Shield and in the predominance of limestones during the sealevel highstand. Rocks with high porosity generally lie at the top of separate cyclites. The largest concentration of such rocks is typical of the Arab Formation in Saudi Arabia and southern areas of the Persian Gulf. Regressive phases were also accompanied by the accumulation of sandy clastic material with good reservoirs properties in the coastal and littoral facies, e.g., Cretaceous rocks of the Zubair and Burgan formations that are widespread in southern areas of Iraq and in Kuwait. Variable biohermal buildups are one more type of the natural carbonate reservoirs. The largest reservoirs of this type are located along the southern border of the Persian Gulf area (chiefly, in Oman and the U.A.E.). They represent Middle–Late Cretaceous rudist and algal reeflike buildups (Shu’aiba and Mishrif formations). The middle part of the Sarvak Formation includes relicts of carbonate buildups alternating with members of bioclastic (organogenic-clastic or detrital) limestones (Edgell, 1997).

The relatively fast burial of sediments due to high sedimentation rates favored the preservation of the primary structure of pore space. Moreover, dolomitization enhanced porosity and permeability.

Reservoir properties of limestones in the Dalan and Kangan formations are primarily governed by secondary porosity, which is directly related to the development of dolomitization in these rocks. The Northern Dome field located in the Qatar Peninsula and coastal areas of the Persian Gulf is the world’s largest deposit in terms of gas reserves. Several gas pools related to these rocks were also discovered in the Iranian sector of the Persian Gulf (Varvi, Aghar, Bandubast, and Western Namuk). In the continental part of the Mesopotamian Basin, the thickness of the Dalan sequence increases to 700 m. The latter sequence contains bioclastic and oolitic limestones noted for their high initial porosity. These limestones are the principal reservoir rocks for gas pools in many fields, including those situated on the Nahr, Fars, Kangan, Aghar, and Samand uplifts. In the Pars and Kuh-i-Mand fields, gas is extracted from the 200-m-thick Kangan dolomite and dolomitized limestones.

The carbonate platform appeared in the region at the Paleozoic/Mesozoic boundary and actively developed until the end of the Cretaceous. The predominance of carbonate facies was only interrupted at the end of the Early Cretaceous owing to the increased delivery of terrigenous clastic material from uplifted areas of the Arabian–Nubian Shield, resulting in the accumulation of sandy and sandy–clayey sediments that began to dominate in the sedimentary spectrum of western areas of the Persian Gulf. In eastern areas, they were replaced by bioclastic, detrital, oolitic, and pelletal carbonate sediments at the contact with carbonate buildups of different types. These circumstances fostered the very wide distribution of rocks with excellent reservoir properties, which were mainly defined by the high initial porosity. The largest reserves of oil hydrocarbons are found precisely in the terminal Early Cretaceous and initial Late Cretaceous rocks (Zubair, Burgan, Arab, Shu'aiba, Mishrif, and other formations) (Geodekyan et al., 1988). In the majority of oil fields confined to Early–Middle Cretaceous rocks, the fluid seals are represented by clay horizons or low-permeable clayey limestones deposited at transgressive stages of sedimentation cycles.

In the Iranian part within the internal flank of the Mesopotamian Basin, Albian–Cenomanian limestones of the Sarvak Formation (Bangestan Formation in Kurdistan) represent one of the principal Cretaceous reservoirs. Their composition is dominated by foraminiferal–algal, fine-grained, and rudist limestones, which alternate with marls and clays at different levels of the sequence. In the Zagros zone, reservoir properties of these limestones are primarily defined by the secondary porosity (7–14%) rather than the initial values. This property is related to the development of fractures under the influence of compression and deformations at the stage of growth of the Zagros mountain chains.

This statement is also valid for carbonate rocks of the Asmari Formation, which were initially characterized by poor reservoir properties. However, in the 1200-km-long and up to 200-km-wide belt stretching from the northeastern Iraq boundary to southeastern areas of Iran, the Asmari sequence includes bioclastic (biomorphic–detrital) and oolitic limestones formed on near-shore carbonate banks. These rocks frequently show a relatively high initial porosity, and they can serve as reservoirs in a number of regions. In the southern part of the Mesopotamian Basin (Dezful Embayment), terrigenous rocks make up 5–50% of the Asmari sequence. The thickness of medium-grained sandstones, calcareous clays, sandy limestones, and dolomites significantly increases.

However, reservoir properties of the Asmari limestones and underlying rocks in the Mesopotamian Basin are commonly defined by their fracturing related to Neogene tectonic movements. Amplitude of these movements was the highest in the Zagros Fold Belt (Coleman and Sadd, 1978). The Asmari limestones are intensely fractured, first of all, at tops of anticlines with steep wings, where the tectonic compression was maximal that fostered the reservoir properties of rocks. In gentle folds, fracturing in the limestones is relatively moderate. Therefore, their hydrocarbon capacity is considerably lower. The reservoirs usually demonstrate two fracture systems related to different times and oriented along two different directions. Younger fractures are parallel to the axes of anticlinal folds. The density of fractures in limestone beds is inversely proportional to their thickness (McQuillian, 1985). Fracturing increases the rate of dolomitization and favors the development of secondary porosity. Investigations showed that reservoirs in the Asmari Formation and underlying carbonates (Sarvak and Bangestan) are frequently interrelated, and fractures therein frequently act as conduits.

Traps of the anticline (dome) type predominate in the Mesopotamian Foredeep. Purely stratigraphic traps were not known to this date, although pinching out of reservoir horizons is observed in some zones with perspectives for the discovery of hydrocarbon pools. More than 60 petroleum fields, including four supergiant and twelve giant fields have been discovered in the Dezful Province alone. In all of these fields, oil pools are related to the Asmari limestones. In the Khuzestan Province with the total thickness of the sedimentary formation ranging from 320 to 488 m, the thickness of individual beds with good reservoir properties varies from 10 to 280 m.

The initial porosity of the Asmari limestones rarely exceeds 5% and the permeability is a few mD. In fractured places, the porosity and permeability can increase to 25% and 100 mD, respectively. Consequently, oil yield of a well can reach 500 t/day. The detailed investigations showed that megascopic fractures are mainly widespread in limestones developed on large structures. The highest density of fractures is observed at their intersections with rocks at an angle of 20° N–30° E (McQuillan, 1985). Small fractures possibly originated at postsedimentary cycles of the transformation of rocks and they are unrelated to the last tectonic phase in the Zagros zone.

The main orogenic phase manifested in the Zagros zone in the Pliocene–Pleistocene produced a large number of wide and extended anticlinal folds, which were subsequently transformed into ideal traps for hydrocarbon pools. The Kabir Kuh fold, the largest anticline in the area, is 190 km long and the amplitude is several kilometers. Some areas are dominated by concentric folds, and their dimensions frequently decrease with depth. Meanwhile, asymmetric anticlines, several tens of kilometers long and several kilometers wide, are most widespread. Thrusting and disharmonic folding are frequently observed in rocks overlying the Gachsaran salts. This hampers the study of structural pattern of the Asmari limestones and reservoirs at deeper levels.

Many of the giant fields discovered in the Zagros zone have multilayered structure. Moreover, the majority of the producing horizons are related to different levels in the Asmari Formation (Oligocene–Miocene) and Bangestan Group (Upper Cretaceous), where the rocks are intensely fractured. The basement surface is complicated by a large meridional swell that extends from Qatar to the southern end of the Fars Platform. The swell separates the Zagros Fold Zone into two segments that are sufficiently different in terms of the petroleum potential.

The majority of large oil pools were discovered in the Desful Embayment that occurs northwest of the meridional swell and represents a foredeep, which developed in the Neogene in front of the growing High Zagros orogenic system. High rates of subsidence and accumulation of Neogene sediments in this area prevented the washout of the Gachsaran evaporites and, in turn, favored the preservation of hydrocarbon pools in the Asmari limestones. Conditions were less favorable for the preservation of oil pools in limestones developed southeast of the prominence. Moreover, the trough in this sector is significantly complicated by the intrusion of numerous diapirs related to the halokinesis of the Hormuz Salt. Large oil pools are absent in this region. However, large gas pools have been found in Jurassic and Permian limestones. In addition, diagenetic methane pools have been discovered in Miocene reefal limestones in the Guri Formation and some horizons of the Upper Fars sequence.

The structure of hydrocarbon fields in the Iranian part of the Persian Gulf area is defined by numerous buried and exposed salt domes. They evolved during a long time from the Early Mesozoic to Pleistocene. This was necessarily reflected in variations of the thickness of separate formations, as well as in the composition of sediments and the pattern of diagenetic transformation in them. Anticlinal structures in the gulf resemble small domes situated above salt diapirs, and the traps have relatively small sizes. In the Fars Province, more than 100 domes have been revealed above the actively rising diapirs (3–15 km across) to date.

Up to Eocene, Lower Cretaceous Kazhdumi marls and clayey limestones, which are considered source rocks in the Mesopotamian Basin, did not subside deep enough to generate large volumes of liquid hydrocarbons. The main volume of hydrocarbons was transported through faults. Therefore, oil did not accumulate in any transitional reservoirs. In the Asmary limestones, oil accumulated in pores interconnected with fractures and did not impregnated into the carbonate matrix.

CONCLUSIONS

Carbonate rocks, limestones and dolomites formed under variable paleogeographic (lagoon, intertidal, coastal, and external shelf) conditions and characterized by excellent filtration–capacity properties played the most important role in the formation of giant petroleum fields in the Mesopotamian Basin. The presence of evaporites was also essential for the formation of screening horizons at the following levels of the sedimentary cover: Late Permian–Early Triassic (Dashtak Formation), Rhaetian–Sinemurian and Late Jurassic (Hith and Gotnia formations), and Miocene–Pliocene (Gachsaran Formation). Diapirism of the Cambrian Hormuz Salt played the role of the important structure-forming factor that promoted the origination of large anticlinal folds, which were particularly abundant in the Persian Gulf area.

Reservoir properties of the Permian–Triassic, Jurassic, and Cretaceous limestones, which are developed on the Arabian Plate dipping toward Zagros, are related to both initial and secondary forms of porosity created during dia- and catagenesis. Similar properties of Aptian–Cenomanian and Miocene limestones, which enclose the largest oil pools in the Mesopotamian Basin, are primarily dictated by their fracturing.

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