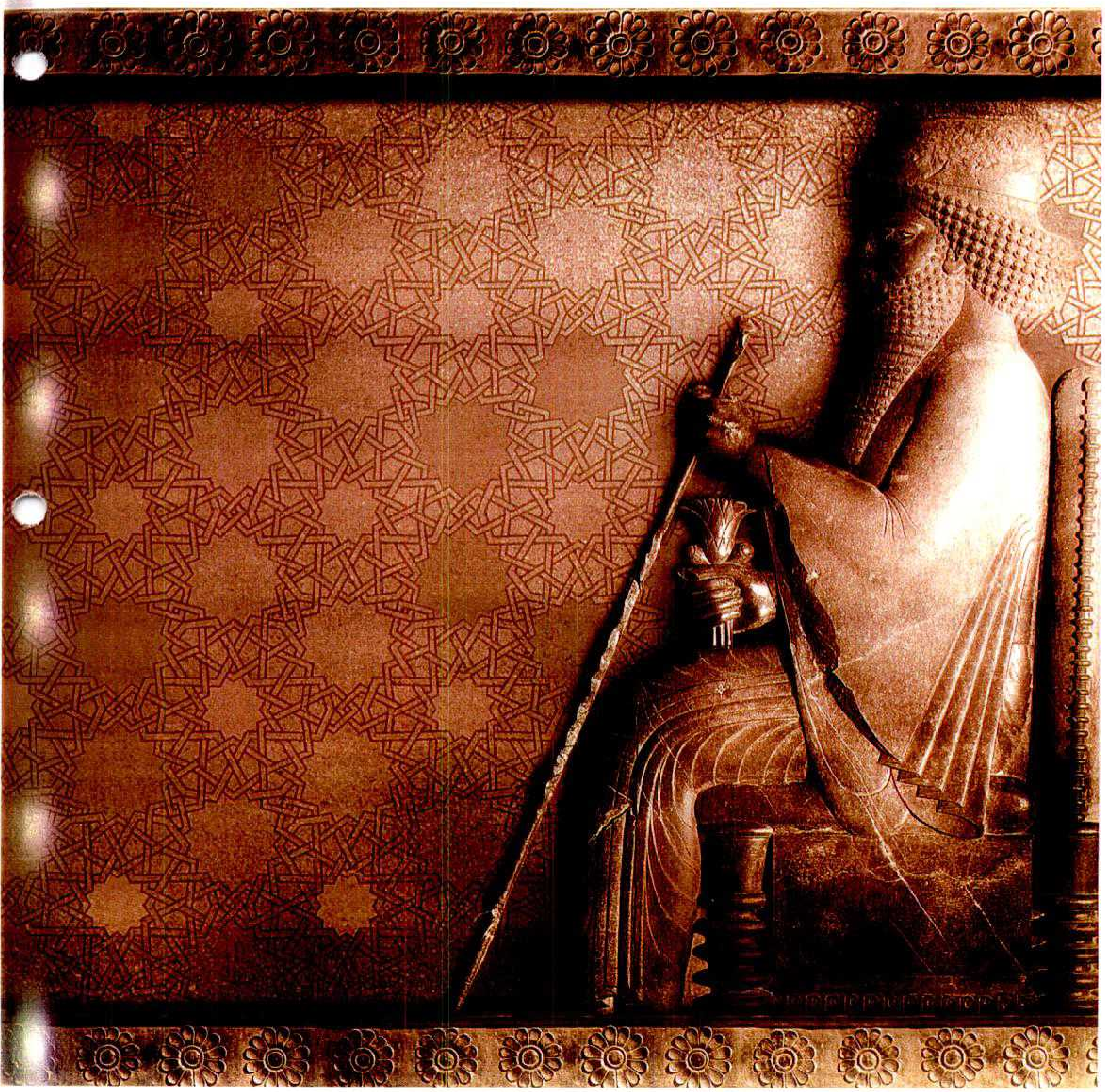
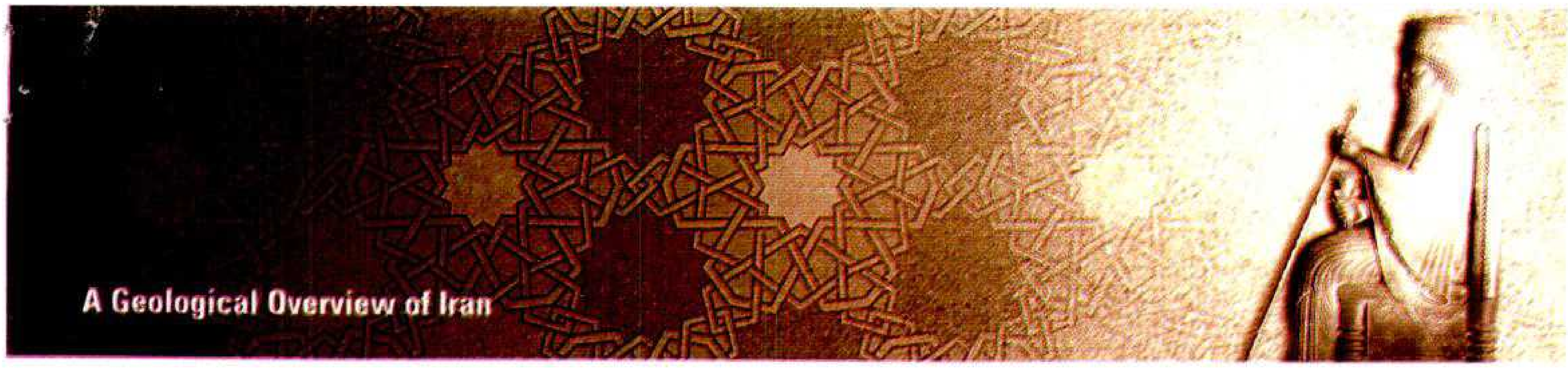
Islamic Republic of Iran 2003

Reservoir Optimization Conference

Chapter 2

A Geological Overview of Iran





The Petroleum Geology of Iran

As one of the world's major hydrocarbon producers, the Islamic Republic of Iran has oil reserves of almost 90 Bbbl and annual production rates in excess of 1.3 Bbbl—second only to Saudi Arabia in terms of global oil-supply potential. Iran has the world's second-largest natural gas reserves and is the largest producer in the Middle East.

Iran is a country of oil giants, with most of its crude oil located in onshore fields in the Dezful embayment. The Ahwaz, Marun, Gachsaran, Agha Jari and Bibi Hakimeh fields account for around two-thirds of total oil production.

The potential for new reserves is immense. Recent studies suggest reserves of 15 Bbbl of oil and 170 Tm^3 of natural gas in addition to current proven reserves. A vigorous and sustained exploration program is expected to locate these potential reserves and, ultimately, to increase the nation's recoverable hydrocarbon resources. Many large surface anticlines in the Zagros fold belt and elsewhere in Iran have yet to be tested. Several hydrocarbon prospects that were identified during the 1970s as showing excellent potential are now undergoing full evaluation.

Iran has played a leading role in the application of new geoscience techniques and helped shape the global development of oil and gas technology. Further geological investigation using state-of-the-art methods is seen as the key to unlocking Iran's vast undiscovered oil and gas potential.

In 1991, National Iranian Oil Company (NIOC) started a major integrated reservoir characterization of the giant Ahwaz field. This study of one of the world's largest hydrocarbon-bearing structures took three years to complete, and was followed by three years of extended studies. It used geostatistical methods that had never before been applied to a field of this size. The result was a combined grid- and object-based geostatistical model that, when simulated, provided a detailed three-dimensional lithofacies distribution within the entire reservoir consistent with traditional geological models. This detailed geological description was then used as a basis for the full-field flow simulation and production predictions.

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Iran sits at the heart of the Middle East, bordering the Persian Gulf, the Gulf of Oman and the Caspian Sea (Figure 1). The country extends to more than 1.6 million km^2 and has a population (July 2000) in excess of 65 million. The climate is mostly arid or semiarid, ranging to

Figure 1: Iran sits at the heart of the Middle East, bordering the Persian Gulf, the Gulf of Oman and the Caspian Sea

subtropical along the coast of the Caspian Sea. Topographically, Iran comprises plateaus surrounded by large mountain ranges. The most important of these are the Alborz range in the north and the Zagros range in the southwest. Iran also contains extensive salt deserts; Dasht-e-Kavir and Kavir-e-Namak (Great Salt Desert) in the north and Dasht-e-Lut in the southeast.

As one of the world's major hydrocarbon producers, Iran has oil reserves of almost

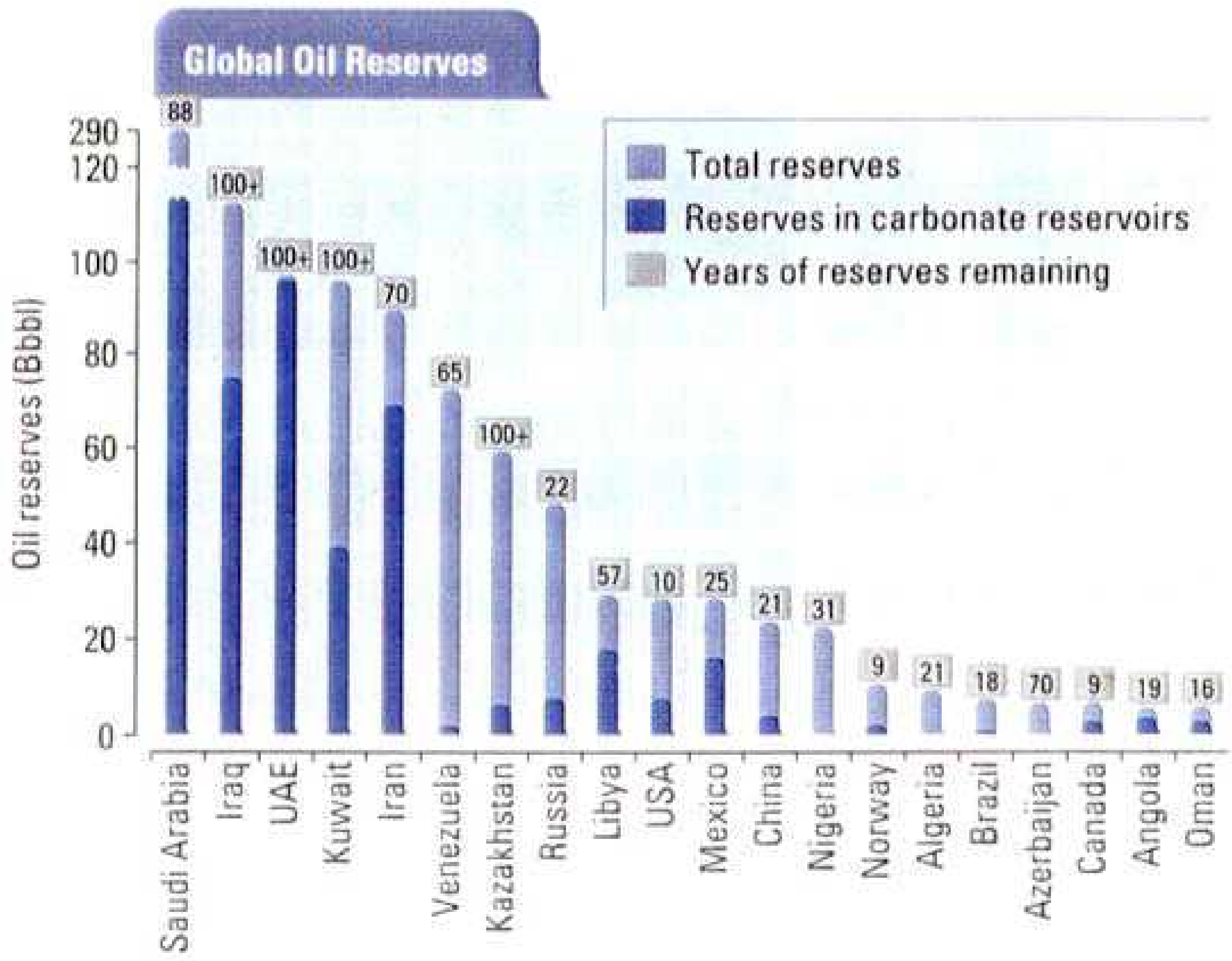


Figure 2: Iran's oil reserves are almost 90 Bbbl

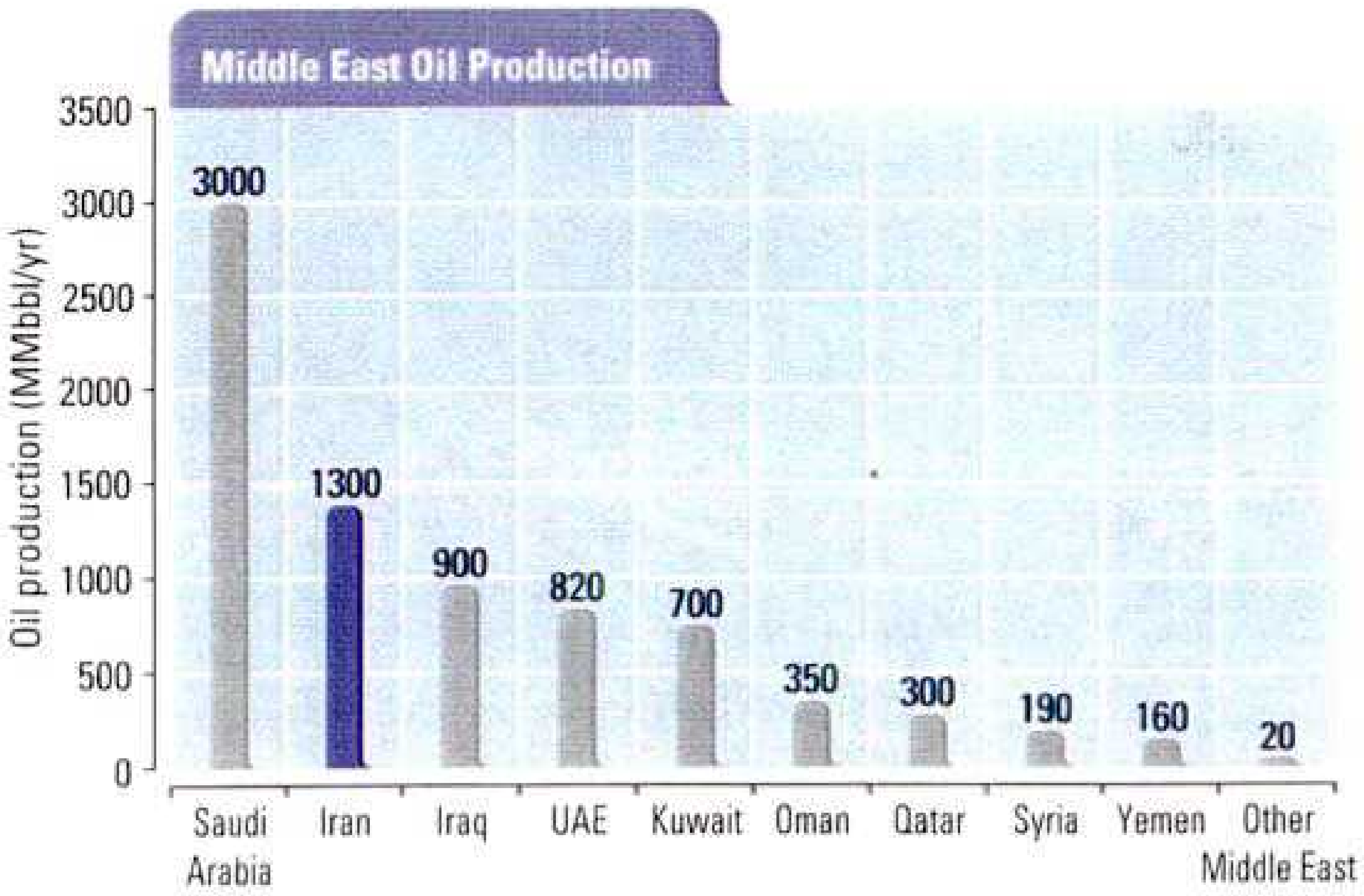


Figure 3: Iran's annual oil production rates are second only to Saudi Arabia

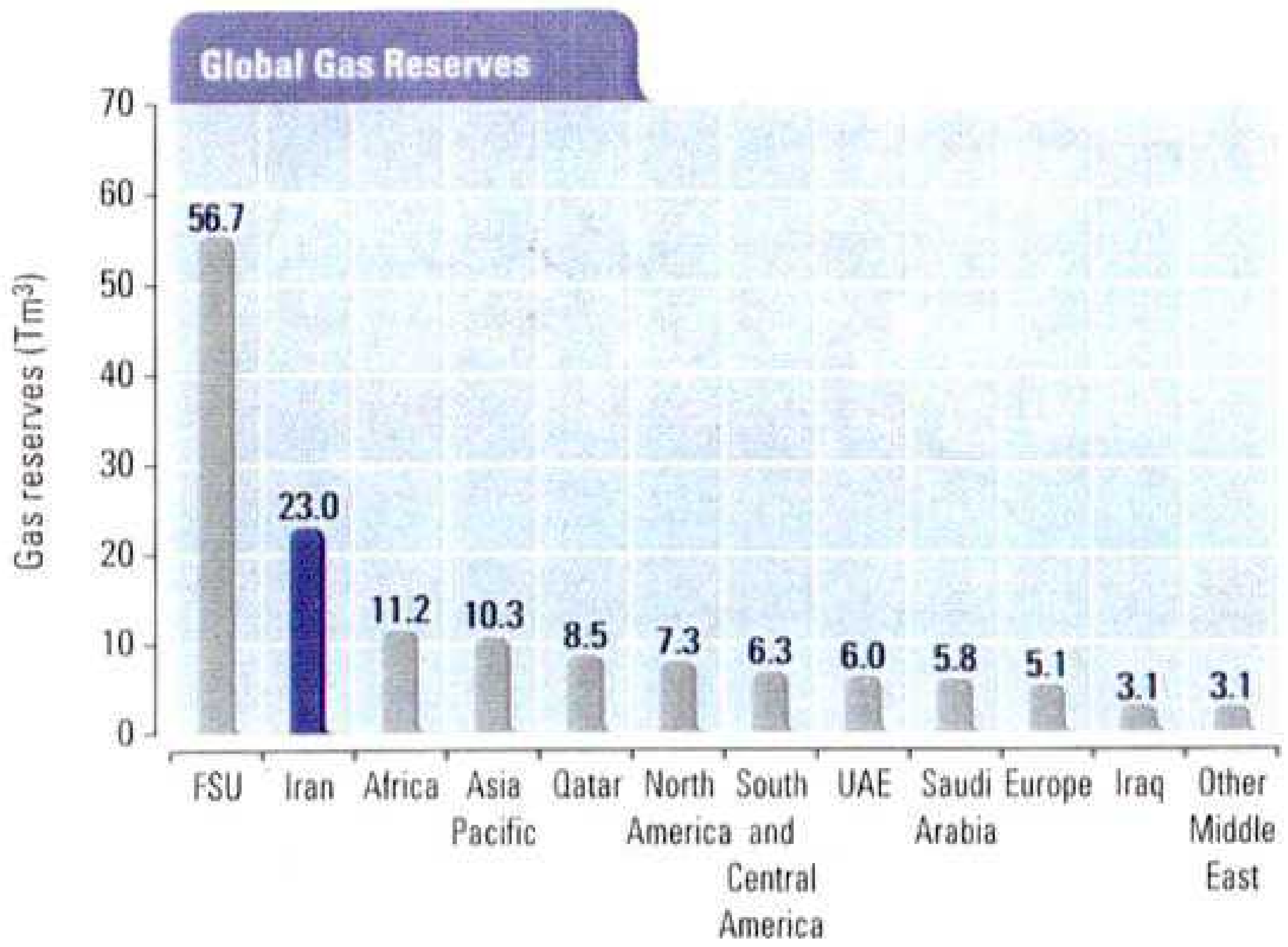


Figure 4: Iran has the world's second-largest natural gas reserves

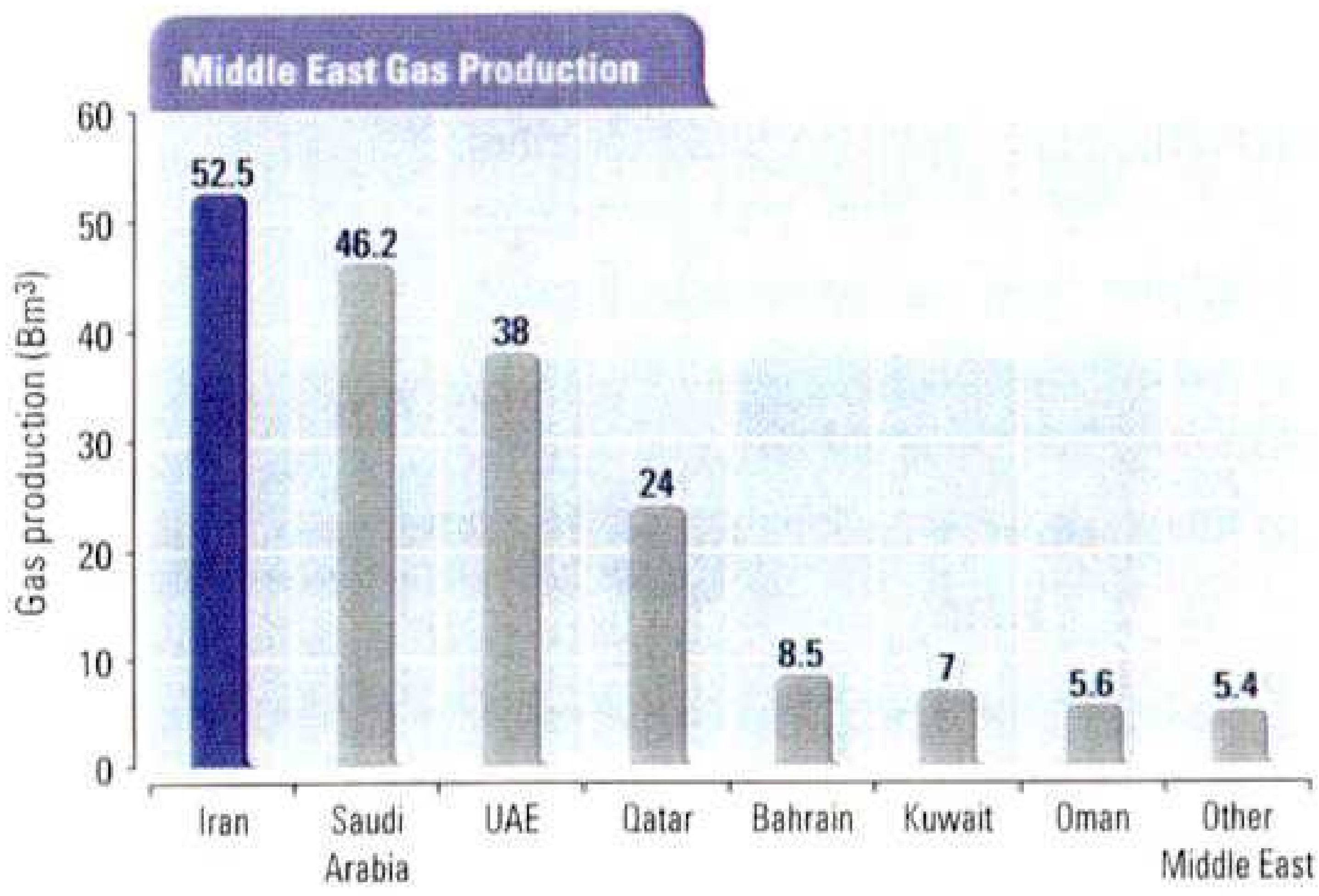


Figure 5: Iran's annual gas production rates are the highest in the Middle East

90 Bbbl (Figure 2) and annual production rates in excess of 1.3 Bbbl (Figure 3). This places Iran second only to Saudi Arabia in terms of global oil-supply potential. Most of the country's crude oil is medium gravity and low in sulfur. Iran has the world's second largest natural gas reserves (after the Former Soviet Union [FSU]) and is the largest producer of natural gas in the Middle East (Figures 4 and 5). Moreover, Iran's hydrocarbons are expected to play an even greater role in the future global energy economy as underexplored areas within the country are opened up for development.

Iran is a country of oil giants, with more than half of the country's 40 producing fields containing in excess of 1 Bbbl of oil. The majority of Iran's crude oil is located in giant onshore fields in the Dezful embayment region. The Ahwaz, Marun, Gachsaran, Agha Jari and Bibi Hakimeh fields account for around two-thirds of its total oil production. Recent studies and surveys suggest that the country may contain 15 Bbbl of oil and 170 Tm^3 of natural gas in addition to current proven reserves. A vigorous and sustained exploration program is expected to locate these potential reserves and, ultimately, to increase the nation's recoverable hydrocarbon resources.

Iran's oil and gas industry has a long and illustrious history that has influenced the development of exploration and production activities in many parts of the world. The country's first oil well entered production in 1909, and many oil and gas historians cite Masjid-i Sulayman as the birthplace of modern oilfield management. Iran has played a leading role in the application of new geoscience techniques and shaped the global development of oil and gas technology. For example, some of the earliest geophysical surveys for petroleum exploration were conducted in Iran during the 1920s and 1930s (Figure 6).

Geological framework

Iran straddles the junction between the Eurasian and Arabian tectonic plates (Figure 7) and is characterized by extensive and active fault movements across a number of major earth structures. As a result, strong earthquakes are a frequent

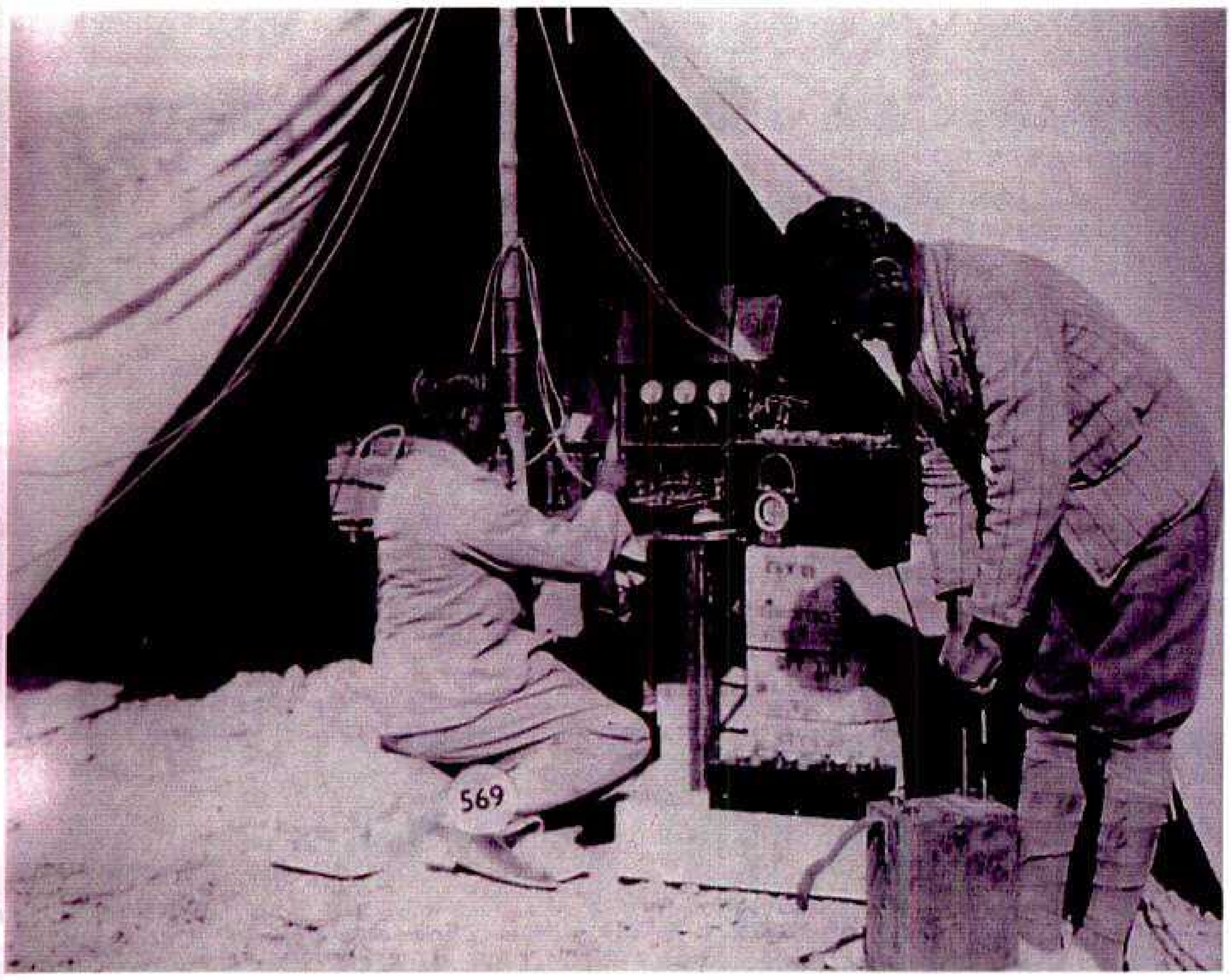


Figure 6: *Geophysicists conducting a seismic refraction survey in the 1920s. The Iranian oil industry adopted seismic exploration methods at an early stage and has been at the forefront of geoscience technology for almost 100 years*

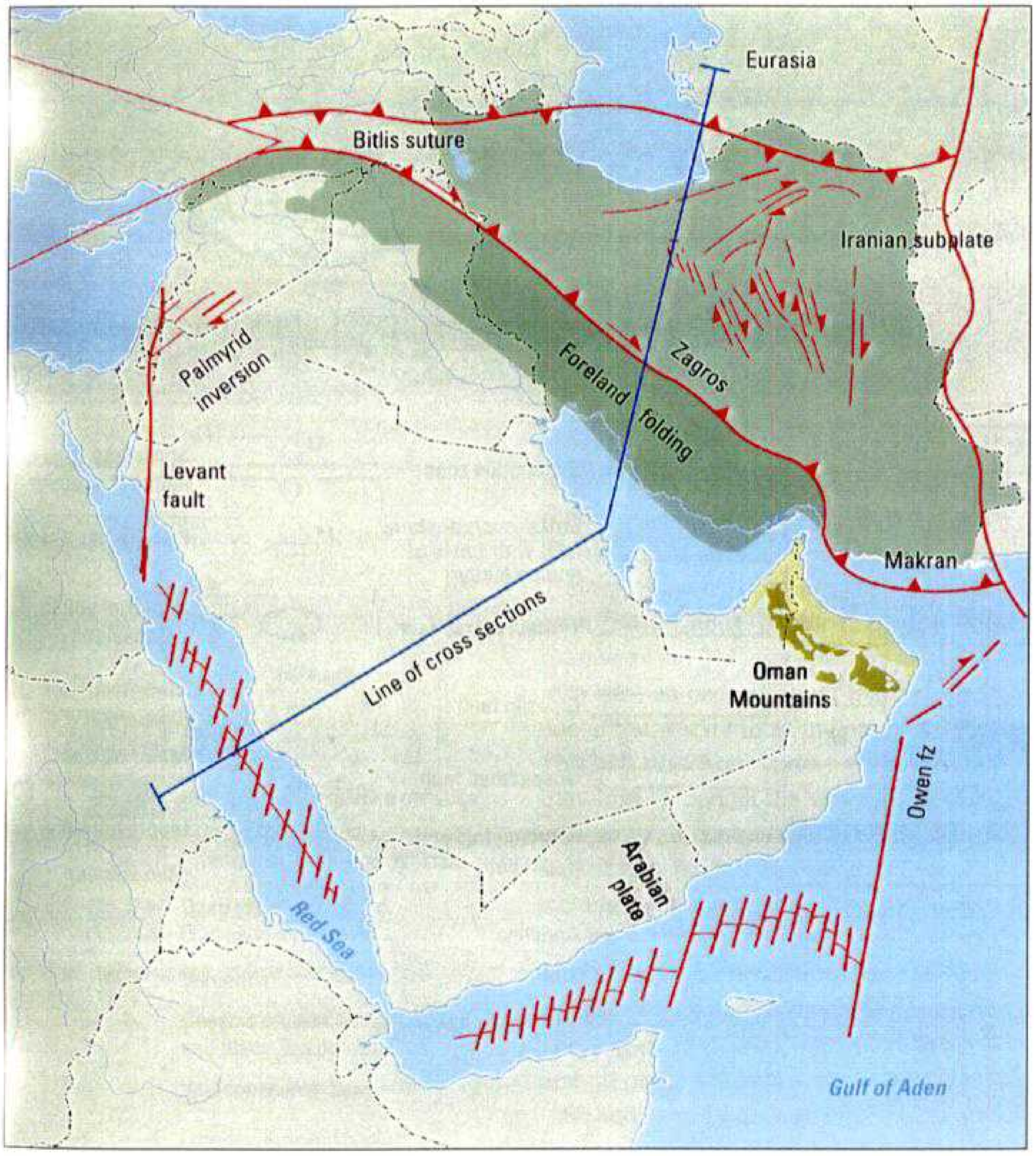
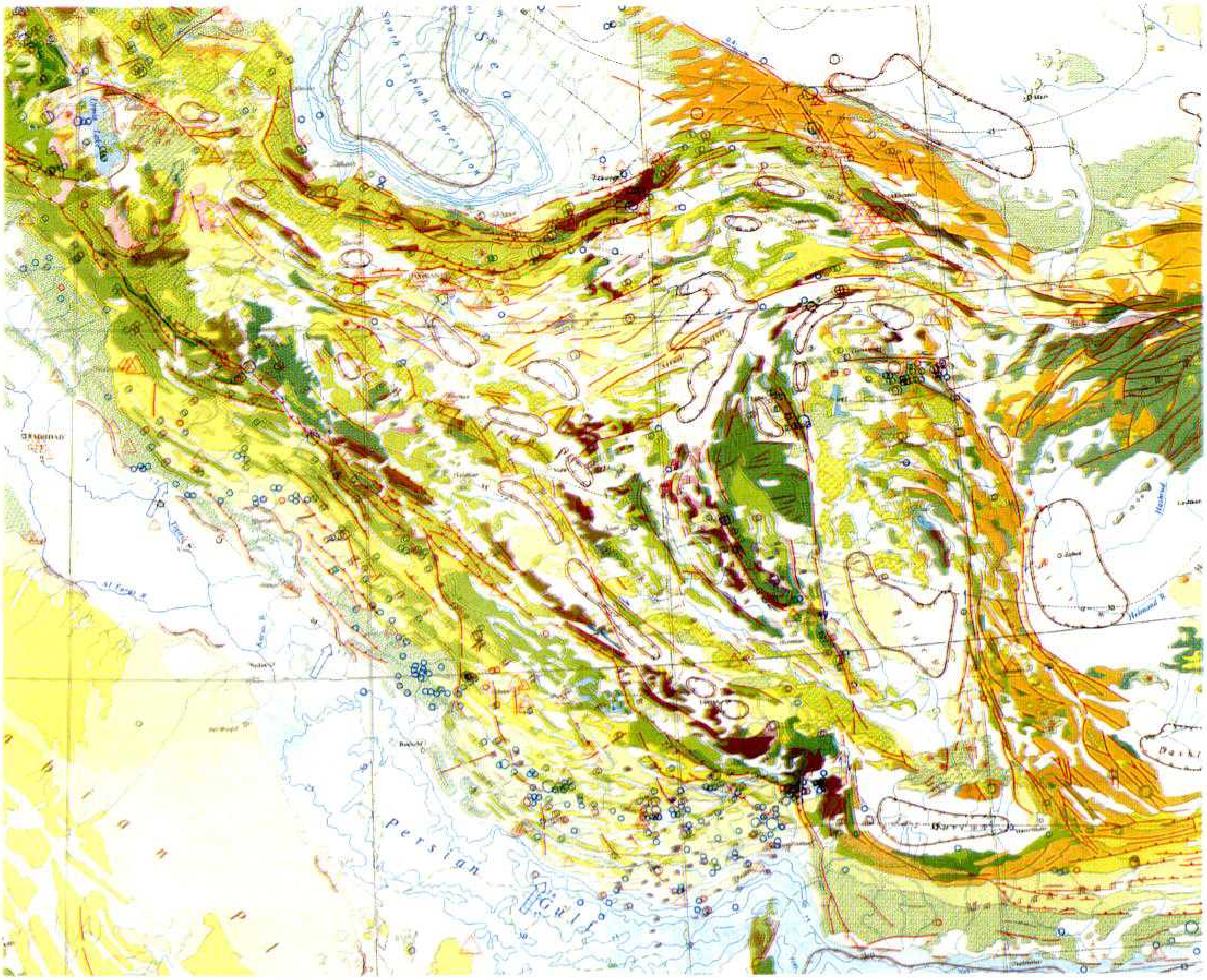


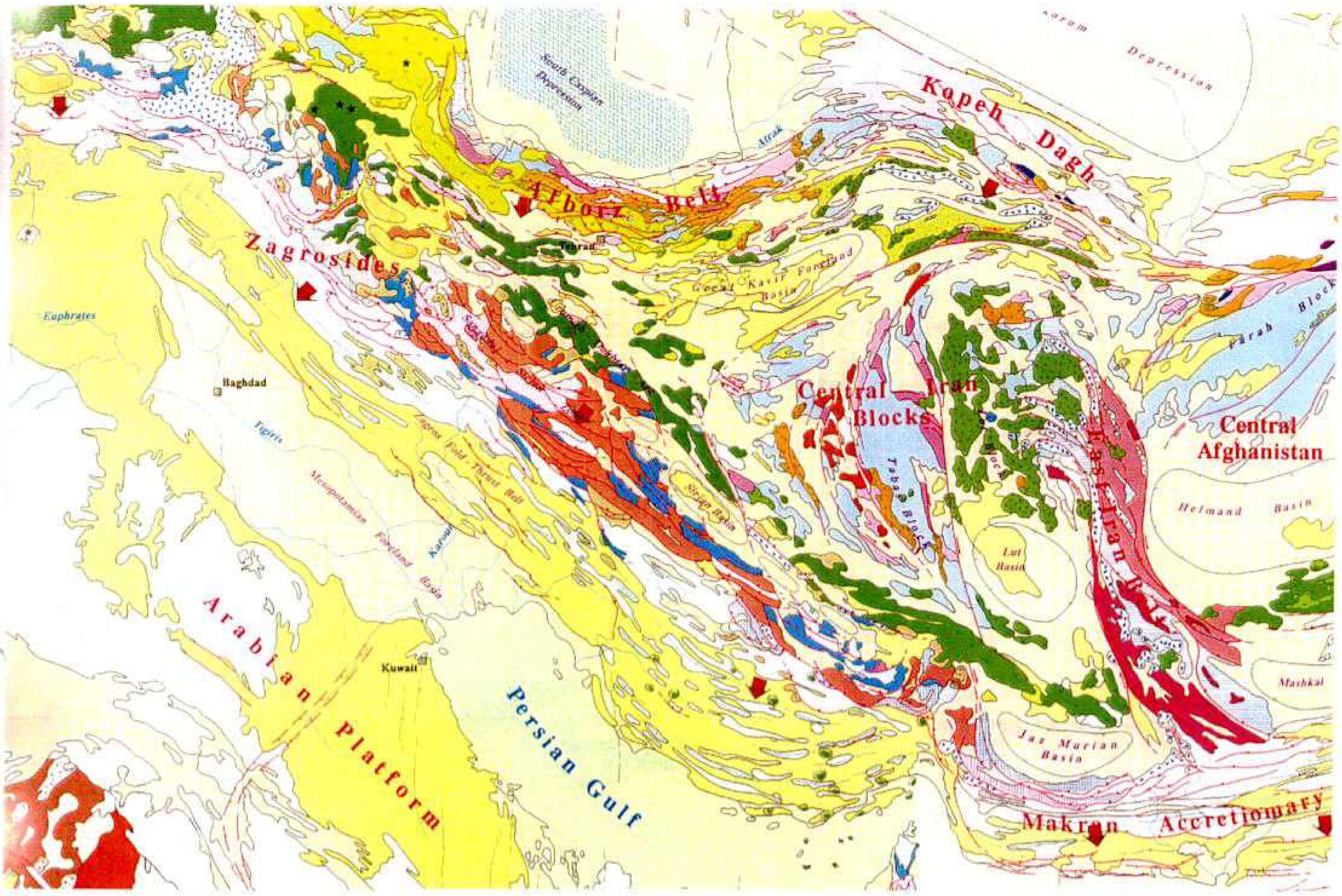
Figure 7: *Situated at the junction of Eurasian and Arabian tectonic plates, Iran's geology is dominated by fold-and-thrust belts and large scale strike–slip faults; see the cross section in Figure 12*



Earthquake epicenters									
Historical third millennium BC 1900 AD		Focal depth (km)	Instrumental						1900–1990
Total		Magnitude (mb)	0–20	21–60	61–100	101–200	201–300	No focal depth	Total
16	△	8 and over	○	○	○	○	○	○	10
138	△	7-7.9	○	○	○	○	○	○	85
268	△	6-6.9	○	○	○	○	○	○	331
571	△	5-5.9	○	○	○	○	○	○	2603
1013		Total	588	1552	210	229	173	277	3029
	△		○		○	○	○	○	○ 10 similar events

- Subduction zone
- Strike–slip/transform fault with sense of motion (cm/yr) (0.2)
- Thrust/reverse fault
- Dip–slip fault
- Unspecified fault
- Foreland fold and thrust belt
- Anticline
- Spreading axis, half rate in cm/yr (1.6)
- Plate vector, absolute motion in cm/yr (3.6)
- Center of young depression
- Moho isopachs in km (approximately) (30)
- Major free air gravity anomaly in milligal (approximately) (+50, -50)
- Mud volcano

Figure 8: Iran's plate boundary position causes frequent and severe earth movements over much of the country. Major earthquakes are concentrated in the Zagros mountain range in the south



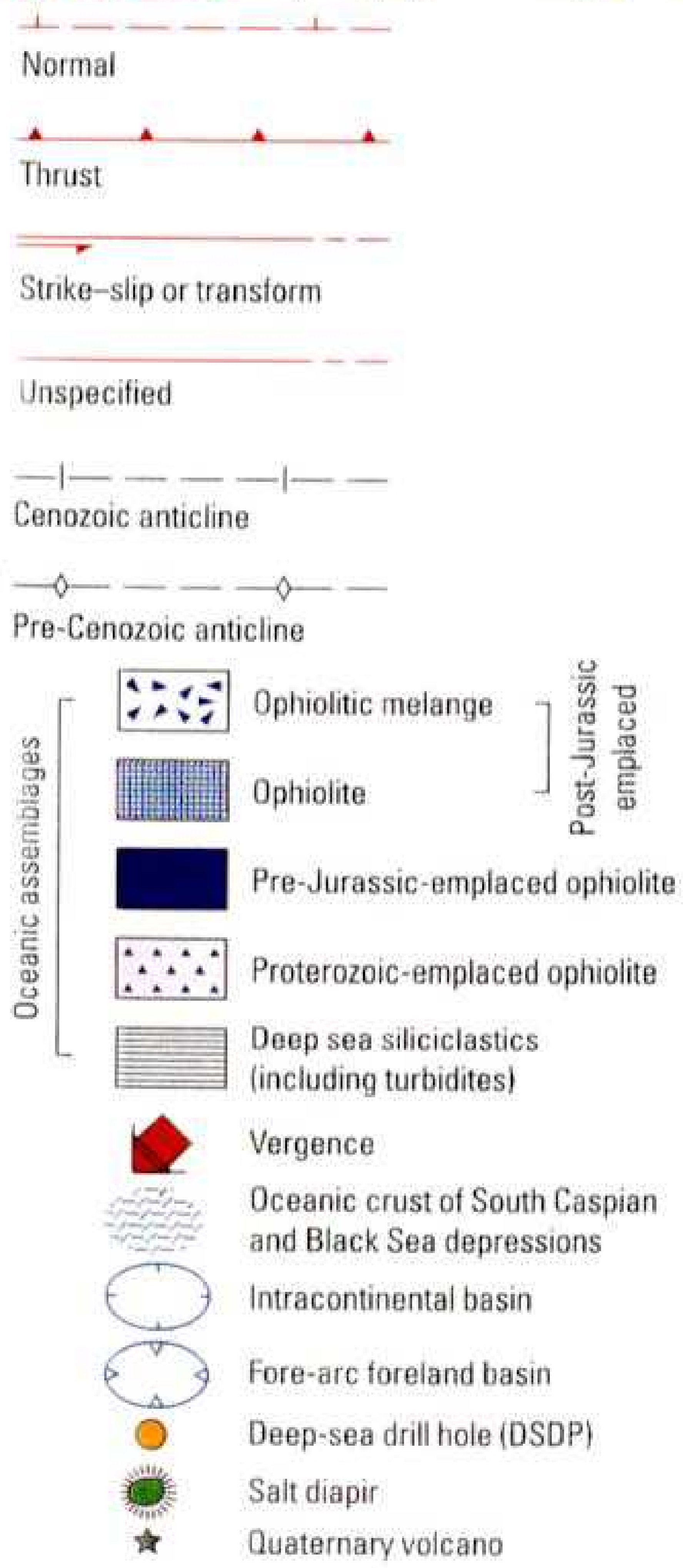


Figure 9: The geology of Iran's major structural divisions—the Zagros range, the central region and the Alborz range

occurrence throughout the region (Figure 8), with the greatest concentration of severe earth movements occurring in the south. The most significant feature is the Hindu Kush fault, which runs from eastern China to central Iran.

Many of the earthquakes are linked to compression along the northern edge of the Arabian plate. This is caused by its collision with Iran, an ongoing event that has created one of the world's most important fold belts. This belt runs from Turkey, parallel to the Iran–Iraq border, all the way to the Straits of Hormuz. It contains some of the world's largest anticlinal oil reservoirs. These include accumulations such as the Ahwaz reservoir, which is around 64 km in length. These huge structural fields have given long periods of high and dependable production. The Asmari formation, the Middle East's first oil-producing horizon, was drilled in 1908 and remains the principal oil producer for Iran.

Geological regions

Two large mountain ranges—the Zagros Mountains in the south and the Alborz Mountains in the north—divide Iran into three geologically different regions: the Zagros range, the central Iranian region and the Alborz range (Figure 9).

The Zagros Mountains

A large proportion of Iran's oil reserves is found in the vast reservoirs that underlie the Zagros Mountain belt, which stretches almost 1770 km (from Turkey to the Gulf of Oman) and crosses most of Iran. A northwest–southeast trending belt of crushed sediment (referred to as the crush zone) runs from the western end of Lurestan to the area northeast of Minab, and marks the northeastern limit of the Zagros range. The area immediately southeast of the crush zone is intensely folded and faulted. The sediments exposed here are generally of Mesozoic age. The

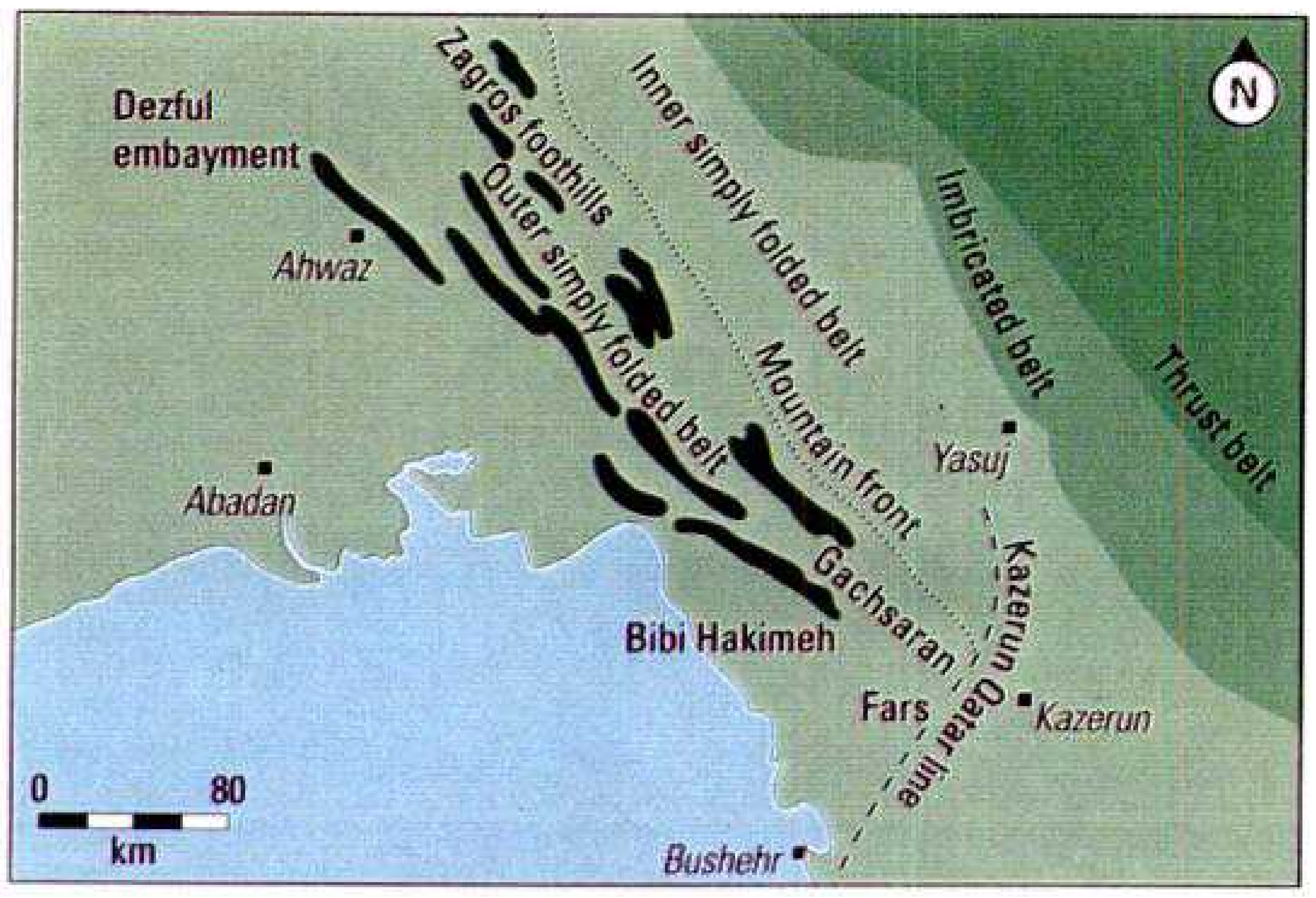


Figure 10: The shape and size of the major oil fields in the Zagros foothills are controlled by the structural grain of the fold-and-thrust belt. Major fields such as Ahwaz, Gachsaran and Bibi Hakimeh clearly follow the east–west line of the mountain front

intensity of folding gradually decreases towards the Persian Gulf where younger rocks are seen in outcrop. The large-scale, fold-and-thrust structures of the Zagros Mountains indicate periods of intense compression and deformation. These major mountain-building episodes (or orogenies) created most of the anticlinal structures where oil and gas have accumulated.

The Zagros orogeny was the strongest tectonic event to affect southwest Iran. Starting in the late Miocene, this mountain-building episode is still active. This can be seen in the tilting that is observed in some very young conglomerate deposits. The orogeny produced a series of northwest–southeast-trending structures of economic significance (Figure 10).

Lateral offsets in the pattern of seismicity along the Zagros fold-and-thrust belt indicate that the transverse faults dividing the Arabian basement are active, deep-seated strike–slip faults. The dominant northwest–southeast-trending features of this belt have undergone repeated horizontal displacements along the transverse faults. These reactivated basement faults controlled the deposition of the Phanerozoic cover before Tertiary–Recent deformation of the Zagros area and probably influenced the entrapment of hydrocarbons on the northeast margin of Arabia and in the Zagros area. Fault patterns observed on landsat images and information on the spatial distribution of earthquakes and their focal mechanism solutions have been used to infer a tectonic model for the Zagros basement.

Deformation in the northwest Zagros region appears to be concentrated on

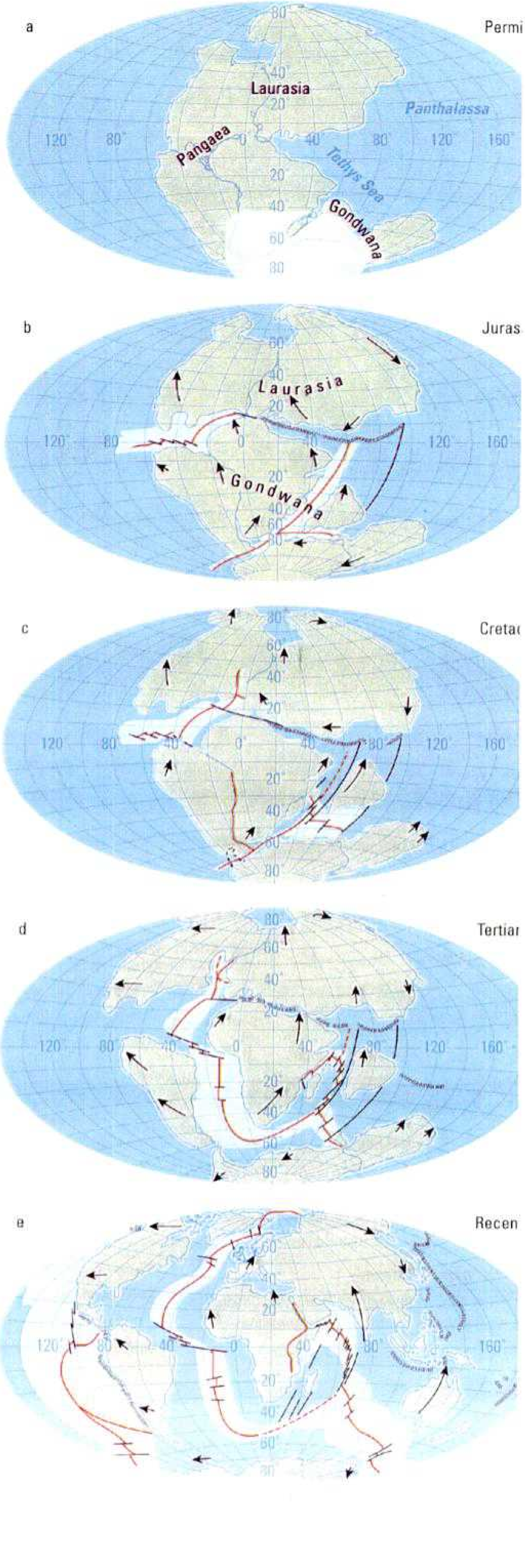


Figure 11: The breakup of Pangaea during the Permian (a) led to the development of the Tethys Sea, where thick, organic-rich marine sediments accumulated. The northward movement of Gondwana reduced the width of the seaway (b and c), ultimately breaking the sea link between the Mediterranean Sea and the Indian Ocean (d) and leading to collision and lock up of the Arabian and Eurasian plates (e)

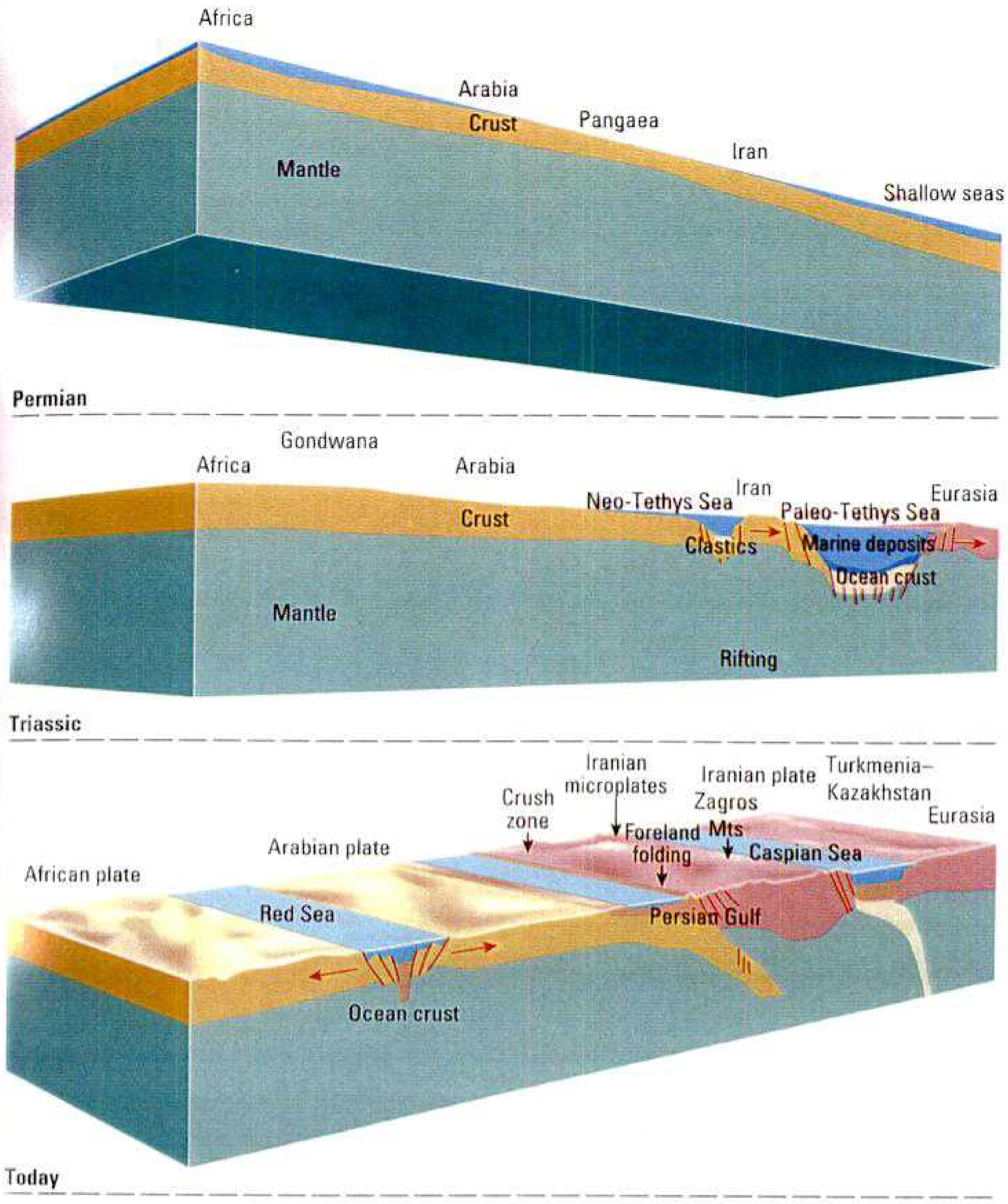


Figure 12: A simplified view of Iran's tectonic evolution

basement thrusts and a few widely spaced north–south-trending, strike–slip faults that separate major structural segments.

In the southeastern part of the Zagros range, geologists have identified two main structural domains. A domain of north–northwest-trending, right-lateral faults in the northern area of the southeast Zagros region implies that fault-bounded blocks are likely to have rotated anticlockwise about vertical axes relative to both Arabia and central Iran. In contrast, the predominance of north–northeast-trending, left-lateral faults in the second domain (the southern part of the southeast Zagros) implies that fault-bounded blocks may have rotated clockwise about vertical axes. Recent studies have proposed a tectonic model with crustal blocks bounded by strike–slip faults in a zone of simple shear that rotate about vertical axes relative to both Arabia and central Iran. Domains of strike–slip and thrust faulting in the Zagros basement suggests that some of the convergence between Arabia and central Iran is accommodated by rotation and possible lateral movement of crust along the belt by strike–slip faulting, as well as by the obvious crustal shortening and thickening occurring along thrust faults.

The central Iranian region

Located between the major mountain ranges of northern and southern Iran, the central portion of the country contains oil and gas in large surface anticlines. These structures occur in the Oligocene–Miocene Qom limestone shale sequence. The Alborz and Serajeh fields contain relatively complex structural reservoirs that have been controlled by thrust faults and salt movement. In Alborz field, the Qom formation changes rapidly from reef limestone to inter-reef marl over very short distances, but the productive interval in the reservoir is a few hundred meters thick.

The anticlinal structure of Serajeh field (32 km long and 8 km wide) can be seen in outcrops above the reservoir. The reservoir layer is a Qom formation member and occurs at depths between 8000 and 9000 ft.

The Alborz Mountains, northeast basin and Caspian Sea

The Alborz Mountains lie between the south Caspian basin and the Arabian–Eurasian suture zone. The ages of uplift and deformation events affecting this area have been determined by radiometric dating of folded and faulted Phanerozoic strata and two plutons in the Alam Kuh area—the Akapol igneous suite and the Alam Kuh granite.

Oil and gas exploration in the northern part of Iran is centred on the Sarakhs area. The thick accumulation of marine sediments and the absence of volcanic activity, which could interfere with hydrocarbon accumulation and maturation, have attracted the attention of petroleum geologists for years. Khangiran and Gonbadli fields are among the most important accumulations in this part of the country.

Beyond the northern coast of Iran, attention is turning to the oil and gas potential of the Caspian Sea. The geology of the Caspian Sea is not well known and generally assumed to be similar to that of the Former Soviet State of Azerbaijan. Following successful oil and gas developments by other countries around the Caspian Sea, this relatively underexplored play is seen as a major new frontier for the Iranian oil and gas industry.

Geological evolution of Iran's hydrocarbon wealth

The development of Iran's major oil and gas fields has been directly influenced by the development and demise of major earth structures over the past 250 million years (Figure 11).

The origins of the Zagros Mountains and the huge anticlinal structures that hold so much of the Middle East's hydrocarbon wealth can be traced back to the breakup of the land mass known as Pangea. During the Permian, this supercontinent broke up to form a northern continent—Laurasia—and a southern continent—Gondwana. In the late Permian and the Triassic, rifting in what is now Iran and surrounding countries, fragmented the continental crust and created two seas—Paleo-Tethys in the north and Neo-Tethys to the south (Figure 12).

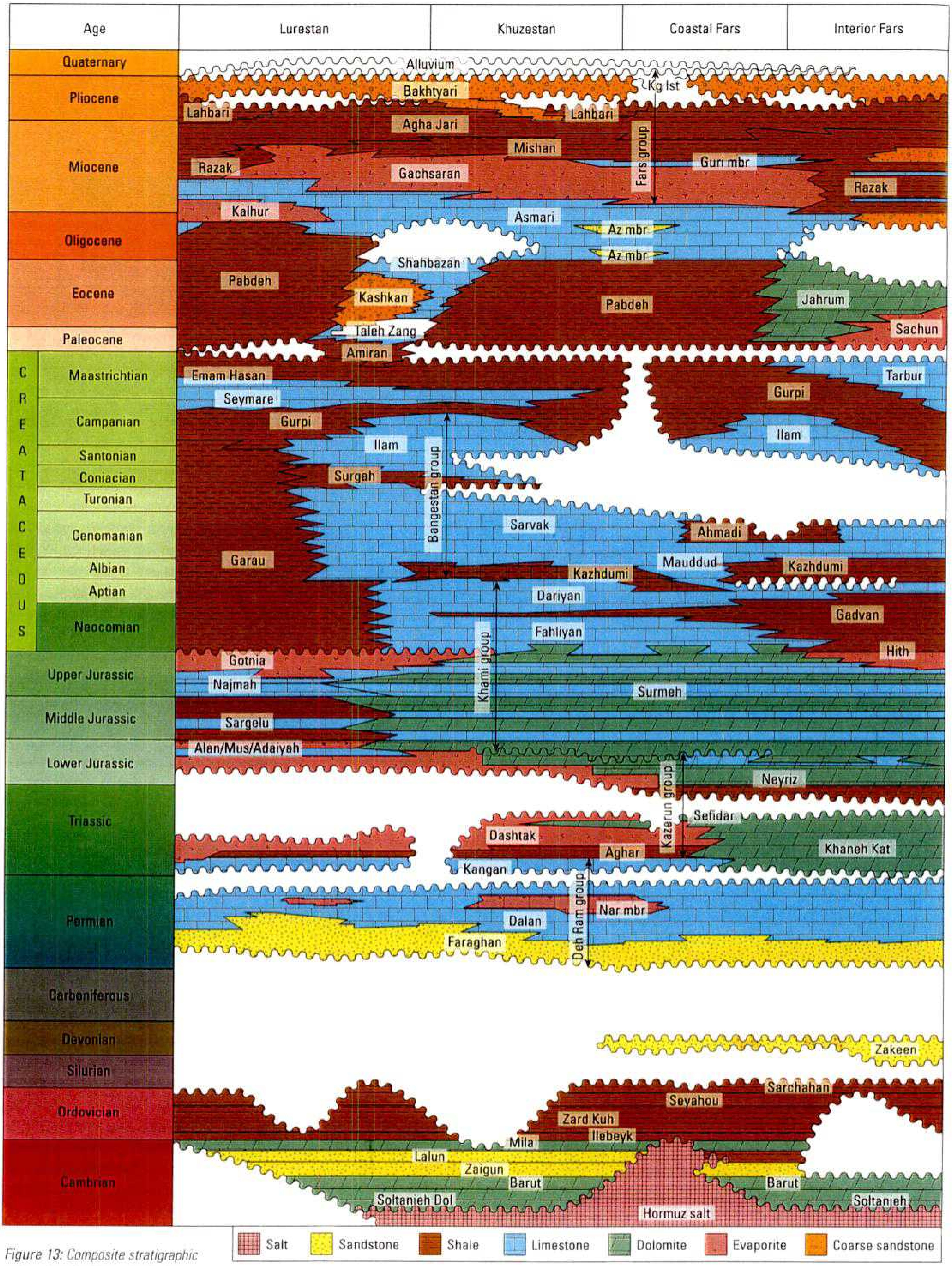


Figure 13: Composite stratigraphic column for the Zagros basin, Iran

The Neo-Tethys Sea stretched from the Indian Ocean, across the Middle East, to southern Europe. These marine rifts proved to be ideal sites for the deposition of carbonate and clastic reservoir sequences and, in some places, organic-rich sediments in intracratonic basins, marginal basins, shelf and platform margins.

The last remnants of the Tethys seaway had almost disappeared when the ocean areas were overridden by continental crust. At the same time, there was intense deformation of sediment in the zones where tectonic forces pushed the Arabian and Eurasian plates together. Attempts to reconstruct the Permo–Triassic paleogeography of the region have proved difficult. The challenge is compounded by the subduction of some crust and the deformation that created the mountain range that stretches from the Black Sea to the Indian Ocean.

The economically significant Asmari carbonates deposited in the Zagros basinal trough were the last open-marine deposits laid down in the Neo-Tethys Sea. As global sea levels dropped during the Miocene, the seaways became restricted and isolated and eventually dried out—an event marked by the deposition of thick evaporite layers such as the Gachsaran formation. In Iran, these evaporites serve as effective seals for oil and gas generated in Cretaceous rocks. Paleontological evidence indicates that the final closure of Tethys began around 1.5 million years ago. Thereafter, the organisms in the Indian Ocean evolved separately from those in the Mediterranean.

The stratigraphic sequence

The area southwest of the main Zagros thrust has been under geological investigation since the late nineteenth century. Active oil and gas seeps attracted early explorationists to the area and since then, oil companies have conducted numerous surveys. A complete modern stratigraphy of the region was published in 1965. To the northeast of the main Zagros thrust, stratigraphic studies had been conducted since the nineteenth century. However, it was not until the establishment of NIOC in 1950 that systematic stratigraphic investigations were conducted across this area (Figure 13).

Southwest Iran

Paleozoic

The patchy records of Paleozoic rocks make it difficult to establish a regional stratigraphy for that time period. In areas where Paleozoic rocks are exposed, the sequences are dominated by the red shales and dolomites of the Barut formation and the shales and sandstones of the overlying Zaigun formation. These are the oldest units represented at surface, being late Precambrian or lower Cambrian. The Cambrian sequence at these localities consists of red shales and siltstones of the Lalun formation and limestone–shale sequences of the Mila formation. The sandstones and shales of the Ilebeyk formation are now known to be of Tremadoc (lower Ordovician) age. These sediments are overlain by Devonian (Zakeen) and Permian (Faraghan) rocks at Kuh-e Dinar and by the Ordovician formation at Zard Kuh.

The Permian sediments comprise a thick unit of limestone and dolomite that is widely distributed over southwest Iran. These carbonates, the Dalan formation, are equivalent to the Dalan unit found throughout the region. The formation is gas bearing in the western part of Fars Province.

During the early and middle Paleozoic, a huge marine platform covered the whole of Iran. In the late Triassic, a major tectonic event split the Paleozoic platform in two; each part subsequently followed entirely different courses of structural development. The line separating the two units developed into the main Zagros thrust during the Alpine orogeny. Southwest of this structural line, the Zagros basin developed as a steadily subsiding trough. This trough was a site of continuous sedimentary deposition from the Permian to the Tertiary. A combination of factors ensured the hydrocarbon value of the region southwest of the Zagros thrust:

- a long period of quiet sedimentation
- deposition of organic-rich source beds in a marine environment
- development of thick rock sequences that could act as reservoirs
- deposition of excellent cap rocks and large structural traps formed at the appropriate time.

Mesozoic

The Mesozoic record is more complete than the Paleozoic record and it displays a great deal of facies and thickness variation. The Triassic sequence consists mainly of anhydrite, limestone and dolomites of restricted, shallow-water origin. Evaporites are absent, for example, from some areas to the south of the crush zone, indicating nondeposition or subsequent erosion.

Jurassic

Towards the end of the early Jurassic, a transgressive event affected the whole of southwest Iran. Deposition of marine carbonates—the Surmeh formation—continued until the end of the Jurassic. The Surmeh is overlain by Hith evaporites in Fars Province and the Dezful embayment. In Lurestan, however, the basal part of the Jurassic sequence is represented by the Neyriz formation—a mixed sequence of dolomites, shales and evaporites. Above the Neyriz formation, there are more carbonates and evaporites in the Adaiyah, Mus and Alan formations. In Lurestan, the basinal shales and limestone of the middle Jurassic Sargelu formation overlie the Alan formation and are overlain disconformably by the Najmah and Gotnia formations, which complete the Jurassic sequence.

Cretaceous

At the end of the Jurassic, the eastern part of the region underwent substantial uplift. This is particularly apparent in Fars Province. Subsequent erosion removed parts of the Hith evaporite and the underlying Surmeh formation. The area was then submerged by another transgression from the north, and deposition of the Fahliyan formation limestones began.

During the early Cretaceous, the western parts of the Dezful embayment and the whole of Lurestan were depocenters for bituminous black shales of the Garau formation. By the middle Cretaceous, the basin was less extensive—with accumulation of Garau sediments being confined to central Lurestan, where deposition continued until the start of the Coniacian.

The marine sediments of the Fahliyan formation were deposited to the east of these basins, in a shallow shelf environment. The Fahliyan, which now forms a prominent limestone unit across the Dezful embayment and Fars Province, has good reservoir characteristics in places and is gas-bearing in parts of the Dezful embayment.

In some areas, the Fahliyan formation is separated from the overlying Dariyan formation by shales, siltstones and minor limestone beds of the Gadvan formation. However, in Lurestan and parts of the Dezful embayment and Fars Province the Gadvan is absent—making it difficult to define the precise boundary between the Fahliyan and Dariyan formations.

The Aptian–Dariyan formation consists of shallow-water, neritic limestones that form a good reservoir unit, which is oil bearing in the Dezful embayment. A widespread regression at the end of the Aptian marked the end of Dariyan deposition. The emergence and erosion of sedimentary deposits at this time are evident in the regional unconformity across Fars Province. In central parts of the Dezful embayment, the limestones of the Dariyan formation pass into the shales and marls of the Albian–early-Cenomanian Kazhdumi formation. This clastic unit overlies the Dariyan formation, except in Lurestan where sedimentation of the basinal Garau formation continued without interruption.

The shallow, near-shore carbonates of the Sarvak formation conformably overlie the Kazhdumi formation. The Sarvak is an important reservoir unit in the Dezful embayment where good production has been secured from several fields. The Sarvak formation is separated from the overlying Ilam limestones by shales belonging to the Surgah formation in Lurestan and a shaly unit (equivalent to the Laffan formation) in the coastal part of the Fars Province. Elsewhere, limestones of the Santonian–Campanian Ilam formation directly overlie the Sarvak formation, making it difficult to establish the lithostratigraphical boundary.

A major rise in sea level at the start of the late Cretaceous created the depositional environment for the shales and marls of the Gurpi formation. Deposition of this formation persisted until the end of the Cretaceous across much of southwest Iran—except for a narrow belt to the north of Shiraz where rudist-reef limestones of the Tabur formation were deposited.

Cenozoic

Paleocene–Eocene

The Paleocene–Eocene sequence comprises shallow-water limestones and dolomites of the Jahrum formation and deeper-water marls of the Pabdeh formation. In northeastern Lurestan, the Pabdeh formation is partly replaced by sandstones, siltstones and marls of the Amiran formation, red sandstones and conglomerates of the Kashkan formation and limestones of the Taleh Zang formation. The Jahrum formation in this part of Lurestan is replaced by the Shahbazan formation. In the interior of Fars Province, an evaporitic marl—the Sachun formation—replaces the basal portion of the Jahrum formation.

Oligocene–Miocene

The Asmari formation, which overlies the Pabdeh and its time equivalents the Shahbazan and Jahrum formations, consists of shallow-water, Oligocene–Miocene limestones. The Asmari was the first reservoir to produce commercial quantities of oil in Iran. The production capacity of the Asmari formation is extremely high and provides the bulk of oil production from southwest Iran. Apart from matrix porosity, fracture permeability plays a crucial role in the high production capacity of the Asmari.

Miocene–Pliocene

The Miocene–Pliocene sediments that overlie the Asmari formation are divided into three formations: a lower evaporitic unit (the Gachsaran formation); a middle marl and limestone sequence (the Mishan formation); and an upper unit of sandstones, siltstones and marls (the Agha Jari formation). The first indications of tectonic disturbance related to the Zagros orogeny are seen at this level.

The composition of the Gachsaran formation changes from evaporite to the red marls and sandstones of the Razak formation in Fars Province. The Mishan formation, a prominent unit in the Dezful embayment and Fars, gradually wedges out towards Lurestan.

Northeast Iran

The Sarakhs area in northeast Iran is part of the Kopet Dagh, Hezar-Masjed basin. This basin contains a sedimentary sequence that is more than 16,000-ft thick and unaffected by major stratigraphic breaks or volcanic activity. The sequence extends from the middle Jurassic to the lower Oligocene and consists of thick, porous dolomites, limestones and sandstones—with reservoir potential—and thick, interbedded shaly intervals that can form effective seals. This sequence and the associated structures provide a highly favorable environment for the entrapment of hydrocarbons. Black, organic-rich shales in the middle and upper Jurassic exhibit excellent source rock potential.

A major transgressive episode during the Jurassic inundated the Sarakhs area. This phase of rising sea level was reversed at the end of the Jurassic. The regression that occurred at that time may have been linked to epeirogenic movements. In the western part of the area there are several lagoonal–marine cycles in the sequence, suggesting an alternation between minor regressive and transgressive events at a local or regional scale. Throughout the upper Jurassic and lower Cretaceous, the eastern part of the Sarakhs area was coastal.

The second major transgression occurred during the lower Cretaceous, and the continuous sedimentary record that follows this event indicates a stable marine environment during this time. The clastic sediments of the Neyzar and Kalat formation suggest that sea level fell once again during the Maastrichtian. The end of this regressive phase is marked by deposition of Paleocene red beds.

Further sea-level changes are recorded in the middle Paleocene (transgression) and the lower Oligocene (regression). In terms of tectonic activity, there were no major changes in northeast Iran during this time, but the area was subsequently affected by the late Alpine orogeny.

Oil and gas distribution

Iran can be divided into three main oil-producing areas: north, central and southwest.

The Sarakhs region of northeast Iran contains a thick sequence of marine sediments unaffected by the volcanic activity that cause problems elsewhere. Important accumulations in this region include Khangiran and Gonbadli fields. In the central Iranian plateau, oil is found in large surface anticlines. At Alborz and Serajeh fields, the reservoirs have been created by thrust faulting and salt tectonic movements. Khangiran field in northeast Iran was discovered by mapping the surface exposures of an anticline.

In southwest Iran, large, anticlinal structural traps are the key to hydrocarbon production. One of the most spectacular examples of outcropping anticlinal structures lies on the north shore of the Straits of Hormuz in the Persian Gulf. These folds comprise the foothills of the Zagros Mountains. They were formed when the Arabian shield collided with the western

Asian continental mass between 4 and 10 million years ago. Subduction still continues slightly further east, beneath Baluchistan, but is inactive in the Persian Gulf itself. The shortening expressed by the folds is accompanied by extensive thrusting on the easterly dipping planes. All the deformation is geologically young; the folded sediments are Paleogene and Neogene.

Elsewhere in southwest Iran, salt domes rise diapirically from the Cambrian Hormuz salt horizon and pass through younger sediments on their way to the surface. In the hot, arid environment of the Persian Gulf the exposed salt escapes rapid erosion. The structures associated with salt domes often provide excellent traps for hydrocarbons. Many offshore structures in the Persian Gulf produce from carbonate sequences in Jurassic and Cretaceous units, including the Surmeh, Fahliyan, Dariyan and Sarvak formations.

Most of Iran's known gas reserves and production are concentrated around Fars in the southeast of the country, within the Permo–Triassic Deh Ram group, which is a complex carbonate–evaporite sequence.

Oil and gas stratigraphy

Iran's hydrocarbon resources are found in reservoir rocks ranging from the Permian (about 240 million years) to the much younger Miocene rocks (around 2 million years). Most of the major oil reserves are found in Oligocene–Miocene carbonate rocks of the prolific Asmari formation (see Focus on the Asmari formation, page 27), which provides key reservoirs across much of southwest Iran (Figure 14).

Reservoir rocks

Khangiran field produces oil from two horizons—the upper Jurassic Mozduran formation and the shales, sandstones and conglomerates of the lower Cretaceous Shurijeh formation. The Mozduran formation at Khangiran field is a thick carbonate unit with minor amounts of shale. The carbonate comprises alternating layers of dolomite and limestone with porosity often correlated to dolomite content. Porosity in the reservoir interval is typically 10 to 25%, with secondary porosity more common in the dolomitic zones. The Shurijeh formation consists of continental clastic rocks such as shales, sandstones and conglomerates. At Khangiran field, the Shurijeh formation contains sandstone cycles interbedded with thin shales and separated from other cycles

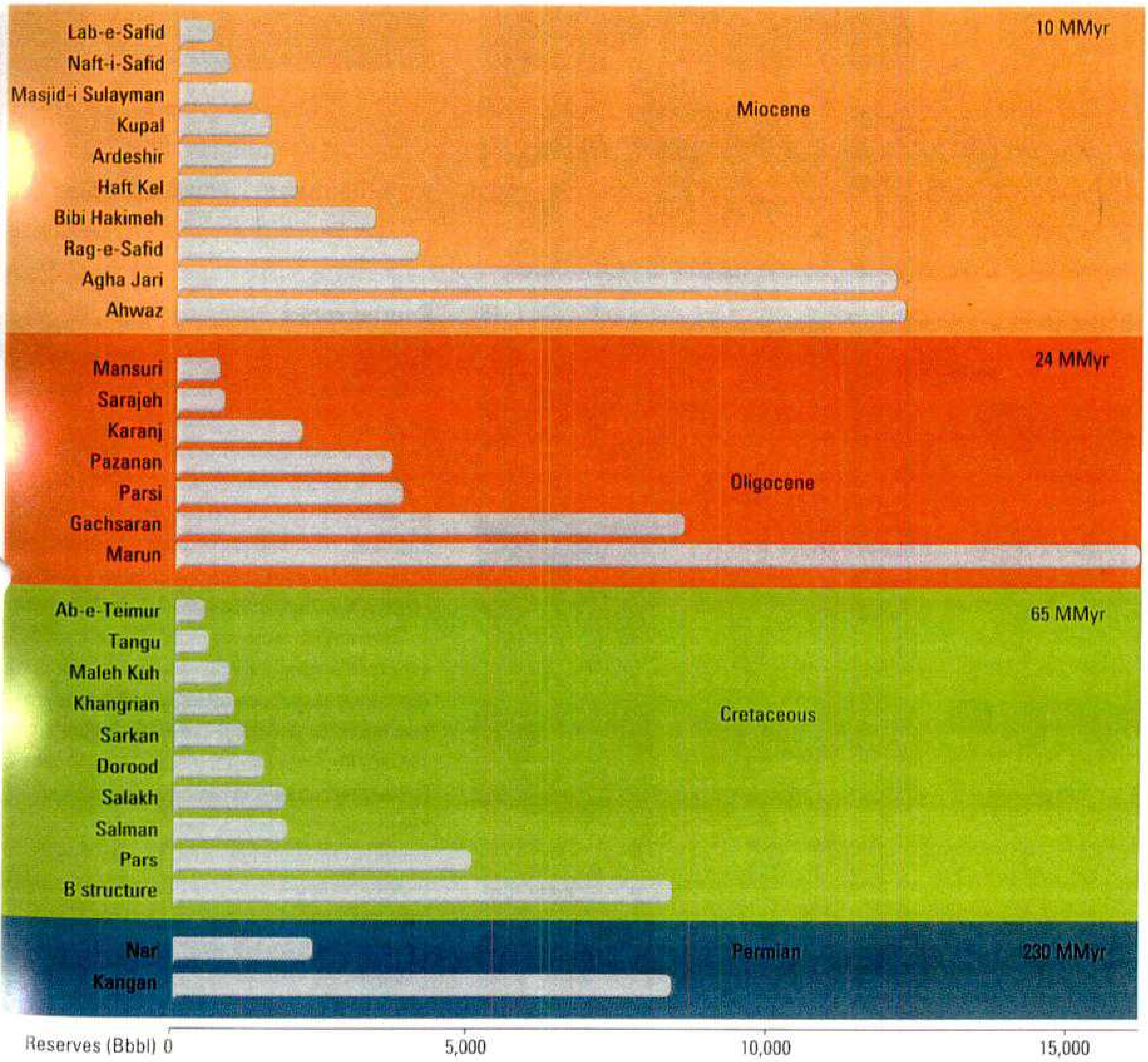


Figure 14: The stratigraphic distribution of Iran's hydrocarbon reserves

by thicker shale units. Porosity in these gas sandstones is typically less than 10%.

On the central Iranian plateau, reservoirs are found in the Oligocene–Miocene Qom formation. At Alborz field, this formation is characterized by rapid facies changes. The three clay-free horizons vary in thickness from 20 to 50 ft and are separated by marly units. The gas reservoir at Serajeh field is located in the Qom formation and attains a thickness of more than 500 ft.

In southwest Iran, the distribution of known oil and gas reservoirs is controlled by structural traps and large anticlinal structures that may be affected by faulting, fracturing or the effects of salt movement (Figure 15). The Permian to Triassic Deh Ram group (comprising the Kangan, Dalan and Faraghan formations) is the world's richest gas-bearing rock. In Iran, it houses supergiant and giant fields such as Kangan field (Figure 16). Onshore the gas is dry, while offshore—in South Pars field for example—it is wet and plentiful. The Deh Ram group is about 3000-ft thick in the Fars area and comprises limestone, dolomite and anhydrite zones.

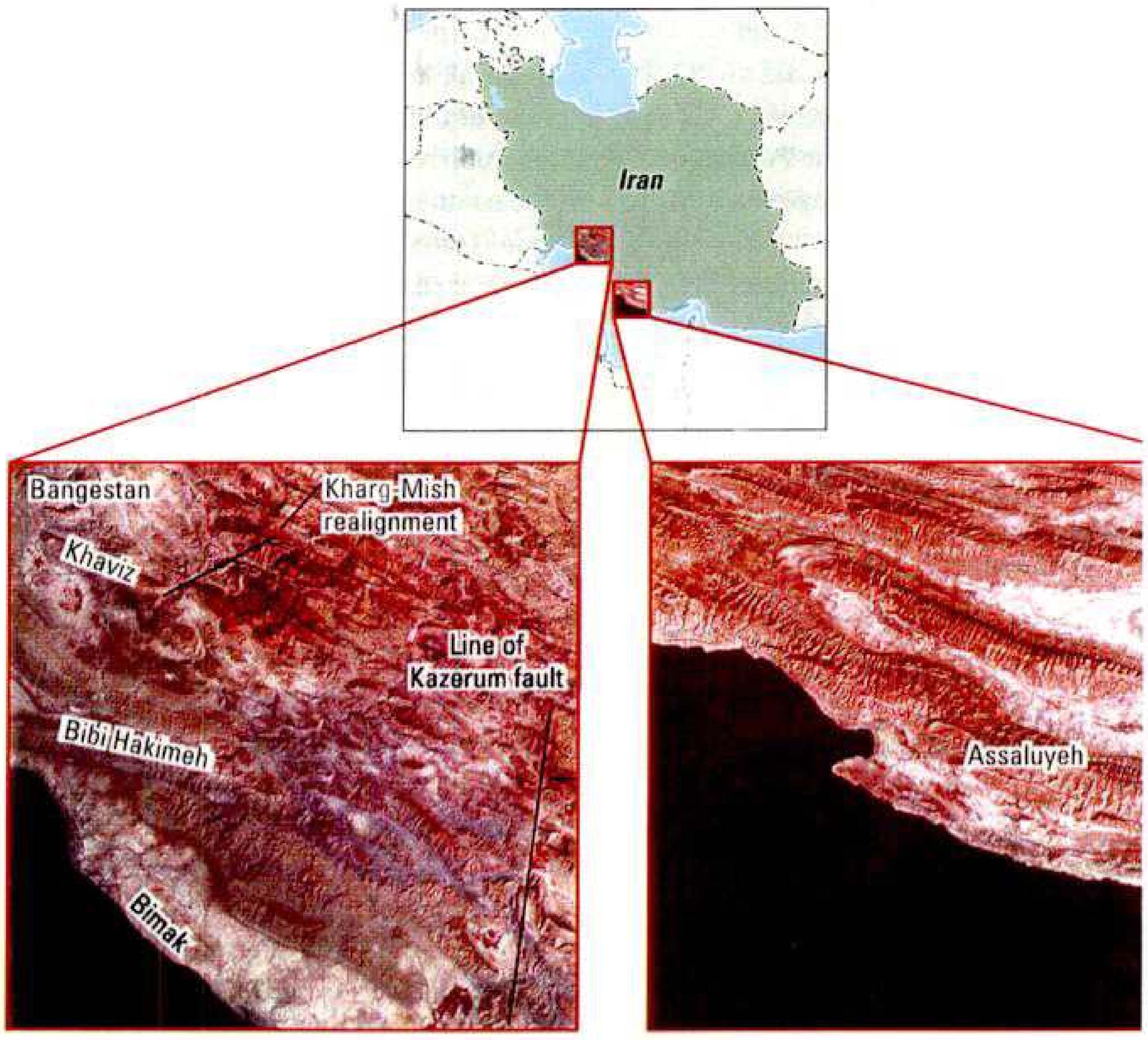


Figure 15: Landsat images of Iran's Persian Gulf coast. These satellite images show some of the huge, oil-bearing anticlines that characterize the Zagros mountain range and the major faults that modify the fold structures

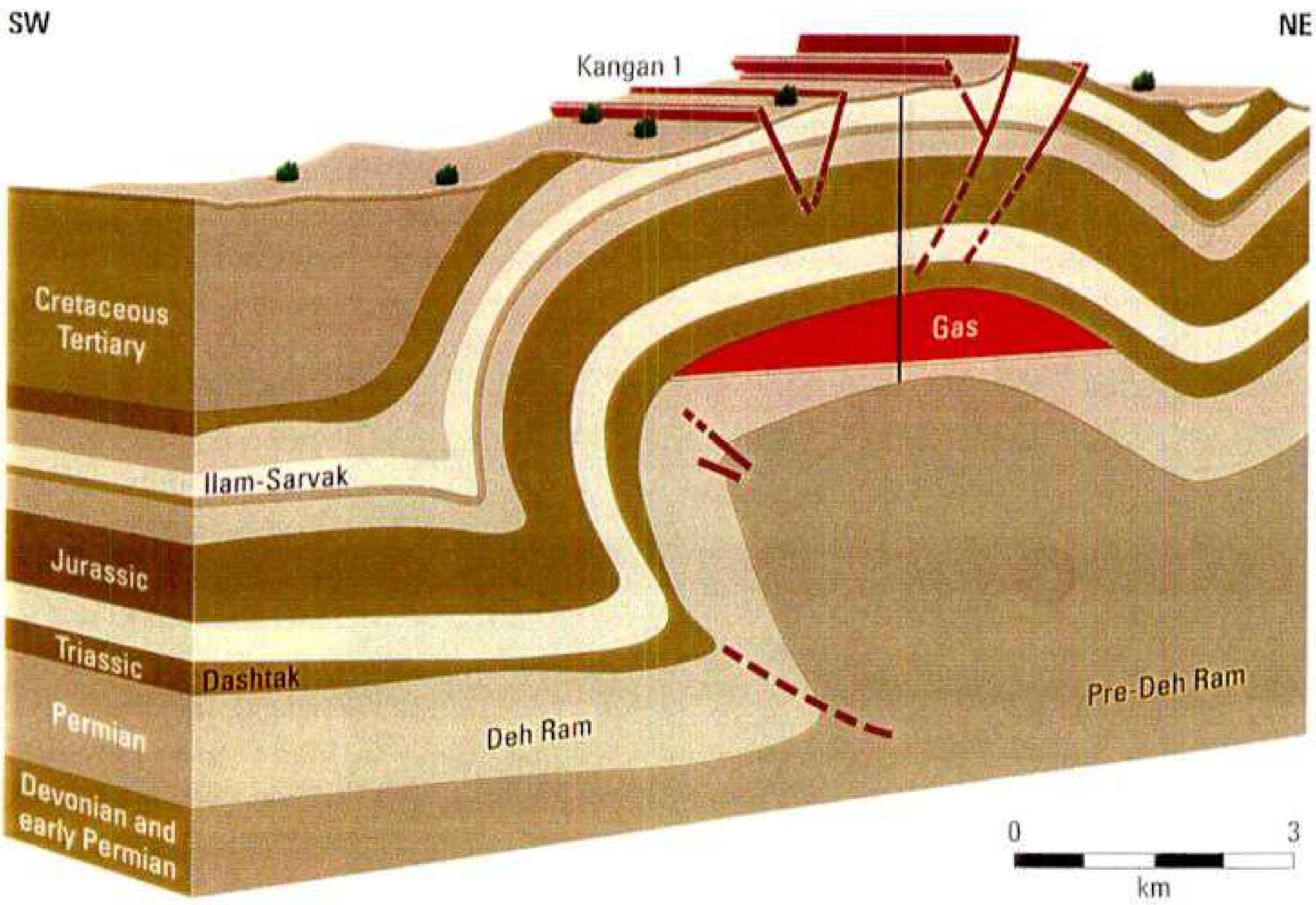


Figure 16: A simplified cross section of Kangan field showing the relationship between a deep-seated thrust and the steep southwest limb of the anticline

Source rocks

Geological and geochemical studies in southwest Iran have revealed a great de: about source rock characteristics and hydrocarbon migration in the country's ı fields. Analysis of burial history, for exan has shown that hydrocarbon generation migration occurred at the same time as t mountain-building episode (orogeny) th created the Zagros Mountains.

Source rocks have been deposited at ; variety of stratigraphic levels across Iran the important oil-producing provinces of Dezful embayment and Lurestan, source rocks have been identified in Jurassic, lo Cretaceous and lower Tertiary formation The overall thickness of organic-rich lay increases towards Lurestan, the result of tectonic events leading to the deposition the thick pre-Santonian shales of the Ga formation in this region. This variation reflects a gradual uplift of Lurestan relat the Dezful embayment. The presence of structural highs and lows within the basi influenced the depositional pattern obse in the younger Gurpi and Pabdeh format

Geologists have tried to identify the source of the vast oil accumulations found in the Asmari formation. Since the earliest days of commercial production it has been apparent that the Asmari is not self-sourcing because its hydrocarbon content is immature. In addition, oil extracted from the Asmari formation is the same as oil found in deeper formations. Possible oil-generating sediments for the Asmari include organic-rich Cretaceous and early Tertiary rocks that have been buried deeply in the structural trough to the west of the Zagros fold belt.

Shales found in the Cretaceous Kazhdumi formation are the key source of oil in southwest Iran. This lowermost formation of the Bangestan group has a rich organic content and is considered a prolific source. Other potential sources in the Cretaceous sequence—the thermally immature Gurpi (Campanian–Maastrichtian) and Gadvan (Neocomian–Aptian) formations—have less organic potential. The Surgah and Garau formations contain significant organic content, but their contribution to oil generation is not clear.

Focus on the Asmari formation

The Asmari formation is the best known reservoir in Iran. It has been in production for more than 90 years. It contains many supergiant and giant oil fields and makes a huge contribution to hydrocarbon production in Iran. However, the discovery of oil at Masjid-i Sulayman on May 26, 1908 had repercussions far beyond the Middle East. Initially, geologists assumed that the oil was being produced from the Gachsaran formation, which overlies much of the Asmari formation. But when geologists showed that oil being produced at Masjid-i Sulayman was coming from a carbonate reservoir, the discovery challenged the principles of oil and gas exploration at the time. Until then, explorationists had focused their attention solely on clastic sandstone reservoirs. The acceptance of carbonates as possible reservoirs changed exploration across the world and led to the discovery of other major Middle East accumulations.

The early explorationists concentrated their drilling efforts on the crests of anticlinal structures (Figure 17). Trial and error revealed that the position of the anticlines in the Gachsaran formation did not coincide with the structures in the Asmari formation that contained oil.

Companies then introduced gravity and magnetic surveying methods to locate the key structural highs, but these were unsuccessful. During the 1930s, surface seismic methods were introduced to improve drilling success rates.

Most of the supergiant and giant Asmari fields lie along the southwest flank of the Zagros fold belt. The distribution of productive Asmari sediments is controlled by the distribution of the overlying Gachsaran evaporite, which serves as a cap rock. Where this Miocene evaporite layer has been removed by erosion the oil has escaped.

Many Asmari fields are found in asymmetric anticlines with limbs dipping steeply to the southwest. The amplitudes of these folded structures can be very large, with differences of more than 19,000 ft between the crest of one fold and the bottom of the nearest syncline (Figure 18). The main producing section within the

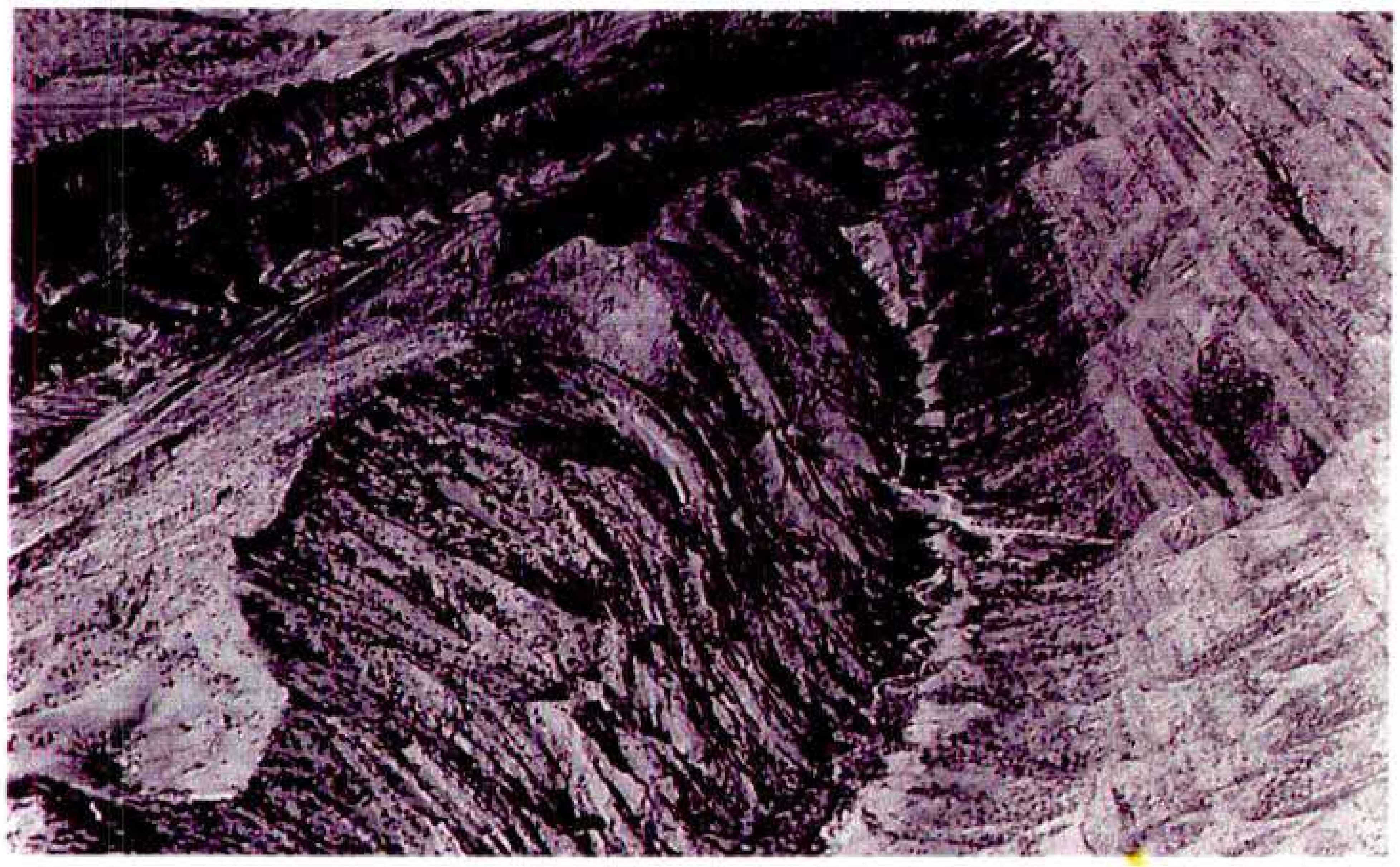


Figure 17: The Asmari formation forms the ring exposed around the northeast flank of Kuh-e-Patdeh in the Dezful embayment. The core of the anticline is a Cretaceous limestone

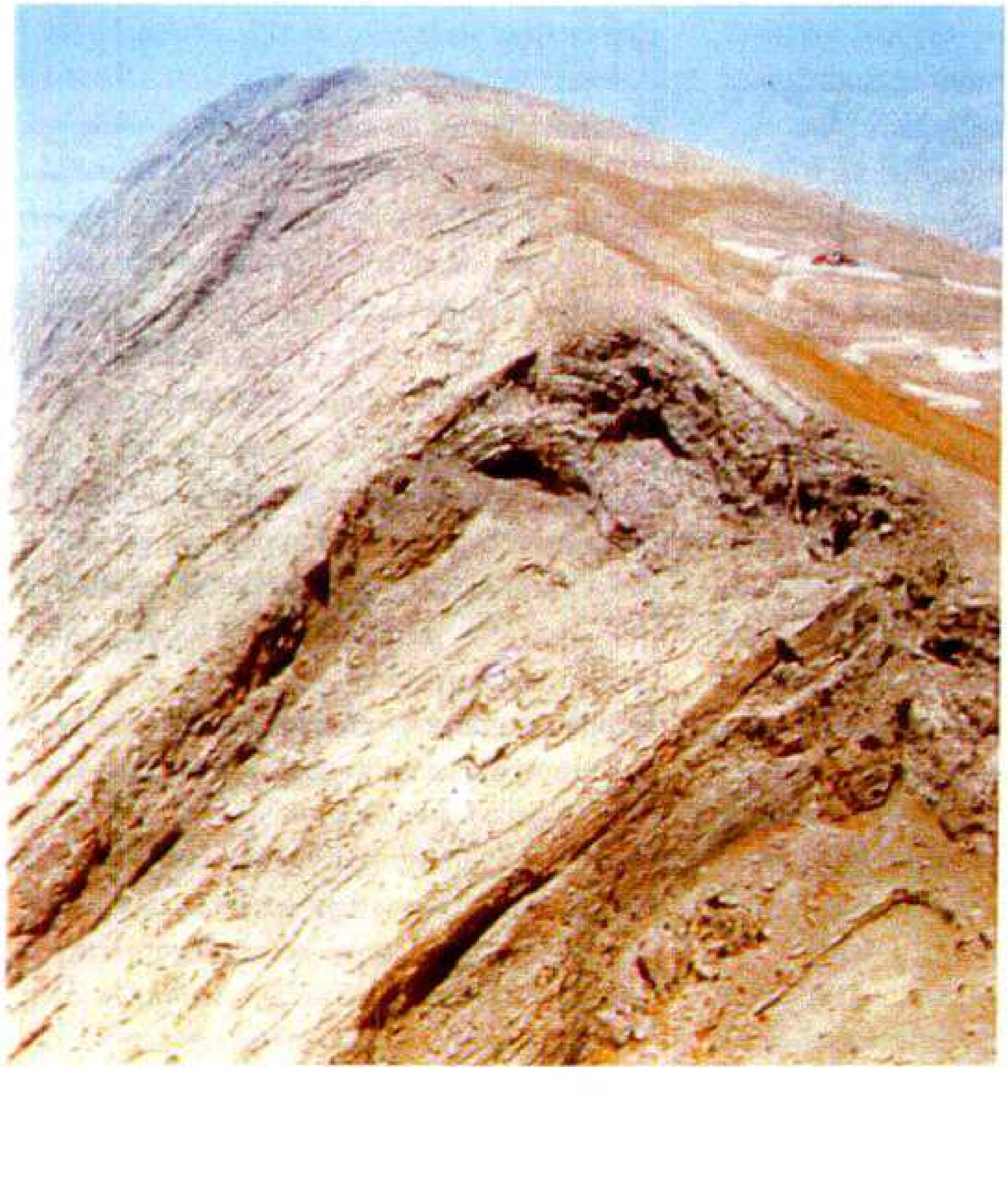


Figure 18: A drilling rig perched on the shoulder of a giant Asmari anticline

Asmari formation is 1000 to 1700-ft thick. In some fields, however, the vertical difference between the spill point and the crest can be more than 6500 ft. At Gachsaran field (Figure 19), for example, the oil column between gas–oil and water–oil contacts is around 6000-ft thick. The spill points on the Asmari anticlines are at the southeastern ends of these structures. This is the result of a northwest regional tilt or subsidence in the area.

The Asmari formation is not all carbonate. The Ahwaz sandstone, for example, is an important and extensive member of the Asmari formation. Extending across Kuwait, southeast Iraq, the northern end of the Persian Gulf and into Iran, the sandstone is around 800-ft thick at Ahwaz field where it comprises nearly half of the Asmari formation. Near Ahwaz, the Asmari lithology is a mixture of dolomite, limestone, anhydrite and shales interbedded with the Ahwaz member sandstones. The sandstones are generally quartz rich and poorly consolidated. Typical porosity values for the Ahwaz sandstone are in a range from 22 to 24%, substantially better than the interbedded carbonates that comprise the Asmari formation. In these units, porosity is typically 12 to 15%.

In Ahwaz field, the median sandstone permeability is more than 3 darcies, and reaches 15 darcies in some locations. Carbonate units within the Asmari formation can have higher permeabilities where fracturing has been extensive. The Ahwaz sandstone is not fractured, but the poorly consolidated nature of the clastic sediment means that sanding can be a problem for field operators.

Major basins, fields and structural features

Jurassic and Cretaceous basin development

Many of the north–south structural trends of the Arabian platform continue northwards into Iran. A major, uplifting tectonic event during the upper Cretaceous caused erosion of Cretaceous units through most of southern Iran, except in the basinal trough centered on Lurestan. In this trough, basinal sedimentation seems to have continued well into the Tertiary.

Jurassic and Cretaceous carbonate reservoirs are found along Iran's southern borders. These are related to the prolific carbonate reservoirs in countries to the south. During the late Jurassic and early Cretaceous, a deeper basin developed that covered the Lurestan area and extended beyond Iran's western border. This organic-rich basin contains source rocks for much of the oil found in Jurassic and Cretaceous reservoirs around the Persian Gulf. The shallow carbonate margins around the edges of the basin were marked by the development of a dolomite reef.

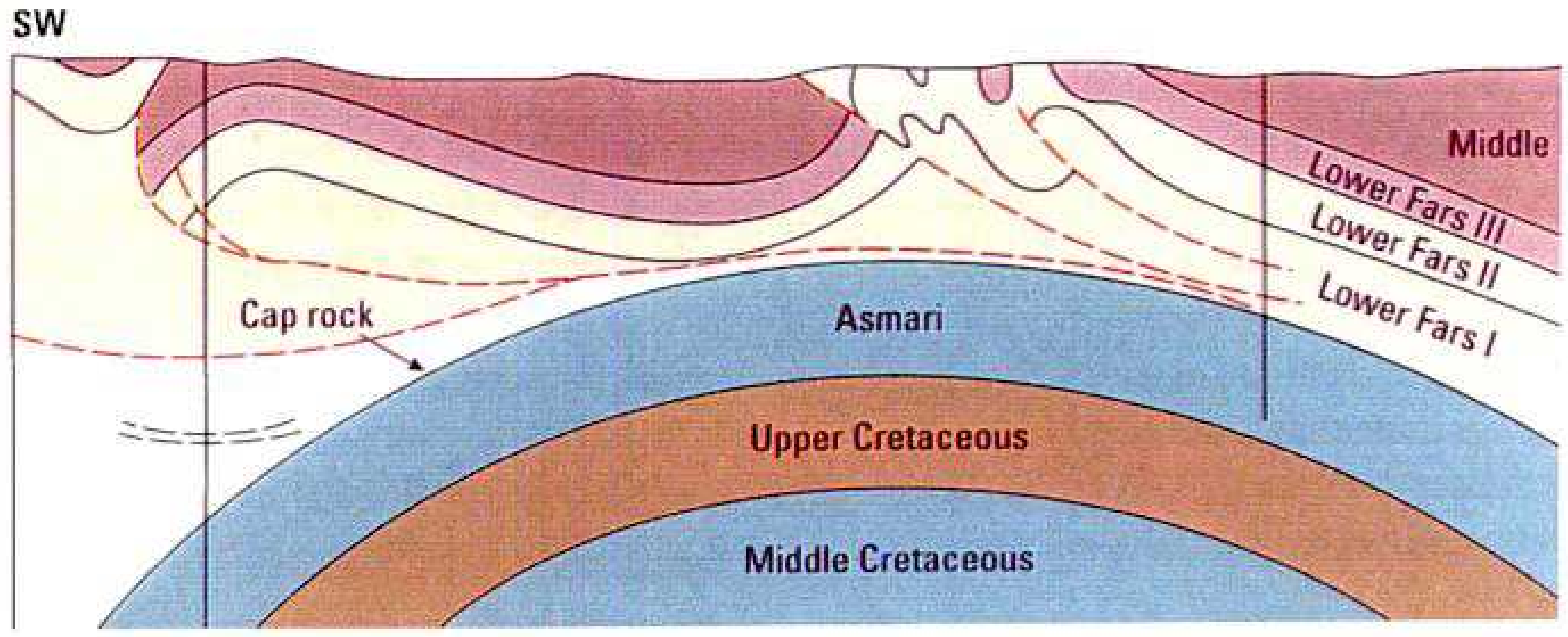


Figure 19: Cross section of the prolific Gachsaran field

Oolite shoals developed during the Jurassic and Cretaceous and are found in the Persian Gulf, with bioturbated grainstones deposited further to the south and east. The seal for these Surmeh formation reservoirs is provided by the Hith anhydrite formation—a widespread and persistent cap rock that extends across much of the region beyond Iran.

Cretaceous reservoirs in the offshore fields include oolite shoals and rudist patch reefs. These are associated with depositional highs formed by salt structures, such as the Sirri fields in the east central portion of the Persian Gulf. The Middle Cretaceous sequence in the western part of the Persian Gulf also includes deltaic and coastal sandstone reservoirs, some of which contain oil.

Jurassic and Cretaceous shelf carbonate deposits from Lurestan to the Straits of Hormuz are part of the Khami and Bangestan groups. These groups are separated by a regional unconformity and their shelf carbonates interfinger with deeper-water, basinal deposits towards southwest Lurestan.

Most of Iran's Cretaceous reservoirs are fractured, but exhibit good primary porosity in the packstone and grainstone units at the top of various regressive sedimentary cycles. In the Sarvak formation, for example, facies from the high-energy parts of the shelf have porosities up to 20% and permeabilities of several hundred millidarcies. The Sarvak formation is more than 3500-ft thick, and the large-amplitude anticlinal folds that affect it have trapped huge volumes of oil and ga Unfortunately, the fracture systems in tl carbonate sequences are not as well connected as those of the Asmari.

Typical structural styles in Iranian fields

The Zagros Mountains are well known f detachment-style folding related to the infra-Cambrian Hormuz salt, but folds o this type are confined to the original sal basin boundaries. As the thickness of sa the paleo-Hormuz salt basin diminishes, styles of structural deformation change the Zagros from salt-related, detachmer style folding, to salt swells and pillows associated with fault-propagation-style folding, and fault-related folding.

The Fars region of the southern Zagro Mountains is characterized by salt-detachment folding with upright, concen folding. This style of deformation varies drastically in the Dezful embayment in tl north, as folding is largely fault related. (Dezful structures may or may not be linl to salt-related folding and exhibit coinci thinning over the structures. Thrusts in Tertiary Gachsaran formation are often (of-sequence thrusts that ramp up from deeper detachments verging westward. ' hanging-wall anticlines related to thrusts the Gachsaran formation are not general coincident with deeper fault-related structures formed earlier. Growth strata are also seen and related to fault-genera structures in the Gachsaran and deeper detachments. Changes in structural style and regional seals along strikes in the Za Mountains complicate the petroleum sys of the Dezful embayment. Understandin style of deformation and the limits of th Hormuz salt basin and consideration of intermediate detachments help to explai the variations in maturity and migration hydrocarbons in the Zagros range.

The importance of fractures

In 1920, engineers working at Masjid-i Sulayman field began to measure downhole pressure. They showed that reservoir communication could only be explained by the presence of fractures. The study also indicated that the field could be drained with fewer and more widely spaced wells than had ever been used before. Large fracture systems provided communication between the Asmari and deeper Bangestan group (Cretaceous) reservoirs. This also provides some explanation of the discovery of very similar oil types in the Cretaceous and in younger Asmari reservoirs. Where there is good fracture communication across the 2000 to 3000-ft interval of shales and marls that separates the units, vertical migration from the Cretaceous layer has created or modified the Asmari accumulations. These fracture systems still influence hydrocarbon movements today.

Carbonate reservoir studies indicate that fracture distributions and orientations have a major influence on field development and the performance of waterflooding operations. Without careful planning to accommodate fractures, engineers face the prospect of early water breakthrough (Figure 20). Fracture examination is best achieved immediately after a well has been drilled. If the well has intersected open fractures, the key steps are to establish whether oil is present and to determine fracture depth, frequency and aperture width. This information is important for the design of well tests and completion programs.

Reservoir modeling and waterflood projects require an understanding of the fracture distributions around the wellbore and in the areas between wells. Interference tests between wells can reveal flow anisotropies caused by fractures, but it is difficult to define the effect of fractures on drainage and fluid movement in between-well areas far from the wellbore.

Borehole imagery (see Figure 21) is the best way to determine the morphology and orientation of fractures intersected by the borehole. Imaging tools can help geologists and engineers to differentiate various fracture types on the basis of their shape and orientation. It can also indicate if the fractures have been affected by mineralization. In many carbonate fields, partial mineralization of fractures can preserve the porosity and permeability that would otherwise have been lost during deep burial.

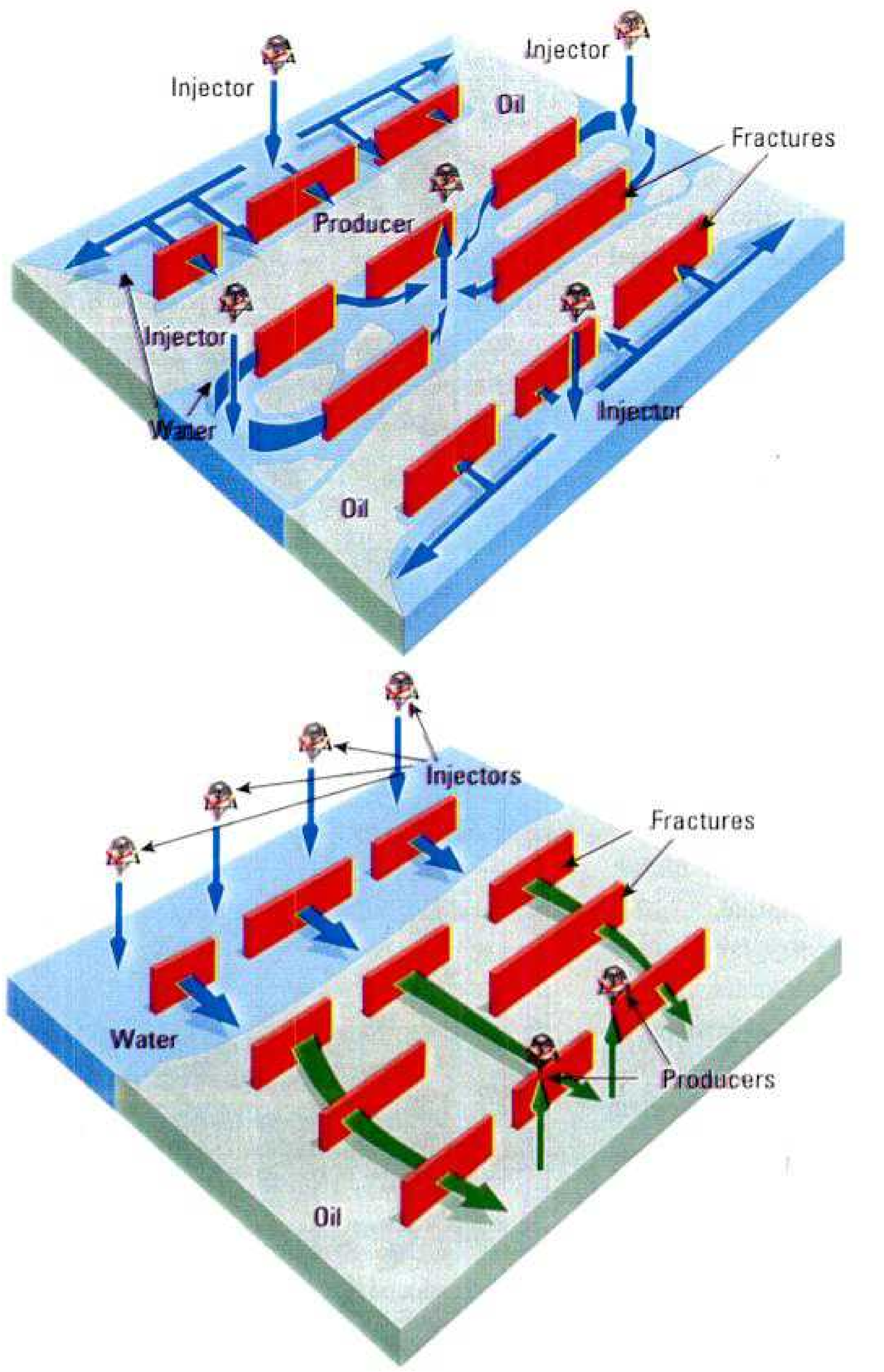


Figure 20: The orientation, distribution and extent of fractures are vital pieces of information for any oil and gas reservoir. For example, when reservoir engineers plan a waterflood operation, the optimum positions of injector and producer wells will be influenced strongly by fractures. Waterfloods that ignore fracture orientation (top) may suffer early water breakthrough and leave large volumes of bypassed oil in the reservoir. Waterfloods that use the fracture network (bottom) can increase sweep efficiency and should delay water breakthrough at producers

Geologists try to understand the probable distribution of fractures throughout a field by extrapolating from the information gathered at each well. The first step for the geologist is to determine if the fractures are related to folding or faulting. Fault-related fractures, for example, are usually restricted to a small envelope around the fault, but may have much larger vertical communication than the more widespread fracture sets related to folds.

Ahwaz field—a giant among giants

The Ahwaz reservoir has been in production since 1959. It is water driven, and water run-off from west to east helps to maintain reservoir pressure.

In 1991, a major, integrated reservoir characterization project started at Ahwaz field (see Figure 22). This field, one of the largest hydrocarbon-bearing structures in the world, is a large northwest–southeast-trending anticline with a subsurface area of 80 by 10.5 km. NIOC's integrated study of this field took three years to complete, and was followed by three years of extended studies on history matching and simulation using different development scenarios. The study included field geology, petrophysics, and history matching and forecasting of future performance. It used geostatistical methods that had never before been applied to a field of this size.

Geostatistics helped reservoir engineers to evaluate the distribution of fluids across the reservoir and to create a detailed model of the reservoir. The characterization team faced some daunting challenges in data management and analysis.

Ahwaz field has 14 active reservoir layers, eight sandstone units and six carbonate units. With more than 200 wells, there was no shortage of production and pressure data on which to base the model. There were also 50 RFT* Repeat Formation Tester tool logs and more than 40 TDT* Thermal Decay Time logs to be examined and integrated into the model.

Depletion of the main producing layer at Ahwaz field encouraged the operators to examine the most cost-effective way of developing the remainder of the reservoir. Oil at Ahwaz field is produced from the Asmari sandstone layers within the reservoir, but some reservoir engineers have suggested developing the lower-permeability carbonate layers using horizontal wells.

The main units at Ahwaz field are high-porosity and high-permeability, siliciclastic-rich units that serve as flow conduits. In contrast, the carbonate-rich units, which exhibit lower average porosities and permeabilities, behave as relative baffles to fluid flow. The shale units act as fluid barriers. Maps show the large-scale geological framework for the field and are used for calculations of original oil in place and recoverable reserves.

Porosity and permeability values are extremely variable at Ahwaz, and the initial geological model provided essential information about the geometry, continuity and connectivity of major flow units. It also gave some indication of the small-scale, heterogeneous lithofacies distributions within individual units. However, lithological heterogeneity, extensive diagenesis and the scarcity of well data relative to the 880-km^2 mapping area convinced the reservoir characterization team that a geostatistical model was needed to provide reliable lithofacies distribution data for areas between the wells.

Traditional geological models were developed from the structural interpretation of seismic data, detailed sedimentological core studies and petrophysical analysis of 182 wells. Lithofacies distributions were determined along each wellbore using petrophysically derived mineral concentrations. Each reservoir unit with a distinct depositional facies was analyzed using proportion curves and variograms to quantify the relative frequency and spatial continuity of each lithofacies in the unit.

The result was a combined grid- and object-based geostatistical model that, when simulated, provided a detailed three-dimensional lithofacies distribution within the entire reservoir consistent with traditional geological models. The model honored the large-scale deterministic unit maps and the vertical lithology distributions in all of the wells. This detailed geological description was then used as a basis for the full field flow simulation and production predictions.

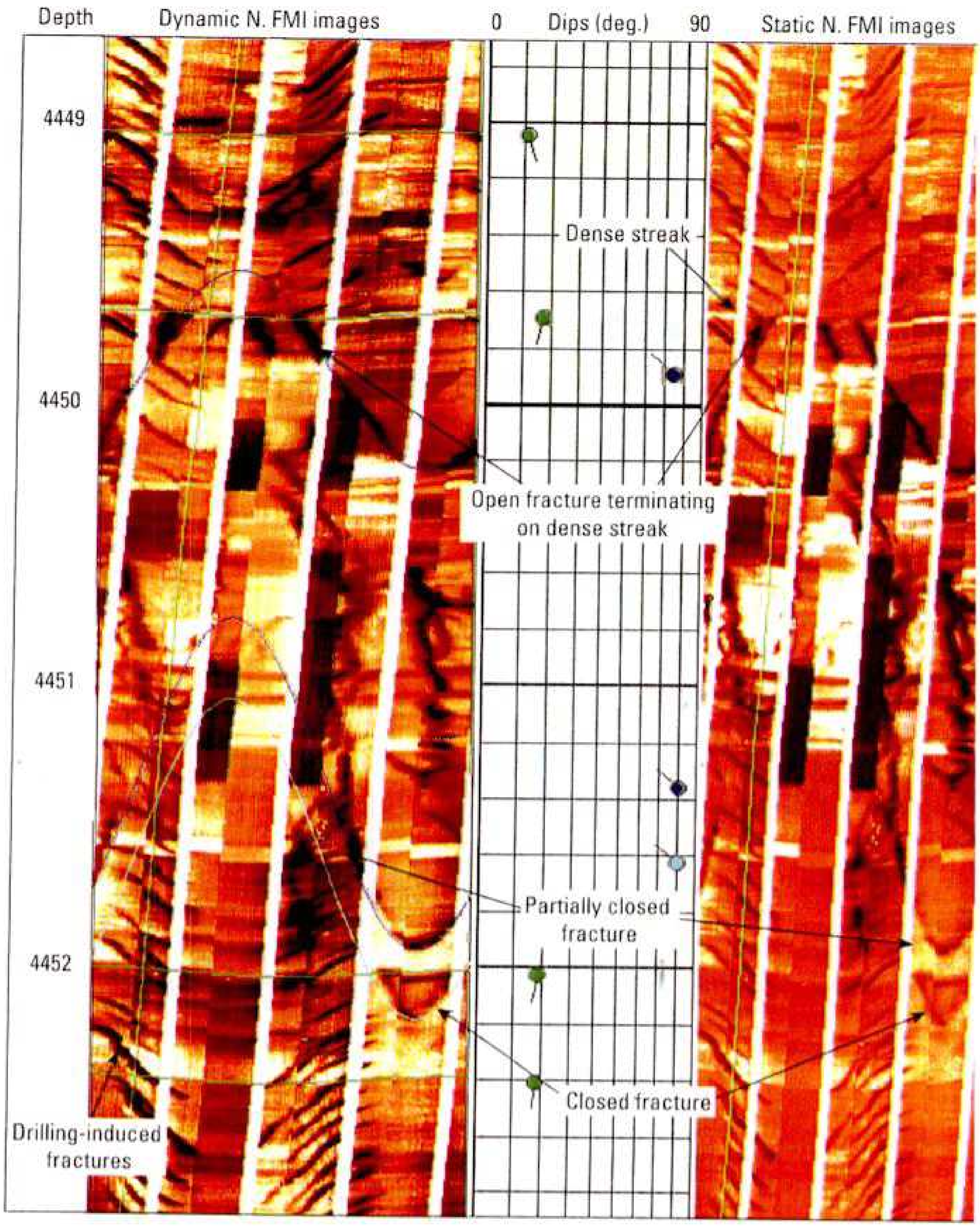


Figure 21: This FMI plot shows how much information on fractures can be derived from modern borehole imaging methods

New discoveries and current exploration

Exploration is a key part of Iran's current oil and gas strategy, and work is in progress to extend the country's reserves. The potential for new hydrocarbon reserves in Iran is immense. Many large surface anticlines in the Zagros fold belt and elsewhere in Iran have yet to be tested. Several hydrocarbon prospects identified in the 1970s as showing excellent potential are currently undergoing full evaluation.

Many structures that have previously been tested and then plugged would now be economic to produce today utilizing modern technology. These structures offer a large inventory of low-risk exploitation projects. Complex structures and difficult data areas offer potential for undiscovered reserves u modern 3D seismic acquisition techniques.

The existing fields in Iran are structura traps that have often been tested by shal stratigraphic wells, providing significant deeper pool exploration prospects. There are no stratigraphic traps currently defin in Iran.

Modern analytical structural and stratigraphic techniques (sequence stratigraphy and balanced structural sections) are currently used in Iran. Ther is significant potential in footwall, subthrust-style traps (onshore) and salt-flank traps (offshore).

Recent discoveries of multibillion-barr fields in Iran by NIOC have reinforced th future potential for giant discoveries. Petroleum systems composed of multiple reservoirs (clastic and carbonate), sources and seals are present in the Tertiary, Cretaceous, Jurassic and Paleozoic. Many of these petroleum systems are the same as in the Gulf States and neighboring countries, but the lower Cretaceous, Jurassic and Paleozoic systems of Iran have yet to be exploited.

The Caspian Sea—a new frontier

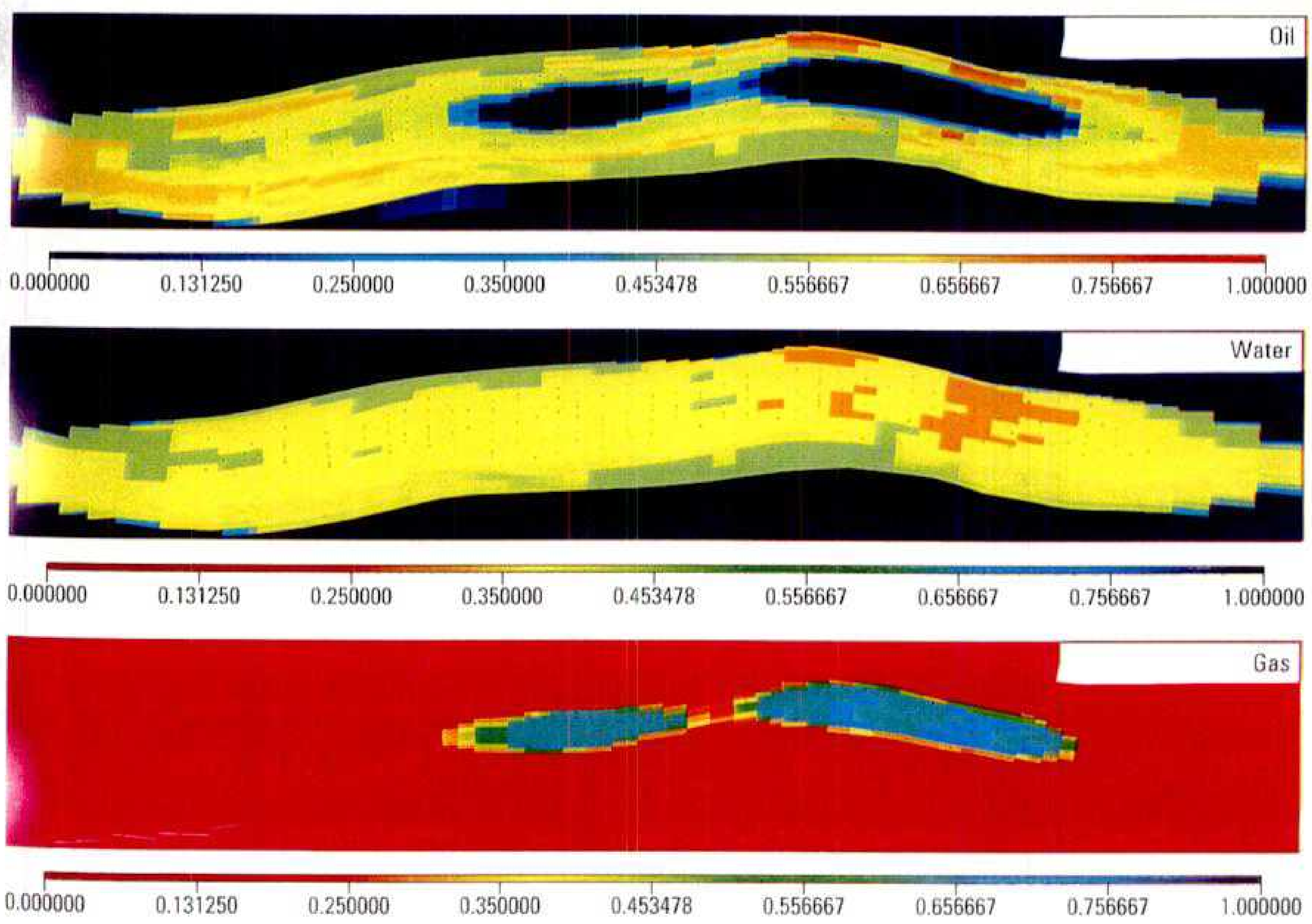
In June 1998, His Excellency Ali Majedi, Iran's Deputy Oil Minister for Caspian Sea Oil and Gas Affairs, invited several international oil companies to submit proposals for an exploration program in the Caspian Sea. From the proposals submitted and evaluated, the Khazar Exploration and Production Company (KEPCO), a Caspian affiliate of NIOC, awarded the exploration contract to the Royal Dutch/Shell Group and Lasmo in December 1998. KEPCO is the operating company and controls the exploration program on behalf of NIOC.

The initial exploration phase includes the acquisition, processing and interpretation of at least 10,000 km of 2D seismic data, the acquisition of seabed cores, and geological modeling of the southern portion of the Caspian basin. The study area, approximately 155,000 km^2, comprises deep and relatively unexplored waters. The initial seismic phase aims to identify potential plays and prospects prior to the identification and delineation of exploration blocks.

Gas—the environmental choice

In the future, Iran's gas will play a major and increasing role in meeting regional and global energy demands. Iran's largest nonassociated gas accumulation is South Pars field. First identified in 1988 and originally appraised at 3.6 Tm^3, recent studies have shown that the field contains an estimated 6.8 Tm^3 (much of which will be recoverable) and at least 3 Bbbl of condensate. Iran's other major nonassociated gas reserves include the offshore, 1.3-Tm^3 North Pars field, the onshore Nar-Kangan fields, the 0.37-Tm^3 Aghar and Dalan fields in Fars province, and the Sarkhoun and Mand fields.

As regional and global consumers use gas to meet more of their energy requirements, there will be significant changes in the way gas fields are developed. There will be a new emphasis on the effective use of gas resources. In Iran, the move towards gas power for domestic consumption in industry, domestic heating and transportation systems is well under way, underlining the country's commitment to the efficient exploitation of its natural resources and environmental responsibility.



OOIP: 1416 MMSTB
Mobile oil: 453 MMSTB—water
Mobile oil: 572 MMSTB—gas
COP: 10 MMSTB
Recovery: 0.7% wrt OOIP
Recovery: 2.2% wrt water
Recovery: 1.7% wrt gas

Figure 22: An example of the water, oil and gas saturation maps that resulted from the integrated reservoir characterization study in a dolomitic reservoir of the Ahwaz field