Oligocene–Miocene Maykop/Diatom Total Petroleum System of the South Caspian Basin Province, Azerbaijan, Iran, and Turkmenistan

By Linda S. Smith-Rouch

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Foreword

This report was prepared as part of the World Energy Project of the U.S. Geological Survey. In the project, the world was divided into eight regions and 937 geologic provinces. The provinces have been ranked according to the discovered oil and gas volumes within each (Klett and others, 1997). Then, 76 "priority" provinces (exclusive of the United States and chosen for their high ranking) and 26 "boutique" provinces (exclusive of the United States and chosen for their anticipated petroleum richness or special regional economic importance) were selected for appraisal of oil and gas resources. The petroleum geology of these priority and boutique provinces is described in this series of reports. A detailed report containing the assessment results is available separately (U.S. Geological Survey, 2000). The South Caspian Basin Province ranks 20th in the world, exclusive of the United States, for known recoverable hydrocarbons. The province is part of the Former Soviet Union Region (Klett and others, 1997).

The purpose of this effort is to aid in assessing the quantities of oil, gas, and natural gas liquids that have the potential to be added to reserves within the next 30 years. These quantities either reside in undiscovered fields whose sizes exceed the stated minimum-field-size cutoff value for the assessment unit (the cutoff value is variable, but must be at least 1 million barrels of oil equivalent) or occur as reserve growth of fields already discovered.

The total petroleum system constitutes the basic geologic unit of the oil and gas assessment. A total petroleum system includes all genetically related petroleum generated by a pod or by closely related pods of mature source rock. The system includes both shows and accumulations (discovered and undiscovered) and exists within a limited mappable geologic space. This space encompasses the essential mappable geologic elements (source, reservoir, seal, and overburden rocks) that control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum (Magoon and Dow, 1994). The minimum petroleum system is that part of a total petroleum system encompassing discovered shows and accumulations together with the geologic space in which the various essential elements have been proved by these discoveries.

An assessment unit is a mappable part of a given total petroleum system in which discovered and undiscovered fields constitute a single relatively homogeneous population. Application of the total petroleum system assessment methodology allows estimation of the number and sizes of undiscovered fields in each assessment unit. A total petroleum system might equate to a single assessment unit, or it may be subdivided into two or more assessment units such that each is sufficiently homogeneous in terms of geology, exploration considerations, and risk to assess individually. Assessment units are considered ***established*** if they contain more than 13 fields, *frontier* if they contain 1 to 13 fields, and *hypothetical* if they contain no fields.

The principal elements of a total petroleum system are graphically portrayed in an event chart that shows (1) the times of deposition of essential rock units; (2) the times that processes, such as trap formation, necessary to the accumulation of hydrocarbons took place; (3) the critical moment in the total petroleum system; and (4) the preservation time, if any.

A numeric code identifies each region, province, total petroleum system, and assessment unit; these codes are uniform throughout the project and will identify the same item in any of the publications. The codes, listed in Klett and others (1997), are as follows:

Rank	Numerical position	Example
Region	single digit	**3**
Province	three digits to the right of region code	3**162**
Total petroleum system	two digits to the right of province code	3162**05**
Assessment unit	two digits to the right of total petroleum system code	3162050**4**

Oil and gas reserves quoted in this report are derived from the Petroleum Exploration and Production database (Petroconsultants, 1996) and other area reports from Petroconsultants, Inc., unless otherwise noted.

Boundaries of total petroleum systems, assessment units, and pods of active source rocks were compiled by using geographic information system (GIS) software. Political boundaries and cartographic representations were taken, with permission, from ArcWorld 1:3 million digital coverage (Environmental Systems Research Institute, Inc., 1992); they have no political significance and are displayed for general reference only. Oil and gas field center points are reproduced, with permission, from Petroconsultants (1996).

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Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
barrel (bbl) (1 barrel = 42 gallons)	0.1590	cubic meter (m^3)
	Mass	
milligram	0.001	gram (g)
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F = (1.8 × °C) + 32.

Altitude, as used in this report, refers to distance above or below sea level.

Oligocene–Miocene Maykop/Diatom Total Petroleum System of the South Caspian Basin Province, Azerbaijan, Iran, and Turkmenistan

By Linda S. Smith-Rouch[1]

Abstract

The South Caspian Basin encompasses the southern extension of the Caspian Sea, including land areas in eastern Azerbaijan, western Turkmenistan, and northern Iran. The region is endowed with abundant petroleum resources, and oil and gas production has played an important commercial role in the region for more than 150 yr, especially in Azerbaijan and to a lesser extent in Turkmenistan. Major oil reserves are concentrated in 2,500–3,500 m of shallow-marine, deltaic to lacustrine deposits of middle Pliocene age. To date, some 620 oil and gas fields have been discovered in strata ranging in age from Miocene to Quaternary; however, less than a dozen fields produce from both Miocene and Quaternary reservoirs. The principal reserves and targets for future exploration are in the middle Pliocene Productive Series.

The South Caspian Basin is unusual in several respects:

- sediment accumulated at exceptionally high rates (as high as 4.5 km/m.y.);
- sediment accumulation in each of three depocenters was as great as 20 km (5 km of Pliocene sedimentary deposits);
- there was low sediment compaction;
- geothermal gradients are relatively low (1.5°C/100 m); and
- abnormally high pressures exist in some basin areas.

In this depositional environment, good reservoir porosities and permeabilities could be preserved to depths as great as 12 km. Analysis of source rock samples collected from outcrops, cores, and mud-volcano ejecta shows total organic carbon contents to range from 1.2 to more than 10 percent, the richest being in the middle part of the Oligocene–Miocene Maykop Series. Source rocks, with thicknesses ranging from 100 m to more than 2,500 m, form the cores of many anticlines in the basin. Reservoir rocks, consisting of fluviodeltaic clastic deposits ranging in texture from mudstone to conglomerate, are mostly in the middle Pliocene Productive Series, but some Miocene and lower Pliocene reservoirs are also present. Reservoir seals are formed by interbedded shales. Hydrocarbon traps developed mainly during the late Pliocene and early Pleistocene.

The Oligocene–Miocene Maykop/Diatom Total Petroleum System within the South Caspian Basin is separated into five hydrocarbon assessment units:

1. Apsheron-Pribalkhan Zone,
2. Lower Kura Depression and Adjacent Shelf,
3. Gograndag-Okarem Zone,
4. Central Offshore, and
5. Iran Onshore-Nearshore.

Introduction

The Caspian Sea region is well known for its abundant oil reserves. Naturally burning gas seeps led to the ancient name “Land of Fire,” which provided a center for Zoroastrian religious activity and warmth for travelers following the Silk Road. “Caspian Sea” is the English translation from the Azerbaijani “Hazar Deniz,” so named after an ancient regional tribe called the Hazarians. Today, the countries of Azerbaijan, Iran, and Turkmenistan border the South Caspian Sea.

The South Caspian Basin Province (province number 1112 of the U.S. Geological Survey’s World Energy Project) occupies the southern part of the Caspian Sea and adjacent narrow strips of land (fig. 1); approximately 45 percent lies in Azerbaijan, 35 percent in Turkmenistan, and 20 percent in Iran. The province stretches 680 km north to south and 547 km east to west; it includes about 189,000 km^2. The area covered by water (maximum depth, ≈1,000 m) is about 545 km north to south and 460 km east to west. Saline content of the water is 12–13 percent. Water level is 25 m below sea level, but has fluctuated in historic times.

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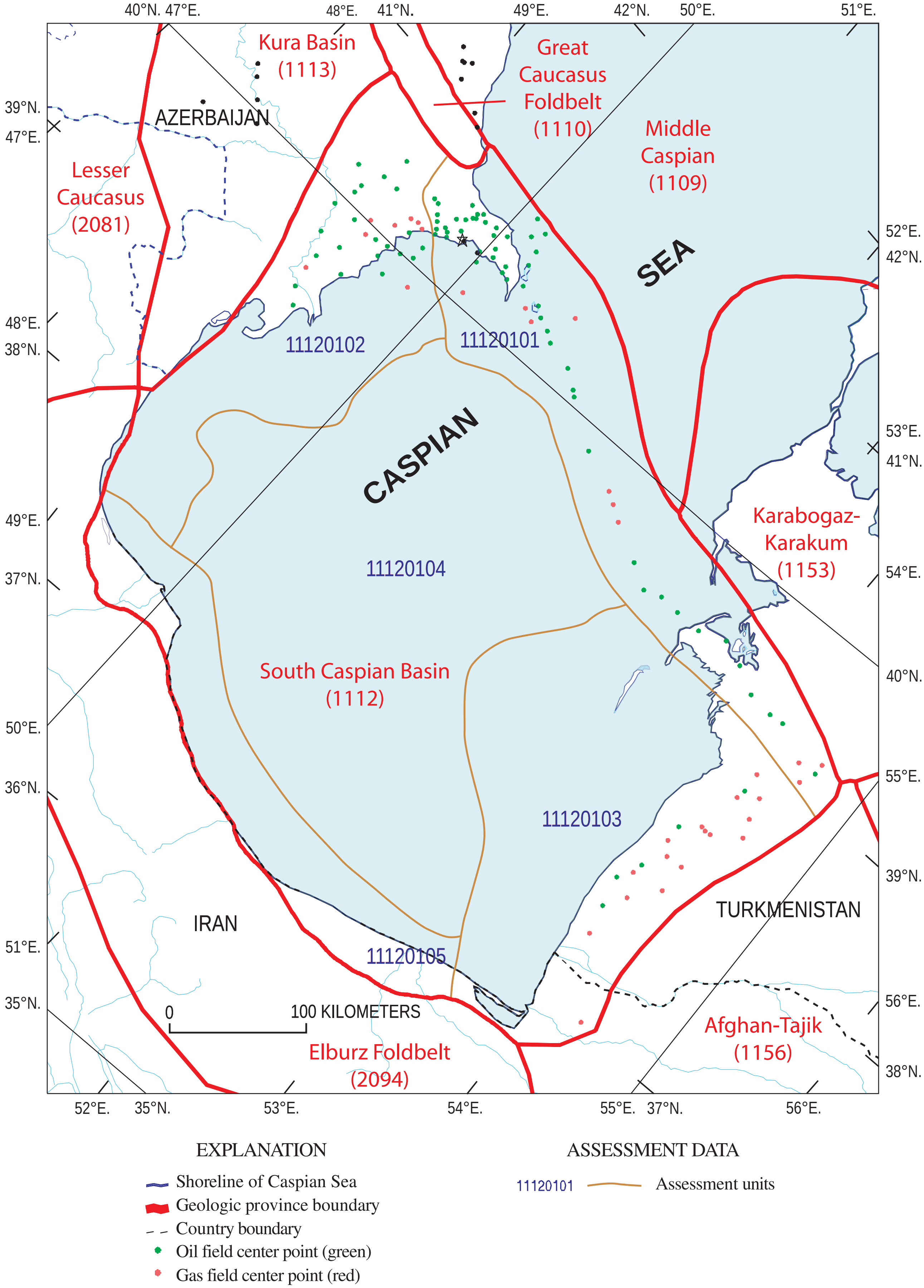

Kura Basin
(1113)
Great
Caucasus
Foldbelt
(1110)
Middle
Caspian
(1109)
AZERBAIJAN
Lesser
Caucasus
(2081)
SEA
CASPIAN
11120102
11120101
11120104
11120103
11120105
South Caspian Basin
(1112)
Karabogaz-
Karakum
(1153)
IRAN
TURKMENISTAN
Afghan-Tajik
(1156)
Elburz Foldbelt
(2094)
0
100 KILOMETERS
EXPLANATION
Shoreline of Caspian Sea
Geologic province boundary
Country boundary
Oil field center point (green)
Gas field center point (red)
ASSESSMENT DATA
11120101
Assessment units

The primary petroleum system of the South Caspian Basin is the Oligocene–Miocene Maykop/Diatom Total Petroleum System (TPS number 111201), which includes the entire basin area (fig. 1). Secondary hydrocarbon sources may be Jurassic and Cretaceous carbonates, Eocene shales, and Pliocene mudstones in western Turkmenistan. Major oil reserves are concentrated in 2,500–3,500 m of shallow-marine, deltaic to lacustrine deposits of middle Pliocene age. To date, some 620 oil and gas fields have been discovered in rocks ranging from Miocene to Quaternary in age; of these, less than a dozen accumulations are in both Quaternary and Miocene reservoirs. Middle Pliocene rocks remain the principal target for future exploration.

The South Caspian Basin depositional system is unusual in several respects. It was (or continues to be) the site of

- an exceptionally high rate of sediment accumulation (as high as 4.5 km/m.y.),
- deposition of more than 20 km of basin-fill sediment (5 km in the Pliocene),
- low sediment compaction,
- relatively low geothermal gradients (1.5°C/100 m), and
- abnormally high pressures in the central and southeastern parts of the basin (Abrams, 1996; Tagiyev and others, 1997).

As a result, reservoir-quality porosity and permeability properties have been preserved to depths as great as 12 km.

Exploration History

Oil and gas production has played an important commercial role in Azerbaijan for more than 150 yr, the first well in that country having been drilled in 1848. The first oil discovery in western Turkmenistan was on the Cheleken Peninsula (fig. 2) in 1876. To date, some 105 fields have been discovered in the South Caspian Basin, of which 65 are in Azerbaijan, 35 in western Turkmenistan, and the remainder in Iran. Active exploration of Azerbaijan offshore areas began in the early 1950s, resulting in the discovery of several large oil and gas fields. By 1993, a total of 930 wells had been drilled offshore in the South Caspian Sea. A fourth of the wells (180) are 5 km deep or more, and 30 wells are deeper than 6 km (Narimanov and Palaz, 1995).

As of 1997, the total known petroleum volumes (cumulative production plus remaining reserves) were listed as 23.9 billion barrels of oil equivalent (BBOE) (Klett and others, 1997). Exploration and production were mostly limited to areas of shallow water (tens of meters), leaving the medium-depth (100–300 m) and deep-water (more than 300 m) basin areas untested. In 1994, the Azerbaijan International Oil Company (AIOC) commenced a 30-yr program to develop three Caspian Sea fields—Azeri, Chirag, and Gyuneshli (see fig. 8)—that have estimated reserves of 3–5 billion barrels of oil. Commercial oil production in Turkmenistan began with the discovery of the giant Nebot-Dag field (located in the Cheleken Peninsula area; spot location not shown in fig. 2) in 1933, at reservoir depths ranging from 385 m to 5,200 m, but extensive exploration did not occur until after World War II. The first offshore discovery was made in 1968. Iran's part of the South Caspian Basin Province remains the most isolated and least developed, but the National Iranian Oil Company formed a consortium with Royal Dutch Shell and Lasmo UK to conduct a seismic survey and to identify offshore Caspian Basin prospects.

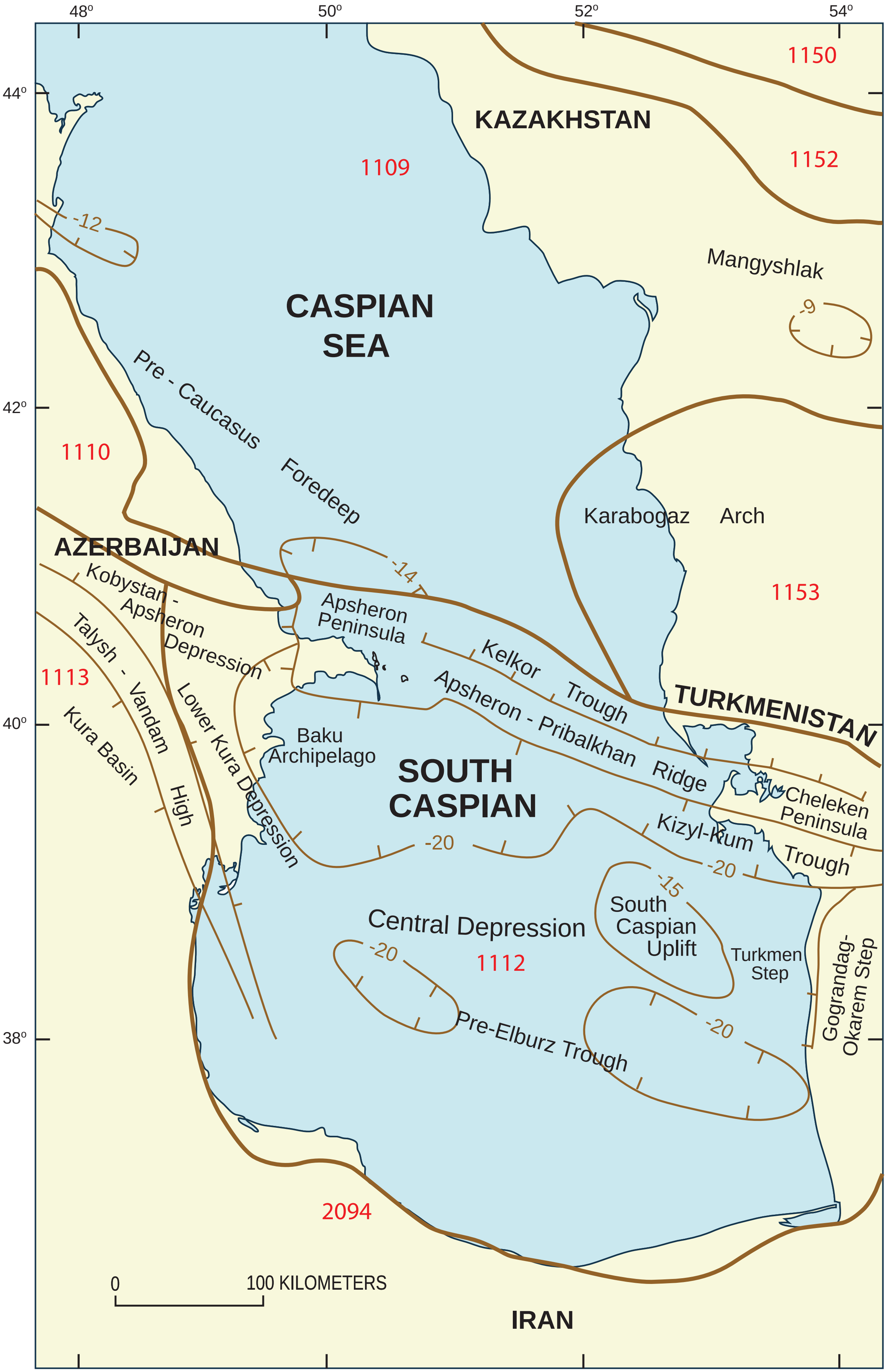
The geographically isolated nature of the South Caspian Basin has posed several development problems for the three countries in the province, especially with regard to the location and construction of pipelines to distribute petroleum products to viable markets. Of major importance is the recent completion (May 2005) of the 86.5- to 107-cm-diameter, 1,760-km-long pipeline from Baku, Azerbaijan, west to T'bilisi, Georgia, thence southwest through Turkey to the port of Ceyhan on the eastern Mediterranean Sea (Wikipedia, 2005). Operation of a smaller-capacity pipeline from Baku to the Black Sea port of Suspa, Georgia, began in 1999.

Geology of the South Caspian Basin Province

The South Caspian Basin is an intermontane depression bounded

- on the north by the Apsheron-Pribalkhan Ridge (fig. 2; also known as the Apsheron-Pribalkhan Zone or Apsheron-Pribalkhan Compression/Wrench System, fig. 3), which is the eastward extension of the Greater Caucasus Mountains to the west (figs. 3, 4);
- on the east by the Kopet Dag Range (fig. 3);
- on the south and southwest by the Elburz (sometimes referred to as Alborz) Mountains in Iran and the Talysh Range in Azerbaijan (figs. 3, 4); and
- on the west by the Lesser Caucasus Mountains (fig. 4).

Figure 1 (preceding page). Geologic provinces (identified by names and four-digit numbers in red) in the southern Caspian Sea region and assessment units (eight-digit numbers) in the South Caspian Basin Province. Political boundaries and cartographic representations were taken, with permission, from ArcWorld 1:3 million digital coverage (Environmental Systems Research Institute, Inc., 1992). Oil and gas field center points are reproduced, with permission, from Petroconsultants (1996).


48º
50º
52º
54º
44º
42º
40º
38º
1150
KAZAKHSTAN
1152
1109
-12
Mangyshlak
CASPIAN
SEA
-9
Pre - Caucasus Foredeep
1110
Karabogaz Arch
AZERBAIJAN
-14
1153
Kobystan - Apsheron Depression
Apsheron Peninsula
Kelkor Trough
Talysh - Vandam High
1113
Lower Kura Depression
Apsheron - Pribalkhan Ridge
TURKMENISTAN
Kura Basin
Baku Archipelago
SOUTH
CASPIAN
Cheleken Peninsula
Kizyl-Kum Trough
-20
-20
-15
South Caspian Uplift
Central Depression
Turkmen Step
-20
1112
Gograndag-Okarem Step
Pre-Elburz Trough
-20
2094
0
100 KILOMETERS
IRAN

The present-day basin can be subdivided into several depressions and uplifts, as shown by structure contours drawn on top of the basement rocks in figure 2. One of the depressions is the Kelkor Trough (fig. 2), which lies at the north edge of the South Caspian Basin Province, and another is the large Central Depression that covers much of the central part of the basin (fig. 2). In the eastern part, the Kizyl-Kum Trough occupies both offshore and onshore areas of western Turkmenistan. The Turkmen Step, also in western Turkmenistan (fig. 2), is a broad, shallow-water structural terrace that extends west and south into the basin. To the south, the Pre-Elburz Trough occupies offshore Iran and contains two of the three deepest depressions (outlined by the –20-km contours in fig. 2) within the South Caspian Basin. The third and areally the largest depression lies adjacent to and south of the Apsheron-Pribalkhan Ridge. Other water depths in the Central Depression are about 1,000 m.

Geologic Setting

The Caspian Sea and the Black Sea were part of a Mesozoic chain of back-arc basins stretching over a distance of 3,000 km, which also included the Carpathian Basin in central Europe and the Vallesian Trough in Switzerland (Dercourt and others, 1986). This chain was located between the continental margin of Eurasia to the north and the Mesozoic–Paleocene volcanic belts to the south. Neo-Tethys was south of the island-arc system. Zonenshain and Le Pichon (1986) suggested that the basins formed during three separate tectonic episodes—in Middle Jurassic, Late Jurassic, and Late Cretaceous times.

From Middle Jurassic to Early Cretaceous time, extension occurred north of the Pontic–Trans-Caucasus arc (general region of the Lesser Caucasus, fig. 4), resulting in rifting and the formation of the early Black Sea and South Caspian Basins. To the east, the rate of spreading was more rapid and resulted in the development of an oceanic basin, the remnants of which now form the South Caspian Sea basin. The combined Caspian Sea–Black Sea paleobasin reached its maximum extent during the Paleocene, occupying an area 900 km wide and 3,000 km long (Steininger and Rogl, 1984; Zonenshain and Le Pichon, 1986).

Renewed convergence between the Arabian and Eurasian plates in the late Eocene–Oligocene, resulting in uplift of the Caucasus region, initiated the separation of the Black Sea and Caspian Sea Basins. During the northward migration of the Iranian plate, the Elburz Mountains rose (fig. 4), separating central Iran from the Caspian paleobasin. The northward movement of the Arabian plate continued through the Oligocene into the early Miocene, developing a mosaic of deformed blocks in the region between the South Caspian Sea and the east end of the Black Sea and in the Central and Eastern Pontides and adjacent areas to the south (fig. 4). In the middle Miocene, further uplift of the Greater Caucasus caused the connection between the Black Sea and the Caspian Sea to become more restricted and ultimately resulted in the development of anaerobic conditions in each of the basins that led to the formation of the organic-rich Maykop-Diatom stratigraphic sequence (fig. 5).

Basement in the central part of the present South Caspian Basin, at depths as great as 20 km below sea level (fig. 2), is formed by oceanic crust, as indicated by a seismic velocity of 7 km/s and large magnetic anomalies (Berberian, 1983). Basement rocks along the periphery of the basin are granite and have seismic velocities of 5.6–6.2 km/s. The continental basement is interpreted to be of Proterozoic and Paleozoic age, whereas the age of the oceanic basement is most likely Middle to Late Jurassic. The region is still tectonically active, as evidenced each year by the large number of earthquakes and the eruption of mud volcanoes (Etiope and others, 2004).

Tectonic features in the South Caspian Basin area are shown in figure 4; also shown are the locations of thrust belts and strike-slip faults bordering the basin and arrows depicting the northward migration of the Arabian plate, the southeastward movement of the Iranian block, and the southwestward movement of the Turkish block. The basin has been divided into fold and shale-diapir zones by Lebedev and others (1987) and into structural zones by Devlin and others (1999). Tectonic movement along the Apsheron-Pribalkhan Ridge area has created shale diapirs and mud volcanoes in the central and western parts of the basin (Abdullayev, 1999; Devlin and others, 1999) by forcing overpressured shales into zones of weakness (faults), thereby piercing sedimentary layers as single-diapir stocks or forming shale-diapir ridges and walls. Philip and others (1989) and Devlin and others (1999) have referred to this area as the zone of buckle folds and shale diapirs (fig. 3).

Structures are oriented northwest-southeast in the western part of the South Caspian Basin and north-south to northeast-southwest in the eastern part (fig. 3). In the western part, such as in the Lower Kura Depression (fig. 2), oblique thrusting along thrust faults, high sediment loading, and extremely high pore pressures produced gravity-driven diapirism (Lebedev and others, 1987; Smale and others, 1997; Abdullayev, 1999). The Turkmen block in the eastern part (fig. 3) is defined as a zone of slumps and growth faulting; Abdullayev (1999) suggested that these slumps originated in the late Pliocene shelf margin that overlies basement structures. The north-south alignment of the eastern onshore structures is deflected to northeast-southwest as they approach the Ashgabat Convergent Wrench System (fig. 3).

Figure 2 (preceding page). Map showing geographic and geologic features in and around the South Caspian Basin. Contours (in kilometers relative to sea level) are drawn on top of the basement rocks. Geologic-province boundaries drawn with heavy lines; provinces identified by red number, as follows: 1109, Middle Caspian; 1110, Greater Caucasus Foldbelt; 1112, South Caspian Basin; 1113, Kura Basin; 1150, North Ustyurt Basin; 1152, Mangyshlak-Ustyurt Foldbelt; 1153, Karabogaz-Karakum Foldbelt; 2094, Elburz Foldbelt.

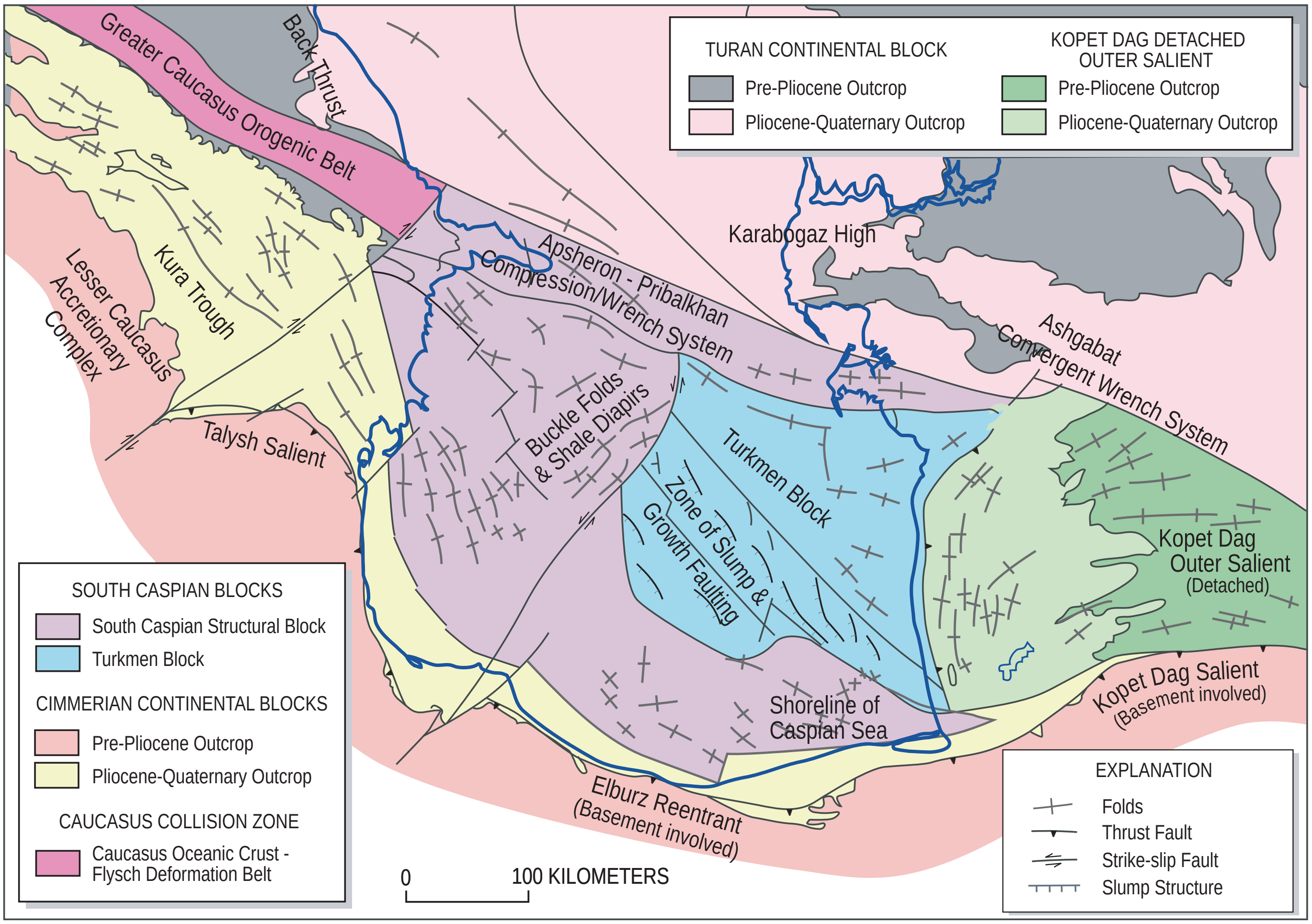


Figure 3. Major structural features in the South Caspian Basin region. Note that alternate terms are used for some of these features in the text and in other figures, depending on the context in which they are discussed. (Map is modified from Devlin and others, 1999, and is printed with permission from Exxon/Mobil.)

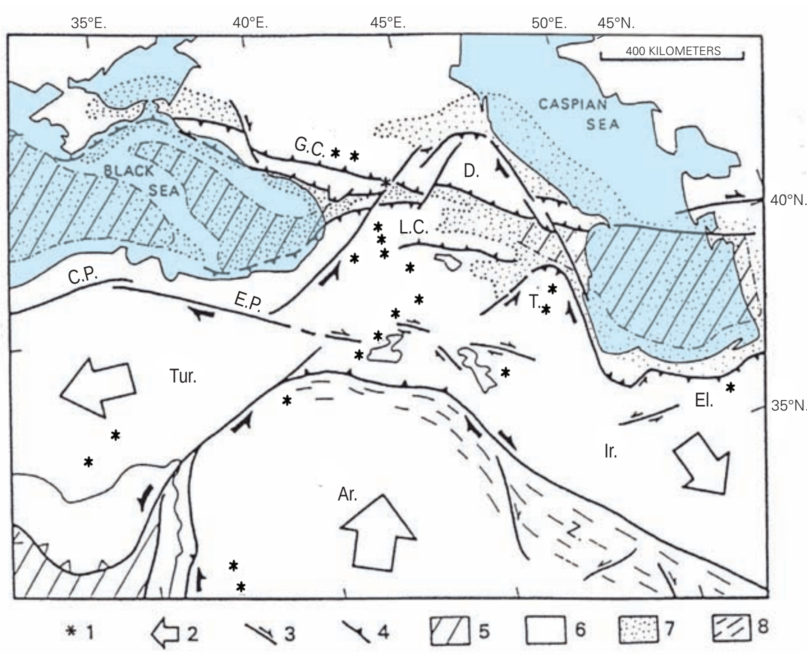


Figure 4. Principal tectonic features in the Caspian Sea–Black Sea regions. Numbered symbols: 1, volcanoes; 2, relative motion of crustal blocks; 3, major strike-slip faults (arrows show relative movement); 4, major thrust faults (saw teeth on overriding block); 5, oceanic or intermediate crust; 6, continental crust; 7, main sedimentary basins; 8, zone of folding. Abbreviations: Ar., Arabian plate; C.P., Central Pontides; D., Dagestau; E.P., Eastern Pontides; El., Elburz Mountains; G.C., Greater Caucasus; Ir., Iranian block; L.C., Lesser Caucasus; T., Talysh high; Tur., Turkish block; Z., Zagros belt. (Based on Berberian, 1983.)

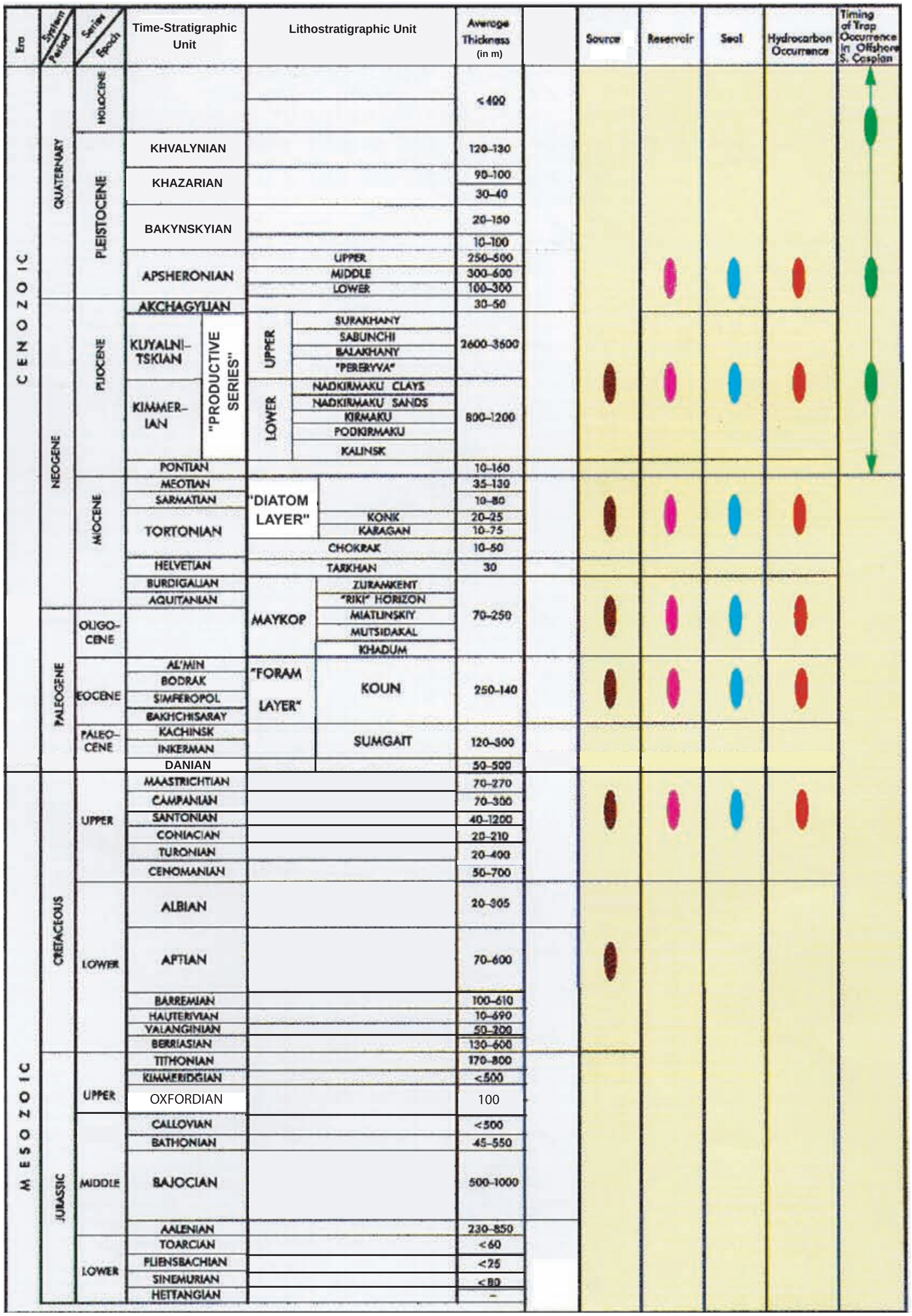


Figure 5. Sequence of stratigraphic units in the South Caspian Basin region. Columns on the right show average thicknesses, which units include source and reservoir rocks and stratigraphic seals, which units are petroleum bearing, and the timing of trap formation. (Modified from Frydl and others, 1995.)

Stratigraphy and Paleogeography

Sedimentary strata in the South Caspian Basin attain thicknesses of as much as 20 km in each of three main depocenters—Azerbaijan offshore, western Turkmenistan onshore and offshore, and Iran offshore (fig. 2). The rocks range in age from Early Permian or Early Jurassic to Quaternary (fig. 5). The stratigraphic sequence is not continuous across the basin, and in some areas there are five major unconformities:

1. between Lower Permian strata and the basement,
2. between Middle and Lower Triassic strata,
3. at the base of lower Miocene strata,
4. at the base of lower Pliocene strata, and
5. at the base of middle Pliocene strata (between Nadkirmaku and "Pereryva" rocks, fig. 5).

In the region of the South Caspian Basin, stratigraphic sequences are divided into "suites" rather than formations, the term "suite" referring to related lithologic units that are smaller than formational rank (Caster, 1934; Gary and others, 1972). It should be noted, however, that the Russian use of "suite" is equivalent to "formation" in that both are mappable stratigraphic units (G. Ulmishek, oral commun., 2000).

Lower Permian

In the Apsheron and Kura areas of Azerbaijan (fig. 2), unnamed Lower Permian strata unconformably overlie pre-Permian basement rock (Eyer and others, 1995). The Permian rocks are dominantly limestones, marls, and carbonaceous siltstones, indicating deposition in a probable marine environment prior to development of the South Caspian Basin.

Jurassic

Jurassic shales are exposed in the Caucasus Range northwest of the South Caspian Basin (fig. 3); in the Lower Kura Depression, drilling penetrated 3 km of Jurassic volcanic rocks lying below 3.5 km of Cenozoic and Cretaceous strata (Shakhilibelili, 1981; Zonenshain and Le Pichon, 1986). Nine wells located along the northern rim of the Baku Archipelago (fig. 2) also penetrated Jurassic rocks, which consist of mottled siliciclastic rocks and flysch ranging from 500 to 1,500 m in thickness in that area (Frydl and others, 1995). Berberian (1983) described a Mesozoic failed-rift system in the border area between Azerbaijan and Iran. Three sequential paleogeographic maps of the South Caspian Basin region are shown in figure 6 for Jurassic time. They depict the evolution from an Early Jurassic "protobasin" with large areas of exposed land to a mostly marine carbonate basin by the Late Jurrassic.

Lower Jurassic rocks, more than 2,000 m thick, are widely distributed throughout the Greater Caucasus orogenic belt (fig. 3). The lithology is dominantly volcaniclastic rocks with minor claystones, argillaceous shales, limestones, and calcareous sandstones. During the Early Jurassic, a shallow sea covered the Caspian region from the Greater Caucasus to the Elburz region (fig. 6*A*). Small land areas were exposed in the southern part of the basin along the present-day Elburz and Kopet Dag Ranges (Lebedev and others, 1987), and small river deltas formed on the shallow narrow shelf (Frydl and others, 1995). To the north and northeast, a large area of land was exposed that may have provided sediment into the basin.

Middle Jurassic deposits (1,500–3,400 m thick), which are present in several oil- and gas-bearing districts, generally consist of porphyry, tuff breccia, various thin interbeds and lenses of argillaceous shale, and poorly sorted, coarse-grained sandstones. The South Caspian Basin deepened during the Middle Jurassic (Callovian), and the shelf edge retreated westward. On the north slope of the Greater Caucasus, these rocks include calcarenite and reef limestone (300 m thick); the south slope consists of flysch-like variegated, silicified, and carbonaceous shales (500 m thick). The southeastern part of the basin was subjected to a transgressive phase that flooded the previous shallow shelf in the Kopet Dag and Elburz Range areas, and a small area of land was exposed along the east margin (fig. 6*B*).

In Late Jurassic time, a shallow carbonate platform formed at the east margin of the South Caspian Basin, in the area now occupied by the Kopet Dag Range and adjacent areas to the north, and extended to the west side of the basin (fig. 6*C*). The Elburz Range area was the site of cyclic deposition of pelagic carbonate and chert (Frydl and others, 1995). Upper Jurassic carbonate breccia located near deposits of ejecta from mud volcanoes indicates a carbonate environment with little terrigenous input from the Elburz Range. The Greater Caucasus area continued to receive flysch and marl deposits, and Frydl and others (1995) discussed the presence of uppermost Jurassic evaporites along the north margin of the South Caspian Basin.

Cretaceous

The presence of Lower Cretaceous rocks in some onshore deep wells in Azerbaijan and western Turkmenistan is interpreted to indicate that the Early Cretaceous was a time of relative tectonic stability. In the Greater Caucasus (fig. 3), the strata are 500–2,000 m thick and consist of calcareous flysch. In the Lesser Caucasus and possibly the Lower Kura Depression (fig. 3), the Lower Cretaceous is represented largely by tuffaceous, clastic, and calcareous rocks (Berberian, 1983), but in other areas east and west of the present Caspian Sea, the strata are mostly shale (as much as 990 m thick) with interbeds of marl and sandstone (fig. 7*A*).

By early Late Cretaceous time (Cenomanian), the South Caspian Basin was part of a back-arc basin with a chain of island arcs, now represented by the Pontides-Caucasus complex, that extended from Talysh Range on the east to the Black Sea on the west (fig. 4). Terrigenous and chalky deposits covered extensive areas across the region. In latest Cretaceous

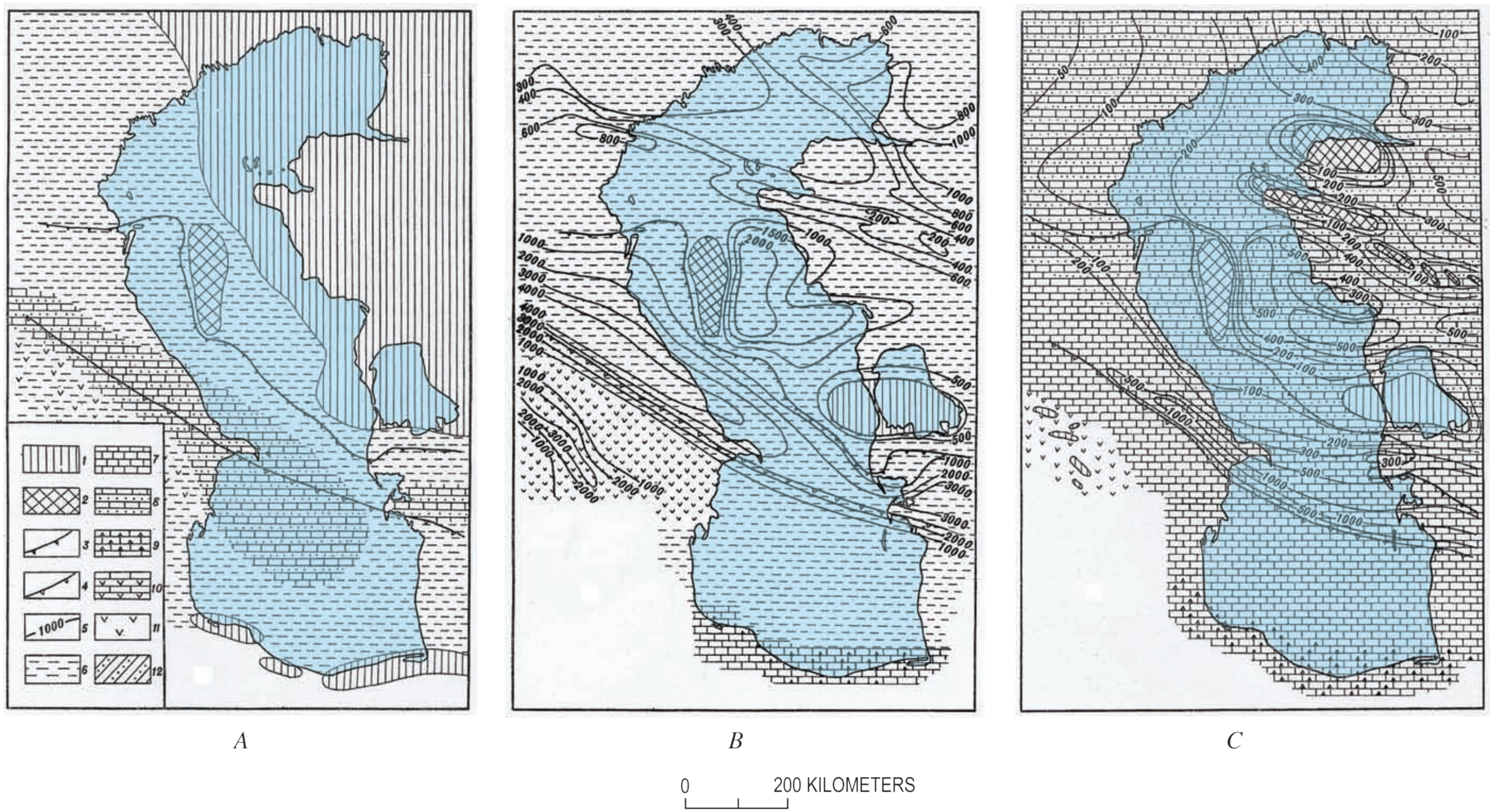


Figure 6. Maps showing depositional patterns in the Caspian Sea region during (*A*) Early, (*B*) Middle, and (*C*) Late Jurassic time. Numbered symbols: 1, emergent land areas; 2, zone of underwater washout or limited sediment accumulation; 3, shelf edge; 4, foot of shelf slope; 5, thickness in meters; 6, marine clastic deposits; 7, carbonate deposits; 8, interbedded marine clastic and carbonate deposits; 9, siliceous carbonate deposits; 10, interbedded marine volcanic and carbonate deposits; 11, volcaniclastic deposits; 12, flysch deposits. (After Lebedev and others, 1987.)

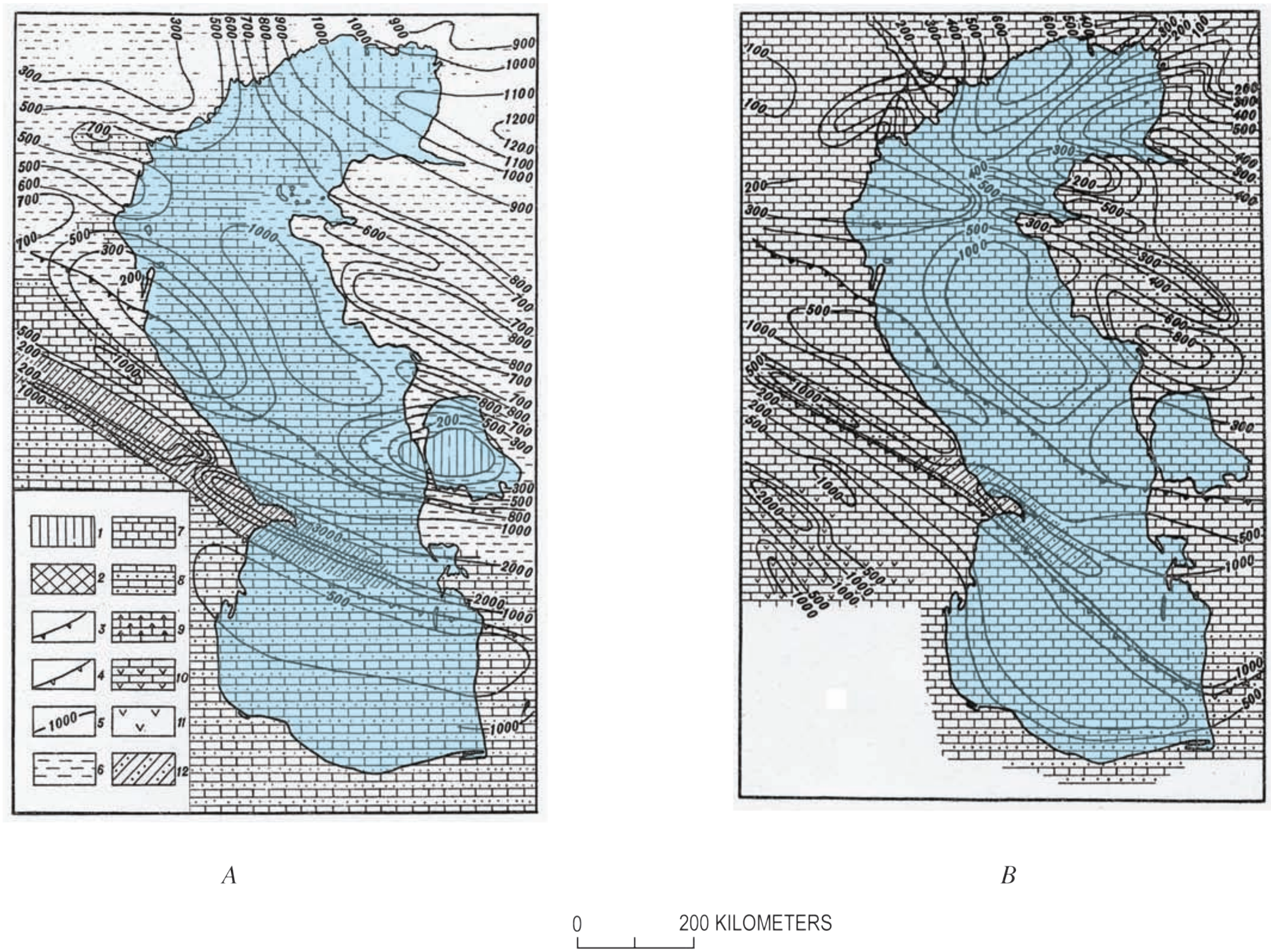


Figure 7. Maps showing depositional patterns in the Caspian Sea region during (A) Early and (B) Late Cretaceous time. Explanation of numbered symbols given in figure 6. (After Lebedev and others, 1987.)

time (Maastrichtian), the Caspian and Black Seas were connected, as indicated by pervasive limestone deposition and the lack of exposed land (fig. 7*B*). Upper Cretaceous pelagic limestones, pillow basalts, and ophiolites in southern Azerbaijan and northwestern Iran provide evidence of Mesozoic tectonic activity in that part of the South Caspian Basin. The volcanic rocks diminish toward the central and eastern Elburz region in Iran (fig. 3; Berberian, 1983). Drilling penetrated Upper Cretaceous clastic and carbonate rocks in the Lower Kura Depression of Azerbaijan; in offshore areas to the east, thicknesses of the Upper Cretaceous units range from 300 m to more than 730 m.

Tertiary

The sedimentary sequences in the South Caspian Basin are among the thickest Tertiary sections in the world, more than 20 km in some areas. In general, the Paleocene and Eocene strata (Sumgait and Koun Suites, fig. 5) are dominantly claystones interbedded with marl and limestone. The Oligocene–Miocene Maykop and Diatom Suites stratigraphic interval (fig. 5) consists of claystone, sandstone, organic-rich shale, and tuffaceous sandstone (Eyer and others, 1995); this sequence includes the thick marine shale source rock of the Maykop Suite. The Pliocene Productive Series contains thick fluviodeltaic rocks that form some of the main hydrocarbon reservoirs in the South Caspian Basin Province.

Paleocene–Eocene

Paleocene strata range in thickness from about 1,700 m to as much as 2,800 m in the northwestern part of the South Caspian Basin. Within the Lower Kura Depression to the south (fig. 2), combined Paleocene and Eocene rocks are more than 3,000 m thick. Paleocene deposits are also present in the Lam Bank and Gubkin Bank fields toward the east end of the Apsheron-Pribalkhan Zone (fig. 8) (also termed “ridge” in fig. 2 and “compression/wrench system” in fig. 4).

Increased tectonic activity during the Eocene was manifested by separation of the Caspian Sea from the Black Sea to the west. Several thick prograding fluviodeltaic sedimentary sequences developed on the perimeter of the South Caspian Basin. Uplift in the Elburz Range and Kopet Dag areas (figs. 3, 9) at this time provided the source of sediment being transported into the basin from the south and southeast. Sources of sediment in the northwestern part were in the Caucasus region (fig. 9). The Eocene Koun Suite (fig. 5) is divided into three sequences:

1. The lower Eocene, 850–1,200 m thick in the Lower Kura Depression, consists of shale with interbedded sandstone, marl, limestone, and volcanic tuff.

2. Middle Eocene strata, from 100 to more than 400 m thick, are tuffaceous and terrigenous rocks with interbedded shale and marl.

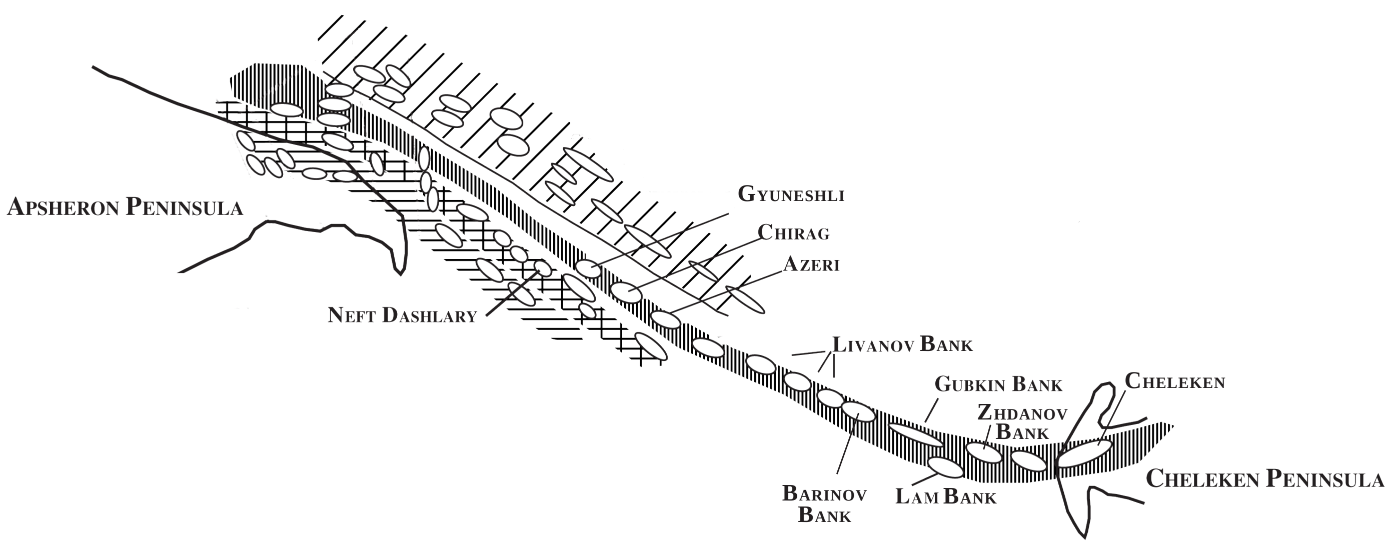


Figure 8. Schematic map of Apsheron-Pribalkhan Zone (labeled “ridge” in fig. 2) stretching across the northern part of the South Caspian Basin between the Apsheron Peninsula on the west and the Cheleken Peninsula on the east (fig. 2) for a distance of approximately 275 km (scale not shown). Zone is eastward extension of the Greater Caucasus orogenic belt (fig. 3). Structures are shown diagrammatically as domal and elongate anticlines; names refer to oil and gas fields shown in figure 12 or otherwise mentioned in text. Patterns indicate different structural alignments.

3. The upper Eocene sequence, 450–550 m thick, is argillaceous.

In the southern Elburz Mountains, Eocene–Oligocene basalt lavas were reported by Annells and others (1975).

Oligocene–Miocene

Oligocene sediment was deposited in a body of marine waters that stretched from western Turkmenistan westward to the Black Sea. In early Miocene time, the organic-rich sediment now forming the Maykop Suite, which constitutes the principal hydrocarbon source rock in the South Caspian Basin region, also accumulated in this marine environment. Thickness of the Oligocene and Miocene rocks in the center of the basin is as great as 3,000 m (fig. 10; Eyer and others, 1995). The Maykop Suite was reported by Alizade and others (1966) to be 3,500 m thick in the Lesser Caucasus Mountains (figs. 3, 4). Uplift of the major tectonic compression zones resulted in formation of the Greater Caucasus (fig. 4) and Kopet Dag (fig. 3) mountain ranges. As the highlands rose, the connection with open-marine waters became restricted, producing anoxic conditions in the Caspian Sea.

The middle Miocene Tarkhan, Chokrak, Karagan, and Konk Suites overlie the Maykop Suite (fig. 5). These strata, which have been penetrated by a number of wells, consist of shale and marl with interbeds of sandstone and siltstone. A marine connection from the Mediterranean Sea to the Caspian Sea deposited the Diatom Suite, which consists of shales, marls, sandstones, and limestones with interbeds of volcanic ash and coquina. This time period marks the last connection between the two seas. Sussli (1976) and Berberian (1983) noted that middle and upper Miocene marine sedimentary deposits are 520 m thick in the northern limb of the Elburz Mountains. Sussli (1976) observed that upper Miocene to lower Pliocene marine sedimentary rocks are also exposed in the folded north flank of the Elburz Mountains (currently at an elevation of 2,000 m).

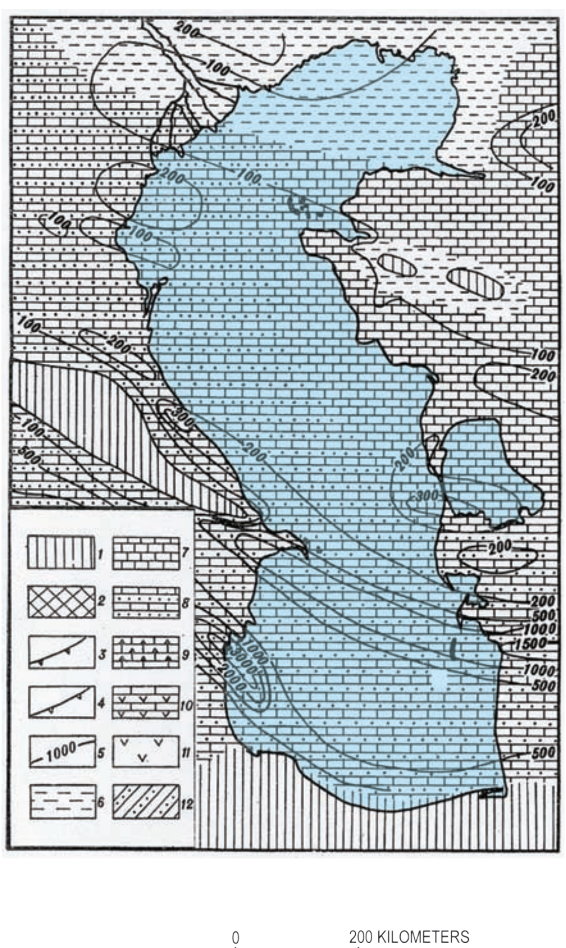


Figure 9. Map showing depositional patterns in the South Caspian Basin region during Paleocene and Eocene time. Explanation of numbered symbols given in figure 6. (After Lebedev and others, 1987.)

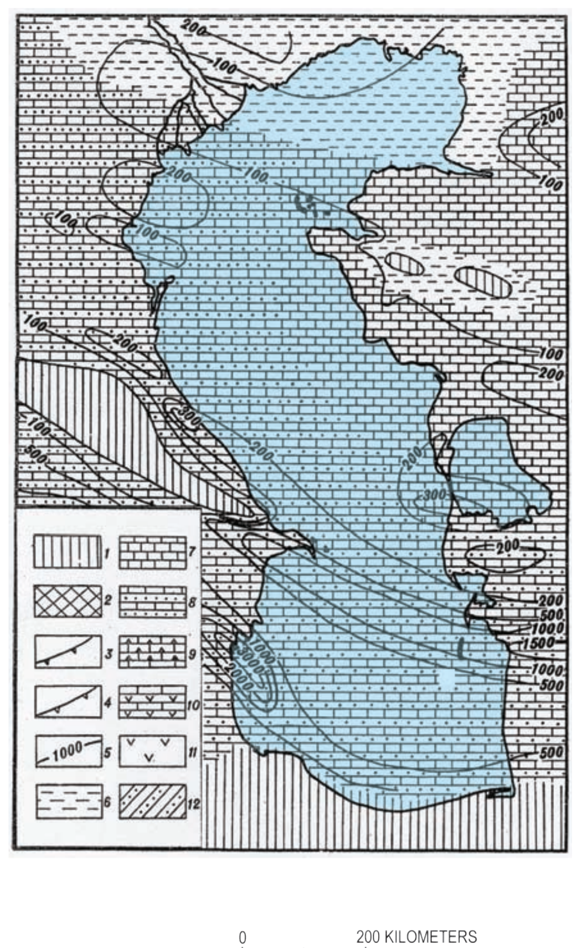


Figure 10. Map showing depositional patterns in the South Caspian Basin region during Oligocene and Miocene time. Explanation of numbered symbols given in figure 6. (After Lebedev and others, 1987.)

Pliocene

The Caspian Sea was completely isolated from marine waters, including the Black Sea, by early Pliocene time (late Pontian, fig. 5). The total area of the sea was reduced to half its present size, allowing the Volga paleodelta (fig. 11) to prograde south to the Apsheron Peninsula (fig. 2; Mamedov, 1994), at which time the Pliocene Productive Series (fig. 5) was deposited. This series also incorporates large volumes of sedimentary deposits contributed by other river systems, including the Kura paleodelta in Azerbaijan, the Amu Darya paleodelta in Turkmenistan, and the Sefidrud and other small paleodeltas in Iran (fig. 11). However, there is some debate as to whether sediment from sources to the east and southeast was transported as far as the central, deep part of the South Caspian Basin, because structures such as mud volcanoes, anticlinal folds, and uplifted fault blocks may have formed intervening barriers. Petrographic analyses of some of the sedimentary strata reveal distinct properties that are characteristic of each of the source areas (Frydl and others, 1995); for example, sediment deposited in the Volga paleodelta was derived from the Russian platform (which lies north of the Turan continental block, fig. 3), whereas the sources of sediment in the Kura paleodelta were feldspathic and volcaniclastic rocks from the Caucasus Ranges.

The Pliocene consists of the lower Pliocene Pontian, the middle Pliocene Productive Series (referred to as the Red Bed Series in western Turkmenistan), and the upper Pliocene Akchagylian (fig. 5). Correlation of suites and relative thicknesses of various units from Azerbaijan to western Turkmenistan along the Apsheron-Pribalkhan Zone (fig. 8) are shown in figure 12.

Lower Pliocene deposits, mainly argillaceous, are as much as 300 m thick in the Lower Kura Depression, but thin and become coarser grained eastward toward the Baku Archipelago and Apsheron Peninsula (fig. 2). Near the Apsheron-Pribalkhan Zone, sandstone content and stratigraphic thicknesses increase in the lower Pliocene section. Upper Miocene strata are absent on several structures, indicating uplift and erosion of parts of the zone before Pliocene time (Frydl and others, 1995).

The Productive Series and the correlative Red Bed Series (fig. 12) contain the main reservoir rocks in the South Caspian Basin Province. These two series are characterized by highly cyclic fluviodeltaic sequences of interbedded sandstone, siltstone, and shale, as well as beds containing reworked Paleogene and Neogene fossils such as foraminifera and ostracodes.

The Productive Series is divided into lower and upper units (fig. 5); the boundary between the two is defined by an unconformity at the base of the "Pereryva" Suite. Thicknesses range from 800 to 1,200 m in the lower part and from 260 to 3,600 m in the upper part. The lower unit, which may in part be as old as late Miocene, comprises the Kalinsk, Podkirmaku, Kirmaku, and Nadkirmaku Suites (fig. 5), which are mostly sandstone and mudstone. The Kalinsk and Kirmaku were deposited in lagoon or nearshore (marginal-marine and brackish) environments in a relatively shallow basin. On the basis of stratigraphic modeling, Smith-Rouch and others (1996) predicted the presence of a sandy unit (now known as the Kalinsk Suite) that onlaps the basin margin in Azerbaijan. The Podkirmaku and Nadkirmaku Suites, as well as some of the rocks in the upper part of the Productive Series (for example, the "Pereryva" and Balakhany Suites), were deposited in predominantly deltaic environments. Results of the stratigraphic modeling of these units by Smith-Rouch and others (1996) indicated that gravity-flow deposits may have accumulated farther offshore, thus offering the possibility that good-quality reservoirs exist in middle Pliocene strata in the deep basin. This interpretation is illustrated in figure 13, which portrays two versions of a stratigraphic model constructed along a line extending from the west edge of the Volga paleodelta (north of the Apsheron Peninsula) southward for a distance of about 100 km (location shown in fig. 11). Nine different time "slices" from the late Miocene to the late Pliocene have been incorporated in the computer generation of the sedimentary patterns shown on the two profiles. The simulations, supported in part by data from wells located both north and south of the Apsheron Peninsula (see fig. 1) and from seismic surveys, incorporate the sea-level curve and sediment-flux rates of Mamedov (1989) as major variables. Other primary considerations were (1) paleogeographic maps emphasizing changes in shelf-margin positions through time, (2) subsidence rates, and (3) climate factors. The only difference between the two profiles is the initial sand to shale ratios introduced into the model: in the figure 13*A* model, sand content is 15 percent, whereas in the figure 13*B* model, sand content is 5 percent. In both cases, turbidites are formed, and several extend across much of the deeper part of the basin, although those in figure 13*A* are slightly thicker. The stronger shale component in figure 13*B* produces tighter reservoir seals in the deeper parts of the basin. Stratigraphic modeling also shows two sediment sources for middle Pliocene strata in the Apsheron-Pribalkhan Zone, one from the direction of the Volga paleodelta and the other from the Turkmenistan paleodeltas (fig. 11).

In places in western Turkmenistan, the Red Bed Series unconformably overlies an eroded Cretaceous–Paleogene surface. Upper Pliocene strata are represented by the Akchagylian Stage (fig. 5). Zubakov and Borzenkova (1990) and Smale and others (1997) identified several transgressive events within the sequence along the margin of the South Caspian Basin. The rocks—predominantly shale interbedded with sandstone, conglomerate, and volcanic ash—range in thickness from 70 to 690 m in the Lower Kura Depression and from 20 to 100 m in the Apsheron Peninsula area (fig. 2). Eyer and others (1995) reported that the maximum thickness of Akchagylian strata may exceed 4.5 km in the central part of the South Caspian Basin. In contrast, Abdullayev (1999) showed the sequence to be thin to absent across the crest of several anticlines in the region.

Berberian (1983) reported the presence of a 1,600- to 2,000-m-thick sequence of continental sedimentary strata of Pliocene to Quaternary age that were penetrated in deep wells

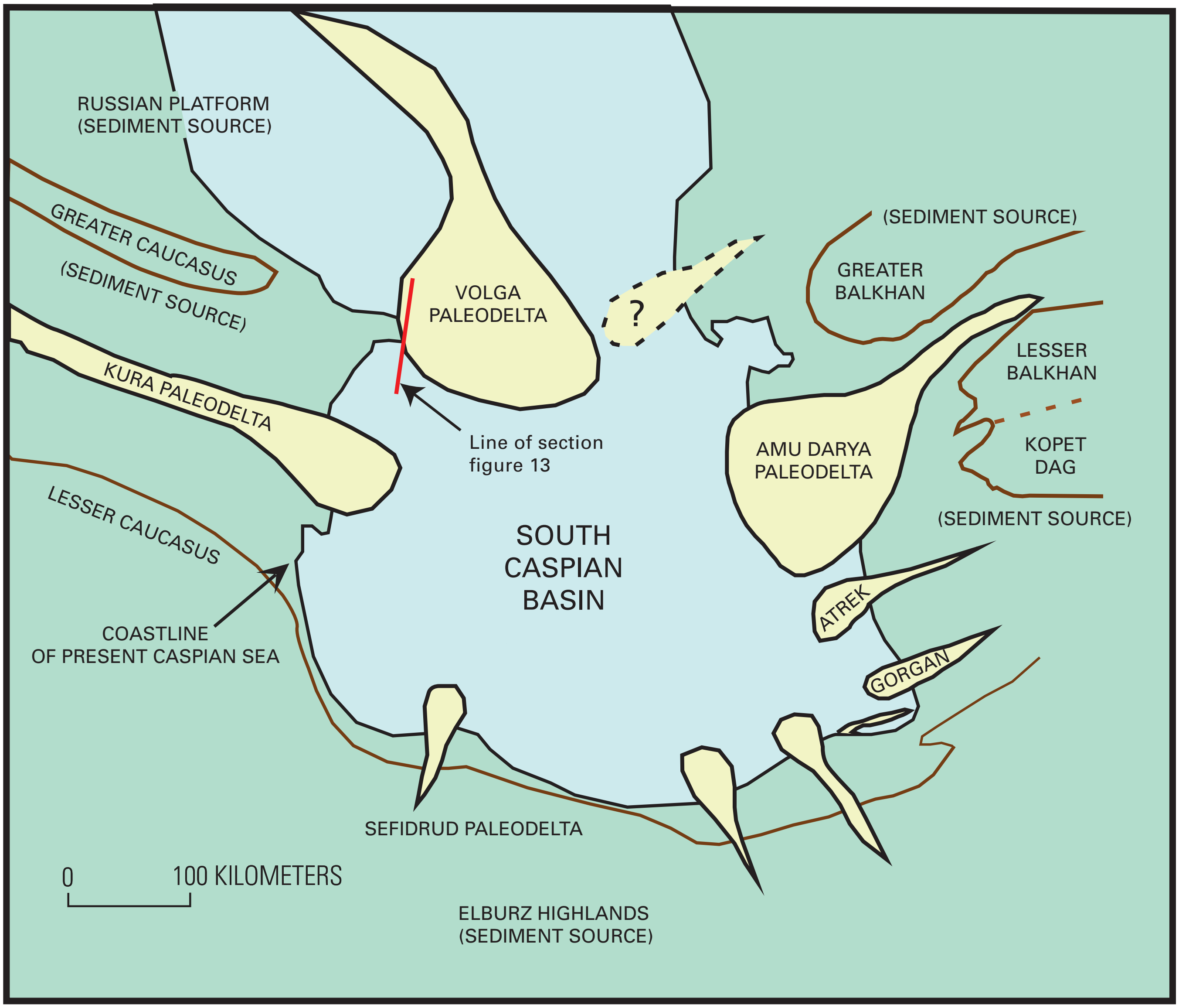


Figure 11. Schematic map of possible sources of sediment deposited in paleodeltas prograding into the South Caspian Basin during middle Pliocene time. (Modified from Narimanov, 1993, and Eyer and others, 1995.) Location of line of section for figure 13 is shown.

in the coastal plain of northern Iran (fig. 2). The source of the sediment, which includes fragments of Eocene basaltic lavas and Oligocene marine shales, was in the Elburz Mountains to the south.

Quaternary

Quaternary sedimentary deposits are distributed widely in the South Caspian Basin. An erosional unconformity marks the contact between the upper Pliocene and the Pleistocene (lower Apsheronian, fig. 5) in the Apsheron-Pribalkhan Zone. Dominant lithofacies are sandstone, limestone, siltstone, and shale deposited in deltaic environments; turbidites and gravity-flow sequences are also present. Stratigraphic thicknesses across the basin range from 200 to 3,000 m; maximum thicknesses of 1,800 m, 1,800–2,000 m, and 2,000 m are in the Lower Kura Depression, the Baku Archipelago, and the Kizyl-Kum Trough in western Turkmenistan, respectively (fig. 2).

The Apsheronian was originally placed in the late Pliocene; however, the base was subsequently correlated with the erosional unconformity in the Apsheron-Pribalkhan Zone, and the age is now considered early Pleistocene (fig. 5). The lithofacies are interbedded arenaceous shale, gypsum, sandstone, limestone, and volcanic ash. Thicknesses are 100 m in the Apsheron area, 350 m in the Lower Kura Depression, 800 m in the Baku Archipelago, and 2,000 m in western Turkmenistan. The Apsheronian Stage strata are divided into lower, middle, and upper units; the middle and upper units typically

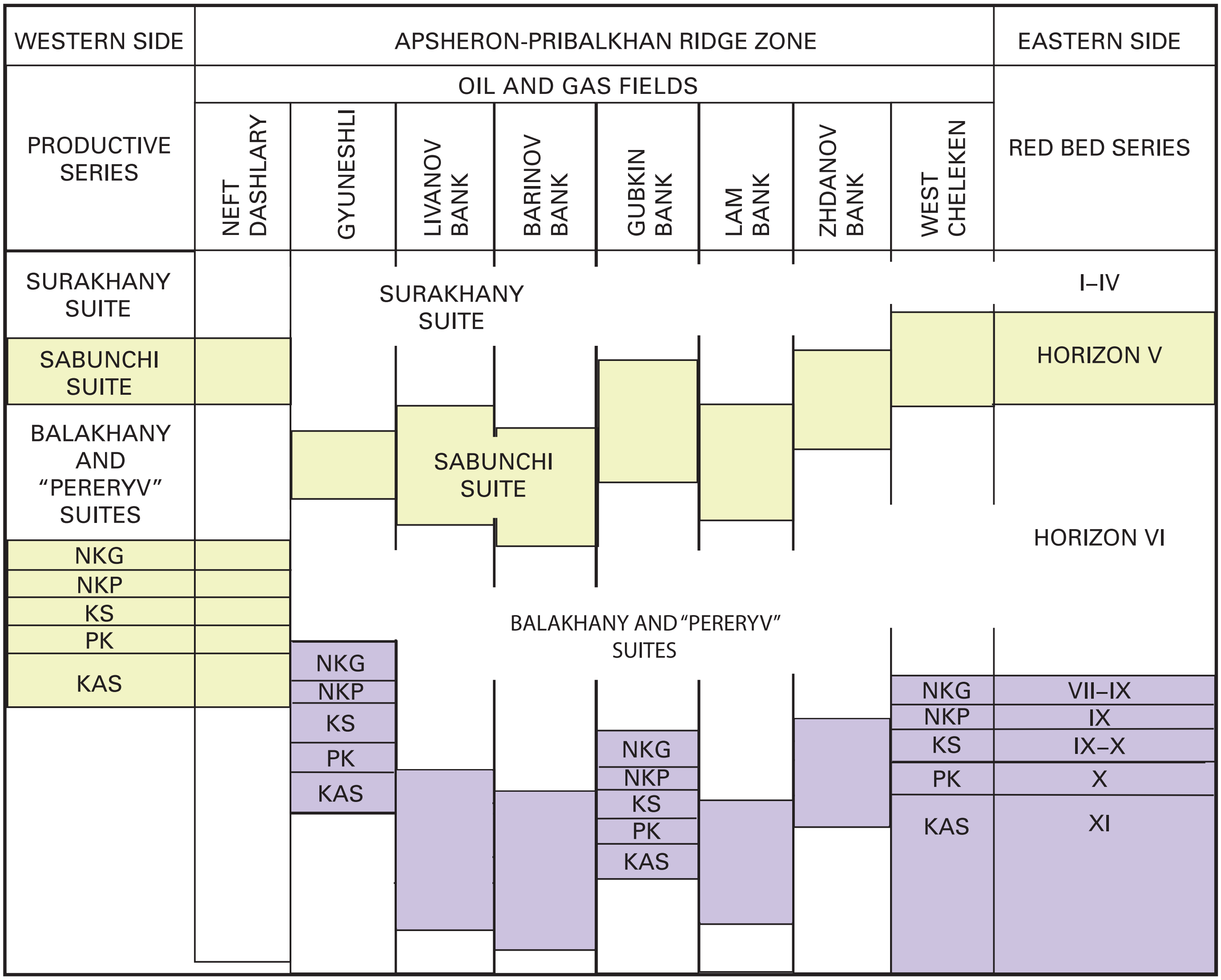


Figure 12. Diagram showing stratigraphic relations (correlations and relative thicknesses) between units in the Pliocene Productive Series and the Red Bed Series within the Apsheron-Pribalkhan Zone, extending west to east across the northern part of the South Caspian Basin. Vertical positions of units reflect relative subsidence or uplift with respect to adjacent structures. Locations of oil and gas fields shown in figure 8; West Cheleken field is at west end of Cheleken field. NKG, Nadkirmaku Suite clays; NKP, Nadkirmaku Suite sands; KS, Kirmaku Suite; PK, Podkirmaku Suite; KaS, Kalinsk Suite. (Modified from Guseinov and Abbasov, 1992.)

contain limestone and sandstone that form numerous islands and ridges. Younger Pleistocene units include the Bakynskyian, Khazarian, and Khvalynian Stages (fig. 5).

By Quaternary time, the Volga paleodelta had retreated northward owing to tectonic influences and the subsequent increase in fresh water from glacial/interglacial climate cycles. This retreat reduced the volume of sediment being transported into the South Caspian Basin from the north. At the same time, however, the Amu Darya paleodelta system was delivering large volumes of sediment into the eastern part of the basin, a relationship that was considered by Abdullayev (1999) to serve as an analogue for the middle Pliocene Productive Series on the basis of several similarities, including (1) seismic reflection geometries, (2) stratal thickness, (3) large delta progradation, and (4) density and gravity flows.

Abdullayev (1999) presented a three-stage model for the deposition of Pleistocene sediment in the shelf-margin and offshore areas of Turkmenistan. In the first stage, the shelf break was distal to the present-day shoreline, diapirs were passively emplaced, and strong amalgamated delta lobes were deposited. Stage two involved tectonic movement along a zone of flexures and folds across which westward-draining channel systems were developed. This scenario was followed, in the third stage, by rapid westward progradation of the Amu Darya paleodelta.

Cores of Holocene sediments reveal oolitic sands and shell fragments from the shelf area and organic oozes farther

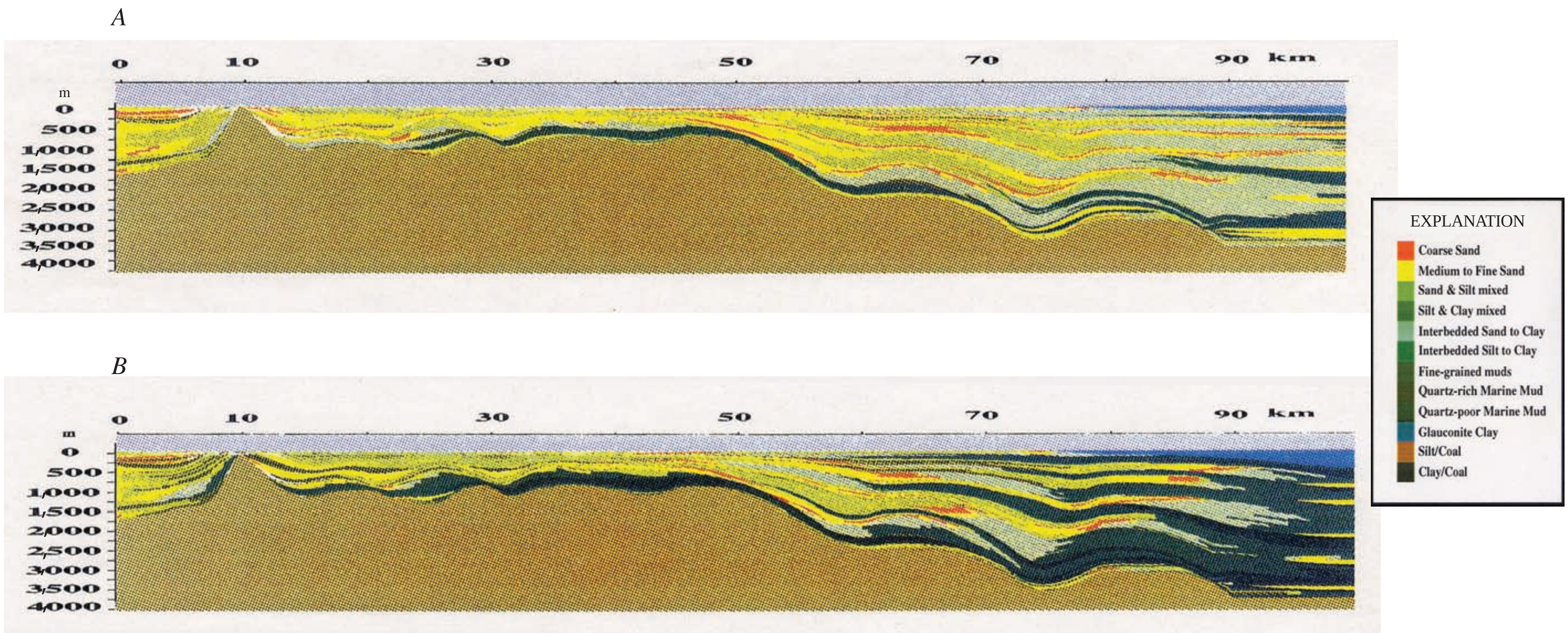


Figure 13. Profiles showing results of stratigraphic modeling of depositional patterns during late Miocene to late Pliocene time along a 100-km-long, north-south line in the northwestern part of the South Caspian Basin. (Location of profiles shown in fig. 11.) (*A*) Sand/shale ratio is 15 percent. (*B*) Sand/shale ratio is 5 percent.

offshore (Lebedev and others, 1987). The Holocene decrease in clastic deposits basinward is thought to reflect the deflection of the major Amu Darya paleodelta (fig. 11) eastward from the Caspian Sea to the Aral Sea in late Pleistocene time (Yunov and Martirosyan, 1991).

Oligocene–Miocene Maykop/Diatom Total Petroleum System

The Oligocene–Miocene Maykop/Diatom Total Petroleum System (TPS), as designated by the U.S. Geological Survey (Klett and others, 1997), includes the entire South Caspian Basin as well as some adjacent areas, covering a total of some 189,000 km^2 (fig. 1). Known oil and gas fields are in the onshore Azerbaijan, offshore Baku Archipelago, onshore and offshore Apsheron-Pribalkhan Zone, and onshore and offshore western Turkmenistan areas. The primary source rocks are the marine Oligocene to lower Miocene Maykop Suite and the upper Miocene Diatom Suite (fig. 14). Dominant oil and gas reservoirs are in the fluviodeltaic Productive Series and the correlative Red Bed Series (fig. 12).

Klett and others (1997), in their ranking of the world's petroleum provinces (exclusive of the United States), ranked the South Caspian Basin Province as the 20th largest, with known volumes (cumulative production plus remaining reserves) of 23.9 billion barrels of oil equivalent. Assessment of undiscovered resources by the U.S. Geological Survey World Assessment Team (2000) resulted in mean estimates of 15,725 million barrels of oil (MMBO), 173,310 billion cubic feet of gas (BCFG), and 8,115 million barrels of natural gas liquids.

Source Rock

The marine source rocks of the Maykop and Diatom Suites vary in total organic content (TOC), but are richest (TOC > 10 percent) in the middle Maykop. Most oils are sourced from this organic facies, which is slightly calcareous, and an algal marine clastic facies. Palynological analyses by Saint-Germes and others (1997) show that Maykop shales contain mainly amorphous organic matter, composed of both marine (dinocyst, algal, and foram linings) and terrestrial particles (pollen, spores, and small wood fragments). The source rock contains type II–type III kerogen (Schoellkopf and others, 1997). Oils are highly paraffinic and low in trace metals and sulfur contents (Frydl and others, 1996). The density ranges from viscous tars to clear condensates; the tars have been altered by biodegradation and phase migration. Oils from the Apsheron Peninsula (fig. 2) contain high amounts of saturated hydrocarbons and low amounts of aromatic hydrocarbons. The pristane/phytane ratios are between 1.3 and 1.6, and the vitrinite-reflectance equivalents range from 0.8 to 1.0 (Abrams and Narimanov, 1997). Hydrogen indices range from 150 to 500 mg of hydrocarbons per gram of organic

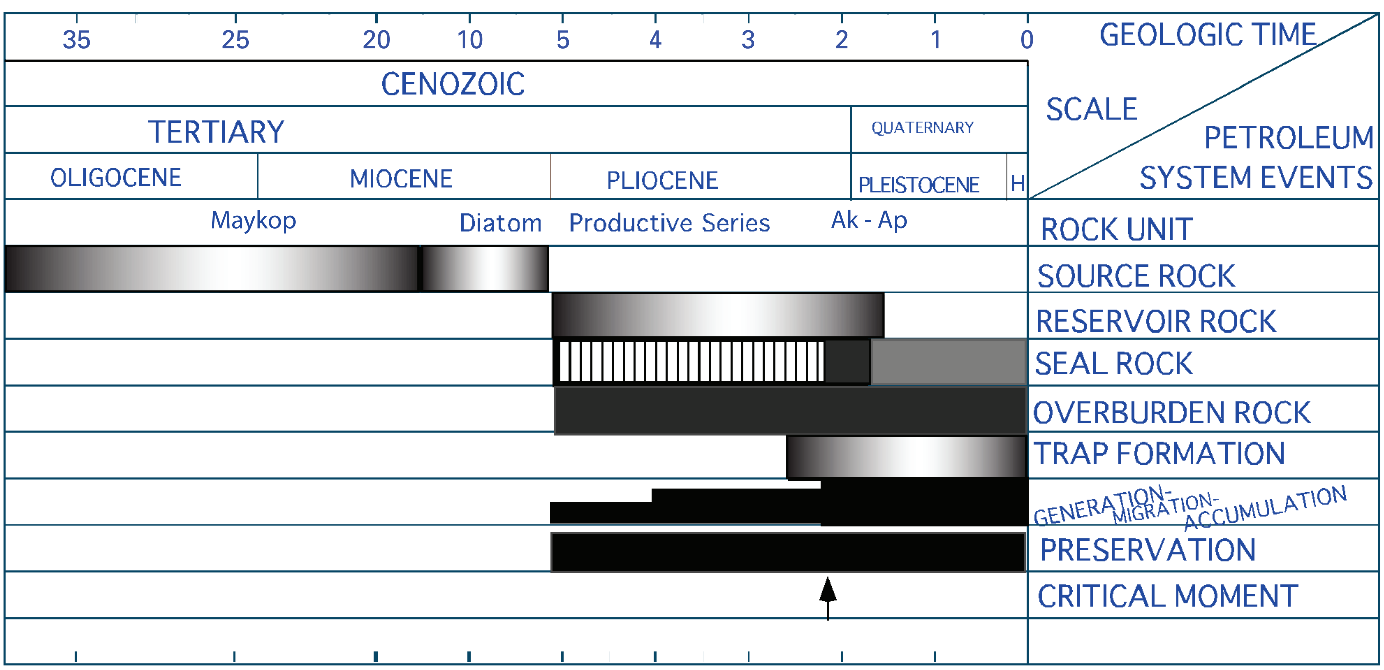


Figure 14. Geologic events chart for the Oligocene–Miocene Maykop/Diatom Total Petroleum System in the South Caspian Basin Province, showing temporal relations among the various elements involved in the generation, migration, and accumulation of hydrocarbons. Abbreviation: Ak-Ap, Akchagylian (uppermost Pliocene) and Apsheronian (lower Pleistocene) strata.

carbon (Gulliev and Feizullayev, 1996); median values are interpreted to be the result of reduction of hydrocarbons by sulfate-metabolizing bacteria during early diagenesis (Saint-Germes and others, 1997).

Analysis of source rock samples collected from outcrop, core, and mud-volcano ejecta reveal TOCs of 1.2 to more than 10 percent. Thicknesses range from 100 m to more than 2,800 m within the South Caspian Basin (Narimanov and Palaz, 1995; Alizade and others, 1966), and the general interpretation is that the Maykop and Diatom Suites thicken toward the central and eastern parts of the basin. However, Alizade and others (1966) noted that a maximum thickness of 3,500 m is located outside the basin, near the Lesser Caucasus Mountains. These Oligocene–Miocene source shales occupy cores of anticlines within the basin.

Isotopic and molecular characterizations of gas samples in the western sector of the South Caspian Basin by Narimanov and Abrams (1997) indicate the bulk of gas within offshore accumulations to be thermogenic; it is possible that some admixing of low-temperature biogenic gas has occurred. Narimanov and Abrams (1997) also stated that the gases were not derived from the same organic facies as the oils, whereas Frydl and others (1996), by using a dynamic three-dimensional Mobil thermal model, suggested that the oil and gas were sourced from the same marine depositional environment and facies.

Less important source rocks, not included in the Oligocene–Miocene Maykop/Diatom TPS, are in Upper Cretaceous deep-water marine rocks with less than 1 percent TOC and Eocene algal marine rocks with 1–2 percent TOC. Middle Miocene marine, nonmarine deltaic, turbidite, and flysch or molasse rocks are more gas prone; their TOCs range from less than 1 to 2 percent. Another potential source rock is in Pliocene–Pleistocene strata in western Turkmenistan.

Petroleum Generation and Migration

The earliest hydrocarbon generation within the marine source rocks of the Oligocene–Miocene Maykop and Diatom Suites, in the area of the Baku Archipelago (fig. 2), was probably during early Pliocene time (fig. 14) and was related to tectonism in the Caucasus Mountains and contemporaneous subsidence of the adjacent Lower Kura Depression (fig. 2). High sedimentation and burial rates in the basin during the middle Pliocene also promoted hydrocarbon generation. In offshore western Turkmenistan, south of the Apsheron-Pribalkhan Ridge (fig. 2), thick sedimentary cover and low temperature gradients indicate that potential Pliocene source rocks may have been in the oil-generating window since the late Apsheronian interval of the early Pleistocene (fig. 5).

Most investigators of the South Caspian Basin (for example, Narimanov, 1993; Lawrence and Babaev, 2000; Frydl and others, 1996) agree that major hydrocarbon migration began in Pliocene time (most likely in the middle Pliocene) and continues to the present. Satellite imagery reveals numerous oil seeps in the southern part of the Caspian Sea associated with deep-water structures, indicating that oil is still actively migrating and that Pliocene–Pleistocene reservoirs are potentially being charged with hydrocarbons in the basin interior (Frydl and others, 1995).

Hydrocarbon Traps

There is uncertainty among investigators as to the dominant trap style within the South Caspian Basin Province. The Petroconsultants database lists stratigraphic traps as constituting about two thirds of the total and structural traps forming one third. In the Azerbaijan and Turkmenistan parts of the basin, however, most workers have identified structural traps as being dominant but have indicated that stratigraphic traps are also important. Narimanov and Abrams (1997) and Sawlan and others (1997) proposed a multistage model of hydrocarbon emplacement in structural and stratigraphic traps for the Azerbaijan sector of the South Caspian Basin. In this model, some traps may have formed in the early middle Pliocene, but the bulk of tectonic movement and trap formation occurred since the early Pleistocene. In the Apsheron-Pribalkhan Zone, undercompacted and overpressured Maykop shales were subjected to plastic flow in the cores of high-amplitude, tightly folded and faulted anticlines. In the Lower Kura Depression and adjacent shelf areas, Neogene and Quaternary strata were also highly compressed in steep to overturned and faulted anticlines (Aliev and Alizade, 1989). The amplitudes of these folds decrease with depth, and folding of the underlying Paleogene and Mesozoic strata was more subdued. In western Turkmenistan, deformation was limited to broad anticlinal folding. In the deeper-water areas (depths of more than 200 m), 53 or more untested anticlines may prove to be structural traps with large reservoir capacity (O'Connor and others, 1993). Stratigraphic traps on the flanks of shale diapirs may also prove to be important exploration targets in future years.

Reservoir Rock

Pliocene–Pleistocene reservoir rocks in various parts of the South Caspian Basin received distinctly different types of sediment. The best reservoir properties are exhibited by the quartz-rich rocks deposited in the Volga paleodelta (fig. 11) that were derived from the Russian platform, which lies north of the Turan continental block shown in figure 3. Kura paleodelta reservoirs consist of a mixture of volcanic rocks, feldspathic sandstones, and claystones eroded from sedimentary rocks in the Caucasus Mountains.

Reservoir rocks in the middle Pliocene Productive Series (fig. 5) are highly cyclic fluviodeltaic clastic rocks ranging from mudstones to conglomerates. Reynolds and others (1998) identified four reservoir types in the Apsheron Peninsula and Baku Archipelago areas on the basis of facies associations, stratigraphic architecture, cementation, and faulting patterns. The four different facies were deposited in fluvial, delta-plain, proximal delta-front, and distal delta-plain environments. The best reservoirs developed in the fluvial facies; rocks in this facies contain no major porosity or permeability barriers. The delta-plain facies formed laterally extensive seals, creating stacked reservoirs that may have been compartmentalized by enclosing mudstones and faults. In the proximal delta-front facies, stacked, relatively homogeneous reservoirs were developed that became sealed vertically by delta-front siltstones; these reservoirs are likely to be compartmentalized by faults (Reynolds and others, 1998). The distal delta-front facies is characterized by tabular sandstone beds separated by siltstones and mudstones that greatly restrict vertical permeability; horizontal permeability, in turn, is strongly controlled by vertical faults.

The Productive Series is divided into upper and lower parts by the conglomeratic "Pereryva" Suite (as much as 10 m thick in some oil and gas fields). Primary reservoirs are in the Balakhany Suite (fig. 5), which consists of more than 300 m of interbedded siltstone and sandstone. In western Turkmenistan, reservoirs are mainly in the upper part of the middle Pliocene Red Bed Series (fig. 12), and potential reservoirs may be in the lower part of that unit and in underlying Miocene strata. The reservoir sequences are thicker than 4 km in the offshore areas, having been deposited by the Amu Darya paleodelta system (fig. 11). Reservoirs consist of fluviodeltaic, slope, and turbidite facies; seismic surveys indicate that potential turbidite reservoirs may exist offshore (Mamedov, 1989, 1994). Good-quality Miocene reservoirs have been drilled in the Kizyl-Kum Trough (fig. 2; O'Connor and others, 1993). Onshore to the south, Miocene reservoirs occupy fold crests, but are thinner and of poorer quality; those on the flanks of folds may have better potential.

As discussed in an earlier section, computer-simulated models by Smith-Rouch and others (1996) show that gravity-flow deposits possibly developed in the Miocene–Pliocene stratigraphic sequences (for example, as part of the Productive Series) in some of the deep areas of the South Caspian Basin; such a sedimentary pattern is shown by two versions of a simulated depositional model (fig. 13) in the area of the Volga paleodelta (fig. 11). Stratigraphic modeling shows a similar facies to possibly exist along the Aspheron-Pribalkhan Zone (fig. 8), as well as in areas near the south basin margin (Smith-Rouch and others, 1996). Other potential reservoirs are in compartmentalized fields with stacked reservoir-quality rocks, stratigraphic traps, flanks of large structures, and turbidite deposits. Turbidites, in particular, may hold substantial oil and gas accumulations.

Seal Rock

Intraformational shales form seals within the middle Pliocene stacked reservoirs. Transgressive shale sequences within the Productive Series and Akchagylian and Apsheronian strata (fig. 5) provide effective seals for the middle Pliocene reservoirs, although the South Caspian Basin is somewhat "leaky" because of the discontinuity of some thin seals. Active tectonic compression continues, even in modern times, to influence hydrocarbon migration and reduce seal integrity. Seal thickness and age may vary from place to place within the basin, owing to differences in the sediment sources that were involved in reservoir and seal development. In Azerbaijan, seals for potential Miocene reservoirs are formed by upper Maykop, Karagan, and upper Diatom Suite strata. Stratigraphic models show the Kalinsky Suite to be effectively sealed by the Podkirmaku and Nadkirmaku Suites (fig. 5).

Assessment Units

Five assessment units (AUs) have been designated for the purpose of assessing the hydrocarbon-resource potential in the Oligocene–Miocene Maykop/Diatom TPS (fig. 1; U.S. Geological Survey, 2000):

1. Apsheron-Pribalkhan Zone AU (11120101),
2. Lower Kura Depression and Adjacent Shelf AU (11120102),
3. Gograndag-Okarem Zone AU (11120103),
4. Central Offshore AU (11120104), and
5. Iran Onshore-Nearshore AU (11120105).

The units are separated by different structural styles, as discussed in the following sections.

Apsheron-Pribalkhan Zone Assessment Unit 11120101

The land and offshore areas of AU 11120101 are split between Azerbaijan and Turkmenistan (Azerbaijan onshore, 2726 km^2; Turkmenistan onshore, 5316 km^2; Turkmenistan offshore 20,378 km^2; fig. 1). The Apsheron-Pribalkhan Zone, which is the eastern extension of the Greater Caucasus orogenic belt (fig. 1), is divided into four subparallel lines of domal and elliptical folds (fig. 8). Some of the folds are transected by faults, and a large uplifted block is located near the Gubkin Bank field (fig. 8).

According to Guseinov and Abbasov (1992), middle Pliocene strata in the eastern part of the Apsheron-Pribalkhan Zone are more uniform in thickness and lithology than in the western part. Several of the sequences in the central part are deeply eroded, reflecting differential tectonic movement along the zone. In the western part, tectonic uplift in latest Pliocene time is evidenced by the absence of rocks of that age in several of the oil and gas fields. The unconformity is also present in that part of the zone extending west from the West Cheleken field to the Gubkin Bank field (fig. 12). The thickest Pliocene sections are in the vicinity of the Gubkin Bank field (fig. 8), which may reflect the area of greatest subsidence during the Pliocene. Altogether, the Apsheron-Pribalkhan Zone contains one of the thickest accumulations of sedimentary strata (20 km) in the South Caspian Basin Province, having received large volumes of sediment from the Volga and Amu Darya paleodeltas and the Caucasus Mountain alluvial fan (fig. 11).

Structural and stratigraphic traps within the Apsheron-Pribalkhan Zone AU are listed in the Petroconsultants database (1996). Oil fields in the unit range in size from approximately 2 to 300 million barrels of oil (MMBO). Reservoir porosities range from 13 to 35 percent, and permeabilities range from 7 to 1,600 millidarcies (mD).

Lower Kura Depression and Adjacent Shelf Assessment Unit 11120102

All of the onshore and offshore areas of AU 11120102 lie in Azerbaijan (onshore area, 10,537 km^2; offshore area, 16,463 km^2) (fig. 1). The Lower Kura Depression near the Greater Caucasus Mountains is characterized by a complex system of folds shown in figure 15. Shale diapirism led to the folding in the Neogene to Quaternary deposits; the folds commonly have steep flanks and are commonly overturned and faulted (Aliev and Alizade, 1989), but the folds' amplitudes diminish at depth into the flat-lying Mesozoic–Paleogene strata (fig. 15). Traps developed mainly during late Pliocene time.

Reservoirs, consisting mostly of volcaniclastic rocks and feldspathic sandstones, are primarily in the middle Pliocene Productive Series, but some Miocene and lower Pliocene reservoirs are also present. Middle Pliocene strata, however, have been completely eroded in some parts of the AU. Reservoir porosities range from 14 to 33 percent, and permeabilities are from 10 to 1,400 mD. Seals are interbedded throughout the middle Pliocene sequence, isolating individual sandstone reservoirs. Reservoirs are also further compartmentalized in onshore fields that are highly faulted.

Traps are about 95 percent structural (anticlines, some of which are recumbent) and 5 percent stratigraphic. On average, reserves in developed fields exceed 1 MMBO; of the 16 known oil field sizes listed in the Petroconsultants database (1996), 6 contain reserves estimated to range from 100 to 700 MMBO. The largest field discovered to date has estimated reserves of 670 MMBO and 2,140 BCFG.

Gograndag-Okarem Zone Assessment Unit 11120103

The onshore area of AU 11120103 lies almost entirely in Turkmenistan, but a small part is in Iran (fig. 1). Typical fields are developed in anticlines cored by shale diapirs and mud volcanoes, and structures have been oriented by deep transcurrent faults active since the Mesozoic. The relatively cool nature of the temperature gradient in the southeastern part of the South Caspian Basin resulted in the oil-generating window for source rocks in the Maykop and Diatom Suites being at greater depths there than in other parts of the basin (Tagiyev and others, 1997; Lawrence and Babaev, 2000). Reservoirs and seals within the AU are primarily in the upper part of the middle Miocene Red Bed Series. The reservoir sequence, more than 4 km thick in the offshore areas, consists of fluviodeltaic, slope, and turbidite facies alternating with shales and siltstones; the more sand-rich units are in the Kizyl-Kum Trough (fig. 2). Seals may be less effective in the southern part of the AU, inasmuch as gas leaks are interpreted from seismic data.

The most important hydrocarbon-producing zones are in the area of the Gograndag-Okarem step (fig. 2; O'Connor and others (1993). Lawrence and Babaev (2000) divided western Turkmenistan into five structural zones (figs. 16, 17, 18). In the shale-swell zone, shale movement was triggered by compression above a basal detachment within a ductile shale sequence rather than by sediment loading (Devlin and others, 1999; Lawrence and Babaev, 2000). In the central zone, structural growth occurred from the Akchagylian to the present.

The middle Pliocene rocks consist of braided-fluvial, deltaic, slope, and turbidite depositional facies, and siltstones and shales are the dominant lithologies. Reservoir porosities range from 17 to 23 percent, and permeabilities are 10 to 710 mD. Traps are both structural and stratigraphic. Average reserves in 39 of the oil fields exceed 1 MMBO; reserves in five fields range from 10 to 500 MMBO; gas field sizes are between 10 and 900 BCFG (Petroconsultants, 1996). The lower part of the Red Bed Series is considered to have the best potential for future exploration (O'Connor and others, 1993).

Central Offshore Assessment Unit 11120104

Assessment Unit 11120104 is a hypothetical unit with no known fields, but it lies within the known area of source rock deposition in the South Caspian Basin Province. The unit area is entirely offshore, covering some 66,300 km^2 (fig. 1), and has water depths ranging from 300 to 1,000 m. Paleogeographic maps of Oligocene through Miocene time show that source rocks were deposited throughout the basin and that accumulations thicken into the basin interior (Devlin and others, 1999). There is evidence that oil is currently seeping from deep-water structures, indicating that hydrocarbon generation and migration are occurring (Frydl and others, 1996). This AU contains potential deep-water turbidites from the Volga and Kura paleodeltas to the north and west and from the Amu Darya paleodelta to the east (fig. 11).

The Central Offshore AU can be divided into two sections separated by a left-lateral strike-slip fault that extends from the Apsheron-Pribalkhan structural trend on the north to the Elburz Mountains on the south (fig. 3). The western section is characterized by buckle folds, shale diapirs, and mud volcanoes, whereas the eastern section is a zone of slumps, growth faulting, and mud volcanoes (fig. 3). Paleogeographic maps and seismic profiles show gravity-flow deposits in Pliocene–Pleistocene strata in the eastern section (Mamedov, 1989; Abdullayev, 1999).

It should be noted that turbidites, wherever deposited in the South Caspian Basin, may also contain fine-grained lithologies, which would tend to lower reservoir quality.

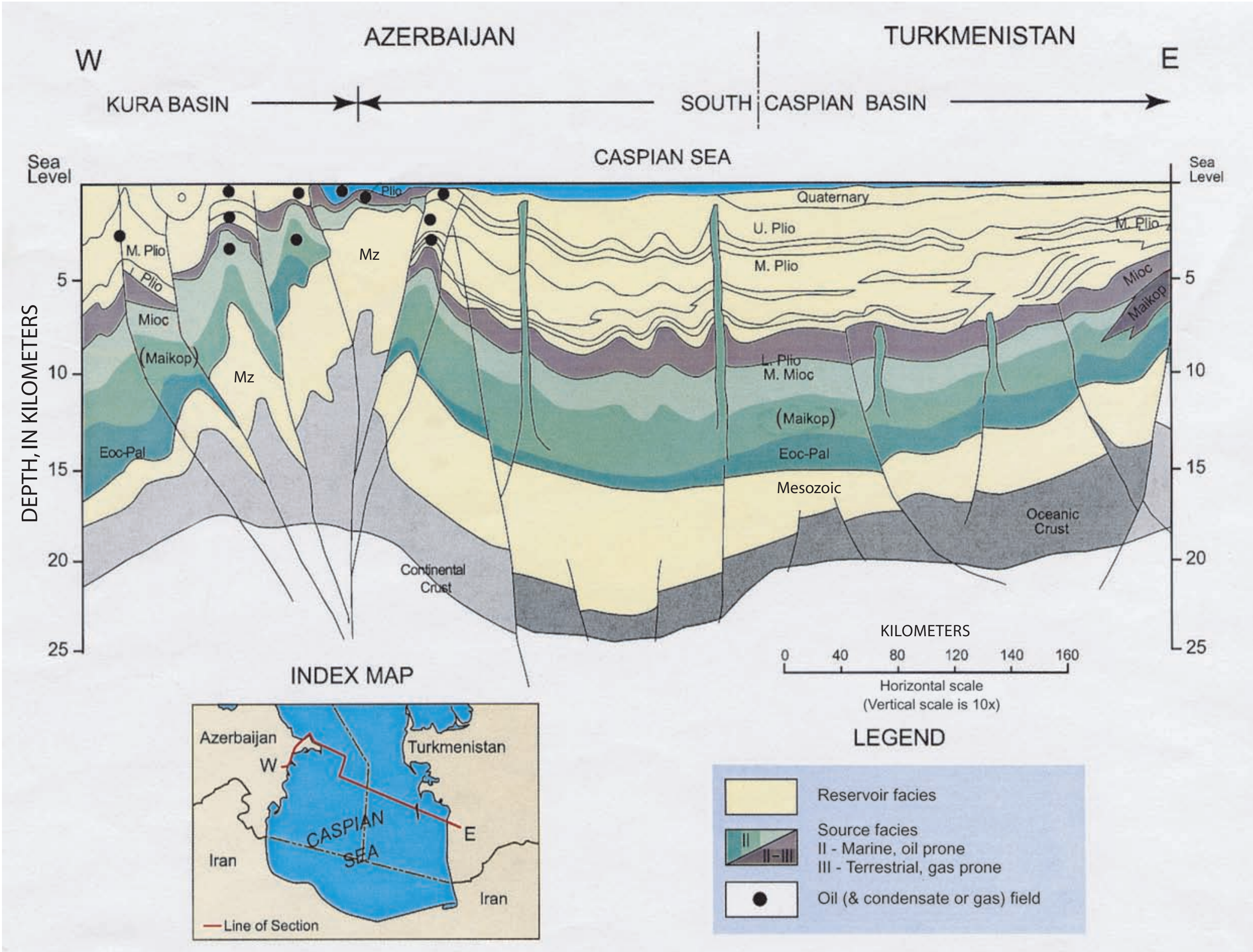


Figure 15. Cross section through the southern Caspian Sea region showing stratigraphy and structure from the Kura Basin in Azerbaijan eastward through the Apsheron-Pribalkhan Zone into western Turkmenistan. Note that the vertical scale in kilometers is 10× the horizontal scale.

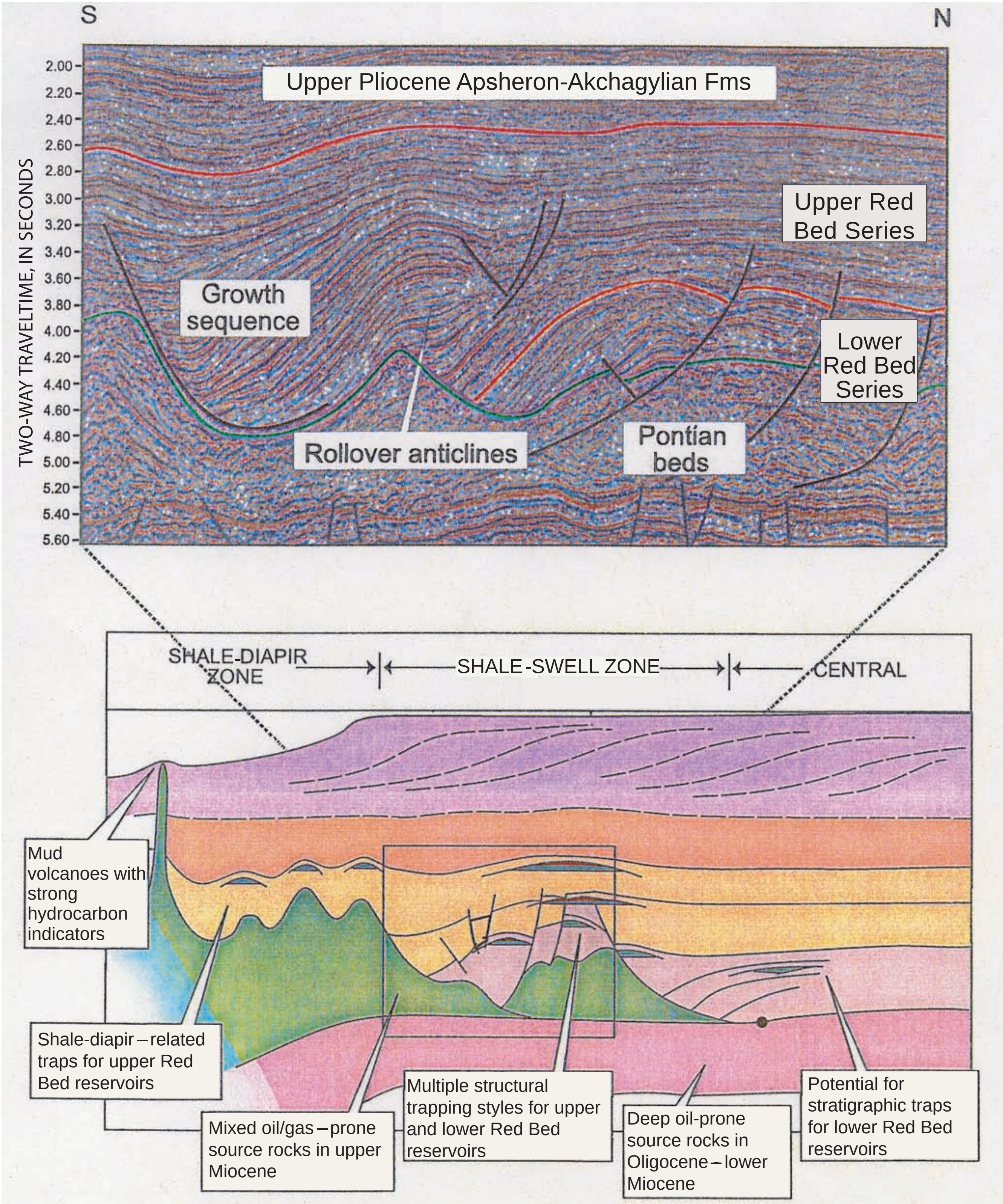


Figure 16. Seismic profile and schematic structure section across a part of the offshore area of western Turkmenistan showing shale-diapir and shale-swell zones and their relations to hydrocarbon traps. Boundary between the two zones is formed by a down-to-the-north listric fault against a diapiric shale "wall." According to Devlin and others (1999), shale diapirs developed as a result of compression above a basal detachment layer. For general location, see figure 17. (Printed with permission of *Oil and Gas Journal*.) (Structure section not to scale.)

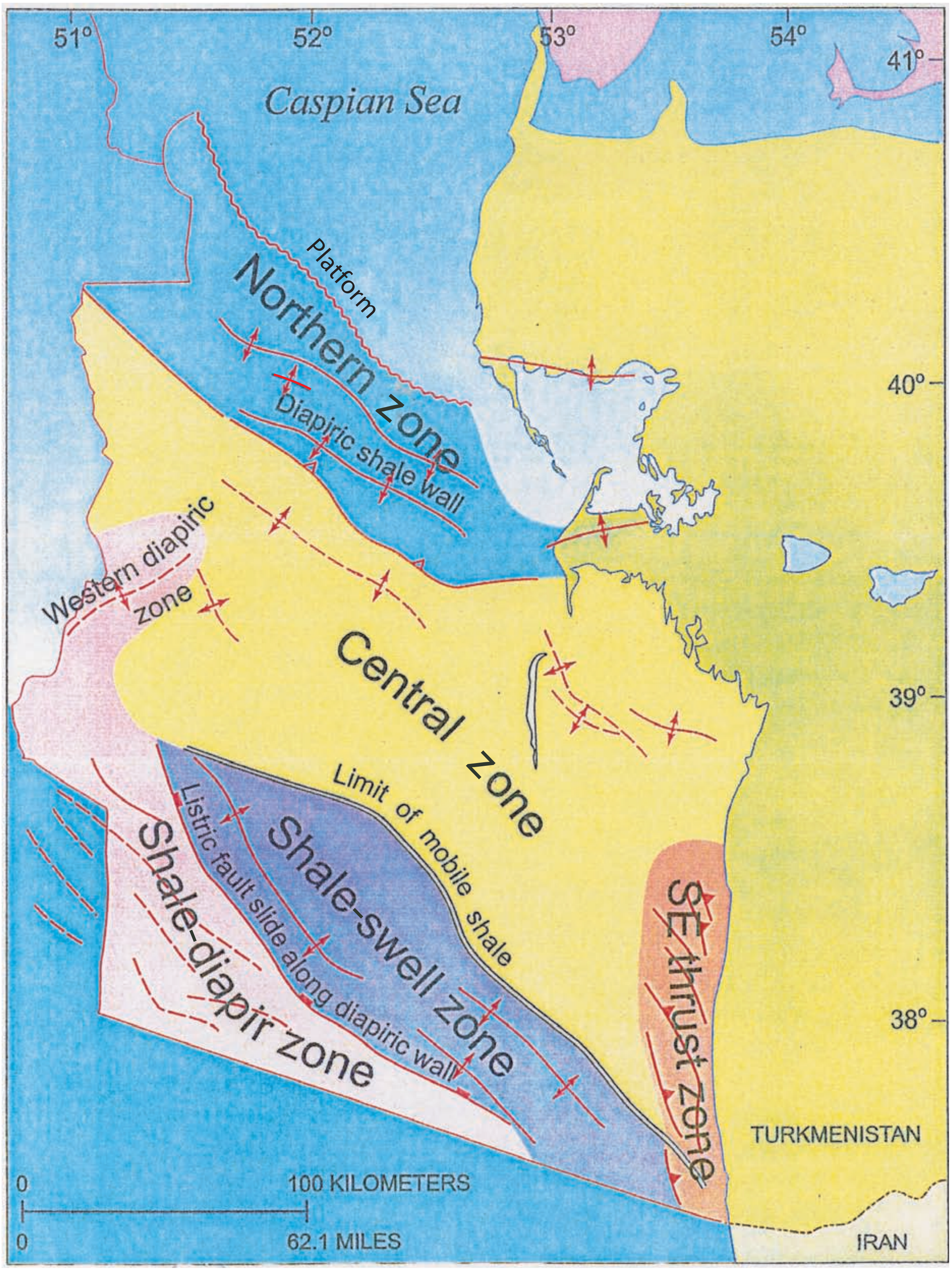


Figure 17. Structural zones identified from seismic surveys in offshore area of western Turkmenistan. (Based on Lawrence and Babaev, 2000; printed with permission of *Oil and Gas Journal*.)

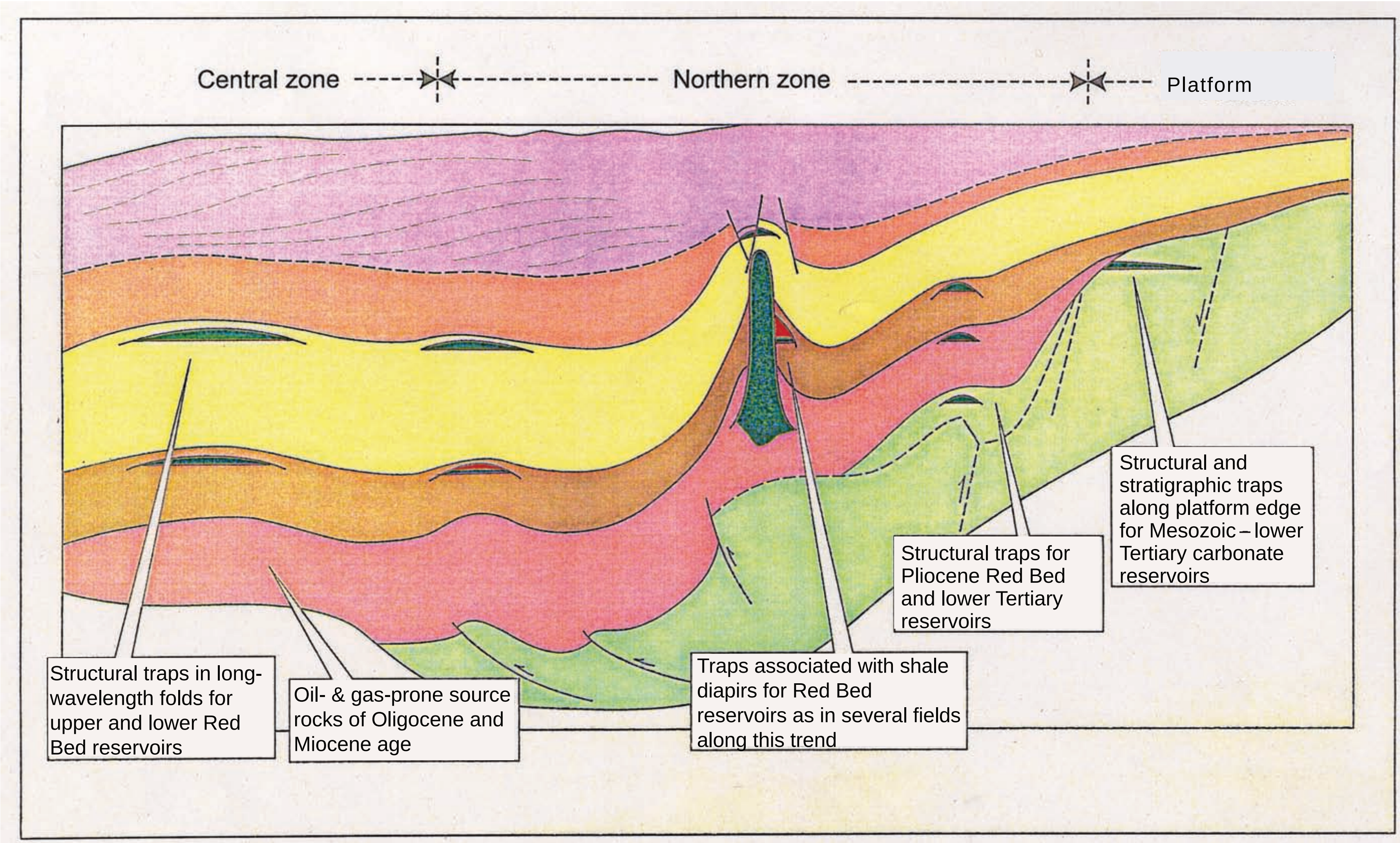


Figure 18. Cross section showing hydrocarbon-trapping conditions in Tertiary reservoirs across central and northern structural zones in the offshore area of western Turkmenistan. For general location, see figure 17. (Based on Devlin and others, 1999; printed with permission of *Oil and Gas Journal*.) (Not to scale.)

Iran Onshore-Nearshore Assessment Unit 11120105

Assessment Unit 11120105 is also a hypothetical unit, covering both onshore (1,082 km^2) and offshore (7,493 km^2) areas of Iran (fig. 1). Little information is available from these areas; consequently it is difficult to assess the assessment unit's potential. Berberian (1983) estimated that there may be as many as five fields to be discovered in the unit, on the basis of paleogeographic maps showing the Maykop Suite source rocks to be present in the subsurface. Three small modern deltas continue to deliver sediment eroded from the Elburz Mountains to the south (fig. 11). If sediment was also being transported to these deltas in the basin during the Pliocene and Pleistocene, potential reservoir rocks could have been deposited. Berberian (1983) reported that Pliocene–Quaternary continental strata are 1,600–2,000 m thick in the coastal plain north of the thrust fault that marks the north flank of the Elburz Mountains (fig. 4); it is likely that this sequence thickens northward into the basin and may represent potential reservoirs.

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