Petroleum Geology and Resources of the North Caspian Basin, Kazakhstan and Russia

By Gregory F. Ulmishek

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Petroleum Geology and Resources of the North Caspian Basin, Kazakhstan and Russia

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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 8 regions and 937 geologic provinces. The provinces have been ranked according to the discovered oil and gas volumes within each (U.S. Geological Survey World Energy Assessment Team, 2000). Then, 76 “priority” provinces (exclusive of the U.S. and chosen for their high ranking) and 26 “boutique” provinces (exclusive of the U.S. 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.

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 volumes either reside in undiscovered fields whose sizes exceed the stated minimum-field-size cutoff value for the assessment unit (variable, but must be at least 1 million barrels of oil equivalent) or occur as reserve growth of fields already discovered.

The petroleum system constitutes the basic geologic unit of the oil and gas assessment. The total petroleum system includes all genetically related petroleum found in shows and accumulations (discovered and undiscovered) that has been generated by a pod or by closely related pods of mature source rock. This petroleum exists within a limited mappable geologic space, together with the essential mappable geologic elements (source, reservoir, and seal) that control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum.

An assessment unit is a mappable part of a total petroleum system in which discovered and undiscovered fields constitute a single relatively homogeneous population such that the chosen methodology of resource assessment based on estimation of the number and sizes of undiscovered fields is applicable. A total petroleum system might equate to a single assessment unit. If necessary, a total petroleum system may be subdivided into two or more assessment units such that each assessment unit is sufficiently homogeneous in terms of geology, exploration considerations, and risk to assess individually.

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 code is as follows:

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 petroleum system code	316205**04**

The codes for the regions and provinces are listed in U.S. Geological Survey World Energy Assessment Team (2000).

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

A map, figure 1 of this report, shows boundaries of the total petroleum system and assessment units; it was compiled using geographic information system (GIS) software. Political boundaries and cartographic representations were taken, with permission, from Environmental Systems Research Institute’s ArcWorld 1:3 million digital coverage (1992), have no political significance, and are displayed for general reference only. Oil and gas field centerpoints, shown on this map, are reproduced, with permission, from Petroconsultants, 1996.

Abstract

The North Caspian basin is a petroleum-rich but lightly explored basin located in Kazakhstan and Russia. It occupies the shallow northern portion of the Caspian Sea and a large plain to the north of the sea between the Volga and Ural Rivers and farther east to the Mugodzhary Highland, which is the southern continuation of the Ural foldbelt. The basin is bounded by the Paleozoic carbonate platform of the Volga-Ural province to the north and west and by the Ural, South Emba, and Karpinsky Hercynian foldbelts to the east and south. The basin was originated by pre-Late Devonian rifting and subsequent spreading that opened the oceanic crust, but the precise time of these tectonic events is not known.

The sedimentary succession of the basin is more than 20 km thick in the central areas. The drilled Upper Devonian to Tertiary part of this succession includes a prominent thick Kungurian (uppermost Lower Permian) salt formation that separates strata into the subsalt and suprasalt sequences and played an important role in the formation of oil and gas fields. Shallow-shelf carbonate formations that contain various reefs and alternate with clastic wedges compose the subsalt sequence on the

basin margins. Basinward, these rocks grade into deep-water anoxic black shales and turbidites. The Kungurian salt formation is strongly deformed into domes and intervening depressions. The most active halokinesis occurred during Late Permian–Triassic time, but growth of salt domes continued later and some of them are exposed on the present-day surface. The suprasalt sequence is mostly composed of clastic rocks that are several kilometers thick in depressions between salt domes.

A single total petroleum system is defined in the North Caspian basin. Discovered reserves are about 19.7 billion barrels of oil and natural gas liquids and 157 trillion cubic feet of gas. Much of the reserves are concentrated in the supergiant Tengiz, Karachaganak, and Astrakhan fields. A recent new oil discovery on the Kashagan structure offshore in the Caspian Sea is probably also of the supergiant status. Major oil and gas reserves are located in carbonate reservoirs in reefs and structural traps of the subsalt sequence. Substantially smaller reserves are located in numerous fields in the suprasalt sequence. These suprasalt fields are largely in shallow Jurassic and Cretaceous clastic reservoirs in salt dome-related traps. Petroleum source rocks are poorly identified by geochemical methods. However, geologic data indicate that the principal source rocks are Upper Devonian to Lower Permian deep-water black-shale facies stratigraphically correlative to shallow-shelf carbonate platforms on the basin margins. The main stage of hydrocarbon generation was probably in Late Permian and Triassic time, during deposition of thick orogenic clastics. Generated hydrocarbons migrated laterally into adjacent subsalt reservoirs and vertically, through depressions between Kungurian salt domes where the salt is thin or absent, into suprasalt clastic reservoirs.

Six assessment units have been identified in the North Caspian basin. Four of them include Paleozoic subsalt rocks of the basin margins, and a fifth unit, which encompasses the entire total petroleum system area, includes the suprasalt sequence. All five of these assessment units are underexplored and have significant potential for new discoveries. Most undiscovered petroleum resources are expected in Paleozoic subsalt carbonate rocks. The assessment unit in subsalt rocks with the greatest undiscovered potential occupies the south basin margin. Petroleum potential of suprasalt rocks is lower; however, discoveries of many small to medium size fields are expected. The sixth identified assessment unit embraces subsalt rocks of the central basin areas. The top of subsalt rocks in these areas occurs at depths ranging from 7 to 10 kilometers and has not been reached by wells. Undiscovered resources of this unit did not receive quantitative estimates.

Introduction

This report describes the regional and petroleum geology of the North Caspian (in some publications Precaspian, Pricaspian, or Peri-Caspian) basin in Kazakhstan and Russia. The location and boundaries of the basin are shown in figure 1. Discovered petroleum volumes in the basin are listed at 45.8 billion barrels of oil equivalent (BBOE) in the Petroconsultants (1996) file, of which 57 percent is gas. The basin is ranked 12th among 102 provinces designated for appraisal of undiscovered oil and gas resources by the U.S. Geological Survey (U.S. Geological Survey World Energy Assessment Team, 2000). The recent, potentially supergiant oil discovery in the Kashagan prospect in the northern Caspian Sea can substantially increase the amount of the basin's reserves.

A single total petroleum system (TPS), the North Caspian Paleozoic TPS, was defined in the basin. The TPS encompasses the entire North Caspian basin area and includes both subsalt (Upper Devonian–Lower Permian) and suprasalt (Upper Permian–Tertiary) stratigraphic sequences separated by the Kungurian (uppermost Lower Permian) salt formation. Both sequences were charged with hydrocarbons that were generated from Paleozoic deep-water black-shale facies. These facies are developed in the central basin areas and are stratigraphic equivalents of carbonate platform formations of the basin margins. The peak of hydrocarbon generation probably occurred in Late Permian–Triassic time, contemporaneously with deposition of thick orogenic clastics and after deposition of the Kungurian salt seal. Major hydrocarbon reserves of the basin occur in subsalt carbonate reservoirs, largely in various carbonate buildups (atolls, pinnacle and barrier reefs).

Despite almost 100 years of exploration history, the North Caspian basin remains an exploration frontier. Six assessment units (AU) were identified for resource appraisal; four include subsalt rocks of the basin margins and the fifth includes suprasalt clastic rocks of the entire basin and TPS area. The sixth AU, encompassing subsalt rocks of the basin central area, occurs at depths exceeding 7 km and was not quantitatively assessed. Definitions of the TPS and AU are given in the Foreword, and the assessment technique and procedure are described in U.S. Geological Survey World Energy Assessment Team (2000). The results of the assessment are shown in table 1. The largest portion of undiscovered petroleum resources is expected in Paleozoic carbonate reservoirs of the south basin margin.

Province Overview

Province Location and Boundaries

The North Caspian Basin province (1016) occupies the northern part of the Caspian Sea and a large plain to the north (figs. 1, 2); it covers about 500,000 km^2. The basin is bounded to the east by the Ural foldbelt and the Mugodzhary zone, the latter being a southern continuation of the Urals that is partially buried beneath a thin section of Mesozoic rocks. Hercynian deformation in the foldbelt began in Late Carboniferous time after collision of the Russian (East European) craton with the Kazakhstan continent. The Paleozoic South Emba high (fig. 2) borders the basin to the southeast. The high is covered by flat-lying Mesozoic sediments, and its geology is poorly understood. The crest of the high is marked by large gravity and magnetic anomalies and is probably composed of Lower and Middle(?) Devonian volcanics (Kan and Tropp, 1996). Younger Paleozoic sedimentary rocks form the northwestern flank. The high is structurally expressed as an uplift of upper Paleozoic strata but is underlain by a deep trough in the basement surface. Possibly,

Figure 1. Petroleum system and assessment units of North Caspian basin.

the Devonian volcanics formed an oceanic volcanic arc that was accreted on the craton margin in pre-Late Devonian time. The South Emba high plunges southwestward, and the gravity and magnetic anomalies gradually diminish and disappear east of the Caspian Sea.

The southwestern basin boundary is the Karpinsky foldbelt, known in Russian literature as the Karpinsky Ridge (fig. 2). The foldbelt is composed of deformed Carboniferous fine clastics, which reach a thickness of 15 km as interpreted from seismic data. The rocks were deposited in a postrift sag above the Devonian rift that extended northwest into the Donets coal basin of Ukraine (Ulmishek and others, 1994). In middle Early Permian (Artinskian) time, the Devonian rift basin was structurally inverted, folded, and thrust onto the North Caspian basin margin (Khain, 1977). The foldbelt extends into the Caspian Sea where it becomes poorly defined.

The 1,500-km-long north and west margins of the basin separate the North Caspian basin from the Volga-Ural petroleum province. The boundary is defined by a sedimentary escarpment in subsalt Paleozoic rocks. Across the escarpment, thick shallow-water carbonate rocks of the Volga-Ural province pass into much thinner deep-water black-shale facies of the North Caspian basin. The top of the escarpment is formed by a Lower Permian barrier reef.

More than three-quarters of the North Caspian basin lies in Kazakhstan; the remaining part is in Russia (fig. 1). The area has a semiarid continental climate with hot summers and cold windy winters. The northern Caspian Sea is characterized by shallow

Figure 2. Structural map of North Caspian basin (modified from Solovyev, 1992). Contours are on top of basement. Hydrocarbon fields shown by red numbers; 1, Orenburg; 2, Karachaganak; 3, Zhanazhol; 4, Tengiz; 5, Astrakhan; 6, Kenkiyak.

water; the water depth does not exceed 200 m and is less than 5 m in about 70 percent of the offshore area.

Tectono-Stratigraphic Development

The North Caspian basin is one of the deepest basins in the world, containing sedimentary strata more than 20 km thick (fig. 2). Deep seismic sounding data indicate that oceanic or thinned continental crust underlies the central basin areas (Kleshchev and others, 1995). Most geologists believe that the basin originated as a rift, but the time of rifting is disputable. Two models have been proposed with rifting time in the Riphean (Middle–Late Proterozoic, 1,650 to 650 million years (Ma) old), or alternatively in the Middle Devonian (Malushin, 1985; Zonenshain and others, 1990; Volchegursky and others, 1995). However, I argue here for the third possibility that seems more probable, that is, that rifting took place in Early Ordovician time contemporaneously with rifting in the Urals that resulted in opening of the Uralian ocean. A partially inverted Ordovician graben filled with a ≈5-km-thick sequence of coarse to fine clastics is present north of the northeast basin margin where it underlies the supergiant Orenburg gas field (fig. 2; Nazhmetdinov, 1991; Yakhimovich, 1996). Probably, original rifting and formation of grabens occurred in both areas at the same time, but subsequent spreading that started in the North Caspian graben resulted in cessation of rifting and following compression and structural inversion in the Orenburg graben. As a result of spreading in the North Caspian basin, cratonic blocks that presently form a series of arches along the south and east basin margins (Astrakhan-Aktyubinsk system of highs in fig. 2) moved away from the Russian craton and opened the oceanic crust.

Tectonic development during Devonian, Carboniferous, and much of Early Permian time (rocks older than Middle Devonian have not been reached by drill) was characterized by continuous subsidence of the basin and deposition of carbonate and clastic formations on its margins. Basinward, these strata grade into deep-water black shales and turbidites that presently occur at great depths and are only locally penetrated by wells in areas close to the basin margins. Hercynian deformation started in the Late Carboniferous in the Ural foldbelt and in the Early Permian (Sakmarian-Artinskian) in the Karpinsky foldbelt and South Emba high. Thick Upper Carboniferous–Lower Permian orogenic molasse clastics are present on the east and south basin margins. Continental collisions along the basin margins separated the North Caspian small deep-water oceanic basin from the Tethys ocean. Consequently, the basin was filled by a Kungurian (latest Early Permian) evaporite sequence, which is dominantly composed of salt and has an estimated original depositional thickness of 4–5 km (Komissarova, 1986; Volchegursky and others, 1995).

Orogeny in the Urals, rapid subsidence of the basin, and deposition of thick sedimentary sequences continued during Late Permian and Triassic time. Sediments of this age were mostly continental orogenic clastics, but some Upper Permian (Kazanian Stage) carbonates and evaporites and Lower and Middle Triassic marine shales and marls are present in the western areas. Active deformation of Kungurian salt began soon after its deposition, and Upper Permian–Lower Triassic sediments are several kilometers thick in depressions between salt domes. Intense tectonic subsidence of the basin floor terminated by Jurassic time. Various narrow (commonly one stage) stratigraphic intervals of the Jurassic through Tertiary section attain large (to 3 km) thickness only locally, in depressions near domes that experienced active growth during corresponding time. Deformation of salt continues at present and some salt domes are exposed on the surface.

Present-Day Structure

The basement surface of the North Caspian basin occurs at depths reaching more than 20 km in the Central depression (fig. 2). The depression is about 450 km long from west to east. Two narrow troughs extend from the depression to the southwest and northeast (Sarpin and Novoalekseev troughs, respectively). These troughs were probably deep straits that connected the North Caspian oceanic basin with the Tethys and Uralian oceans. The north and west basin margins are narrow and steep. In contrast, the south margin is wide, being formed by a series of structural arches in which the basement lies at depths of 7–8 km. From the crests of the arches, the basement dips both toward the Central depression and toward the marginal troughs in front of the Hercynian foldbelts.

At the top of subsalt rocks (seismically expressed in most basin areas as principal reflector P1), the Central depression is a gentle structure with a maximum depth of about 10 km. The marginal troughs are absent and the top of subsalt rocks dips away from the margins toward the basin center. Carbonate platforms and organic buildups are expressed as structural highs.

The regional structural pattern of Upper Permian and younger strata is dominated by salt tectonics. More than 1,000 salt domes have been identified in the basin. In marginal areas, the domes are arranged in salt ridges that are generally parallel to the basin margins.

Total Petroleum System

Oil and gas fields of the North Caspian basin have been discovered in both subsalt (pre-Kungurian) and suprasalt sequences. In the subsalt sequence, large oil and gas reserves occur in Upper Devonian through Lower Permian carbonate and clastic reservoirs in structural traps and reefs. All basin margins where subsalt rocks can be reached by drilling are productive, demonstrating a prolific hydrocarbon system. In the Upper Permian to Tertiary suprasalt clastic sequence, production has been established over the entire basin area. Most hydrocarbons in this sequence are found in Jurassic and Cretaceous reservoirs in traps associated with salt domes. However, despite the large area, the considerable thickness of the sedimentary column, and the wide stratigraphic range of productivity, only one TPS is presently identified in the basin. The designation of a single petroleum system stems from the geologic model in which a pod of upper Paleozoic source rocks is present throughout the entire central area of the North Caspian basin. Hydrocarbons generated from this pod have migrated into both subsalt and suprasalt reservoirs.

North Caspian Paleozoic Total Petroleum System

Overview

The North Caspian Paleozoic TPS (101601) encompasses the entire North Caspian basin (fig. 1). It is probable that some oil and gas fields discovered in adjacent areas of the Volga-Ural petroleum province and on the North Buzachi arch in the western North Ustyurt basin were formed by hydrocarbons that migrated laterally updip from the North Caspian basin. However, no geochemical data exist to support or reject this hypothesis. Thus, the TPS area may extend onto slopes of the Volga-Ural platform to the north and the North Buzachi arch to the south (fig. 2).

According to Petroconsultants (1996), discovered reserves of oil, condensate, and gas of the system are 45.8 billion barrels of oil equivalent (BBOE) of which 57 percent is gas. Most hydrocarbons are in subsalt carbonate rocks in three supergiant fields (Tengiz, Karachaganak, and Astrakhan), each with reserves exceeding 5 BBOE. Another potentially supergiant discovery was recently made offshore in the Kashagan prospect about 100 km offshore of the Tengiz field (fig. 7). Most fields producing from the suprasalt sequence have been found in the southeast quarter of the basin. Hydrocarbons in both subsalt and suprasalt sequences were generated from upper Paleozoic deep-water basinal facies that were deposited in central basin areas and are stratigraphically correlative with marginal carbonate platforms.

Discovery History

Oil shows in shallow suprasalt rocks were recorded in wells drilled in the late 19th century. The first commercial discovery was made in the South Emba area (southeastern part of the basin) in 1911. By 1970 more than one hundred fields had been discovered in the suprasalt sequence, primarily in Jurassic and Cretaceous sandstone reservoirs. The majority of these fields are located in the South and North Emba regions (areas south and north of Emba River, fig. 1). The new exploration stage began in the 1970's following discovery in 1967 of the first subsalt oil and gas condensate accumulation in a Lower Permian reef near the northern basin border. Exploration was most successful in the late 1970's and early 1980's when all of the major fields were found. In recent years, a significant amount of seismic surveys have been conducted offshore, and a well drilled in 2000 on the huge Kashagan prospect tested oil in 2000. The northern Caspian Sea is environmentally very sensitive because of shallow depths and the high content of sulfur in oil and gas. Moreover, the area is the main feeding ground for sturgeon fish that produce the famous Russian caviar.

Petroleum Occurrence

Oil and gas fields have been found over the entire North Caspian basin, but the main petroleum reserves are concentrated on the margins. In subsalt rocks, a chain of relatively small oil and gas condensate fields occurs in the Lower Permian barrier reef reservoirs along the north and west basin boundaries. A few fields near these boundaries are in the Middle Carboniferous barrier reef. The supergiant Karachaganak gas condensate and oil field in an Upper Devonian–Carboniferous atoll and overlying Lower Permian pinnacle reef is also located on the north margin (fig. 2). On the east-southeast margin, several oil and gas fields, among which the Zhanazhol oil field is largest, have been discovered in carbonate reservoirs in structural traps and reefs. Several accumulations in Lower Carboniferous and Lower Permian clastic reservoirs found on the east-southeast margin are small. Two supergiant discoveries, Tengiz oil and Astrakhan gas fields, have been made in Upper Devonian–Middle Carboniferous carbonates along the south basin margin. The Tengiz field produces from a carbonate buildup and the Astrakhan field from a structural trap on the crest of the Astrakhan regional arch (fig. 2). The Kashagan discovery well located offshore in the Caspian Sea tested oil from a carbonate buildup similar to that of Tengiz, but areally the buildup is almost three times larger than Tengiz. Except for several oil accumulations near the east basin boundary, all subsalt reservoirs are highly overpressured with reservoir pressure commonly 1.8–2.1 times greater than hydrostatic pressure (Belonin and Slavin, 1998).

In suprasalt clastic rocks, most fields and the dominant reserves are concentrated in the southeastern part of the basin, in the old producing South Emba and North Emba regions (south and north of the Emba River in fig. 1). The most productive horizons are Jurassic and Cretaceous rocks in salt dome-related traps at depths less than 1,000 m. During the last two decades, deeper production has been established in several fields in these regions, and some small gas and oil fields have been found in lightly explored suprasalt rocks farther to the west and north.

Oils in subsalt carbonate reservoirs are of low to medium gravity (38°–46°API) and sulfurous; gas-oil ratios are high. Associated gas commonly contains a large proportion of hydrogen sulfide (18 percent in the Tengiz field). Oil in several small pools discovered in subsalt clastic reservoirs along the east-southeast basin margin is sweet. Subsalt gas is sulfurous: hydrogen sulfide content ranges from 3.2 percent in the Karachaganak field to about 20 percent in the Astrakhan field. Gas in the Astrakhan field also contains nearly 20 percent carbon dioxide. Many gas accumulations have a high condensate content. Most oils in suprasalt fields are medium and heavy, and are biodegraded to various degree. In the group composition, naphthenes and aromatics dominate over alkanes (Maksimov and Botneva, 1981). Gas-oil ratio is commonly low and the sulfur content varies from 0.2 to nearly 2 percent. A few gas pools in Tertiary strata contain dry methane, possibly of biogenic origin.

Stratigraphy of Subsalt Upper Paleozoic Rocks

The oldest rocks that have been drilled in the North Caspian basin are of Early and Middle Devonian age. Lower

Eifelian shallow-shelf carbonates overlain by upper Eifelian–Givetian deep-water organic-rich calcareous black shales were penetrated in the Karachaganak field on the north basin margin (Konyukhova, 1998). Undivided Lower Devonian–Eifelian and Givetian shallow-shelf carbonate rocks were also encountered in several wells on the east basin margin at depths of 5–6 km (Akhmetshina and others, 1993). Distribution of pre-Upper Devonian rocks and paleogeographic conditions of their deposition in the North Caspian basin are virtually unknown. The stratigraphy of younger, upper Paleozoic (Upper Devonian–Lower Permian) subsalt rocks is known much better; this stratigraphy is complex and varies significantly on different basin margins.

North and West Basin Margin

The narrow north and west margin is characterized by the presence of three thick carbonate formations in the Upper Devonian–Lower Permian interval. These formations are separated by lower-middle Visean and lower Moscovian (Verey Horizon) clastic sections (fig. 3). Each carbonate formation forms a barrier reef trend and grades basinward into thin deep-water black-shale facies (Grachevsky and others, 1976). The clastic formations form clinoforms (clastic wedges) on the paleoslope (fig. 3). Both basinward progradation of the formations and backstepping of younger barrier reefs toward the outer shelves are known in different parts of the margin. Only a few local carbonate buildups (atolls, pinnacles) have been discovered basinward from the barrier reefs, one of which contains the giant Karachaganak field (fig. 4). Several carbonate banks with possible pinnacle development are inferred at depths of 6–7 km along the margin, but only two such banks have been penetrated by several wells. Therefore, the extent as well as the presence of some of the banks remains speculative (Solovyev and others, 1992; Mikhalkova and others, 1990).

East-Southeast Basin Margin

The main carbonate section of the east-southeast basin margin is of late Visean–Late Carboniferous (in places as young as Early Permian) age. The section is separated into two parts, informally called KT-I (upper) and KT-II (lower) in Russian literature (KT stands for carbonate formation in Russian), by a shale interval in the middle Moscovian (Podol Horizon). Basinward, both carbonate formations grade into organic-rich black shales (radioactive shale beds of local nomenclature). The lower formation extends farther west and north compared to the upper one. Barrier reefs are present along basinal edges of both formations, but they are not as well developed as on the north and west margin (fig. 5).

The carbonate section of the east-southeast margin is underlain by the graywacke clastic Izembet (Zilair) Formation of Late Devonian–Early Carboniferous (Famennian-Visean) age (Bakirov and others, 1991). Seismic data indicate that from the crests of basement arches of the Astrakhan-Aktyubinsk system toward the Urals and toward the South Emba high (fig. 2), the formation thickens from about 500 m to as much as 7,500 m (Dalyan and Akhmetshina, 1998). Clastic material was derived from the Mugodzhary microcontinent and Silurian volcanic arc (both presently incorporated into the Ural foldbelt), which were accreted to the craton in Middle Devonian–Frasnian time (Zonenshain and others, 1990; Arabadzhi and others, 1993). Fine clastic material dominates the lower part of the Izembet Formation, which also contains some detrital carbonates; these rocks were probably deposited in a deep-water basin. Upward in the section, clastic material coarsens, and beds of conglomerates and thin coal seams appear. Apparently, clastic sediments from the Mugodzhary provenance did not reach the north half of the east basin margin. There, rocks correlative to the Izembet Formation are thin deep-water black shales overlying Frasnian limestones (Dalyan and Bulekbaev, 1993). Several wells have reached the bottom of the graywacke formation; they penetrated Lower Devonian and Frasnian carbonates (Akhmetshina and others, 1993). However, because of the great burial depths the distribution of Devonian carbonate rocks remains poorly known (Kan, 1996; Dalyan, 1996).

The Middle–Upper Carboniferous carbonate formation is overlain by a thick section of Lower Permian orogenic clastics that form fans descending from the Urals and the South Emba high (Bakirov and others, 1980; Sapozhnikov and others, 1986). Along the Urals, the clastic rocks are deformed into several lines of long, narrow anticlines probably associated with thrusts.

South Basin Margin

Pre-Permian clastic rocks have not been encountered in wells on the carbonate platforms of the south basin margin; however, indirect evidence suggests that they may be present in the Middle Devonian of the Astrakhan arch (N.V. Lopatin, oral commun., 1999). A few meters of clastic rocks recently penetrated at the bottom of a deep well at a depth of almost 6 km may lie at the top of the Middle Devonian (Orlov and Voronin, 1999). The Karaton-Tengiz zone in the eastern part of the south basin margin is composed of Upper Devonian through Bashkirian (Middle Carboniferous) carbonates that form large atolls many hundreds of meters high (figs. 6, 7). Outside the atolls, the carbonate rocks grade into a deep-water basinal facies. The tops of atolls are unconformably overlain by thin Lower Permian (mainly Artinskian) anoxic black shale that was deposited on submerged uplifts below the depth of organic carbonate sedimentation. The shale thickens rapidly on slopes of the atolls. The zone extends into the Caspian Sea, where several carbonate buildups have been mapped by seismic surveys (Murzagaliev, 1995; Kerimov and others, 1990). The Kashagan prospect, located in the western part of Shaburbali platform (fig. 7), is one of these buildups; it was recently drilled and shows potential for being a supergiant discovery.

The Astrakhan platform west of the Caspian Sea is also composed of Upper Devonian to Bashkirian carbonate rocks. However, unlike in the Karaton-Tengiz zone, the platform is actually a flat carbonate bank slightly deformed into a gentle regional arch above the basement high (fig. 8). The giant

Cross section through north basin margin (modified from Grachevsky, 1974). The section is located in westernmost portion of no

Figure 4. Cross section through Karachaganak carbonate buildup (modified from Golov and others, 1983). D_3, Upper Devonian; C_1, C_2, and C_3, Lower, Middle, and Upper Carboniferous; P_1, Lower Permian (Asselian-Artinskian); C_1t, Tournaisian; C_1v–s, Visean–Serpukhovian.

Figure 5. Cross section through east basin margin (modified from Solovyev and others, 1990). Suprasalt oil fields are not shown. Subscripts 1, 2, and 3 denote lower, middle, and upper subunits. D, Devonian; C, Carboniferous; P, Permian; t, Tournaisian; v, Visean; m, Moscovian; pd, Podol Horizon; P_1k, Kungurian; Tr, Triassic; J, Jurassic; K, Cretaceous.

Figure 6. Cross section of Karaton-Tengiz zone (modified from Lisovsky and others, 1992). D_2 and D_3, Middle and Upper Devonian; C_2, Middle Carboniferous; P_1 and P_2, Lower and Upper Permian; Tr, Triassic; K, Cretaceous; Cz, Cenozoic.

Figure 7. Carbonate buildups of northern Caspian Sea (modified from Murzagaliev, 1995). Scale approximate.

Figure 8. Cross section of Astrakhan arch (modified from Brodsky and others, 1994). The arch constitutes westernmost segment of Astrakhan-Aktyubinsk system of highs shown in figure 2. Scale is not available. Total length of section is about 60 km. AR, Archean; PR, Proterozoic; PZ, Paleozoic; D, Devonian; C, Carboniferous; P, Permian. Subscripts 1, 2, and 3 denote lower, middle, and upper subunits. Symbols *B*, *I P*, *II P*, *II P'*, and *F* are referred to seismic reflectors.

Astrakhan gas field is located on the crest of the arch. Barrier reefs are developed along edges of the carbonate platform. The top of the platform is unconformably overlain by thin Lower Permian deep-water shales. Seismic data suggest the presence of a similar platform in the western area of the Caspian shelf (fig. 7).

South and west of the Astrakhan carbonate platform, the south basin margin is formed by a thrust belt north of the Hercynian Karpinsky foldbelt (fig. 2). In this thrust belt, known as the Karakul-Smushkov zone of deformation, Lower Carboniferous to Bashkirian carbonates are the oldest rocks penetrated by drilling. The carbonates underlie the Middle Carboniferous–Lower Permian clastic section that thickens to the north and is truncated by a pre-Jurassic unconformity to the south. The upper part of the section is composed of Artinskian orogenic clastic rocks as much as 1,000 m thick.

Throughout most of the basin, the Devonian–Lower Permian sequence is overlain by the Kungurian (uppermost Lower Permian) evaporite sequence, which is primarily composed of salt but includes some clastic and anhydrite beds. The evaporites are absent only in an extreme marginal zone adjacent to the Urals and along the south basin boundary where they are truncated by pre-Late Permian or pre-Jurassic unconformities (fig. 6).

Source Rocks

Paleogeographic conditions of sedimentation and facies architecture indicate that the principal petroleum source rocks in the North Caspian basin are basinal black-shale facies contemporaneous with upper Paleozoic carbonate platform deposits on the basin margins (fig. 9). Because of great depths, the small number of wells drilled into basinal facies, and the paucity of cores, the geochemical characteristics of the source rocks are poorly documented. Only limited analytical data are available from published sources. Lower Permian basinal facies of the west basin margin are characterized by total organic carbon (TOC) content ranging from 1.3 to 3.2 percent and hydrogen index (HI) of about 300 to 400 mg HC/g TOC (Punanova and others, 1996). Lower Permian black shale on flanks of the Karachaganak reef has TOC measurements as high as 10 percent (Maksimov and Ilyinskaya, 1989). In Middle Carboniferous basinal black shales on the east basin margin, TOC reaches 7.8 percent (Dalyan, 1996). In the Biikzhal deep well located basinward from the southeast margin, Middle Carboniferous black shale at a depth of more than 5.5 km has TOC of 6.1 percent (Arabadzhi and others, 1993). Although data are few, high TOC and silica contents in basinal shales of all margins and characteristically high X-ray readings on gamma logs are typical of the deep-water anoxic black-shale facies. This facies contains type II kerogen and is the principal oil source rock in Paleozoic (and many Mesozoic) basins of the world (Ulmishek and Klemme, 1990).

Russian geologists believe that the Upper Devonian–Lower Carboniferous Izembet (Zilair) Formation of the east and southeast margins of the North Caspian basin contains significant petroleum source rocks (Arabadzhi and others, 1993; Tverdova and others, 1992). This coarsening-upward clastic section, especially its lower part, was partially deposited under relatively deep water conditions. Measured TOC content varies from 0.1 to 7.8 percent and averages 0.75 percent (Tverdova and others, 1992). Organic matter is of mixed terrestrial and marine sapropelic origin. On the Van Krevelen diagram, most samples are located near the boundary between kerogen types II and III. Measured HI varies from less than 100 to 450 mg HC/g rock. These data indicate that organic-rich units of the Izembet Formation could have generated gas and probably some oil. Thick Lower Permian orogenic clastics of the east and south basin margins contain only terrestrial organic matter and could have generated some gas (Arabadzhi and others, 1993).

The presence of source rocks in the suprasalt sequence has long been disputed, and some investigators believe that oil pools in salt dome-related traps were generated from these strata (Botneva, 1987; Botneva and others, 1990). Although some source rocks of inferior quality may be present among Triassic strata (see fig. 9), these rocks could have reached maturity only in some deepest depressions between salt domes and thus are of only local significance. Recent geologic and geochemical data show that suprasalt oils were generated from subsalt source rocks and migrated upward from depressions between domes where the salt has been completely or almost completely withdrawn (Kuanyshev and Shayagdamov, 1992; Sobolev, 1993, Murzagaliev, 1994; Groshev and others, 1993).

Vitrinite reflectance and geochemical data indicate that in most fields and prospects drilled along margins of the North Caspian basin, the top of subsalt rocks occurs in the oil window or in the upper part of the gas window (Volkova, 1992). The geothermal gradient in the basin is relatively low apparently because of the cooling effect of the thick Kungurian salt sequence. The south basin margin is hotter; at the top of subsalt rocks at depths of 4–4.2 km the temperature is 100°–120°C compared to about 80°C at comparable depths on the north margin. Standard maturation modeling is difficult to apply because of differences in thermal conductivity of evaporite and clastic/carbonate rocks. Geothermal gradients in salt domes and adjacent depressions are different, and the modeling is further complicated by uncertainties in timing of salt dome formation. The difference in measured temperature at similar depths at the top of subsalt rocks under a salt dome 3.5 km thick and in an adjacent depression (in Karatobe field of the east basin margin) was 18°C (Navrotsky and others, 1982). This difference may reach 60°C under the largest salt domes of the basin. Qualitatively, it can be stated that maturation in deep parts of the basin started before deposition of the salt. Most oil generated at this stage probably was lost because of the absence of a regional seal (local seals among mostly carbonate rocks are uncommon and easily breached). This loss of early-generated hydrocarbons is demonstrated by heavy, paleo-biodegraded oils found in a number of fields at depths reaching 5.5 km (Botneva and others, 1990; Tikhomolova and others, 1989).

The principal stage of hydrocarbon generation and formation of fields, especially in marginal, shallower areas of the basin, probably was in Late Permian–Triassic time when the Kungurian salt seal was in place and thick orogenic molasse clastics were deposited (Borovikov, 1996; fig. 9). Significant hydrocarbon generation in later times could have occurred only

Figure 9. Events chart of North Caspian Paleozoic Total Petroleum System. Queries indicate uncertainties in extent or identification.

locally in depressions adjacent to growing salt domes. Deposition of thick Mesozoic and Tertiary sediments in these depressions resulted in additional heating of subsalt source rocks. Triassic source rocks considered as speculative could also have reached maturity in the deepest depressions and generated some hydrocarbons.

Reservoir Rocks

In the subsalt sequence, carbonate reservoirs are of better quality than clastic reservoirs. Reservoir properties of carbonate rocks strongly depend on diagenetic changes, primarily on leaching. Vuggy porosity related to leaching is better developed in reef reservoirs, especially in reef-core carbonates. For example, porosities averaging 10–14 percent are characteristic of reefal vuggy, porous limestones and dolomites in the Karachaganak field (fig. 4), whereas porosity of adjacent inner lagoonal facies is lower, commonly 6–10 percent or less (Shershukov, 1986). Porosity of Upper Devonian–Middle Carboniferous carbonate reservoir rocks in the Tengiz field (fig. 6) varies from a few percent to 20 percent and averages 6 percent over this extensive atoll. Most of the porosity in this field is related to vugs, whereas the primary pore space does not exceed 2–3 percent (Maryenko and others, 1985). Porosity exceeding 10 percent is characteristic of a ring-shape zone of the atoll's reef core (Pavlov, 1993). Porosity of carbonates deposited on slopes and in the central lagoon is significantly lower. Permeability of carbonates of the Tengiz atoll and other reefs is mainly controlled by fracturing and, in laboratory measurements, was observed to vary widely from a few to hundreds of millidarcies. In the Astrakhan field, Bashkirian detrital and oolitic limestones were deposited on a shallow bank. Porosity of the limestones averages 6 percent and is about equally divided between primary and diagenetic porosity (Mitalev and others, 1987). Measured permeability in samples is low, commonly only 1–2 mD. However, fracturing is intensive, and most wells yield 5–10 million cubic feet (MMCF) of gas per day.

Several small oil discoveries have been made in sandstones of the upper part of the Upper Devonian–Lower Carboniferous Izembet Formation on the east and southeast basin margins. Daily oil flows from most tested wells were low considering great depths and overpressures, and did not exceed several tens of barrels with the exception of one well that tested nearly 2,000 barrels per day. Porosity of most sandstone and gravelstone samples ranges from 10 to 20 percent; permeability is variable, in some samples reaching hundreds of millidarcies (Dalyan and Akhmetshina, 1998). The sandstones are poorly sorted, have variable but locally high content of carbonate cement, and are commonly laterally discontinuous; consequently, reservoir beds of the Izembet Formation, though locally exhibiting high porosity and permeability, are largely of moderate to poor quality (Proshlyakov and others, 1987). Preservation of porosity in "dirty" graywacke sandstones at great depths is probably related to high overpressure that may be twice that of hydrostatic pressure at the same depth (Dalyan and Akhmetshina, 1998).

Lower Permian (and in places also Upper Carboniferous) orogenic molasse clastics of the east and south margins of the North Caspian basin are characterized by variable, but generally poor, reservoir properties. Exploration of this clastic play, conducted in the 1950's and 1960's, was in compressional anticlines located within the Aktyubinsk trough on the east basin margin (fig. 10) and farther south in the Ostansuk trough. In both troughs, the orogenic molasse sequence is as much as 5 km thick. Sandstones in the more eastern anticlinal trends that were drilled are tight, probably because of deep burial and subsequent tectonic stress and unloading. The same causes resulted in poor reservoir properties of orogenic sandstones in compressional thrust-related anticlines of the Karakul-Smushkov zone in the western part of the south margin (fig. 2).

Reservoir properties of Lower Permian sandstones outside the zones of compressional anticlines are somewhat more favorable. Several oil accumulations have been discovered in these rocks; in the largest accumulation (Kenkiyak field), at depths of 4–4.5 km, porosity varies from 5 to 11 percent and permeability does not exceed 50 mD. The main reservoir problem is the discontinuous character of sandstone beds, which probably resulted from the rapid progradational deposition of the orogenic clastic sequence (Kunin and others, 1984, 1987). Highly variable original yields of wells that range from less than 40 to greater than 2,000 barrels/day resulted from these geologic conditions (Solovyev, 1992).

Reservoir properties of Jurassic and Cretaceous sandstones that occur at shallow depths above salt domes are excellent; porosity ranges from 25 to 35 percent, and permeability is high, commonly several hundred millidarcies. Reservoir properties deteriorate somewhat in the more deeply buried Triassic and Upper Permian strata, but in a few fields where these rocks are productive, porosity remains higher than 20 percent and permeability varies from 30 to 500 mD (for example, Kenkiyak field; fig. 5).

Seal Rocks

The Lower Permian Kungurian evaporite sequence is the principal regional seal for subsalt reservoirs of the North Caspian basin (fig. 9, seal rock); it covers the entire basin area except for a narrow zone along the east and south margins where salt either was not deposited or was truncated by pre-Jurassic erosion. Kungurian salt is deformed into numerous domes alternating with depressions, in which the deposits are thin or absent due to lateral flowage (for example, see figs. 5 and 6). Where the otherwise impermeable seal is absent, hydrocarbons were afforded avenues to migrate from subsalt source rocks vertically into suprasalt reservoirs. Some high-amplitude carbonate buildups likely are water bearing because hydrocarbons have leaked into suprasalt rocks (for example, Karaton buildup on the Primorsk carbonate platform, figs. 6 and 7). Nevertheless, the salt formation divides the sedimentary succession into two well-defined hydrodynamic systems. Ubiquitous overpressure and significantly higher salinity of formation waters characterize the subsalt system (Pomarnatsky and Gusarova, 1991), whereas pressure is hydrostatic and salt content in formational water is lower in the suprasalt system. Various local and semiregional shale seals that directly overlie hydrocarbon pools in subsalt

Figure 10. Tectonic map of northern part of east basin margin and adjacent Ural foldbelt (modified from Kan, 1996).

reservoirs probably would not be effective without the Kungurian salt. Upper Jurassic and Cretaceous marine shale beds seal hydrocarbon pools in suprasalt rocks. Both subsalt and suprasalt hydrodynamic systems constitute a single total petroleum system (TPS) because they were charged by hydrocarbons from the same subsalt source rocks; however, the upper system was designated as a separate assessment unit within the TPS.

Traps

As discussed previously, carbonate reefs are the most important traps in subsalt rocks. Various morphological types of reefs are present, but atolls and pinnacle reefs contain the largest hydrocarbon accumulations. Pools in barrier reefs are much smaller because the maximum height of the oil/gas column is defined by the back-reef slope and does not exceed 150–200 m. Several subsalt fields on the east basin margin are in structural anticlinal traps (Zhanazhol and adjacent fields, fig. 2). These traps are related to Hercynian compression from the Urals and were formed during Permian-Triassic time approximately contemporaneous with peak hydrocarbon generation (fig. 9). Only the giant Astrakhan gas field is apparently controlled by basement-related uplift in the crestal portion of a regional arch (fig. 8).

All hydrocarbon pools in subsalt clastic rocks (most of them noncommercial) have been discovered on anticlinal prospects. However, the discontinuous character of clastic reservoir rocks in both Lower Carboniferous and Lower Permian sections and large variability in flows from adjacent wells suggest that hydrodynamic connection between the wells is poor or absent and that many of these pools are actually in stratigraphic traps.

In the suprasalt section, all productive traps are related to salt tectonics and are morphologically variable. Among them, anticlinal uplifts with a salt core and traps sealed updip by faults and by walls of salt domes are the most common types. In recent years more modern seismic equipment has improved the ability to map the structure of suprasalt rocks in depressions between salt domes, resulting in new types of structures being mapped in Upper Permian rocks (Dalyan, 1998)—such as arches in depressions and semi-arches against slopes of salt domes. These structures are expressed only in Upper Permian rocks but are absent in both younger and older strata. Formation of the traps is related to non-uniform withdrawal of salt into adjacent domes.

Assessment Units

Six assessment units (AU) have been identified in the North Caspian Paleozoic TPS (fig. 1). Four AU's (10160101, 10160102, 10160103, and 10160104) embrace subsalt rocks on the basin margins, and their external boundaries coincide with the basin boundaries. The basinward boundaries of these AU's are drawn along the 7-km structural contour line on top of subsalt rocks and thus were determined more by economic considerations than by geologic conditions. However, each AU is defined in a way that includes carbonate platforms with reefs and their basinward slopes. The fifth AU (10160106) includes suprasalt rocks that cover the entire total petroleum system area. Assessment results for undiscovered conventional oil and gas for these five assessment units are shown in table 1, and supporting statistical data on the assessment can be found in U.S. Geological Survey World Energy Assessment Team (2000). The sixth AU (10160105), which includes Paleozoic subsalt rocks that occur at depths greater than 7 km in the central basin area, is considered unconventional and has not received quantitative assessment.

Assessment Unit 10160102, North and West Margin Subsalt Barrier Reefs

This AU includes barrier reef prospects of the north and west basin margin (figs. 1, 3). Most fields in the unit are in the Lower Permian barrier reef, although two or three fields have been discovered in Bashkirian carbonates of the Lower–Middle Carboniferous (upper Visean–Bashkirian) reef trend. All fields are small because of limited trap volume, and future discoveries are expected to also be of small size (table 1). The Lower Permian reef is extensively explored, but little drilling has penetrated the Carboniferous and, especially, the Upper Devonian barrier reefs that extend for many hundreds of kilometers. All of these pre-Permian prospects are at depths of 4–5 km and greater. Petroleum potential of the unit is relatively low. Gas with medium to high condensate content will probably dominate in resources (table 1).

Assessment Unit 10160101, North and West Margin Subsalt Pinnacle Reefs

The AU covers the same area as AU 10160102, but includes prospects other than barrier reefs. Only one field has been discovered in the unit, but that one was the giant Karachaganak gas condensate and oil field (fig. 4). The field is in an Upper Devonian to Middle Carboniferous atoll that is unconformably overlain by a Lower Permian pinnacle reef. The height of the hydrocarbon column is about 1,600 m, perhaps one of the thickest in the world. Atolls and pinnacles surrounded by Lower Permian basinal facies are expected to be the dominant trap type for future discoveries. The presence of structural traps in some areas is also possible, and Bashkirian carbonates are the principal exploration targets in these traps. Most likely areas for new field discoveries are in the vicinity of the Karachaganak field, in the Karasal monocline in the southwest corner of the basin, and in suspected Carboniferous (and possibly Upper Devonian) carbonate banks basinward from the Lower Permian barrier reef (mainly along the west basin margin). The main deterrent to exploration within this AU is the great depths to exploration targets—deeper than 5 km and in many areas deeper than 6 km. Exploration risk at great depths is aggravated by poor seismic resolution in the salt dome environment. Gas condensate will probably be the dominant hydrocarbon resource, although some light oil discoveries are probable, especially on the Karasal monocline. Estimates of undiscovered resources for the AU are shown in table 1.

Assessment Unit 10160103, East and Southeast Margin Subsalt

This AU includes subsalt rocks of the east and southeast basin margin (fig. 1). The AU encompasses Devonian and (or) Carboniferous carbonate platforms, the deep Aktyubinsk and Ostansuk troughs that are filled with Lower Permian molasse clastics, and basement arches of the Astrakhan-Aktyubinsk system located west of the carbonate platforms. The main fields in the AU are in Middle Carboniferous carbonate reservoirs in structural traps, and a few are probably in reefs (fig. 5). Several tens of known structural traps are reportedly undrilled (Dalyan, 1996). Small oil accumulations (including some paleo-biodegraded oils) occur in Lower Carboniferous and Lower Permian clastic rocks in which the trap types are poorly understood. Reefs are not well developed in this AU, possibly because the area was on a leeward side relative to dominating wind direction. The best potential for both oil and gas is in the Lower to Middle Carboniferous carbonate platform north of the main discovered fields (Zhanazhol field area, fig. 2). This includes the Temir carbonate platform (fig. 10), where only a few wells have been drilled. Drilling depths to the top of the carbonate platform range from about 4 km in the south to more than 7 km in the north. On the slope of the South Emba high (southeast basin margin), the carbonate platform is narrow. A portion of this platform and the overlying Kungurian salt seal are truncated by the pre-Jurassic unconformity. Potential for new field discoveries in this area is low. Locations of Devonian (including Lower Devonian) carbonate platforms along the entire east-southeast margin are poorly understood. They may extend westward from edges of the Middle Carboniferous platforms and cover crests of the basement arches. Drilling depths to the Devonian prospective reservoirs will range from about 5 to 7 km.

Potential of the Lower Carboniferous Izembet Formation is uncertain because few data are available. Reservoir rocks preserve porosity to depths of 6 km (Biikzhal field), but sandstones are lenticular (Proshlyakov and others, 1987). However, this largely stratigraphic play covers the entire assessment unit area, and significant discoveries are possible. Drilling depths range from about 4 to 7 km. Sweet oil will constitute the major portion of resources.

Lower Permian orogenic molasse clastics in anticlines toward the east side of the Aktyubinsk trough (fig. 10) were drilled in the 1960's. The Kungurian evaporite seal is absent in this area, and the clastic rocks crop out on the surface. All wells had significant gas shows, but reservoir rocks were tight. These low permeable clastics likely contain an unconventional continuous (basin center) gas accumulation (not assessed in this report). A similar accumulation was recently identified in correlative orogenic clastics in more northern areas of the Ural foredeep, in the Timan-Pechora basin (Law and Spencer, 1998). In the more western anticlinal trends of the Aktyubinsk trough, reservoir properties probably improve because of decreased tectonic stress (Zholtaev, 1990), and the Kungurian evaporite seal is present. Conventional gas fields may be found there and may be large, because individual anticlinal traps have large sizes. Petroleum potential of Lower Permian clastics in prospects other than these large traps, including traps in the Ostansuk trough immediately south of the area shown in figure 10, is not high because of poor reservoir properties of sandstones (exemplified by subsalt pools of the Kenkiyak field). However, many smaller pools may be found in structural traps as well as in stratigraphic traps in progradational clinoforms. Stratigraphic traps may also be present in turbidites on slopes of the deep-water basin west of the Carboniferous carbonate platforms (figs. 5, 10).

Assessment Unit 10160104, South Margin Subsalt

This AU, occupying the southern basin margin, was estimated to have the highest amount of undiscovered resources in the North Caspian Paleozoic TPS (table 1). The AU includes the Karaton-Tengiz zone of carbonate buildups east of the Caspian Sea (fig. 6), the Astrakhan carbonate platform west of the sea (fig. 8), and the entire offshore area of the basin (fig. 7). It also contains the giant Tengiz oil and Astrakhan gas fields—the two largest discoveries in the basin (exclusive of the recent Kashagan discovery, whose size, although great, is yet to be estimated). In the east part of the northern Caspian shelf, seismic surveys identified three carbonate buildups morphologically similar to the Tengiz atoll (Murzagaliev, 1995; this report, fig. 7); the Kashagan discovery is in one of these buildups. A carbonate platform similar to the Astrakhan platform extends offshore from the west coast of the sea. During the last 2 years, a consortium of Western oil companies has conducted new seismic surveys offshore, but the results of these surveys were unavailable for this study. Therefore, the present resource assessment (made before the Kashagan discovery) relied heavily upon the data presented in Murzagaliev (1995). Although the assessment was made before the Kashagan discovery, the potential for giant field discoveries in the AU was recognized.

The principal uncertainty in assessment of the Tengiz-type carbonate buildups offshore is the integrity of the Kungurian evaporite seal. The Tengiz atoll and the satellite Korolev pinnacle are properly sealed and productive. The Karaton and Tazhigali reefs of the Primorsk carbonate buildup north of Tengiz (fig. 7) contain only small pools of residual heavy oil. Apparently, oil leaked upward through areas where salt is thin or absent, which is indicated by the presence of oil fields in suprasalt Mesozoic rocks at both Karaton and Tazhigali. Exploration risk is significant in this area because existing data do not allow evaluation of which offshore structures are properly sealed; however, where sufficient seals occur, the resulting field could be large. Smaller pinnacles on the carbonate pedestals are also likely, but because of the smaller areas involved, the sealing risk for these prospects is lower. Light gassy sour oil is more probable, but gas with a high condensate content is also possible, as reflected in the assessment (table 1).

The carbonate platform in the western part of the Caspian shelf strongly resembles the Astrakhan platform (fig. 7). However, seismic data do not indicate the presence of salt domes (Murzagaliev, 1995). If the salt is present, but thinner and undeformed, the sealing conditions could be excellent and the hydrocarbon potential is high. If the evaporite seal is absent, on the other hand, large accumulations are unlikely. Reefs along the perimeter of the platform and structural traps on the platform are the main prospects. Sour gas with a high to moderate amount of condensate is the likely hydrocarbon type, but pools of light oil and oil legs in gas pools may also be present.

To the north, carbonates of the Astrakhan and Karaton-Tengiz massifs grade into basinal black-shale facies. Recently two or three wells penetrated into subsalt strata on top of the Guryev arch (central segment of the Astrakhan-Aktyubinsk system of highs) where Lower Permian (?) clastics devoid of reservoir rocks were encountered (B.M. Kuandykov, oral commun., 2000); additional information on these wells is not available. No other deep wells have been drilled in this entire area. Paleogeographic reconstructions suggest that source rocks may be present in the Upper Devonian–Carboniferous interval, but this interval probably does not contain reservoir rocks. Composition of older rocks is unknown. The petroleum potential of the AU's areas north of the carbonate platforms and buildups between Astrakhan and Primorsk (fig. 7) is therefore uncertain, but probably is low, especially for conventional accumulations. Drilling depths to the top of the subsalt sequence are mainly in the range from 6 to 7 km.

The petroleum potential of the Karakul-Smushkov zone of thrust-related anticlines extending along the south basin boundary west of the Caspian Sea (fig. 2) is low. The southwestern part of the zone is devoid of a salt seal. In the northeastern part, the salt is underlain by tight Middle Carboniferous–Lower Permian clastic rocks. Below the clastics are subthrust autochthonous Bashkirian carbonates in which gas was tested in several wells. However, the gas contains high carbon dioxide contents, ranging from 25 to almost 100 percent, and the accumulations are noncommercial.

Assessment Unit 10160105, Basin Center Subsalt

This AU includes subsalt rocks of the central basin areas. Depths to the top of the AU everywhere exceed 7 km and reach as much as 10 km. No wells have been drilled to these depths, and the composition of the subsalt section may only be inferred from regional paleogeographic reconstructions. Petroleum potential of the AU was not quantitatively assessed in this study as no explored analogs are present worldwide and almost no experience of exploration at these depths exists. Based on data from the basin margins, however, it is probable that the Upper Devonian–Lower Permian sequence of the AU consists of alternating strata of organic-rich black shales (potential source rocks) and turbidites (potential reservoirs). Black shales are correlative to carbonate platforms on the margins, and turbidites are stratigraphic equivalents of clastic wedges. Ages of these rock types vary in different parts of the basin. Underlying Silurian–Middle Devonian rocks probably are lithologically similar. Synrift coarse clastics of Ordovician(?) age occur at extreme depths of more than 12–15 km. All the rocks are sealed by Kungurian salt and are probably highly overpressured. Whether clastic turbidite rocks can preserve porosity and permeability at these conditions and be capable of producing hydrocarbons is unclear. Possibly, unconventional oil and (or) gas accumulations of continuous type can be present. Exploration is obviously uneconomic at present, but large amounts of generated hydrocarbons, a part of which could have been preserved below the salt seal, provide impetus for future investigation.

Assessment Unit 10160106, Suprasalt

This AU geographically covers the area of the entire North Caspian Paleozoic TPS and stratigraphically includes suprasalt rocks. Although drilling for oil within this AU started at the beginning of the 20th century, exploration is still in the immature stage. Until recently, the resolution of seismic surveys was inadequate to define prospects in depressions between salt domes and near steep salt walls. Virtually all field discoveries are shallow; only a few were made at depths exceeding 1 km. Suprasalt rocks in depressions reaching thicknesses of 6–7 km and probably greater represent a significant exploration opportunity. Recent seismic exploration has revealed new types of traps in Upper Permian–Triassic rocks in the depressions and below salt overhangs (Dalyan, 1998; Groshev and others, 1993). These traps have received almost no exploration.

The great majority of discoveries have been made in the eastern-southeastern part of the basin (North Emba and South Emba regions) where oil fields dominate. Only a few fields, many of them gas, have been found in the rest of the assessment unit. The causes for concentration of fields in east and southeast areas of the basin are not clear. Probably, for some yet unknown reasons migration of hydrocarbons from subsalt sources into Jurassic and Cretaceous reservoirs was more facile in these areas. However, the relative abundance of discovered fields in the east and southeast areas compared to the rest of the AU may at least partly stem from the fact that far less exploration has been conducted outside the North and South Emba regions. Tertiary sediments (especially thick upper Pliocene shales and sands), which are much more widespread in the western and central areas of the AU, may inhibit surface seeps that for many years were used in the North and South Emba regions to define exploration targets. Potential resources of the AU are significant, considering the presence of more than 1,000 salt domes in the basin (table 1). Discovery of giant fields similar to those in subsalt rocks has a low probability, but many medium-size fields may yet be found.

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