Petroleum Geology and Resources of the West Siberian Basin, Russia

By Gregory F. Ulmishek
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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 52 "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 total 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:

Example 1
Province, three digits to the right of region code 1174
Total petroleum system, two digits to the right of province cod 117401
Assessment unit, two digits to the right of petroleum system code 11740104

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 systems 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 center points, shown on this map, are reproduced, with permission, from Petroconsultants (1996).

Abstract

The West Siberian basin is the largest petroleum basin in the world covering an area of about 2.2 million km2. The basin occupies a swampy plain between the Ural Mountains and the Yenisey River. On the north, the basin extends offshore into the southern Kara Sea. On the west, north, and east, the basin is surrounded by the Ural, Yenisey Ridge, and Turukhan-Igarka foldbelts that experienced major deformations during the Hercynian tectonic event and the Novaya Zemlya foldbelt that was deformed in early Cimmerian (Triassic) time. On the south, the folded Caledonian structures of the Central Kazakhstan and Altay-Sayan regions dip northward beneath the basin's sedimentary cover. The basin is a relatively undeformed Mesozoic sag that overlies the Hercynian accreted terrane and the Early Triassic rift system. The basement is composed of foldbelts that were deformed in Late Carboniferous–Permian time during collision of the Siberian and Kazakhstan continents with the Russian craton. The basement also includes several microcontinental blocks with a relatively undeformed Paleozoic sedimentary sequence.

The sedimentary succession of the basin is composed of Middle Triassic through Tertiary clastic rocks. The lower part of this succession is present only in the northern part of the basin; southward, progressively younger strata onlap the basement, so that in the southern areas the basement is overlain by Toarcian and younger rocks. The important stage in tectono-stratigraphic development of the basin was formation of a deep-water sea in Volgian–early Berriasian time. The sea covered more than one million km2 in the central basin area. Highly organic-rich siliceous shales of the Bazhenov Formation were deposited during this time in anoxic conditions on the sea bottom. Rocks of this formation have generated more than 80 percent of West Siberian oil reserves and probably a substantial part of its gas reserves. The deep-water basin was filled by prograding clastic clinoforms during Neocomian time. The clastic material was transported by a system of rivers dominantly from the eastern provenance. Sandstones within the Neocomian clinoforms contain the principal oil reservoirs. The thick continental Aptian–Cenomanian Pokur Formation above the Neocomian sequence contains giant gas reserves in the northern part of the basin. Three total petroleum systems are identified in the West Siberian basin. Volumes of discovered hydrocarbons in these systems are 144 billion barrels of oil and more than 1,300 trillion cubic feet of gas. The assessed mean undiscovered resources are 55.2 billion barrels of oil, 642.9 trillion cubic feet of gas, and 20.5 billion barrels of natural gas liquids. The largest known oil reserves are in the Bazhenov-Neocomian total petroleum system that includes Upper Jurassic and younger rocks of the central and southern parts of the basin. Oil reservoirs are mainly in Neocomian and Upper Jurassic clastic strata. Source rocks are organic-rich siliceous shales of the Bazhenov Formation. Most discovered reserves are in structural traps, but stratigraphic traps in the Neocomian clinoform sequence are pro-ductive and are expected to contain much of the undiscovered resources. Two assessment units are identified in this total petroleum system. The first assessment unit includes all

conventional reservoirs in the stratigraphic interval from the Upper Jurassic to the Cenomanian. The second unit includes unconventional (or continuous), self-sourced, fractured reservoirs in the Bazhenov Formation. This unit was not assessed quantitatively.

The Togur-Tyumen total petroleum system covers the same geographic area as the Bazhenov-Neocomian system, but it includes older, Lower–Middle Jurassic strata and weathered rocks at the top of the pre-Jurassic sequence. A Callovian regional shale seal of the Abalak and lower Vasyugan Formations separates the two systems. The Togur-Tyumen system is oil-prone; gas reserves are insignificant. The principal oil reserves are in sandstone reservoirs at the top and bottom of the Lower–Middle Jurassic Tyumen Formation; comparatively small reserves are in pre-Jurassic carbonate and clastic rocks. The principal source rocks are lacustrine to marine shales of the Toarcian Togur Bed. Traps are structural, stratigraphic, or a combination of the two. The total petroleum system was ass-sessed as a single assessment unit. Most of the undiscovered resources are expected in stratigraphic and combination traps.

The northern onshore and offshore parts of the basin are included in the Northern West Siberian Mesozoic Composite total petroleum system that encompasses the entire sedimentary cover. The system is strongly gas-prone; it contains giant gas reserves and comparatively small oil reserves. The major part of hydrocarbon reserves is dry gas in the upper Aptian–Cenomanian sandstones (Pokur Formation and equivalents). Smaller reserves of wet gas and some oil are in Jurassic and Neocomian sandstones. Source rocks for the dry gas in the Pokur Formation that constitutes more than 80 percent of the hydrocarbon reserves are unknown. Wet Neocomian gas and oil were generated from Jurassic source rocks, including the Bazhenov Formation. Almost all discovered reserves are in structural traps; however, stratigraphic traps in the Neocomian interval probably contain large undiscovered gas resources. The onshore and offshore parts of the total petroleum system were assessed as separate units because of different exploration maturity and different infrastructure requirements. The onshore area is substantially explored, especially in the shallow Aptian–Cenomanian sequence, whereas only three exploratory wells have been drilled offshore. Undiscovered gas potential of both assessment units is very high.

Introduction

The West Siberian basin is the richest petroleum province of Russia and the Former Soviet Union. The location and boundaries of the basin are shown in figure 1. Discovered petroleum volumes in the basin are listed at 355.6 billion barrels of oil equivalent (BBOE) in the Petroconsultants (1996) file, of which 59.6 percent is gas. The basin is ranked 1st among 128 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 basin contains several tens of giant and supergiant oil and gas fields, including the Samotlor oil field with nearly 28 billion barrels (BB) of original oil reserves and the Urengoy gas field with more than 350 trillion cubic feet (TCF) of original gas reserves (fig. 15).

Three total petroleum systems (TPS) are identified in the West Siberian basin. Two of them occupy the central and southern areas of the basin and are stratigraphically superposed. The upper TPS, Bazhenov-Neocomian, contains the bulk of the basin’s oil reserves. Source rocks for this TPS are deep-marine, organic-rich, siliceous shales of the Volgian–Berriasian Bazhenov Formation. The principal reserves of the TPS are in

Neocomian deltaic sandstone reservoirs. Upper Jurassic sandstones underlying the Bazhenov Formation are also productive. The Togur-Tyumen TPS covers the same area and stratigraphically underlies the Bazhenov-Neocomian TPS. The principal source rocks of the Togur-Tyumen TPS are lacustrine to marine organic-rich shales of the Toarcian Togur Bed. The main reservoir rocks are sandstones in the largely continental Tyumen Formation of Early–Middle Jurassic age. Possibly, some hydrocarbons in Upper Jurassic reservoirs also were derived from Togur source rocks. The Togur-Tyumen TPS contains 8.4 percent of the basin’s oil reserves. The Northern West Siberian Mesozoic Composite TPS is in the northern part of the basin, and it extends offshore into the Kara Sea. The TPS contains the dominant part of the basin’s gas reserves and relatively small volumes of discovered oil. Most gas reserves are reservoired in continental clastics of the upper Aptian–Cenomanian Pokur Formation; smaller volumes of gas are contained in Neocomian sandstones. Source rocks for the gas are not known with certainty; most investigators suggest that the gas was generated from marginally mature, continental to paralic, coal-bearing rocks of the Pokur Formation.

The first hydrocarbon discovery was made in 1953, when a well tested gas in the Berezov field on the western margin of the basin. Most of the giant oil and gas fields that contain the bulk of the basin’s reserves were discovered during the 1960s and 1970s. In the following years, the sizes of newly discovered fields gradually diminished. Large-scale production began in the early 1970s, and presently the basin produces over three-quarters of both oil and gas in Russia. In spite of large volumes of drilling and seismic surveys, the basin remains only moderately explored, especially in its northern regions. Only three wells have been drilled offshore in the Kara Sea, and they discovered two potentially giant gas fields. Five assessment units (AU) were identified in the three TPS of the basin. One AU embraces the entire Togur-Tyumen TPS. The second AU encompasses the Bazhenov-Neocomian TPS except for unconventional self-sourced fractured reservoirs of the Bazhenov Formation. These reservoirs were included in a third AU that has not been quantitatively assessed. Two AU were identified in the Northern West Siberian Mesozoic Composite TPS; one of them encompasses the onshore area of the TPS and the other is offshore. Because the exploration maturity is dissimilar, size distributions of undiscovered fields in these two AU are different.

Province Overview

Province Location and Boundaries

The West Siberian basin occupies a large swampy plain between the Ural Mountains and the Yenisey River and extends offshore into the southern part of the Kara Sea (fig. 1). The permafrost is hundreds of meters thick in the northern onshore areas of the basin and gradually thins to zero north of the east-west segment of the Ob River. The basin, with an area of more than 2.2 million km2, of which almost 350,000 km2 is offshore, is one of the largest petroleum-productive regions in the world. The Ural foldbelt is a Hercynian structure, where deformation and orogeny started in Late Carboniferous to Early Permian time and continued into the Triassic. The northwestern part of the basin boundary both onshore and offshore is the Novaya Zemlya foldbelt (fig. 1), which is a continuation of the present day structure of the Urals. However, the Novaya Zemlya foldbelt is younger than the Urals, and the main deformation there had not occurred until Triassic time.

To the south, the Mesozoic–Tertiary sedimentary fill of the West Siberian basin gradually thins and pinches out toward the Central Kazakhstan and Altay-Sayan folded regions (fig. 1). The southern boundary of the West Siberian basin is drawn approximately along the 1.5-km isopach of the Mesozoic sedimentary cover. South of the boundary, Jurassic–Tertiary sedimentary rocks are water-flushed, and no oil or gas shows have been detected there. Both folded regions have complex structural frameworks and histories of development. Most areas of the foldbelts consist of a mosaic of Precambrian massifs separated by volcanic arcs, accretionary clastic wedges, and deep-ocean sediments (Khain, 1977, 1979). Final accretion of these structures took place in Silurian time. The accretion was followed by the principal stage of orogeny and deposition of orogenic molasse clastics in the Devonian. However, two remnant oceanic basins, the Junggar-Balkhash basin in the Central Kazakhstan region and the Zaysan-Gobi basin in the Altay-Sayan region were closed only in Carboniferous time, and orogeny and deformations continued into the Permian. The shallow Turgay depression, filled with upper Mesozoic and Tertiary rocks less than 1,500 m thick, joins the West Siberian basin at its southwestern corner (fig. 1) where the basin boundary crosses the crest of a structural saddle that separates these two structures. On the east side, the West Siberian basin is bounded by the Yenisey Ridge foldbelt and its northern continuation, the Turukhan-Igarka uplift. The Yenisey Ridge foldbelt is composed of very thick (10–12 km) Riphean (Late Proterozoic) clastic and carbonate rocks that were deposited on the passive margin of the Siberian continent. The rocks were strongly deformed, intruded by granites, and partly metamorphosed during the Baikalian orogeny 850–820 million years ago (Ma). Younger Late Proterozoic and Paleozoic strata, where preserved, consist of carbonate and clastic rocks deposited in platform conditions. These rocks extend westward under the Mesozoic–Tertiary cover of the West Siberian basin. The entire sedimentary section of the Yenisey Ridge was again deformed, folded, and thrust eastward during the Hercynian orogeny owing to collision of the Siberian and Kazakhstan continents with the Russian craton (Basharin and others, 1996). The Turukhan-Igarka uplift (fig. 1) is poorly exposed and less studied. However, its geology is believed to be generally similar to that of the Yenisey Ridge foldbelt (Milanovsky, 1987).North of the Turukhan-Igarka uplift, the West Siberian basin borders the Yenisey-Khatanga basin and the southwestern slope of the Taimyr-Kara high (fig. 1). The Yenisey-Khatanga basin is a northeastern structural bay of the West Siberian basin. Although the Mesozoic–Tertiary stratigraphic successions of the two basins have much commonality, the basins are structurally separated by Mesozoic uplifts in the westernmost part of the Yenisey-Khatanga basin. The Yenisey-Khatanga basin probably is a Mesozoic–Tertiary sag that was formed above an Early Triassic rift (Kontorovich, 1994). The central zone of the rift graben is marked by strong magnetic and gravity anomalies related to intrusion of basic rocks (Yaskevich and others, 1980). Early Cretaceous compression and partial inversion of the rift resulted in formation of narrow, elongated arches in the central area of the basin. The Taimyr-Kara high consists of the Taimyr foldbelt in the south and two continental tectonic blocks to the north. The foldbelt was originally deformed in Late Carboniferous or Permian time and then experienced major deformation in Late Jur-assic to Early Cretaceous time (Zonenshayn and others, 1990). Offshore in the Kara Sea, the West Siberian basin boundary extends along a large uplifted structure, the North Siberian sill. Limited seismic data indicate that the Mesozoic–Tertiary sequence on the top of the sill is only about 1 km thick, and Cretaceous rocks directly overlie the basement (Kulakov, 1984). The sill connects the northern parts of the Novaya Zemlya foldbelt and Taimyr-Kara high.

Tectono-Stratigraphic Development

The West Siberian basin is a gentle Mesozoic–Tertiary sag superposed over the Early Triassic rift system. The basement of the basin is heterogeneous; it consists of various tectonic terranes accreted during the Hercynian closing of oceanic basins and collision of the Siberian and Kazakhstan continents with the eastern margin of the Russian craton. Structures of the Hercynian Ural foldbelt plunge eastward under Mesozoic rocks and compose the basement on the western margin of the West Siberian basin (fig. 2). Another Hercynian foldbelt extends northward in the central part of the basin; this foldbelt resulted from Late Carboniferous–Permian closing of the Ob-Zaysan ocean—a northern continuation of the Zaysan-Gobi oceanic basin of the Altay-Sayan region. Prior to closing, the Ob-Zaysan oceanic basin was connected with the Uralian ocean south of the Yamal Peninsula. These two oceanic basins bounded the Uvat (Khanty-Mansi) massif that may have been a continuation of the Kazakhstan continent or a separate microcontinent with the Precambrian(?) basement (Zonenshain and others, 1990). Caledonian structures of the Central Kazakhstan and Altay-Sayan folded regions extend to the north, where they underlie Mesozoic rocks of the southern part of the basin. These structures include another large microcontinental block (Mezhov massif) covered by only slightly deformed Paleozoic platform carbonates (Kontorovich and others, 1991). A few other microcontinental blocks are possibly present inside the Hercynian and Caledonian foldbelts (fig. 2).

In the eastern part of the West Siberian basin, the basement is formed by the western continuation of the Siberian platform (fig. 2). This area of the platform is underlain by Precambrian microcontinental blocks (Surkov and others, 1996) and by the western continuation of the Yenisey Ridge foldbelt. The microcontinents collided with the passive margin of the Siberian continent at about 850–820 Ma, which resulted in the Baikalian orogeny, metamorphism, and formation of the foldbelt. The microcontinents and folded structures were subsequently overlain by latest Proterozoic and Paleozoic platform deposits, including thick Lower Cambrian salt. These deposits were identified by seismic surveys and penetrated by wells below Mesozoic rocks of the West Siberian basin in a zone approximately 150–200 km wide (Kashtanov and Filippov, 1994; Kontorovich, Danilova, and others, 1999a). Deformed and metamorphosed lower Paleozoic volcanics and clastics were drilled in a well west of the buried margin of the Siberian platform (Kontorovich, Saraev, and others, 1999).

The composition of the basement in the northern part of the West Siberian basin, including the southern Kara Sea, is disputable and remains largely unknown. Many geologists believe that subhorizontal reflectors seen on seismic records below Triassic sedimentary and volcanic rocks indicate the presence of upper and lower Paleozoic platform sedimentary strata overlying the Precambrian basement (Aplonov, 1986; Girshgorn and others, 1987; Rudkevich and others, 1988). Other geologists argue that the basement in northern West Siberia probably is composed of deformed and metamorphosed Paleozoic rocks similar to those drilled on the southern shore of the Ob Inlet (fig. 1) (Bochkarev, 1995). The subhorizontal reflectors below the Triassic sequence are interpreted as density inhomogeneities in basement rocks. A recent seismic interpretation shows that Paleozoic carbonates of the Siberian platform may extend west as far as the eastern Yamal Peninsula (Brekhuntsov and others, 2001).

The available data indicate that in most of the West Siberian basin, the basement probably consists of deformed and variously metamorphosed Paleozoic rocks. This folded basement includes Precambrian massifs (microcontinental blocks) overlain by weakly deformed lower and middle Paleozoic, largely carbonate rocks and the eastern margin of the Siberian platform. In these areas, pre-Mesozoic rocks may contain targets for oil and gas exploration. The two largest identified Precambrian massifs are the Uvat (Khanty-Mansi) massif east of the Ural foldbelt and the Mezhov massif in the southeastern part of the basin (fig. 2). A large Precambrian massif may also underlie the northern part of the basin and extend offshore into the Kara Sea; however, the existence of this massif is uncertain. All structural units of the basement are intruded by Hercynian granite plutons. After Hercynian compression and deformation, Paleozoic rocks were deeply eroded in pre-Triassic time. The next, taphrogenic stage of basin development took place in Early Triassic time, when the Paleozoic basement was rifted and the rifts were filled by largely basic and ultrabasic volcanic rocks of the Turin series (fig. 3). The largest and better-studied rift, the Koltogor-Urengoy rift, extends onshore for 1,800 km from the south to the north, deepening northward, and probably continues offshore across the entire southern Kara Sea (Ryabukhin and Zinin, 1992). In its north-central part, the rift graben was penetrated by a deep stratigraphic test (Tyumen superdeep well SG-6), which drilled through more than 1,000 m of Lower Triassic basic volcanics with beds of tuffs and clastic rocks (Kazakov and others, 2000). Several other rifts of regional dimension are also present (fig. 3). Much thinner Triassic basalts, dolerites and their tuffs were also penetrated by many wells outside the main rifts in the southern and central parts of the basin. These extrusives fill local grabens and depressions and form volcanic plateaus (Nesterov and Bochkarev, 1991). These rocks are generally correlative with Triassic plateau basalts and tuffs of the Siberian platform and Taimyr foldbelt, which were formed during a regional extensional event. Deposition of the basinal sedimentary cover of West Siberia commenced in Middle Triassic time in the northern part of the basin. During the Triassic and through Early Jurassic time, the depositional area gradually expanded southward reaching the present-day basin boundary in Bajocian time. The Triassic Tampey series is composed of continental clastic rocks that unconformably overlie the basement or Lower Triassic volcanics (fig. 4). The overlying Lower–Middle Jurassic Tyumen Formation and its stratigraphic equivalents consist largely of continental coal-bearing clastic rocks in the southern basin areas (fig. 5). Northward, these continental rocks pass to paralic facies composed of interbedded continental and nearshore marine clastic beds. Marine rocks become more abundant northward and upward in the section. Farther north, the proportion of marine facies continues to increase until, on the Yamal and Gydan Peninsulas (fig. 1), much of the Jurassic section is composed of marine rocks. By the end of Middle Jurassic time, the Tyumen Formation completely filled the surface relief of the underlying basement and Triassic volcanics. The positive features of this relief presently are targets for petroleum exploration. Thickness of the Tyumen Formation and its stratigraphic equivalents varies from 150–200 m in the southern basin areas to 2–2.5 km on the Gydan Peninsula (fig. 5). The total thickness of the Tampey series and Tyumen Formation is greatest (1–5 km) in depressions over the Early Triassic rifts, whereas on the intervening uplifts between the rifts it does not exceed 500 m (Surkov, 1998). A marine transgression started in Callovian time and covered the entire basin except its extreme southeastern part that lies outside the total petroleum system boundaries. Through Kimmeridgian time, the transgression deposited clastic sediments 50 – 200 m thick. In the central and southern parts of the basin, the Callovian–Kimmeridgian section consists of alternating sandstones and shales of the Vasyugan Formation, which is 50–150 m thick over most of the area and thickens to 400 m in the northeastern area (fig. 6). To the west and north, sandstones pinch out, and the section consists of deeper-marine shales of the Abalak Formation (fig. 4). Farther west, in the marginal zone of the basin, the Upper Jurassic section is composed of nearshore coarse clastics of the Vogulkin Formation that commonly overlies the basement on local uplifts. The first hydrocarbon discovery in the West Siberian basin was gas in the Vogulkin Formation of the Berezov field (fig. 15).

In Volgian– early Berriasian (latest Jurassic–earliest Cretaceous) time, a deep-water anoxic depression formed in the entire central part of the West Siberian basin. The area of the deep-water depression exceeded one million km2, and over this area the depth of the sea was more than 300 m (Vyshemirsky, 1986) and probably was as much as 700 m (Rudkevich and others, 1988). Black, organic-rich, siliceous shales of the Bazhenov-Formation were deposited in the deep-sea basin, whereas thicker nearshore organic-lean shales devoid of sandstone beds accumulated in marginal zones (fig. 7). Although the Bazhenov Formation is only 20–50 m thick, it is the principal oil-source rock in West Siberia. On the Yamal and Gydan Peninsulas, shales of the Bazhenov Formation contain less organic matter indicating more hydrodynamically active environments at the sea bottom. The Bazhenov Formation is locally absent on crests of some of the uplifted structures probably due to pre-Cretaceous erosion (Aleksin and others, 1983).

During Neocomian time, the Bazhenov deep-water basin was gradually filled with deltaic clastic wedges. The dominant amount of clastic material was derived from the Siberian platform, and the clastic wedges (clinoforms) prograded westward. Seismostratigraphic studies indicate the presence of 19 (Mkrtchyan and others, 1987) to 25 (Kunin and others, 1993) major west-facing clinoforms in the stratigraphic interval from the Berriasian to the Barremian. Each clinoform consists of a shelf zone that is formed by near parallel, subhorizontal sandstone and shale beds deposited in shallow water, a slope with beds tilted basinward, and a deep-water zone at the toe of the slope that is filled with turbidite deposits. An example of the stratigraphic relationships in a clinoform is shown in figure 8. The clinoforms are a few tens of kilometers wide and hundreds of kilometers long extending from the south to the north end of the West Siberian basin. They are also present in the southern Kara Sea, where at least 7 clinoforms have been identified on seismic profiles (Sosedkov, 1993). Thickness of each clinoform at the shelf break varies from 50 to 150 m (Mkrtchyan and others, 1990). The tilt of beds on the clinoform slope varies from 2• to 5•. The shallow-shelf Neocomian section of the central areas of the basin is divided into the Megion and Vartov Formations (fig. 4). Slope deposits and toe-of-slope clastic fans are combined into the Achimov Formation that includes rocks from the Berriasian Stage in the east to the Barremian Stage in the west. East-facing clinoforms that were derived from the Ural provenance are identified from seismic data on the western margin of the West Siberian basin, but they are narrow, do not contain sandstone reservoir beds, and therefore only lightly studied (Mkrtchyan and others,1990).

In the central part of West Siberia, the deep-water basin inherited from Volgian–early Berriasian time was not completely filled by Neocomian prograding clastic sediments. At the end of the Barremian, a narrow deep-water zone still existed with the axis near the western margin of the West Siberian basin (fig. 9). By Aptian time, the development of the deltaic system from the Siberian platform had terminated, and the remnant deep-water basin was filled by lower Aptian shales. The Neocomian–lower Aptian prodeltaic to shallow-marine section of this remnant basin is designated as the Frolov Formation. In the northern part of West Siberia, filling of the basin was largely completed by the beginning of late Hauterivian time (Girshgorn and Sosedkov, 1990). Berriasian–

Hauterivian prodeltaic sediments of the axial zone of the deep-water basin there that are correlative with clastic clinoforms developed to the east are designated as the Akh Formation (fig. 4). During Aptian, Albian, and Cenomanian time, shallow-marine to paralic sedimentation occurred in the western part of the West Siberian basin and on the Yamal and western Gydan Peninsulas. The sedimentary section consists of Aptian sandstones and shales of the Tanopcha Formation (or upper Aptian sandstones of the Vikulov Formation in the axial zone of the Neocomian basin), a shale section of the Albian Khanty-Mansi Formation, and largely sandstones of the Cenomanian Uvat Formation (fig. 4). In the eastern and northeastern parts of the basin, sedimentation took place on alluvial plains. The Aptian–Cenomanian section there is composed of continental coal-bearing sandstones and shales of the Pokur Formation that contains the major gas reserves of West Siberia. The total thickness of the Neocomian – Cenomanian complex increases from 1.4–1.5 km in the southern part of the West Siberian basin to a maximum of more than 2 km in the area of the Ob Inlet. A regional Turonian transgression covered the entire West Siberian basin and deposited siliceous shales of the Kuznetsov Formation (fig. 4). In the northeast part of the basin, this formation contains a sandstone tongue (Gaz-Salin Bed) that is gas-productive in several fields. The Kuznetsov Formation is overlain by a dominantly shale section of the upper Turonian–Campanian Berezov Formation and largely Maastrichtian Gankin Formation. Sandstone beds are present mainly in the marginal southern areas of the basin. The lower Berezov Formation contains a 20-m-thick bed of diatomite that is commonly saturated with gas (Agalakov and Bakuev, 1992). The Upper Cretaceous post-Cenomanian section is as thick as 600 m in the northern areas of the basin, where it constitutes the regional seal for giant gas accumulations. Marine clastic sedimentation continued until the end of middle Eocene time. A significantly different stage of basin development started in the late Eocene and continued through the rest of Tertiary time. The depocenter that was located in the northern part of the basin in the area of the Ob Inlet during all of Mesozoic time shifted to the southern part of the basin, where more than 750 m of upper Eocene–Pliocene, largely continental clastics with beds of coals, were deposited. Only during late Eocene and late Oligocene time was a shallow sea present in the southeastern part of the basin (Surkov and Smirnov, 1994). The northern part of the West Siberian basin experienced uplift and erosion that started in Oligocene time and continued until middle Pliocene time. As much as 700 m of sediments could have been removed by erosion (Surkov and Smirnov, 1994). The uplift was probably related to a west-east compressional stress that produced a substantial structural growth of high-amplitude linear arches in Mesozoic rocks. These arches contain the principal gas reserves of the basin. Late Pliocene–Quaternary glacial marine sediments as thick as 100–200 m on the Yamal and Gydan Peninsulas and on the Kara Sea shelf overlie the erosional surface. Present-Day Structure of Jurassic-Cretaceous Rocks In the structure of Jurassic–Cretaceous strata, the West Siberian basin is a gentle depression superposed on various Paleozoic structures and a system of Early Triassic rifts. The marginal zones of the basin are monoclines that are gently tilted basinward. The base of Jurassic rocks on the monoclines generally occurs at depths of 2–3 km. In the central area of the basin, the base of Jurassic strata is tilted northward from about 3–3.5 km in the south part to as much as 5–6 km in the north part. In the north, Middle–Upper Triassic sedimentary rocks are present below the Jurassic, and the base of the Mesozoic sedimentary cover may occur deeper than 8 km (Surkov and Zhero, 1981; this report, figure 2). At the top of the Upper Jurassic (regional reflector B corresponding to the Bazhenov Formation), the regional structure is gentler. This surface gently dips from the margins to 2.5–3 km in the south-central part of the basin and to 4–4.5 km in the deepest northern area (fig. 10). Jurassic–Cretaceous strata of the West Siberian basin are mildly deformed into regional arches, depressions, and monoclines (fig. 11). In the south part of the basin and on marginal monoclines, the arches are commonly isometric to moderately elongate. The closures of the arches at the base of the Jurassic do not exceed 600 m, and their amplitudes over the bottoms of the adjoining depressions are commonly 1–1.2 km (Dikenshtein and others, 1981). On flanks of the arches, the lower part of the Tyumen Formation pinches out, and in the structure of the Upper Jurassic Bazhenov Formation the arches are much gentler. A part of the structural relief at the bottom of the Jurassic is related not to structural growth during Early–Middle Jurassic time, but rather to filling of the pre-Jurassic topography. The structural relief decreases further in younger stratigraphic horizons, and many of the arches and depressions are not expressed or only slightly expressed in the structure of Upper Cretaceous and Tertiary rocks (fig. 12). Thus, the principal structural growth in marginal and southern areas of West Siberia took place during Jurassic to Early Cretaceous time. The arches contain many local uplifts with closures not exceeding 150 m and commonly less than 100 m. Faults are uncommon, and where found, their amplitudes are low (often below seismic resolution). The local uplifts on arches contain the major oil reserves of the basin. Local uplifts in the depressions are fewer, and they are less productive. The morphology of regional structures in the northern part of the West Siberian basin is different than in the southern part. The dominant structures in the north are linear arches and depressions of northern, northwestern, and northeastern strike. Closures of the arches are substantially larger than in southern areas, and at the top of the Jurassic and in Lower Cretaceous rocks the closures are as high as 1,000 m (fig. 13). Faults penetrating through Cretaceous strata are more common than in southern areas, and some of the faults show a component of lateral displacement (Belyakov and others, 1998). Much of the structural growth took place in Late Cretaceous and Tertiary time, and the structural arches are well expressed at the top of the Cenomanian reservoir where closures of gas-productive anticlines are 200–250 m (Grace and Hart, 1986; Melnikova, 1992).

Little information is available on the structural pattern of the southern Kara Sea. Limited seismic data indicate that the north to northwest trending linear structural arches extend offshore from the Yamal Peninsula (fig. 14). Three wells were drilled and tested on two uplifts of the Rusanov arch, and both uplifts contain giant to supergiant gas fields (Nikitin and Rovnin, 2000). Farther north, regional arches have a northeastern trend parallel to the Novaya Zemlya Archipelago. Closures of all arches decrease upward in the section. However, similarly to adjacent onshore areas, the arches are clearly expressed in the structure of Cenomanian and younger rocks, which indicates active structural growth during Late Cretaceous–Tertiary time (Kulakov, 1984). More than 60 local uplifts that are located on and outside the arches have been detected on the shelf (fig. 14).

Oil-and Gas-Producing Regions

Ten petroleum-producing regions are traditionally identified in the productive onshore area of the West Siberian basin (fig. 15). Although boundaries of these regions do not coincide with those of the total petroleum systems, the regions are briefly described in this report because their names are widely used in the geologic literature.

The Near-Ural petroleum region with an area of 113,000 km2 is located in the westernmost part of the West Siberian basin. About 30 oil and gas fields have been discovered there. Oil fields are concentrated in the central part of the region, whereas most gas fields are in its northern part. The majority of fields are in basal transgressive Upper Jurassic sandstones that occur directly on the basement. Overlying Upper Jurassic sandstones are also productive. All the fields are of small to medium size (not more than several tens of million barrels of oil equivalent).

The Frolov petroleum region is east of the Near-Ural region. The area of the Frolov region is 204,000 km2 (Gabrielyants and others, 1991). The principal oil reserves are in a group of fields on the Krasnolenin arch, and a large portion of the reserves is in the giant Talin field in the western part of the arch (fig. 15). Most of these fields are in Jurassic reservoirs in stratigraphic and combination structural and stratigraphic traps. Aptian sandstones are also productive. Reservoirs in the Neocomian section are few, and they are of poor quality. About 10 fields have been discovered outside the arch.

The Middle Ob region with an area of 160,000 km2 is located in the central part of the West Siberian basin, along the east-to-west-flowing part of the Ob River. The region includes the Surgut and Nizhnevartov arches where most of the giant oil fields, including the Samotlor field with reserves of more than 27 billion barrels (BB), are found. The region is dominantly oil-prone; most of the gas reserves are in gas caps of oil fields. The principal oil reserves are in Neocomian sandstone reservoirs. Much smaller reserves are in Jurassic and Cenomanian sandstones.

The Nadym-Pur region (area 166,000 km2) is situated between the Nadym and Pur Rivers north of the Middle Ob region (fig. 15). The region includes several giant gas fields, the largest of which is the Urengoy field with reserves of about 350 trillion cubic feet (TCF). Several large oil fields are also present in the southern part of the region, but their reserves constitute only 12 percent of the total hydrocarbon reserves (Gabrielyants and others, 1991). Major gas accumulations are in the Aptian– Cenomanian Pokur Formation that contains 90 percent of the gas reserves of the region. The rest of the gas reserves and most of oil reserves are in the Neocomian reservoirs. Jurassic rocks are also productive, but the reserves are much smaller.

The Pur-Taz region is in the northeastern part of the West Siberian basin, east of the Nadym-Pur region. The area of the region is 174,000 km2. Most of production is in the western area of the region; to the east, much of the section is sandy, and seals there are scarce. The region contains several giant gas pools in the Aptian–Cenomanian Pokur Formation; these pools contain 90 percent of the gas reserves of the region (Dikenshtein and others, 1983). Oil reserves are smaller, and they are largely in Neocomian and Jurassic reservoirs. A significant part of the oil reserves is in oil legs below gas accumulations. The Russkoye field contains 7 BB in-place resources of heavy oil in a leg below the 10-TCF Cenomanian gas reservoir. Large accumulations of heavy oil are uncommon in West Siberia, and the field is probably related to a large fault crossing the structure that breaches the Turonian seal and enhances biodegradation of oil.

The Yamal region with an onshore area of 111,000 km2 occupies the Yamal Peninsula in the northwestern part of West Siberia south of the Kara Sea (fig. 15). The region contains a number of large and giant gas fields, many of which are in structures of the Nurmin arch that crosses the peninsula in a northwest direction and extends offshore (fig. 11). The principal dry gas reserves are in the Cenomanian Uvat Formation (fig. 4); smaller reserves of wet gas are in Neocomian and Aptian sandstones. Oil reserves are insignificant and mainly in Upper Jurassic reservoirs.

The Gydan petroleum region (onshore area 85,000 km2) occupies the Gydan Peninsula and adjacent land in the northeastern onshore part of the West Siberian basin. Gas reserves in this region are a few tens of TCF, which is much smaller than in the neighboring Yamal region. In contrast to the Yamal region, Cenomanian reservoirs in the Gydan region are less productive and contain only about one-half of the region's reserves, probably because the quality of the Upper Cretaceous seal deteriorates eastward. Most of the rest of the gas reserves are in the Barremian–Aptian Tanopcha Formation (fig. 4); older Jurassic and Neocomian sandstones also contain gas pools, some of them with oil legs.

The Vasyugan and Paydugin petroleum regions (areas of 78,000 km2 and 185,000 km2, respectively) occupy the southeastern part of the West Siberian basin (fig. 15). Most of the Paydugin region is barren of petroleum reserves; it contains only several oil and gas fields in Upper Jurassic sandstones along its western boundary. The Vasyugan region is mostly oil-productive. The majority of fields contain oil pools in Upper Jurassic rocks. The Lower–Middle Jurassic and lower Neocomian sections also produce oil. A few pools are present at the weathered top of basement rocks.

The Kaymysov petroleum region is in the southernmost part of the West Siberian basin. The area of the region is 140,000 km2. The region is dominantly oil-productive; gas reserves are insignificant. The majority of fields and most of the reserves are in Upper Jurassic sandstone reservoirs. Many of the fields also contain reservoirs in the Lower–Middle Jurassic Tyumen For-mation and in weathered Paleozoic carbonates below the pre-Jurassic unconformity. The only hydrocarbon accumulation found in Paleozoic carbonates much deeper than the pre-Jurassic unconformity is the Maloich oil field, which is located in the Nyurol depression of the Kaymysov region (fig. 11).

Total Petroleum Systems

Three total petroleum systems (TPS) were identified in the West Siberian basin (fig. 1).

The Bazhenov-Neocomian TPS (117401) contains the principal (more than 80 percent) initial oil reserves of the basin that amount to 117.5 BB (Petroconsultants, 1996). The discovered volumes of gas are smaller and equal 97.6 TCF. The TPS occupies the central and south areas of the basin and includes six southern petroleum regions and the southern parts of the Nadym-Pur and Pur-Taz regions (figs. 1, 15). The northern boundary of the TPS separates dominantly oil-prone and dominantly gas-prone basin areas. Stratigraphically, the TPS encompasses Callovian–Upper Jurassic (Vasyugan and Abalak Formations; fig. 4) and younger rocks. Major oil reserves of the TPS are in Neocomian reservoirs in structural and, to a lesser extent, in stratigraphic traps. Upper Jurassic rocks are also regionally oil-productive, but the reserves are much smaller. The Volgian–lower Berriasian Bazhenov Formation contains unconventional self-sourced oil reservoirs in fractured siliceous shales. The in-place resources of oil in these reservoirs are probably very large, but the technical difficulties of production have not been overcome. The principal source rocks for the TPS are organic-rich marine shales of the Bazhenov Formation that are present in the entire TPS area. Neocomian prodeltaic shales possibly also generated some hydrocarbons in the western areas of the TPS, but their contribution to petroleum resources, if any, is small. Available data indicate that Bazhenov-sourced oil migrated not only upward, but also downward into underlying Upper Jurassic sandstone reservoirs (Petrov, 1994; Peters and others, 1994; Kontorovich and others, 1997). However, these reservoirs that are included in this report in the Bazhenov-Neocomian TPS may also contain an admixture of oils that were derived from older source rocks of the underlying Togur-Tyumen TPS.

The Togur-Tyumen TPS (117402) encompasses the same area as the Bazhenov-Neocomian TPS and includes the Lower– Middle Jurassic Tyumen Formation and its stratigraphic equivalents and also Paleozoic and Triassic reservoirs directly underlying the pre-Jurassic unconformity. Actually, the productive area of the Togur-Tyumen TPS extends south of that of the Bazhenov-Neocomian TPS; however, data available for this report did not allow separate mapping of the two boundaries. The Togur-Tyumen TPS is largely oil-productive; the amount of discovered oil equals 11.8 BB (Petroconsultants, 1996). Gas reserves are relatively small (3.7 TCF). These oil and gas reserves are contained in fields in which the major reservoirs are in the Tyumen Formation and directly underlying basement rocks. The reserve numbers above do not include those Tyumen Formation reservoirs that are in fields, which have the principal reserves in the overlying Bazhenov-Neocomian TPS. No data on reserves of separate pools in these fields are available, and the fields were included in the Bazhenov-Neocomian TPS. Most productive reservoirs of the Togur-Tyumen TPS are in the basal part of the Tyumen Formation, where channel sandstones are present. Higher in the section, reservoir properties of sandstones are much poorer. The principal source rocks are organic-rich shales of the lower Toarcian Togur Bed, which were deposited in lacustrine to estuarine environments (Kontorovich and others, 1997). Some oil could have been generated from other transgressive shale beds in the Tyumen Formation.

The Northern West Siberian Mesozoic Composite TPS (117403) occupies the northern petroleum regions of the West Siberian basin, north of the Bazhenov-Neocomian and Togur-Tyumen TPS, and extends into the southern Kara Sea to the basin boundary (fig. 1). The West Siberian Mesozoic Composite TPS encompasses the entire Mesozoic–Tertiary sequence. It is largely gas productive; oil is chiefly found as oil legs beneath gas caps in the Neocomian and infrequent oil pools in the Jurassic. The TPS contains about 1,230 TCF of discovered gas and 4.4 BB of oil (Petroconsultants, 1996). Dry gas in the Aptian–Cenomanian Pokur Formation and its stratigraphic equivalents constitutes the largest part of the hydrocarbon reserves (fig. 4). Smaller, but still large, reserves of wet gas occur in the Neocomian section. Jurassic rocks are sparsely productive and contain wet gas and some oil. Source rocks for gas, especially for the principal reserves of dry gas, are not known with certainty, and competing models of gas generation coexist. Multiple source rocks are probable; therefore, only one composite TPS was identified.

Bazhenov-Neocomian Total Petroleum System Discovery History Exploration in the West Siberian basin commenced after World War II, and in 1948–1953 several unsuccessful wells were drilled in the southernmost area along the Trans-Siberian railroad. The first discovery in the Bazhenov-Neocomian TPS (117401) and in the entire basin was made in 1953, when a well in the Berezov field east of the Urals (fig. 15) produced a gas flow from Upper Jurassic sandstones and organic limestones. This discovery was a disappointment as Soviet geologists were searching for new major sources for oil supply. The first success came in 1960, when the Trekhozer oil field, also in Upper Jurassic reservoirs, was opened in the Shaim area east of the Urals, about 400 km south of the Berezov field. This oil discovery stimulated further drilling, and in 1961 the first oil field in Neocomian rocks was found in the Middle Ob region. During the 1960s, a number of giant and large fields, including the largest in West Siberia, Samotlor field, were discovered in the Middle Ob region. Oil production started in 1964 and rapidly increased during the rest of the 1960s and in the 1970s. The progressive decline in the size and number of new discoveries began in the middle 1980s and continues to the present.

Petroleum Occurrence

Several hundred hydrocarbon fields have been discovered in the Bazhenov-Neocomian TPS. Most of the fields are oil; gas fields are mainly located on the western basin margin.

These gas fields are of small to medium size, and they produce from Upper Jurassic clastic and carbonate reservoirs. Separate pools of gas and gas caps are also present in oil fields.

The largest oil reserves are concentrated on the Niznevartov and Surgut arches (fig. 11) in the Middle Ob petroleum region (fig. 15), which contains more than 250 oil fields (Energy Information Administration, 1997). Sixteen oil fields of this region each contain oil reserves of more than 1 BB, and reserves of the largest, Samotlor field, exceed 27 BB (Gavura, 1996). Four more oil fields with reserves of more than 1 BB are located in adjacent areas of the Nadym-Pur and Vasyugan petroleum regions. The principal reserves are in structural traps in sandstone reservoirs of the shelf parts of the Neocomian clinoforms. Most of the fields contain several productive strata. Reserves in structural and stratigraphic traps in slope and toe-of-slope turbidite facies are smaller, although one of the giant fields, the Priob field with reserves of more than 3 BB (fig. 15), has its main pays in these deep-marine facies (Pinous and others, 1999). Many structural traps of the TPS have productive reservoirs in Upper Jurassic sandstones underlying the Bazhenov source rocks. The Aptian– Cenomanian Pokur Formation also contains some pools of heavy oil. The Bazhenov-Neocomian TPS contains large in-place resources in unconventional, self-sourced reservoir rocks. The rocks are fractured siliceous shales of the Bazhenov Formation. Oil shows and noncommercial flows were tested in a large number of wells; however, commercial production is limited to the Salym and adjacent fields in the Middle Ob petroleum region (fig. 15). The nature of the reservoir and the distribution of fractured rocks are poorly understood, and the volumes of produced oil are relatively small. Most oils in Neocomian reservoirs of the Bazhenov- Neocomian TPS are of medium gravity (29•–37• API), although lighter and heavier oils are also present. In fields with multiple reservoirs, there is a general tendency of increasing gravity of oils upward in the section. Upper Jurassic oils are commonly lighter, whereas oils in the Aptian–Cenomanian Pokur Formation are heavy (20°– 26° API) and are partially biodegraded. The content of solid paraffins varies from 1.8 to 5.1 percent, although in most oils it does not exceed 4 percent. The content of sulfur in most oils ranges from 0.8 to 1.3 percent, but in some pools it is as high as 1.9–2.1 percent. Non-associated gases in the western areas of the TPS have high concentrations of methane (90–96 percent), only 1–3 percent heavier hydrocarbon gases, 2–6 percent nitrogen, and 0.3–1 percent carbon dioxide. Source RocksOrganic-rich, siliceous, calcareous shales of the Bazhenov Formation (fig. 4) are the principal source rocks of the Bazhenov-Neocomian TPS. These rocks generated about 90 percent of oil reserves of the West Siberian basin. The genetic relationship between oils in the Neocomian to Cenomanian sequence and also oils in the Upper Jurassic reservoirs were identified in a number of recent studies (Kontorovich, Peters, and others, 1991; Peters and others, 1993, 1994; Petrov, 1994; Kontorovich and others, 1997).

The Bazhenov Formation commonly is 20–40 m thick;locally the thickness increases to 50–60 m. The formation covers an area of almost one million square kilometers and contains about 18 trillion tons of organic matter (Kontorovich and others, 1997). The sediments were deposited in a deep-water marine basin during the most extensive Late Jurassic transgression. The absence of sessile fossils and bioturbation indicates anaerobic or disaerobic conditions in bottom water and probably a euxinic environment in sediments (Vyshemirsky, 1986). The deepest part of the sea was in the central area of the West Siberian basin. The sea depths gradually decreased toward the basin margins. On the margins, Bazhenov rocks grade into less organic-rich (total organic carbon (TOC) content 1–3 percent) dark-gray shales and siltstones of proximal facies (fig. 16). Along the basin boundary, the shales give way to siltstones and sandstones with TOC of less than 1 percent. Rocks of the Bazhenov Formation are thinly laminated to massive, siliceous, carbonaceous shales with layers of argillaceous silicilith. The content of silica varies from 20 to 30 percent, and it is as high as 50–60 percent in the silicilith (Nesterov and others, 1987). The content of carbonate material (mostly coccoliths) is commonly less than 10 percent and increases from the bottom to the top of the formation (Klubova, 1988). The formation is characterized by a high level of natural radioactivity that is related to high concentrations of uranium.

The organic matter in the Bazhenov Formation is derived from plankton and bacteria. The TOC content averages 5.1 percent over the entire formation (Kontorovich and others, 1997). In a large central part of the basin, TOC is higher than 9 percent, and in many analyzed samples it is higher than 15 percent. The kerogen is of type II; it contains 7–8.5 percent hydrogen and is strongly oil-prone. In the upper part of the oil window, the hydrogen index (HI) is as high as 400–500 mg HC/g TOC. With increasing maturity, HI decreases to 100–200 mg HC/g TOC at the bottom of the oil window.

In most of the West Siberian basin, the Bazhenov Formation is presently in the thermal regime of the oil window (fig. 17). The formation is immature only on the basin periphery, where its stratigraphic equivalents are composed of organic-lean marginal facies. The maturity increases from the upper part of the oil window in the basin marginal areas to the lower part of the oil window in the central and northern areas due to increased depths of burial. Over most of the Bazhenov-Neocomian TPS, the Bazhenov Formation entered the oil window in Late Cretaceous–Paleocene time (fig. 18). The maximum maturity was reached in Pliocene time (Kontorovich and others, 1997); however, some models suggest that the maximum temperature was reached in late Eocene time (Lopatin and others, 1998). In the northernmost areas of the TPS, the maturation was terminated by uplift and erosion that started in Oligocene time.

Distal, deep-water, prodeltaic shales stratigraphically equivalent to the Valanginian–Hauterivian clinoform bodies possibly also generated some oil. These shales are present mainly in the western areas of the Bazhenov-Neocomian TPS, in the Khanty-Mansi depression and adjacent structures (fig. 11). Limited geochemical data indicate the presence of high TOC contents (4.5–9 percent) and type II kerogen (Peters and others, 1994). Actually, this prodeltaic facies, although it is stratigraphically younger, has much similarity with the facies of the Bazhenov shales. However, the Valanginian–Hauterivian prodeltaic shales are immature to marginally mature. On the basis of biomarker composition, no oils have been found that can be correlated with organic matter of these shales (Peters and others, 1994; Kontorovich and others, 1997). Even if some oils generated by the prodeltaic shales are found in the future, the contribution of these source rocks into the oil resources may not be substantial. Shales that compose Neocomian clinoforms and interfinger with productive reservoirs contain only 0.3–0.7 percent TOC and mostly terrestrial type III kerogen (Kontorovich, Peters, and others, 1991; Peters and others, 1994). The oil generation potential of these shales is negligible, and they cannot be a source for oil fields in the Middle Ob region contrary to supposition of some geologists (Maksimov, 1990; Clarke, 1994; Karagodin and Yershov, 1994). Pre-Bazhenov Upper Jurassic shales are also poor in organic matter, and they are not a source for petroleum (Kontorovich, Peters, and others, 1991).

Reservoir Rocks

Clastic reservoir rocks contain almost all oil and gas reserves of the Bazhenov-Neocomian TPS. Only in the Near-Ural petroleum region (fig. 15), have several oil and gas pools been found in Upper Jurassic limestones that onlap basement uplifts. The Neocomian clinoform section contains the economically most important oil reservoirs of the West Siberian basin that are responsible for more than 90 percent of cumulative oil production (Pinous and others, 1999). Two groups of clastic reservoir rocks are present in this section. The first group includes reservoir rocks (primarily in the Megion and Vartov Formations) that were deposited on shelves of prograding clinoforms east of their basinward slopes and in topset Barremian–Aptian strata (upper part of the Vartov Formation) that overlie the clinoforms. This group contains the most productive reservoirs of the West Siberian basin. The second group of Neocomian reservoir rocks includes sandstones and siltstones (primarily the diachronous Achimov Formation) deposited on slopes and in adjacent parts of the deep sea. Reservoir rocks of the first group (Megion and Vartov Formations) are polymictic, fine- to medium-grained sandstones and coarse-grained siltstones, mostly with clay cement. Rock fragments commonly compose 20–30 percent of the rock. The sandstones comprise a variety of shallow-water and nearshore facies such as mouth bars and wave-dominated deltas (Karagodin and others, 1994). Diagenetic alterations leading to porosity and permeability loss at depths less than 3 km are insignificant. The sandstone beds are assigned local nomenclature. The thickness of productive sandstone varies, but commonly it is as large as 30–50 m. Net pay ranges from several to 20 m. Porosity of the sandstones is high, commonly in the range of 20–26 percent. Permeability generally is higher than 100 mD and locally is higher than one darcy (Gavura, 1996; Korchemkin and others, 1997). Original oil production from wells in many fields was several hundred to a few thousand barrels per day (b/d). Reservoir properties of the second group of Neocomian sandstones (reservoirs of the Achimov Formation) that are developed on slopes of the clinoform bodies and in the toe-of-slope turbidite fans are substantially worse. Porosity is relatively high (commonly 18–20 percent), but permeability is low, varying from several millidarcies to a few tens of millidarcies. Sandstone beds, 1–2 m to several meters thick, alternate with shales. Sandstones are laterally discontinuous and form lens-like bodies. Yields of wells at early stages of field production commonly were 100 to 200 b/d or less. Many discovered oil pools in Achimov sandstones remain undeveloped.

More than one hundred oil pools have been discovered in the Bazhenov-Neocomian TPS in marine sandstones of the Callovian–Kimmeridgian Vasyugan Formation. Sandstone beds are in the upper part of the formation, whereas its lower part is composed of shales that separate the Bazhenov-Neocomian TPS from the underlying Togur-Tyumen TPS. In the Middle Ob petroleum region and adjacent areas, the thickness of the upper Vasyugan Formation is several tens of meters. The sandstones are fine- to medium-grained, quartzose and feldspathic, with clay and carbonate cement. The amount of cement ranges from 10 to 20 percent. Porosity of the sandstones in most oil fields varies from 15 to 20 percent and permeability varies from several to several tens of millidarcies. In many fields of the Near-Ural petroleum region, productive Upper Jurassic sandstones directly overlie the basement. They are coarse-grained, friable, and have high porosity and permeability. Original yields of gas from many wells were as large as 100 million cubic feet per day (MMCFD) (Korzh, 1978).

Unconventional reservoirs in fractured Bazhenov shales are poorly understood. The shales are commercially productive in the Salym and adjacent fields (Greater Salym area), where nearly 200 wells were drilled into the Bazhenov Formation and the reservoir rocks are best studied (fig. 15). No significant commercial production has been established in other areas of the Bazhenov-Neocomian TPS, although oil flows were tested in many wells. The conventional analytical measurements of porosity and permeability in cores do not reflect properties of the shale rocks at reservoir depths because of fracturing induced during drilling and lifting of the cores (Dorofeeva and others, 1992). Well logs also are unable to identify reservoir intervals in the formation (Klubova, 1988). Indirect estimates of porosity of productive reservoir rocks in the Greater Salym area vary between 5 and 10 percent. Porosity is related to leaching of silica from radiolarians (Dorofeeva and others, 1992), transformation of montmorillonite to illite (Klubova, 1988), or to both processes. Permeability of the shales results totally from fracturing, although the volume of fractures is small compared with the pore volume. Horizontal fracturing strongly dominates over fracturing in other directions. In some instances, the fracturing is so intense that the rocks cannot be cored. The fracturing was originated by hydrocarbon generation and related increase of pore pressure (Nesterov and others, 1987).

Oil produced in the Greater Salym area from fractured self-sourced reservoirs of the Bazhenov Formation contains little or no water, as bottom water in conventionally producible pools is absent. Productive wells commonly alternate with dry wells. Only about 20 percent of drilled wells are commercially productive, another 20 percent are dry, and the rest of the wells produced noncommercial or marginally commercial oil flows (Dorofeeva and others, 1992). During the last 25 years, only about 20 million barrels of oil were produced from the Bazhenov reservoirs of the area (Shakhnovsky, 1996). Oil pools are strongly overpressured; the reservoir pressure in the Salym field is 1.7 times higher that the hydrostatic pressure. At a depth of 2,700 m, the reservoir pressure is as high as 50 MPa (7,250 psi) (Matusevich and others, 1997). Laterally, the magnitude of overpressure commonly changes from well to well. The hydrodynamic connection commonly is absent even between neighboring producing wells. Nevertheless, a limited number of wells have been producing hundreds of barrels of oil per day for more than 5 years. Maximum original yields of wells were as high as 40,000 b/d; however, in most cases yields decreased abruptly in a short period of time, probably because of collapse of the reservoir rocks with decreasing pressure (Nesterov and others, 1987). The vertical and lateral extent of conventionally producible pools has not been determined. Some investigators suppose a large lateral extent of the pools despite uneven well productivities (Dorofeeva and others, 1992). Another model infers the existence of a large number of small (generally less than one million barrels) disconnected oil pools that are preferably located along tectonic faults (Lopatin and others, 1998; Lopatin and Emets, 2001). All produced oil pools in the Bazhenov Formation are probably “sweet spots” in a continuous unconventional oil accumulation, but the potential productivity of this accumulation outside the “sweet spots” has not been demonstrated and is unlikely with existing technologies. The Greater Salym area is located in a hot spot of the West Siberian basin. The temperature at the top of the Bazhenov Formation at depths of 2700 – 2800 m ranges from 115°C to 130°C (Kurchikov and Stavitsky, 1987). The Bazhenov Formation there is in the lower part of the oil window. In other areas of the Bazhenov-Neocomian TPS, maturity of Bazhenov rocks is lower. The Greater Salym area also is in the zone of maximum concentration of organic matter in Bazhenov rocks. The high content of organic matter and the advanced maturation probably resulted in more intensive hydrocarbon generation and associated fracturing (Lopatin and others, 1998).

Traps

Most of the discovered oil and gas reserves of the Bazhenov-Neocomian TPS are in structural traps. These traps contain all giant oil fields of the TPS except for the Priob field (fig. 15), in which major reserves are in a system of stratigraphic traps. The structural traps are gentle, platform-type anticlinal uplifts with dips on the flanks seldom exceeding 2°. Closures of the uplifts commonly vary from several tens of meters to 150 m. The closures are larger in the lower part of the stratigraphic section and gradually decrease upward. Faults are not common; the majority of identified faults have a displacement of a few tens of meters. These faults seldom penetrate above the Lower–Middle Jurassic Tyumen Formation. Most of the anticlinal uplifts are located on regional arches; the number of uplifts per unit of area in depressions is much smaller. High density of productive traps on regional arches is well shown in figure 11. The structural growth of the uplifts was most active in Early–Middle Jurassic time, and its intensity decreased afterwards. Some of the early discoveries in the West Siberian basin were in combination traps in the Near-Ural region. The exploration was targeted at high amplitude basement uplifts, but soon it was found that prospective Upper Jurassic reservoir rocks are absent on their crests. These rocks onlap the flanks of the uplift and form pinch-out stratigraphic traps (bald structures). Subsequently, oil pools in stratigraphic traps of the Achimov Formation were discovered in some of the giant fields of the Middle Ob region. These pools contain only small portions of the fields' reserves. They are in sandstone lenses at the base of clinoform slopes that shale out both updip and downdip, and they occur below the major pays in structural traps. Exploration targeted specifically at stratigraphic traps in the Bazhenov-Neocomian TPS began much later, when all large structural traps had been drilled. The largest success of this exploration was the discovery of the giant Priob field (commonly also called Priob petroleum zone) (fig. 15). The field was discovered in 1982 by a well drilled on a local anticlinal uplift. The principal reserves of the field (more than 90 percent) are in reservoirs of the Achimov Formation, which is composed of turbidite clastic fans developed at the base of the clinoform slope (fig. 19). Stratigraphically, the fans are separated by transgressive shale beds deposited during rises of the sea level. The largest pool in pays of the AS12 group has an area of 25 km by 45 km (Gavura, 1996). Outlines of all the pools are controlled by shaling out of turbidite sandstones; none of the pools has bottom water. Sandstone bodies on the slope of the clinoform and on the shelf margin are also productive. Sandstone turbidite fans extend northeast for about 300 km. Sandstone bodies on slopes of the clinoforms and turbidite fans contain several other large oil fields in the Middle Ob region (Girshgorn and Sosedkov, 1990). A wide morphologic variety of stratigraphic traps related to progradational deposition of the Neocomian clinoforms are abundant in the Bazhenov-Neocomian TPS, and they will be the principal exploration objective in the future (Zharkov, 2001). Stratigraphic and combination traps are not as common in Upper Jurassic rocks underlying the Bazhenov Formation. These traps are present chiefly in the marginal zones of the West Siberian basin. In addition to the combination traps in bald structures of the Near-Ural petroleum region, a high potential for finding oil pools in stratigraphic and combination traps exists in the southeastern part of the basin (Belozerov and others, 1991). The traps are developed in the transitional zone from Upper Jurassic marine facies of the central area of West Siberia to continental facies of its southeastern margin. Probable stratigraphic traps are nearshore sand bars, sandstones of tidal channels, and other geomorphic forms of the zone. Shales of the Bazhenov Formation and its stratigraphic equivalents form a regional seal for these traps.

Assessment Units

Two assessment units (AU) were identified in the Bazhenov-Neocomian TPS. The first assessment unit (11740101) includes all conventional traps in the stratigraphic interval from the Upper Jurassic to the Cenomanian. The assessment results for undiscovered oil and gas resources for this AU 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 second AU (11740102) includes unconventional traps in self-sourced, fractured, siliceous shales of the Bazhenov Formation. Because the available data are inadequate, this AU did not receive a quantitative assessment.

Upper Jurassic-Cretaceous Sandstones Assessment Unit

The Upper Jurassic-Cretaceous Sandstones AU (11740101) encompasses the entire area of the Bazhenov-Neocomian TPS (fig. 1) and includes all conventional oil and gas resources in structural and stratigraphic traps in the Upper Jurassic through Cenomanian stratigraphic interval. This AU contains the principal discovered oil reserves of the West Siberian basin and the largest part of its undiscovered oil resources. The largest fields and the main reserves of the AU are presently in Neocomian shelf sandstones in structural traps. However, all, or almost all, of the large structures have been drilled, and only smaller prospects remain. On the other hand, exploration for stratigraphic and combination traps is still in its infancy, and discovery of large reserves is expected there. The prime exploration targets are sandstone lenses on shelf margins and slopes of the Neocomian clinoforms and, especially, sandstones of the turbidite clastic fans in deep-water facies adjacent to the slopes. Given the large number of the clinoforms and their north-south extension for hundreds of kilometers, the number of prospects is very large. The majority of discoveries probably will be of medium to small size, but some large and even giant (hundreds of million barrels) fields can be expected.

The undiscovered potential of Upper Jurassic strata that underlie the Bazhenov Formation is substantially lower but still significant. Undrilled structural traps and stratigraphic traps on the basin margins will be the exploration objectives. The Pokur Formation in the assessment unit area contains mainly heavy, biodegraded oil and some gas. Its petroleum potential is relatively low. The Bazhenov source rocks are in the oil window over the entire AU area, and oil will dominate the resources.

Self-Sourced Bazhenov Fractured Reservoirs Assessment Unit

The undiscovered unconventional petroleum resources of the Self-Sourced Bazhenov Fractured Reservoirs AU (11740102) were not assessed quantitatively in this study. The quantitative assessment was precluded by the lack of data and, significantly, by the poor understanding of factors that control the formation of fractured oil reservoirs and their areal distribution. The commercially productive area of the Bazhenov reservoirs is limited to the Greater Salym area, which includes the Salym and adjacent fields (fig. 15). In recent years, flows of oil as high as 3,500 b/d were obtained in some wells in several fields on the western slope of the Nizhnevartov arch (fig. 11; Lopatin and others, 2001). Only noncommercial or marginally commercial oil flows have been tested in other areas of the TPS. Even in the Greater Salym area, only about 20 percent of the drilled wells are productive, and they alternate with dry and noncommercial wells.

A large number of studies that attempted to understand the distribution of the fractured, overpressured Bazhenov reservoirs and factors controlling their productivity have been performed during the last 25–30 years, but without significant success. In-place oil resources of the Bazhenov Formation are probably very large, but extraction of these resources meets geologic and technical difficulties. Yields of many wells that were tested at hundreds and thousands of barrels per day decrease abruptly in a short period of time, probably because of collapse of the reservoirs. Hydrofracturing and even nuclear explosions have not been proved effective. Future geologic studies and development of the appropriate drilling, completion, and production techniques possibly will provide the means for development of this potentially very large unconventional resource base.

Togur-Tyumen Total Petroleum System Discovery History

Occasional oil pools and noncommercial shows were discovered in the Togur-Tyumen TPS (117402) early in the exploration history of the West Siberian basin by deep wells that were drilled below the main exploration objectives in Neocomian rocks. However, the commercial value of these discoveries was low compared with giant oil accumulations in Neocomian reservoirs. The first significant discoveries in the Lower–Middle Jurassic Tyumen Formation were made in the early 1970s on the Krasnolenin arch in the Frolov petroleum region (figs. 11, 15). Soon it became clear that the arch contained a number of oil pools in stratigraphic and combination traps of the Tyumen Formation that are loosely controlled by local structures. Most of these pools are in the upper part of the Tyumen Formation, beneath the Callovian shale seal. Because of the lateral discontinuity of the reservoirs, it is not clear whether these pools are hydrodynamically connected and thus constitute a single field as shown in figure 15, or they form several fields as shown in figure 11. Several oil pools were discovered in the weathered top of the basement.

The largest field of the Togur-Tyumen TPS, the giant Talin field with oil reserves of nearly two billion barrels was discovered in 1976 in the western part of the Krasnolenin arch. Unlike the previous discoveries on the arch, the Talin field is in sandstone reservoirs at the basal part of the Tyumen Formation. The sandstones fill a paleo-river valley and form a large stratigraphic trap. In the 1980s and 1990s, exploration in the Togur-Tyumen TPS was mostly concentrated in the marginal areas of the West Siberian basin, especially in its southeastern part, where exploration objectives occur at depths of approximately 2.5–3 km. No major new discoveries were made in the TPS during this time.

Petroleum Occurrence

Several tens of hydrocarbon pools, among which oil pools dominate, have been discovered in the Togur-Tyumen TPS at depths of 2,200 to about 3,000 m. The majority of them are in the upper part of the Lower–Middle Jurassic Tyumen Formation beneath the Callovian regional shale seal (Yekhanin, 1990). About 60 percent of these pools are in structural and combination traps; the rest are in various stratigraphic traps (Surkov and others, 1991). Only nine pools are in the basal part of the Tyumen Formation, but among them is the giant Talin field. The rest of the discovered accumulations are either in the middle part of the Tyumen Formation or at the eroded top of pre-Jurassic rocks.

The main hydrocarbon reserves of the Togur-Tyumen TPS are confined to two areas—the Krasnolenin arch and its slopes in the west and the southeastern part of the basin (fig. 11). The Talin field is largest in the Krasnolenin arch area (fig. 20). The oil is in two sandstone beds separated by the shale of the lower Toarcian Togur Bed. The productive sandstones and gravelstones represent a river-valley fill at the base of the Lower–Middle Jurassic Tyumen Formation. The river flowed northward into a system of lakes and alluvial plains north of the area shown in figure 20. However, no significant reservoir sandstones have been found in wells in this northern area (Karagodin and Izarova, 1993). Sandstone bodies extending east of the main river channel were formed in tributaries that drained the uplifted Krasnolenin arch. Thickness of each productive sandstone reservoir varies from 0 to 30 m. Other fields on the Krasnolenin arch are reservoired principally in the upper part of the Tyumen Formation. Thirty-eight oil and gas fields of small to medium size (from a few to several tens of million barrels) have been discovered in the Togur-Tyumen TPS in the southeastern part of the West Siberian basin, primarily in the Kaymysov and Vasyugan productive regions (Surkov and others, 1999; this report, fig. 15). Most production comes from sandstones in the upper part of the Tyumen Formation and weathered carbonate rocks at the top of the Paleozoic sequence. Several pools were found in the lower and middle parts of the Tyumen Formation. Although most wells were drilled on structural prospects, hydrocarbon pools in the Tyumen Formation are commonly affected by pinch-outs of reservoir sandstones. Pools at the top of Paleozoic carbonate rocks and in basal Jurassic sandstones are dominantly stratigraphic and are controlled by the presence of reservoir rocks (fig. 21). A number of oil pools have been discovered in the Tyumen Formation of the Middle Ob petroleum region; most of these pools are in the upper part of the formation, beneath the Callovian shale seal (lower part of the Vasyugan Formation; fig. 4). Data on these pools that are available for this report are incomplete because most of them are in fields with the principal reserves in the overlying Bazhenov-Neocomian TPS. For example, significant oil pools were discovered in the upper Tyumen Formation in the giant Fedorov field, in which the principal reservoirs are in the Neocomian Megion and Vartov Formations (Surkov and others, 1991). Oils in the Togur-Tyumen TPS are mostly of medium and low gravity (lighter than 39° API), with low sulfur content (less than 0.25 percent), and with commonly high (as much as 10 percent and, in some fields, more than 20 percent) content of solid paraffin (Kontorovich and others, 1975). The lightest oils known are on the Krasnolenin arch and in the greater Salym area (fig. 15), both of which are characterized by high geothermal gradients. The oils are heavier and more sulfurous in the Yugan depression and on adjoining slopes of the Nizhnevartov and Surgut arches (Rudkevich and others, 1988; this report, fig. 11).

Source Rocks

For many years, Russian geologists believed that oils in the Togur-Tyumen TPS were generated from continental coaly shales and coals of the Tyumen Formation. Only recently, when the geologists received access to modern geochemical analytical equipment, did it become clear that most of oils of the TPS were derived from organic-rich shales of the lower Toarcian Togur Bed in the lower part of the Tyumen Formation. The Togur Bed is composed of black to dark-brown illite, montmorillonite, and kaolinite shales that are commonly 25 to 50 m thick. The shales onlap the slopes of Paleozoic topographic highs and commonly pinch out on the crests of the highs (fig. 21). In the adjoining depressions, the Togur Bed overlies Sinemurian–Pliensbachian alluvial deposits. In peripheral areas of the basin, the Togur Bed contains sandstone and siltstone layers. The Togur Bed was deposited during a worldwide eustatic event; the sea-level rise in West Siberia is estimated at 300–400 m (Surkov and others, 1999). From the northern areas of the West Siberian basin, the sea transgressed south and covered the central part of the basin (Surkov and others, 1999b). The southern areas of the basin were characterized by complex landscapes, which included marshes, lakes, estuaries, and lagoons. Low wave energy resulted in mostly reducing bottom-water conditions. Paleozoic topographic highs were islands covered by rich vegetation. At maximum transgression, the sea penetrated into the lakes and swamps, which resulted in varying water salinities. However, marine fossils were found in some layers of the Togur Bed even in the southernmost areas of the basin (Devyatov and others, 1994). The complex paleogeography affected the composition of organic matter, in which land-derived and aquatic components are present in various proportions (Kontorovich and others, 1997; Surkov and others, 1999a).

Source rocks of the Togur Bed have been cored and geochemically analyzed in a relatively small number of wells as compared to the Bazhenov Formation. Many depressions where good quality lacustrine source rocks can be expected have not been drilled (Kontorovich and others, 1997). Except in organic-lean marginal facies, the average TOC content in Togur shales ranges from 1 to more than 5 percent (fig. 22). However, in separate layers the TOC content is as high as 17 percent (Lopatin and others, 1997a). The biomarker and isotopic compositions of oils and source rocks indicate both marine (algal, planktonic, and bacterial) and continental (higher plants) sources for organic matter. Geochemical data show a high generative potential of Togur shales. In the Middle Ob region, the remaining generative potential (Rock-Eval S2 value) of the shales, which occur in the lower to middle part of the oil window, was measured at 4 to 26 mg HC/g rocks and HI varied from 100 to165 mg HC/g TOC (Lopatin and others, 1997a). Biomarkers indicate the affinity of oils in the weathered top of Paleozoic rocks with bitumen of the Togur shales. In the Nyurol depression (southeastern part of the basin; fig. 11), shales of the Togur Bed that occur in the middle part of the oil window (Ro 0.8) are still characterized by a high remaining generative potential. Measured HI in these shales varies from 200 to 600 mg HC/g TOC and averages 500 mg HC/g TOC, and bitumen extract varies from 0.2 to 0.7 weight percent of rock (Kontorovich and others, 1997). The content of extractable bitumen in organic matter in the same area is as high as 198 mg per gram TOC (Surkov and others, 1999a). On the basis of the biomarker and isotopic compositions, most oils can be correlated with organic matter of the Togur Bed. Over most of the TPS area, source rocks of the Togur Bed are catagenetically mature and occur in the oil window (fig. 23). The rocks are immature to marginally mature on the extreme periphery of the basin and on slopes of structural uplifts. The Krasnolenin arch is characterized by a high geothermal gradient, and Togur source rocks there are in the lower part of the oil window and in the upper part of the gas window. In the main productive areas, the rocks reached maturity in the latest Early Cretaceous and Late Cretaceous time (Kontorovich and others, 1997; this report, fig. 24).

Some oil of the Togur-Tyumen TPS could have been generated from source rocks other than the Togur Bed. In some areas, especially in the Middle Ob region, shales of the upper Toarcian to lower Aalenian Radom Bed (fig. 21) are characterized by fair to good generative potential. The Radom Bed constitutes a transgressive part of the sedimentary cycle and was deposited in environments similar to those of the Togur Bed. In some layers of the Radom Bed, the shales contain as much as 17 percent TOC and, in the middle part of the oil window, HI ranges from 120 to 290 mg HC/g TOC (Lopatin and others, 1997a). Kerogen is probably of mixed types II and III, with type III more abundant. Although the available data are sketchy, south and west of the Middle Ob region the Radom shales are probably of poorer quality for oil source rocks, primarily because of coaly character of the organic matter (Grausman and others, 2000; Surkov and others, 1999a). However, geologic and some geochemical data indicate that several oil pools in the Tyumen Formation of the Nyurol depression (fig. 11) likely contain oils derived from the Radom Bed (Surkov and others, 1999). Radom source rocks occur only several tens of meters shallower than the Togur Bed, and the maturities of both stratigraphic units are similar. In addition, coaly organic matter and coal beds are widespread in other parts of the Tyumen Formation and have certain gas generative potential; however, this potential largely has not been realized because of insufficient thermal maturity over most of the TPS area. Much of the gas in more northern parts of the West Siberian basin probably was generated from rocks of this formation.

The generative potential of Paleozoic rocks underlying the Tyumen Formation is poorly known. Over most of the West Siberian basin, these rocks are strongly overmature with respectto oil generation (Fomin, 1999). Only in limited areas, primarily in the western part of the Nyurol depression, are rocks at the top of the Paleozoic sequence in the middle part of the oil window (Fomin, 1982). Although potential Paleozoic source rocks have not been met in any of the drilled wells, their presence is indicated by discovery of the Maloich field in the Nyurol depression in 1974, where a well tested oil from Silurian carbonates at a depth of about 1,000 m below the top of the Paleozoic sequence (Zapivalov and others, 1997). This oil flow, although noncommercial, may indicate that a separate TPS may be present in Paleozoic rocks of the West Siberian basin. Although the data are scarce, the petroleum potential of this TPS is probably very low, and it is not discussed in this report. Some interpretations of geochemical data suggest that Paleozoic-derived oil may be present in some pools in carbonate reservoirs at the top of the Paleozoic sequence and in clastic reservoirs in the basal part of the Tyumen Formation (Kontorovich, Danilova, and others, 1998; Stasova and others, 1998; Zapivalov, 1999). However, as indicated by geochemical data, the majority of oils in these reservoirs were derived from clastic source rocks of the Tyumen Formation, primarily from the Togur Bed (Peters and others, 1994; Kontorovich and others, 1997). Paleozoic oil-source rocks may be present only locally and could not have generated significant volumes of hydrocarbon reserves of the Togur-Tyumen TPS.

Reservoir Rocks

The quality of reservoir rocks is the main limiting factor for hydrocarbon richness of the Togur-Tyumen TPS. In general, continental sandstone reservoirs of the Tyumen Formation are characterized by lateral discontinuity and strong lateral and vertical variations of porosity and permeability. Abrupt changes of porosity also are characteristic of reservoir rocks at the top of the Paleozoic sequence.

The best reservoir rocks of the Tyumen Formation are the alluvial and proluvial sandstones that fill the paleo-river valley in the Talin field (fig. 20). The sandstones are medium- to coarse-grained, poorly sorted, with numerous lenses of conglomerate. They have a substantially quartzose composition (70–90 percent); the rest of the matrix is composed of feldspar and rock fragments (Pyatkov and others, 1988). Vugs that were formed by postsedimentary dissolution of unstable components of the rock, such as feldspars, are common; vuggy porosity may be as high as 6 to 7 percent, but commonly it ranges from 1 to 3 percent. The vugs are partially filled with kaolinite. The total intergranular and vuggy porosity commonly varies from 14 to 18 percent, and in some samples it is as high as 23 percent (Pyatkov and others, 1988; Belkin and Bachurin, 1991). Fracturing is present, but is not widely developed. Measured permeability of the sandstones varies widely from several millidarcies to 2–3 darcies and strongly depends on the presence of vugs and fractures. Toward the margins of the paleo-river valley, reservoir beds become thinner, the amount of shale layers increases, and reservoir properties of sandstones deteriorate (Afanasyev and others, 1993).

Outside the paleo-river valley, the reservoir properties of sandstones in the lower part of the Tyumen Formation are generally poorer, primarily because of increasing amounts of feldspathic and lithic grains, although quartzose sandstones with high porosity and permeability are locally present, especially on slopes of basement topographic uplifts that were the source of clastic material (Samoletov and others, 1989). Porosity and permeability deteriorate with depth, mainly because of diagenetic alteration of feldspar and volcanic rock fragments. Reservoir rocks with primary intergranular porosity are absent at depths of more than 3250 m (Grausman and others, 2000). Reservoir rocks with secondary porosity are possible but have not yet been found.

In the middle and upper parts of the Tyumen Formation, reservoir sandstones are characterized by significant heterogeneity and lateral discontinuity. Dominant reservoir rocks are fine- to medium-grained polymictic sandstones with quartz content varying from 40 to 70 percent and lithic fragments constituting as much as 40 percent of the rock matrix. Cement is composed of clay and, less commonly, of carbonate minerals (Mukher andIrbe, 1988). Significant fracturing is uncommon. Porosity varies from 10 to 16 percent, and permeability varies from a few to several tens of millidarcies. Reservoir rocks with higher porosity and permeability are only locally present.

Reservoir properties of productive rocks at the weathered top of the pre-Jurassic sequence are extremely variable and strongly depend on the lithologic composition of subcropping rocks, fracturing, and development of the weathering crust. Hydrothermal alterations of rocks supposedly play an important role in formation of secondary porosity (Abrosimova and Ryzhkova, 1998). The best reservoirs have been found in Devonian fractured, vuggy carbonates of probable reef origin in some fields of the Nyurol depression in the southeastern part of the West Siberian basin (fig. 11; Zapivalav and others, 1997). Measured porosity of the carbonates is as high as 12–13 percent and permeability is about 60 mD (Abrosimova and Ryzhkova, 1998). Tested oil flows were 250–350 b/d on a 4- to 5-mm choke. Porosity and permeability of off-reef facies are lower. Adequate reservoir properties also are characteristic of disintegrated granites and bauxites of the weathering crust (Kontorovich and others, 1991). Upper Paleozoic siliceous shales and Triassic extrusive rocks as well as their weathered varieties have lower porosities. Because of strong faulting and deformation of the Paleozoic sequence, rocks of various age and lithology commonly form different tectonic blocks and are abruptly terminated laterally against faults at the block boundaries.

Traps

Stratigraphic and combination structural and stratigraphic traps are dominant in the Togur-Tyumen TPS. In the basal part of the Tyumen Formation, several pools have been discovered, and all of them are in stratigraphic traps (Surkov and others, 1991). The pools are in shoestring sandstone bodies that were deposited in river valleys and are located in structurally low areas. Clastic material was derived both from areas outside the basin and from Paleozoic topographic highs inside the basin. The basal part of the Tyumen Formation, including sandstone beds, pinches out on slopes of the highs forming stratigraphic traps. The Talin field is in such a trap (fig.20).

Among 126 hydrocarbon pools that had been discovered by 1990 in the upper part of the Tyumen Formation (this number includes several pools in the basin areas north of the Togur-Tyumen TPS), 47 pools are in stratigraphic traps (Surkov and others, 1991). The genesis of the sandstone bodies is not well understood; probably, most of them were deposited as nearshore marine sand bars and beaches (Kovylin, 1990). The rest of the pools were discovered in structural prospects on local uplifts. However, because of the discontinuous character of the sandstone beds, the majority of these pools are actually in combination traps, and their outlines are controlled by pinch-outs of reservoir rocks.

Some of the pools, for example, a large pool in the Kamennoye field on the Krasnolenin arch (fig. 11), did not produce water from any of the drilled wells, and apparently it is devoid of an oil-water contact (Samoletov and others, 1989).

Most of the fields in the upper part of the Paleozoic sequence have not been delineated, and the exact nature and geometry of their traps are poorly known. Most of the discovered fields are on basement topographic highs or their slopes (see, for example, fig. 21). However, the pool outlines are chiefly controlled by lithology, fracturing, and deformation of rocks that compose the section beneath the pre-Jurassic unconformity and by the presence and composition of the weathering crust (Kontorovich and others, 1991). None of the discovered oil accumulations in these traps has a significant extent, and the reserves are relatively small, probably not exceeding a few tens of million barrels.

Assessment Units

A single assessment unit, the Pre-Upper Jurassic AU (11740201), was identified in the Togur-Tyumen TPS. The assessment unit encompasses the entire area of the TPS (fig. 1) and includes all discovered and undiscovered hydrocarbon fields in the Tyumen Formation and in the upper part of the pre-Jurassic section. The regional lower Callovian shale seal overlies the assessment unit and separates it from the Bazhenov-Neocomian TPS. The assessment results for undiscovered oil and gas resources for the Pre-Upper Jurassic AU 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). Oil profoundly dominates the discovered hydrocarbon reserves of all exploration plays in the AU and is expected to dominate undiscovered resources.

Presently, about three-quarters of the discovered oil reserves are contained in more than one hundred fields that produce from the upper part of the Tyumen Formation, and the majority of the fields are of small to medium size. The principal limiting factor for the volume of undiscovered resources is the mediocre quality and lateral discontinuity of reservoir rocks. Most of the fields are located on structural uplifts; however, the pool outlines are controlled by pinch-out of reservoir rocks. Exploration was targeted at local structures, and very little drilling was specifically directed to search for stratigraphic traps. These traps will be the prime target for future exploration and a large number of small- to medium-size discoveries are expected. Most of the fields will be found in the uppermost part of the Tyumen Formation because its middle part is devoid of extensive seals. In the north-central part of the Pre-Upper Jurassic AU area, north of the Surgut and Nizhnevartov arches (fig. 11), the top of the Tyumen Formation occurs deeper than 3–3.5 km, and primary intergranular porosity of the reservoirs probably will be low (Grausman and others, 2000). Development of secondary, diagenetic porosity is possible, but in general the undiscovered potential of this area is less than that of the more southern areas of the AU.

About one quarter of discovered reserves of the Pre-Upper Jurassic AU reside in only a few fields with reservoirs in the basal sandstones of the formation. Most of these reserves are in the giant Talin field. All the fields are in stratigraphic traps, primarily in sandstones of the river-valley fill. The shoestring sandstone bodies are located in structurally low areas between highs of the pre-Jurassic relief. Exploration for these stratigraphic traps is difficult as the river valleys presently are poorly identifiable on 2-D seismic records. However, the undiscovered potential of the lower Tyumen Formation is probably high. Although the distribution of sandstone bodies is uneven, the section contains the best quality reservoir rocks in the AU. Considering the humid Early Jurassic climate and dissected topography, many more river valleys should be present, and probably they can be identified by improved seismic imaging. The river-valley sandstones underlie and overlie the Togur source rocks, and the charge risk is minimal. Shales of the Togur and Radom Beds provide regional seals for the shoestring sandstone bodies, which will contain future discoveries in the lower Tyumen Formation.

The “buried hill”, or paleotopographic high, play has been proved highly productive in a number of basins of the world, for example, in the North China (Bohaiwan) basin. Therefore, the similar play in topographic highs of pre-Jurassic rocks of the Togur-Tyumen TPS may seem attractive. However, no fields with reserves in excess of a few tens of million barrels have been found so far in these highs in West Siberia although a significant number of prospects have been drilled. Intensive deformation of Paleozoic rocks, block faulting, variable lithologies subcropping at the base of Jurassic strata, and uneven distribution of weathered rocks contribute to the complexity of traps and limit their sizes. The evaluation of prospectivity of this play in the Togur-Tyumen TPS has a large degree of uncertainty. However, presently available data indicate that undiscovered potential of this play probably is relatively small.

Northern West Siberian Mesozoic Composite Total Petroleum System

Discovery History

Exploration in the northern areas of the West Siberian basin commenced soon after the first large oil discoveries in the Middle Ob petroleum region. The first discovery in the Northern West Siberian Mesozoic Composite TPS (117403) was made in 1962 in the Taz field (fig. 15) where a large gas pool with reserves of more than 3 TCF was discovered in Cenomanian sandstones at a depth of 1150 m. During the 1960s and early 1970s about three dozen giant and large dry gas fields were discovered in the Aptian–Cenomanian Pokur Formation and its stratigraphic equivalents in the Nadym-Pur, Pur-Taz, and Yamal regions (fig. 15). Among these fields was the supergiant Urengoy gas field with reserves of about 350 TCF (Zhabrev, 1983). Very large areal extents, high amplitudes of the structures, and shallow depths of drilling facilitated exploration. During the same time, some wells that were drilled deeper than the main exploration objectives in the Pokur Formation discovered wet gas pools with a moderate content of condensate in the Neocomian and Jurassic sections. Gas production in northern West Siberia started in 1972 in the Medvezhye field (fig. 15), and production in the Urengoy field began in 1978.

In the following years, the sizes of new discoveries onshore began to decrease as all huge, easy-to-find structures had been drilled. Because of harsh arctic conditions, offshore drilling did not commence until the late 1980s. The first wells were drilled in the south Kara Sea in 1989 and 1990, and two giant gas fields with total in-place resources as high as 300 TCF, the Rusanov and Leningrad fields, were discovered (fig. 14; Nikitin and Rovnin, 2000). Recently, a large field (North Kamennomys field) was discovered in the Ob Inlet (fig. 14), but no data on the location of this field and its size are available.

The first oil discovery was made in 1968 when large reserves of heavy biodegraded oil below a dry gas cap were identified in the Russkoye field (fig. 15). In spite of significant efforts, an exploration program for oil that was targeted primarily at deep Jurassic reservoirs has not been successful although several discoveries, the largest of which is in the Novoport field, have been made.

Petroleum Occurrence

About 70 hydrocarbon fields, the majority of them gas, have been discovered in the Northern West Siberian Mesozoic Composite TPS. The TPS is extremely rich in hydrocarbons and is decidedly gas-prone. More than 1,150 TCF, or nearly one-quarter of the world gas reserves, is concentrated in the relatively small (on the world scale) area of the TPS that has been explored only in its onshore part. The rich gas-productive area extends into the adjoining Yenisey-Khatanga basin (fig. 1). On the other hand, oil reserves of the TPS are comparatively small and only slightly exceed 4 billion barrels. About 80 percent of the gas reserves are in the Aptian– Cenomanian Pokur Formation and its stratigraphic equivalents (fig. 4). Another 10 to 15 percent of the gas is in Aptian sandstones where they are separated from Cenomanian sandstones by a shale seal. All fields, including two offshore giant gas discoveries, are in structural traps and are sealed by thick shales of the Turonian Kuznetsov Formation. The gas is dry and contains very little condensate. Depths to the top of gas reservoirs vary from about 600 m to a maximum of 1500 m. In the large (about 10 TCF of gas) Russkoye field (fig. 15), the Cenomanian gas pool is underlain by a thick oil layer that contains large reserves of heavy biodegraded oil. Several small gas pools also have been found in a sandstone bed (Gaz-Salin Bed), which is present in the middle part of the Turonian Kuznetsov Formation in eastern areas of the TPS.

The lower productive complex of the Northern West Siberian Mesozoic Composite TPS includes Jurassic and Neocomian rocks. The complex contains gas accumulations in many fields that are also productive from Albian–Cenomanian rocks. In several fields, Neocomian pays constitute the principal reservoirs. Most of the discovered pools occur in a depth interval of 2,000– 3,500 m. The gas is wet and contains significant volumes of condensate. Some of the gas pools in the lower productive complex have oil fringes, and several oil pools are present. Gas reserves in the Jurassic–Neocomian productive complex constitute about 5 to 10 percent of the total gas reserves of the TPS.

The main part of the oil reserves is in the giant Novoport field (fig. 15) that contains more than 1.5 billion barrels of oil. The field also contains a large gas pool in the Pokur Formation and several oil and gas-oil pools in Neocomian, Upper Jurassic, and Lower–Middle Jurassic rocks. The single gas pool found so far in eroded Paleozoic carbonates, possibly of reef origin, that underlie Mesozoic rocks of the TPS is also in this field (Girshgorn, 1988).

Gases in the Albian–Cenomanian productive complex are dry, isotopically light, and contain very little condensate. Hydrocarbons are almost exclusively represented by methane; the content of ethane is commonly less than 0.1 percent, and heavier hydrocarbon gases are present only in trace concentrations. The gases contain 0.2–0.5 percent carbon dioxide and 0.2–4.5 percent nitrogen. Neocomian gases are much different. They are wet, isotopically heavy, and contain variable amounts of condensate. Methane constitutes 85–90 percent of the hydrocarbon fraction; the rest is heavier hydrocarbon gases including butane and pentane. The contents of carbon dioxide and nitrogen vary from 0.1–4.7 percent and from 0.2–9 percent, respectively.

Oils in oil pools and in the legs of gas pools of the lower productive complex are of two types (Soboleva and Stroganov, 1993). The first type includes oils that have lost the light fraction by evaporation into the gas caps. These are paraffinic (3.5–11.2 percent), medium gravity (32–38° API) oils. Oils of the second type are actually retrograde condensates precipitated from gas due to the decrease of pressure. Gravity of these oils ranges from 46° to 51.5° API and they contain 1.9–3.6 percent solid paraffin.

Source Rocks

Source rocks that generated gas reserves of the Northern West Siberian Mesozoic Composite TPS are poorly identified. Potential oil source rocks and abundant potential gas source rocks are present in the entire sedimentary section, but no reliable source rock-dry gas correlation has been substantiated.

The Triassic Tampey series penetrated by a few wells contains at least some organic-rich intervals with the TOC contents ranging from 3 to 5 percent (Surkov and others, 1997). However, in most of the area the rocks occur at great depths and the generative potential of organic matter is largely exhausted. For example, very low pyrolitic S2 and HI (hydrocarbon index) values were measured in samples from the depth interval of 6–6.4 km in the superdeep Tyumen SG-6 well that was drilled in the northern part of the Pur trough (fig. 11; Lopatin and others, 1997a).

The Lower–Middle Jurassic Tyumen Formation, which is as thick as 1–2 km in the TPS area, contains abundant coaly organic matter and, in the Lower Jurassic section, coal beds. The average TOC content in the formation is estimated by different authors from 0.86–1.24 percent (Nesterov and Ushatinsky, 2000) to 2.5–2.8 percent (Rylkov, 1995). Maturity of the rocks varies from the oil window to the lower part of the gas window (fig. 23) and in the deepest areas the generative potential of organic matter is exhausted (Lopatin and others, 1997a). Data on the lower Toarcian Togur Bed are limited because of its deep occurrence; however, in drilled wells the bed is characterized by TOC contents of 3–5 percent (fig. 22), and the organic matter contains a significant sapropelic component (Kontorovich and others, 1997). Oil generation in shales of the Togur Bed commenced in Early Cretaceous time and continued until middle Late Cretaceous time when the rocks entered the gas window (Lopatin and others, 1997a).

Clastic rocks of the Upper Jurassic Vasyugan Formation in the Tyumen SG-6 superdeep well contain highly variable TOC contents (0.4–11 percent), but low to moderate contents are more common (Yekhlakov and others, 1991). The organic matter is of terrestrial origin (gas-prone type III kerogen). The Bazhenov Formation is present over the entire area of the Northern West Siberian Mesozoic Composite TPS. Although its source quality is not as high as in the Middle Ob region, the formation still contains good oil source rocks with TOC ranging from 3 to 7 percent (fig. 16) and dominantly type II kerogen. The maturity varies from the oil window to the upper and middle parts of the gas window (fig. 17). In the deepest areas of the TPS, such as the northern Pur depression (fig. 11), oil generation in Bazhenov shales started in Albian time and was mainly completed in Eocene time (Lopatin and others, 1997a). Regional uplift, erosion, and cooling of sedimentary rocks in northern West Siberia commenced in middle Oligocene time and continued through the middle Pliocene.

Organic matter in the Lower Cretaceous–Cenomanian sequence of northern West Siberia is dominated by coaly material. The upper part of this sequence is especially rich in organic matter. Paralic and continental conditions of sedimentation that prevailed during late Hauterivian–Cenomanian time (fig. 9) resulted in deposition of clastic rocks enriched by dispersed coaly material and numerous coal beds. The average content of TOC in shales is estimated at 1.3 percent (Rylkov, 1995). The number of coal beds, which are 1–5 m thick on well logs, varies in most wells from 10 to 30 and their combined thickness is several tens of meters (Nemchenko and others, 1999). In addition, numerous thin coal seams and lenses are abundant in the rocks. The amount of coaly organic matter in the Hauterivian–Cenomanian section is estimated at 15.5x1012 tons, of which 6.9x1012 tons are immature lignites and brown coals, and the rest is at the early stage of maturity corresponding to the uppermost part of the oil window (Nemchenko and others, 1999). Although potential source rocks are abundant in the sedimentary section, the origin of giant accumulations of dry gas in the Aptian–Cenomanian Pokur Formation remains poorly understood in spite of extensive research efforts. Large differences in the molecular and isotopic compositions of Pokur Formation gases compared to gases from Neocomian and older rocks require explanation, and different hypotheses on the origin of the Pokur Formation gases have been proposed.

Based on the light isotopic composition of carbon in methane, earlier investigators believed that gases in accumulations in the Pokur Formation had a biogenic origin, possibly with an admixture of gas that migrated from deep parts of the sedimentary sequence (Rice and Claypool, 1981; Grace and Hart, 1986). However, a large volume of analytical data obtained in recent years shows that in most pools the isotopic compositions of both carbon and hydrogen (-50 to -60o/oo and -210 to -237 o/oo, respectively) are inconsistent with biogenic gases (Shoell and others, 1997). Recently, the concept of mixing deep thermogenic gas and biogenic gas was revitalized by Littke and others (1999) and Cramer and others (1999). According to their calculations, the admixture of thermogenic methane in largely biogenic Cenomanian gases constitutes about 10 percent of their volume.

Many Russian geologists support a hypothesis of the early catagenetic origin of gases in the Pokur Formation (Vasilyev andothers, 1979; Galimov, 1988; Rovenskaya and Nemchenko, 1992; Stroganov, 1990; Nemchenko and others, 1999). According to this hypothesis, dry, isotopically light gas in Cenomanian reservoirs was generated by coaly organic matter and coals of the Pokur Formation and its stratigraphic equivalents at low maturities corresponding to vitrinite reflectance of 0.4–0.6 percent. However, pyrolysis experiments show that at these low maturities dominantly carbon dioxide and very little methane is generated, and the generated methane is isotopically heavier and contains a much larger admixture of ethane than methane in pools of the Pokur Formation (Littke and others, 1999).

Vertical migration of gas from Jurassic source rocks that occur in the thermogenic gas window into Pokur Formation reservoirs (Prasolov, 1990) is apparently contradicted by large differences in the molecular and isotopic compositions of gases in Neocomian and Cenomanian reservoirs. Neocomian gases are typical thermogenic; they are isotopically much heavier (-34o/oo to -38o/oo), contain a large fraction of ethane and heavier gases, and are moderately rich in condensate. Gases tested from Jurassic rocks in several fields have similar characteristics. In spite of the large compositional difference between Cenomanian and Neocomian gases, the concept of different sources for these gases is problematic. Geologic considerations indicate that ver-tical migration of hydrocarbons in the northern West Siberian basin is feasible.

The entire sedimentary section between Jurassic rocks and the Turonian Kuznetsov Formation does not contain extensive regional seals. In similar conditions, in the Middle Ob region, oils generated from the Jurassic Bazhenov Formation are present in Neocomian and Aptian–Cenomanian strata. It is not clear why in the northern areas more mobile (compared with oil) gas would not be able to migrate vertically into the same stratigraphic units. The common presence of abnormally high pressure in Jurassic rocks may not be considered a hydrodynamic barrier, as vertical migration in similar conditions is ubiquitous in other basins of the world, for example, in the South Caspian basin. Moreover, the overpressuring in Jurassic rocks most probably results from active

hydrocarbon generation and should facilitate rather than prevent migration. The hydrodynamic unity of Jurassic and
Neocomian rocks in fields of the Yamal Peninsula is convincingly indicated by the geochemical similarity of oils and condensates in these two sections (Chakhmakhchev and others, 1990). Vertical migration of hydrocarbons into Cenomanian reservoirs, at least in some areas, is demonstrated by the presence of an oil layer underlying gas caps in several gas fields, for example, in the Taz field (fig.15). The oils are heavy and naphthenic; probably they were substantially biodegraded. Biomarker data indicate that these biodegraded oils were derived from marine Jurassic source rocks, not from continental Aptian– Cenomanian rocks (Kontorovich, Danilova, and others, 1999). No oil-source rocks are present above the Bazhenov Formation, which indicates vertical migration through the thick Cretaceous sequence. In several fields that are devoid of oil legs, vertical migration through fault zones is indicated by a much higher concentration of heavier hydrocarbon gases (up to 1.1 percent) in wells adjacent to these zones, although the faults commonly die out in Neocomian rocks and do not penetrate into Cenomanian reservoirs (Bespalova and Bakuev, 1995).
The compositional difference between Cenomanian and Neocomian gases should be explained by causes other than their generation by different source rocks and the absence or insignificance of vertical migration, although these causes presently are not clear. Perhaps, the prevalent mode of vertical migration was diffusion, which resulted in molecular and isotopic fractiona-tion of gas; the latter is due to a higher diffusion coefficient and lower solution and sorption coefficients for isotopically light molecules. The significance of isotopic fractionation during diffusion, especially through organic-rich rocks, was recently shown experimentally (Zhang and Krooss, 2001). This hypothesis may be supported by the molecular and isotopic gas compositions in pools in the lower (Aptian–Albian) part of the Pokur Formation. The compositions of these gases are intermediate between gases in Neocomian and Cenomanian reservoirs.
The fractionation probably was far less efficient in fault zones, along which single-phase gas migration was dominant, and this resulted in accumulation of isotopically heavier and wetter gas pools with occasional oil legs. Multiple events of exsolution and dissolution of gas under local seals along migration routes and perhaps formation and destruction of gas hydrates (Razmyshlyaev, 2001) also could have affected gas composition. Some biodegradation of gas is also possible, as indicated by the dominantly naphthenic composition of condensate (probably biodegraded) in Aptian–Albian gas pools on the Yamal Peninsula (Stroganov, 1988). Our poor understanding of the formation of isotopically light gas is demonstrated by gas pools in the Berezov area (fig. 15), which occur in Upper Jurassic and Neocomian rocks at depths of 1200–1800 m. Gas in these pools is isotopically light (from -52o/oo to -58 o/oo) similar to Cenomanian gas in northern West Siberia (Prasolov, 1990), although gas in the Berezov area was undoubtedly generated thermogenically from Jurassic rocks.
The hypotheses of biogenic and early thermogenic generation of Cenomanian gas encounter significant volumetric difficulties in attempting to explain the accumulation mechanisms of supergiant gas fields, such as the Urengoy field. Mass-balance calculations show that the amount of gas generated in this way in the charge area of the Urengoy field is insufficient to explain the huge field reserves there (Littke and others, 1999). Therefore, a hypothesis of gas exsolution during northward migration of water in the Cretaceous aquifer was proposed (Kortsenshteyn, 1977; Surkov and Smirnov, 1994). The exsolution was largely driven by the pressure decrease that resulted from uplift and

erosion of the northern basin areas (Cramer and others, 1999). Although the hypothesis is attractive, it is not well substantiated by data. The model of water degassing along the route of regional flow through the Cretaceous aquifer shifts the generation area several hundred kilometers to the south, but does not solve the problem of the unusual gas composition in Cenomanian reservoirs. The uplift and erosion of 830 m of sediments used to calculate the pressure decrease in the model (Cramer and others, 1999) is probably overestimated, and a smaller uplift estimated at 200–350 m (Mishulsky and Rysev, 1995; Lopatin and others, 1997a) to 700 m (Surkov and Smirnov, 1994) is more probable. Some hydrogeologic data seemingly contradict the model. Firstly, the composition of dissolved salts in Cenomanian reservoirs in the southern part of the TPS (Urengoy fieldand adjacent areas) differs strongly from that on the Yamal and Gydan Peninsulas (Zorkin, 1989). Secondly, water-dissolved gas in Cenomanian sandstones contains substantially more ethane (as much as 1.1 percent) than gases in the adjacent Cenomanian gas fields (Zorkin, 1989). The opposite should be expected considering the lower solubility of ethane compared to methane. Thirdly, although estimates of different investigators vary, some of these authors indicate undersaturation of Cenomanian water with gas (Rudkevich and others, 1988; Kruglikov, 1992) that would prevent degassing. Finally, abnormally low reservoir pressure (0.3–0.4 of hydrostatic pressure), which is related to thick permafrost, is ubiquitous in large and giant gas fields of the Yamal and Gydan Peninsulas (Matusevich and others, 1997). This strong underpressuring may suggest weak hydrodynamic connection between these areas and the more southern, normally pressured region, which contradicts an active fluid flow through the continuous aquifer. All the above-discussed facts put the exsolution hypothesis into doubt.

The abundance of potential gas source rocks at many stratigraphic levels in northern West Siberia and uncertainties in correlation of the principal gas reserves with specific source rock intervals prompted us to identify in this area a single composite TPS that includes sedimentary rocks of the entire stratigraphic succession.

Reservoir Rocks

In the Northern West Siberian Mesozoic Composite TPS, productive reservoirs have been found in the sedimentary section from the Lower–Middle Jurassic Tyumen Formation through the upper Aptian–Cenomanian Pokur Formation.

Reservoir rocks of the principal gas-productive formation, the Pokur Formation, are characterized by very high porosity and permeability, especially in its upper, Cenomanian part. Porosity of the sandstones is mainly in the range of 25–35 percent, and permeability varies from a few hundred millidarcies (mD) to several darcies averaging about 500 mD (Leonenko and Karnyushina, 1988). The top of the formation in most areas occurs at depths of 700–1200 m, and much of the formation is above the oil window. Sandstones constitute from one-half to two-thirds of the formation thickness. Individual sandstone beds are from a few to 20 m thick and are characterized by lateral discontinuity, especially in the middle part of the formation (Mishulsky and Rysev, 1995). The matrix of the sandstones is primarily composed of quartz and feldspar grains with kaolinite, chlorite, and hydromica cement. No significant diagenetic alterations are present. In the largest fields, original gas flows were 100–250 million cubic feet per day (Khanin, 1973). Significant reduction of porosity owing to compaction and diagenetic changes begins approximately at the upper boundary of the oil window at depths from 1800 to 2500 m in the Vartov Formation (Tanopcha and Akh Formations on the Yamal and Gydan Peninsulas; fig. 4). The formation occurs in the upper part of the oil window zone. It is composed of paralic to nearshore marine clastic sediments with coals. Sandstone beds are lithologically variable and commonly laterally discontinuous.

In the Pur-Taz region, shallow-shelf facies of the Neocomian clinoforms also occur in the upper part of the oil window zone. Through this part of the zone, porosity decreases from 25–30 percent to 16–20 percent; permeability decreases to 40–80 mD (Leonenko and Karnyushina, 1988). Most of the wet gas and condensate pools of the TPS are in this part of the sedimentary sequence.

The Achimov Formation, which is composed of slope and turbidite facies of the Neocomian clinoforms, includes reservoir sandstones and siltstones that were studied primarily in the Urengoy, Taz, and adjacent fields (Greater Urengoy area) where they contain potentially large resources of gas with a high condensate content. Many of the pools contain oil legs, and, in the southern part of the TPS, oil pools are also present. The Achimov Formation in this area lies at depths from 3.5 to more than 4 km, which corresponds to the lower part of the oil window. Abnormally high formation pressures are common. The sandstones are arkosic, with argillaceous and minor calcite cement; they contain 40 –55 percent feldspars, 25–40 percent quartz, and 5–20 percent rock fragments, and grains are commonly poorly rounded (Borodkin and others, 2001). The rocks have undergone strong compaction and diagenetic alterations, primarily quartz overgrowth and calcite dissolution (Leonenko and Karnyushina, 1988). Reservoir sandstones form multiple lens-like bodies; the hydrodynamic connectivity between the bodies is uncertain and can be determined only from data on the extended pilot production (Balin and others, 2001). Each sandstone body consists of alternation of thin sandstone and siltstone beds and intervening shales. In most of the studied samples, porosity of reservoir sandstones varies from 15 to 19 percent; however, samples with porosities to 21 percent are present. Rocks with porosities less than 15 percent are effectively impermeable (Moiseev and others, 2001). Permeability is typically low and commonly is measured in cores at 0.2 to 10 mD. Thin (up to 0.5 m) beds with higher permeability (as much as 70 mD) are present in sandstone lenses. However, production and well-logging data indicate substantially higher permeability, which is probably related to fracturing. Well logs commonly indicate a permeability range from 1 to 500 mD with average permeability of several to a few tens of millidarcies in different reservoirs (Balin and others, 2001). Many wells were tested at 5 to 15 million cubic feet of gas per day with several hundred barrels of associated condensate.

Over much of the area of the Northern West Siberian Mesozoic Composite TPS, Callovian–Kimmeridgian rocks, which are highly productive in the southern part of the West Siberian basin, compose the Abalak Formation that consists of shales and does not contain reservoir rocks. Only in the southern part of the TPS does this stratigraphic interval, represented by the Vasyugan Formation, include productive reservoir sandstones (Kulakhmetov and others, 1994). Sandstone beds are also present in the eastern marginal zone of the TPS, but no hydrocarbon accumulations have been discovered there. In the southern Greater Urengoy area, Vasyugan Formation sandstones are in the lower part of the oil window at depths of about 3,500–3,700 m. The sandstones have undergone intense diagenesis and compaction. The average porosity is less than 15 percent and permeability is a few millidarcies (Leonenko and Karnyushina, 1988).

Thick Triassic and Lower–Middle Jurassic strata of northern West Siberia include alluvial, paralic, and shallow-marinefacies. Continental rocks are predominant in the Triassic and basal Jurassic strata, whereas mainly marine rocks compose the overlying sequence. Triassic and the lower part of Lower Jurassic rocks as thick as 800–900 m are

mainly present in regional depressions, where they occur at depths of 4–5 km and more, and they pinch out on slopes of uplifts. The rocks are mostly in the lower part of the gas window. They consist of alternation of shales and sandstones and include conglomerate beds. Sandstones are lithoclastics and graywackes; rock fragments constitute about 65 percent of the rock matrix, and sorting is generally poor (Timoshenkova, 1992). The rocks have undergone substantial diagenetic changes and are intensely compacted. Samples with porosities of more than 12 percent are nearly absent, and the sandstones are effectively impermeable. No potential reservoir rocks have been found in the section.
The younger Lower and Middle Jurassic rocks of the Tyumen Formation that are 800–1,100 m thick include a number of sandstone-rich intervals, but most of the discovered pools are in the uppermost sandstone near the top of the formation (bed Yu-2 of local nomenclature). Individual sandstone beds of the formation are laterally discontinuous and commonly occur as a series of lens-like bodies. The sandstones are composed of quartz, feldspars, and rock fragments with argillaceous and partially carbonate cement. Generally, the percentage of rock fragments decreases and the percentage of feldspar increases toward the top of the formation (Timoshenkova, 1992). Commonly, the sandstones are poorly sorted. The amount of cement varies from 10 to 25 percent; the larger amounts are characteristic of more carbonate cement composition (Zonn and Dzyublo, 1990). Porosity of the sandstones does not correlate with the grain size and largely depends on the amount of cement. Most of the porosity relates to preservation of original pore space. Secondary porosity, largely caused by recrystallization of hydromica and dissolution of carbonate material in cement, is minor (Zonn and Dzyublo, 1990).
Permeability of Tyumen Formation sandstones is poorly correlated with porosity; generally, rocks with porosity less than 13 percent are effectively impermeable. Sandstones with higher porosities are mainly present in the upper part of the formation, primarily in the uppermost sandstone bed (bed Yu-2). In the lower part of the formation, only a small percentage of analyzed sandstone samples have porosities in excess of 13 percent and potential reservoir rocks are nearly absent (Timoshehkova, 1992). Production from this part of the formation has been established only in shallow areas, for example, in the Novoport field (fig. 15), where the Lower–Middle Jurassic pays are at depths of only 2,000–2,600 m. In deeper areas, such as the Greater Urengoy area, porosity of sandstones decreases to several percent and permeability decreases to less than 1 mD below depths of 3.5–4 km (Ushatinsky, 1988). For example, no reservoirs have been identified in Triassic and Lower–Middle Jurassic sandstones in the Tyumen SG-6 superdeep well, in which the top of this sequence is at a depth of about 4 km (Yekhlakov and others, 1991).
Sandstones in the uppermost part of the Tyumen Formation are the best reservoir rocks in the Triassic–Middle Jurassic sequence. Reservoir sandstones are largely present in the southern half of the TPS area where they were deposited in nearshore marine environments and contain beach and sand bar deposits (Zonn and Dzyublo, 1990). Sandstones are well sorted and are composed of quartz and feldspar grains; the amount of rock fragments is small. In many areas, porosity of sandstones commonly exceeds 13 percent and permeability is more than 1 mD. In the northern part of the TPS, rocks of the upper Tyumen Formation were deposited on a deeper shelf, and potential reservoirs there are scarce.

Traps

The dominant part of discovered reserves of the Northern West Siberian Mesozoic Composite TPS, including the entire dry gas reserves in the Pokur Formation reservoirs,

are in structural traps. Most of the traps are on elongated, high-amplitude (1–1.5 km) anticlinal uplifts of regional dimension (150–300 km long). Some of the regional uplifts, such as the Urengoy and Yamburg arches, are filled with gas to the spill point (Mishulsky and Rysev, 1995). Many of the uplifts contain faults in Jurassic rocks; some of the faults penetrate into Neocomian strata, and only on a few uplifts do the faults extend upward into the upper Aptian–Cenomanian Pokur Formation (Mishulsky and Rysev, 1995).
Unlike the southern parts of the West Siberian basin, where the major stage of structural growth was in Jurassic time (Brekhuntsov and others, 2001), structures in the northern part of the basin are young. Some structures began to form in Neocomian time and continued to grow in post-Cenomanian time (German and Perugin, 1992; Melnikova, 1992). Others, including the Urengoy arch, formed largely or completely in post-Cenomanian time. Much of the structural growth probably took place during Neogene time when the northern areas were regionally uplifted and eroded. Many of the largely post-Cenomanian structural traps, including those that contain the largest fields, are filled to the spill point, which emphasizes the young age of the gas accumulations.
Exploration for stratigraphic and combination structural and stratigraphic traps in the Northern West Siberian Mesozoic Composite TPS was mainly limited to the Achimov Formation of the Greater Urengoy area where a number of gas condensate and oil pools have been discovered (Levinzon and others, 2001). The types of traps are similar to those in the Middle Ob region. These are lens-like sandstone bodies on slopes of the Neocomian clinoforms and toe-of-slope turbidite fans. The pools are commonly in combination traps where these sandstone bodies intersect structural uplifts, but pools in purely stratigraphic traps are also known (Borodkin and others, 2001). Some of the productive traps are in sandstones sealed laterally by faults (Trushkova and others, 1989).

Assessment Units

Two assessment units (AU) were identified in the Northern West Siberian Mesozoic Composite TPS. The first of them, the Northern West Siberian Onshore Gas AU (11740301), encompasses the entire onshore area of the TPS (fig. 1). The second assessment unit, the South Kara Sea Offshore AU (11740302), covers the offshore area and extends northward to the TPS boundary. The two assessment units are separated on the basis of drastically different exploration maturity. The onshore AU is substantially explored, and historical data on discovery rates was used to support the geologic resource assessment. Only two prospects have been drilled in the offshore AU, and the assessment relied heavily upon the extrapolation and analogy with the onshore areas. The assessment results for undiscovered oil and gas resources for the 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). Gas is expected to be the dominant commodity in undiscovered resources of both AU.

Northern West Siberian Onshore Gas Assessment Unit

The main discovered reserves of the Northern West Siberian Onshore Gas AU are in the upper Aptian–Cenomanian Pokur Formation and its stratigraphic equivalents on the Yamal Peninsula (fig. 4), especially in its upper, Cenomanian part. All large structural uplifts in the upper Pokur Formation have been drilled, and the chances for giant discoveries are small. However, some smaller structures in the eastern area of the AU remain undrilled, but their potential resources are insignificant compared with the discovered reserves. Higher potential for discovery of medium-size and even large fields exists in the less explored middle and lower parts of the Pokur Formation where local

shale seals are present. Structural mapping in these parts of the Pokur Formation is hampered by the uncertainties in correlation of the infrequent and areally limited seismic reflectors. In addition, gas pools in this part of the section were commonly bypassed during drilling to deeper targets (Mishulsky and Rysev, 1995). Reinterpretation of well-log data may result in discoveries of bypassed pools and reserve growth in existing fields. Relatively small reserves have been discovered in Cenomanian rocks of the Gydan Peninsula supposedly because the Kuznetsov
Formation becomes sandy and loses its sealing quality. The potential of this area probably is not high. A limited potential for discovery of relatively small gas fields is related to the middle Turonian Gaz-Salin sandstone that forms a clastic tongue in the Kuznetsov Formation shales in the eastern area of the AU.

The Neocomian clinoform sequence, including the Achimov Formation, has been penetrated by wells in all or most of the fields of the Northern West Siberian Onshore Gas AU. However, because of geologic complexity, the exploration maturity of this sequence remains low, and large new resources can be expected. Much of the exploration was concentrated in the eastern part of the Greater Urengoy area where more than 200 wells penetrated the Achimov Formation, which occurs at depths of 3.5–4 km. In this area, four clinoform bodies are areally close and partly overlap each other. A number of gas-productive reservoirs were discovered in these clinoforms, each with net reservoir thickness as large as 50 m. The largest discovered pool supposedly extends 145 km in the north-south direction; it is 30 km wide and covers an area of 2960 km2 (Levinzon and others, 2001). The gas has a high content of condensate, and daily production of liquids from some wells exceeds 2,000 barrels. Neocomian clinoforms are present in most of the AU area, and they extend into the southern part of the Kara Sea (Sosedkov, 1993). Structural, stratigraphic and combination prospects in the Neocomian clinoform sequence contain the principal resources and the largest undiscovered fields of the AU. Most of the resources are gas with medium to high liquid content, but light oil pools are also probable, especially in the marginal zones of the TPS.

Russian geologists estimate that about one-third of the undiscovered gas and liquid hydrocarbon resources of northern West Siberia are in Jurassic and pre-Jurassic (mainly Triassic) rocks (Kontorovich, Nesterov, and others, 1998). However, we differ in this assessment. The principal problem for petroleum potential of the Jurassic sequence is the scarcity of reservoir rocks, which is related to the great depths of their occurrence. Few reservoir rocks have been found in the entire Triassic through Middle Jurassic sequence except in its uppermost part. The Upper Jurassic Vasyugan Formation, which contains reservoir sandstones, is present only in the southern area of the AU, and it grades into shales of the Abalak Formation northward. The Vasyugan Formation has been drilled in most of the known structures, and its remaining potential is moderate because the undrilled prospects will be relatively small. In general, undiscovered resources of the pre-Cretaceous sequence are probably much smaller than those of the Cretaceous sequence.

In conclusion it should be noted that the Northern West Siberian Onshore Gas AU possibly contains an unconventional (continuous) gas accumulation in the lower part of the Coniacian–Campanian Berezov Formation (fig. 4). The formation includes a 20-m-thick bed of diatomite with porosity of 30–43 percent and permeability of less than 1 mD (Agalakov and Bakuev, 1992). Fracturing is common, especially on the tops of structural uplifts, where fracture permeability may be as high as 50 mD. The diatomite bed is present in most areas of the AU and extends south into the Middle Ob region. It occurs at depths of less than 800 m. Gas shows were recorded in numerous wells that were drilled to deeper targets. The bed was tested in three wells and produced gas flows of 90 to 125 thousand cubic feet per day (Agalakov and Bakuev, 1992). The drilling regime was designed for deeper objectives, and no well stimulation was applied. In the Greater Urengoy area, gas saturation was also identified in synclines between structural uplifts. In spite of low temperatures and the proximity of the permafrost zone, the formation pressures are abnormally high. Whether the diatomite bed contains an extensive unconventional gas accumulation in the low permeability reservoir, and the fractured zones are the "sweet spots" in this accumulation, or the bed is a conventional reservoir, is not clear. However, the unconventional nature of the accumulation seems to be more probable.

South Kara Sea Offshore Assessment Unit

Two prospects have been drilled in the southern Kara Sea offshore from the Yamal Peninsula, and two giant fields, the Rusanov and Leningrad fields, were discovered (fig. 14). In bothields, gas accumulations occur in Aptian–Cenomanian sandstones beneath the Kuznetsov Formation seal. Only three wells were drilled, and the fields' reserves are not known with certainty; however, preliminary estimates indicate that in-place gas resources of the two fields are about 300 TCF (Nikitin and Rovnin, 2000). Recently, the North Kamennomys field was discovered in the middle part of the Ob Inlet (fig. 14) also in Aptian–Cenomanian sandstones, but no data on the precise location of this field and its reserves are available.

Most of the seismic surveys conducted to date are in the western part of the South Kara Sea where about 60 local structures were mapped (fig. 14). Many of these structures are arranged in linear arches 150–350 km long. The northern to northwestern structural grain of northern West Siberia extends offshore from the Yamal Peninsula and is terminated by northeasterly striking structures farther northwest. The extension of the Yamal Peninsula geology into the area occupied by the northwesterly trending structures is obvious from existing seismic and drilling data. The principal gas-producing Aptian–Cenomanian section was drilled in the Rusanov and Leningrad fields, and it is similar to this section in the Kharasavey and adjacent fields onshore (fig. 14). On seismic data, Neocomian clinoforms also extend at least into the southern part of the offshore area (Sosedkov, 1993), and this indicates a high probability for the presence of Bazhenov Formation source rocks that were deposited in a deep-water basin later filled with the clinoform sediments. The presence of thick Lower–Middle Jurassic and probably Triassic sequences also is indicated by seismic data (Kulakov, 1984; Nikitin and others, 1999). Farther offshore, the probability of changes in the stratigraphic composition of the sedimentary cover increases, and the exploration risk is higher. The thick Triassic–Jurassic sequence is present in the central part of the sea, but it onlaps the basement and pinches out toward the Novaya Zemlya Islands (Nikitin and others, 1999). Probably, the Vikulov arch (fig. 14) is at or near the pinch-out zone. This sequence also pinches out on the northeastern basin margin. A well drilled on Sverdrup Island (fig. 1) penetrated 1,400 m of Cretaceous and 228 m of Upper Jurassic rocks overlying the metamorphic basement (Kulakov, 1984). No oil or gas shows have been reported. The stratigraphic equivalents of the Bazhenov Formation in marginal zones probably are represented by organic-lean facies similar to the onshore West Siberian basin. If the discussed model of gas generation from Jurassic source rocks is correct, the exploration risk in marginal zones may be high. In addition, the quality of the key Turonian seal may deteriorate owing to increasing amounts of sandstones. On the other hand, shallower marginal zones, in which

Bazhenov organic-rich shales are present and the possibility of gas escaping through the Turonian seal exists, may appear to be more oil-prone. The petroleum potential of the eastern offshore part of the basin probably is much lower judging from the geology of the Gydan Peninsula where no major gas discoveries have been made. In general the undiscovered gas potential of the South Kara Sea Offshore AU is very high although the assessment (table 1) reflects a substantial uncertainty range owing to the frontier character of the AU. Most of the gas resources undoubtedly will be found in the Aptian–Cenomanian sandstones, but older rocks, especially Neocomian clastics, also have a high potential.

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Figure 1. Total petroleum systems and assessment units of West Siberian basin

Figure 2. Basement tectonic map of West Siberian basin (modified from Zonenshayn and others, 1990). Contours on base of Mesozoic rocks.

Figure 3. Early–Middle Triassic rift system of West Siberian basin (modified from Surkov and others, 1997). Rift grabens: I–Koltogor-Urengoy, II–Khudosey, III–Yamal, IV–Agan, V–Ust-Tym, VI–Chuzik.

Figure 4. Columnar sections of Mesozoic rocks of West Siberian basin.

Figure 5. Lithofacies and isopach map of Lower–Middle Jurassic Tyumen Formation. Modified from Rudkevich and others (1988). Major oil and gas accumulations are shown.

Figure 6. Lithofacies and isopach map of Callovian–Kimmeridgian rocks (Abalak and Vasyugan Formations and equivalents). Modified from Rudkevich and others (1988). Major oil and gas accumulations are shown.

Figure 7. Lithofacies and isopach map of Bazhenov Formation and stratigraphic equivalents. Modified from Rudkevich and others (1988). Major oil and gas accumulations are shown.

Figure 8. Example of Neocomian clinoforms in Middle Ob region (modified from Nezhdanov and others, 1990). Approximate location is shown in figure 11.

Figure 9. Lithofacies and isopach map of upper Hauterivian–Barremian rocks (part of Vartov Formation and equivalents). Modified from Rudkevich and others (1988). Major oil and gas accumulations are shown.

Figure 10. Thickness of post-Jurassic sedimentary rocks of West Siberian basin (modified from Energy Information Administration, 1997).

Figure 11. Structural map of West Siberian basin. Modified from Rovenskaya and Nemchenko (1992).

Figure 12. Schematic east–west cross section I–I' through southern part of West Siberian basin (modified from Rudkevich and others, 1988). Approximate location is shown in figure 11. J1, J2, and J3, Lower, Middle, and Upper Jurassic, respectively; K1b, Berriasian; K1v, Valanginian; K1g, Hauterivian; K1a, Aptian; K1al, Albian; K2c, Cenomanian; K2t, Turonian; Pg1, Pg2, and Pg3, Paleocene, Eocene, and Oligocene, respectively; Q, Quaternary.

Figure 13. Cross section II–II' through northern part of West Siberian basin (modified from Rovenskaya and Nemchenko, 1988). Location is shown in figure 11. J1, J2, and J3, Lower, Middle, and Upper Jurassic, respectively; K1b, Berriasian; K1v, Valanginian; K1g, Hauterivian; K1br, Barremian; K1a, Aptian; K1al, Albian; K2c, Cenomanian; K2t, Turonian; Pg1, Paleocene; Pg2-3, Eocene – Oligocene; Q, Quaternary.

Figure 14. Oil and gas fields and structural prospects of Kara Sea (modified from Nikitin and Rovnin, 2000).

Figure 15. Map showing petroleum regions and oil and gas fields of West Siberian basin mentioned in text. Modified from Maksimov (1987).

Figure 16. Distribution of total organic carbon (TOC) in Bazhenov Formation and stratigraphic equivalents of West Siberian basin (modified from Kontorovich and others, 1997).

Figure 17. Vitrinite reflectance (Ro) at base of Bazhenov Formation of West Siberian basin (modified from Kontorovich and others, 1997).

Figure 18. Bazhenov-Neocomian total petroleum system events chart. Query indicates uncertainty in extent of event.

Figure 19. Cross section through AS group of pays (Achimov Formation) of Priob field (modified from Karagodin and others, 1994). Length of section is approximately 15 km.

Table 1. West Siberian Basin, Province 1174, Assessment Results Summary—Allocated Resources.

Figure 20. Map and cross section of Talin field (modified from Kontorovich and others, 1995). Structural contours on top of upper productive reservoir, contour interval 25 m.

Figure 21. Cross section of productive uppermost Paleozoic and Lower Jurassic rocks of southeastern part of West Siberian basin (modified from Surkov and others, 1999). Fields are located on Mezhov high shown in figure 11. D1, D2, and D3 are Lower, Middle, and Upper Devonian, respectively; C1 is Lower Carboniferous.

Figure 22. Distribution of total organic carbon (TOC) in Lower Jurassic rocks of West Siberian basin (modified from Kontorovich and others, 1997).

Figure 23. Vitrinite reflectance (Ro) at top of Lower Jurassic rocks of West Siberian basin (modified from Kontorovich and others, 1997). This surface is a few tens of meters above Togur Bed.

Figure 24. Togur-Tyumen total petroleum system events chart. Queries indicate uncertainties in extent or identification of event.