Geology and Assessment of Undiscovered Oil and Gas Resources of the Lena-Vilyui Basin Province, 2008

Chapter V of
The 2008 Circum-Arctic Resource Appraisal

Professional Paper 1824

U.S. Department of the Interior
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Cover. Eocene strata along the north side of Van Keulenfjorden, Svalbard, include basin-floor fan, marine slope, and deltaic to fluvial depositional facies. The age and facies of these strata are similar to Tertiary strata beneath the continental shelves of Arctic Eurasia, thus providing an analog for evaluating elements of those petroleum systems. Relief from sea level to top of upper bluff is approximately 1,500 feet. Photograph by David Houseknecht.

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The 2008 Circum-Arctic Resource Appraisal

Chapters

North Atlantic Ocean

Eurasia

Arctic Ocean

Contents

Appendix

[Available for download at https://doi.org/10.3133/pp1824X]

Figures

Tables

The 2008 Circum-Arctic Resource Appraisal
Edited by T.E. Moore and D.L. Gautier
U.S. Geological Survey Professional Paper 1824

Chapter V

Geology and Assessment of Undiscovered Oil and Gas Resources of the Lena-Vilyui Basin Province, 2008

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Abstract

The U.S. Geological Survey (USGS) recently assessed the potential for undiscovered oil and gas resources of the Lena-Vilyui Basin Province, north of the Arctic Circle, as part of the Circum-Arctic Resource Appraisal program. The province is in the Russian Federation and is situated between the Verkhoyansk fold-and-thrust belt and the Siberian craton. The one assessment unit (AU) defined for this study—the Northern Priverkhoyansk Foredeep AU—was assessed for undiscovered, technically recoverable resources. The estimated mean volumes of undiscovered resources for the Northern Priverkhoyansk Foredeep in the Lena-Vilyui Basin Province are ~400 million barrels of crude oil, 1.3 trillion cubic feet of natural gas, and 40 million barrels of natural-gas liquids, practically all (99.49 percent) of which is north of the Arctic Circle.

Province Description

Province-Boundary Definition

The Lena-Vilyui Basin Province consists of the Lena-Vilyui Basin, which is situated along the eastern margin of the Siberian craton in east-central Russia (figs. 1, 2). Only the part of the province north of the Arctic Circle is considered in this study, the southern boundary of which is placed at an east-northeast trending fault shown by Persits and Ulmishek (2003) and Grantz and others (2011) near the location of the Arctic Circle (figs. 1, 2). Geologically, this area lies west of the Verkhoyansk fold-and-thrust belt, south of the Olenek fold zone, and encompasses the northern part of the Priverkhoyansk foreland basin.

Petroleum Occurrence

Although six new-field wildcat wells and three stratigraphic test wells have been drilled in the study area (fig. 1), no fields have been discovered in the northern part of the Lena-Vilyui Basin Province as of this study (IHS Energy Group, 2007). In the Lena-Vilyui Basin Province south of the Arctic Circle, known fields contain mostly natural gas and condensates in upper Paleozoic and Mesozoic clastic rocks (Vagin and others, 1987; Sokolov, 1989). Extensive degraded petroleum (called “bitumen,” not assessed in this study) deposits crop out along the margins of the Olenek High (Ivanov, 1979; Parfenov, 1985), but no fields have been discovered on the high.

Tectonostratigraphic Evolution

The Lena-Vilyui Basin Province was a system of Proterozoic rifts upon which a carbonate platform and shelf developed. The platform and shelf composed a passive margin that existed until the Cretaceous, when it was deformed by the west-vergent Verkhoyansk fold-and-thrust belt. Deposition during and after the deformation occurred in a foreland basin setting west of the Verkhoyansk belt. Geologic cross sections (fig. 3) show the characteristics of the basin fill and structure of the adjacent thrust belt.

Proterozoic and Early Paleozoic Section

The Lena-Vilyui Basin Province originated by rifting along the Siberian craton during the late Proterozoic (Riphean), followed by subsidence and deposition on an early Paleozoic carbonate shelf (Gusev and others, 1985; Vagin and others, 1987). Rift-related sedimentary deposits include hundreds to thousands of meters of siliciclastic and clastic-carbonate materials (Safronov and Bodunov, 1987).

Uplift, deformation, and erosion during late Proterozoic time resulted in the formation of an angular unconformity between Riphean and overlying Vendian rocks (Zonenshain and others, 1990; Ulmishek, 2001). The uplift and erosion deposited clastic rocks in the lower part of the Vendian section and isolated the southern part of the Siberian craton, allowing a large shallow

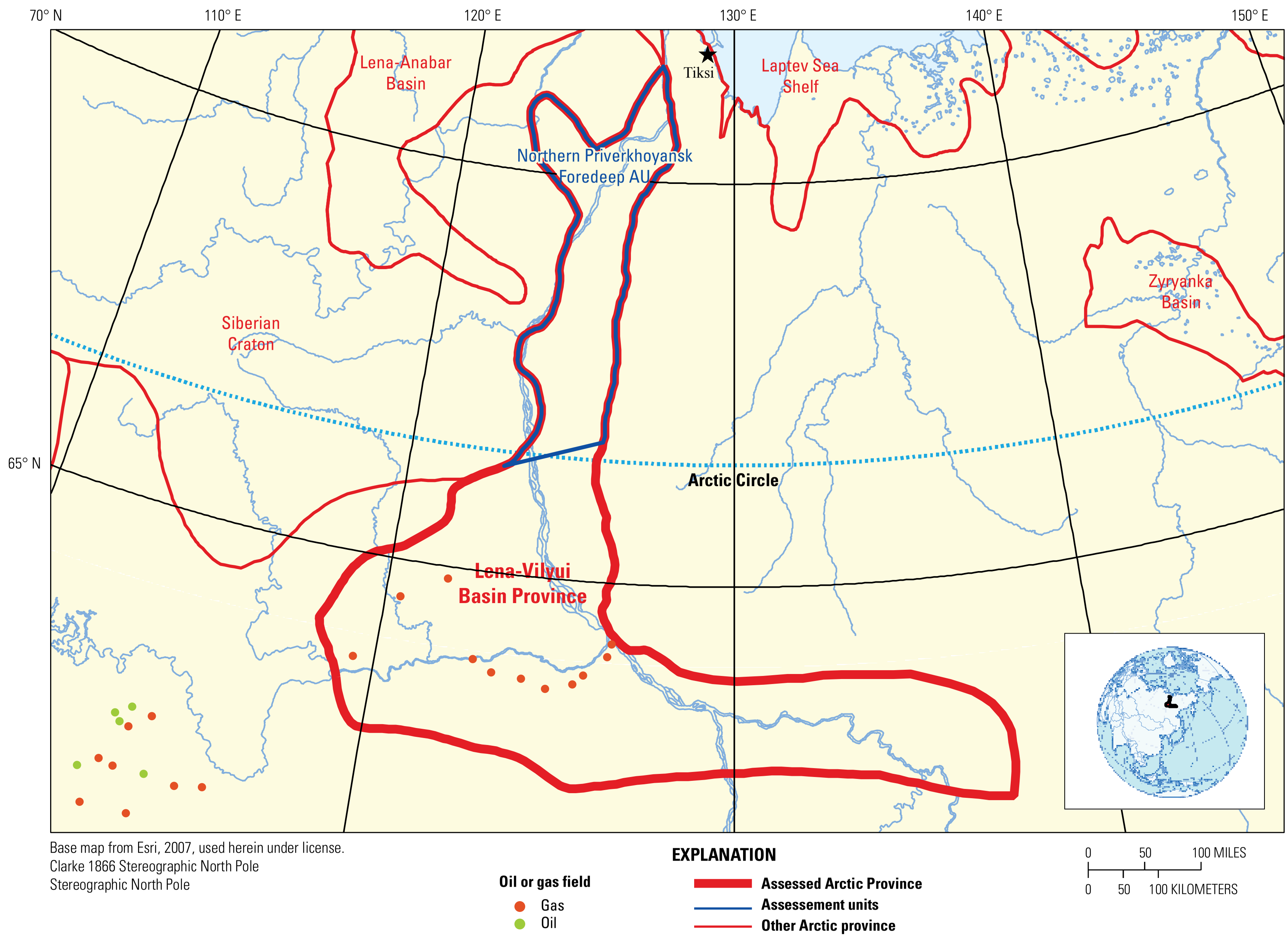


Figure 1. Map of the Arctic, showing location of the Lena-Vilyui Basin Province and assessment unit (AU). Data on oil and gas fields from IHS Energy Group (2007).

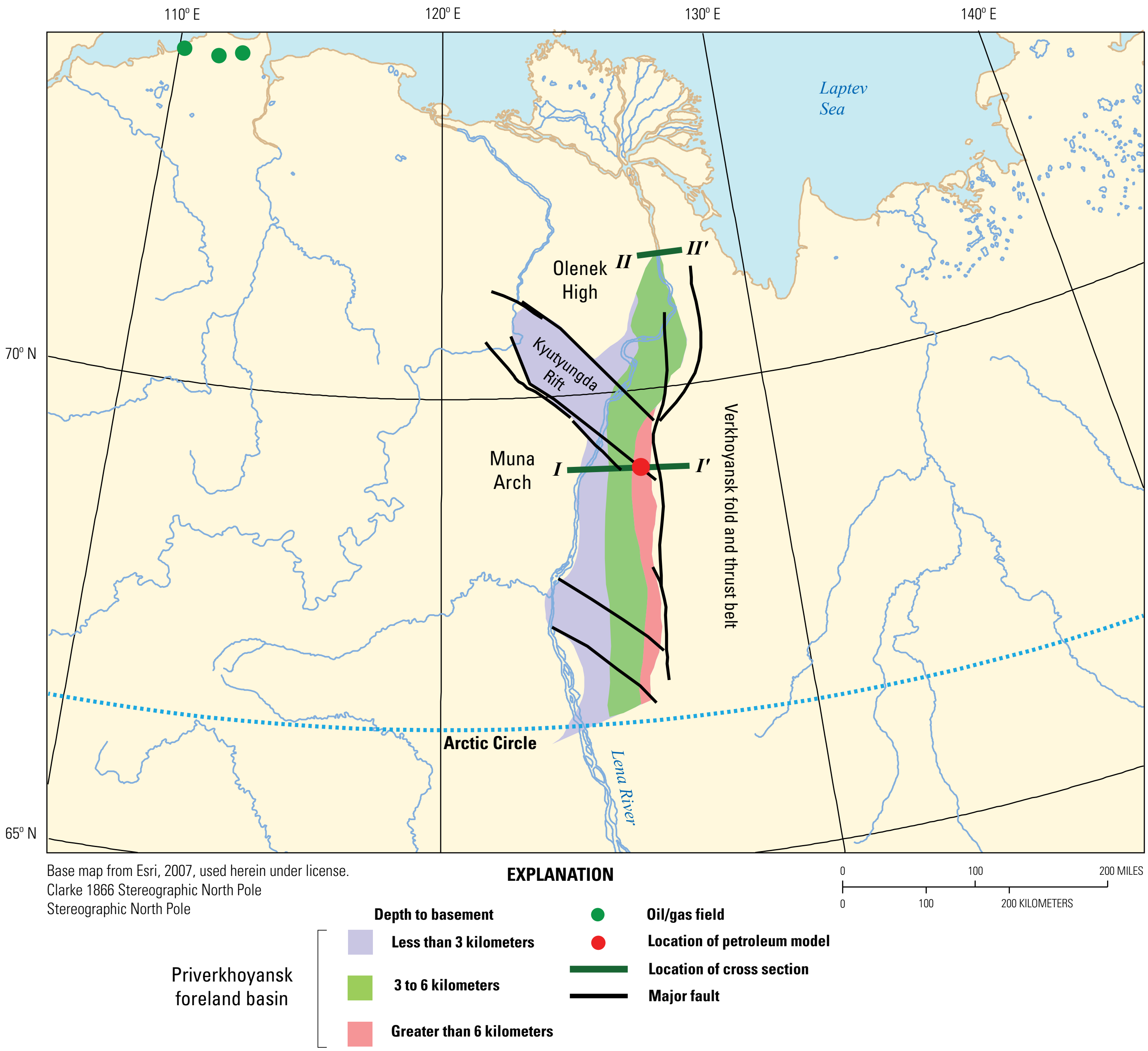


Figure 2. Map showing major structural features, approximate depth to economic basement, and location of geologic cross sections and petroleum-system models used in assessment of the Lena-Vilyui Basin Province. Data from Persits and Ulmishek (2003) and IHS Energy Group (2007).

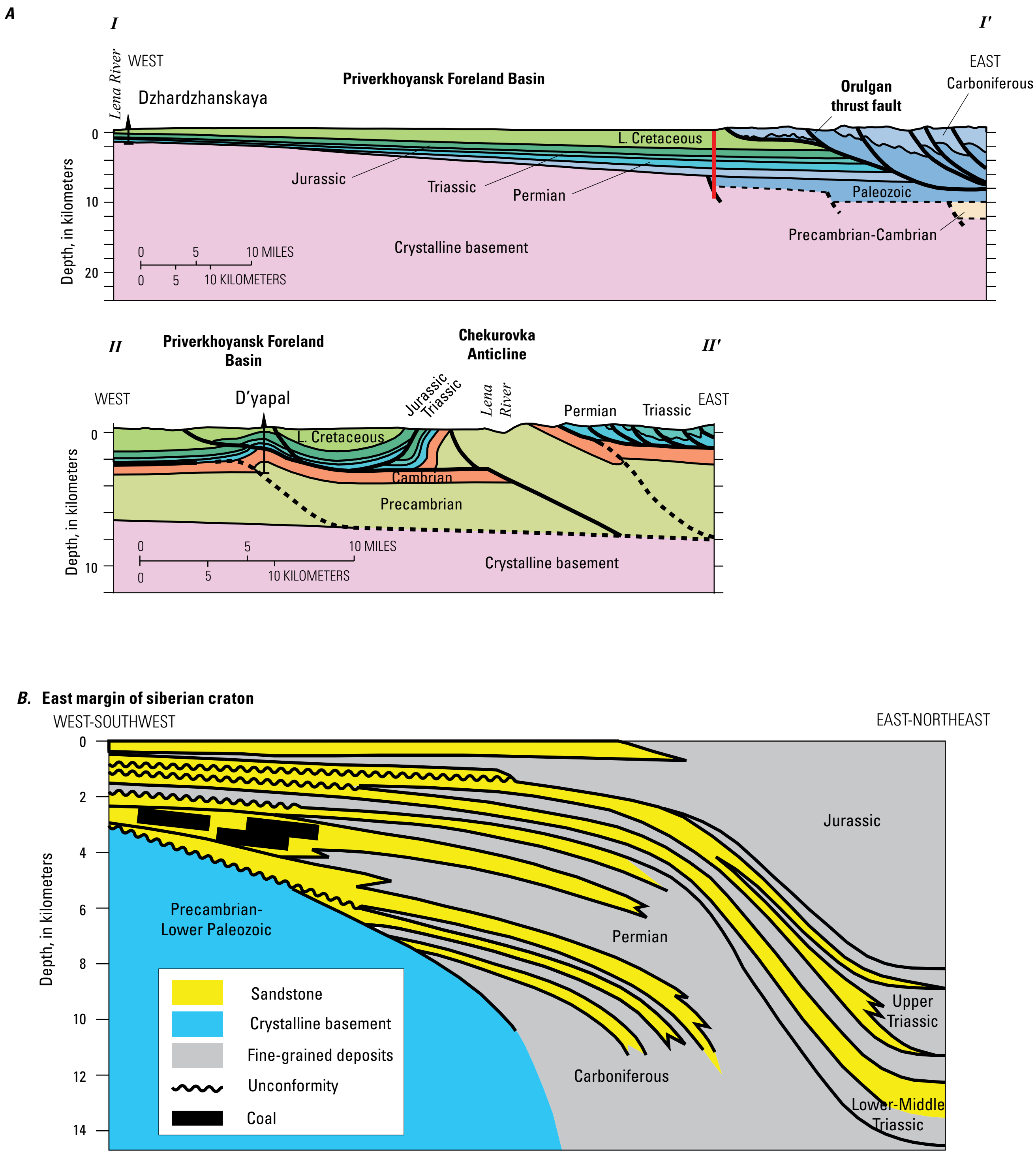


Figure 3. Regional geologic cross sections in the Lena-Vilyui Basin Province. Vertical red line denotes location of pseudowell used for petroleum-generation model (see fig. 2). Modified from Parfenov and Prokopiev (1993) and Parfenov and others (1995).

lagoon in which evaporites were deposited during the late Vendian and Early Cambrian (Zonenshain and others, 1990). The lagoon was rimmed by carbonate shelves on its present-day southeast and southwest sides, and separated from the open ocean by a zone of reefs on the present-day north and northeast (Ulmishek, 2001). In the Lena-Vilyui Basin, as much as 3.5 km of Vendian and Lower Cambrian carbonates, evaporites, and some clastic rocks were deposited (Safronov and Bodunov, 1987), which represent lagoonal conditions in the west and marine conditions in the east.

Carbonate platform and shelf conditions continued along the rifted passive margins of the Siberian craton throughout the early Paleozoic. Organic-rich (bituminous) mudstone was deposited beyond the reefs in the northern and northeastern parts of the craton during the Early and Middle Cambrian. In the Lena-Vilyui Basin, ~1 km of Middle and Upper Cambrian carbonate strata were deposited (Safronov and Bodunov, 1987). Upper Paleozoic rocks are absent across most of the Siberian craton (Ulmishek, 2001), and little, if any, sedimentary materials were deposited in the Lena-Vilyui Basin.

Late Paleozoic Section

The Siberian craton drifted northward from the Devonian to the Triassic, moving from a warm dry climate at low to middle latitudes into a cooler humid climate at higher latitudes (Zonenshain and others, 1990). During the Devonian, the craton passed over a mantle plume (hotspot), causing rifting and magmatism along the present-day southeastern and northern margins of the craton and forming rift grabens (aulacogens) beneath the Lena-Vilyui Basin, including the Kyutyungda rift graben (fig. 2), and other rift grabens beneath the present-day Khatanga Saddle and the Yenisey-Khatanga Basin, which lie outside the area of figures 1 and 2. At that time, basaltic magma intruded the Lena-Vilyui Basin area, and kimberlite dikes intruded across the craton (Zonenshain and others, 1990). These rift grabens are presumed to be reactivated Precambrian rifts (Gusev and others, 1985; Sokolov, 1989).

In the Vilyui Basin, the rift grabens contain Devonian and lower Carboniferous evaporites, carbonates, and clastic rocks (Sokolov, 1989). Organic-rich mudstone might have been deposited within the grabens before evaporite deposition (G.F. Ulmishek, oral commun., 2006). Opening of an ocean basin by rifting from the late Carboniferous to the Triassic resulted in subsidence as the eastern margin of the Siberian craton developed into a passive divergent margin (Vagin and others, 1987; Sokolov, 1989).

As the Siberian craton moved to higher latitudes, carbonate deposition changed to clastic deposition (Zonenshain and others, 1990). The margins of the craton remained passive during the late Paleozoic and early Mesozoic, and thick successions of deltaic, paralic, nearshore marine, and submarine-fan strata were deposited along the Lena-Vilyui Basin (see fig. 5; Vagin and others, 1987; Sokolov and Yapaskurt, 1988; Sokolov, 1989; Zonenshain and others, 1990). Upper Carboniferous and Permian rocks, including turbidites, were deposited in deep-marine conditions. As deposition and progradation continued, the marginal basin shallowed, and thick Permian to Cretaceous shallow-marine and continental clastic rocks were deposited (Vagin and others, 1987).

Mesozoic Section

Extension, magmatism, and volcanism occurred during the formation of a triple junction along the present-day northwestern margin of the Siberian craton in the late Permian–Early Triassic (Girshgorn, 1996; Kontorovich and others, 1994; Allen and others, 2006). Rifting and emplacement of basaltic magma occurred as far east as the Lena-Vilyui Basin (Vagin and others, 1987; Sokolov and Yapaskurt, 1988).

Collision of the Omolon and Chukotka microcontinents (Kolyma block) with the eastern margin of the Siberian craton during the Late Jurassic and Early Cretaceous formed the Verkhoyansk fold-and-thrust belt (Sokolov and Yapaskurt, 1988; Zonenshain and others, 1990). The fold-and-thrust belt conformed to the outlines of the Devonian rift systems (Zonenshain and others, 1990). The Priverkhoyansk foreland basin formed along the thrust front of the Verkhoyansk fold-and-thrust belt. A thick section of alternating marine and continental clastic sedimentary rocks with coal was deposited during Late Jurassic and Early Cretaceous time (Vagin and others, 1987; Sokolov and Yapaskurt, 1988).

Cenozoic Section

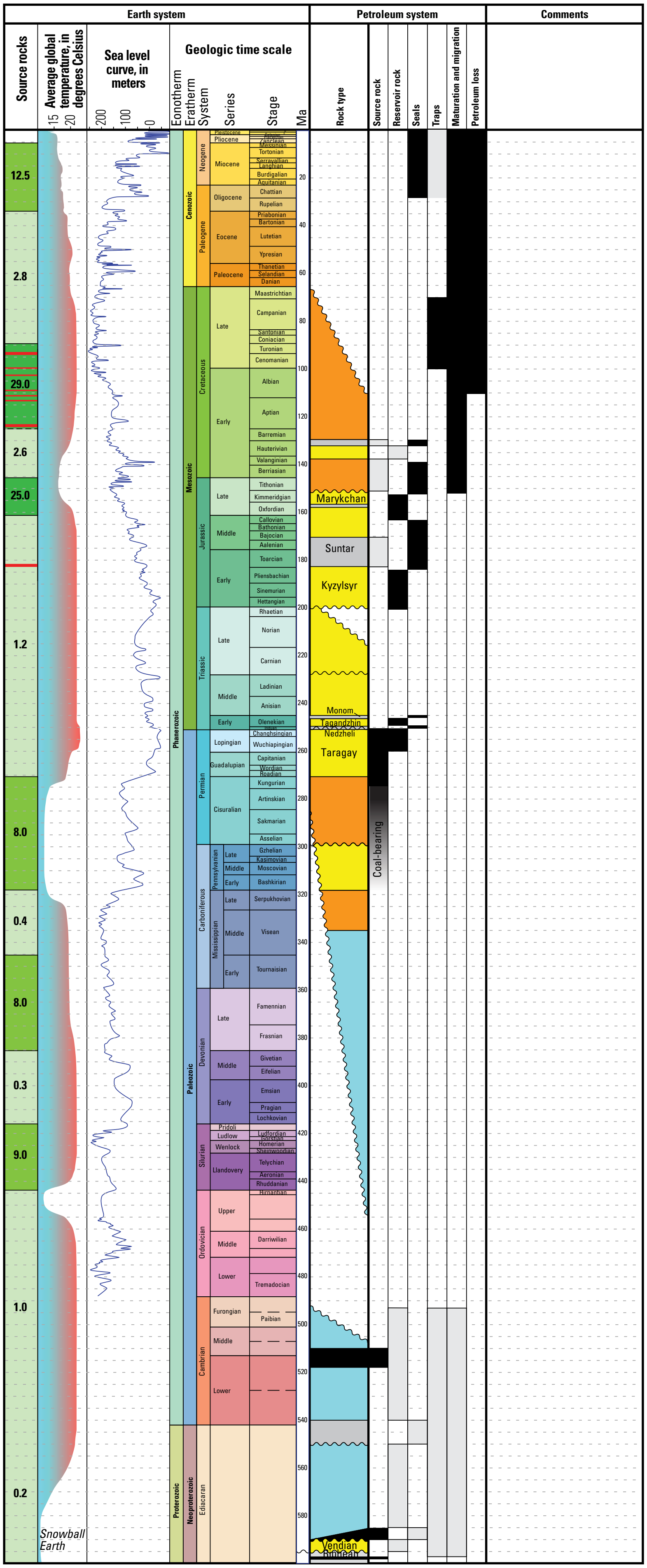
The main phase of folding and thrusting occurred during the Cretaceous and Cenozoic, depositing coarse orogenic clastic sediments in structural lows (Vagin and others, 1987). Tectonic quiescence during the Paleogene was followed by uplift of 1.5 to 2 km during the Oligocene to Quaternary (Sokolov, 1989).

Petroleum-System Elements

Because of presumed mixing of petroleum, a single Proterozoic-Paleozoic-Mesozoic composite total petroleum system (TPS) was identified for the Lena-Vilyui Basin Province. A lithostratigraphic column and TPS events chart with petroleum-system elements is shown in figure 4.

Source Rocks

Main potential source rocks include Precambrian and Cambrian oil-prone organic-rich carbonates and mudstone, as well as Permian gas-prone carbonaceous mudstone in the Northern Priverkhoyansk foreland basin. In the southern part of the province the main source rocks are presumed to be a Permian gas-prone coal-bearing interval that contains 1 to 3.8 weight percent total organic carbon (TOC) in mudstone (Izosimova and others, 1988; Sokolov, 1989). Minor source



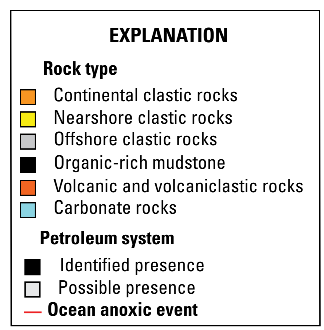


Figure 4. Lithostratigraphic column and total-petroleum-system events chart for the Lena-Vilyui Basin Province. Source rocks column shows the percent of the world's total petroleum reserves generated by source (modified from Ulmishek and Klemme, 1990). Average global temperature data is from Frakes and others (1992) and Barrett (2003). Sea level curve is from Golonka and Kiessling (2002) and Hardenbol and others (1998). Geologic time scale is that of Gradstein and others (2004). Data from Safronov and Bodunov (1987), Vagin and others (1987), Izosimova and others (1988), Sokolov and Yapaskurt (1988), Sokolov (1989), Bakhturov and others (1990), and Baranova (1996).

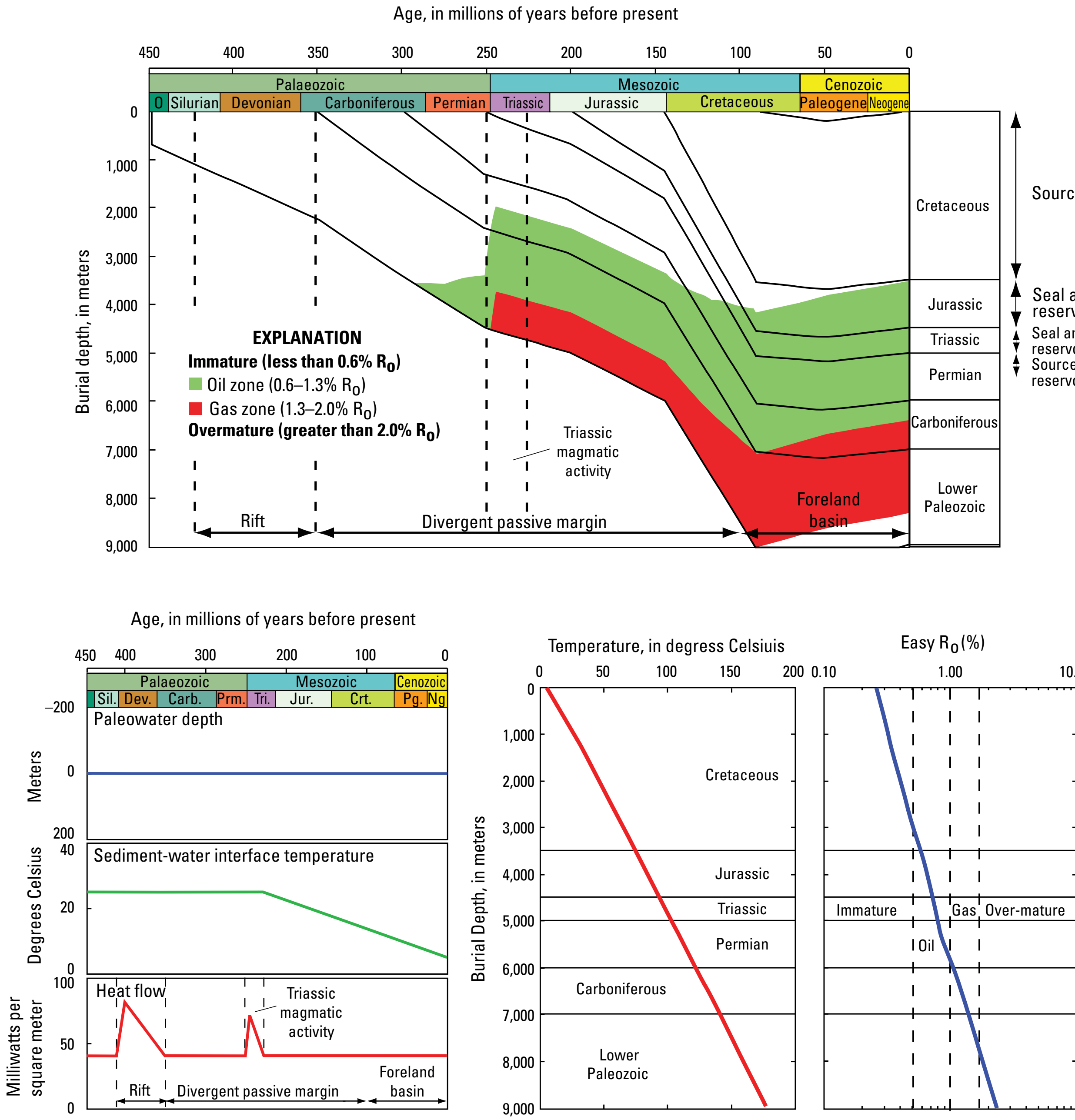


Figure 5. Burial-history model for pseudowells in the Northern Priverkhoyansk Foredeep Assessment Unit in the Lena-Vilyui Basin Province depicting thermal maturity. See figure 2 for locations of wells. Ro, vitrinite reflectance, in percent (%). Data from Duchkov and others (1982), Frolov and others (1987), Izosimova and others (1988), Sokolov and Yapaskurt (1988), Parfenov and Prokopiev (1993). Petromod references are from Wygrala (1989), Sweeney and Burnham (1990), Integrated Exploration Systems (2008).

rocks in this area are gas prone, including Jurassic (maximum 2.2 weight percent TOC in the upper part), Lower Cretaceous (maximum 1.6 weight percent TOC), and possibly Triassic mudstone (Sokolov, 1989). The presence of bitumen deposits along the northern and eastern margins of the Olenek High (Ivanov, 1979; Parfenov, 1985), presumably from Precambrian and Cambrian source rocks, indicate that the northern part of the province might be oil prone rather than gas prone as in the southern part of the province. Gas fields discovered to date are located in the southern part of the basin.

On the basis of petroleum-generation models, Permian and Mesozoic source rocks began to generate petroleum by the end of the Mesozoic (fig. 5). These source rocks are presently in the gas-generation window in deeper parts of the basin and in the oil window in shallower areas. Maturation of Proterozoic and Cambrian source rocks is modeled to have occurred during the Paleozoic, assuming that a sufficient thickness of Paleozoic rocks was deposited; otherwise, these rocks would have entered the oil-generation window during Mesozoic time due to burial beneath the Cretaceous foredeep deposits.

Reservoir and Seal Rocks

Reservoir rocks in the Northern Priverkhoyansk foreland basin are assumed to be similar to those in the southern part of the Lena-Vilyui Basin Province. Lithic and arkosic Permian through Jurassic sandstones become predominantly arkosic in the Upper Jurassic and Lower Cretaceous intervals (Sokolov, 1989), sourced primarily from the Siberian craton. In the northernmost part of the foreland basin, these clastic rocks are coarser grained in the west along the Olenek High, fining eastward into more distal marine environments. Sedimentary patterns changed by Early Cretaceous (Barremian) time with the eastward advance of the Verkhoyansk fold-and-thrust belt toward the Siberian craton. Clastic sedimentary rocks contain material sourced from the Verkhoyansk fold-and-thrust belt and fine westward (Parfenov and others, 1995). Several reservoir and seal pairs are known in southern part of the Lena-Vilyui Basin Province and occur in the upper Permian, Lower Triassic, and Lower through Upper Jurassic stratigraphic intervals. Potential reservoir and seal pairs in the northern part of the province include those within the Middle and Upper Triassic, Middle and Upper Jurassic, and Lower Cretaceous sections (Vagin and others, 1987; Sokolov, 1989). Although Precambrian and Cambrian clastic rocks and carbonates with mudstone seals have not been explored in the study area, they could have accumulated Precambrian- and Cambrian-sourced petroleum. Cambrian through Silurian carbonates and Devonian evaporites would act as seals.

Traps and Timing

Potential traps in the Northern Priverkhoyansk foreland basin include simple or faulted anticlines and thrust-fault-related structures related to the collision of the Kolyma block with the Siberian craton during the Late Cretaceous, and updip stratigraphic pinchouts (Baranova, 1986; Vagin and others, 1987; Sokolov, 1989; Kontorovich, 1994). However, most of the pre-Cretaceous source-rock maturation and petroleum generation occurred by Late Cretaceous time, before and during trap formation. The foreland basin is a relatively undeformed monocline, with few traps between the fold and thrust belt and the updip basin margin.

According to petroleum-generation models for the adjacent Lena-Anabar Basin (see chapter T of this volume), maturation of Proterozoic and Cambrian source rocks likely occurred during the Paleozoic, assuming that a sufficient thickness of Paleozoic rocks was deposited. However, the probability of preservation would likely be low because of pre-Permian erosion. Otherwise, Proterozoic and Cambrian source rocks, as well as Permian and Mesozoic source rocks, generated petroleum during the Mesozoic before and during compressional deformation along the Verkhoyansk fold-and-thrust belt. Although some accumulated petroleum was probably lost, generation may have continued during trap formation (Sokolov and Yapaskurt, 1988).

Petroleum migrated vertically along faults, laterally over short distances into reservoirs juxtaposed to source rocks by fault displacements, or laterally updip over long distances through permeable carrier beds from deeper parts of the foredeep to the basin margin (Parfenov, 1985). Bitumen accumulations along the Olenek High are evidence of such long-distance migration (Parfenov, 1985) and are assumed to indicate that little petroleum was captured in sedimentary traps in the basin.

Assessment Units

One AU, the Northern Priverkhoyansk Foredeep AU, was defined for the Lena-Vilyui Basin Province. For this study, an AU is defined as a volume of rock within the TPS that has similar geologic characteristics. The estimated numbers and sizes of undiscovered oil and gas fields in this AU are reported in appendix 1, and the geologic-analog data used to evaluate the AUs are summarized in tables 1 and 2.

Northern Priverkhoyansk Foredeep Assessment Unit

The Northern Priverkhoyansk Foredeep AU coincides with the foreland basin north of the Arctic Circle, and includes strata that onlap updip onto the Siberian craton (the Olenek High and the Muna Arch), which forms the west boundary of the AU. The AU is bounded on the north and east by the Verkhoyansk fold-and-thrust belt, and on the south by the edge of the Lena-Vilyui rift graben (figs. 1, 2). Stratigraphically, the AU includes the entire sedimentary section from Proterozoic through Mesozoic.

The AU area of ~56,000 km^2 is completely onshore, and more than 99 percent is north of the Arctic Circle.

The AU began as a rift basin during the Precambrian and was later reactivated in the early and middle Paleozoic. The Kyutyunda rift part of the AU contains Devonian and lower Carboniferous strata associated with rifting. The AU later developed into an eastward-facing passive divergent margin. Upper Carboniferous and Permian turbidites are overlain by a thick Permian through Cretaceous marine, shallow-marine, and continental clastic succession. Jurassic and Cretaceous deformation created a foreland basin in front of the present-day Verkhoyansk fold and thrust belt.

Geologic Analysis of Assessment-Unit Probabilities

No oil or gas fields have been discovered in the Northern Priverkhoyansk Foredeep AU as of 2007, and so source, reservoir, and seal rocks and trap configurations can only be inferred. The probability that the AU contains at least one field equal to or larger than the minimum size of 50 million barrels of oil equivalent (MMBOE) is 40 percent (0.40). Input distributions and probabilities for the Northern Priverkhoyansk Foredeep AU are reported in appendix 1 and summarized below.

Charge Probability.—A charge probability of 1.0 was estimated because large amounts of bitumen occur along the updip limits of the AU.

Rock Probability.—A rock probability of 0.8 was estimated because the presence of reservoirs, seals, and traps is likely but unknown.

Timing and Preservation Probability.—A timing and preservation probability of 0.5 was estimated because pre-Cretaceous source rocks were predicted to enter the petroleum-generation window before and during Cretaceous deformation and trap formation. Bitumen deposits along the north and east margins of the Siberian craton indicate that some generated oil might not have been trapped.

Geologic Analogs for Assessment

Two analog datasets were chosen from the USGS Analog Database (Charpentier and others, 2008): (1) foreland basins (24 analogs) and (2) rifted passive margins and foreland basins with mixed clastic and carbonate depositional systems (15 analogs). The analog datasets were used to estimate the numbers and sizes of undiscovered fields (tables 1, 2). Both datasets contain discovered oil and gas fields larger than the minimum size (50 MMBOE) defined for this assessment. The analog categories include extensional and compressional structures and traps with carbonate and clastic depositional systems (table 1). Four AUs are common to both analog datasets.

Numbers of Undiscovered Fields.—The numbers of undiscovered oil and gas fields was estimated by comparing field densities (estimated numbers of undiscovered fields plus numbers of discovered fields larger than 50 MMBOE per 1,000 km^2) of the two analog datasets (table 2). The median and maximum densities of discovered fields are 0.2 and 1.1 fields per 1,000 km^2, respectively, whereas the median and maximum densities of discovered plus undiscovered fields are 0.3 and 1.6 fields per 1,000 km^2, respectively. Minimum, medium, and maximum densities of 0.02, 0.1, and 0.9, respectively, were used in this assessment. These densities are slightly lower than those in the analog dataset because no economic discoveries were made in the AU despite exploration, and a carbonate shelf might not have existed over the entire study area. The total minimum, median, and maximum numbers of undiscovered fields are 1, 7, and 50, respectively (see appendix. 1). An oil/gas mixture of 0.5 (± 0.2) was assumed because of the possible contributions from both gas-prone Mesozoic source rocks and oil-prone Proterozoic and Paleozoic source rocks. The estimated minimum, median, and maximum numbers of undiscovered oil fields are 1, 4, and 35, respectively, and of undiscovered gas fields are 1, 4, and 35, respectively (see appendix. 1).

Sizes of Undiscovered Fields.—The minimum, median, and maximum sizes of undiscovered oil and gas fields in the Northern Priverkhoyansk Foredeep AU are reported in appendix 1. The minimum sizes of undiscovered oil and gas fields defined for the AU are 50 million barrels (MMB) of crude oil and 300 billion cubic feet (BCF) of natural gas (6 BCF equals 1 MMBOE). The median sizes of undiscovered oil and gas fields in the AU are 125 MMB of crude oil and 500 BCF of natural gas. The median size of undiscovered oil fields is approximately equal to the mean size in the analog dataset, 130 MMBOE, but the median size of undiscovered gas fields is considerably smaller because traps for natural gas in this AU might not be efficient (table 1). Low-probability maximum sizes of undiscovered oil and gas fields in the AU are 2,500 MMB of oil and 1,000 BCF of gas, allowing for the probability of a large oil field within the Proterozoic and Paleozoic section.

Expected Maximum Size of Undiscovered Fields.—The expected maximum sizes of oil and gas fields 400 MMB of oil and 100 BCF of gas, respectively, are based on the distribution of sizes of discovered fields in the analog dataset, particularly the median size of discovered fields.

Petroleum Composition and Properties of Undiscovered Fields.—Coproducts and petroleum-quality properties were estimated from global statistics (table 3) and petroleum properties of the nearby Baikal-Patom Foldbelt Riphean-Craton Margin Vendian AU (province number 12100101).

Table 1. Provinces used as geologic analogs in assessment of the Northern Priverkhoyansk Foredeep Assessment Unit.

[Analog data from Charpentier and others (2008)]

Province name (Assessment Unit number)	Structural setting	Trap system	Depositional system
		Foreland basins	
Middle Caspian Basin (11090101)	Compressional	Compressional anticlines, folds, thrusts	Carbonate shelf; paralic clastics
Amu-Darya Basin (11540101)	Compressional	Compressional anticlines, folds, thrusts; Basement-involved block structures	Paralic clastics; carbonate shelf
Amu-Darya Basin (11540102)	Passive	Compressional anticlines, folds, thrusts; Stratigraphic undeformed	Paralic clastics; carbonate shelf
Amu-Darya Basin (11540103)	Compressional	Compressional anticlines, folds, thrusts	Paralic clastics
Rub Al Khali Basin (20190101)	Compressional; Extensional	Compressional anticlines, folds, thrusts	Carbonate shelf
Rub Al Khali Basin (20190102)	Compressional	Compressional anticlines, folds, thrusts; Salt-induced structures	Carbonate shelf
Rub Al Khali Basin (20190103)	Compressional	Compressional anticlines, folds, thrusts	Carbonate shelf
Zagros Fold Belt (20300101)	Compressional	Compressional anticlines, folds, thrusts	Continental clastics; carbonate shelf
Zagros Fold Belt (20300102)	Compressional	Compressional anticlines, folds, thrusts	Carbonate shelf; continental clastics
Zagros Fold Belt (20300201)	Compressional	Compressional anticlines, folds, thrusts	Carbonate shelf
Junggar Basin (31150101)	Compressional	Compressional anticlines, folds, thrusts; Basement-involved block structures	Continental clastics
Sichuan Basin (31420101)	Compressional	Compressional anticlines, folds, thrusts	Carbonate shelf
Tarim Basin (31540101)	Compressional	Compressional anticlines, folds, thrusts; Basement-involved block structures	Carbonate shelf; paralic clastics
North Carpathian Basin (40470101)	Passive	Compressional anticlines, folds, thrusts	Paralic clastics; slope, clinoforms, turbidites
North Carpathian Basin (40470201)	Compressional	Compressional anticlines, folds, thrusts	Paralic clastics; slope, clinoforms, turbidites
San Jorge Basin (60580102)	Compressional	Compressional anticlines, folds, thrusts	Paralic clastics
Middle Magdalena (60900101)	Compressional	Compressional anticlines, folds, thrusts	Paralic clastics
Middle Magdalena (60900102)	Compressional	Compressional anticlines, folds, thrusts	Paralic clastics
Llanos Basin (60960101)	Compressional; Extensional	Compressional anticlines, folds, thrusts	
Llanos Basin (60960102)	Compressional; Extensional	Compressional anticlines, folds, thrusts	
East Venezuela Basin (60980101)	Compressional	Compressional anticlines, folds, thrusts	Paralic clastics

Table 1. Provinces used as geologic analogs in assessment of the Northern Priverkhoyansk Foredeep Assessment Unit.—Continued

[Analog data from Charpentier and others (2008)]

Province name (Assessment Unit number)	Structural setting	Trap system	Depositional system
East Venezuela Basin (60980102)	Compressional	Compressional anticlines, folds, thrusts	Paralic clastics
Maracaibo Basin (60990102)	Compressional	Compressional anticlines, folds, thrusts	Paralic clastics
Deformed Belt (61170101)	Compressional	Compressional anticlines, folds, thrusts	Carbonate shelf
	Rifted passive margins		
Timan-Pechora Basin (10080102)	Compressional	Basement-involved block structures; Paleogeomorphic	Paralic clastics; carbonate shelf
Timan-Pechora Basin (10080103)	Compressional	Compressional anticlines, folds, thrusts	Paralic clastics; carbonate shelf
Volga-Ural Region (10150101)	Passive	Basement-involved block structures; Paleogeomorphic	Paralic clastics; carbonate shelf
Volga-Ural Region (10150102)	Compressional	Basement-involved block structures	Paralic clastics; carbonate shelf
Middle Caspian Basin (11090101)	Compressional	Compressional anticlines, folds, thrusts	Carbonate shelf; paralic clastics
Amu-Darya Basin (11540101)	Compressional	Compressional anticlines, folds, thrusts; Basement-involved block structures	Paralic clastics; carbonate shelf
Nepa-Botuoba Arch (12100101)	Compressional	Basement-involved block structures; Stratigraphic undeformed	Paralic clastics; Carbonate shelf
Ma'Rib-Al Jawf/Masila Basin (20040101)	Extensional	Extensional grabens and other structures related to normal faulting	Paralic clastics; Carbonate shelf
Fahud Salt Basin (20160201)	Compressional; Extensional	Compressional anticlines, folds, thrusts	Paralic clastics; carbonate shelf margin, reefs
Zagros Fold Belt (20300101)	Compressional	Compressional anticlines, folds, thrusts	Carbonate shelf margin, reefs, slope, clinoforms, turbidites
Zagros Fold Belt (20300102)	Compressional	Compressional anticlines, folds, thrusts	Continental clastics; carbonate shelf
Pelagian Basin (20480101)	Compressional; Extensional	Extensional grabens and other structures related to normal faulting; Transtensional and transpressional	Carbonate shelf; continental clastics
Pelagian Basin (20480201)	Compressional; Extensional	Extensional grabens and other structures related to normal faulting; Transtensional and transpressional	Carbonate shelf; paralic clastics
Tarim Basin (31540101)	Compressional	Compressional anticlines, folds, thrusts; Basement-involved block structures	Paralic clastics; carbonate shelf
Bombay (80430101)	Extensional	Basement-involved block structures; Stratigraphic undeformed	Paralic clastics; carbonate shelf
			Paralic clastics; carbonate shelf margin, reefs

Table 2. Field densities, median oil and gas field sizes, and exploration maturities of geologic analogs used in Northern Priverkhoyansk Foredeep Assessment Unit assessment.

[Analog data from Charpentier and others (2008). Asterisk (*), not reported in analog database. Gas volumes are nonassociated. MMBOE, million barrels of oil equivalent; MMB, million barrels; BCF, billion cubic feet]

Province name (Assessment Unit number)	*Field density Number of discovered fields >50 MMBOE per 1,000 km^2	Field density Number of discovered and undiscovered fields >50 MMBOE per 1,000 km^2	Field size distribution Median field size >50 MMBOE	Exploration maturity Percent petroleum equivalent volume in all fields >50 MMBOE	Maximum field size (MMBOE)
			Foreland basins		
Middle Caspian Basin (11090101)	0.38	1.15	116	61	
Amu-Darya Basin (11540101)	0.12	0.13	111	94	
Amu-Darya Basin (11540102)	0.17	0.29	110	97	
Amu-Darya Basin (11540103)	0.08	0.09	149	96	
Rub Al Khali Basin (20190101)	0.09	0.18	204	90	
Rub Al Khali Basin (20190102)	0.54	0.80	175	95	
Rub Al Khali Basin (20190103)	0.27	0.55	109	54	
Zagros Fold Belt (20300101)	0.20	0.57	162	79	
Zagros Fold Belt (20300102)	0.19	0.59	126	83	
Zagros Fold Belt (20300201)	0.30	1.55	213	57	
Junggar Basin (31150101)	0.11	0.17	121	98	
Sichuan Basin (31420101)	0.07	0.12	98	89	
Tarim Basin (31540101)	0.02	0.13	112	14	
North Carpathian Basin (40470101)	0.22	0.27	119	99	
North Carpathian Basin (40470201)	0.09	0.10	77	98	
San Jorge Basin (60580102)	0.07	0.29	124	99	
Middle Magdalena (60900101)	1.13	1.25	177	99	
Middle Magdalena (60900102)	0.73	0.92	115	91	
Llanos Basin (60960101)	0.24	0.44	123	58	
Llanos Basin (60960102)	0.09	0.22	147	66	
East Venezuela Basin (60980101)	0.64	1.38	187	73	
East Venezuela Basin (60980102)	0.07	0.46	90	16	

Table 2. Field densities, median oil and gas field sizes, and exploration maturities of geologic analogs used in Northern Priverkhoyansk Foredeep Assessment Unit assessment.—Continued

[Analog data from Charpentier and others (2008). Asterisk (*), not reported in analog database. Gas volumes are nonassociated. MMBOE, million barrels of oil equivalent; MMB, million barrels; BCF, billion cubic feet]

Province name (Assessment Unit number)	*Field density Number of discovered fields >50 MMBOE per 1,000 km^2	Field density Number of discovered and undiscovered fields >50 MMBOE per 1,000 km^2	Field size distribution Median field size >50 MMBOE	Exploration maturity Percent petroleum equivalent volume in all fields >50 MMBOE	Maximum field size (MMBOE)
Maracaibo Basin (60990102)	0.44	0.60	112	90	
Greater Antilles Deformed Belt (61170101)	0.02	0.03	102	67	
Median	**0.18**	**0.37**	**120**	**89**	**874**
Mean	**0.26**	**0.51**	**132**	**78**	**6,926**
		Rifted passive margins			
Timan-Pechora Basin (10080102)	0.26	0.44	115	74	
Timan-Pechora Basin (10080103)	0.01	0.23	103	53	
Volga-Ural Region (10150101)	0.25	0.29	114	100	
Volga-Ural Region (10150102)	0.14	0.14	116	100	
Middle Caspian Basin (11090101)	0.38	1.15	116	61	
Amu-Darya Basin (11540101)	0.12	0.13	111	94	
Nepa-Botuoba Arch (12100101)	0.02	0.07	117	76	
Ma'Rib-Al Jawf/ Masila Basin (20040101)	0.20	0.41	100	66	
Fahud Salt Basin (20160201)	0.23	0.28	223	92	
Zagros Fold Belt (20300101)	0.20	0.57	162	79	
Zagros Fold Belt (20300102)	0.19	0.59	126	83	
Pelagian Basin (20480101)	0.12	0.19	157	94	
Pelagian Basin (20480201)	0.01	0.02	63	66	
Tarim Basin (31540101)	0.02	0.13	112	14	
Bombay (80430101)	0.06	0.11	106	82	
Median	**0.14**	**0.23**	**115**	**79**	**1,666**
Mean	**0.15**	**0.32**	**123**	**76**	**8,007**
		Summary of all analogs used			
Median	**0.15**	**0.29**	**116**	**86**	**1,025**
Mean	**0.22**	**0.43**	**129**	**78**	**5,810**
Maximum	**1.13**	**1.55**	**223**	**100**	

Assessment Results

The assessment results for the Northern Priverkhoyansk Foredeep AU are summarized in table 4. Estimates represent undiscovered, technically recoverable, conventional petroleum resources.

The mean undiscovered crude-oil resource in the Northern Priverkhoyansk Foredeep AU (north of the Arctic Circle) is 377 MMB, with a 95-percent-confidence probability (F95) of 0 MMB and an F5 of 1,732 MMB. Given the probability of 0.40 for an oil and gas field of minimum size, a probablility of 50 percent (0.50) that no crude-oil or natural-gas resources exist is estimated for this AU (table 4). The mean volume of undiscovered nonassociated natural-gas resource is 1,039 BCF, with an F95 of 0 BCF and an F5 of 4,319 BCF. The maximum expected size of an undiscovered oil field is ~393 MMB, and the maximum expected size of an undiscovered gas field is ~619 BCF.

The total estimated mean volume of undiscovered petroleum resources in the Northern Priverkhoyansk Foredeep in the Lena-Vilyui Basin Province north of the Arctic Circle is the same as for the Northern Priverkhoyansk Foredeep AU (table 4). Additional statistics are provided in table 4.

The geologic probabilities of the AUs in this study were determined on the basis of a consideration of the geology of this province but also from the geologic probabilities assigned to AUs during the assessment of all Arctic basins. Thus, the probabilities were consistently applied throughout the Arctic in this assessment project.

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Table 3. World statistics for porpoduct ratios, ancillary data, and depths.

[Data from Charpentier and others, 2008]

Variable	Minimum	Median	Maximum
Coproduct ratios			
Ratio of natural gas to crude oil in oil accumulations (cubic feet per barrel)	100	1,000	20,000
Ratio of natural gas liquids to natural gas in oil accumulations (barrels per thousand cubic feet)	5	25	85
Ratio of natural gas liquids to natural gas in gas accumulations (barrels per thousand cubic feet)	5	25	75
Ancillary data for oil accumulations			
API gravity (degrees)	20	38	55
Viscosity (centipoise)	0.01	3	30
Sulfur content of oil (percent)	0	0.3	1.5
Ancillary data for gas accumulations			
Inert gas content (percent)	0	2	10
Carbon dioxide content (percent)	0	1.5	10
Hydrogen sulfide content (percent)	0	0.5	3.5
Depths			
Depth (m) of water (if applicable)	0	50	2,700
Drilling depth (m)	350	2,000	7,000

Table 4. Assessment results of the Lena-Vilyui Basin Province (conventional undiscovered resources).

[MMB, million barrels; BCF, billion cubic feet. Results shown are fully risked estimates. For gas fields, all liquids are included under the natural gas liquids (NGL) catagory. F95 denotes a 95-percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. TPS, total petroleum system; AU, assessment unit. N/A, not applicable]

Total Petroleum Systems and Assessment Units	AU probability	Field type	Oil (MMB)				Gas (BCF)				NGL (MMB)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Lena-Vilyui Basin Province, Proterozoic-Paleozoic-Mesozoic composite total petroleum system														
Northern Priverkhoyansk AU	0.400	Oil	0	0	1,732	377	0	0	1,448	296	0	0	39	8
		Gas	N/A	N/A	N/A	N/A	0	0	4,319	1,039	0	0	116	28
Total undiscovered petroleum resources			0	0	**1,732**	**377**	0	0	**5,767**	**1,335**	0	0	**155**	**36**

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Appendix. Input data for the Northern Priverkhoyansk Foredeep Assessment Unit

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