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

Chapter T of
The 2008 Circum-Arctic Resource Appraisal

Professional Paper 1824

U.S. Department of the Interior
U.S. Geological Survey

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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RYAN K. ZINKE, Secretary

U.S. Geological Survey
James F. Reilly II, Director

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Chapter T

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

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Abstract

The U.S. Geological Survey (USGS) assessed the potential for undiscovered oil and gas resources of the Lena-Anabar Basin Province as part of its Circum-Arctic Resource Appraisal program. The province is in the Russian High Arctic and is located between the Laptev Sea and the Siberian craton. Three assessment units (AUs) were defined for this study—the Lena-Anabar Basin AU, the Lena-Anabar Basin Updip AU, and the Sukhan-Motorchun Riphean Rift AU—and were assessed for undiscovered, technically recoverable resources. The estimated mean volumes of undiscovered oil and gas resources for the Lena-Anabar Basin Province are ~2 billion barrels of crude oil, ~2 trillion cubic feet of natural gas, and <1 billion barrels of natural gas liquids. All of the undiscovered petroleum resources are north of the Arctic Circle.

Lena-Anabar Basin Province

Province Boundary Definition

The boundary of the Lena-Anabar Basin Province is drawn to encompass the Lena-Anabar and Udzhin-Khastahk-Motorchun sedimentary basins of the northern Siberian platform (fig. 1). This geologic province is flanked by the Anabar Anticlise on the east, the Olenek High and Muna Arch on the west, the Olenek fold-and-thrust belt (a Mesozoic compressional or transpressional front) on the north, and the limit of upper Proterozoic (Riphean) rifts on the south. The province is approximately 125,000 km^2 in area. Major structural features and approximate depth to economic basement are shown in figure 2.

Sedimentary rocks in the geologic province include upper Proterozoic (Riphean and Vendian) carbonate and clastic rocks, Cambrian carbonate rocks with a karstified unconformity at the top, and Permian to Cretaceous clastic rocks. Paleozoic (Ordovician through Carboniferous) rocks are absent along the Siberian craton in the southern part of the province because of nondeposition and erosion. To the north, however, the Paleozoic section becomes more complete and progressively younger (Shishkin and Isaev, 1999).

The Lena-Anabar Basin Province is divided into three assessment units (AUs) sufficiently homogeneous in terms of geology and exploration maturity to be assessed—the Lena-Anabar Basin, the Lena-Anabar Basin Updip, and the Sukhan-Motorchun Riphean Rift AUs. Only the Lena-Anabar Basin AU was quantitatively assessed.

Petroleum Occurrence

Approximately six exploration wells have been drilled in the Lena-Anabar Basin Province. A few wells had natural gas shows, but no economic discoveries were made (IHS Energy Group, 2007). Extensive degraded petroleum (bitumen) deposits are present along the western and northeastern basin margins along the Anabar Anticlise and Olenek High (Ivanov, 1979). The deposits along the northeastern margin of the province are volumetrically enormous and potentially recoverable. These continuous (unconventional) accumulations, however, were not assessed in this study.

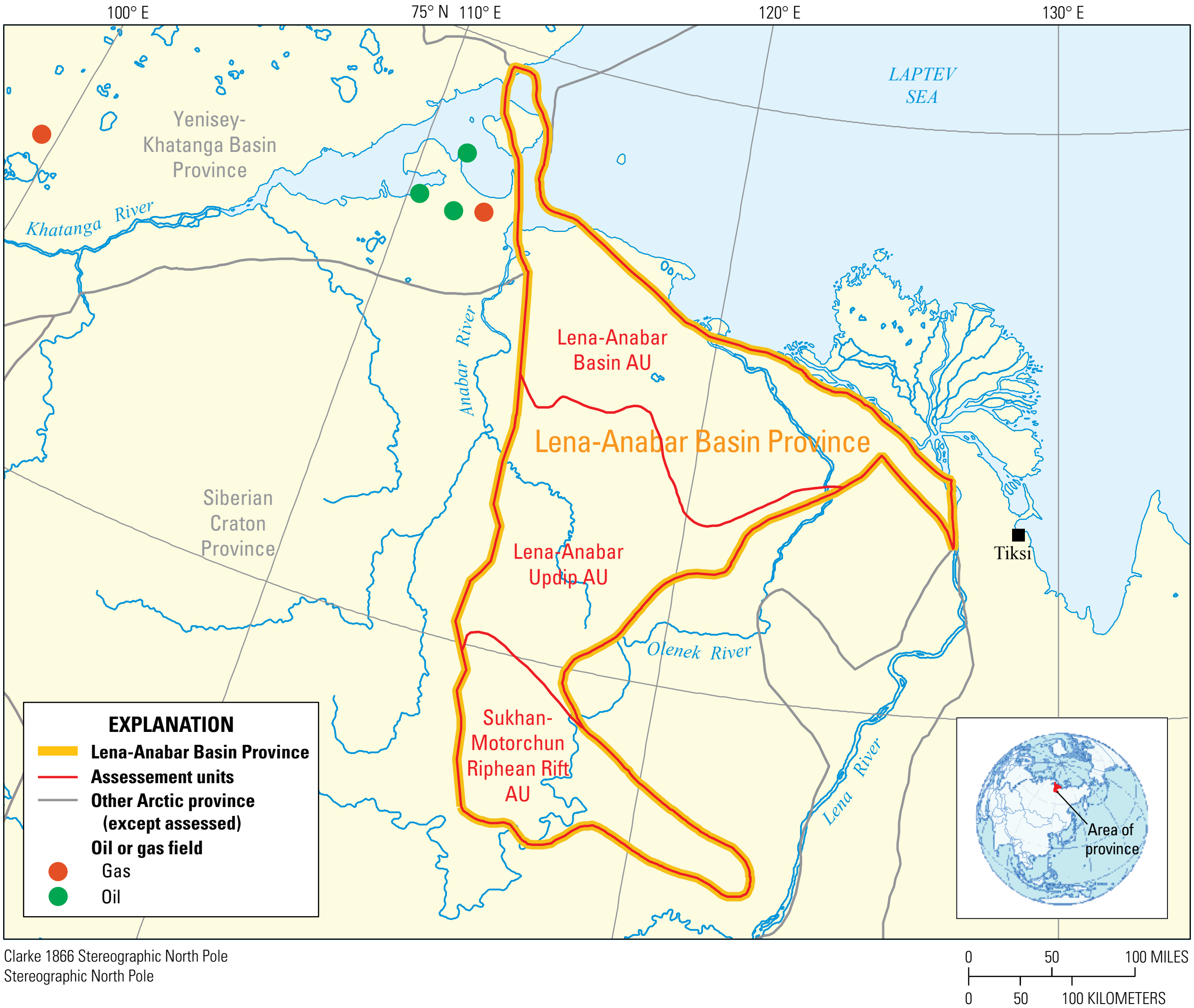


Figure 1. Map of the Lena-Anabar Basin Province and assessment units (AUs). Oil and gas field data from IHS Energy Group (2007).

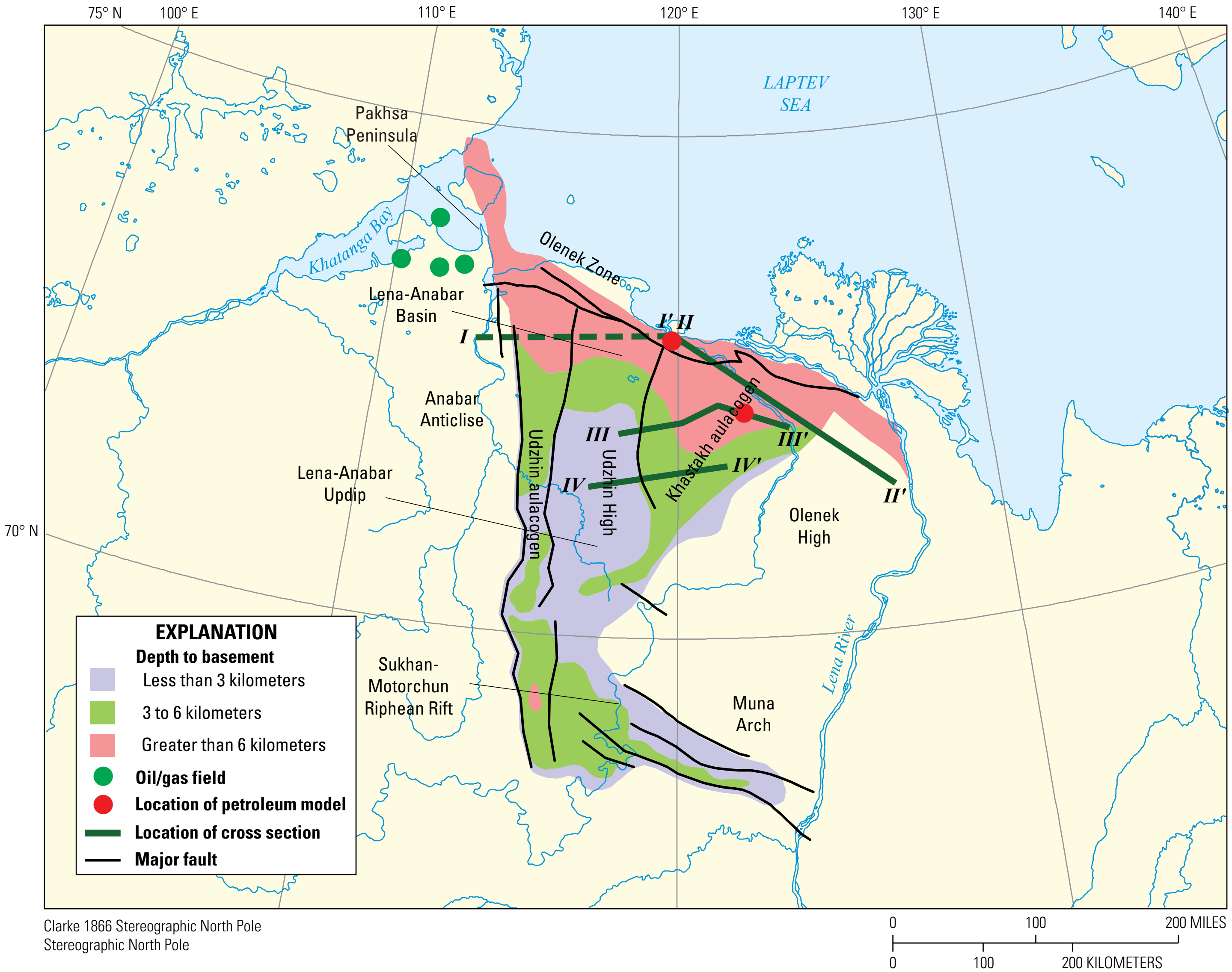


Figure 2. Map of the Lena-Anabar Basin Province's major structural features, approximate depth to economic basement, and location of geologic cross sections and petroleum system models used in the assessment. Data from IHS Energy Group (2007) and Persits and Ulmishek (2003).

Tectonostratigraphic Evolution

The Lena-Anabar Basin Province began as a system of Proterozoic rifts upon which a carbonate platform and shelf formed. The area was a passive margin until the Cretaceous, when it became a foreland basin in front of the Olenek fold-and-thrust belt. The geologic cross sections in figures 3*A* and *B* show the character of the basin fill and structure.

Proterozoic and Early Paleozoic

Intracratonic extension and rifting occurred during late Proterozoic (Riphean) time, along with deposition of carbonate and clastic sediments. A thick succession of sediments was deposited within the grabens (7 to 9 km thick in the Udzhin graben between the Anabar Anticlise and Olenek High) (Zonenshain and others, 1990). Sediments were thickest along

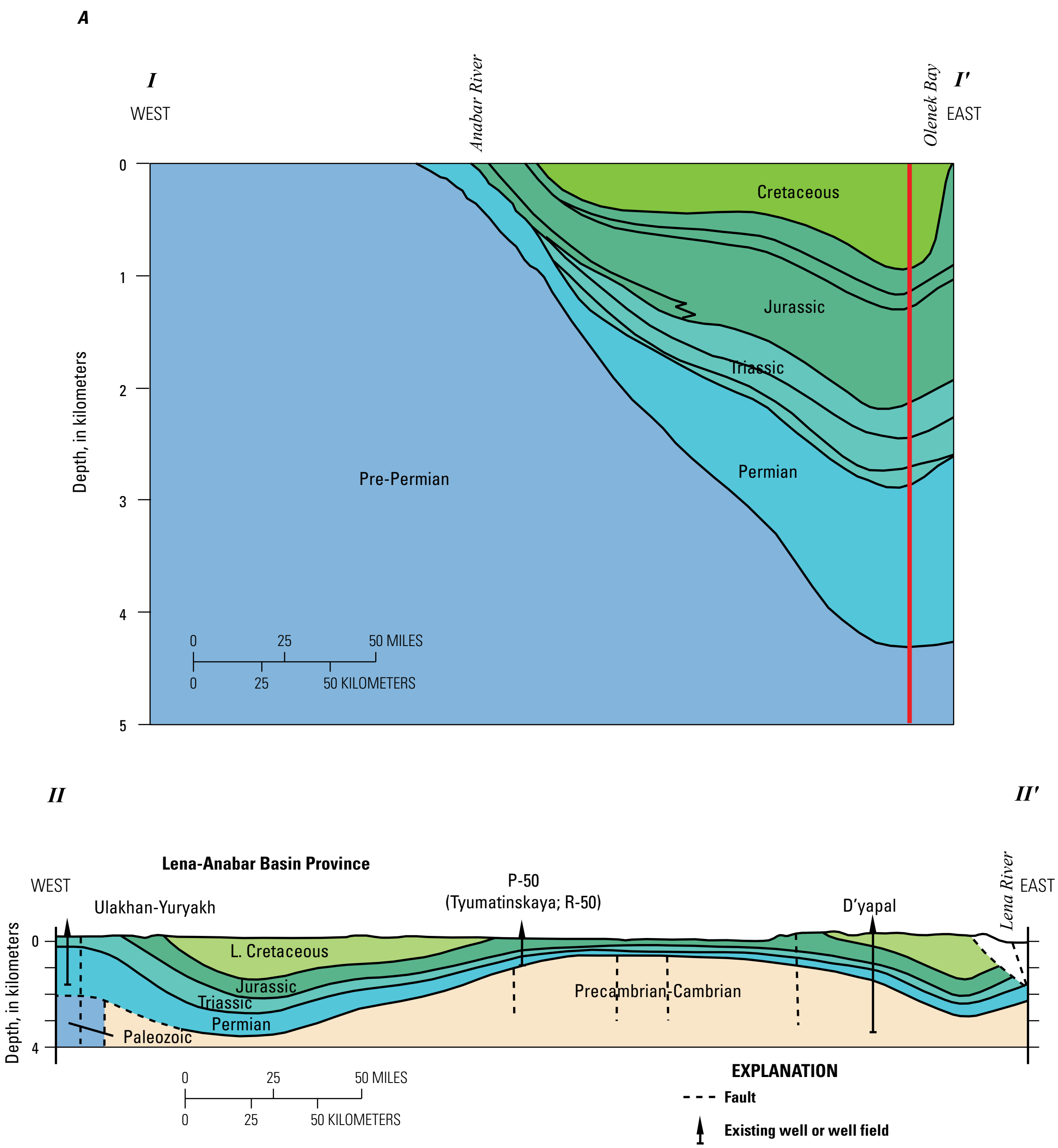
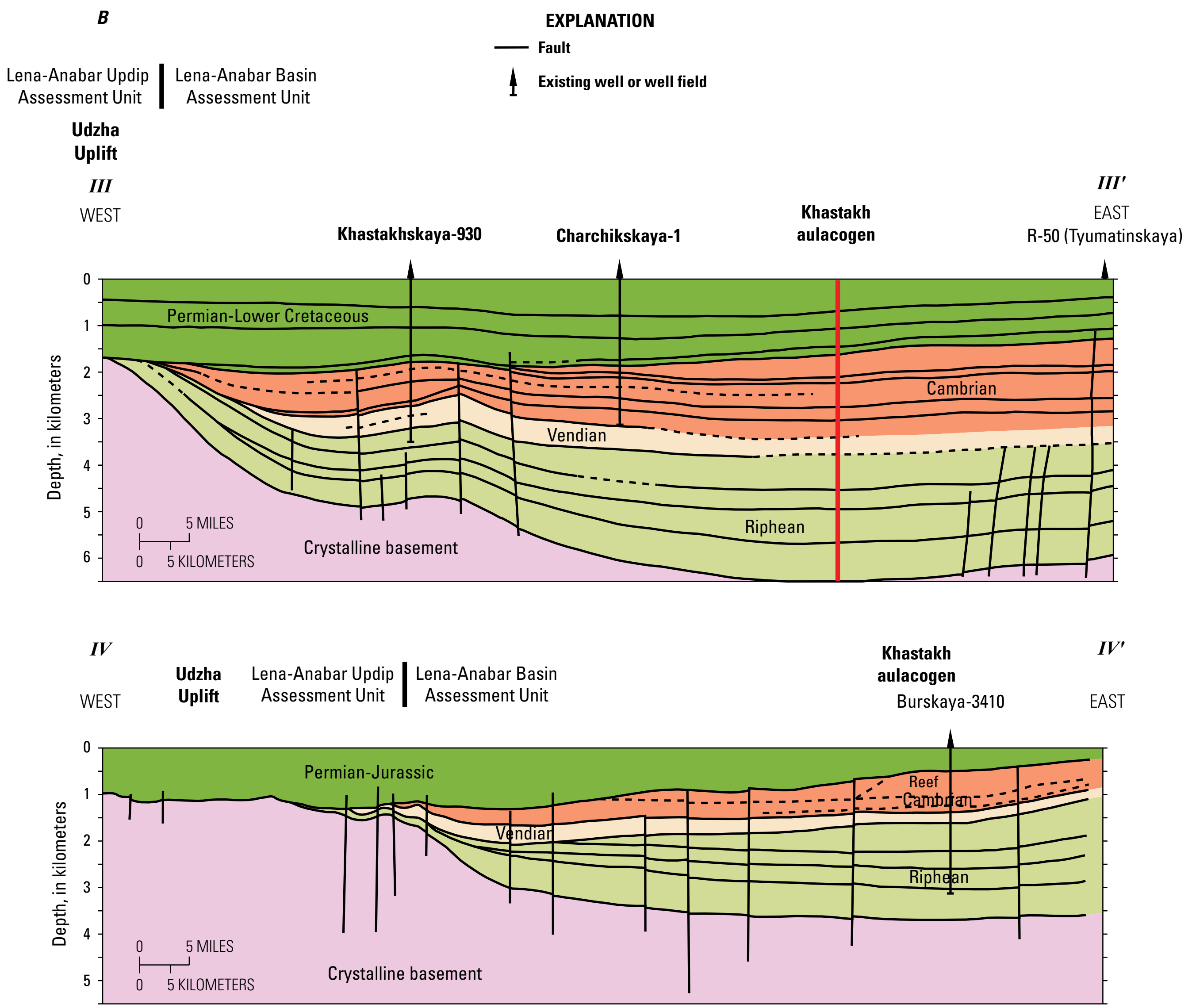


Figure 3. Regional geologic cross sections in the Lena-Anabar Basin Province. Locations shown on figure 2. Vertical red lines are locations of wells or pseudowells used for petroleum-generation models. Modified from Filipiov and others (1999); Polyakova and others (1986); Shishkin and Isaev (1999); Sokolov (1989); and Surkova (1987).



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the passive continental margins of the Siberian craton, but thin elsewhere (Ulmishek, 2001).

Uplift, deformation, and erosion during late Proterozoic time resulted in an angular unconformity between Riphean and overlying Vendian rocks (Zonenshain and others, 1990; Ulmishek, 2001). Uplift and erosion caused the deposition of clastic rocks in the lower part of the Vendian section (fig. 4*B*). Rocks in the upper part of the Vendian section include dolostone with local beds of anhydrite. Uplift was isolated within the southern part of the Siberian craton, allowing a large, shallow lagoon to form during the late Vendian and Early Cambrian into which evaporites were deposited. The lagoon was rimmed by carbonate shelves on the present-day southeastern and southwestern margins of the craton and separated from the open ocean by reefs along the present-day north and northeast margins (Gogina and Leonov, 1983; Astashkin and others, 1984; Bakhturov and others, 1990; Ulmishek, 2001).

Carbonate platform and shelf conditions continued along the rifted passive margins of the Siberian craton into the early Paleozoic. Lower and Middle Cambrian rocks include carbonate rocks and mudstone. Organic-rich (bituminous) mudstone was deposited beyond the reefs in the north and northeast part of the craton during the Lower and Middle Cambrian (fig. 4*B*) (Bakhturov and others, 1990). Permian rocks unconformably overlie Cambrian rocks in the Lena-Anabar Basin. Paleozoic rocks younger than Cambrian but older than Permian might exist in the present-day northern part of the basin. The southern part of the province was a positive structural feature until Permian time.

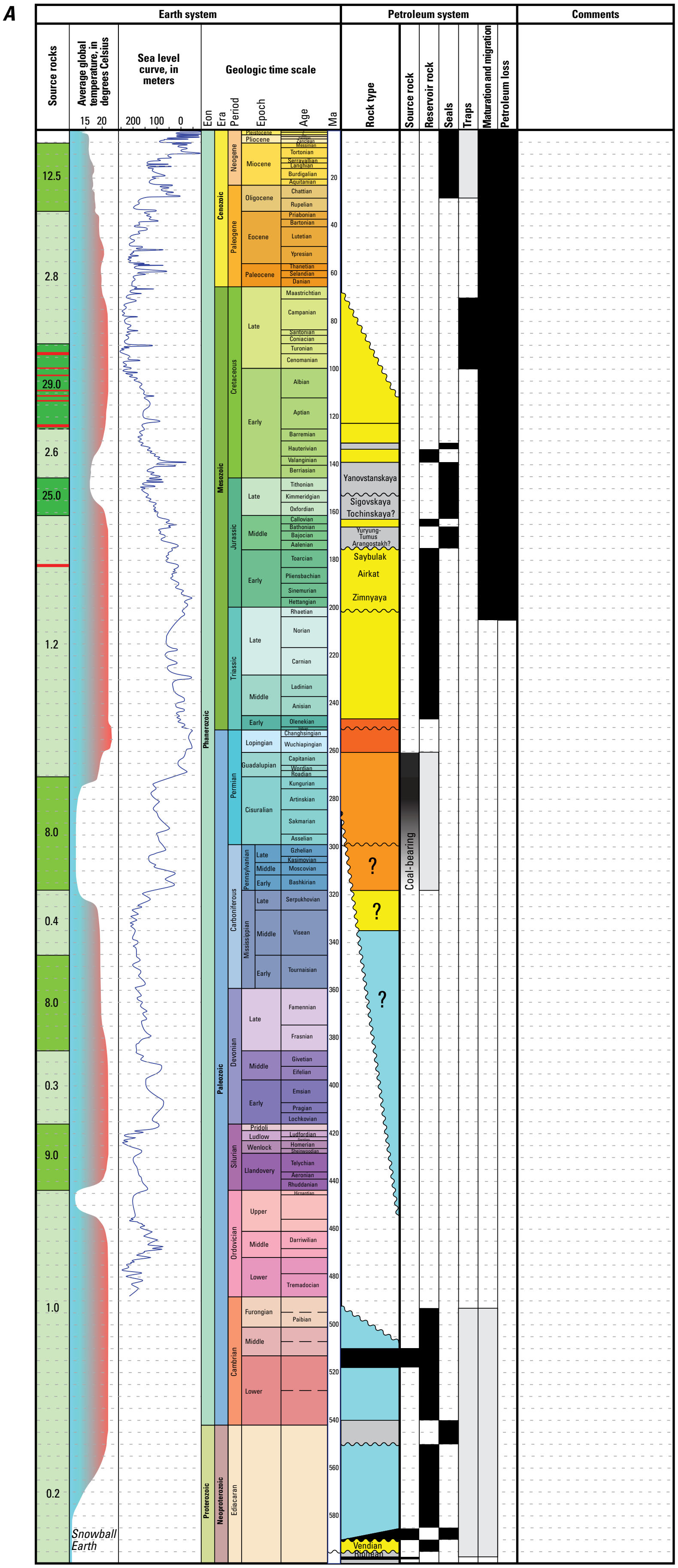


Figure 4. Lithostratigraphic column and total petroleum system events chart for the Lena-Anabar Basin Province. Source rocks column shows the percent of the world's total petroleum reserves generated by source (modified from Ulmishek and Klemme, 1990). Average global temperature data is from Frakes and 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 Filipiov and others (1999); Grausman (1996); Kontorovich and others (1994); Lebchuk (1990); Shenfil' (1991); Shishkin and Isaev (1999); and Surkova (1987).

EXPLANATION

Rock type
- Continental clastic rocks
- Nearshore clastic rocks
- Offshore clastic rocks
- Organic-rich mudstone
- Volcanic and volcaniclastic rocks
- Carbonate rocks

Petroleum system
- Identified presence
- Possible presence
- **Ocean anoxic event**

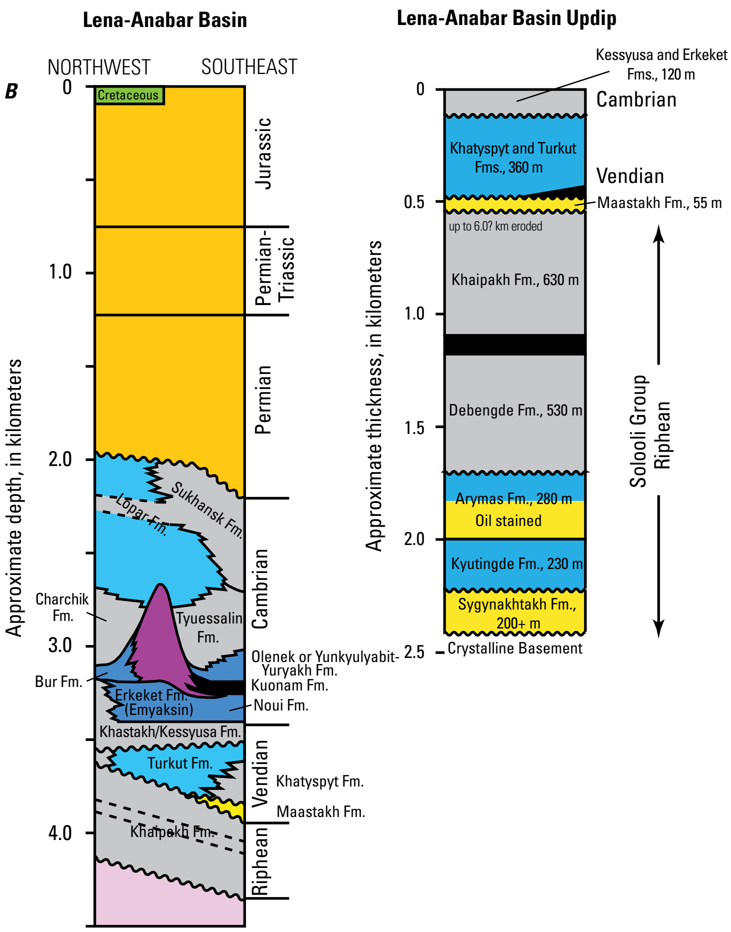


Figure 4.—Continued

Late Paleozoic and Mesozoic

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). The margins of the craton remained passive during the late Paleozoic and into the early Mesozoic, but thick successions of deltaic, paralic, nearshore marine, and submarine fan strata were deposited in the Lena-Anabar Basin (fig. 3*A*). During the Permian and Cretaceous, >4 km of clastic continental and shallow marine sediment was deposited (Polyakova and others, 1986).

The Olenek fold-and-thrust belt is a Cretaceous deformation front that bounds the northern margin of the Lena-Anabar Basin. During the deformation, an asymmetric foreland basin developed along the distal part of the Lena-Anabar Basin passive margin. Cenozoic rocks are absent in the area.

Petroleum System Elements

Several total petroleum systems could exist in the Lena-Anabar Basin Province; possible source rocks include Proterozoic, Cambrian, Permian, and Triassic strata. Because of suspected mixing of petroleum, however, only one potential system was identified: the Proterozoic-Paleozoic-Mesozoic composite total petroleum system (TPS). A lithostratigraphic column and total petroleum system events chart showing petroleum system elements are depicted in figure 4*A*, and detailed stratigraphy is shown in figure 4*B*.

Source Rocks

The most likely petroleum source rocks in the Lena-Anabar Basin Province are Proterozoic and Cambrian mudstone. Proterozoic source rocks include organic-rich, in some places bituminous, carbonate rocks and mudstone of the Riphean Khaipakh Formation and the Vendian Khatyspyt Formation (fig. 4*B*) associated with Proterozoic rift/sag areas (Shenfil', 1991; Shishkin and Isaev, 1999). Cambrian source rocks studied in outcrop and cores include the Chaburskaya Formation and the bituminous Kuonam Formation mudstone and carbonate rocks, which probably did not generate petroleum in the shallower parts of the basin where they were studied (Ivanov, 1979; Bakhturov, 1985; Bakhturov and others, 1990), though they could be thermally mature for petroleum generation in deeper parts of the basin (figs. 3*A* and *B*).

Petroleum-generation models indicate that Proterozoic and Cambrian source rocks would have generated oil and natural gas in the deeper northern part of the province. These source rocks entered the oil window by the end of the Cambrian (fig. 5*A*). If there was no deposition during the Paleozoic, crude oil might have been trapped and preserved until the present; otherwise, substantial burial would have cracked crude oil into natural gas and possibly dispersed it by subsequent uplift and erosion (fig. 5*B*).

Permian continental to marine rocks might be another source of petroleum. The clastic rocks are carbonaceous, contain ~2 percent total organic carbon (as terrestrial organic material), and are presumed to be one of the sources of petroleum in the Khatanga Saddle, which is located northwest of Lena-Anabar Basin Province (Ivanov, 1979; Polyakova and others, 1984, 1986). Permian source rocks entered the oil-generation window during the Mesozoic in deeper parts of the basin, in the northern part of the province, and are presently in the oil-generation window, according to petroleum-generation models (fig. 5*C*). Triassic and Upper Jurassic (Tithonian) mudstones are organic rich, but these rocks are most likely immature in most of the basin.

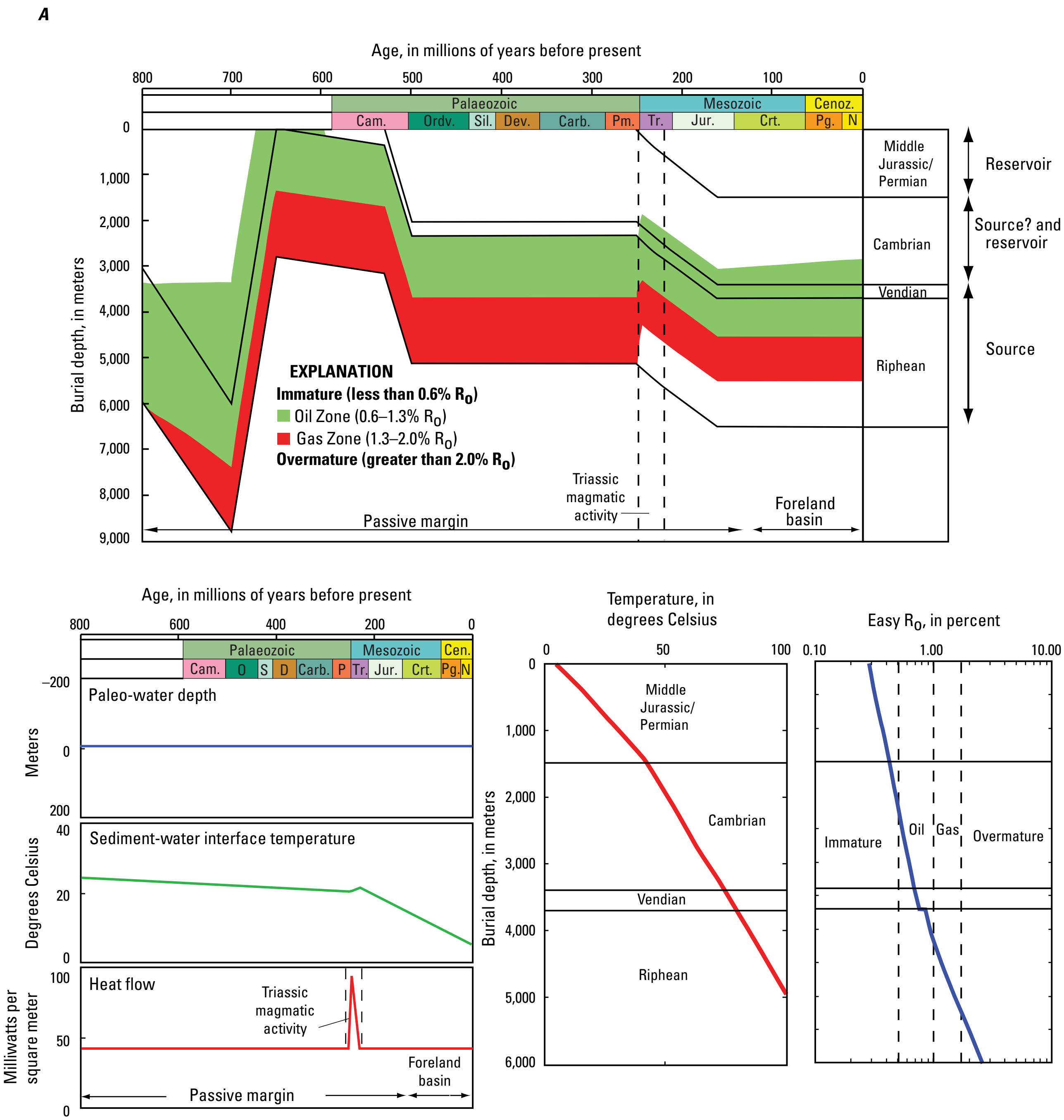
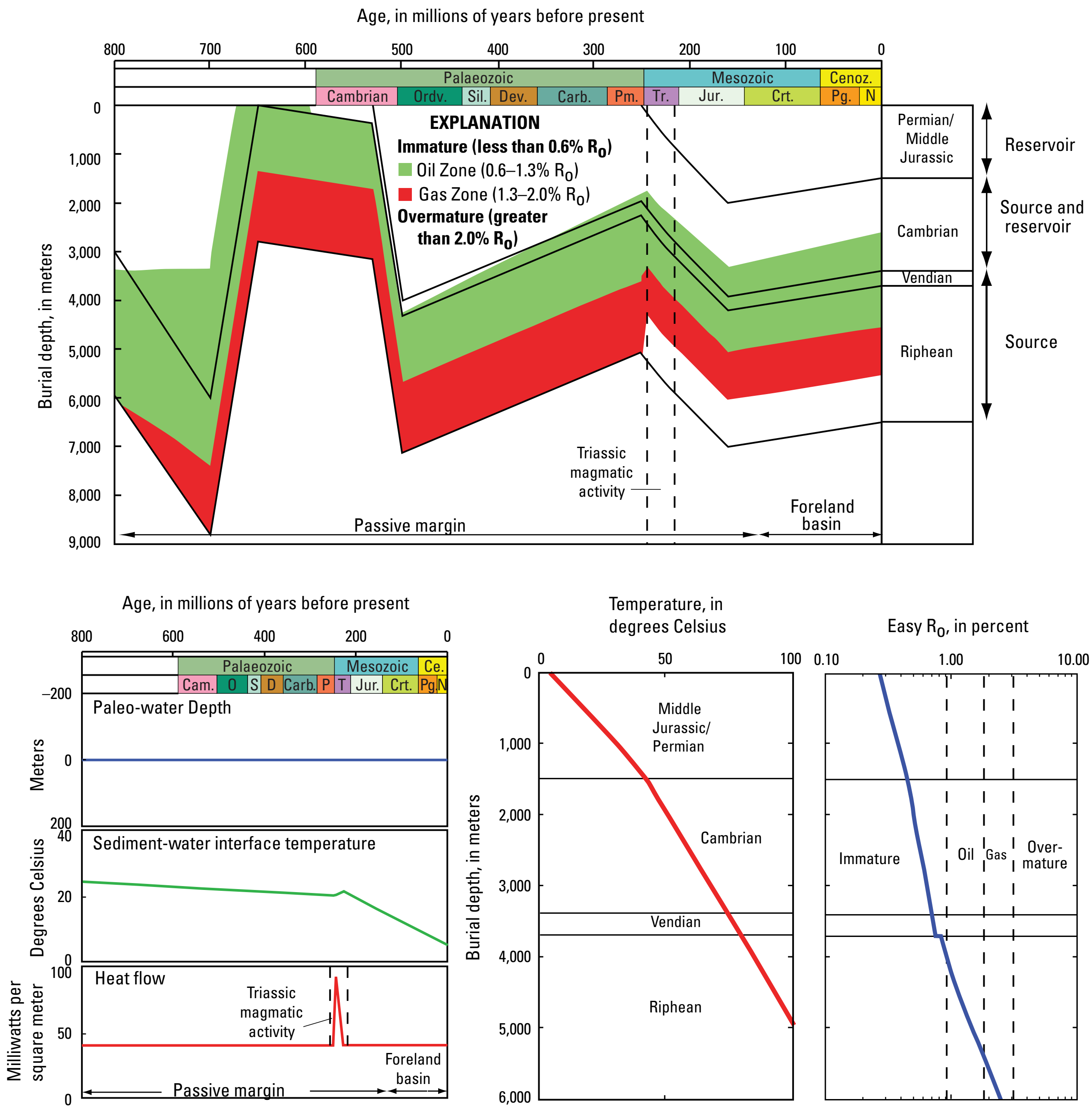


Figure 5. Burial history model for pseudowells in the Lena-Anabar Basin Province assessment units (AUs), depicting thermal maturity. Locations of wells shown in figure 2. *A*, Petroleum system model for Lena-Anabar Basin AU northern pseudowell (shown in figure 3*A*) under scenario 1, the base case, in which there is nondeposition of a middle and late Paleozoic section, followed by deposition, petroleum generation, and accumulation during the Permian and Mesozoic. *B*, Petroleum system model for Lena-Anabar Basin AU northern pseudowell (shown in figure 3*A*) under scenario 2, the worst case, in which there is deposition of a middle and upper Paleozoic section with petroleum generation and accumulation, followed by middle to late Paleozoic erosion. *C*, Petroleum system model for Lena-Anabar Basin AU for southern pseudowell (shown in figure 3*B*). Ro, vitrinite reflectance, in percent (%). Data from Duchkov and others (1982); Polyakova and others (1986); and Shishkin and Isaev (1999). Petromod references: Integrated Exploration Systems (2008); Sweeney and Burnham (1990); and Wygrala (1989).

B



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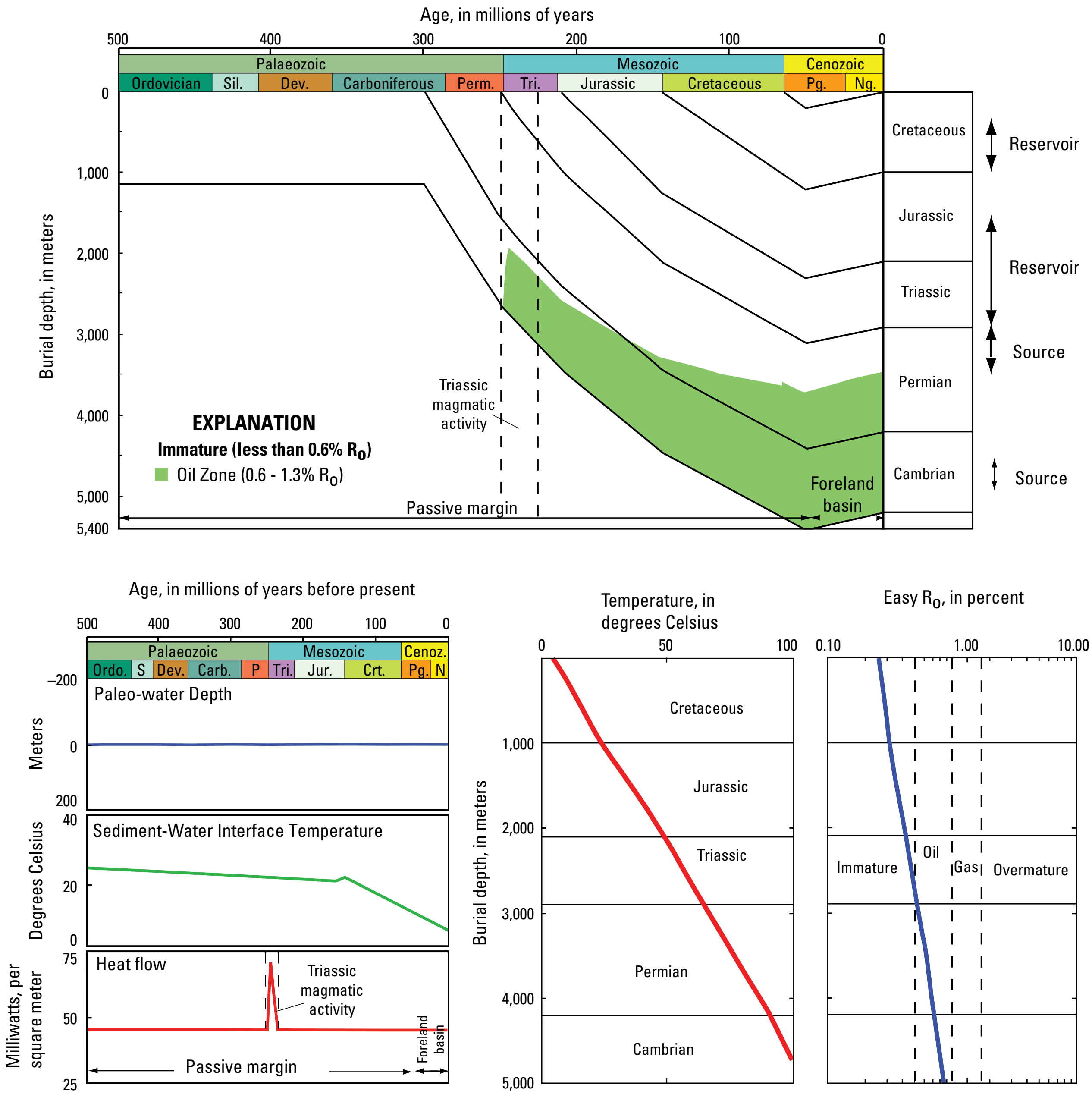

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Reservoir and Seal Rocks

The main reservoir and seal rocks in the northern part of the Lena-Anabar Basin Province are inferred to be similar to those in the neighboring Khatanga Saddle and include Upper Permian-Triassic sandstone with a Lower Triassic (Olenekian) mudstone seal. However, most Triassic clastic rocks have relatively poor reservoir quality (G.F. Ulmishek, oral commun., 2006). Lower Jurassic lithic and arkosic sandstone with 8–30 percent porosity is a potential reservoir where present.

Although Vendian rocks, as well as Cambrian reefs and reef-associated facies, might provide adequate reservoirs (Shishkin and Isaev, 1999), potential seal rocks are presently unknown. Reservoir rocks containing bitumen in the Lena-Anabar Basin Province include karsted Upper Cambrian carbonate rocks (Lopar Formation) and basal Permian sandstone and siltstone that directly, but unconformably, overlie Cambrian rocks (Ivanov, 1979).

Traps and Timing

Basement normal faults associated with Proterozoic and Paleozoic extension, as well as anticlines, thrust-fault structures, and inverted basement blocks that formed during Cretaceous deformation could provide traps in downdip areas of the northern part of the province. Stratigraphic pinchout traps and “tar mat” traps are inferred to exist updip, as well as traps with basement-associated normal faults and those related to reef facies (Ivanov, 1979; Shishkin and Isaev, 1999). Within the Proterozoic rift/sag areas, potential traps include grabens and faults related to rift structures.

According to petroleum-generation models, maturation of Proterozoic and Cambrian source rocks occurred during the Paleozoic, assuming that a sufficient thickness of Paleozoic rocks was deposited. However, preservation of petroleum accumulations would be low because of pre-Permian erosion (a worst-case scenario). Proterozoic and Cambrian source rocks, as well as Permian and Mesozoic source rocks, probably generated petroleum during the Mesozoic before compressional deformation along the Olenek fold-and-thrust belt when the basin fill was greatest.

Petroleum from Proterozoic or Cambrian source rocks is postulated to have migrated vertically and longitudinally along faults and fractures because matrix permeability is low and might not be sufficient for migration. However, petroleum most likely migrated by long-distance lateral migration along permeable carrier beds southward and updip. Extensive bitumen deposits occur in upper Proterozoic, Cambrian, and the unconformably overlying Permian rocks on both the east and west margins of the province. Numerous other bitumen occurrences and natural gas shows in wells have been identified throughout the province. The source of the bitumen is inferred to be Proterozoic and Cambrian mudstone, although some studies (Ivanov, 1979 for example) suggest that Permian mudstone is the source.

Assessment Units

Three AUs—the Lena-Anabar Basin, Lena-Anabar Basin Updip, and Sukhan-Motorchun Riphean Rift—were defined for the Lena-Anabar Basin Province. In 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 each AU are reported in appendixes 1 through 3, and the geologic analog data used to evaluate the AUs are summarized in table 1.

Table 1. Geologic analogs used in the assessment of the Lena-Anabar Basin 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

Table 1. Geologic analogs used in the assessment of the Lena-Anabar Basin Assessment Unit. —Continued

Province name (assessment unit number)	Structural setting	Trap system	Depositional system
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
East Venezuela Basin (60980102)	Compressional	Compressional anticlines, folds, thrusts	Paralic clastics
Maracaibo Basin (60990102)	Compressional	Compressional anticlines, folds, thrusts	Paralic clastics
Greater Antilles 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

Lena-Anabar Basin Assessment Unit

The Lena-Anabar Basin AU coincides with a foreland basin that is shallow to the south and west and deepens to the north and east. The basin and AU are bounded on the north by the deformation front of the Olenek fold-and-thrust belt, on the south by the approximate limit of effective petroleum-generating thickness (3 to 4 km) of Permian and Mesozoic rocks, on the east by the Olenek High, and on the west by the Anabar Anticlise. Stratigraphically, the AU includes the entire Proterozoic through Mesozoic sedimentary section. Approximately six wells have been drilled in this AU, a few of which flowed natural gas, but none are considered economic discoveries. The AU is approximately 55,000 km^2, 7 percent of which is located offshore in the Laptev Sea.

Assessment of the Lena-Anabar Basin AU was based on two scenarios, because a single timing probability was insufficient to characterize the timing of petroleum generation in Proterozoic and Paleozoic source rocks with respect to trap development. Permian and Mesozoic rocks directly overlie Cambrian rocks throughout much of the AU, but whether a complete Paleozoic section was deposited and subsequently eroded is unknown. The two scenarios are: (1) a base case (having a 90 percent probability)—nondeposition of a middle and late Paleozoic section, followed by deposition, petroleum generation, and accumulation during the Permian and Mesozoic; and (2) a worst case (having a 10 percent probability)—deposition of a middle and upper Paleozoic section with petroleum generation and accumulation, followed by middle to late Paleozoic erosion.

Geological Analysis of Assessment Unit Probability

The probability that the Lena-Anabar Basin AU contains at least one field equal to or greater than the minimum field size of 50 million barrels of oil equivalent (MMBOE) is less than 50 percent (0.50). As of 2007, no fields have been discovered in the Lena-Anabar Basin AU, and so source, reservoir, and seal rocks, and trap configurations can only be inferred. The probability of at least one field greater than the minimum field size is estimated to be 0.48 for the base case scenario and 0.32 for the worst case scenario. Assessment input data for this AU are reported in appendix 1 and summarized below.

Charge Probability.—A charge probability of 1.0 was estimated for both scenarios because large accumulations of bitumen are present in Cambrian and Permian rocks along the northeastern and northwestern margins of the basin and because some of the exploration wells drilled in this AU flowed natural gas.

Rock Probability.—A rock probability of 0.8 was estimated for both scenarios. The existence of reservoir rocks and traps is inferred but unproved.

Timing and Preservation Probability.—Timing and preservation probabilities were estimated for two scenarios, 0.6 and 0.4. The two scenarios are (1) base case—nondeposition of a middle and late Paleozoic section followed by deposition and maturation during the Permian and Mesozoic, and accumulation; and (2) worst case—deposition of a middle and late Paleozoic section with petroleum generation and accumulation, followed by middle to late Paleozoic erosion. The timing of petroleum generation with respect to trap formation, and preservation of petroleum in accumulations, is unknown. In addition, the occurrence of migrated petroleum might indicate that traps did not exist for accumulation.

Geologic Analogs for Assessment

Two analog sets from the USGS Analog Database (Charpentier and others, 2008) were used for the assessment of the Lena-Anabar Basin AU: foreland basins (24 analogs) and rifted passive margins and foreland basins with mixed clastic and carbonate depositional systems (15 analogs). These analogs were used to estimate the numbers and sizes of undiscovered fields (tables 1 and 2) in the AU. The analog sets have discovered fields greater than the minimum size defined for this assessment (50 MMBOE). Analog categories include both extensional and compressional structural settings and traps that have carbonate and clastic depositional systems (table 1). Four AUs are common to both analog sets.

Numbers of Undiscovered Fields.—The numbers of undiscovered oil and gas fields in the Lena-Anabar Basin AU (see appendix 1) were estimated by comparing field densities (estimated number of undiscovered fields plus number of discovered fields >50 MMBOE per 1,000 km^2) in the analog dataset (table 1). The density of discovered fields, which is generally smaller than the density of both discovered and undiscovered fields, was used to calibrate the estimated densities of undiscovered fields. Densities of 0.02, 0.4, and 1.8 (minimum, median, and maximum, respectively) were estimated for scenario 1 (the base case) in the assessment of the Lena Anabar Basin AU, because accumulations sourced by Proterozoic and Paleozoic source rocks could exist in the Mesozoic section. For scenario 2 (the worst case), the median and maximum densities were estimated to be approximately half those of scenario 1 (0.02, 0.2, and 0.9 minimum, median, and maximum, respectively) because petroleum accumulations sourced from Proterozoic and Paleozoic rocks would exist only in the Paleozoic section. The median density of each scenario approximates the average density of the two analog datasets (from 0.2 for only discovered fields to 0.4 for discovered plus undiscovered fields). Maximum densities approximate those of the analog datasets (1.1 to 1.6). An oil-rich oil/gas mixture of 0.9±0.1 was assumed for both scenarios because Proterozoic and Paleozoic source rocks are oil prone, large bitumen deposits occur along the flanks of the basin, and gas-prone Mesozoic source rocks may not be fully mature with respect to petroleum generation except in the deepest parts of the basin.

For scenario 1, the total minimum, median, and maximum numbers of undiscovered fields are 1, 20, and 100, respectively (see appendix 1). The estimated numbers of undiscovered oil fields are 1 (minimum), 20 (median), and 100 (maximum); and the estimated numbers of undiscovered gas fields are 0 (minimum), 2 (median), and 20 (maximum).

For scenario 2, the densities and estimated numbers of undiscovered fields are half those of scenario 1. The total minimum, median, and maximum numbers of undiscovered fields are 1, 10, and 50, respectively (see appendix 1). The estimated numbers of undiscovered oil fields are 1 (minimum), 9 (median), and 50 (maximum); and the estimated numbers of undiscovered gas fields are 0 (minimum), 1 (median), and 10 (maximum).

Sizes of Undiscovered Fields.—The minimum, median, and maximum sizes of undiscovered oil and gas field sizes in the Lena-Anabar Basin AU are reported in appendix 1. Minimum sizes of undiscovered 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 size of oil fields in the AU (125 and 100 MMBOE for scenarios 1 and 2, respectively) were estimated to approximate the mean and median of the median size of the analog data sets. The low-probability maximum oil field size, 2,500 MMBOE, is larger than the median of the largest discovered field size in the analog datasets that includes rifted passive margin and foreland basins (1,700 MMBOE), whereas sizes of gas fields are less (median sizes of 83 and 75 MMBOE; maximum sizes of 167 MMBOE) because gas-prone Mesozoic source rocks may not be fully mature with respect to gas generation, resulting in incomplete trap fill.

Expected Maximum Size of Undiscovered Fields.—The expected maximum oil field size (750 to 1,000 MMBOE) is based on the distribution of sizes of discovered fields in the analog dataset, particularly the median of the maximum discovered field sizes. The expected maximum gas field size (~100 MMBOE or 600 BCF) is again smaller because gas-prone Mesozoic source rocks may not be fully mature with respect to gas generation.

Petroleum Composition and Properties of Undiscovered Fields.—Coproducts and petroleum-quality properties were estimated on the basis of global averages and data for the Baikal-Patom fold belt and the Proterozoic-Paleozoic AU of the neighboring Nepa-Botuoba High Province to the south.

Lena-Anabar Basin Updip Assessment Unit

The Lena-Anabar Basin Updip AU, which is the updip part of the Lena-Anabar Basin, is bounded on the east and west by the Olenek High and the Anabar Anticlise, respectively. The Permian to Mesozoic clastic section significantly thins and the Cambrian carbonate section presumably overlies crystalline or metamorphic basement rocks. Much of the pre-Permian Paleozoic section is absent, owing to either nondeposition or erosion. Proterozoic rocks fill rift grabens. Stratigraphically, this AU includes the Proterozoic through Mesozoic sedimentary section. No wells have been drilled in this AU, and only seismic exploration was conducted. The AU is approximately 43,000 km^2 in area, with no offshore portion.

Geological Analysis of Assessment Unit Probability

No oil or gas fields have been discovered in the Lena-Anabar Basin Updip AU. The likelihood that the AU contains at least one field with accumulations equal to or greater than the minimum size (50 MMBOE) is 8 percent (0.08), which is below the minimum probability (0.10) defined for this assessment, and so the AU was not quantitatively assessed. Input data for the Lena-Anabar Basin Updip AU are reported in appendix 2 and summarized below.

Charge Probability.—A charge probability of 1.0 was estimated because large amounts of bitumen are present in Cambrian and Permian rocks along the northeastern and northwestern margins of the basin.

Rock Probability.—A rock probability of 0.8 was estimated because the presence and quality of reservoir and seal rocks are unknown.

Timing and Preservation Probability.—A timing and preservation probability of 0.1 was estimated because the age of trap formation with respect to timing of petroleum generation is unknown.

Sukhan-Motorchun Riphean Rift Assessment Unit

The Sukhan-Motorchun Riphean Rift AU, which is at the extreme updip edge of the Lena-Anabar Basin, includes the Proterozoic (Riphean) Sukhan and Motorchun rift-graben system. These grabens are filled with as much as 6 km of Proterozoic to Upper Cambrian carbonate and clastic rocks. In the southern part of the Siberian craton, crude oil and natural gas commonly flow from similar Proterozoic rocks and from kimberlite dikes that penetrate these rocks. Stratigraphically, this AU includes the Proterozoic through Mesozoic sedimentary section. The extent of exploration is unknown, but some seismic exploration may have been conducted. The AU is approximately 27,000 km^2 and is completely onshore.

Geological Analysis of Assessment Unit Probability

No oil or gas fields have been discovered in Sukhan-Motorchun Riphean Rift AU. The likelihood that the AU contains at least one field with accumulations equal to or greater than the minimum field size (50 MMBOE) is 7 percent (0.07), which is below the minimum probability (0.10) defined

Table 2. Field densities, median oil and gas field sizes, and exploration maturities of geologic analogs used in the Lena-Anabar Basin Assessment Unit assessment.

[Analog data from Charpentier and others (2008). Foreland basins analogs listed in table 1. Asterisk (*), not reported in analog database. Gas volumes are nonassociated. MMBOE, million barrels of oil equivalent]

Province name (assessment unit number)	Field density (fields >50 MMBOE per 1,000 km^2)		Field size distribution (median size >50 MMBOE)	Exploration maturity (percent petroleum equivalent volume in fields >50 MMBOE)	Maximum field size (MMBOE)
	*Discovered fields	Discovered and undiscovered fields			
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	
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 statistics for all analogs					
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	

for this assessment, and so the AU was not quantitatively assessed. The input data for this AU are reported in appendix 3 and summarized below.

Charge Probability.—A charge probability of 0.9 was estimated because Proterozoic source rocks likely exist within the rift grabens.

Rocks Probability.—A rock probability of 0.8 was estimated because the presence and quality of reservoir and seal rocks are unknown.

Timing and Preservation Probability.—A timing and preservation probability of 0.1 was estimated because the timing of trap formation with respect to petroleum generation is unknown. In addition, oil and natural gas derived from rift grabens during the Paleozoic probably would not be preserved because of erosion and absence of adequate seals, such as evaporites.

Lena-Anabar Basin Province Assessment Results

The assessment results for the Lena-Anabar Basin AUs in the Lena-Anabar Basin Province are summarized in table 3. Estimates represent undiscovered, technically recoverable, conventional petroleum resources.

The mean undiscovered crude oil resource in the Lena-Anabar Basin AU is estimated to be 1,913 MMB, with a 95-percent probability (F95) of 0 MMB and a 5-percent probability (F5) of 7,207 MMB. Given that the aggregated AU probability is 0.462 for a field of minimum size, the probability that no crude oil or natural gas resources exist in this AU is 0.50 (see table 3). The mean volume of undiscovered nonassociated natural gas resources is 605 BCF, with an F95 of 0 BCF and an F5 of 2,538 BCF. The largest expected undiscovered oil field size is ~731 MMB, and the largest expected undiscovered gas field size is ~563 BCF. The total estimated mean undiscovered petroleum resources in the Lena-Anabar Basin Province are the same as for the Lena-Anabar Basin AU (table 3).

The geologic probabilities of the AUs in this study were determined based on a consideration of the geology of the 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 for this assessment project.

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Table 3. Assessment results for the Lena-Anabar 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 and so on for F50 and F5. Fractiles are additive under the assumption of perfect positive correlation. AU, assessment unit. TPS, total petroleum system. NA, not applicable]

Assessment units	AU probability	Field type	Oil (MMB)				Total undiscovered resources gas (BCF)				NGL (MMB)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Lena-Anabar Basin Province Proterozoic-Paleozoic-Mesozoic composite TPS														
Lena-Anabar Basin AU Scenario 1, 90 percent probability	0.480	Oil	0	0	7,451	2,074	0	0	6,174	1,628	0	0	169	44
		Gas	NA	NA	NA	NA	0	0	2,693	654	0	0	73	17
Lena-Anabar Basin AU Scenario 2, 10 percent probability	0.320	Oil	0	0	2,611	526	0	0	2,143	416	0	0	58	11
		Gas	NA	NA	NA	NA	0	0	993	195	0	0	28	5
Lena-Anabar Basin AU aggregate*	0.462	Oil	0	0	7,207	1,913	0	0	6,022	1,502	0	0	163	40
		Gas	NA	NA	NA	NA	0	0	2,538	605	0	0	69	16
Lena-Anabar Updip AU	0.080	Not quantitatively assessed												
Sukhan-Motorchun Riphean Rift AU	0.072	Not quantitatively assessed												
Total undiscovered petroleum resources			0	0	**7,207**	**1,913**	0	0	**8,560**	**2,170**	0	0	**232**	**56**

*Aggregate means for the entire assessment unit equal the means times the scenario probability of each scenario.

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Appendixes

Appendix files are available online only, and may be accessed at https://doi.org/10.3133/pp1824T.

Appendix 1. Assessment input data for Lena-Anabar Basin Assessment Unit. *A*. Base case scenario (scenario 1). *B*. Worst case scenario (scenario 2).

Appendix 2. Assessment input data for Lena-Anabar Basin Updip Assessment Unit.

Appendix 3. Assessment input data for Sukhan-Motorchun Riphean Rift Assessment Unit.

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