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Geology and Assessment of Undiscovered Oil and Gas Resources of the East Barents Basins Province and the Novaya Zemlya Basins and Admiralty Arch Province, 2008

Chapter O 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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Chapter O

Geology and Assessment of Undiscovered Oil and Gas Resources of the East Barents Basins Province and the Novaya Zemlya Basins and Admiralty Arch Province, 2008

By Timothy R. Klett

Abstract

The U.S. Geological Survey (USGS) recently assessed the potential for undiscovered petroleum resources of the East Barents Basins Province and the Novaya Zemlya Basins and Admiralty Arch Province as part of its Circum-Arctic Resource Appraisal. These two provinces are situated northeast of Scandinavia and the northwestern Russian Federation, on the Barents Sea Shelf between Novaya Zemlya to the east and the Barents Platform to the west. Three assessment units (AUs) were defined in the East Barents Basins Province for this study: the Kolguyev Terrace AU, the South Barents and Ludlov Saddle AU, and the North Barents Basin AU. A fourth AU, defined as the Novaya Zemlya Basins and Admiralty Arch AU, coincides with the Novaya Zemlya Basins and Admiralty Arch Province. These four AUs, all lying north of the Arctic Circle, were assessed for undiscovered, technically recoverable resources, resulting in total estimated mean volumes of ~7.4 billion barrels of crude oil, 318 trillion cubic feet (TCF) of natural gas, and 1.4 billion barrels of natural-gas liquids.

Province Boundary Definitions

Two geologic provinces were defined for this report: the East Barents Basins Province and the Novaya Zemlya Basins and Admiralty Arch Province (fig. 1), both situated on the Barents Sea Shelf between long 30° and 80° E. and between lat 67° and 85° N. These two provinces, which are bounded by the Baltic Shield and the Timan-Pechora Basin to the south, by the Barents Platform to the west, by Novaya Zemlya and the North Kara Basin to the east, and by the Barents Shelf margin to the north (fig. 2), cover an area of ~987,000 km^2 entirely north of the Arctic Circle. Most of the study area is offshore, in water depths of <600 m, generally <200 m.

The East Barents Basins Province comprises the North and South Barents Basins and the Kolguyev Terrace. A northeast-trending arch, the Ludlov Saddle, separates the North Barents Basin from the South Barents Basin (fig. 2). The Grummant High, the North Novaya Zemlya Basin, and the St. Anna (Svyataya Anna) Trough are included within the North Barents Basin (fig. 2). The Kolguyev Terrace is a faulted transition zone between the updip, southeastern part of the South Barents Basin and the Timan-Pechora Basin. The geographic boundary between the Kolguyev Terrace and the Timan-Pechora Basin is delineated along a hingeline that separates the shallow Pechora block from the deeper Timan-Pechora Basin. Kolguyev Island is situated on this structural terrace. The Paleozoic and Mesozoic history and stratigraphic successions of the East Barents Basins Province are similar, and so they are discussed in this report as a single rift/sag basin that was subsequently divided. The basins are filled with 18 to 20 km of strata, including pre-upper Permian carbonate rocks and upper Permian and younger clastic rocks (fig. 3).

The Novaya Zemlya Basins and Admiralty Arch Province, which consists of structural highs and depressions on the Admiralty Arch, the Novaya Zemlya Monocline, and the Sedov Trough (figs. 1, 2), forms a complex of compressional features in front of and bounded by the Novaya Zemlya fold belt to the east.

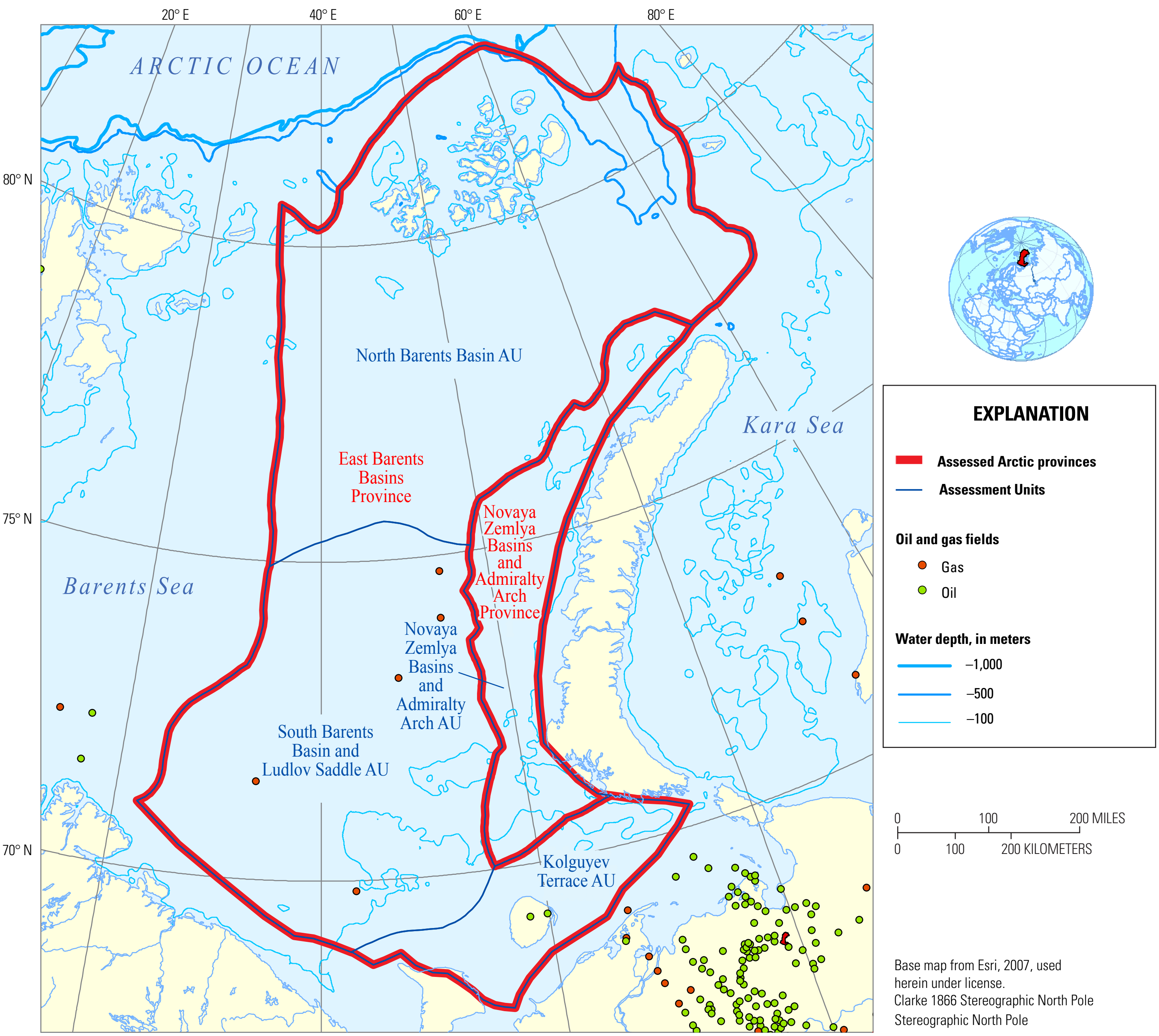


Figure 1. Map of the Barents Sea, Russian Arctic, showing locations of geologic provinces and assessment units (AUs). Data from Persits and Ulmishek (2003); data on oil and gas fields from IHS Energy Group (2007).

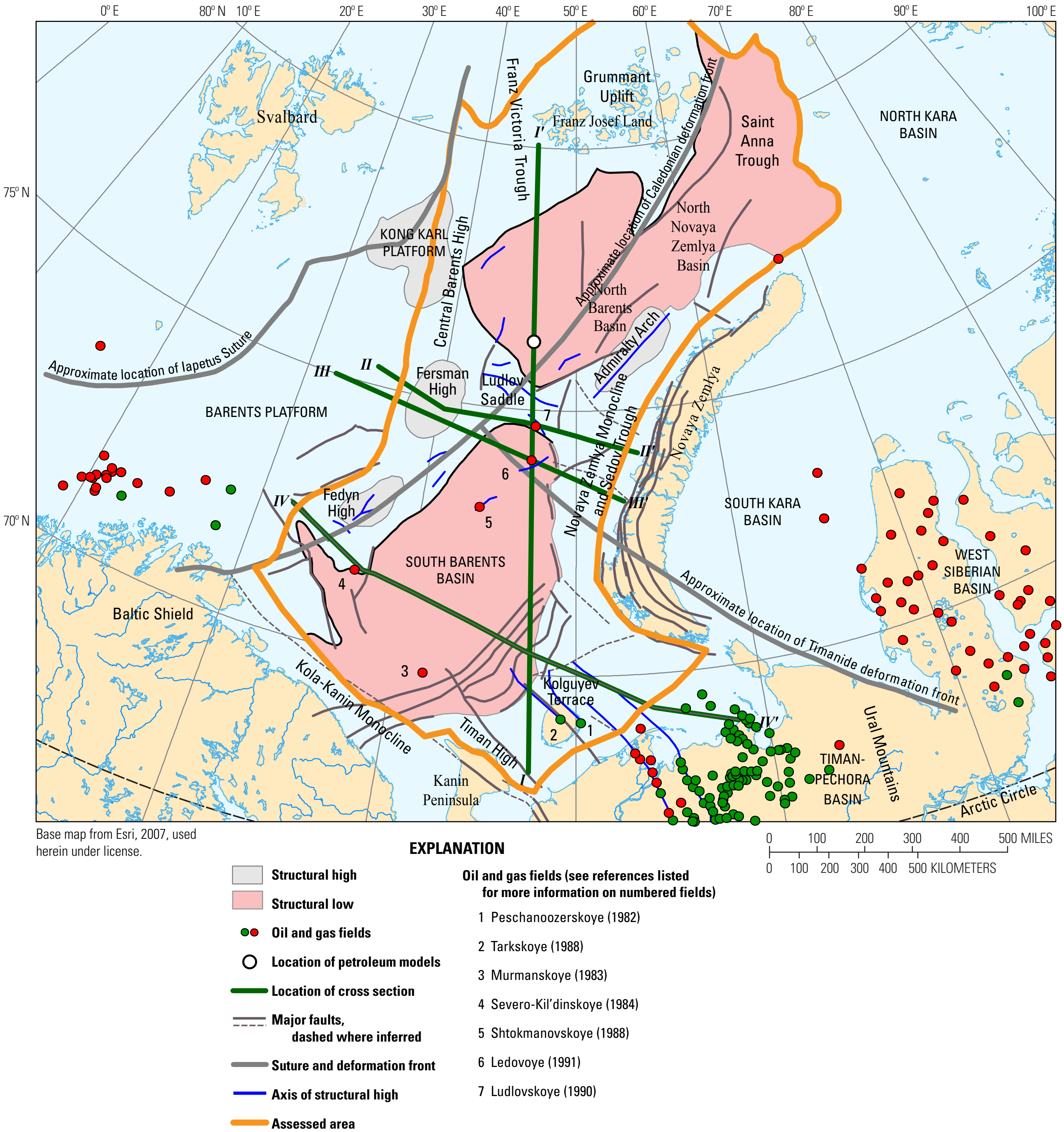


Figure 2. Russian Arctic, showing major structural features, principal oil and gas fields (1-7), geologic structures, and locations of geologic cross sections and petroleum-system models used in assessment. Data from Grantz and others (2008), Persits and Ulmishek (2003) and IHS Energy Group, (2007).

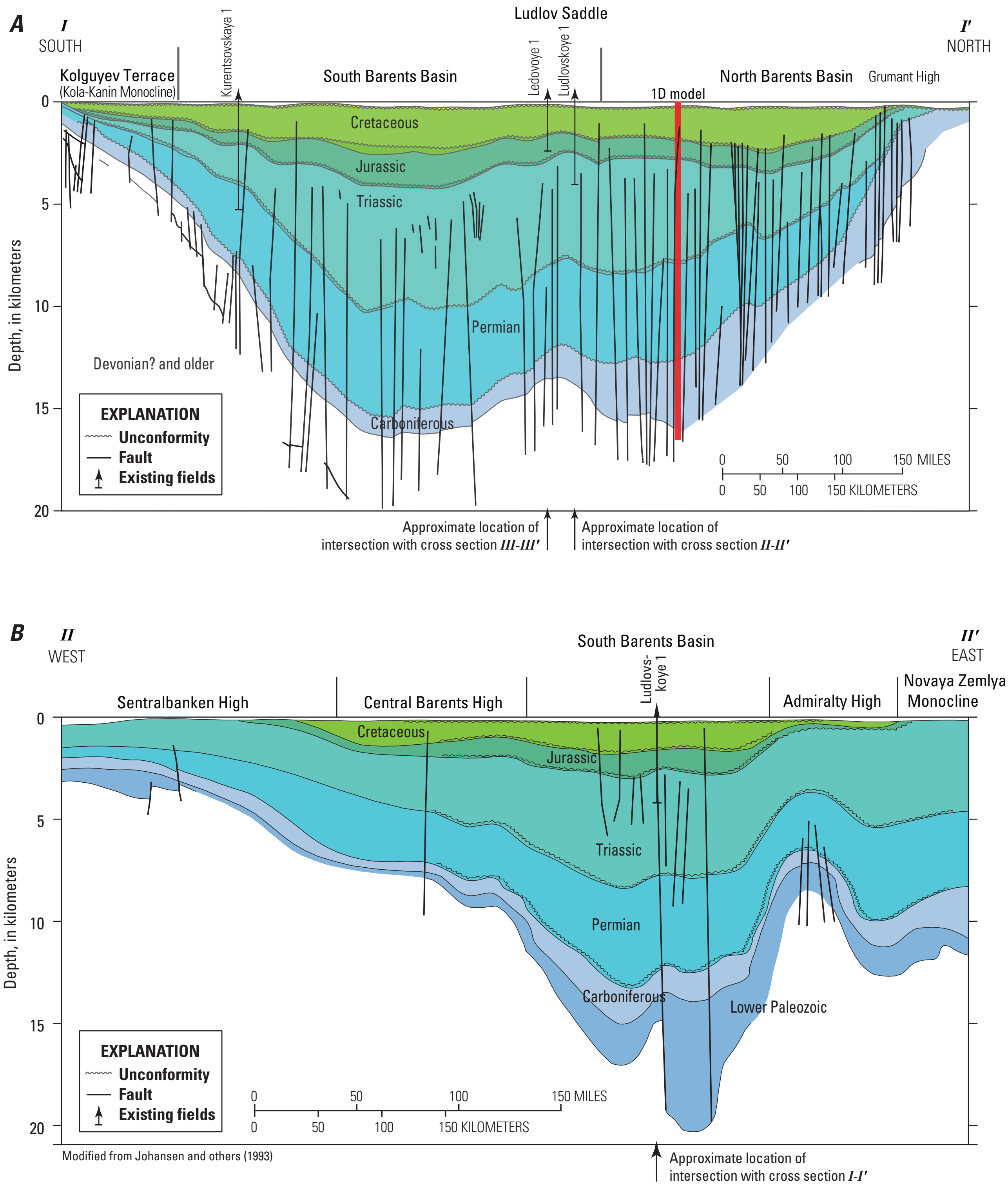
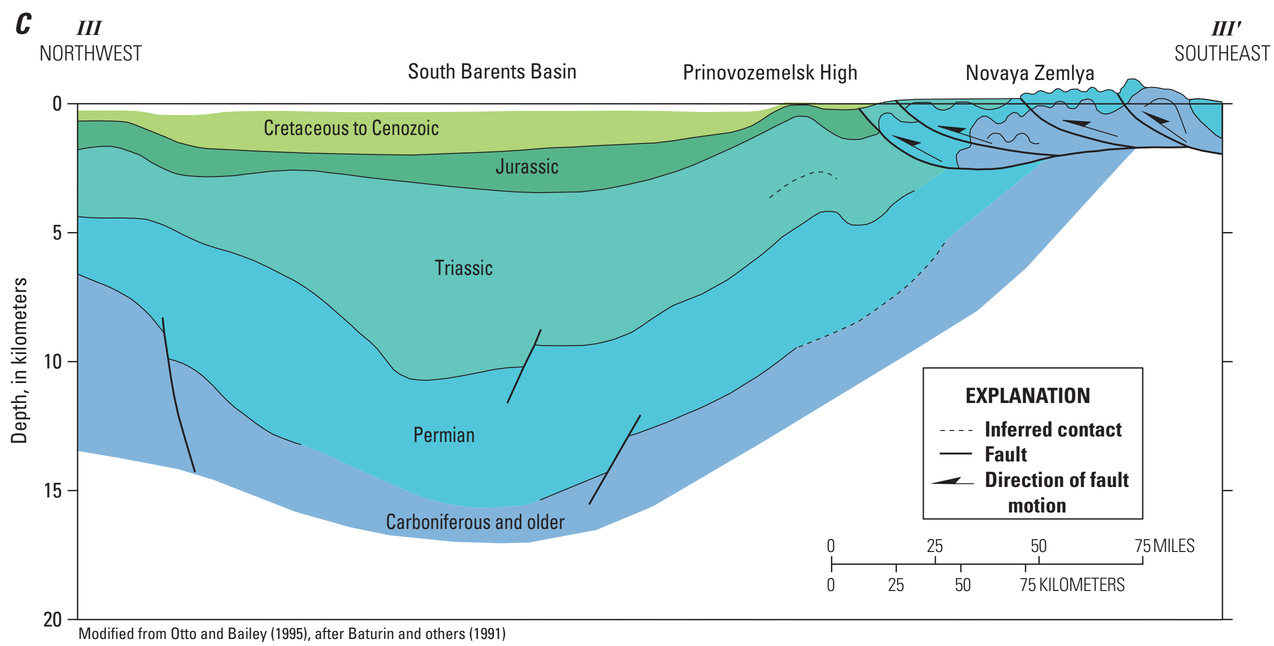
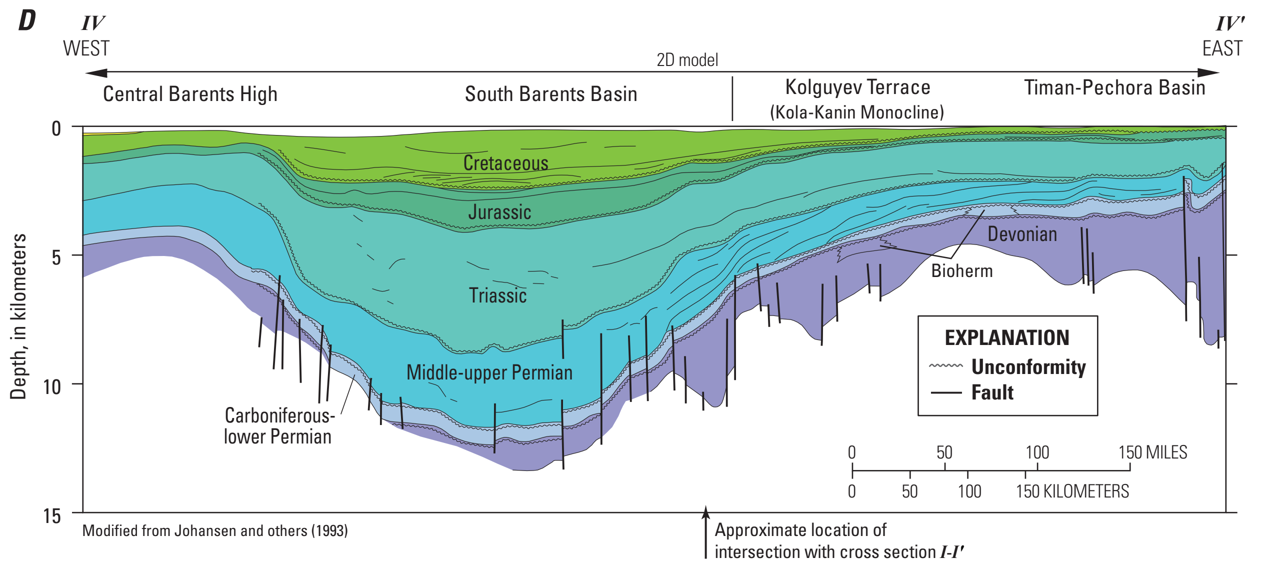


Figure 3. Regional geologic cross sections in study area (see fig. 2 for locations). *A*, I-I′, modified from Johansen and others (1993). *B*. II-II′, modified from Johansen and others (1993). *C*, III-III′, modified from Otto and Baily (1995), after Baturinn and others (1991). *D*, IV-IV′, modified from Johansen and others (1993). Vertical red line on cross section I-I′ denotes location of one-dimensional (1D) thermal-maturity model; cross section IV-IV′ was used to construct a regional two-dimensional (2D) thermal-maturity model.





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Petroleum Occurrence

A total of seven oil and gas fields have been discovered in the East Barents Basins (fig. 2). The two fields discovered on the Kolguyev Terrace contain ~100 million barrels of oil equivalent (MMBOE) of recoverable petroleum, and the five fields discovered in the South Barents Basin contain 20.4 billion barrels of oil equivalent of recoverable petroleum (IHS Energy Group, 2007). No petroleum discoveries have been reported in the North Barents Basin, Novaya Zemlya Basins, or on the Admiralty Arch.

The Peschanoozerskoye and Tarkskoye fields were discovered on Kolguyev Island in 1982 and 1988, respectively (fig. 2). Both fields consist of Lower Triassic fluvial sandstone reservoirs in anticlinal traps (Shipilov and Murzin, 2002). The Peschanoozerskoye field produces crude oil, natural gas, and natural-gas liquids, whereas the Tarkskoye field contains crude oil and natural gas but is not presently producing (Shipilov and Murzin, 2002).

Of the five fields discovered in the South Barents Basin, none is presently producing (fig. 2). Two of these fields—the Murmanskoye, discovered in 1983, and the Severo-Kil’dinskoye, discovered in 1984—which are in the southern part of the basin, contain natural gas. The Murmanskoye field is situated on a local high with complex, multipooled Lower and Middle Triassic sandstone reservoirs (Shipilov and Murzin, 2002). The Severo-Kil’dinskoye field, which is situated on the flank of the Fedyn High along the western basin margin, has Lower Triassic sandstone reservoirs (Shipilov and Murzin, 2002). The other three fields—the Shtokmanovskoye, Ledovoye, and Ludlovskoye, discovered in 1988, 1991, and 1990, respectively, are situated on faulted anticlines associated with the Ludlov Saddle, and contain natural gas and natural-gas liquids in Middle and Upper Jurassic reservoirs (Shipilov and Murzin, 2002). Together, these fields contain >90 percent of the recoverable petroleum in the East Barents Basin Province as of 2007, of which the Shtokmanovskoye field is the largest (IHS Energy Group, 2007). Natural gas and two oil shows have been reported in Cretaceous rocks on the Ludlov Saddle and in the South Barents Basin (Lindquist, 1999a).

Reservoir and seal quality deteriorate as structural complexity and faulting increase northward from the South Barents Basin to the North Barents Basin (Shipilov and Murzin, 2002). However, bitumen, observed in Franz Josef Land near dolerite dikes in Upper Triassic and Lower Jurassic sandstone, might have been sourced from deeper parts of the North Barents Basin (Bezrukov, 1997; Cherevko, 1999; Kravchenko, 2003), indicating an active petroleum system. Heavy-hydrocarbon gases, some with high helium contents, were sampled in the Franz Viktoria and St. Anna Troughs (Klubov and others, 2000).

Upper Devonian through lower Permian carbonates on the west coast of Novaya Zemlya, in the Novaya Zemlya Basins and Admiralty Arch Province, have numerous viscous oil shows and bitumen (Semenovich and Nazaruk, 1992), and Silurian bioherms locally display crude oil stains (Shipel’kevich, 2007). Gas shows (with water) have been observed in Upper Devonian through lower Permian carbonates on the Admiralty Arch (Semenovich and Nazaruk, 1992), with some gas samples containing as much as 77 volume percent carbon dioxide and 10 percent nitrogen. One well had oil shows in Triassic rocks (Nikitin and others, 2000).

Tectonostratigraphic Evolution

The East Barents Basins were formed during major extensional events in the Devonian and Carboniferous and in the late Permian and Early Triassic (Baturin and others, 1991; Johansen and others, 1993) and underwent strong subsidence during the Triassic (fig. 4). The geologic cross sections in figure 3 show the characteristics of the basin fill and structure.

During the early Proterozoic, the East European Platform was accreted to the Archean Baltic Shield (Lindquist, 1999a). Late Proterozoic (Riphean) rifting on this platform resulted in separation of some microcontinents and their drifting into the pre-Ural Ocean. During latest Precambrian and earliest Paleozoic (Vendian) time (650–530 Ma), some of these microcontinents were accreted to, and then collided with, the East European Platform (Aplonov and others, 1996; Kostyuchenko and others, 2006). This collisional event, known as the Timanide orogeny, resulted in the formation of the northwest-trending Kanin-Timan Ridge and the Kola-Kanin Monocline. The East European Platform and the Baltic Shield continuously drifted northward from equatorial latitudes after Cambrian time (Ustritskiy, 1991; Lindquist, 1999a).

Closure of the Iapetus Ocean began in the Late Cambrian and Early Ordovician (~500 Ma) before the Caledonian orogeny, which began in the middle and late Silurian (~420 Ma; Aplonov and others, 1996) and culminated in the Early Devonian (~400 Ma; Doré, 1995). The locations of the Caledonian suture zone and deformation front in the study area are shown in figure 2. Some studies suggest that closure of the northern Iapetus Ocean was incomplete, with a remnant of oceanic crust preserved on the Barents Platform (Ustritskiy, 1991; Aplonov and others, 1996).

During Devonian time, extension in the Timan-Pechora Basin stretched the continental crust and formed grabens and half-grabens in the study area (fig. 2; Johansen and others, 1993; Aplonov and others, 1996; Lindquist, 1999b; Ivanova and others, 2006). Episodic structural inversions occurred in the Devonian and latest Carboniferous (Lindquist, 1999b). Pre-Upper Devonian rocks have not been penetrated in the East Barents Basins but, if present, would be deeply buried and possibly metamorphosed (Johansen and others, 1993). Along the western margin of Novaya Zemlya (Nikitin and others, 2000), Devonian rocks are as much as 6 to 8 km deep.

On the basis of the type and composition of pre-Upper Devonian carbonate rocks observed in the Timan-Pechora Basin, temporally equivalent rocks in the East Barents Basins are inferred to be primarily reef carbonates that become more

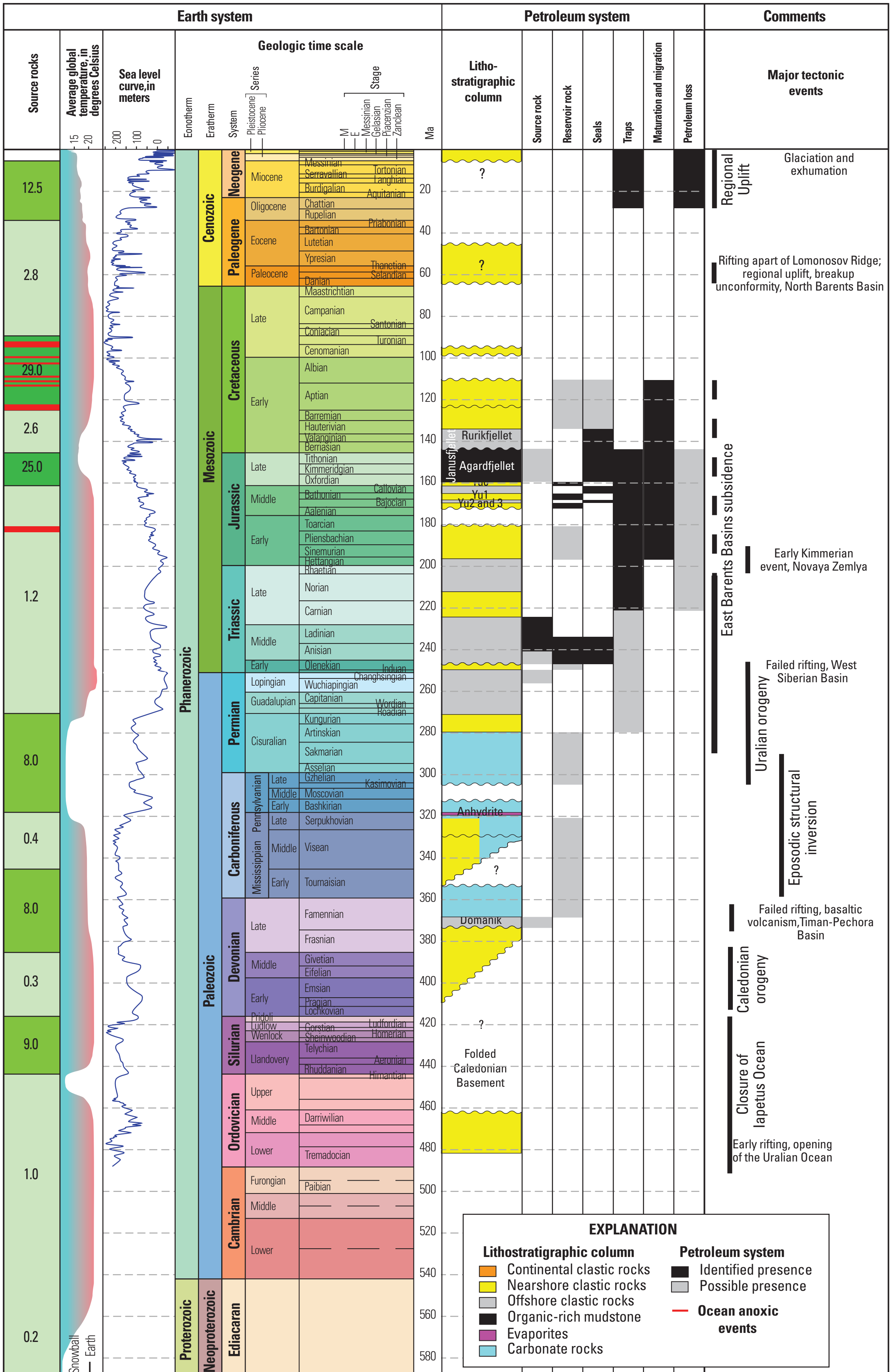


Figure 4. Lithostratigraphic column of the East Barents Basin Province, Russian High Arctic, showing petroleum-system elements and major tectonic events. Source rocks column shows the percent of the world's total petroleum reserves generated by source (modified from Ulmishek and Klemme, 1990). Average 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). Petroleum system data are from Gee and others (2006) and Lorenz and others (2007). Data from Ziegler (1988), Bro and others (1991), Embry (1992), Johansen and others (1993), Glazovskij (1995), Preobrazhenskaya and others (1998), Shipilov and Tarasov (1998), Lindquist (1999a,b), and Shipilov and Murzin (2002).

siliceous basinward toward the Uralian Ocean in the east, where deeper water conditions prevailed (Johansen and others, 1993). Along the east flanks of southern and central Novaya Zemlya, Paleozoic carbonates and carbonate clastic rocks with possible reefs are present, indicating a passive margin and shallow-water conditions (Murzin and others, 1986; Korago and others, 1989; Stupakova, 2001), whereas deep-marine and slope conditions were present in northern Novaya Zemlya (Gee and others, 2006).

Late Carboniferous and Permian collision of the Kazakh/Siberia Plate with the Baltica Plate during the Uralian orogeny resulted in closure of the Uralian Ocean (Aplonov and others, 1996). A convergent zone of compressional deformation and magmatic intrusions created by this collisional event is assumed to extend from the main Taimyr suture zone along the Ural Mountains (Aplonov and others, 1996; Gee and others, 2006).

During the late Carboniferous, a carbonate platform with reefs and evaporites formed in shelf areas, with deeper water conditions basinward (Gérard and Buhrig, 1990; Heafford, 1993; Johansen and others, 1993). During orogenesis, carbonate deposition was replaced by clastic deposition, and a broad coastal plain formed in the northern part of the Timan-Pechora Basin (Stupakova, 1992; Oknova, 1993). Upper Permian strata with clinoforms, chaotic slope/basin features, and turbidites are present in the vicinity of Novaya Zemlya where water depths are inferred to be >1,200 m (Alekhin and others, 1992; Semenovich and Nazaruk, 1992). Possible Triassic gravity slides and turbidites are exposed in outcrops on Novaya Zemlya (Alekhin and others, 1992). On the Admiralty Arch, upper Permian and Triassic rocks consist mostly of deep-marine, thin-bedded mudstone and siltstone (Semenovich and Nazaruk, 1992).

Extension in the East Barents Basins, as well as in the West Siberia Basin, resulted in rifting and normal faulting during the late Permian and Early Triassic (Verba and others, 1990; Ustritskiy, 1991; Johansen and others, 1993; Gramberg, 1997; Allen and others, 2006; Ivanova and others, 2006). The East Barents Basins are believed to be rift/sag basins that formed over oceanic or attenuated continental crust during this extensional event (Verba and others, 1990; Pavlenkin, 1990; Ustritskiy, 1991; Ivanova and others, 2006). Subsidence and sediment-accumulation rates in the East Barents Basins were highest during the Triassic, as indicated by the thick section of Triassic rocks preserved in these areas (Johansen and others, 1993). Clastic sediment shed from the developing Ural Mountains was transported from the southeast and, possibly, the east through submarine canyons and by channel systems that formed on the flanks of the basins (Johansen and others, 1993). During the Middle and Late Triassic, continental conditions existed to the south and east as a delta system was prograding northward and westward, filling in the basins (Johansen and others, 1993). The marine conditions in the central and northern parts of the basins throughout the Middle Triassic became widespread during the Late Triassic (Johansen and others, 1993).

In response to Late Triassic and Early Jurassic (early Cimmerian) deformation, Novaya Zemlya was compressed and detached along a basal thrust plane to form a thin-skinned allochthonous nappe. This nappe, which overrode the eastern margin of the East Barents Basin (fig. 3*C*), might have promoted the formation of the Ludlov Saddle by transpression and inversion (Otto and Bailey, 1995; Bogdanov and others, 1997; Lopatin and others, 2001). Structures on the eastern margin of the East Barents Basins consist of a series of thrust-related folds (G.F. Ulmishek, oral commun., 2008) or anticlines (Otto and Bailey, 1995), including three large highs, the Krestov, Admiralty, and Pakhtusov (Nikitin and others, 2000). Regional seismic profiles across the North and South Barents Basins (figs. 3*B*, 3*C*) show none of the asymmetric basin geometries typically associated with foreland basins (Otto and Bailey, 1995; O'Leary and others, 2004). Instead, the Permian and Triassic stratigraphic succession thickens westward rather than eastward toward Novaya Zemlya, as would be expected in a foreland-basin setting (figs. 3*B*, 3*C*).

The North and South Barents Basins were a single basin until separated by the Ludlov Saddle. Some studies indicate this saddle began to form during the Triassic (Ostisty and Cheredeev, 1993; O'Leary and others, 2004), whereas others (for example, Gramberg and others, 2002) indicate that its growth began as late as the Middle Jurassic. Middle and Upper Jurassic rocks are present, but thin, on the saddle. The Ludlov Saddle might have originated from a combination of several events in which the south flank formed earlier than the north flank. This feature became most pronounced during the Late Cretaceous and Paleogene (K. Rønning, oral commun., 2007).

Subsidence and sediment-accumulation rates in the North and South Barents Basins decreased from the Late Triassic to the Early and Middle Jurassic (Johansen and others, 1993), leading to subaerial exposure and erosion of the basin margin. A major truncation during the Middle Jurassic can be interpreted from seismic profiles. Thrusting and uplift of western Novaya Zemlya and structures on the Central Barents High to the west and, possibly, on the Grummant Uplift to the north were sources of clastic sediment during this time (Shipel'kevich, 2001; Carstens and Holte, 2005). In addition, some sediment might have been transported southeastward from the Urals, bypassing the Timan-Pechora Basin. Sediment shed from these areas was transported into surrounding depressions and deposited in the marine basin under nearshore and deltaic conditions, as expressed on seismic profiles (Shipel'kevich, 2001; Gramberg and others, 2002; Sakharov and Tolstikov, 2003).

Marine transgression reached a maximum during the Late Jurassic, depositing deep-marine, fine sediment and organic-rich mud in the North and South Barents Basins (Johansen and others, 1993). The Upper Jurassic interval is thickest (at most 2 km) in the central part of the South Barents Basin. Anticlines probably began to form during the Late Jurassic, mainly during the Early Cretaceous (Neocomian).

Lower Cretaceous rocks, which were deposited as southward-prograding clinoforms in the northern and northeastern parts of the Barents Shelf, are presumed to be deltaic in the St. Anna Trough (Murzin and others, 1986). Cretaceous mudstone was deposited in basinal areas of the St. Anna Trough, and coarser clastic material and some brown coal in shallower areas (Johansen and others, 1993).

The Late Cretaceous opening of the Atlantic Ocean and the Eurasia Basin and the Paleogene separation of the Lomonosov Ridge resulted in uplift and erosion of the Barents and North Kara Basins during the Late Cretaceous and Paleogene and the Oligocene and Miocene (Musatov, 1999). During the Late Cretaceous and Paleogene, uplift ranged from tens of meters to ~1,000 m in the Barents and North Kara Basins, from 1,000 to 1,500 m on large arches and swells, and from 2,000 to 2,500 m on archipelagos (Gustavsen and others, 1997; Musatov, 1999). The erosional extent in the East Barents Basins and along the basin margins ranged from ~250–1,200 m (Vågnes and others, 1992; Johansen and others, 1993). As much as 1,800 m of exhumation occurred in the St. Anna Trough (Vågnes and others, 1992).

North-south- to northeast-striking reverse faults and associated folds formed in response to Late Cretaceous and Paleogene compression (Gustavsen and others, 1997). Mild compression during the Oligocene and Miocene produced limited inversion and uplift along preexisting faults (Otto and Bailey, 1995) and on the former Lomonosov Rift shoulder along the present-day shelf edge from Svalbard to Severnaya Zemlya. Estimates of Cenozoic uplift range from 200–1,500 m to as much as 2,000–3,000 m (Johansen and others, 1993; Otto and Bailey, 1995; Musatov, 1999; Ryabukhina and others, 1999). Paleogene and Neogene mudstone is preserved only locally in the North and South Barents Basins because of erosion elsewhere. During this same period, mudstone was deposited as the East Barents and North Kara depressions subsided 200 to 300 m. Most known petroleum accumulations in the South Barents Basin are in anticlines that formed during the Late Jurassic and Early Cretaceous; these structures were modified during the Cenozoic by transpression. Recent tectonic activity might have caused petroleum in the North and South Barents Basins to remigrate within or away from the structures, as occurred in the West Siberian Basin (Musatov, 1999; Ryabukhina and others, 1999).

The East Barents and North Kara Basins, which lie within the Arctic Circle, most likely underwent glaciation from the late Pliocene (2.7 Ma) onward, although glacial activity in northeastern Eurasia was most prevalent during the late Pleistocene (Bowen and others, 1986). This period also marks the onset of ice-related erosion in the Barents Sea, as indicated by late Cenozoic sedimentary wedges that dominate the western margin of the Barents Shelf (Ryseth and others, 2003). The thickness, duration, and extent of ice sheets in the East Barents Basins and, in turn, the severity of glacial exhumation are poorly constrained. High-resolution basin modeling has demonstrated that variations in ice load on the Barents Platform (for example, in the Snøhvit field) caused significant pore-pressure fluctuations in the petroleum system (Cavanaugh and others, 2006). Episodic ice loading in the East Barents Basins and oscillations in reservoir pressure, thus causing gas expansion, over the past million years might explain the prevalence of gas in the South Barents Basin and indicate a predominance of gas over oil in undiscovered fields in the North Barents and North Kara Basins.

Total Petroleum System

A Paleozoic and Mesozoic composite total petroleum system (TPS) was defined for both the East Barents Basins Province and the Novaya Zemlya Basins and Admiralty Arch Province. Its name implies that potential source and reservoir rocks occur in both Paleozoic and Mesozoic stratigraphic successions. Seal rocks, traps, and timing are also elements of the TPS. A lithostratigraphic column and events chart for the TPS are shown in figure 4.

Source Rocks

Although source-rock intervals are present in Upper Jurassic, Lower and Middle Jurassic, Upper Triassic, and Middle Triassic strata (Ferriday and others, 1994), Lower and Middle Triassic mudstone is considered to be the main source rock in the East Barents Basins (Kiryukhina and others, 2006). The mudstone commonly contains from >10 to as much as 20 weight percent total organic carbon (TOC) as Types II and III kerogen; the rock locally is coaly and ranges in thermal maturity from mature to overmature (Ferriday and others, 1994). The mudstone interval ranges in gross thickness from hundreds of meters to 6 km (Belonin and others, 1997). Triassic sedimentary deposits, derived from the southeast, grade from coarse-grained continental orogenic clastic rocks through paralic, lagoonal, and sabkha clastic rocks in the Severo-Kil'dinskoye and Murmanskoye fields to shelf mudstones farther north (Belonin and others, 1997). On the basis of the presence of dark-gray Triassic mudstones in the Severnaya and Khaysa wells in Franz Josef Land, deep-water mudstone containing 5 to 11 weight percent sapropelic organic matter is presumed to be present in the northwestern part of the East Barents Basins. This potential source rock is also expected to be present in the North Barents Basin and in the northwestern part of the South Barents Basin (Belonin and others, 1997). The age-equivalent Middle Triassic Botnehia Formation of Svalbard is considered to be a good oil-prone source rock on the Barents Platform (Forsberg and Bjorøy, 1981; Isaksen, 1996). Organic-rich Lower and Middle Triassic rocks occur in the lower part of the oil window in the western part of the Barents Platform at Bjørnøya (Bjorøy and others, 1981).

Oil-prone Upper Jurassic mudstone in the East Barents Basins contains 3 to 15 weight percent TOC with Type II kerogen (Ferriday and others, 1994). These source rocks have low vitrinite reflectances (R_o = 0.55–0.65 percent; Ferriday and others, 1994) and are thermally immature to mature with respect to petroleum generation everywhere in the province.

The Upper Jurassic Hekkingen Formation on the Barents Platform is an oil-prone mudstone containing 3 to 36 weight percent TOC (Isaksen, 1996; Langrock and others, 2003) with Type II kerogen, and with hydrogen indices ranging from 400 to 500 mg/g TOC (Langrock and others, 2003). Stratigraphic equivalents of the Upper Jurassic Janusfjellet Formation (Agardhfjellet Member), an organic-rich mudstone (>7 weight percent TOC), crop out in Franz Josef Land (Bezrukov, 1997).

Upper Triassic and Middle Jurassic source rocks are limited in extent and of secondary importance in the East Barents Basins. Middle Jurassic mudstone there is thin, contains 1.5 to 3 weight percent TOC with Type II and, possibly, Type I kerogen, and is only marginally thermally mature (Ferriday and others, 1994). Upper Triassic rocks are carbonaceous and locally coaly, contain 1 to 20 weight percent TOC with Types II and III kerogen, and range in thermal maturity from early mature to mature (R_o = 0.65–1.00 percent; Ferriday and others, 1994).

The upper Permian section might contain source rocks that are thermally mature in deeper parts of the East Barents Basins. Upper Permian rocks on Kolguyev Island include clastic rocks deposited in coastal plain, deltaic, and nearshore marine environments (Grigoriev and Utting, 1998). Mudstone commonly contains abundant woody and coaly organic matter and is thermally immature with respect to petroleum generation (R_o = 0.45 percent); maximum depth of burial is <2 km (Grigoriev and Utting, 1998). On the basis of well data from the Admiralty Arch, upper Permian rocks could be potential sources of petroleum, although the rocks have low TOC contents.

Oil-prone potential source rocks of Paleozoic age were observed on Novaya Zemlya and in the Timan-Pechora Basin. Those on Novaya Zemlya are Silurian, Lower and Middle Devonian, Upper Devonian, lower Carboniferous (Tournaisian and Visean), and lower Permian (Asselian through Artinskian; Kiryukhina and others, 2006), and those in the Timan-Pechora Basin are Upper Devonian (Frasnian and Fammenian) “Domanik Facies.” Paleozoic rocks may also occur farther west in the East Barents Basins (Alsgaard, 1993). The Admiralty Arch might contain petroleum accumulations derived from middle and upper Paleozoic and Mesozoic source rocks in the East Barents Basins (Kiryukhina and others, 2006). Upper Devonian source rocks of the “Domanik Facies,” present in restricted depressions in the Timan-Pechora Basin, might extend into the South Barents Basin and along Novaya Zemlya, but their westward extent is unknown (Alsgaard, 1993; Johansen and others, 1993).

Upper Paleozoic rocks have some source potential on the Barents Platform (Bjørnøya), where they are not thermally overmature (Bjorøy and others, 1981). Paleozoic rocks are deeply buried (5–>20 km) in the East Barents Basins and probably are thermally overmature with respect to petroleum generation. The highest probability for discoveries of Paleozoic-sourced petroleum is along Novaya Zemlya (Johansen and others, 1993) and the western margin of the East Barents Basins. Petroleum generation, migration, and accumulation in structures on the flanks of the basins probably occurred during the Permian and Triassic, when subsidence rates were highest (Johansen and others, 1993). However, leakage from these structures and subsequent petroleum remigration may have taken place during later tectonic events (Johansen and others, 1993).

Burial-history modeling for this report (fig. 5) indicates that Lower and Middle Triassic rocks, the most likely source-rock interval in the South Barents Basin, reached sufficient thermal maturity to generate petroleum during Late Triassic time, as a result of burial by a thick upper Mesozoic section, and may still be generating petroleum today. Triassic source rocks presently are thermally mature along the basin margin and mature to overmature in the basin center. The modeled thermal maturity of the Upper Jurassic source interval, if present, indicates that these rocks entered the oil window in the deepest part of the basin during the Late Cretaceous but that they are immature along the basin flanks. Paleozoic source rocks are thermally overmature in the basin center and mature at the basin margin, with generation of hydrocarbons beginning in the Triassic and ending in the early Cenozoic.

Major source rocks in the North Barents Basin are inferred to be Middle Triassic mudstones. Although the basin has not been drilled and the distribution of depths in the basin is unknown, these source rocks should be widely present and comparable in age and origin to the source-rock intervals in the South Barents Basin. Additionally, dark-gray Triassic mudstones have been observed in Franz Josef Land (Embry, 1992; Belonin and others, 1997). Assuming that these same rocks were deposited in the North Barents Basin, they should be good to excellent sources of oil and gas. Middle Triassic source rocks in the deepest part of the North Barents Basin probably began generating petroleum during the late Triassic (fig. 6), and petroleum generation might be ongoing. Other potential source rocks in the North Barents Basin include Jurassic mudstones, as well as Paleozoic mudstones similar to those of Novaya Zemlya. Paleozoic source rocks are thermally overmature in the basin center but probably mature along the basin flanks. Potential Jurassic source rocks are thermally immature throughout the basin except in the deepest part where locally they might be mature (Sakharov and Tolstikov, 2003).

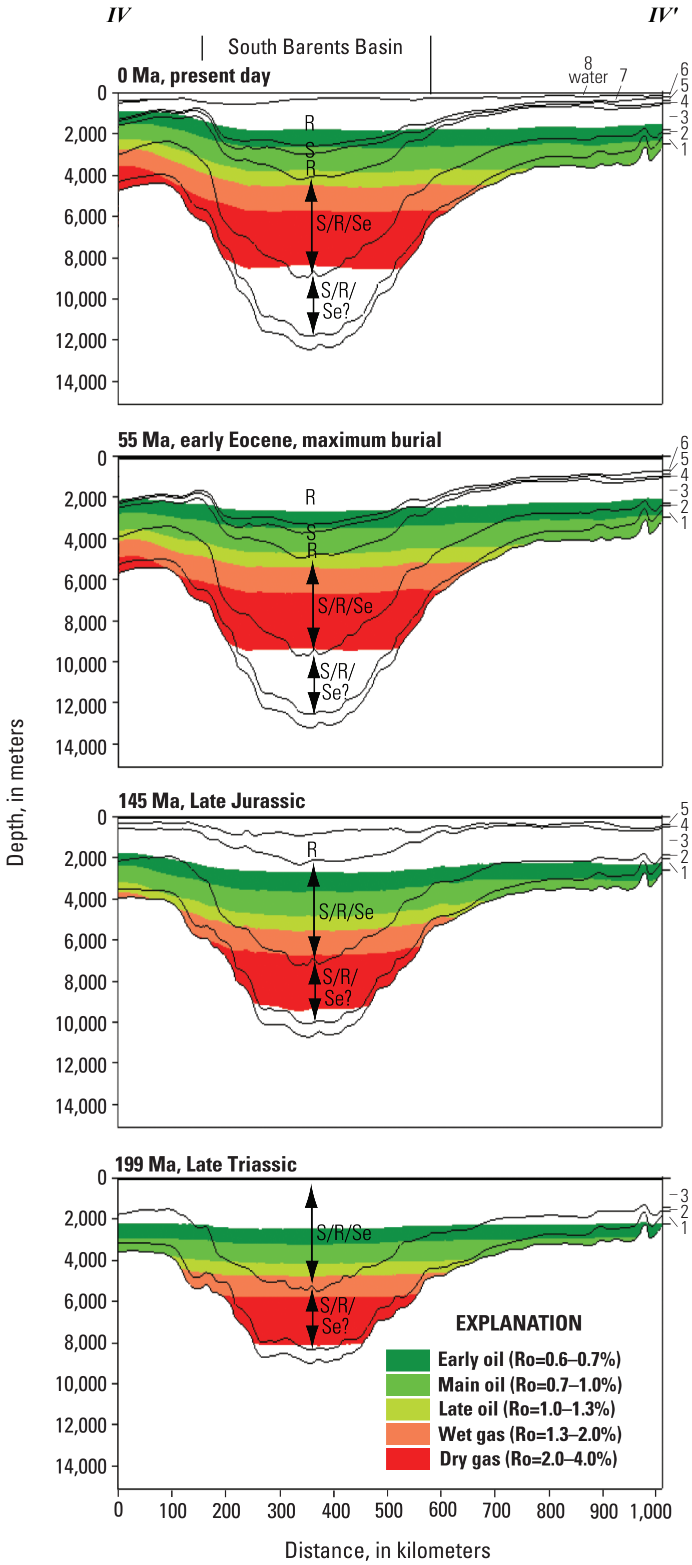


Figure 5. Petroleum-system model of the interpreted cross section IV-IV′ (see fig. 2 for location) across the South Barents Basin and Ludlov Saddle Assessment Unit (fig. 3D), showing thermal maturation over time. Note that from the late Miocene through the Pleistocene, ~500 to 1,500 m of Cretaceous section was eroded in the area of the model. Vertical exaggeration, ~85×. Stratigraphic ages: 1, Carboniferous; 2, Permian; 3, Triassic; 4, Early through Middle Jurassic; 5, Late Jurassic; 6, Cretaceous. R, reservoir interval; S, source-rock interval; Se, seal. Ro, vitrinite reflectance, in percent (%). Data from Levashkevich and others (1992), Vågnes and others (1992), Johansen and others (1993), Kazantsev (1993), Sakharov and Kulibakina (1998), Verzhbitskii (2000, 2002), Khutorskoi and Podgornykh (2001), Bugge and others (2002), Khutorskoi and others (2003; 2008), and Cavanaugh and others (2006); PetroMod data from Wygrala (1989), Sweeney and Burnham (1990), and Integrated Exploration Systems (2008).

Reservoir and Seal Rocks

The major reservoir and seal unit in the East Barents Basins is 400 to 600 m thick and comprises Middle Jurassic sandstone underlying Upper Jurassic (Callovian through Tithonian) and Lower Cretaceous mudstone (Johansen and others, 1993; Oknova, 1993; Zakharov and Yunov, 1995; Gramberg and others, 2002; Sakharov and Tolstikov, 2003). Middle Jurassic seals are also present and include mudstone of Aalenian through lower Bathonian and Bathonian and Callovian age (Zakharov and Yunov, 1995; Sakharov and Tolstikov, 2003). Deltaic and marine sandstones of Aalenian (Yu2, Yu3), Bajocian (Yu1), and Callovian (Yu0) age are the major reservoirs (Shipel'kevich, 2001). Eastward- to westward-prograding clinoforms were observed on seismic profiles in the Bathonian and Callovian interval. Some clastic sediment, however, was transported eastward from the Fersman High (fig. 2) and deposited as fans on the paleoflanks of the structure. The sandstone reservoirs, which are highly porous, are sealed laterally by transgressive marine mudstone (Gramberg and others, 2002; Sakharov and Tolstikov, 2003). Jurassic rocks are thin and less sandy south of the Fersman High (Sakharov and Tolstikov, 2003). Lower and Middle Jurassic rocks in the East Barents Basins are thicker in the northern and central depressions and thinner or completely eroded on major uplifts (Zakcharov and others, 1993; Sakharov and Tolstikov, 2003). Porosity in the Ledovoye, Ludlovskoya, and Shtokmanovskoya fields in the South Barents Basin ranges from 15 to 25 percent, and permeability from hundreds of millidarcies to more than one darcy (Zakharov and Yunov, 1995; IHS Energy Group, 2007).

Lower and Middle Triassic fluvial, deltaic, paralic, and marine sandstones also are reservoirs in the East Barents Basins (for example, in the Murmanskoye and Severo-Kil'dinskoye fields), but the intervals are thin, compartmentalized, and of poor reservoir quality (Johansen and others, 1993; Oknova, 1993). Lower and Middle Triassic rocks are commonly overpressured (Semenovich and Nazaruk, 1992; Lindquist, 1999a), and Triassic mudstone provides good local seals (Semenovich and Nazaruk, 1992; Oknova, 1993; Zakharov and Kulibakina, 1998). Triassic clinoforms prograding southeastward to northwestward have been observed on seismic profiles at several stratigraphic intervals in the southwestern part of the East Barents Basins. Reservoirs and traps might be associated with these clinoforms.

Lower Cretaceous rocks, mainly mudstone-rich clinoforms and possibly submarine channel and fan sandstone, are other potential reservoirs in the East Barents Basins (Alekhin, 1992). Early Cretaceous uplift and erosion to the north and west of these basins resulted in contemporaneous deposition of sandstone (Gustavsen and others, 1997); a high probability for petroleum discoveries exists in these areas (Johansen and others, 1993). Traps formed as structural drapes and stratigraphic pinchouts along the basin margins, with Lower Cretaceous mudstone seals (Johansen and others, 1993).

Upper Paleozoic (Upper Devonian through lower Permian) carbonate reservoirs similar to those in the Timan-Pechora Basin might also be present in Novaya Zemlya and along the western margin of the East Barents Basins (Johansen and others, 1993). Carbonate buildups have been observed on seismic profiles and mapped around the periphery of the South Barents Basin (Gérard and Buhrig, 1990; Bruce and Toomey, 1993; Cecchi, 1993; Johansen and others, 1993; Nilsen and others, 1993; Blendinger and others, 1997; Ivanova, 1997; Elvebakk and others, 2002; Belyakov, 2006). Buildups include barrier reefs on the West Barents Platform and single-mound bioherms formed on older structures (Johansen and others, 1993). On the Barents Platform, upper Carboniferous and lower Permian (upper Bashkirian through Asselian) carbonates were deposited in a warm, semiarid to arid environment and subjected to dolomitization and dissolution that resulted in good reservoir quality. Upper lower Permian (Artinskian) and upper Permian carbonates, in contrast, were deposited under cold temperate conditions and, except for primary porosity or subareal exposure, are of poor reservoir quality (Gérard and Buhrig, 1990; Stemmerik and others, 1999). In the Timan-Pechora Basin, reefs contain porous limestone and dolostone that were subjected to leaching (Johansen and others, 1993). Carboniferous and lower Permian reefs drilled on Kolguyev Island are of good reservoir quality (Ivanova, 1997). Carbonate deposition in and adjacent to the East Barents Basins ended in late Permian time because of a regional rise in sea level (Nilsen and others, 1993).

Traps and Timing

All fields and wildcat wells in the East Barents Basins are on structural closures. Many prospective structures have been mapped (Fedorovskiy and Zakharov, 2006), but most are untested as of 2008. Discovered and potential structural traps are associated with folds and faults that formed during late Paleozoic rifting and Neogene (early Cimmerian) compression. These traps formed before and during petroleum generation. However, Cenozoic compression and uplift might have caused previously accumulated petroleum to remigrate or be destroyed. Potential traps in the East Barents Basins and along the basin margins include structural highs, fault-related structures, drapes over structures, stratigraphic onlaps and pinchouts, carbonate shelf- and reef-associated deposits, stratigraphic traps (submarine fans and channels), and salt structures in the extreme western part of the basins. Favorable areas for drilling are stratigraphic pinchouts updip, toward the Kola-Kanin Monocline and along the western basin margin of the West Barents Platform, the Admiralty Arch, and the northern margin of the North Barents Basin (Gramberg and others, 2001).

Proterozoic (Riphean and Vendian) terrigenous rocks in Mesoproterozoic (Riphean) grabens and lower and middle Permian spiculitic rocks may have petroleum potential near the Kola-Kanin Monocline (Ivanova, 2001; K. Rønning, oral commun., 2007). Plays include anticlines and fault-controlled traps in Mesoproterozoic (Riphean) and Carboniferous rocks, pinchouts of Devonian and Carboniferous clastic rocks, Carboniferous and Permian carbonate buildups, Silurian through Upper Devonian carbonate buildups, upper Permian clinoforms, and Triassic sandbars (Ivanova, 2001).

Assessment Units

Assessment units (AUs) are mappable volumes of rock within a TPS that are sufficiently homogeneous that the methodology of resource assessment is applicable (Klett and others, 1997). Three AUs—the Kolguyev Terrace AU, the South Barents Basin and Ludlov Saddle AU, and the North Barents Basin AU—were defined for the East Barents Basins Province, and one AU— the Novaya Zemlya Basins and Admiralty Arch AU—for the Novaya Zemlya Basins and Admiralty Arch Province. The estimated numbers and sizes of undiscovered oil and gas fields in each AU are reported in appendixes 1 through 4, and the geologic analog data used to evaluate the AUs are summarized in tables 1 and 2.

Kolguyev Terrace Assessment Unit

The Kolguyev Terrace AU in the East Barents Basins Province is bounded on the east by Novaya Zemlya, on the north by the South Barents Basin, on the south by the Timan-Pechora Basin, and on the west by the Timan High (figs. 1,2). The AU area of ~79,000 km^2 includes Kolguyev Island and stratigraphically includes the Paleozoic and Mesozoic sedimentary sections.

Probable source rocks are thermally mature Lower and Middle Triassic mudstone in the deeper part of the South Barents Basin north of the AU. Petroleum generated from Triassic mudstone is interpreted to have migrated updip to the discovered fields. Upper Devonian marine “Domanik Facies” and upper Permian mudstone are source rocks in the neighboring Timan-Pechora Basin. Although the “Domanik Facies” was not observed on Kolguyev Island or in any wells in the South Barents Basin, it might be present in the eastern part of the AU. Upper Permian mudstone is thermally immature on Kolguyev Island but possibly mature elsewhere. Known reservoir rocks and seals are Triassic paralic clastic rocks. Upper Devonian through lower Permian carbonates and reefs, similar to those in the Timan-Pechora Basin, might also be reservoirs.

Geologic Analysis of Assessment-Unit Probability

The probability that the Kolguyev Terrace AU contains at least one field equal to or larger than the minimum field size of 50 MMBOE (50 million barrels [MMB] of crude oil and 300 billion cubic feet [BCF] of natural gas) is estimated at 100 percent (1.00) because one producing field in the AU exceeds this minimum size (IHS Energy Group, 2007). Another nonproducing field almost of minimum size (IHS Energy Group, 2007) has also been discovered (fig. 2). Both fields contain oil, natural gas, and natural-gas liquids. The assessment input data are reported in appendix 1 and summarized below.

Charge Probability.—A charge probability of 1.00 was estimated because the AU area has a petroleum system sufficient to charge one field equal to or larger than the minimum size (50 MMBOE).

Rock Probability.—A rock probability of 1.00 was estimated because the AU area has a petroleum system sufficient to charge one field equal to or larger than the minimum size (50 MMBOE).

Timing and Preservation Probability.—A timing and preservation probability of 1.00 was estimated because the AU area has a petroleum system sufficient to charge one field equal to or larger than the minimum size (50 MMBOE).

Geologic Analogs for Assessment

Data for rift/sag basins (table 1) from the USGS Analog Database (Charpentier and others, 2008) were used to estimate the number and density of undiscovered oil and gas fields in the Kolguyev Terrace AU. The analog dataset contains 11 AUs representing extensional and compressional rift/sag basins composed of both clastic and carbonate rocks (table 1). The density of prospects mapped by seismic surveys (Fedorovskiy and Zakharov, 2006) was used to calibrate the estimated number of undiscovered oil and gas fields in the AU.

Numbers of Undiscovered Oil and Gas Fields.—The total number of undiscovered oil and gas fields in the Kolguyev Terrace AU (see appendix 1) was estimated by comparing the field densities (estimated number of undiscovered fields plus number of discovered fields larger than 50 MMBOE per 1,000 km^2) in the analog dataset (table 1). The density of discovered fields, which is typically lower than that of both discovered and undiscovered fields, was used to calibrate the density of undiscovered fields. An estimated field density of 0.01 (minimum), 0.075 (median), and 0.15 (maximum) was used in the assessment. The estimated median field density (0.075) is lower than that of fields in the analog dataset (median density of discovered fields and of both discovered and undiscovered fields, 0.13); and the estimated maximum field density (0.15) also is lower than that of fields in the analog dataset (maximum density of discovered fields, is 0.35; maximum density of both discovered and undiscovered fields, 0.43). The estimated median and maximum field densities used in the assessment approximate the field densities calculated from mapped and undrilled prospects, assuming that the prospects will become fields larger than the minimum size of 50 MMBOE. The estimated total number of undiscovered oil and gas fields is 1 (minimum), 4 (mean), and 15 (maximum) (see appendix 1); the estimated total number of undiscovered oil fields is 0 (minimum), 1 (median), and 9 (maximum); and the estimated total number of undiscovered gas fields is 1 (minimum), 3 (median), and 14 (maximum).

Table 1. Rift/sag basins used as geologic analogs in assessment of the Kolguyev Terrace Assessment Unit.

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

Province name (assessment unit number)	Structural setting	Trap system	Field density (fields >50 MMBOE per 1,000 km^2)		Field size distribution		Exploration maturity	
			*Number of discovered fields	Number of discovered and undiscovered fields	Median oil field size (>50 MMB)	Median gas field size (>300 BCF)	Percent oil by volume in fields >50 MMB	Percent gas by volume in fields >300 BCF
Bohaiwan Basin (31270101)	Extensional	Extensional grabens and other structures	0.31	0.43	110	594	90	65
Bohaiwan Basin (31270102)	Extensional	Extensional grabens and other structures	0.08	0.13	113	544	66	0
Dnieper-Donets Basin (10090102)	Extensional	Basement blocks		0.12	92	555	0	0
North Ustyurt Basin (11500201)	Compressional	Local uplifts, uncertain origin	0.01	0.04	58	752	53	87
North Ustyurt Basin (11500301)	Compressional	Local uplifts, uncertain origin		0.04		610		0
Pannonian Basin (40480101)	Extensional	Stratigraphic undefined, growth faults, basement blocks	0.11	0.09	106	585	100	96
Pannonian Basin (40480201)	Extensional	Stratigraphic undefined, growth faults, basement blocks	0.15	0.13	85	1097	100	96
Sirte Basin (20430101)	Extensional	Extensional grabens and other structures	0.35	0.41	164	342	93	100
Sirte Basin (20430102)	Extensional	Extensional grabens and other structures	0.23	0.36	122	614	89	75
Songliao Basin (31440101)	Unknown	Extensional grabens and other structures	0.10	0.17	108	343	92	0
Songliao Basin (31440201)	Compressional/ Extensional	Extensional grabens and other structures		0.02		370		0
Median			**0.13**	**0.13**	**108**	**585**	**90**	**65**
Mean			**0.17**	**0.18**	**106**	**582**	**76**	**47**

Table 2. Rift/sag basins used as geologic analogs in assessments of South Barents Basin and Ludlov Saddle Assessment Unit and North Barents Basin Assessment Unit.

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

Province name (assessment unit number)	Structural setting	Trap system	Field density (fields >50 MMBOE per 1,000 km²)		Field size distribution		Exploration maturity	
			*Number of discovered fields	Number of discovered and undiscovered fields	Median oil field size (>50 MMB)	Median gas field size (>300 BCF)	Percent oil by volume in fields >50 MMB	Percent gas by volume in fields >300 BCF
Bohaiwan Basin (31270101)	Extensional	Extensional grabens and other structures	0.31	0.43	110	594	90	65
Bohaiwan Basin (31270102)	Extensional	Extensional grabens and other structures	0.08	0.13	113	544	66	0
Dnieper-Donets Basin (10090102)	Extensional	Basement blocks		0.12	92	555	0	0
Malay Basin (37030101)	Compressional	Basement-involved blocks	0.39	0.64	104	677	88	52
Malay Basin (37030102)	Compressional	Basement-involved blocks		0.16	70	375	0	0
Malay Basin (37030201)	Compressional	Basement-involved blocks	0.36	0.51	212	1045	100	93
North Sea Graben (40250101)	Extensional	Extensional grabens and other structures	1.12	1.78	125	851	84	88
North Sea Graben (40250102)	Extensional	Extensional grabens and other structures	0.64	0.83	111	380	92	98
North Sea Graben (40250103)	Extensional	Stratigraphic undeformed, salt-induced structures, extensional grabens and other structures related to normal faulting	0.77	1.05	116	572	82	69
North Ustyurt Basin (11500201)	Compressional	Local uplifts, uncertain origin	0.01	0.04	58	752	53	87
North Ustyurt Basin (11500301)	Compressional	Local uplifts, uncertain origin		0.04		610		0
Pannonian Basin (40480101)	Extensional	Stratigraphic undefined, growth faults, basement blocks	0.11	0.09	106	585	100	96
Pannonian Basin (40480201)	Extensional	Stratigraphic undefined, growth faults, basement blocks	0.15	0.13	85	1097	100	96
Sirte Basin (20430101)	Extensional	Extensional grabens and other structures	0.35	0.41	164	342	93	100
Sirte Basin (20430102)	Extensional	Extensional grabens and other structures	0.23	0.36	122	614	89	75
Songliao Basin (31440101)	Unknown	Extensional grabens and other structures	0.10	0.17	108	343	92	0
Songliao Basin (31440102)	Compressional/ Extensional	Extensional grabens and other structures	0.55	0.71	264	574	100	100
Songliao Basin (31440201)	Compressional/ Extensional	Extensional grabens and other structures		0.02		370		0
West Siberian Basin (11740101)	Compressional	Basement-involved blocks, stratigraphic undefined	0.15	0.32	130	1171	78	99
West Siberian Basin (11740201)	Passive	Basement-involved blocks, stratigraphic undefined	0.01	0.13	100	778	68	90
Median			**0.27**	**0.25**	**110**	**590**	**89**	**81**
Mean			**0.33**	**0.40**	**122**	**641**	**76**	**60**

Sizes of Undiscovered Oil and Gas Fields.—The minimum, median, and maximum sizes of undiscovered oil and gas fields in the Kolguyev Terrace AU are reported in appendix 1. The estimated minimum sizes of undiscovered fields in the AU are 50 MMB of crude oil and 300 BCF of natural gas (6 BCF equals 1 MMBOE). The estimated median sizes of undiscovered fields (100 MMB of crude oil and 600 BCF of natural gas) are slightly smaller than those of fields in the analog dataset (108 MMB of crude oil and 585 BCF of natural gas, table 1) and of discovered fields larger than the minimum size in the neighboring Timan-Pechora Basin (IHS Energy Group, 2007). The estimated low-probability maximum sizes of undiscovered fields in the AU (500 MMB of crude oil and 3,000 BCF of natural gas) are about half the mean and median sizes of the largest fields in the analog dataset (800 and 1,500 MMBOE, respectively) and about half the size of the largest discovered fields in the Timan-Pechora Basin (IHS Energy Group, 2007). These maximum field sizes reflect the smaller structures in the Kolguyev Terrrace AU. The expected maximum sizes of undiscovered fields in the AU are 125 MMB of crude oil and 940 BCF of natural gas (not reported in appendix 1). These field sizes, which are expected on the basis of the size and density of fields in the Timan-Pechora Basin, are smaller than the estimated low-probability maximum field sizes.

Petroleum Composition and Properties of Undiscovered Oil and Gas Fields.—Oil/gas mixtures, coproducts, and petroleum-quality properties for the Kolguyev Terrace AU were obtained from data gathered from discovered oil and gas fields on Kolguyev Island and in the Timan-Pechora Basin, as well as from world statistics (table 3). An oil/gas mixture of 0.1 (minimum), 0.3 (mode), and 0.6 (maximum) (see appendix 1) was estimated because natural gas is assumed to be more abundant than crude oil in this AU. The drilling depth for undiscovered fields, estimated from interpreted seismic profiles and wells drilled in the AU, is 1.3 km (minimum), 3.0 km (median), and 5.0 km (maximum) (see appendix 1).

South Barents Basin and Ludlov Saddle Assessment Unit

The South Barents Basin and Ludlov Saddle AU in the East Barents Basins Province is bounded on the east by Novaya Zemlya and the Admiralty Arch, on the north by the North Barents Basin, on the south by the Kolguyev Terrace and the Kola-Kanin Monocline, and on the west by the Central Barents High (figs. 1,2). The AU area of ~322,000 km^2 stratigraphically includes the sedimentary section from upper Paleozoic through Cretaceous.

Table 3. World statistics for oil and gas coproduct ratios, ancillary data, and depths.

Variable	Minimum	Median	Maximum
Coproduct Ratios			
Natural Gas-to-Crude Oil Ratio in Oil Accumulations (cubic feet per barrel)	100	1,000	20,000
Natural gas liquids-to-natural gas ratio in oil accumulations (barrels per thousand cubic feet)	5	25	85
Natural gas liquids-to-natural gas ratio 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

Major source rocks are inferred to be Triassic mudstone and possible upper Paleozoic and Jurassic mudstone, all of which are presumed to be thermally mature in the South Barents Basin. Upper Devonian marine “Domanik Facies” mudstone is a potential source rock; however, it was not observed in the Kolguyev Terrace AU or penetrated in any wells in the South Barents Basin. In the Kolguyev Terrace AU, upper Permian mudstone is thermally immature but might be mature deeper in the South Barents Basin. Upper Jurassic mudstone could also be a source rock in limited parts of the deeper basin but is thermally immature elsewhere. Known reservoir rocks in the AU are primarily Jurassic paralic and marine sandstones and Permian and Triassic fluvial, deltaic, and nearshore marine sandstones. The Permian and Triassic reservoirs are thin and compartmentalized. The Jurassic sandstones have good reservoir quality and contain most of the discovered petroleum. Upper Devonian through lower Permian carbonates and reefs, similar to those in the Timan-Pechora Basin and observed on seismic profiles around the periphery of the South Barents Basin, could provide reservoirs. Lower Cretaceous submarine channel and fan sandstones are also potential reservoirs. Traps in which petroleum was discovered in the South Barents Basin are mainly broad, gentle anticlines that formed from Late Triassic through Early Cretaceous time.

Geologic Analysis of Assessment-Unit Probability

The probability of at least one field equal to or largerer than the minimum field size of 50 MMBOE in the South Barents Basin and Ludlov Saddle AU is 100 percent (1.00) because four gas fields larger than this minimum field size and one natural-gas discovery smaller than this minimum field size have already been discovered. Known gas fields in the AU are as large as 100 TCF of natural gas (IHS Energy Group, 2007); no oil fields have been discovered. The assessment input data are reported in appendix 2 and summarized below.

Charge Probability.—A charge probability of 1.00 was estimated because the AU area has a petroleum system sufficient to charge one field equal to or greater than the minimum size (50 MMBOE).

Rocks Probability.—A rock probability of 1.00 was estimated because the AU area has a petroleum system sufficient to charge one field equal to or greater than the minimum size (50 MMBOE).

Timing and Preservation Probability.—A timing and preservation probability of 1.00 was estimated because the AU area has a petroleum system sufficient to charge one field equal to or larger than the minimum size (50 MMBOE).

Geologic Analogs for Assessment

A slightly different analog dataset was used to estimate the numbers and sizes of undiscovered fields in the South Barents Basins and Ludlov Saddle AU and the North Barents Basin AU. The analog dataset contains 20 AUs representing rift/sag basins in extensional and compressional structural settings, composed of either clastic or carbonate rocks or both (tables 2). All 20 AUs contain discovered fields larger than the minimum size defined for this assessment (50 MMBOE). The density of prospects mapped by seismic surveys was used to confirm and adjust the estimated number of undiscovered fields in the AU.

Numbers of Undiscovered Oil and Gas Fields.—The total number of undiscovered oil and gas fields in the South Barents Basin and Ludlov Saddle AU (see appendix 2) was estimated by comparing field densities (estimated density of undiscovered fields plus density of discovered fields larger than 50 MMBOE per 1,000 km^2) in the analog dataset (table 2). The density of discovered fields, which is typically lower than that of both discovered and undiscovered fields, was used to calibrate the densities of undiscovered fields in the AU. An estimated field density of 0.01 (minimum), 0.15 (median), and 0.3 (maximum) was used in this assessment. The estimated median field density (0.15) is lower than that of fields in the analog dataset (~0.25, table 2) and approximately equal to the field density calculated for mapped, undrilled prospects, should these prospects become fields larger than the minimum size. The estimated maximum field density (0.3) is less than that of fields in the analog dataset (density of discovered fields, 1.12; density of both discovered and undiscovered fields, 1.78, table 2). Excluding extreme values that do not represent this AU, the maximum density of fields in the analog dataset is 0.4 to 0.6 (table 2). The estimated total number of undiscovered oil and gas fields is 3 (minimum), 45 (median), and 100 (maximum) (see appendix 2); the estimated total number of undiscovered oil fields is 0 (minimum), 6 (median), and 40 (maximum); and the estimated total number of undiscovered gas fields is 3 (minimum), 38 (median), and 100 (maximum).

Sizes of Undiscovered Oil and Gas Fields.—The minimum, median, and maximum sizes of undiscovered oil and gas fields in the South Barents Basin and Ludlov Saddle AU are reported in appendix 2. The estimated minimum sizes of undiscovered fields in the AU are 50 MMB of crude oil and 300 BCF of natural gas (6 BCF equals 1 MMBOE). The estimated median sizes of undiscovered fields (110 MMB of crude oil and 660 BCF of natural gas) are approximately equal to those of fields in the analog dataset (110 MMB of crude oil and 590 BCF of natural gas; table 2). The low-probability maximum sizes of undiscovered oil and gas fields are estimated at 10,000 MMB of crude oil and 500 TCF of natural gas. The estimated maximum size of undiscovered gas fields (500 TCF) is larger than that of the largest gas field, the Shtokmanovskoya, discovered in the South Barents Basin (IHS Energy Group, 2007). The expected maximum sizes of undiscovered oil and gas fields in the AU (not reported in appendix 2) are estimated at 1,000 MMB of crude oil and 80 TCF of natural gas, which is smaller than the calculated low-probability estimates of the maximum sizes undiscovered fields. The expected maximum size of undiscovered gas fields (80 TCF) is smaller than the Shtokmanovskoya field (IHS Energy Group, 2007); however, the estimated maximum size of undiscovered gas fields (500 TCF) suggests that the largest gas field in the South Barents Basin may not have yet been discovered and that it might be comparable in size to the Shtokmanovskoya field. Large petroleum accumulations are expected to occur on structural highs along the basin margins.

Petroleum Composition and Properties of Undiscovered Oil and Gas Fields.—Oil/gas mixtures, coproducts, and petroleum-quality properties for the AU were estimated from analyses of petroleum discovered in the South Barents Basin and in the Kolguyev Terrace AU, as well as from world statistics (table 3). An oil/gas mixture of 0 (minimum), 0.05 (mode), and 0.4 (maximum; see appendix 2) was estimated because the inferred source rocks are gas prone, although some oil fields might be discovered around the periphery of the basin where source rocks are thermally mature with respect to oil, and in the basin center if Jurassic source rocks have expelled petroleum. Drilling depths for undiscovered fields (see appendix 2) were estimated from interpreted seismic profiles and wells drilled in the AU (fig. 3), as well as from petroleum-generation models (fig. 5). The estimated depth of undiscovered oil fields is 1.0 km (minimum), 3.0 km (median), 5.0 km (maximum); and the estimated depth of undiscovered gas fields is 1.0 km (minimum), 3.0 km (median), and 6.5 km (maximum).

North Barents Basin Assessment Unit

The North Barents Basin AU in the East Barents Basins Province is bounded on the east by the Novaya Zemlya and Admiralty Arch Province and the North Kara Basins and Platforms Province (figs. 1,2), on the northeast by the east edge of the St. Anna Trough fault system, on the north by the shelf margin of the Arctic Ocean, on the west by the western margin of the Central Barents High, and on the south by the axis of the Ludlov Saddle. The AU area of ~473,000 km^2 stratigraphically includes the sedimentary section from upper Paleozoic through Cretaceous.

Major source rocks in the AU are inferred to be Triassic mudstone and possible upper Paleozoic and Jurassic mudstone. Thermally mature Middle Triassic mudstone is probably the regional source rock for the entire North Barents Basin. Triassic mudstone crops out in Franz Josef Land in the northern part of the basin. Possible Paleozoic source rocks that crop out along the coast of Novaya Zemlya might also be present but probably are thermally overmature with respect to petroleum generation in deeper parts of the basin. Upper Jurassic mudstone might be thermally mature in deeper parts of the basin but in most areas is immature. Reservoir rocks and seals in the AU, which are expected be similar to those in the South Barents Basin, include Permian through Jurassic paralic and marine sandstones. Upper Devonian through lower Permian carbonates and reefs along the periphery of the basin could be reservoirs, and Lower Cretaceous submarine channel and fan sandstones might provide additional sources. Traps are postulated to be similar to those in the South Barents Basin, which are mainly broad, gentle anticlines. The presence of bitumen and petroleum-stained Jurassic sandstone in Franz Josef Land indicates possible petroleum accumulations in updip stratigraphic pinchouts along the western and northern margins of the basin.

Geologic Analysis of Assessment-Unit Probability

The probability that the North Barents Basin AU contains at least one field equal to or larger than a minimum field size of 50 MMBOE is estimated at 50 percent (0.504). The assessment input data are reported in appendix 3 and summarized below.

Charge Probability.—A charge probability of 0.8 is estimated for the AU because evidence exists of migrated petroleum in Franz Josef Land, although the presence of thermally mature source rocks in the AU has not been proved.

Rocks Probability.—A rock probability of 0.7 is estimated for the AU, although the presence of reservoir rocks and traps is inferred but has not been proved.

Timing and Preservation Probability.—A timing and preservation probability of 0.9 is estimated for the AU because the North Barents Basin has a geologic and tectonic history similar to that of the South Barents Basin, where petroleum discoveries have been made. However, the timing of petroleum generation with respect to trap formation, and the preservation of petroleum in accumulations, is unknown. The presence of migrated petroleum might indicate that traps did not exist for accumulation to occur.

Geologic Analogs for Assessment

As for the assessment of the South Barents Basins and Ludlov Saddle AU, the analog datasets chosen to assess the North Barents Basin AU include 20 AUs representing rift/sag basins with extensional and compressional structural settings, consisting of either clastic or carbonate rocks or both (table 2). All 20 analog AUs contain discovered fields larger than the minimum size defined for this assessment (50 MMBOE). The density of prospects mapped by seismic surveys was used to calibrate the estimated number of undiscovered oil and gas fields in the AU.

Number of Undiscovered Oil and Gas Fields.—The total number of undiscovered oil and gas fields in the North Barents Basin AU (see appendix 3) was estimated by comparing field densities (estimated number of undiscovered fields plus number of discovered fields larger than 50 MMBOE per 1,000 km^2) in the analog dataset (table 2). The density of discovered fields, which is typically lower than the density of both discovered and undiscovered fields, was used to calibrate the density of undiscovered fields in the AU. An estimated field density of 0.01 (minimum), 0.15 (median), and 0.3 (maximum) was used in the assessment. The estimated median field density (0.15) is lower than that of fields in the analog dataset (~0.25, table 2) but equal to that used for the assessment of the South Barents

Basin and Ludlov Saddle AU. The estimated maximum field density (0.3) is lower than the maximum densities of fields in the analog dataset (density of discovered fields, 1.12; density of both discovered and undiscovered fields, 1.78, table 2) but equal to the median density used for the assessment of the South Barents Basin and Ludlov Saddle AU. Excluding extreme values that do not represent the North Barents Basin AU, the maximum density of fields in the analog dataset is 0.4 to 0.6 (table 2). The estimated total number of undiscovered oil and gas fields is 1 (minimum), 70 (median), and 140 (maximum) (see appendix 3); the estimated total number of undiscovered oil fields is 0 (minimum), 22 (median), and 84 (maximum); and the estimated total number of undiscovered gas fields is 1 (minimum), 48 (median), and 126 (maximum).

Sizes of Undiscovered Oil and Gas Fields.—The minimum, median, and maximum sizes of undiscovered oil and gas fields in the North Barents Basin AU are reported in appendix 3. The estimated minimum sizes of undiscovered fields in the AU are 50 MMB of crude oil and 300 BCF of natural gas (6 BCF equals 1 MMBOE). The estimated median sizes of undiscovered fields in the AU (110 MMB of crude oil and 660 BCF of natural gas) are approximately equal to the median sizes of fields in the analog dataset (110 MMB of crude oil and 590 BCF of natural gas, table 2). The estimated low-probability maximum sizes of undiscovered fields in the AU are 30,000 MMB of crude oil and 500 TCF of natural gas. The estimated maximum size of undiscovered oil fields (30,000 MMB) is considerably larger than the expected largest size of 4,000 MMB (not reported in appendix 3). The estimated maximum size of undiscovered gas fields (500 TCF) is larger than either the Shtokmanovskoya or the Urengoyskoye field (IHS Energy Group, 2007); however, the expected maximum size of undiscovered gas fields (90 TCF; not reported in appendix 3) is smaller than either field, suggesting that the largest gas field to be discovered in the North Barents Basin AU would be comparable to, or slightly larger than, the Shtokmanovskoya field. Large petroleum accumulations are expected on structural highs along the basin margins.

Petroleum Composition and Properties of Undiscovered Oil and Gas Fields.—Oil/gas mixtures, coproducts, and petroleum-quality properties for the AU were estimated from analyses of petroleum discovered in the South Barents Basin and Kolguyev Terrace AU, as well as from world statistics (table 3). An oil/gas mixture of 0.1 (minimum), 0.3 (mode), and 0.6 (maximum) is greater than that for the South Barents Basin (0, 0.05, and 0.4, respectively) because potential Triassic source rocks were deposited in a more distal marine environment and are inferred to be more oil prone. Additionally, evidence of liquid petroleum migration was observed in Franz Josef Land. Drilling depths for undiscovered fields (see appendix 3) were estimated from interpreted seismic profiles in the AU and from petroleum-generation models (fig. 6). The estimated depth of undiscovered oil fields is 1.0 km (minimum), 3.0 km (median), and 5.0 km (maximum); and the estimated depth of undiscovered gas fields is 1.0 km (minimum), 3.0 km (median), and 6.5 km (maximum).

Novaya Zemlya Basins and Admiralty Arch Assessment Unit

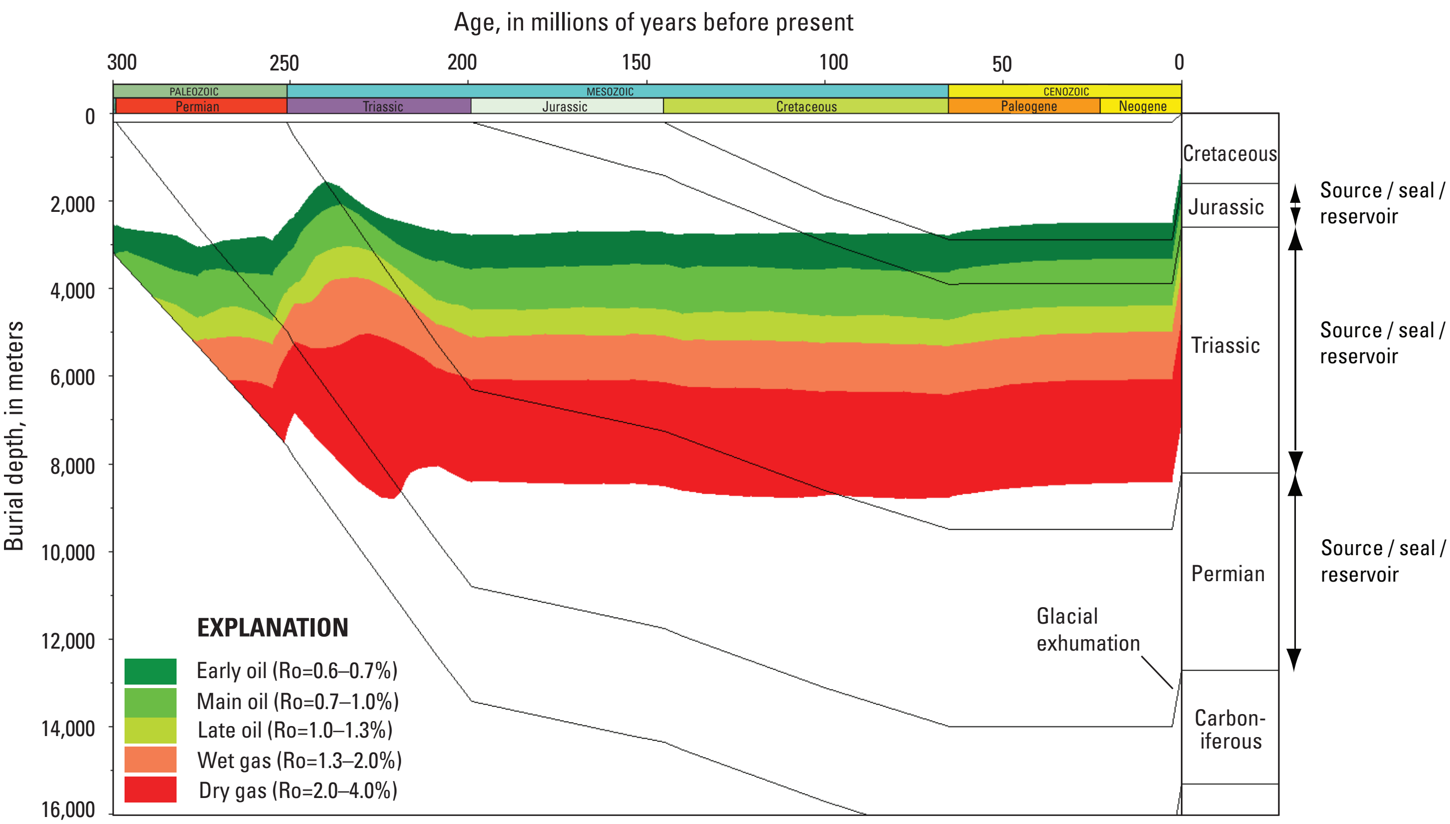
The Novaya Zemlya Basins and Admiralty Arch AU, which follows the outline of the Novaya Zemlya Basins and Admiralty Arch Province (figs. 1,2), is bounded on the west by the South and North Barents Basins; on the east, it coincides with compressed Paleozoic and Mesozoic strata west of Novaya Zemlya, although no significant foreland basin was observed (Otto and Bailey, 1995; O'Leary and others, 2004). The AU area of ~113,000 km^2 stratigraphically includes the entire Paleozoic and Mesozoic sedimentary section.

The AU is situated along what was once an unstable Paleozoic shelf edge, and contains rocks deposited in shelf, slope, and deep-marine environments. Source, reservoir, and seal rocks, as well as trap configurations, in the AU are inferred and not proved. Potential source rocks include Lower and Middle Triassic mudstones, Upper Devonian marine "Domanik Facies," and upper Permian mudstones similar to those observed in the neighboring Timan-Pechora Basin. Upper Permian source rocks, however, have not been observed north of the Kolguyev Terrace AU. Silurian through Carboniferous mudstones that crop out along the coast of Novaya Zemlya are possible source rocks. Bitumen was observed in Devonian rocks, and some Silurian reefs are stained with petroleum in northern Novaya Zemlya. Upper Permian mudstone with a low TOC content was penetrated on the Admiralty Arch. On Kolguyev Island, Permian mudstone is thermally immature but may become more mature northward. Reservoir rocks and seals are similar to those in the Timan-Pechora Basin. Middle Devonian siliciclastic rocks and Upper Devonian through lower Permian carbonate rocks and reefs provide reservoirs and seals in the Timan-Pechora Basin and probably are also present in this AU. Traps formed during an episode of compressional deformation that began in the Jurassic and ended in the Early Cretaceous. Petroleum generation in Paleozoic source rocks, however, probably was complete by the end of the Triassic. Thus, most large petroleum accumulations that might have formed during the Triassic were probably destroyed during early Cimmerian deformation.

Geologic Analysis of Assessment-Unit Probability

No oil or gas fields have been discovered in the Novaya Zemlya Basins and Admiralty Arch AU. As of 2007, however, three wells had been drilled; one well was reported as dry, and the other two have unreported results. The probability that the AU contains at least one field equal to or larger than the minimum field size of 50 MMBOE is estimated at 9 percent (0.09), below the minimum probability (0.10) defined for this assessment. Thus, the AU was not quantitatively assessed for this report. The assessment input data for this AU are reported in appendix 4 and summarized below.

Charge Probability.—A charge probability of 0.6 is estimated for the AU because source rocks in the AU have not been drilled.



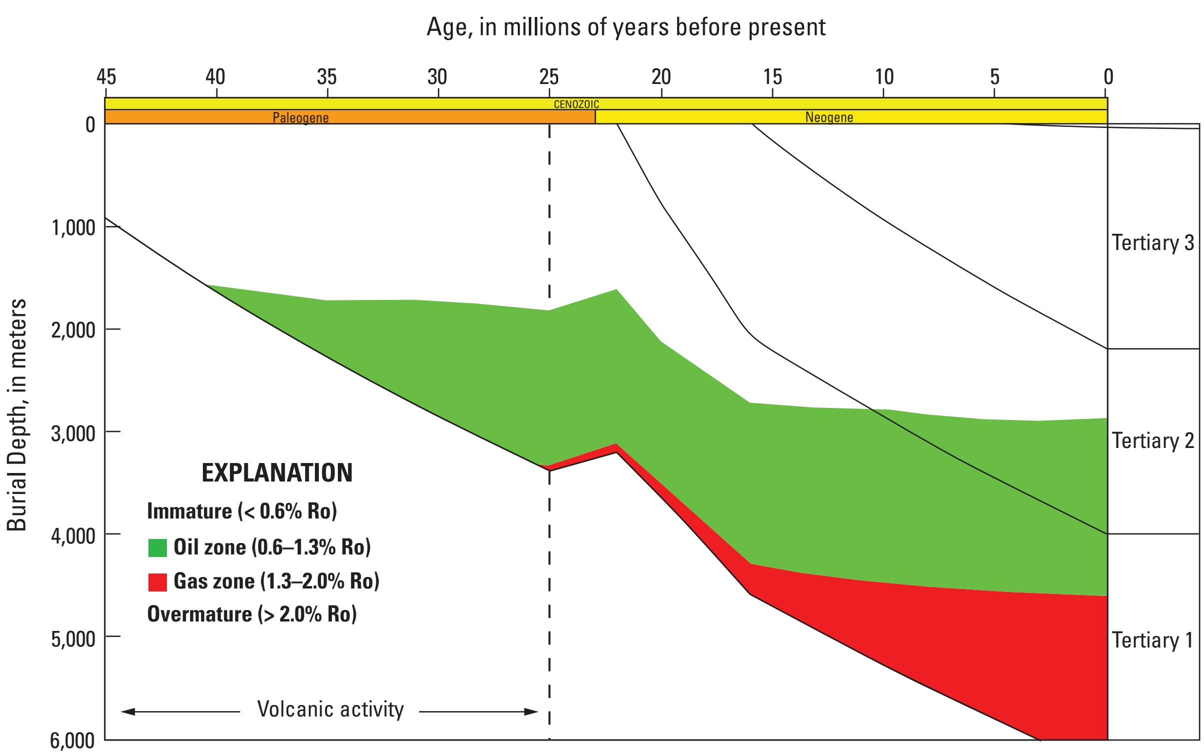


Figure 6. Petroleum-system model showing burial history for a pseudowell (see fig. 2 for location) in the North Barents Basin Assessment Unit (fig. 3*A*) depicting thermal maturity. Ro, vitrinite reflectance, in percent (%). Data from Johansen and others (1993); Petromod data from Wygrala (1989), Sweeney and Burnham (1990), and Integrated Exploration Systems (2008).

Rock Probability.—A rock probability of 0.5 is estimated for the AU because the presence and quality of reservoir and seal rocks in the AU is unknown.

Timing and Preservation Probability.—A timing and preservation probability of 0.3 is estimated for the AU because the age of trap formation postdates the timing of petroleum generation.

Summary of Assessment Results

The assessment results for the Kolguyev Terrace AU, the South Barents Basin and Ludlov Saddle AU, and the North Barents Basin AU in the East Barents Basins Province are summarized in table 4. Estimates represent undiscovered, technically recoverable, conventional petroleum resources.

The mean undiscovered crude-oil resource in the Kolguyev Terrace AU is estimated at 145 MMB, with an F95 of 0 MMB, an F50 of 110 MMB, and an F5 of 398 MMB. The mean volume of undiscovered nonassociated natural-gas resources is estimated at 2,313 BCF, with an F95 of 973 BCF, an F50 of 2,039 BCF, and an F_5 of 4,605 BCF. The expected maximum size of undiscovered oil fields is ~125 MMB, and the expected maximum size of undiscovered gas fields is ~940 BCF. The probability for undiscovered petroleum resources in the AU is 100 percent (1.00).

The mean undiscovered crude-oil resource in the South Barents Basin and Ludlov Saddle AU is estimated at 1,939 MMB, with an F95 of 241 MMB, an F50 of 1,300 MMB, and an F5 of 5,901 MMB. The mean volume of undiscovered nonassociated natural-gas resources is estimated at 183,689 BCF, with an F95 of 44,854 BCF, an F_{50} of 142,293 BCF, and an F5 of 472,507 BCF. The expected maximum size of undiscovered oil fields is ~937 MMB, and the expected maximum size of undiscovered gas fields is ~79,307 BCF. The probability for undiscovered petroleum resources in the AU is 100 percent (1.00).

In the North Barents Basin AU, the AU probability is 0.504. The risked mean undiscovered crude oil resource is 5,322 MMB, with an F95 of 0 MMB, an F50 of 1,197 MMB, and an F5 of 21,424 MMB. The mean volume of undiscovered nonassociated natural-gas resources is estimated at 117,467 BCF, with an F95 of 0 BCF, an F50 of 36,814 BCF, and an F5 of 450,041 BCF. The expected maximum size of undiscovered oil fields is ~4,284 MMB, and the expected maximum size of undiscovered gas fields is ~92,348 BCF. The probability for undiscovered petroleum resources in the AU is 50.4 percent (0.504).

The estimated total mean volumes of undiscovered petroleum resources in the East Barents Basins Province are ~7.4 billion barrels (1,200 million m^3) of crude oil, 318 TCF (9 trillion m^3) of associated and nonassociated natural gas, and 1,400 MMB (220 million m^3) of natural-gas liquids. Additional statistics are listed in table 4.

Table 4. Assessment results (conventional undiscovered resources) for the East Barents Basins Province.

[AU, assessment unit; BCF; billion cubic feet; MMB, million barrels. Results shown are fully risked estimates. For gas accumulations, all liquids are included under the natural gas liquids (NGL) category. F95, 95-percent probability of at least the amount tabulated, and so on for F50 and F5. Fractiles are additive under the assumption of perfect positive ocrrelation. N/A, not applicable. Numbers do not exactly add to totals because totals were added by statistical aggregation]

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
Assessment results—East Barents Basins Province; Paleozoic-Mesozoic composite total petroleum system														
Kolguyev Terrace AU	1	Oil	0	110	398	145	0	155	973	275	0	2	14	4
		Gas	N/A	N/A	N/A	N/A	973	2,039	4,605	2,313	22	54	129	62
South Barents Basin and Ludlov Saddle AU	1	Oil	241	1,300	5,901	1,939	312	2,175	11,900	3,669	3	27	163	50
		Gas	N/A	N/A	N/A	N/A	44,854	142,293	472,507	183,689	126	460	2,080	714
North Barents Basin AU	0.504	Oil	0	1,197	21,424	5,322	0	1,748	41,460	10,145	0	20	557	137
		Gas	N/A	N/A	N/A	N/A	0	36,814	450,041	117,467	0	98	1,808	456
Total conventional resources			389	4,543	24,119	7,406	56,952	259,635	796,922	317,558	211	1,016	4,153	1,423
Assessment results—Novaya Zemlya Basins and Admiralty Arch Province; Paleozoic-Mesozoic composite total petroleum system														
Northwest Laptev Sea Shelf AU	0.09	Not quantitatively assessed												

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Appendixes

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