Geology and Assessment of Undiscovered Oil and Gas Resources of the Lomonosov-Makarov Province, 2008

Chapter CC of
The 2008 Circum-Arctic Resource Appraisal

Professional Paper 1824

U.S. Department of the Interior
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COVER

Two scientists from the U.S. Geological Survey core through the sea ice in the Canada Basin of the Arctic Ocean during a research cruise aboard the U.S. Coast Guard icebreaker *Polar Star*. Photograph by Thomas E. Moore.

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North Atlantic Ocean

Eurasia

Arctic Ocean

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Chapter CC

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Abstract

The Lomonosov-Makarov Province lies in the central Arctic Ocean and encompasses the northern part of the oceanic Amerasia Basin (Makarov and Podvodnikov Basins) and the adjoining Lomonosov Ridge and Siberian continental margins. The Amerasia Basin is thought to have been created in the Jurassic and Early Cretaceous by rotational rifting of the Alaska-Siberia margin away from the Canada margin about a pivot point in the Mackenzie Delta and an associated continental-scale transform fault along the Lomonosov Ridge. The province is bounded on the south by the Cretaceous Alpha-Mendeleev Ridge, an undersea ridge composed of plume-type volcanic rocks that obliquely crosses the Amerasia Basin, dividing it into northern and southern parts. The thickest passive-margin succession in the province lies along the Siberian margin, where sediments thin from a maximum thickness along the continental margin to less than 2 km in the basin. The northern part of the province consists of the Lomonosov Ridge, which was rifted away from the Eurasia Plate in the Paleocene during formation of the oceanic Eurasia Basin, creating an isolated, narrow, submerged, but high-standing microcontinent. This part of the province contains sediments that were shed from the Eurasia Plate in the Mesozoic and covered by pelagic and hemipelagic sediments in the Cenozoic, creating depositional successions with thicknesses ranging from about 1 to more than 5 km.

This tectonic framework provides the basis for division of the province into four assessment units (AUs), including (1) Lomonosov Ridge AU, (2) Makarov Basin Margin AU, (3) Siberian Passive Margin AU, and (4) Makarov Basin AU. The Lomonosov Ridge and Makarov Basin Margin AUs compose a displaced part of the Cretaceous shelf and slope, respectively, of the Eurasia continental margin with a covering drape of pelagic Cenozoic sediments. The Siberian Passive Margin and Makarov Basin AUs represent the slope of the Siberian continental margin and adjoining basin plain deposits, respectively, deposited on oceanic crust of the northern Amerasia Basin. All of the AUs are entirely submarine and covered by the polar icecap, and consequently have not been explored for petroleum. Petroleum source rock units considered in the assessment of the province are mostly hypothetical, and include Triassic and Jurassic platformal marine shale units on the Lomonosov Ridge, and province-wide Lower Cretaceous synrift, Lower and Upper Cretaceous postrift, and Paleogene organic-rich shale intervals. The most prospective reservoirs and traps are envisioned to include base-of-slope turbidite-fan complexes, slope channels and basins, extensional and growth fault structures, and other stratigraphic, structural, and composite trap features typically present on clastic-dominated continental passive margins. Because of concerns about reservoir quality in the Makarov Basin AU and the detrimental effect of Paleocene rifting in the Lomonosov Ridge AU, these units were not quantitatively assessed, as they were judged to have less than 10 percent probability of containing at least one accumulation of hydrocarbons equal to or greater than 50 million barrels of oil equivalent (MMBOE). The mean volumes of undiscovered resources for the Makarov Basin Margin AU are estimated to be 0.12 billion barrels of oil and 0.74 trillion cubic feet of nonassociated gas, whereas the undiscovered resources for the Siberian Passive Margin AU are estimated to be ~1 billion barrels of oil and 4.7 trillion cubic feet of nonassociated gas.

Introduction

The U.S. Geological Survey (USGS) in 2008 completed an appraisal of undiscovered, technically recoverable, conventional oil and gas resources north of the Arctic Circle. Results of that Circum-Arctic Resource Appraisal (CARA) include aggregate resource estimates for the entire Arctic region (Bird and others, 2008; Gautier and others, 2009, 2011a) and documentation of the geologic framework and resource estimates for specific Arctic provinces (Bird and Houseknecht, 2011; Gautier and others, 2011b; Houseknecht and Bird, 2011; Houseknecht and others, 2012a, b; Klett and Pittman, 2011; Klett and others, 2011; Moore and Pitman, 2011; Moore and others, 2011; Schenk, 2011a, b; Sørensen and others, 2011). The procedures and methods used in conducting the Circum-Arctic Resource Appraisal were documented by Charpentier and Gautier (2011) and the location and extent of the basins were delimited by Grantz and others (2010; 2011a). The purpose of this chapter is to provide a synthesis of the petroleum geology of the Lomonosov-Makarov Province, to present the reasoning and input parameters used for petroleum assessment of its constituent assessment units, and to report the complete results of the resource assessment for the province.

Lomonosov-Makarov Province Description

Boundaries

The Lomonosov-Makarov Province of the Circum-Arctic Resource Appraisal (CARA) encompasses the northern part of the Amerasia Basin and its margins, comprising a wedge-shaped area of about 715,000 km^2 in the central part of the Arctic Ocean (fig. 1). The province includes the continental Lomonosov Ridge, oceanic Makarov and Podvodnikov Basins, and the outer shelf and slope of the Siberian continental margin (fig. 2). The province is bounded by the Amundsen Basin of the Eurasian ocean basin, the Canadian and Greenland margins in the Lincoln Sea, the Alpha and Mendeleev Ridges, and the Siberian continental shelf. In detail moving clockwise around the province, the province boundaries were placed at the (1) continent-ocean transition between continental crust of the Lomonosov Ridge and oceanic crust of the Amundsen Basin, (2) transform faults bounding the Lomonosov Ridge against oceanic crust and Greenland continental crust in the eastern Lincoln Sea, (3) depositional limit of volcanogenic deposits of the Alpha Ridge on the Lomonosov Ridge north of Ellesmere Island, (4) edge of onlap and (or) interfingering of sedimentary deposits of the Makarov and Podvodnikov basins onto volcanic rocks of the Alpha and Medeleev ridges, (5) downlap limit of continental slope deposits of the Siberian continental margin onto the Mendeleev Ridge, and (6) southern limit of the Siberian passive margin against the Vilkitski Basin and DeLong Massif on the Siberian Shelf. Boundaries delimiting the lateral extent of the Siberian passive margin deposits along the continental margin were arbitrarily placed at the termination of the Mendeleev Ridge in the east and at the termination of the Lomonosov Ridge in the west. The province boundaries were drawn entirely from geologic observations without regard for the political boundaries in the region. The entire province lies north of the Arctic Circle.

Tectonic Evolution of the Central Arctic Ocean Region

The Lomonosov Ridge is a high-standing submarine ribbon microcontinent that extends from northern Greenland to Siberia via the North Pole and divides the Arctic Ocean into two separate ocean basins: the younger Eurasia Basin and the older Amerasia Basin (figs. 2 and 3). The Eurasia Basin was formed during the Cenozoic by seafloor spreading at the active Gakkel Ridge (Vogt and others, 1979; Brozena and others, 2003; Cochran and others, 2003; Jokat and Micksch, 2004). Magnetic anomalies from the Eurasia Basin indicate that the seafloor spreading began in the late Paleocene (Chron 24 or Chron 25; ~56–58 Ma) and show that the basin developed by nearly orthogonal rifting of the Lomonosov Ridge away from the northern margin of the European continent (Brozena and others, 2003; Glebovsky and others, 2006).

The origin and tectonic development of the Amerasia Basin is less certain because of its thick sedimentary and volcanic fill and because magnetic anomalies are absent or poorly developed over large parts of the basin. The anomalies observed in the basin are geometrically simple and limited to a narrow triangular region having an apex in the Mackenzie Delta in the western Canada Basin (Grantz and others, 2011b). The magnetic anomalies are associated with gravity anomalies that together suggest a rotational mechanism of seafloor spreading, with the Alaska-Siberia margin having been rifted away from the Canadian margin in the Hauterivian (Early Cretaceous, ~135 Ma) about a pivot point in the Mackenzie Delta (Grantz and others, 1990; 2011a). This model requires transform motion along the opposing margin to resolve the plate tectonic geometry of the basin, probably at the boundary between the Lomonosov Ridge and the Amerasia Basin.

The geometry of bathymetric features along the western margin of the Lomonosov Ridge suggest they were deformed by translational shearing and are similar to bathymetric features at other sheared transform margins, supporting the rotational interpretation (Cochran and others, 2006) (fig. 4). Opening of the Amerasia Basin by counterclockwise rotation is not universally accepted, however, and a number of other mechanisms for the tectonic development of the Amerasia Basin have been proposed. The most popular alternative models are sea-floor spreading parallel to either the Alaskan margin or alternatively, parallel to the Canadian margin (see, for example, Lawver and Scotese, 1990). Other recent suggestions include simultaneous rotational openings about opposed poles of rotation in the Mackenzie Delta and near the New Siberian Islands (Kuzmichev, 2009) and separate phases of opening for the Canada Basin and Makarov-Podvodnikov Basin, with the latter having opened in the Late Cretaceous (Alvey and others, 2008). We note that (1) the magnetic and gravity anomalies of the western Canada Basin are fan-shaped and oriented

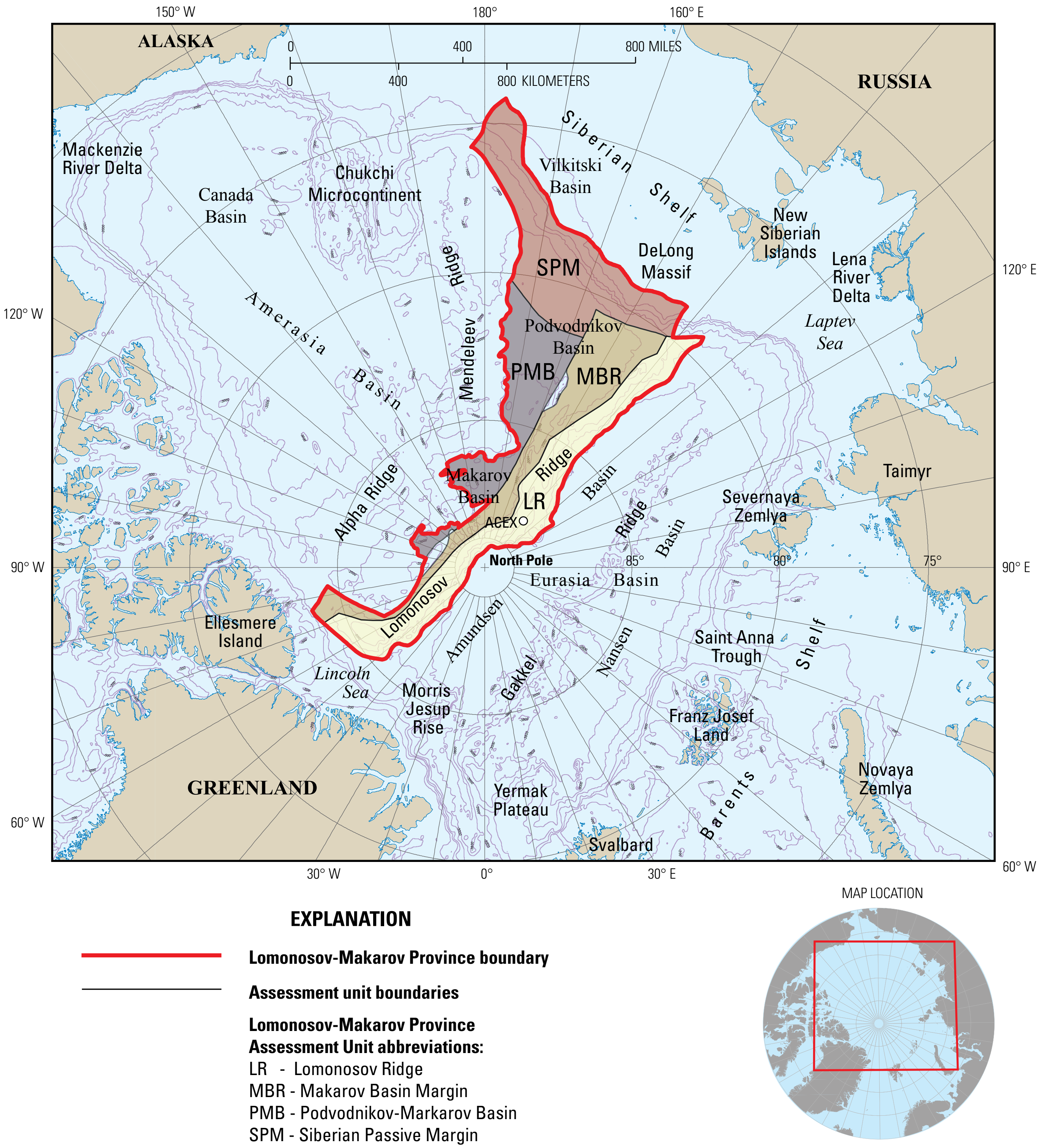


Figure 1. Location of the Lomonosov-Makarov Province and constituent assessment units, central Arctic Ocean. Assessment unit abbreviations: LR, Lomonosov Ridge; MBR, Makarov Basin Margin; PMB, Podvodnikov-Makarov Basin; SPM, Siberian Passive Margin.

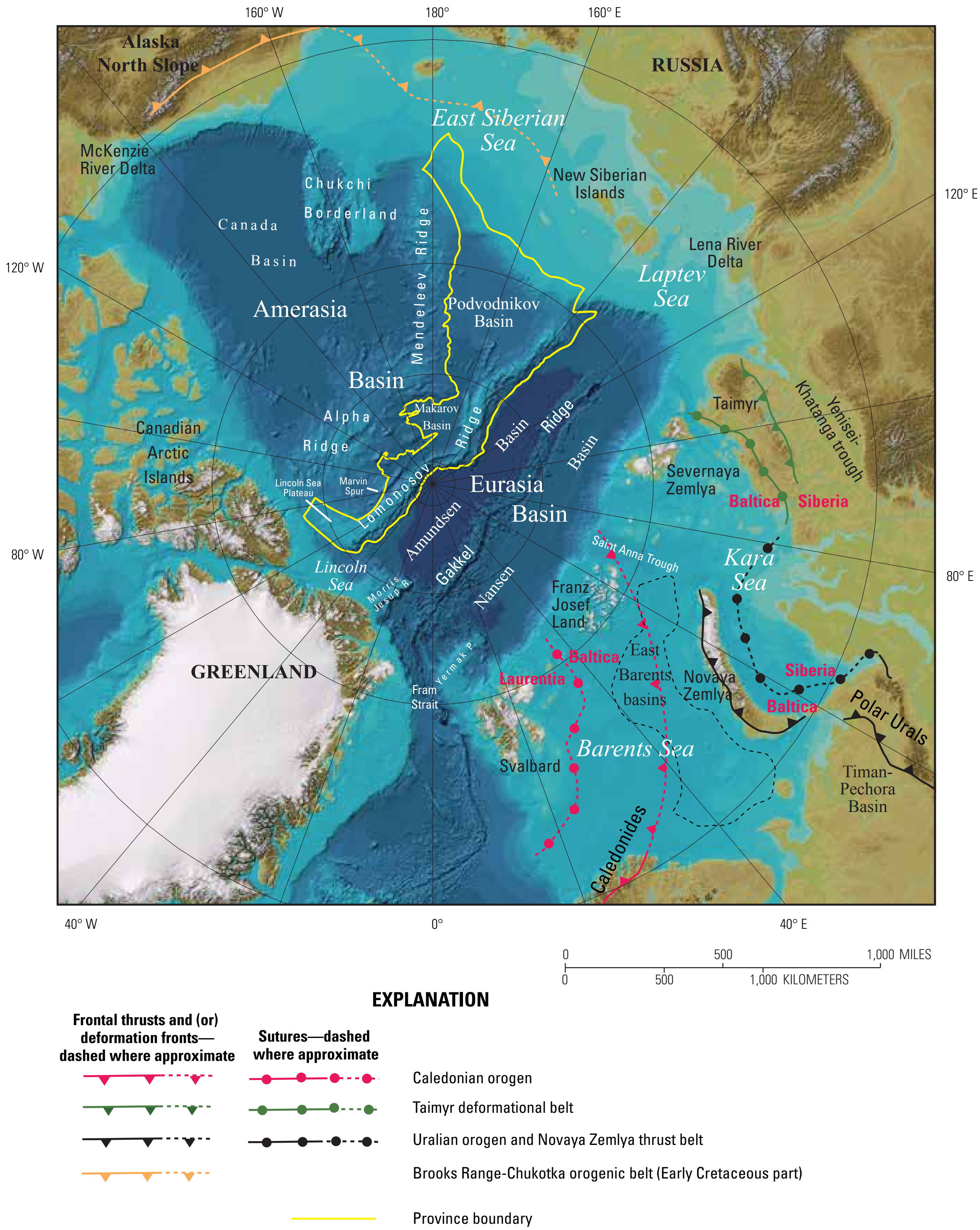


Figure 2. Map showing selected physiographic and tectonic features of the Arctic. Limits of Lomonosov-Makarov Province shown by yellow line. Deformation fronts and sutures from Grantz and others (2011a). Location of East Barents Basin from Ritzman and Faleide (2009). Bathymetry is from Jakobsson and others (2004).

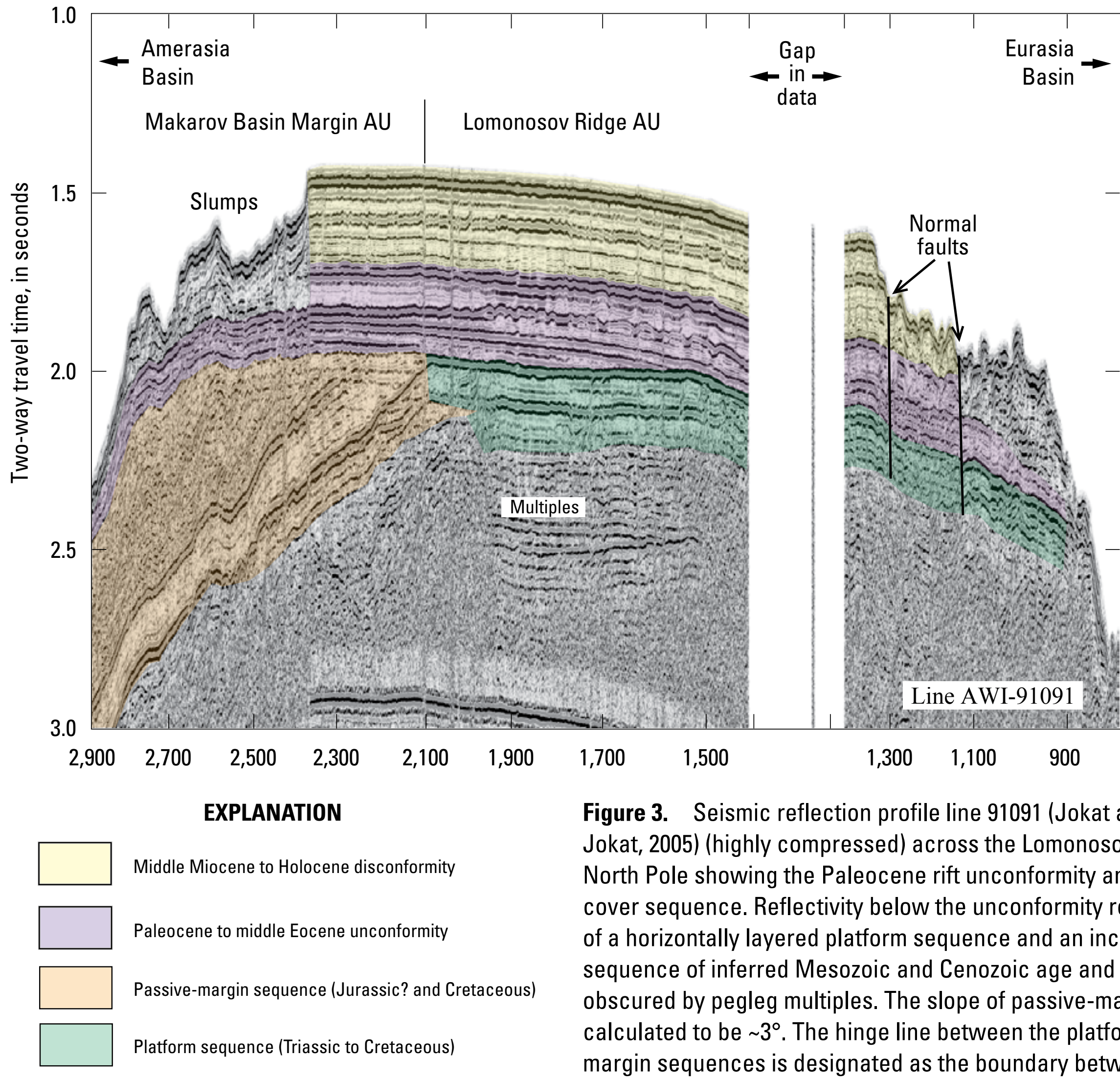


Figure 3. Seismic reflection profile line 91091 (Jokat and others, 1995; Jokat, 2005) (highly compressed) across the Lomonosov Ridge near the North Pole showing the Paleocene rift unconformity and overlying Cenozoic cover sequence. Reflectivity below the unconformity reveals the presence of a horizontally layered platform sequence and an inclined passive-margin sequence of inferred Mesozoic and Cenozoic age and whose bases are obscured by pegleg multiples. The slope of passive-margin reflectors are calculated to be ~3°. The hinge line between the platform and passive-margin sequences is designated as the boundary between the Lomonosov Ridge and Makarov Basin Margin Assessment Units.

obliquely with respect to the Alaskan and Canadian continental margins, with a point of emanation in the Mackenzie Delta; (2) the Alaska-Siberia continental margin has stratigraphic and structural dimensions that are grossly similar to those of the Canadian continental margin, suggesting they may be conjugate margins; and (3) the Alaska-Siberia and Lomonosov Ridge continental margins differ in length and in stratigraphic and structural complexity (see below), suggesting that they probably are not conjugate margins. For these reasons, we conclude that the counterclockwise rotational model of origin for the basin is most consistent with the known relations and this model was therefore assumed in this study.

Although largely covered by Cretaceous and Cenozoic sedimentary deposits ranging from 5 to 12 km thick, the Amerasia Basin itself is subdivided by the broad Alpha and Mendeleev Ridges (fig. 2). Together, these ridges form a dog-leg-shaped ridge that stretches across the basin from Ellesmere Island to the Siberian continental margin at a slightly oblique angle to the Lomonosov Ridge and is commonly referred to as the Alpha-Medeleev Ridge. The southern part of the Amerasia Basin adjacent to Alaska and Canadian margins is the Canada Basin. The northern part between the Alpha-Mendeleev Ridge and the Lomonosov Ridge is generally shown in many publications as the Makarov Basin (for example, Jakobsson and others, 2004). Grantz and others (2010; 2011a), following Russian conventions, divided this part of the Amerasia Basin into a reduced Makarov Basin near the North Pole and the Podvodnikov Basin adjacent to the Siberian continental margin. In this paper, we follow Grantz and others (2010; 2011a) and use the Russian terminology to provide greater specificity to features in the area.

The Alpha-Mendeleev Ridge stands lower than the continental Lomonosov Ridge, and scientific dredging and gravity data indicates that it consists of thick Lower and Upper Cretaceous alkalic basalt and diabase (Weber, 1986; Grantz and others, 2011b). Available seismic refraction and tomography indicate that the ridge has velocities and densities of mafic rocks at depth (Forsyth and others, 1986), which

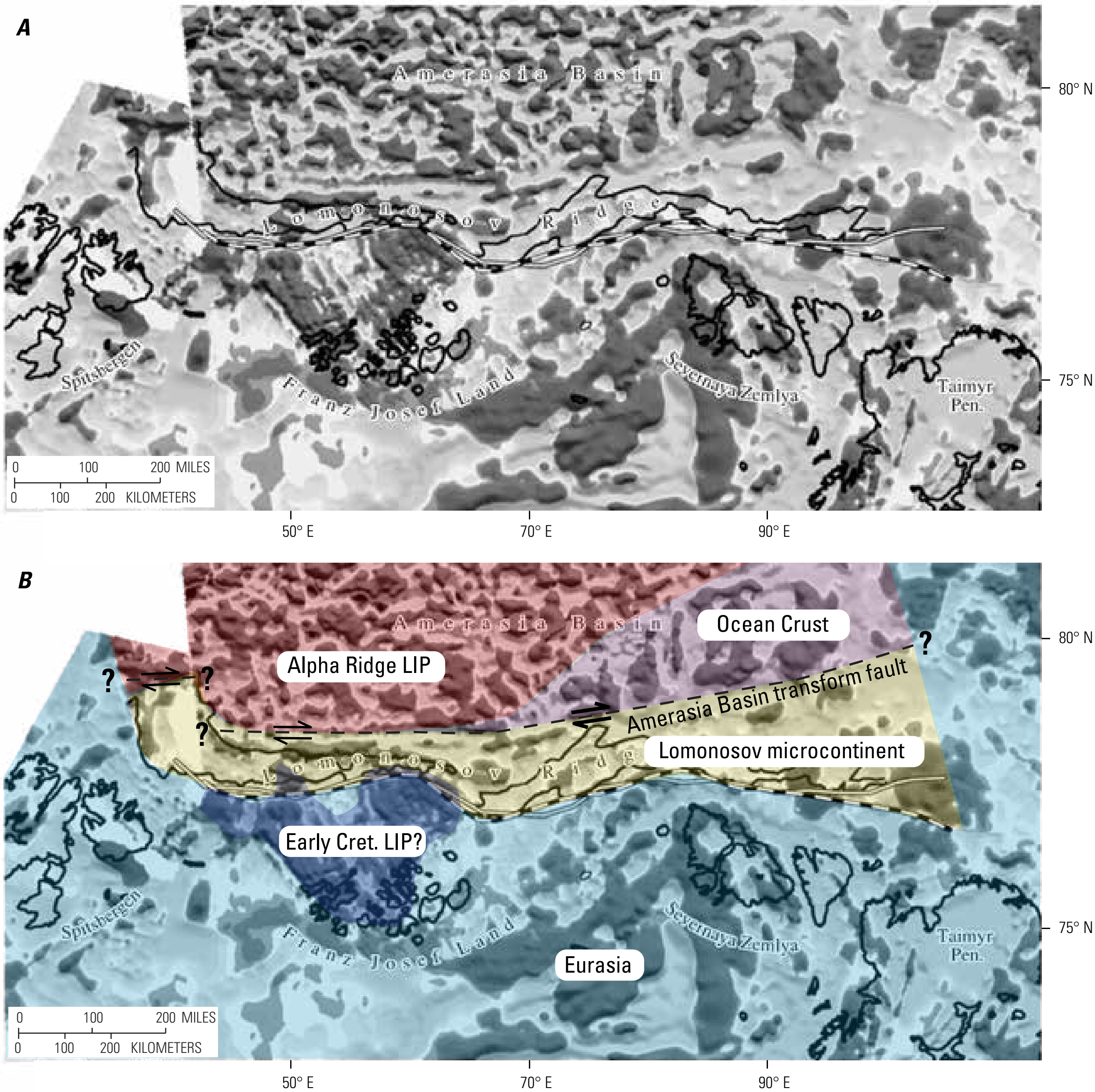


Figure 4. *A*, Magnetic anomaly map of the northern margin of Eurasia, Lomonosov Ridge microcontinent, and northern Amerasia Basin with ocean-crust anomalies of the Eurasia Basin removed and the Lomonosov Ridge restored against the continental margin of Eurasia. Solid white line designates the modern continent-ocean boundary of Eurasia; dashed line designates the modern continent-ocean transition zone boundary of the Eurasian margin of Lomonosov Ridge. Diagram from Glebovsky and others (2006). *B*, Map of Glebovsky and others (2006) with interpreted positions of the Lomonosov microcontinent, Alpha Ridge Large Igneous Province (LIP), oceanic crust of the Amerasia Basin, and Amerasia Basin transform fault of Grantz and others (2009) superimposed. Magnetic anomaly extending from Franz Josef Land northward to Lomonosov Ridge may correspond to Early Cretaceous LIP basalts in Franz Josef Land and correlate to the Alpha-Ridge LIP in the Amerasia Basin. This diagram represents a tectonic map of the Amerasia Basin margin of Eurasia in the Late Cretaceous and early Paleocene prior to opening of the Eurasia Basin in the late Paleocene.

has led most workers to conclude it is an aseismic volcanic ridge that belongs to the class of mafic igneous features called large igneous provinces (LIP). Termed the High Arctic Large Igneous Province (HALIP), the ridge has been interpreted to be the track of a mantle plume (hot spot) that transited the Amerasia Basin in the Late Cretaceous (Van Wagoner and others, 1986; Forsyth and others, 1986). Lawver and Muller (1994) suggested that the volcanic ridge was deposited on the older Lower Cretaceous oceanic crust formed during opening of the Amerasia Basin. Campanian and younger sedimentary deposits overlie the ridge (Mudie and others, 1986) and are interpreted to onlap and pinch out against the mafic rocks of the ridge along both margins (Grantz and others, 2010; 2011a). Alkalic basalt dredged from the ridge reportedly has yielded a whole rock Ar-Ar age of 89 Ma (Grantz and others, 2011b).

Basaltic volcanic flows and dikes of Early Cretaceous age (~130–100 Ma) are also known from Franz Josef Land, the Canadian Arctic Islands, Svalbard, and the New Siberian Islands. These rocks are thought to represent an older succession of hot-spot-type volcanic rocks that was active at the time of spreading of the Amerasia Basin near its spreading center (Drachev and Saunders, 2006). Whether the Early Cretaceous volcanic rocks form the earliest part of the HALIP, or constitute an entirely different LIP, is currently uncertain (fig. 4).

On the basis of limited seismic refraction data, some workers have hypothesized that the Alpha-Mendeleev ridge is underlain by extended continental crust rather than by mafic magmatic rocks (Lebedeva-Ivanova and others, 2006a). If true, this would imply that the Alpha-Mendeleev Ridge and possibly the Makarov Basin may have a basement and an origin that are distinct from those of the Canada Basin, and would imply that counter-clockwise rotational opening of the Amerasia Basin was limited to just the Canada Basin as suggested by Alvey and others (2008) and Kuzmichev (2009). The seismic velocity structure of the Alpha-Mendeleev Ridge, however, is similar to those of plume-generated volcanic rocks in Iceland and the Faroe Ridge and substantially different than those of continents, suggesting that the ridge probably has a crustal structure similar to those of oceanic volcanic plateau LIP provinces (Forsyth and others, 1986; Grantz and others, 2011b). These observations support the mantle-plume model for the origin of the ridge and we accordingly have assumed this model for the development of the Alpha-Mendeleev Ridge in our assessment.

Province Stratigraphy

The stratigraphy of the central Arctic region (fig. 5) strongly reflects the influence of formation of the Amerasia and Eurasia Basins. Prior to the opening of the Eurasia and Amerasia Basins in the Cretaceous and Tertiary, the Lomonosov Ridge (fig. 3) was part of a once much more extensive Baltic platform. In the area of the modern Barents shelf, the platform is underlain by metamorphic rocks deformed by the collision of Laurentia and Baltica during the closure of the Iapetus Ocean and formation of the Caledonian orogenic belt in the Silurian to Early Devonian (Gee and others, 2008) (fig. 2). Following the collision, the orogenic belt underwent a major extensional phase of deformation in the Devonian to early Carboniferous and evolved into a broad stable platform by the middle Carboniferous (Nøttvedt and others, 1992). Devonian extensional basins were filled with coarse clastic units and were succeeded by platform carbonate and evaporite deposits in the middle Carboniferous and early Permian.

During the late Paleozoic and Triassic, Siberia collided with Baltica along the eastern margin of Baltica, producing the west-vergent Uralian orogenic belt. Sediments shed from the Uralian orogenic belt were deposited to the west, forming a foreland basin clastic succession that trends generally northeastward across the eastern Baltic Shelf and laps westward across the shelf at least as far as Svalbard. This basin consists of Permian and Triassic clastic deposits more than 12 km thick, although the thickest sections occur in the deep East Barents Sea Basin, which was formed by extensional processes of uncertain relation to the development of the foreland basin (Ritzmann and Faleide, 2009). Clastic sedimentation diminished somewhat in the Late Triassic and Jurassic, resulting in Triassic and Late Jurassic organic-rich distal shelf facies in the western Barents shelf while coarser clastic sedimentation continued in the eastern part of the shelf (Nøttvedt and others, 1992). The Uralian orogen may continue northward via Novaya Zemlya and Taimyr to the edge of the Eurasia Basin in the northwestern Laptev Sea. Novaya Zemlya is a prominent west-vergent structural salient that was formed at the end of Uralian deformation in the Late Triassic (Otto and Bailey, 1995). Unlike other parts of the Uralian orogen, the Taimyr orogenic belt is south-vergent, lacks an ophiolitic suture, and displays evidence of Triassic and Jurassic deformation in addition to Uralian structures (Inger and others, 1999; Pease and Scott, 2009).

The Barents platform depositional trends were truncated at a high angle in the Jurassic and (or) Early Cretaceous by opening of the Amerasia Basin. Grantz and others (2007; 2011b) proposed a two-phase model for opening of the Canada Basin. The first phase involved formation of seafloor composed of highly extended continental lithosphere in the Jurassic and early Neocomian, whereas the second phase involved formation of new crust by seafloor spreading in the late Neocomian (Hauterivian and Barremian). Translational faulting along the margin of the Lomonosov Ridge is inferred to have been active throughout both phases. Rifting and (or) strike-slip faulting prior to or during opening of the basin may have resulted in local unconformities and basins and extensional structures on the Lomonosov Ridge and possibly included the graben-like structures reported by Kristoffersen and Mikkelsen (2006) at the termination of the ridge near the Canadian margin.

Following opening of the Amerasia Basin in the Early Cretaceous, the Lomonosov Ridge composed the outboard edge of the Barents shelf (fig. 4). Jurassic and (or) Cretaceous sedimentary systems continued to transport sediment from the highlands in the Uralian and Taimyr mountain belts northward across the Barents Shelf, depositing clastic shelf sequences on the platform (Embry, 1994) and a passive-margin sequence along the newly formed continental margin. The clastic shelf deposits are imaged in seismic data from the central Lomonosov Ridge (Jokat and others, 1992) (fig. 6*A*), and sampled by coring near the North Pole (Grantz and others, 2001) and by scientific drilling at the International Ocean Drilling Program Arctic Coring Expedition (ACEX) locations (Moran and others, 2006). The passive-margin sequence is visible in seismic profiles along the Amerasia Basin margin of the Lomonosov Ridge as sedimentary sequences at least

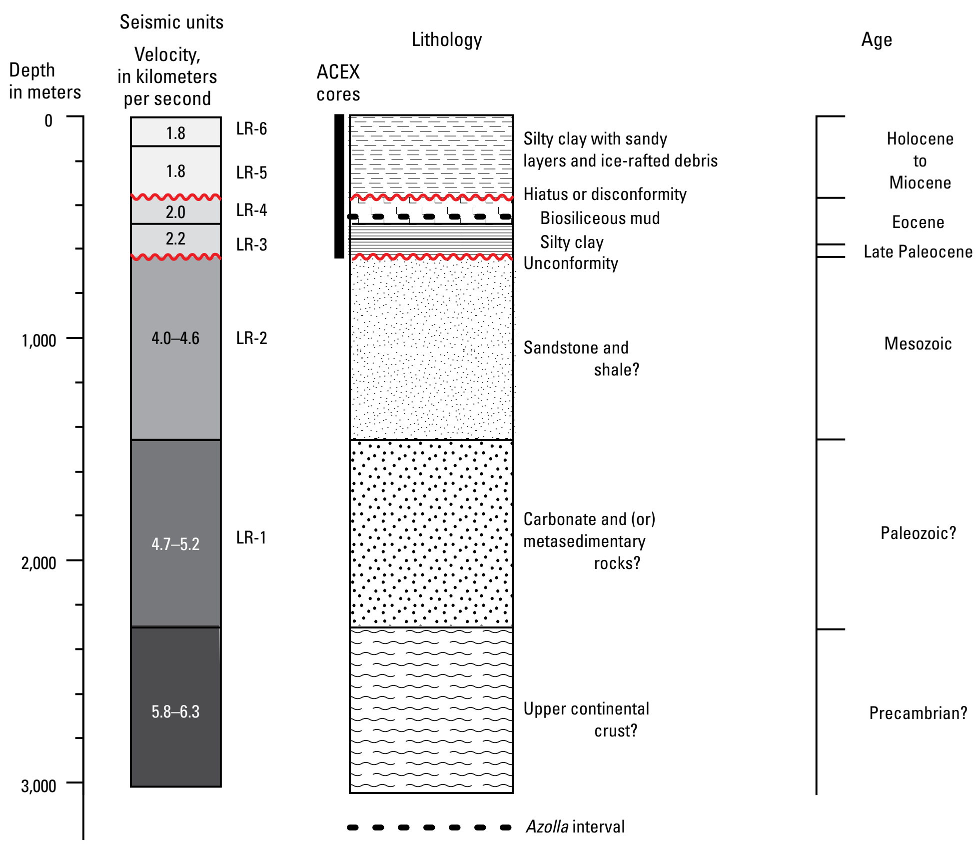


Figure 5. Seismic units, stratigraphy, and lithology of the Lomonosov Ridge. Diagram based on Jokat and others (1995), Jokat (2005), and Backman and others (2008).

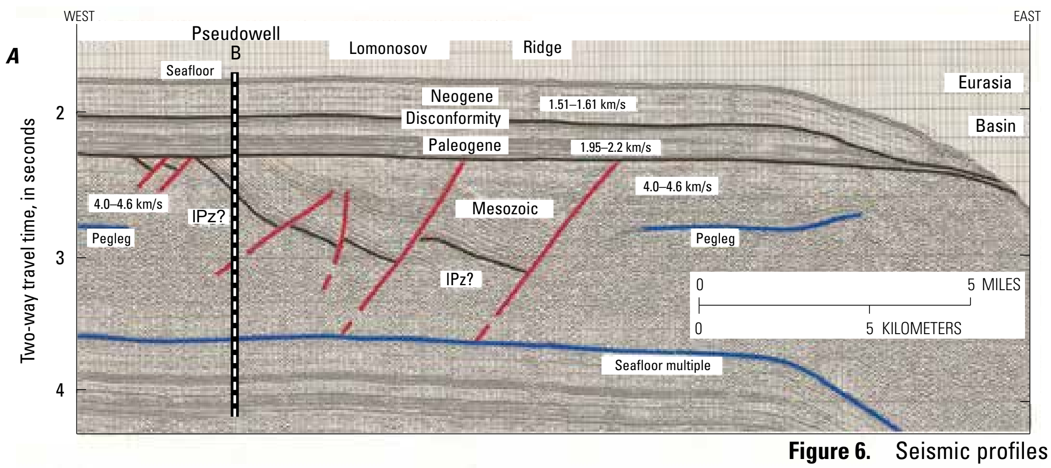
2–3 km thick that dip toward the Amerasia Basin and away from the Lomonosov Ridge (Jokat, 2005; Kristoffersen and Mikkelsen, 2006; Langinen and others, 2008) (figs. 3 and 7). Although not visible on the seismic data, presumably the oldest parts of the sequence are truncated and deformed by the Jurassic and Early Cretaceous transform fault along which the oceanic crust of the Amerasia Basin was emplaced against the Lomonosov Ridge. The overlying part of the passive-margin sequence that is visible in the seismic data probably extends uninterrupted from the Lomonosov Ridge across the transform into the Makarov and Podvodnikov basins, although the transition has not been verified with seismic data.

The initial formation of the Lomonosov Ridge passive margin as a transform margin distinguishes this passive margin from those formed by rifting processes. If the passive-margin depositional system became active as early as the Early Jurassic, as proposed by Grantz and others (2007; 2011b) and was actively depositing continentally derived sediment from the Barents Shelf into the Amerasia Basin until the onset of Gakkel Ridge spreading in the early Tertiary, the period of active passive-margin sedimentation lasted for as much as 140 million years.

By the late Paleocene, seafloor spreading began in the nascent Eurasia Basin, causing the Lomonosov Ridge to split off and separate from the Barents Shelf. Subsequent drift away from the margin severed the depositional systems that linked the highlands in the Uralian and Taimyr highlands to the passive-margin sequence in the Amerasia Basin and reduced drainage areas to just those sourced on the Lomonosov Ridge. Rift-related uplift, followed by subsidence of the Lomonosov Ridge after separation, produced a prominent regional unconformity of late Paleocene age interpreted as the rift unconformity by O'Regan and others (2008) (Lomonosov unconformity of Langinen and others, 2008) (figs. 3, 5, and 6*A*). This unconformity truncated the older rocks and removed an undetermined amount of structural and stratigraphic section (Jokat and others, 1992; Moran and others, 2006; O'Regan and others, 2008). Following the rifting, the Lomonosov Ridge separated from the Eurasia continental margin and subsided below sea level at about 50 Ma (Jokat and others, 1995). Subsequent deposition consisted dominantly of pelagic sediments with submarine slump deposits derived from the Lomonosov margin.

The evolution of the depositional setting of the Lomonosov Ridge after development of the rifting unconformity is documented by the results of scientific drilling of its Cenozoic sedimentary cover by the ACEX project near the North Pole (for example, Moran and others, 2006). At its deepest point, the drilling penetrated the entire 428-m-thick Cenozoic section and the underlying rifting unconformity, beneath which Campanian shallow-marine mudstone was recovered (fig. 5). The earliest sediments deposited above the rifting unconformity are late Paleocene and are approximately the same age as the initiation of the rifting in the Eurasia Basin (~57 Ma) (O'Regan and others, 2008). The lower half of the Cenozoic section is dark and organic rich and consists of upper

A



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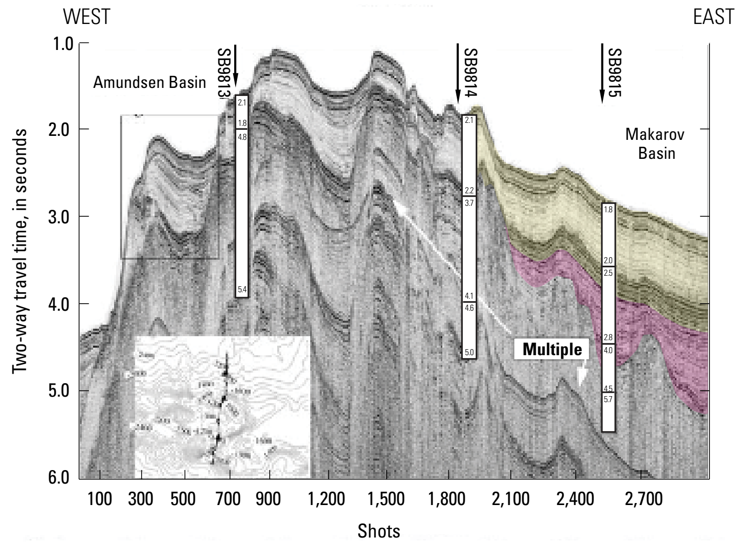

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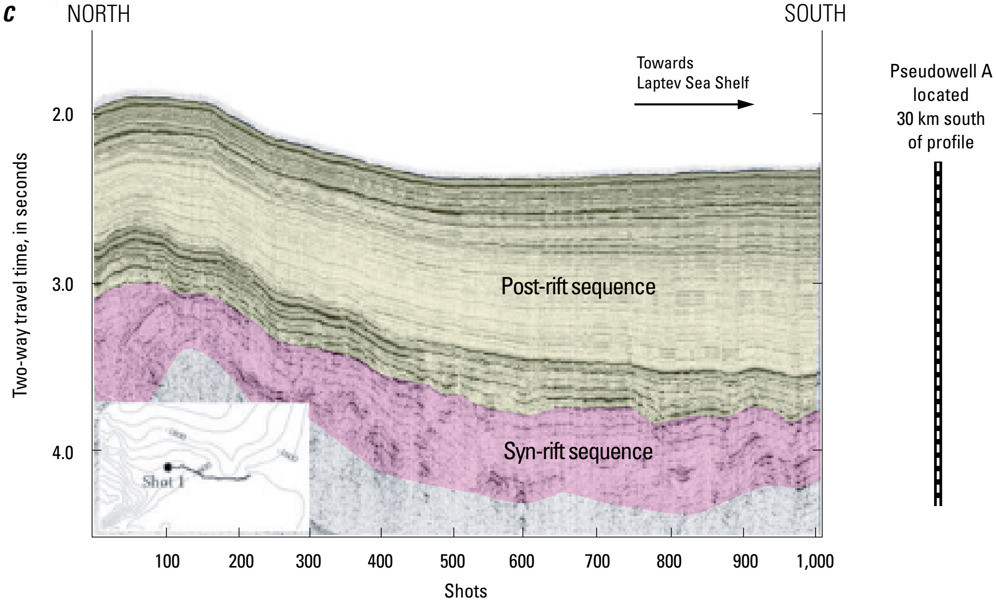


Figure 6. Seismic profiles across the axial part of the Lomonosov Ridge (see fig. 10 for locations). *A*, Part of seismic reflection line 91090 (Jokat and others, 1992, 1995) near the North Pole showing rifting unconformity overlain by about 500 m of Cenozoic sedimentary strata. The Cenozoic strata rest unconformably on tilted fault blocks containing well-bedded strata interpreted to be of Mesozoic age. Underlying weakly reflective units (velocity 4.0–4.6 km/s) may consist of carbonate and (or) metasedimentary units that were involved in Caledonian deformation. Modified from Grantz and others (2001). *B*, Seismic reflection line 98590 (modified from Jokat, 2005), showing horst and graben structure typical of Siberian segment of Lomonosov Ridge. Vertical bars show locations of sonobouys and their velocity functions. *C*, Seismic reflection line 98597 (modified from Jokat, 2005) showing downlap onto the Siberian segment of the Lomonosov Ridge of Cenozoic sedimentary strata sourced from the Laptev Sea shelf. Yellow-shaded seismic units and magenta-shaded units in B and C show Cenozoic post-rift, and synrift sequences, respectively, without a well developed rift unconformity (Jokat, 2005). Seismic velocity of basement rocks in C (3.3–4.3 km/s) suggest compacted sedimentary units; Cenozoic section estimated to be ~1 km thick (Jokat, 2005).

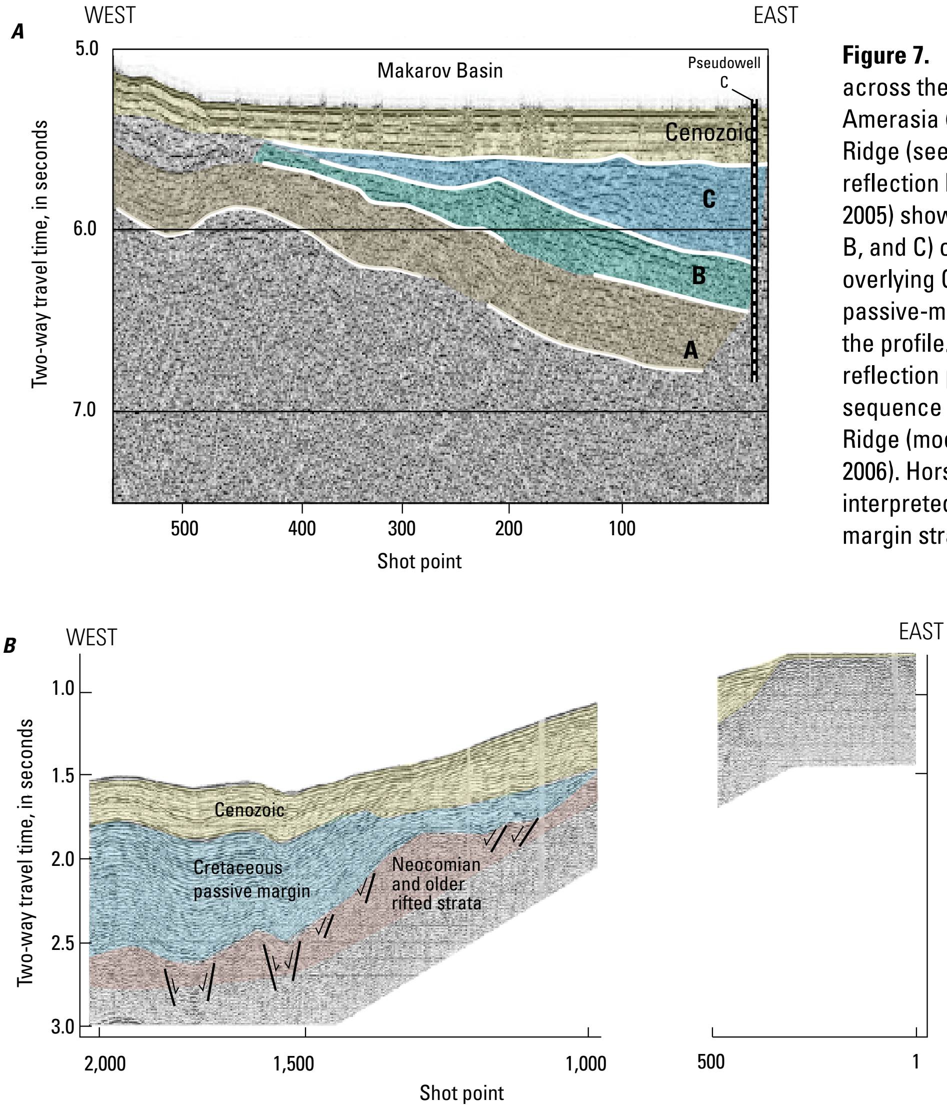


Figure 7. Interpreted seismic reflection profiles across the passive-margin sequence of the Amerasia (Makarov) Basin margin of the Lomonosov Ridge (see fig. 10 for locations). *A*, Part of seismic reflection line 91090 (Jokat and others, 1992; Jokat, 2005) showing basinward dipping sequences (A, B, and C) of the passive-margin sequence and overlying Cenozoic deposits. Basement to the passive-margin sequence is not recognized in the profile. Modified from Jokat (2005). *B*, Seismic reflection profile showing the passive-margin sequence in Greenland segment of Lomonosov Ridge (modified from Kristoffersen and Mikkelsen, 2006). Horst and grabens of Neocomian age are interpreted beneath covering Cretaceous passive-margin strata.

Paleocene and lower Eocene partly laminated silty clay and middle Eocene biosiliceous clay (Backman and others, 2008). Fossil data indicate the sediments were deposited in stratified fresh to brackish water that was underlain by more saline, anoxic water at depth (Brinkhuis and others, 2006; Stickley and others, 2008). Surface waters were particularly fresh at about 49–48 Ma (early middle Eocene), resulting in extraordinary abundances of the free-floating freshwater fern *Azolla*, whose deposits form an organic-rich marker interval that has been recognized regionally in the Arctic (Brikhuis and others, 2006).

The middle Eocene sediments are terminated upward by a disconformity across which 26 m.y. of time (44 to 18 Ma) is missing (Sangiorgi and others, 2008) (fig. 5). The disconformity is interpreted to be due to erosion, which O'Regan and others (2008) concluded indicates the Lomonosov Ridge was at or near sea-level as late as the early Miocene. A few meters of light and dark banded organic-rich clays of early Miocene age rest directly on the unconformity and may provide evidence of the current activity that caused the underlying unconformity. The upper half of the Cenozoic section rests on the banded unit and consists of Miocene to Holocene organic-poor silty mud with abundant dropstones and sand lenses that are indicative of ice-covered marine conditions.

The Cenozoic succession in the ACEX drill holes is interpreted as recording the change of the Arctic Ocean from an enclosed stratified lake-like fresh and brackish water basin in the Paleogene to an estuarine sea in the early Miocene, much like the modern Black Sea, to a fully marine basin caused by the initial of opening of the Fram Strait in the North Atlantic by sea-floor spreading at 17 Ma (Jakobsson and others, 2007) or by the full opening of Fram Strait at 10 Ma (Engen and others, 2008). The succession represents a change in sedimentation from warm, ice free, biologically productive deposition during a time of globally high temperature and sea levels in the late Paleocene to middle Eocene to cooler conditions influenced by glacial conditions in the Miocene, and finally to polar conditions with increased sea ice and icebergs and associated continental ice sheet activity at 3.2 Ma (Moran and others, 2006; Sluijs and others, 2006).

The other major sedimentary sequence in the province is the passive margin succession deposited along the Siberian margin and its extension outboard into the Podvodnikov Basin. Like the passive-margin sequences of the Amerasia Basin along the Lomonosov Ridge, Canada, and Alaska margins, this passive margin sequence probably was initiated during opening of the Canada Basin in the Jurassic and Early Cretaceous. Seismic reflection data collected from ice islands and shipborne seismic refraction data indicate that the passive margin succession has a maximum thickness of about 11 km near the base of the slope, thinning northward across the Podvodnikov Basin to about 2.5 km (Lebedeva-Ivanova and others, 2006b; Langinen and others, 2006). Most of this succession is assumed to consist of turbidites composed of clastic material shed from highlands in Chukotka. On the Siberian Shelf, in contrast, the sediment cover is thin and it rests unconformably on older deformed rocks. Where exposed in several small islands, the basement rocks consist of nonprospective, folded lower Paleozoic fine-grained clastic rocks that are intruded by middle Paleozoic mafic intrusions (Kos'ko and others, 1990; Kos'ko and Trufanov, 2002; Kos'ko and Kim, 2006).

Unlike the Lomonosov Ridge margin of the Amerasia Basin, sedimentation on the Siberian passive margin sequence was not significantly affected by the splintering of the Lomonosov Ridge during opening of the Eurasia Basin. Thus, sedimentation on this passive margin is probably similar to that of the Alaska and Canada margins and has continued uninterrupted since formation by rifting of the Amerasia Basin in the Jurassic and Early Cretaceous.

Structural Characteristics

The Lomonosov Ridge is an aseismic submarine mountain range that rises 2 km above the Amerasia Basin and more than 3 km above the Eurasia Basin. The ridge is narrow, steep-sided, and blocky to flat-topped and ranges from 65 km wide in its central part near the North Pole to more than 200 km at its extremities near the Canadian and Siberian margins (fig. 2). Seismic refraction and gravity experiments show that the Lomonosov Ridge is a sliver of continental crust having a Moho at a depth of 25–28 km (Forsyth and Mair, 1984; Weber and Sweeney, 1990; Lebedeva-Ivanova and others, 2006a). It comprises a single linear, blocky structure from Greenland to about 86°30' N on the Siberian side of the North Pole. South of that point to the Siberian margin, it breaks up into a series of subparallel ridges and basins with the bathymetrically highest and most prominent ridge located along the Eurasia Basin margin (Cochran and others, 2006a; Jokat, 2005) (fig. 6*B*). Beneath a <2 km-thick veneer of covering sediments, seismic reflection studies indicate that as much as 5–6 km of sedimentary deposits are probably present (Lebedeva-Ivanova and others, 2006a).

Along its Eurasian flank, the ridge displays the structural characteristics of nonvolcanic, orthogonally rifted continental margins (fig. 6*B*). Rotated fault blocks step down into the Amundsen Basin along much of this margin and the seaward extent of continental crust is marked by a sharp gravity gradient and clear marine magnetic anomalies (Jokat and others, 1992; Jokat and Micksch, 2004; Cochran and others, 2006). Seismic reflection profiles show the Cenozoic cover succession fills in grabens and onlaps bounding faults, indicating the normal faults have been mostly inactive since the opening of the Eurasia Basin (fig. 6*B*). Seismic data in the central Lomonosov Ridge reveal a half-graben buried beneath the Cenozoic cover sequence and clearly truncated erosionally by the rifting unconformity. This observation provides evidence of an episode of prerift extensional block faulting in the Late Cretaceous or early Paleocene (Jokat and others, 1992; Grantz and others, 2001) (fig. 6*A*). On the part of the Lomonosov Ridge near the Siberian margin, the rifting unconformity is diminished or absent, evidently because the ridge was never high enough to be above sea level. In this area, the middle Mesozoic and early Cenozoic episodes of extension appear to merge into a single protracted synrift extensional event (Jokat, 2005) (fig. 6*C*). The topography between the Eurasia and Amerasia margins in this part of the ridge is characterized by deep troughs bounded by basement highs, all of which are buried beneath covering Cenozoic sediments that are about 1 km thick (Jokat, 2005).

In contrast to the rotated fault blocks along the Eurasia Basin margin, the Amerasia Basin margin of the Lomonosov Ridge is delimited by a linear trough bounded by abrupt 1- to 2.7-km-high scarps and filled with >2 km of sediment (Cochran and others, 2006). These structures can be traced from near the North American margin to a point beyond the North Pole, where they disappear beneath Cenozoic sediments in the Makarov Basin. Gravity and magnetic anomalies suggest that the linear trough continues southward toward the Siberian margin as a buried feature and probably emerges at about 86° N where a prominent scarp bounds the Lomonosov Ridge. This scarp angles southeastward away from the main part of the Lomonosov Ridge south of about 84°30' N, disappearing beneath Cenozoic sediments shed from the continental margin (Cochran and others, 2006). From that point to the Siberian margin, the scarp has no bathymetric expression and its location is marked only by gravity and magnetic anomalies. Cochran and others (2006) pointed out that the scarps, linear troughs, and potential field anomalies form a small circle to the Mackenzie Delta, providing support for the interpretation that the continental margin of the Lomonosov Ridge is a sheared margin formed by a major transform fault active in the late Mesozoic.

Seismic and bathymetric data are sparse in the Makarov and Podvodnikov Basins and along the Siberian continental margin, and the structural characteristics of these areas are only broadly known. Seismic refraction studies show that the total crustal thickness of the Siberian continental margin ranges from 35 to 41 km with a thin veneer (<2 km) of covering sediments (Lebedeva-Ivanova and others, 2006b; Sekretov, 2001). Crustal thicknesses diminish abruptly northward to 15 to 22 km under the Podvodnikof Basin. The crust under the Podvodnikof Basin is interpreted to consist of thickened oceanic crust (Lebedeva-Ivanova and others, 2006b; Sorokin and others, 1999). Farther north, near 83°N and coinciding with the outboard limit of the continental margin sedimentary prism, the crustal thickness in the northern Amerasia Basin increases to more than 25 km. Lebedeva-Ivanova and others (2005) suggested that the crust in this area marks the position of the Early Cretaceous spreading center for the Amerasia Basin, an interpretation suggested earlier by Kovacs and others (1999) because of linear magnetic anomalies in this area (fig. 4).

Seismic data show that the boundary of the oceanic crust of the Amerasia Basin against the continental crust of the Lomonosov Ridge is sharp, with the Lomonosov Ridge standing several kilometers above the oceanic crust in the Podvodnikov and Makarov Basins (Butsenko and Poselov, 2006, fig. 2). This relation supports a transform-margin interpretation of this boundary.

The structural characteristics of the Siberian passive margin are poorly known. The seismic profiles presented by Sekretov (2001) suggest it is comparable to the Arctic Alaska passive margin, which includes rotated normal faults, extensional growth faults, and slope basins (Houseknecht and others, 2012a, this volume).

Petroleum Systems

A petroleum system is defined by the extent of migration of all petroleum from a pod or pods of thermally mature petroleum source rock. In the Lomonosov-Makarov Province, no oil seeps or oil-stained rocks are known, no petroleum exploration wells have been drilled, and the presence of an active petroleum system is uncertain. Scientific drilling on the Lomonosov Ridge and regional stratigraphic arguments nonetheless suggest that petroleum systems might be present in the province. Four depositional settings are considered for the presence of organic-rich strata that might represent possible source rocks for petroleum accumulations: (1) Triassic and Jurassic platform strata on the Lomonosov Ridge, (2) Jurassic to Barremian synrift strata in the Amerasia Basin, (3) Aptian-Albian and Upper Cretaceous postrift strata in the Amerasia Basin, and (4) Paleocene and Eocene strata deposited across the entire province. The possible distributions of these source rock units are shown in figure 8.

Triassic and Jurassic Platform Strata on the Lomonosov Ridge

Triassic and Jurassic source rocks are present on the Barents Shelf, the conjugate margin to the Lomonosov Ridge in the Eurasia Basin. Oil-staining and bitumen are present in Triassic and in Jurassic strata and fractured diabase dikes that intrude these strata (Bezrukov, 1997; Klubov and Vinokurov, 1999; Shkatov and others, 2003). These observations indicate that a petroleum system was active in the Franz Josef Land area. Klubov and others (2000) reported total organic carbon (TOC) of 0.93–2.68 percent from Middle Triassic argillite in cores recovered near Franz Josef Land, and Bezrukof (1997) reported TOC of 7.12 percent from Upper Jurassic shale in eastern Franz Josef Land. Regionally across the Barents Shelf, the Triassic and Jurassic strata are the source rocks for many of the most important hydrocarbon resources on the Barents Shelf (for example, the Shtokman gas field and Nordkapp Basin) (Klett and Pitman, this volume). Nøttvedt and others (1992, their figs. 4 and 5) portrayed the source rock lithofacies of the Barents Shelf as the distal western margin of the Uralian foreland basin deposited in north and northeast-trending fairways that extend across the modern Barents Shelf. If the Lomonosov Ridge is restored to its pre-Cenozoic position prior to opening of the Eurasia Basin, these facies trends would project into the Lomonosov Ridge near the North Pole.

Seismic reflection data from this area show tilted to flat pre-Tertiary strata that are interpreted to be Mesozoic in age (Jokat and others, 1992; Jokat, 2005). A piston core collected from the Lomonosov Ridge near the North Pole yielded quartz siltstone with coal fragments and Jurassic or Cretaceous palynomorphs along with a variety of apparently reworked Devonian and Carboniferous microfossils (Grantz and others, 2001). Compositional data from the core are similar to sandstones derived from the Uralian-Taimyr orogenic belts in Franz Josef Land (Grantz and others, 2001), suggesting they share the same provenance. Vitrinite reflectance measurements from the organic material in the siltstone in the core range from 0.93 to 1.04 Ro, suggesting that at least some of these strata have attained sufficient thermal maturity to have entered the oil window. These results suggest that Triassic to Cretaceous strata may be expected to be present on the Lomonosov Ridge, and are sufficiently thermally mature to generate hydrocarbons.

Synrift (Jurassic to Barremian) Strata of the Amerasia Basin

Grantz and others (2011b) suggested that the oldest sedimentary deposits in the Amerasia Basin compose local sequences, 0 to 2 km thick, of Jurassic and Early Cretaceous synrift strata that were deposited on the older, ocean-continental transitional lithosphere in the marginal parts of the Amerasia Basin. The synrift strata, however, are apparently very thin or absent on the younger mid-ocean ridge basalt (MORB) lithosphere in the center of the basin and postrift Aptian and Albian strata may rest directly on these rocks.

The detailed stratigraphy of the synrift strata in the northern Amerasia Basin, if present, is unknown. Deposits in similar stratigraphic positions on the margins of the southern Amerasia Basin are mostly fine-grained, basinal sequences that were deposited in extensional basins and on the rift flanks of the basin (Grantz and others, 2011a,b). On the Alaskan margin, deposits of this interval include the Jurassic and Early Cretaceous Kingak Shale and Hauterivian and Barremian pebble shale unit, both of which contain some condensed

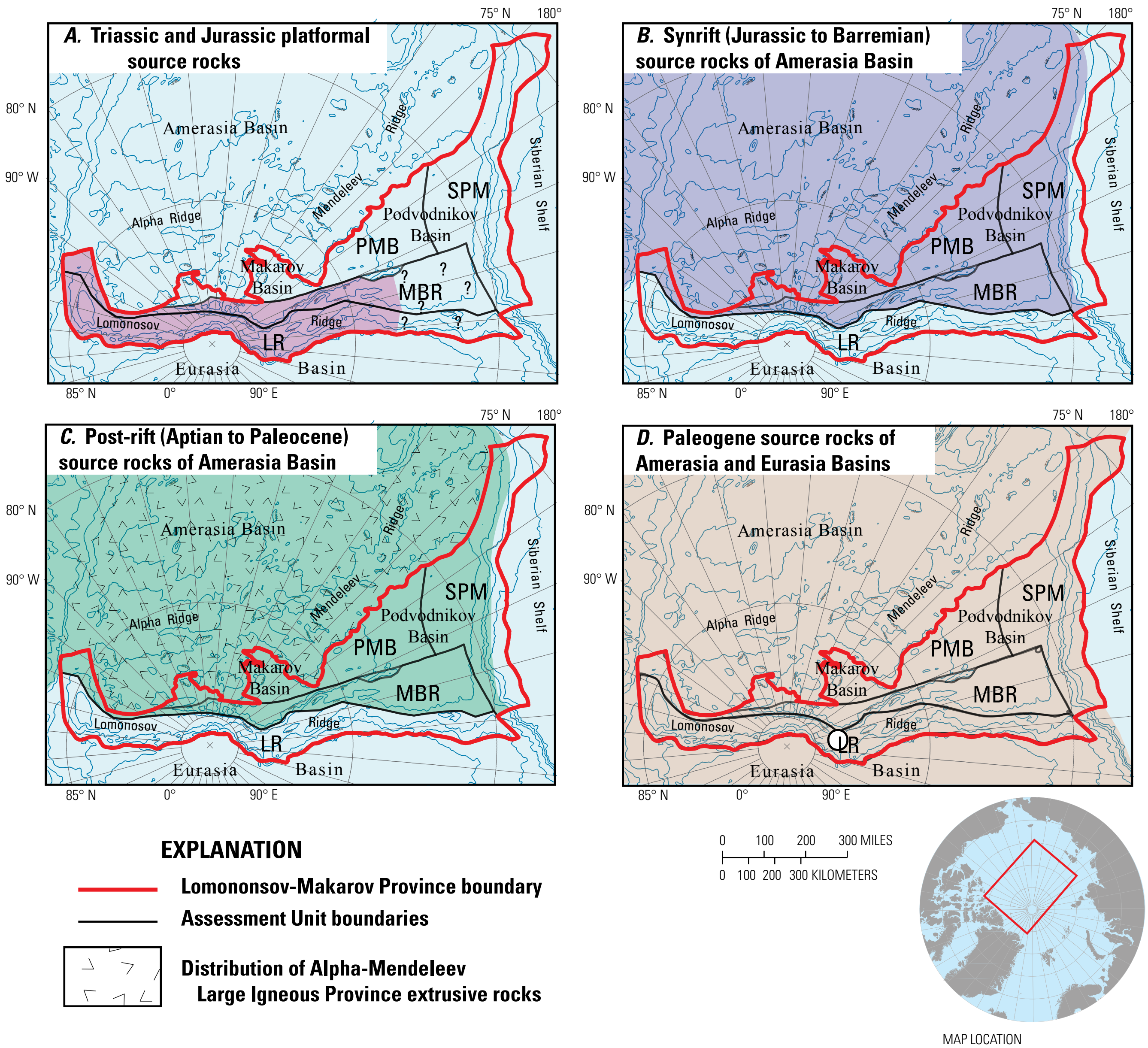


Figure 8. Maximum predicted aerial distribution of four source rock units inferred to be present in the Lomonosov-Makarov province. Assessment unit abbreviations: LR, Lomonosov Ridge; MBR, Makarov Basin Margin; PMB, Podvodnikov-Makarov Basin; SPM, Siberian Passive Margin.

deposits that range from ~1 to >5 percent TOC, display a mixture of type II and III kerogen, and are a major source rock for some of the most important petroleum accumulations in Arctic Alaska (Houseknecht and Bird, 2005; Houseknecht and others, 2007, 2012c, this volume). These strata are widespread in the southern Amerasia Basin and may provide an indication of the nature of the coeval sedimentation in the northern part of the basin during its opening by rifting and prior to the formation of the Alpha-Mendeleev Ridge LIP (Masterson, 2001; Peters and others, 2006).

Because the Lomonosov Ridge margin of the Amerasia Basin was a transform margin rather than a rift margin, deposition along the Lomonosov Ridge probably was influenced by clastic sedimentation from the adjacent truncated continental margin. Foreland basin deposits derived from the Uralian-Taimyr orogenic belt may interfinger with or replace the condensed facies near the central Lomonosov Ridge margin. In addition, LIP-related magmatism in Franz Josef Land, Ellesmere Island, and the New Siberian Islands in the Early Cretaceous (Drachev and Saunders, 2006) could have significantly influenced the deposition of the synrift source rocks along this margin. Sediment derived from these rocks, whether transported directly into the basin as sediment-gravity flows, slumps, or by volcanic airfall potentially could have swamped or significantly reduced the quality of source rocks deposited in the basin. In addition, intrusion of LIP-related dikes and sills directly into the synrift deposits may have produced thermal heating that locally or regionally impacted the viability of the petroleum systems.

Another consideration is that if the Amerasia Basin spreading center intersected the Lomonosov Ridge transform margin at a high angle as suggested by Grantz and others (2011b), the age and thickness of source rocks should vary along the length of the Lomonosov Ridge margin according to the age and type of ocean crust that underlies the deposits. A high angle of intersection is supported by magnetic anomalies that are oriented perpendicular to Lomonosov Ridge as far south as about 83° N. (Kovacs and others, 1999). Pre-Hauterivian syn-rift strata should be restricted to the part of the margin south of about 83° N., where no magnetic anomalies are reported and ocean crust is interpreted to be older and of ocean-continental transitional type (Grantz and others, 2011b). The thickest and oldest sections of synrift strata are expected to be in this area. Similar strata would also be expected to be present along the Canadian part of the margin on the opposite side of the Amerasia Basin, where Grantz and others (2011b) inferred ocean-continental transitional crust intersects the Lomonosov Ridge transform margin. Synrift strata in the latter area, however, probably would be buried beneath, or interstratified with, volcanic rocks of the Alpha-Mendeleev Ridge, depending on the age of LIP magmatism (Grantz and others, 2010; 2011a). Synrift deposits of Early Jurassic to Valanginian age (those deposits corresponding to the Kingak Shale) would be expected in these areas, whereas Hauterivian-Barremian synrift sediments (those corresponding to the pebble shale unit in Arctic Alaska), could be expected along the entire margin of the Lomonosov Ridge. This is because the Hauterivian-Barremian synrift strata could have been deposited on the younger, MORB-type oceanic crust in the central part of the Amerasia Basin as it formed, whereas the older strata would be restricted to areas underlain by older ocean-continental transitional crust along the margins of the Amerasia Basin.

Postrift (Aptian, Albian, and Upper Cretaceous) Strata in the Amerasia Basin

According to the interpretation of Grantz and others (2011b), undeformed, laterally extensive, reflective strata overlying the syn-rift strata are probably Aptian and younger. In the southern Amerasia Basin, Aptian to Turonian strata along the Alaska and Canada margins include widespread shales and condensed deposits. The Aptian-Albian deposits in northern Alaska include the gamma-ray zone of the Hue Shale, which consists of distal condensed shale that forms an important source rock for petroleum accumulations of the North Slope (Peters and others, 2006). Turonian shales are also productive in northern Alaska. Source rock strata of this age occur in the Seabee Formation and part of the Hue Shale in Arctic Alaska and in the Boundary Creek, Smoking Hills, and Kanguk Formations in Arctic Canada. The Turonian strata were deposited during a time of high relative sea level, have source rock characteristics (2 to >10 percent TOC, mixed Type II and III kerogen), and are oil prone across wide areas (Houseknecht and others, 2012c, this volume). Because the Aptian to Turonian condensed deposits form productive petroleum systems along the Alaskan and Canadian continental margins and because their depositional successions become more distal northward toward the Amerasia Basin, they are hypothesized to exist throughout large parts of the basin (Houseknecht and others, 2007, 2012c, this volume). The deposits could extend into the northern part of the Amerasia Basin if deposition was controlled by a regional high stand in sea level. Seismic reflection imaging of the passive-margin succession suggests that these units would be buried at depths of 2–4 km in the Makarov Basin and as much as 5 km along the Siberian margin in the Podvodnikov Basin. The depositional age of these strata, however, are approximately coeval with the time of formation of the Alpha-Mendeleev Ridge LIP, suggesting that they may be interstratified with the volcanic strata. If present, it is possible that the condensed shales have been degraded by the LIP volcanism, particularly where the Alpha-Mendeleev Ridge onlaps the Siberian margin at one end and the Lomonosov Ridge near the Canadian margin at the other end, and potentially throughout all of the northern Amerasia Basin. It is also possible that such condensed deposits were diluted or modified by clastic depositional systems shed across the Lomonosov Ridge and Siberian margins from the Uralian, Taimyr, Chukotka, and Verhoyansk orogens.

Paleocene and Eocene Strata

The ACEX scientific drilling project found that the section above the rift unconformity in Lomonosov Ridge consists of about 200 m of seismically reflective upper Paleocene to middle Eocene organic rich mudstone and claystone and about 200 m (to the seafloor) of less reflective early Miocene to Holocene organic-poor mudstone (Moran and others 2006; Jakobsson and others 2007). A regional disconformity, representing 26 m.y. of missing section, separates the two units. The Paleogene sequence, especially the early and middle Eocene interval at the top, contains good to very good quality source rocks (TOC mostly 1–5 percent; mixed oil and gas-prone kerogen) (Stein, 2007; Mann and others, 2009). The highest TOC values (up to 14 percent) were found, however, in a 2.5-m thick, cross-banded dark and light banded clay at the base of the late early Miocene section that rests on the disconformity. Redeposited Cretaceous to Oligocene fossils in the Miocene deposits suggest that the high TOC in this interval could be the result of winnowed, organic material reworked from the section missing at the disconformity. The winnowing could have been caused by currents and relative changes in sea level resulting from opening of Fram Strait gateway into the Arctic Basin in the early Miocene. If this origin of the banded clay interval is correct, it allows the possibility that an interval of good to very good quality source rocks once may have included upper Eocene, Oligocene, and possibly early Miocene deposits that have been eroded away on the Lomanosov Ridge, in addition to the known early and middle Eocene deposits. The organic-rich character of the Paleogene to Eocene interval beneath the disconformity is thought to have resulted from deposition under mostly anoxic conditions in a stratified basin beneath fresh to brackish surface waters, whereas an early Miocene interval above the unconformity has estuarine-like characteristics (Jakobsson and others 2007; Sangiorgi and others 2008; Stickley and others 2008).

The Cenozoic strata thicken toward the Siberian Shelf, where they are as much as 1.6 km thick and as much as 3 km thick in isolated grabens. The thicker sections in this part of the Lomonosov Ridge are probably due to higher sedimentation rates as a result of sediment shed into the Laptev Sea from the Lena River (Jokat, 2005). The high TOC Paleogene interval above the unconformity, particularly the top of the section, is thought to be highly reflective on seismic profiles and consequently may be traceable over much of the Lomonosov Ridge and in the adjacent Makarov and Eurasia Basins (Butsenko and Poselov, 2006; Langinen and others, 2008) (figs. 3, 6*A*, 6*B*). If true, the highly reflective interval would provide a regional seismic marker (Butsenko and Poselov, 2006; Jakobsson and others, 2007; Backman and others, 2008) that indicates the distribution of organic-rich strata throughout the province.

The results of source-rock analysis and burial history models, however, show that the organic-rich Paleogene strata are thermally immature at the ACEX site and therefore are unlikely to have generated hydrocarbons (Stein, 2007; Mann and others, 2009). Assuming burial beneath 1.6 km of Neogene sediment, which is the maximum thickness known to be present on the Lomonosov Ridge (Jokat, 2005), our simple source-rock modeling indicates that a minimum heat-flow of 110 milliwatts per square meter (mW/m^{-2}) would be required to cause maturation of the organic-rich sediments (fig. 9; see fig. 10, pseudowell A, for location), a conclusion arrived at independently by Mann and others (2009). Such high heat flow has been recognized from the modern Gakkel Ridge in the Eurasia Basin (Drachev and others, 2003), but is substantially higher than the modern heat flow measured on the Lomonosov Ridge (60–65 mWm^{-2}) (Weber and Sweeney, 1990) and likewise is higher than any reasonable model for paleoheat flow in the Neogene for the Lomonosov Ridge and the northern Amerasia Basin. This suggests the Paleogene organic-rich strata may not have attained thermal maturity, not only at the ACEX core site, but across the entire Lomonosov-Makarov province as well.

Assessment Units

Because the Amerasia Basin is subdivided by the volcanic Alpha-Mendeleev Ridge, it is convenient for the purpose of the CARA assessment to separate the basin and its margins into two separate provinces, one lying north of the ridge and the other lying to the south. The northern province includes the Makarov and Podvodnikov Basins and their continental margins, the Lomonosov Ridge and East Siberian continental margin; the southern province consists of the Canada Basin and the Alaskan and Canadian continental margins. The northern province, the subject of this report, is referred to as the Lomonosov-Makarov Province; the southern province is the Amerasia Basin Province, which was discussed by Houseknecht and others (2012a, this volume).

The Lomonosov-Makarov Province is entirely submarine, extremely remote, and mostly covered by the polar icecap year round. It is characterized by sparseness of data and great uncertainty about its geology, and accordingly, little is known or published about its petroleum potential.

Knowledge about the Lomonosov-Makarov Province stems mainly from gravity and bathymetric data (Jakobsson and others, 2004; Cochran and others, 2006) augmented by a number of seismic reflection and refractions lines shot from icebreakers and ice islands (Kristoffersen and Mikkelsen, 2006; Jokat, 2005; Jokat and others, 1992; Lebedeva-Ivanova and others, 2005, 2006a, b; Langinen and others, 2006, 2008) (fig. 10*A*). The ACEX scientific drill holes on the central Lomonosov Ridge near the North Pole (for example, Moran and others, 2006) provide the only well data.

For the purpose of this assessment, we have divided the province into four broadly defined assessment units (AUs) that reflect its primary tectonic features and covering depositional systems. The first-order characteristics of the AUs provide the best clues to the size, number, and timing of potential petroleum traps and petroleum generation and migration in the absence of a thorough knowledge of the stratigraphy, structural geology, and petroleum systems of the area. The defined AUs are (1) the Lomonosov Ridge; (2) Makarov Basin Margin; (3) Podvodnikov-Makarov Basin; and (4) Siberian Passive Margin (figs. 1 and 9). The Lomonosov Ridge AU was defined to include the area underlain by flat-lying Mesozoic shelf strata deposited prior to separation of the ridge from the Baltic Shelf. This AU encompasses most of the upper part of the Lomonosov Ridge and the flank of the ridge that faces the Eurasia Basin, where it is sediment covered. The Makarov Basin Margin AU includes the region underlain by the Cretaceous passive-margin succession that was deposited along the northern margin of the Amerasia Basin prior to separation of the Lomonosov Ridge from the Baltic Shelf in the late Paleocene. This AU is located on the western flank of the Lomonosov Ridge facing the Amerasia Basin outboard of the hingeline of the Cretaceous continental margin depositional systems. The Siberian Passive Margin AU encompasses the area underlain by the Mesozoic and Cenozoic passive margin succession that was shed northward into the Amerasia Basin from the East Siberian Shelf. The Makarov-Podvodnikov Basin AU consists of the basin plain strata deposited on oceanic crust of the Amerasia Basin, including Cretaceous deposits shed from both the Baltic and Siberian Shelves. In the absence of detailed information about the passive margins of this part of the Amerasia Basin, the boundaries of the latter AU

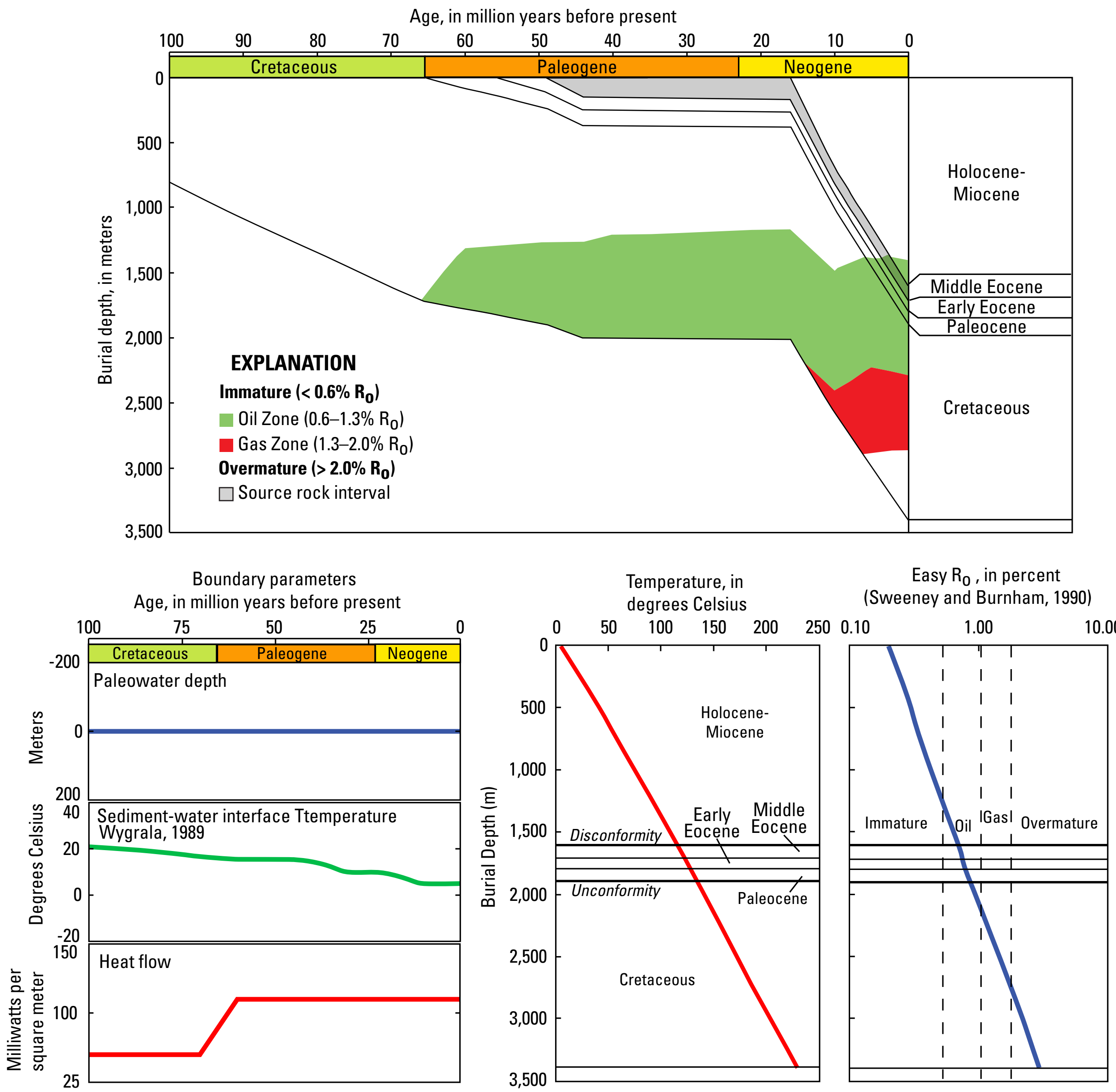


Figure 9. Burial history model for pseudowell A on Lomonosov Ridge near the Siberian margin, where the Cenozoic cover is as much as 1.6 kilometers thick (Jokat, 2005) (see figs. 6*C* and 10*B* for location). Assuming Middle Eocene source rocks similar to those in the ACEX drill site are present and near the base of the Cenozoic section, the model shows that heat-flow values in excess of 110 milliwatts per square meters (mW/m^2) would be required to cause generation. Ro, vitrinite reflectance, in percent (%).

were arbitrarily defined as the Cretaceous transform margin of the Lomonosov Ridge and the 3-km isopach of the Siberian passive margin basinward of the Siberian continental margin, as shown in Grantz and others (2010; 2011a). Sedimentary deposits of the Makarov-Podvodnikov Basin AU also onlap the magmatic rocks along the Alpha-Mendeleev Ridge. The AUs generally conform to units shown for this area by Grantz and others (2010; 2011a) but differ where revisions were made to Grantz and others (2010; 2011a) after the date of our petroleum assessment.

A lithostratigraphic column and events chart summarizing the petroleum geology of the Lomonosov-Makarov Province and its constituent AUs is shown in figure 11. The potential petroleum resources of these AUs are evaluated separately in the following section.

Because the Lomonosov Ridge, Makarov Basin Margin, and Podvodnikov-Makarov Basin AUs cross the Arctic near the North Pole, geographic orientation within the provinces is challenging. In order to avoid confusion for the reader, we describe the various parts of the province by referring to

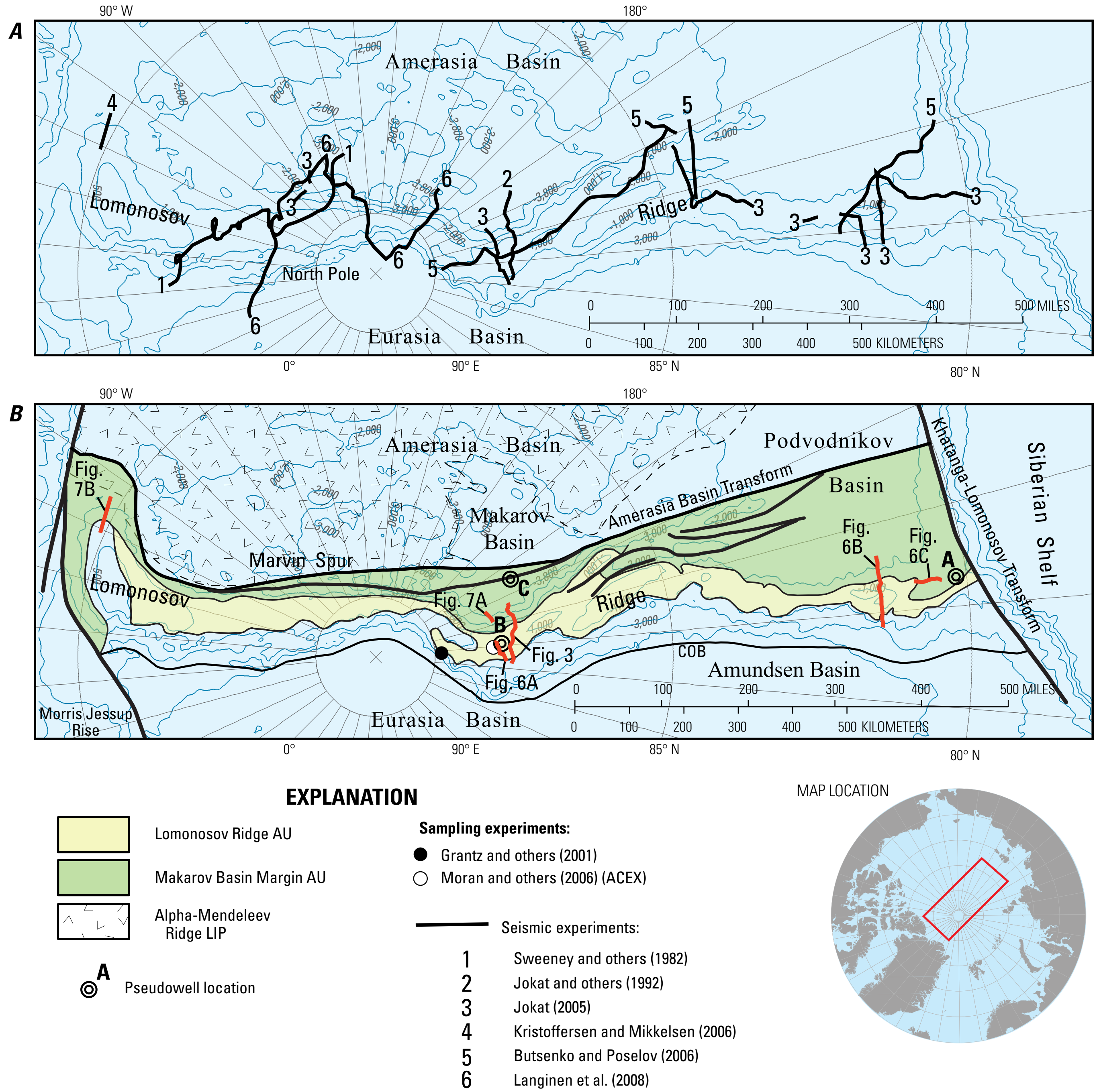


Figure 10. Map of the Lomonosov Ridge and Makarov Basin Margin Assessment Units showing locations of (*A*) seismic profiles and (*B*) Lomonosov Ridge and Makarov Basin Margin AUs, significant faults, scientific drilling and coring sites and pseudowells used for burial history modeling. Seismic profile tracks are irregular because they were conducted from ships following openings in pack ice or from drifting ice islands.

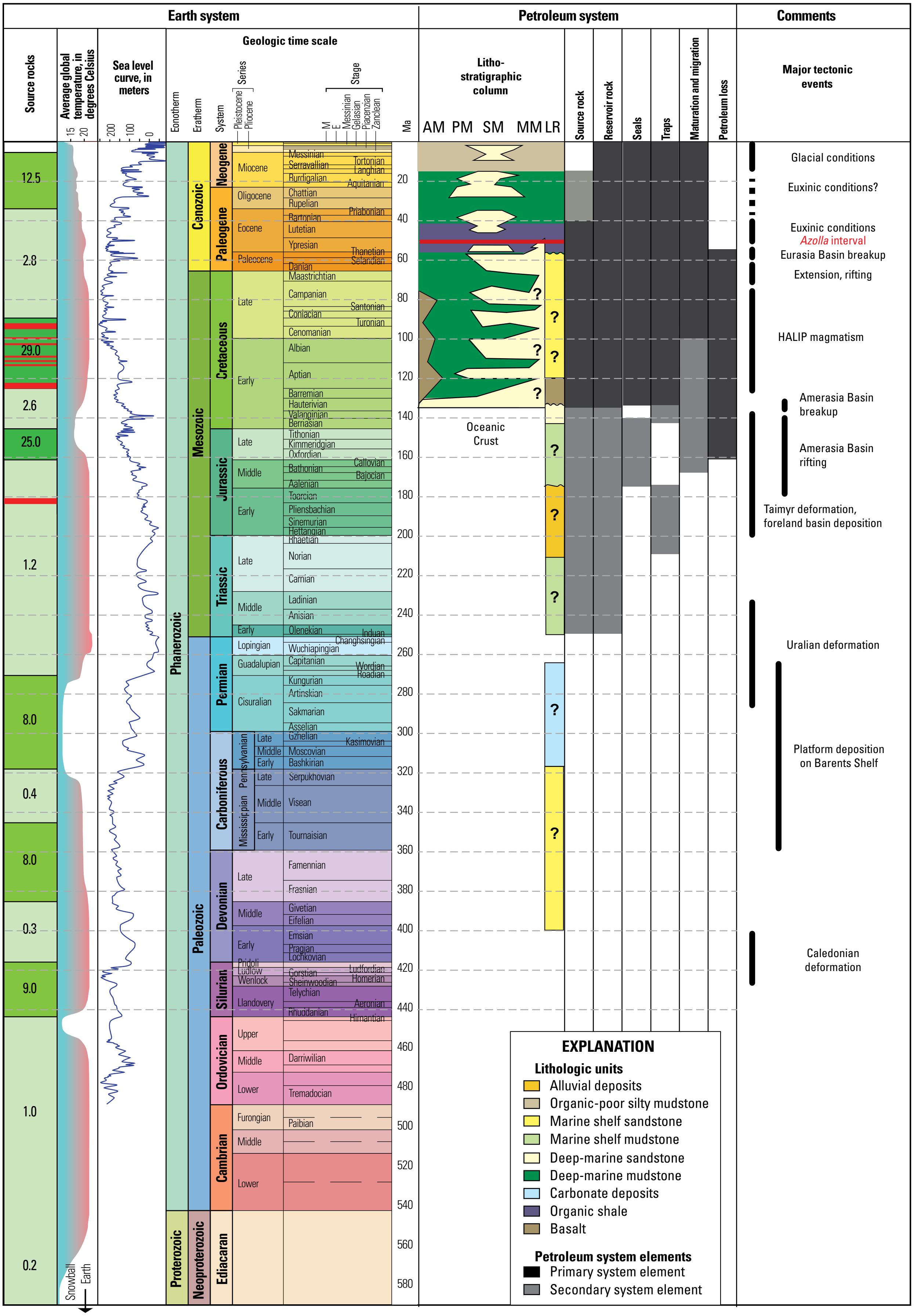
Siberian, central (north of about 87° N.), and Greenland segments of the AUs.

Lomonosov Ridge Assessment Unit

The Lomonosov Ridge AU contains no petroleum exploration wells and very sparse seismic data. This level of exploration places the Lomonosov Ridge into uncertainty category 4 on the scale used by the USGS for the Circum-Arctic Resource Appraisal (Charpentier and Gautier (2011) (appendix 1).

AU Description

The Lomonosov Ridge AU (fig. 10*B*) encompasses all structural and stratigraphic traps that formed in shelf regions


Earth system
Petroleum system
Comments
Source rocks
Average global temperature, in degrees Celsius
Sea level curve, in meters
Geologic time scale
Eonotherm
Eratherm
System
Series
Stage
Ma
Litho-stratigraphic column
AM PM SM MM LR
Source rock
Reservoir rock
Seals
Traps
Maturation and migration
Petroleum loss
Major tectonic events
Glacial conditions
Euxinic conditions?
Euxinic conditions
Azolla interval
Eurasia Basin breakup
Extension, rifting
HALIP magmatism
Amerasia Basin breakup
Amerasia Basin rifting
Taimyr deformation, foreland basin deposition
Uralian deformation
Platform deposition on Barents Shelf
Caledonian deformation
Oceanic Crust
Phanerozoic
Proterozoic
Cenozoic
Mesozoic
Paleozoic
Neoproterozoic
Neogene
Paleogene
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Pennsylvanian
Mississippian
Devonian
Silurian
Ordovician
Cambrian
Ediacaran
12.5
2.8
29.0
2.6
25.0
1.2
8.0
0.4
8.0
0.3
9.0
1.0
0.2
Snowball Earth
EXPLANATION
Lithologic units
Alluvial deposits
Organic-poor silty mudstone
Marine shelf sandstone
Marine shelf mudstone
Deep-marine sandstone
Deep-marine mudstone
Carbonate deposits
Organic shale
Basalt
Petroleum system elements
Primary system element
Secondary system element

on the Lomonosov Ridge while it was part of the Barents Shelf prior to opening of the Eurasia Basin by seafloor spreading or that formed as a consequence of its rifting in the late Paleocene. The limits of the AU are defined by the continent-ocean margin on the Eurasia Basin side of the Lomonosov Ridge and by the hinge line of the Cretaceous passive-margin sequence beneath covering Cenozoic sediments on the Amerasia Basin flank of the ridge as expressed in the available seismic data. Where not imaged by seismic data, this boundary is estimated to approximately correspond to the break in slope in the bathymetry at the top of the Lomonosov Ridge on the Amerasia Basin side of the ridge. The AU is flanked by the Amundsen Basin AU of the Eurasia Basin petroleum province and by the Makarov Basin Margin AU of this province. The AU is bounded by inferred Paleogene strike-slip faults against the Siberian Shelf at one end of the Lomonosov Ridge (Drachev and others, 1998, 2003) and in the submarine trough bounding the Greenland-Canadian Shelf at the other end (Grantz and others, 2010; 2011a). Strike-slip faulting in the latter area is required by the thin crust between the Canadian continental margin and the Lomonosov Ridge north of Ellesmere Island (Forsyth and others, 1994), the northeast-trending linear escarpment at the southeastern corner of the Lomonosov Ridge (Jakobsson and others, 2004), and bathymetric data that suggests that the oceanic or highly extended continental crust underlies the deep Lincoln Sea between Morris Jesup Plateau and the Canadian margin of the Lomonosov Ridge (Jakobsson and others, 2004). The southward truncation of the Eurasia Basin against the northern margin of the Yermak and Morris Jessup Plateaus prior to their separation by rifting at magnetic anomaly 10 (~33 Ma) requires a northeast-trending transform fault to project into this area (Brozena and others, 2003). As defined, this AU includes most of the bathymetrically higher parts of the Lomonosov Ridge. The area of the Lomonosov Ridge AU is 201,000 km^2.

Geologic Model for Assessment

The geologic model for the assessment of the Lomonosov Ridge AU is hypothesized to be a petroleum system generated from Triassic and Jurassic organic-rich source rocks that were deposited while the Lomonosov Ridge was part of the Baltic Shelf prior to opening and seafloor spreading in the Eurasia Basin. The most likely reservoirs are Triassic, Jurassic, and Cretaceous fluvial and marginal marine sandstones similar to those exposed in Franz Josef Land (Embry, 1994). Reservoir facies may also be present in coarse-grained Upper Cretaceous and Paleocene strata deposited in rift grabens associated with opening of the Eurasia Basin. Generation may have begun as early as the Early Cretaceous when a change to high heat-flow conditions may have occurred due to seafloor spreading in the Amerasia Basin. Generation most likely peaked in the late Upper Cretaceous and Paleocene when the extensional faulting and rifting that led to opening of the Eurasia Basin in the late Paleocene and sedimentary burial of the Triassic and Jurassic source rocks were at a maximum. Faults related to the rifting would have provided pathways for migration of the petroleum into stratigraphic and structural traps. In this hypothesis, maturation and migration would have been nearly synchronous and may have coincided with development of structural traps. The traps and reservoirs were filled prior to separation of the Lomonosov Ridge from the Barents Shelf and would have had to survive rift-related uplift, erosion, and extensional faulting and LIP magmatism to be viable on the Lomonosov Ridge.

Geologic Analysis of Assessment Unit Probability

The probability that the Lomonosov AU contains at least one undiscovered accumulation of hydrocarbons equal to or greater than the minimum accumulation size of 50 MMBOE as established for the CARA assessments (Charpentier and Gautier, 2011; Charpentier, 2017) was determined from its geologic and petroleum system characteristics as reviewed below.

Charge.— The primary petroleum source rocks hypothesized for the Lomonosov Ridge AU are organic-rich Triassic and Jurassic shale and siltstone units. Source rock strata of this age are not directly known from the Lomonosov Ridge but may be present on the Barents Shelf, the conjugate margin of the Lomonosov Ridge across the Eurasia Basin. Organic-rich deposits are present in the basinal parts of Early Triassic to Early Cretaceous depocenters that trend northeastward across the Barents Shelf toward the restored position of the Lomonosov Ridge prior to opening of the Eurasia Basin (Nøttvedt and others, 1992). Shale and siltstone of that age are exposed on Franz Josef Land (fig. 12) and have oil source rock composition (Bezrukov, 1997; Klubov and others, 2000). Coal and carbonaceous mudstone are known from the Lower Jurassic and Lower Cretaceous parts of the section (Embry, 1994) (fig. 12) and also could have contributed to a petroleum system. Oil staining and bitumen in Franz Josef Land indicate that a

Figure 11. Lithostratigraphic column and total petroleum system events chart showing petroleum system elements for the Lomonosov-Makarov Province. Data from Embry (1994); Jokat and others (1995); Bezrukov (1997); Drachev and others (1998); Sekretov (2001); Cochran and others (2003); Jokat (2005); Brinkhuis and others (2006); Kristoffersen and Mikkelsen (2006); Stein (2007); Backman and others (2008); Langinen and others (2009); Mann and others (2009). 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 Hardenbol and others (1988)and Golonka and Kiessling (2002). Geologic time scale is that of Gradstein and others (2004). Geologic chart modified from P.J. McCabe (written commun., 2006). Abbreviations: AM, Alpha-Mendeleev Ridge; PM, Podvodnikov-Makarov Basin AU; SM, Siberian Passive Margin AU; MM, Makarov Basin Margin AU; LR, Lomonosov Ridge AU.

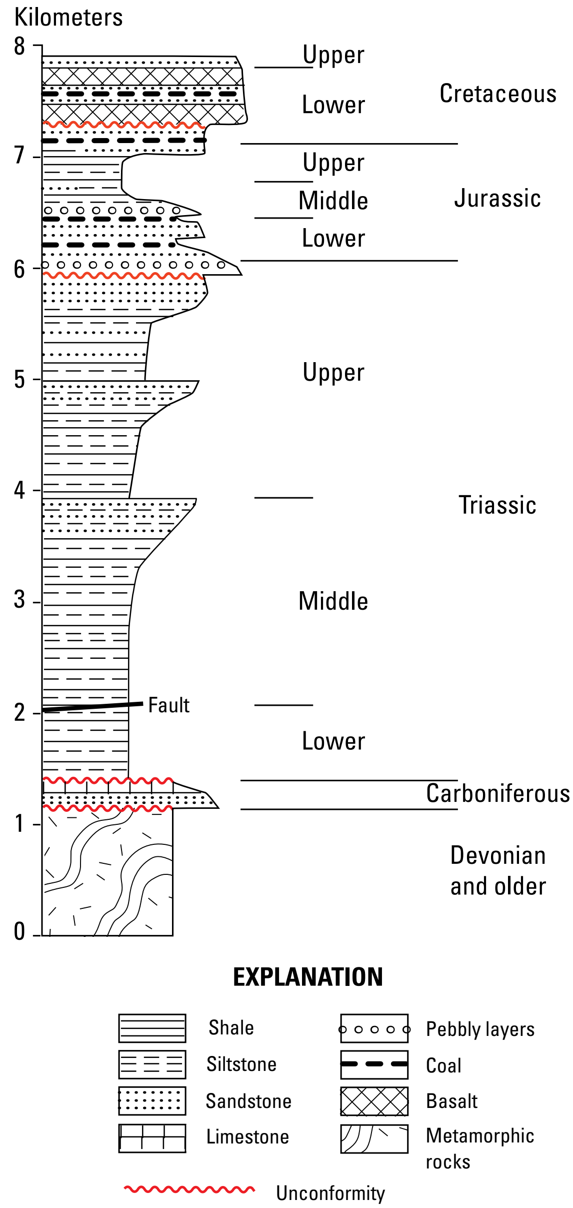


Figure 12. Summary composite stratigraphic column of outcrop and well data from Franz Josef Land (compiled from Embry, 1994). Diagram shows that Uralian-Taimyr foreland basin succession is approximately 6 km thick in Franz Josef Land. Early Cretaceous unconformity is locally significant and cuts out strata younger than middle Triassic in western Franz Josef Land.

petroleum system is present there and allow the possibility of a prerift petroleum system on the Lomonosov Ridge. However, LIP-related mafic dikes intrude the Franz Josef Land section and it is not clear if generation accompanied or postdated the intrusions. The available seismic reflection data do not appear to support igneous intrusions or flows in the Mesozoic strata on the central Lomonosov Ridge, although it is possible they simply have not been detected because of the reconnaissance level of the seismic profiling. These hypothetical petroleum systems are classified together into the Lomonosov Ridge Mesozoic-Cenozoic Composite Total Petroleum System (appendix 1).

The thermal maturity of Jurassic or Cretaceous strata from the Lomonosov Ridge recovered by piston-coring is within the oil window (Grantz and others, 2001). Because covering Cenozoic sediments are not sufficiently thick to have produced this level of thermal maturity (Stein and others, 2006; Stein, 2007), the maturation must have occurred during the Cretaceous prior to the development of the rifting unconformity. Alternatively, the vitrinite measurements reported by Grantz and others (2001) may be interpreted to be organic matter that was redeposited in the Mesozoic from older, more thermally mature, deposits and therefore is not indicative of the thermal maturation of the sedimentary section in which it was found (for example, Klett and Pittman, 2016, this volume). Grantz and others (2001), however, reported that the three samples they analyzed had a narrow range of Ro, which suggests that the maturation occurrred in place rather than representing a mix of detrital vitrinite.

On the basis of this information and the seismic reflection data of Jokat and others (1992), we constructed a petroleum generation model for the Lomonosov Ridge AU (fig. 13, pseudowell B of fig. 10) using the stratigraphy reported from Franz Josef Land by Embry (1994) (fig. 12). Franz Josef Land lies on the conjugate margin of the Eurasia Basin, very close to the point where structural models restore the locations of the cores sampled by Grantz and others (2001), the ACEX drill sites, and the seismic reflection line of Jokat and others (1992) (figs. 3 and 6*A*, see fig. 10 for location). Thus, this area is a good stratigraphic analog for the part of the Lomonosov Ridge AU from which the core and seismic data of Grantz and others (2001) were collected. Embry reported thicknesses of about 2,000 m of Upper Triassic strata, 500 m of Lower Jurassic strata, 450 m of Middle and Upper Jurassic strata, 250 m of uppermost Jurassic and lowermost Cretaceous deposits, and 500 m of upper Lower Cretaceous rocks, mainly basalt flows (fig. 12). Upper Cretaceous strata are mostly not exposed in Franz Josef Land, but recognizing that (1) the section has been eroded beneath the rifting unconformity on the Lomonosov Ridge, (2) mudstone of Campanian age was recovered from the ACEX drill site, and (3) more than 1 km of strata is present in the half graben imaged in the seismic reflection line of Jokat and others (1992) (fig. 6*A*), we estimate that an additional 750 m of Upper Cretaceous strata were once present but have been variably removed by erosion. A thickness

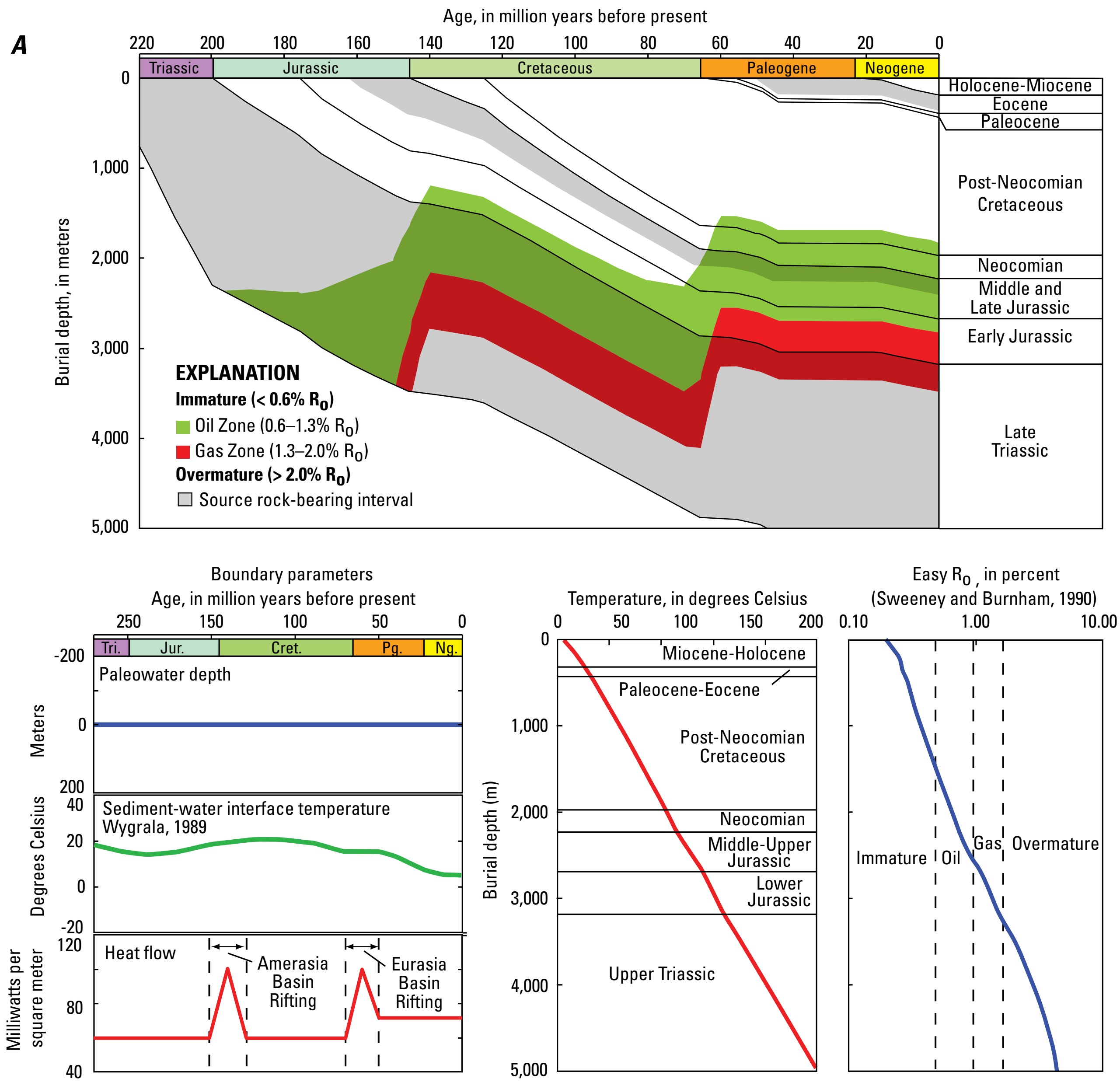


Figure 13. Burial history models for pseudowell B in Lomonosov Ridge AU near ACEX site (see figs. 6*A* and 10*B* for location). Thicknesses of Permian to Neocomian strata taken from Franz Josef Land (Embry, 1994) (see fig. 12); Cretaceous thickness estimated. Amounts of rift-related erosion are variable and therefore not accounted for in models. *A*, Burial history model assuming high heat flow in the Early Cretaceous at the time of opening of the Amerasia Basin along transform fault margin and in the Early Tertiary at the time of opening of the Eurasia Basin. *B*, Burial history model assuming increased heat flow only in the Early Tertiary at the time of opening of the Eurasia Basin. Although the results of the models indicate different levels of thermal maturity for Upper Triassic strata in the Cretaceous, the two models result in similar thermal maturity profiles, with Upper Triassic and Upper Jurassic source rock strata residing in the gas and oil windows, respectively.

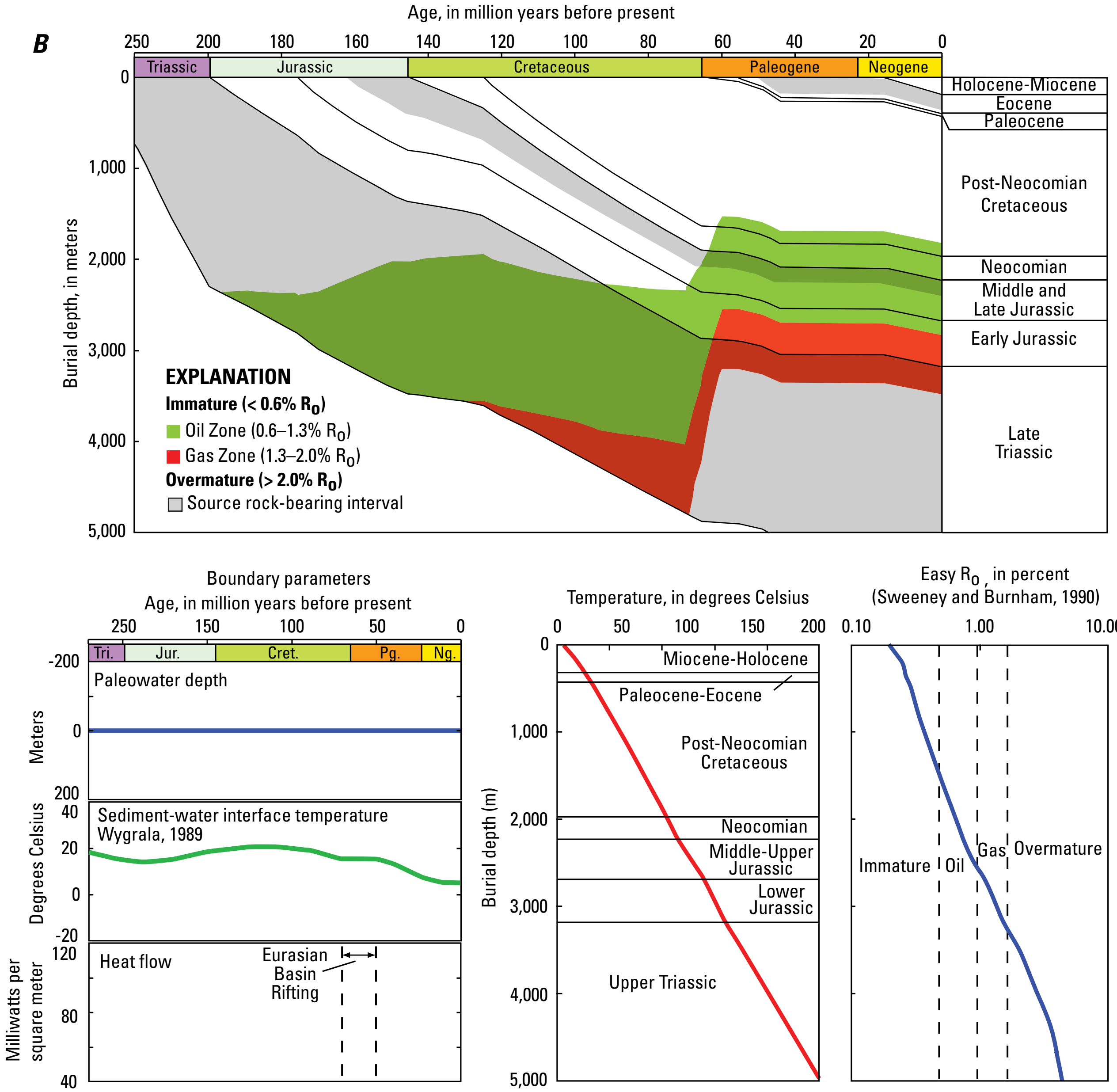


Figure 13.—Continued

of 440 m of Cenozoic strata as determined by ACEX drilling was included. Although as much as 3 km of erosion occurred in Franz Josef Land in the Early Cretaceous (Embry, 1994), it was not modeled because of the possibility that the erosion was a local process caused by the Early Cretaceous magmatism and (or) rift-shoulder uplift along the southern margin of the Eurasia Basin.

The paleoheat flow used in the thermal modeling is of critical importance to its outcome. Weber and Sweeney (1990) reported that modern heat flow values from the Lomonosov Ridge are 60 to 65 mWm^{-2}. We assumed arbitrarily that heat flow increased to about 100 mW/m^2 in the Paleocene at about the time of rifting and initial opening of the Eurasia Basin (~56 Ma), declined to modern values by the early Eocene (~50 Ma), and has remained stable since then. Because the opening of the Amerasia Basin may have had an associated increase in heat flow, we also assumed a similar heat-flow spike at about 140 Ma followed by stable heat flow at 60 mW/m^2 until the Paleocene (fig. 13*A*). Because the Lomonosov margin of the Amerasia Basin is thought to have been a transform rather than rifted margin, and may have involved creation of seafloor without oceanic crust (Grantz and others, 2011b), an increase in heat flow in the Early Cretaceous cannot be assumed. Therefore, we ran a second model without any additional heating in the Early Cretaceous (fig. 13*B*).

The resulting thermal models suggest that the hypothesized Triassic source rocks would have entered the oil window in the Jurassic and remained there until the Paleocene, whereas the Jurassic source rocks would not have entered the oil window until the Paleocene. The primary difference between the two models is that the entire Upper Triassic source rock interval would have remained in the oil and gas window until the Paleocene if there was no thermal heating associated with rifting in the Amerasia Basin during the Early Cretaceous, whereas the older part of the Upper Triassic source rock interval would have become overmature in the Early Cretaceous if heat flow did increase due to Early Cretaceous seafloor spreading. Both models predict that Middle Jurassic to Lower Cretaceous strata are presently in the oil window, which is consistent with the 0.93–1.0 percent Ro reported by Grantz and others (2001) for Jurassic or Cretaceous coaly siltstone from the Lomonosov Ridge. These models also would explain the development of bitumen in Mesozoic deposits in Franz Josef Land.

The distribution of the hypothesized source rock strata outside the central and eastern part of Lomonosov Ridge AU, where the trend of Triassic and Jurassic facies project, is uncertain. On the conjugate margin to the Siberian segment of the Lomonosov Ridge in Severnaya Zemlya, Cretaceous strata rest directly on Devonian rocks, indicating the omission by erosion or nondeposition of upper Paleozoic and lower Mesozoic strata (Egiazarov, 1967; Lorentz and others, 2007, fig. 2). This relation suggests that the Triassic and Jurassic source rock units may not be present in the Siberian segment of the AU. Klubov and others (2002) mentioned that source rocks of Middle Devonian age are present in western Severnaya Zemlya and suggested that the productive Silurian-Devonian section of Timan-Pechora may extend northward into this area, but this has not been confirmed by outcrop or seismic studies. High velocity rocks are present near the surface near the Canadian margin in the AU, suggesting that rift-related erosion has unroofed basement rocks in that area (Kristoffersen and Mikkelsen, 2006; Dahl-Jensen and others, 2008). Therefore, the hypothesized source rocks may be missing due to Paleocene erosion in the Canadian segment of the AU. These considerations might suggest that hypothesized source rocks could be restricted to just the central part of the Lomonosov Ridge.

The uncertainty of source rock quality, thermal history, and their distribution led us to assign a probability of 0.5 for charge sufficiency for an accumulation of minimum size (50 MMBOE) in this AU. This is reduced from the charge probability of 0.7–0.9 for correlative source rocks on the Barents Shelf (Klett and Pitman, 2016, this volume), reflecting questions about the lateral extent and distribution of source rock facies in this AU.

Rocks: Reservoir facies in the central Lomonosov Ridge are anticipated to be similar to coarse-grained deposits in Franz Josef Land, where Lower Jurassic shallow-marine and delta-plain deposits are about 500 m thick and Upper Jurassic and Lower Cretaceous shallow-marine shelf deposits are about 250 m thick (Embry, 1994) (fig. 12). About 450 m of marine shale and siltstone that may form seals overlie the lower interval, whereas the upper unit is overlain by Cretaceous basalt flows and an early Paleogene unconformity that could seal these reservoirs. The reservoir properties of the coarse-grained facies are unknown but appear to be good in Jurassic sandstones in Franz Josef Land (Bezrukov, 1997). Stratigraphic traps are likely and structural traps caused by extensional faulting related to Paleocene rifting are also possible. The presence of Early Cretaceous LIP basalts in Svalbard and Franz Josef Land may suggest that the middle Cretaceous sandstones are volcanogenic and (or) are intruded by dikes and consequently could make poor reservoir facies.

In the Siberian segment of the AU, seismic data reveal complexly deformed strata as much as 5–6 km thick that are thought to include synrift deposits associated with rifting in the Eurasia Basin (Jokat, 2005; Lebedeva-Ivanova, 2006a) (figs. 6*B* and 6*C*). Little is known about these strata, including their thickness, but hypothetically they may include suitable reservoir and sealing facies and stratigraphic and structural traps.

The probability of adequate reservoir rocks, traps, and seals for the presence of a minimum accumulation size (50 MMBOE) in this AU was estimated to be 0.7. This level of probability is equivalent to that estimated for correlative source rocks on the Barents Shelf (Klett and Pitman, 2016, this volume.)

Timing and Preservation.— Burial history modeling indicates that generation from potential Mesozoic source rocks possibly began in Jurassic, peaked in the Cretaceous to Early Tertiary, and could conceivably continue at a low level today in areas of the AU where there was no Cenozoic erosion (for example, the Siberian segment of the ridge). In most places, however, preservation probably is severely compromised by the history of rifting and separation from the Barents Shelf by seafloor spreading in the early Paleogene. Previously formed traps may have been disrupted by normal faults and provided pathways for fluids to escape. Many traps may have been entirely breached by the large displacement extensional faults and limited in size by the narrowness of the continental crust of the AU, especially in its central section. Thermal-related uplift at the time of rifting, and possibly also at the time of the 44–18 Ma disconformity, would have caused fluid expansion due to decompression, encouraging fluid escape. Moreover, the erosion that occurred at the time of rifting was significant and may have removed the entire Mesozoic section and any accumulations it contained in some areas. This possibility is more likely in the Greenland segment of the AU, where Tertiary erosion has removed most of the Mesozoic and upper Paleozoic section on its conjugate margin in northern Svalbard (Nøttvedt and others, 1992, fig. 2; Dahl-Jensen and others, 2008).

Another concern is the presence of thick basalt flows and associated dikes and sills that may have compartmentalized and variably altered any accumulations that existed in the Early Cretaceous at the time of magmatism. On the basis of regional considerations, Drachev and Saunders (2006) suggested the basalts may have once covered much of the AU, although volcanic rocks are suspected only in seismic reflection data collected in the Greenland segment (Kristoffersen and Mikkelsen, 2006).

Because it seems unlikely that many traps could have remained intact and unaffected by rifting and separation of the Lomonosov Ridge from the Barents Shelf, the timing and preservation probability that an accumulation of minimum size is present within the AU was estimated to be 0.2. The most likely part of the AU to contain preserved accumulations of hydrocarbons is in the Siberian part of the AU where the rift-related erosion evidently did not remove much section and synrift extensional faulting may have produced migration pathways and trapping configurations. Associated sedimentation in synrift grabens also may have enhanced prospectivity because of the deposition of coarse-grained reservoir facies and fine-grained sealing facies at the time of the faulting.

Overall Geologic Probability.— The geologic probability of the presence of an accumulation of hydrocarbons of minimum size in the Lomonosov Ridge AU, the product of the three geologic probabilities discussed above, is 0.07 (appendix 1). This level of probability suggests that there is a 7 percent chance for the proper conditions to form at least one oil or gas accumulation of minimum size (50 MMBOE recoverable) under CARA methodology (Charpentier and Gautier, 2011; Charpentier, 2016, this volume. This level of probability, determined from the geology of the AU, was compared to the probabilities of other AUs in the Arctic region to ensure consistency within the CARA project. The level of probability for this AU falls in the lowest 15 percent of all of the AUs evaluated in the CARA project. Although the probabilities are favorable for charging, reservoir, and trapping scenarios, there is a low level of probability that any accumulation >50 MMBOE has been preserved due to prerift mafic intrusions, subsequent rift-related heating, uplift, and faulting, and postrift extensional faulting along the Eurasia Basin margin of the AU.

The overall probability of 7 percent for the Lomonosov Ridge AU is less than the 10 percent minimum necessary for a full quantitative assessment under CARA methodology. Accordingly, an assessment of the sizes and numbers of undiscovered accumulations, the petroleum composition, and other properties was not undertaken for this AU.

Makarov Basin Margin Assessment Unit

The Makarov Basin Margin AU contains no petroleum exploration wells and sparse seismic data. This level of exploration places the margin of the Makarov Basin into uncertainty category 4 on the scale used by the USGS for the Circum-Arctic Resource Appraisal (Charpentier and Gautier, 2011) (appendix 2).

AU Description

The Makarov Basin Margin AU (fig. 10*B*) encompasses all structural and stratigraphic traps that formed in the continental slope and rise of the passive-margin sequence of the Lomonosov Ridge while it was part of the Eurasia-Amerasia Basin margin prior to opening of the Eurasia Basin by seafloor spreading at the Gakkel Ridge in the late Paleocene. The limits of the AU are defined by the continent-ocean margin on the Amerasia (Makarov) Basin side of the Lomonosov Ridge and by the hinge line of the Cretaceous passive-margin sequence beneath covering Cenozoic sediments on the Amerasia Basin flank of the ridge, as expressed in the sparse seismic data. Where not imaged by seismic data, this boundary is estimated to approximately correspond to the break in slope in the bathymetry at the top of the Lomonosov Ridge on the Amerasia side of the ridge. The AU is flanked by the Podvodnikov-Makarov Basin AU and Siberian Passive Margin AU on the side facing Alaska and by the Lomonosov Ridge AU on the side facing Europe. The AU is bounded by inferred Tertiary strike-slip faults against the Siberian Shelf on one end of the Lomonosov Ridge and in the submarine trough bounding Greenland-Canadian Shelf at the other end (Grantz and others, 2010; 2011a). The area of the Makarov Basin Margin AU is 159,000 km^2.

Geologic Model for Assessment

The geologic model for the assessment of the Makarov Basin Margin AU is hypothesized to be a petroleum system that was generated from synrift marine organic-rich Jurassic and Neocomian deposits and (or) upper Lower and lower Upper Cretaceous postrift deposits in the Lomonosov Ridge passive-margin sequence. The most likely reservoirs are slope and submarine-fan sandstones deposited by Cretaceous drainage systems that emanated from Eurasia prior to opening of the Eurasia Basin in the Paleocene. Reservoirs may also have developed in local coarse-grained deposits developed at releasing bends along the transform fault that separates the Lomonosov Ridge from the Amerasia Basin. Petroleum generated from the maturation of the source rocks during burial by the Cretaceous deposits might have migrated into stratigraphic traps, strike-slip fault traps at the base of the section, or extensional passive traps higher in the section.

Geologic Analysis of Assessment Unit Probability

The probability that the Makarov Basin Margin AU contains at least one undiscovered accumulation of petroleum equal to or greater than the minimum accumulation size of 50 MMBOE defined by CARA methodology (Charpentier and Gautier, 2011; Charpentier, 2017, this volume) was determined from its geologic and petroleum system characteristics as reviewed below.

Charge.— The Jurassic to Neocomian and Upper Cretaceous source rocks postulated in the province are inferred to be present on the basis of the regional stratigraphy of the Amerasia Basin (Houseknecht and others, 2007, 2012c, this volume; Grantz and others, 2010; 2011a). The thickness, richness, and quality of these source rocks in the AU are conjectural, although they are thought to be oil prone, similar to correlative source rocks in Arctic Alaska and Canada.

Upper Cretaceous strata are the most likely to be present in the AU; Jurassic to Neocomian strata may not be present over large parts of the province if the tectonic model for opening of the Amerasia Basin of Grantz and others (2011b) is correct. Depending on the location of the regional transform fault thought to underlie the passive-margin sequence, the Triassic and Jurassic platform marine shale source rocks also could be present locally in fault blocks in the AU. Upper Cretaceous source rocks may have poor source rock quality due to coeval volcanism on the Alpha-Medeleev Ridge. This may be particularly true in the Canadian segment of the AU because the Alpha-Mendeleev Ridge onlaps the Lomonosov Ridge in this area. These hypothetical petroleum systems are classified together into the Lomonosov Ridge Mesozoic-Cenozoic Composite Total Petroleum System (appendix 2).

The thermal maturity of postulated source rocks is also uncertain due to questions about their thickness, stratigraphy, and paleoheat flow. The base of the passive-margin sequence is not well imaged in most seismic sections, and the regional configuration of the passive-margin depocenter(s) is unknown. Estimates of the seismic velocity of the sequence range from 2.8 km/s to 4.8 km/s, causing large uncertainties in the calculated thickness of the sequence where it has been seismically imaged. Although a succession of seismic sequences has been identified in the deposits in the central part of the AU (Jokat, 2005), the stratigraphic position of postulated source rocks in this succession, if present, is unknown.

For the purpose of determining whether source rocks in the passive-margin sequence of the Lomonosov Ridge could have generated petroleum, we constructed a simple petroleum generation model based on favorable parameters determined from the published data (fig. 14). We estimated a total stratigraphic thickness of 4.5 km for the passive-margin sequence, including a 500-m thick unit of source rocks at the base, 3,500 m of postrift clastic strata, and 500 m of covering Cenozoic sediments. The same two-stage heat-flow model used for the Lomonosov Ridge AU, featuring spikes in heat-flow at the times of opening of the Amerasia Basin and Eurasia Basin, was used for the thermal maturity modeling of this AU. The resulting model shows that generation would have begun in the Late Cretaceous, with peak generation of both oil and gas occurring in the Paleogene at the time of opening of the Eurasia Basin (fig. 14*A*). Under this scenario, both the synrift and postrift source-rock intervals have been overmature since the Paleocene.

On the other hand, if a constant paleoheat flow is assumed (that is, there was no increase in heat flow in the AU due to opening of the Eurasia Basin) at 70 mWm^{-2} based on modern values (Weber and Sweeney, 1990), and a reduced thickness of 2.5 km is estimated for the entire sequence, only the basal synrift part of the sequence would have been buried deep enough to be in the oil window. In this case, generation occurred primarily in the Paleogene but could have continued at a slower rate in the Neogene (fig. 14*B*). If the latter conditions prevailed in the area near the location of the pseudowell in the central segment of the Lomonosov Ridge, it would suggest that petroleum generation is probably more likely to have occurred in the Siberian segment of the AU, where Cenozoic sedimentary thicknesses are greater due to higher rates of sedimentation.

On the basis of these considerations, we have assigned a probability of 0.4 for charge sufficiency in this AU. This level of probability is mildly unfavorable and reflects a high level of uncertainty about the presence and thermal maturity of source rocks in the AU and the impact of Alpha-Mendeleev Ridge magmatism. However, it also incorporates the expectation that source-rock facies should be present in the AU based on the existing knowledge of the stratigraphy of the Amerasia Basin.

Rocks.— The Lomonosov Ridge margin of the Amerasia Basin is characterized by subrift unconformity reflectors that dip toward the basin and onlap the older rocks of the Lomonosov Ridge at their updip limits (Jokat and others, 1992; Jokat, 2005; Kristofferesen and Mikkelsen, 2006; Langinen and others, 2008). This sequence is interpreted to be Paleocene or older based on the dating at the ACEX locality. The strata display a passive-margin-like offlapping geometry and thicken toward the Amerasia Basin to perhaps more than 5 km. Except for updip onlaps, the basement for the sequence is not recognized in most seismic lines, although a complex zone of normal or strike-slip faults appears to be present at the base of the section near the Greenland margin (Kristoffersen and Mikkelsen, 2006) (fig. 7*B*). Reflectors are weak to strong, and include thick, incoherent reflectors as well as moderate to thinly reflective intervals. Some sequences are unfaulted, but normal faults and rollover anticlines can be inferred on some seismic lines (fig. 7*A*). The up-dip parts in bathymetrically higher areas commonly are eroded at the sea bottom and locally display down-to-basin extensional faults. Elsewhere, especially in bathymetrically lower areas, the sequence is buried beneath covering Cenozoic deposits. The passive-margin sequence has been imaged primarily in the central and Greenland segments of the AU; its presence is suspected but has not been verified in the Siberian segment of the province beneath covering Cenozoic deposits due to a lack of seismic profiling in this area.

Little is known about the lithologies, reservoirs, and traps of the Lomonosov Ridge passive-margin sequence. It is assumed to be composed of clastic turbidites and other sediment-gravity flow deposits that represent the down-basin sedimentary equivalents of the Jurassic and Cretaceous deltaic and nonmarine deposits exposed in Franz Josef Land. Expected sedimentary facies include fine-grained slope deposits with encased channelized facies, base-of-slope turbidite-fan complexes, slope basins formed by gravity sliding and down-to-basin normal faults and low-stand, shelf-margin truncations. Good quality reservoir sandstones are likely to be present because the Cretaceous depositional systems drained granitic and metamorphic rocks across highlands in the Urals, Taimyr and other orogenic belts in Eurasia. Cretaceous basaltic volcanism present in updip shelf areas (for example, Franz Josef Land), however, may have acted to reduce reservoir

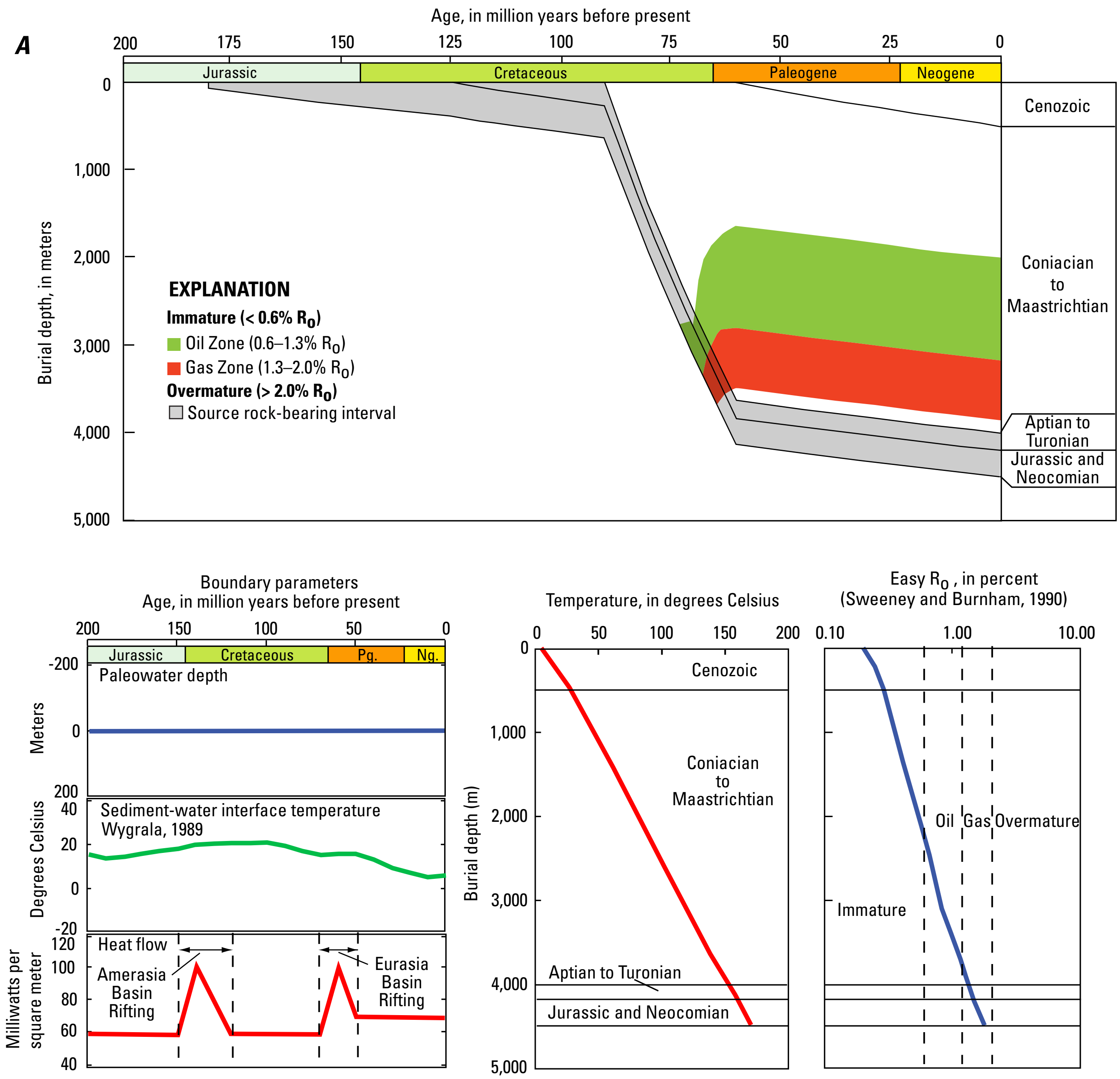


Figure 14. Burial history models for pseudowell C in Makarov Basin Margin AU (see figs. 7*A* and 10*B* for location). *A*, Burial history model assuming a total sedimentary thickness of 4.5 km (near maximum allowed by available seismic data) and a thermal history marked by increases in heat flow in the Early Cretaceous at the time of transform opening of the Amerasia Basin and in the Early Tertiary at the time of rift opening of the Eurasia Basin. *B*, Burial history model assuming a total sedimentary thickness of 2.5 km (near minimum allowed by seismic data) and a constant heat flow that was unaffected by rift events in the Amerasia and Eurasia basins. Model A suggests that postrift, Upper Cretaceous source rocks and synrift, Jurassic and Neocomian, source rocks are overmature, whereas model B suggests that synrift, Jurassic and Neocomian, source rocks are mature but post-rift, Upper Cretaceous, source rocks are immature.

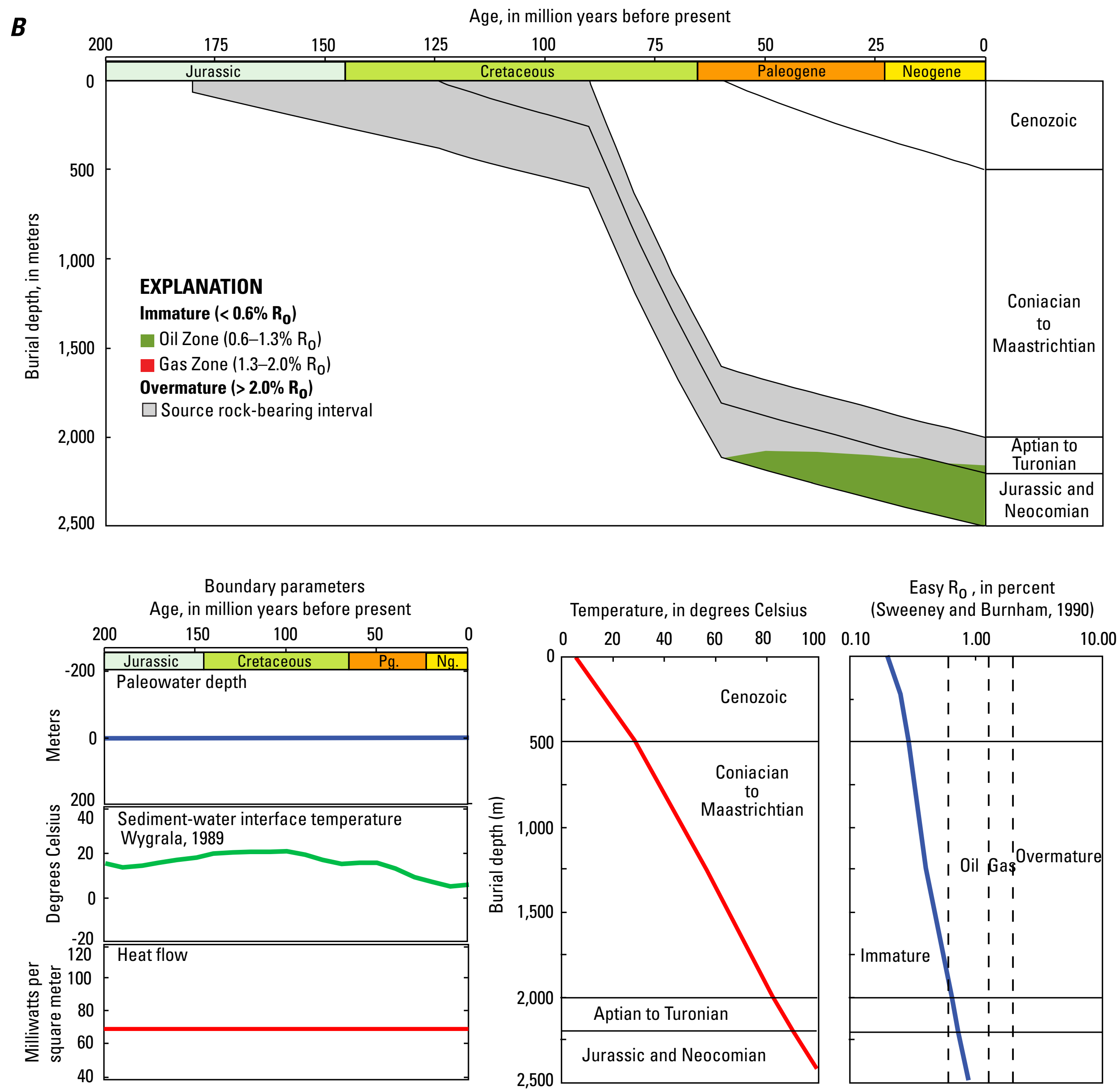


Figure 14.—Continued

quality. Potentially, the sequence is interstratified with basaltic volcanic rocks of the Alpha-Mendeleev LIP. Traps are expected to include both deep marine stratigraphic traps and extensional fault traps common to most clastic-dominated passive margin sequences.

Other depositional settings potentially containing reservoirs, traps, and seals are possible in this AU. These include strike-slip basins along the Makarov Basin Margin of the AU. Cochran and others (2006) calculated that a large-scale releasing bend might be present at depth along the transform margin of the Lomonosov Ridge microcontinent in the central part of the AU. Another possible setting lies in Late Cretaceous and Paleocene grabens and extensional basins formed in association with Eurasia Basin rifting. Such extensional basins may be common in the Siberian segment of the AU, judging from the seismic data published from that area by Jokat (2005) and Butashenko and Poselov (2006) (for example, fig. 6*C*).

A probability of 0.5 was assigned for adequacy of reservoirs, traps and seals in this AU, reflecting the uncertainty in knowledge about the reservoirs, traps, and seals that might be encountered. Although the passive-margin sequence has been identified in seismic data in the central and western parts of the AU, its presence in the eastern (Siberian) part of the AU has not been confirmed by seismic profiling. Considering that the Makarov Basin Margin AU is a displaced part of the Cretaceous (~127 Ma to ~56 Ma) continental margin of Eurasia and consequently includes a ~70-m.y., continentally-derived passive margin succession along its entire length, it seems likely that the passive-margin sequence will be found to be present in all parts of the AU. The most prospective areas are expected to lie in bathymetrically low areas of the AU, where Cenozoic sediments cover the prospective intervals and increase the likelihood that any source rocks present are thermally mature. In all areas, the fine-grained pelagic and hemipelagic deposits drape the AU and would provide an excellent sealing facies.

Timing and Preservation.— The timing of petroleum generation is favorable because formation of the traps and seals occurred prior to the time of generation and are currently at maximum burial. Although updip areas appear to have suffered erosional breaching during the Cenozoic, most downdip areas were largely unaffected by the rifting in the Eurasia Basin and are currently at maximum burial. A moderately favorable probability of 0.7 therefore was assigned for timing and preservation in this AU.

Overall Geologic Probability.— The geologic probability of the presence of an accumulation of minimum size in the Makarov Basin Margin AU, the product of the three geologic and petroleum system probabilities discussed above, is 0.14 (appendix 2). This level of probability suggests that a 14 percent chance for at least one oil or gas accumulation of the minimum prescribed size (50 MMBOE recoverable) exists in this AU. This level of probability, determined from the geology of the AU, was compared to the probabilities of the other AUs evaluated by the CARA project to ensure internal consistency. For example, the AU probability of the Nansen Basin Margin AU, which contains the post-56-Ma continental margin succession of Europe along the modern margin of the Eurasia Basin, was evaluated to be 0.25 (that is, there is a 25-percent likelihood of there being one accumulation of the minimum size) (Moore and Pitman, this volume). The Nansen Basin Margin AU exhibits similarities in the duration of coarse-grained sedimentation on the margin of a large continent (~74 m.y. vs ~56 m.y.), composition (siliciclastic, cratonal provenance), and tectonic position (continental margin of Eurasia) to the Makarov Basin Margin AU, but was judged to have a somewhat higher probability for suitable reservoirs and traps and a better preservation potential. The other passive continental margin sequences of the Amerasia Basin (Alaska, Canada, and Siberian) are thicker and stratigraphically and structurally more complex owing to their longer durations as passive margins (~130 m.y. versus ~70 m.y.). These AUs contain a larger range of reservoirs, traps, and source rock intervals, and consequently the evaluations of their AU probabilities are higher: Alaska Passive Margin AU, 0.54; Canada Basin Passive Margin AU, 0.54; Siberian Passive Margin AU, 0.42 (Houseknecht and others, 2012c, this volume).

The overall probability of 14 percent for the Makarov Basin Margin AU is greater than the 10 percent minimum for the presence of at least one accumulation of the minimum size defined by CARA methodology for a quantitative assessment. Accordingly, an assessment of the sizes and numbers of undiscovered accumulations, the petroleum composition, and other properties was completed for this AU and is discussed below.

Quantitative Assessment of Makarov Basin Margin Assessment Unit

The analog-based assessment methodology described in Charpentier (2016, this volume) was used to make the assessment of the Makarov Basin Margin AU (appendix 2).

Analogs Used in this Assessment

Analog assessment units were selected from the USGS World Analog Database (Charpentier and others, 2008) for the purpose estimating the number and sizes of undiscovered oil and gas accumulations in the Makarov Basin Margin AU. The analog AUs selected for use in this assessment consist of the same suite of 20 AUs employed by Houseknecht and others (2011a, this volume) for assessment of the Canada and Alaska passive margins of the Amerasia Basin. This analog suite includes those AUs having rifted passive margin and passive-margin architecture plus those having gravity-induced, growth-fault trapping systems. Those AUs containing salt structures, basement-related normal faults, carbonate reservoirs, and other geologic parameters not appropriate for the clastic continental margin successions of the Amerasia Basin were culled from the suite used in the assessment described here. See Houseknecht and others (2011a, table 5) for a list of the analog AUs used in this assessment.

Numbers of Undiscovered Oil and Gas Accumulations

The number of undiscovered accumulations of oil and gas was estimated from the discovered and undiscovered accumulations in the analog AUs normalized by area (accumulation densities) as determined from the area and geologic characteristics of the Makarov Basin Margin AU. Because this AU comprises of one of the major passive-margin sequences of the Amerasia Basin, it should exhibit characteristics similar to those of the other passive margins of the basin. This margin differs from the other margins, however, in having been initiated as a transform rather than a rift margin in the Jurassic or Early Cretaceous and did not become a true passive margin until the termination of transform faulting at about 120 Ma. In addition, the passive-margin succession was sundered from the continental drainage systems that fed it by rifting of the Eurasia Basin in the Paleocene and was subsequently abandoned due to the submergence of the Lomonosov Ridge at 50 Ma. Younger deposits consist largely of pelagic and hemipelagic deposits shed from the distant Siberia passive margin. In contrast, continentally-derived sedimentation has continued unabated from about 130 Ma to the present along the Canada and Alaska-Siberia passive margins.

As a result of this evolution, the Makarov Basin margin was the site of large-scale continentally derived sedimentation for roughly 70 m.y., less than half the duration of such sedimentation on the Canada and Alaska-Siberia passive margins. Therefore, the density of accumulations ≥50 MMBOE that are present in the AU is probably less than that for the other passive margins of the Amerasia Basin. The accumulation densities for this AU accordingly were arbitrarily set at about half of those estimated for the Canada Passive Margin AU (Houseknecht and others, 2012c, this volume), at 0.07 and 0.24 accumulations/1000 km^2 at the median and maximum of the probability distribution, respectively. This reasoning yielded 11 and 38 accumulations at the median and maximum, respectively. The minimum number of accumulations was set at 1 because of the paucity of data from the AU.

Although the likely source rocks are thought to be oil-prone marine strata of Turonian age having Type II kerogen, the factors controlling the ratio of oil and gas in the province are very uncertain. Consequently, the proportion of oil and gas in the accumulations was set at the nominal ratios of 0.1, 0.5, and 0.9 at the minimum, median, and maximum, respectively. Accordingly, the estimates for the minimum, median, and maximum numbers of oil and gas accumulations (all undiscovered) are equal, with each being set at 1, 11, and 34 accumulations.

Sizes of Undiscovered Oil and Gas Accumulations

The minimum size of undiscovered oil accumulations in the Makarov Basin Margin AU was set at a minimum of 50 MMBOE, as required by CARA assessment methodology (Charpentier and Gautier, 2011; Charpentier, 2016, this volume). The median undiscovered oil accumulation size was estimated to be 100 MMBO based on the size distribution in the selected analogs (Charpentier and others, 2008). The maximum oil accumulation size was estimated to be 2,000 MMBO on the basis of the sizes of the largest known accumulations in the analog database and through use of the province geologist's estimate of the largest oil field size expected in the AU, 350 MMBO, which takes into account the geology of the AU. The latter estimate does not enter directly into the volumetric calculations but acts as a guide to judge the reasonableness of the maximum oil field size at zero probability. The largest expected gas field is estimated to be 2.5 TCF based on a consideration of the geologic attributes of the AU. The minimum, median, and maximum gas accumulation sizes are set at the same as for those for oil accumulations, which, using an energy-volume equivalence factor of 6, resulted in a distribution of 300, 600, and 12,000 billion cubic feet gas (BCFG), respectively.

Coproduct Ratios and Ancillary Data

Coproduct ratios (gas/oil, natural gas liquids (NGL)/oil, liquids/gas) were estimated from global averages reported in Charpentier and others (2008). Median gas/oil ratio for undiscovered accumulations was estimated to be 1,000 cubic feet of gas per barrel of oil (CFG/BO); the median NGL/gas ratio was estimated to be 25 barrels of natural gas liquids per million cubic feet of gas (BNGL/MMCFG); and the median liquids/gas ratio in undiscovered gas accumulations was estimated to be 25 barrels of liquids per million cubic feet of gas (BBL/MMCFG). Median API gravity was estimated to be 38. Drilling depths for undiscovered accumulations were estimated from the available seismic data, and water depths within the AU were estimated from Jakobsson and others (2004). Drilling depth estimates for undiscovered oil accumulations range from a minimum of 500 m, a median of 2,000 m, and a maximum of 4,000 m. The same range of drilling depths was estimated for undiscovered gas accumulations. Estimates of water depths range from a minimum of 1,500 m to a median of 2,000 m and a maximum of 4,000 m.

Results

Probabilistic estimates of volumes of undiscovered, technically recoverable hydrocarbons for the Makarov Basin Margin AU are summarized in Table 1. These results include mean estimates of undiscovered resources of 123 MMB of oil, 193 BCF of gas and 5 MMB of natural gas liquids in oil fields, and 741 BCF of gas and 20 MMB of natural gas liquids in gas fields. The mean largest expected oil accumulation is calculated at 843 MMBO and mean largest expected gas accumulation is calculated to be nearly 2 TCF.

Podvodnikov-Makarov Basin Assessment Unit

The Podvodnikov-Makarov Basin AU contains no petroleum exploration wells and seismic data from this area are extremely sparse. This level of exploration places the Podvodnikov and Makarov Basins into uncertainty category 4 on the scale used by the USGS for the Circum-Arctic Resource Appraisal (Charpentier and Gautier (2011) (appendix 3).

AU Description

The Podvodnikov-Makarov Basin AU is an elongate area covering 142,000 km^2 between the Makarov Basin Margin AU and the Alpha-Mendeleev Ridge LIP (fig. 15). Toward Greenland, irregularities in the Alpha-Mendeleev province boundary cause the AU to become narrow and segmented, whereas toward the Siberian continental margin the width of the AU expands and shares a boundary with the Siberian Passive Margin AU. This boundary is arbitrarily placed where sediment thickness is inferred to exceed ~3 km based on seismic reflection records (fig. 16).

Geologic Model for Assessment

The geologic model for assessment of the Podvodnikov-Makarov Basin AU hypothesizes that source and reservoir rocks are present in the 3-km-thick Cretaceous and Tertiary clastic succession that overlies Barremian (Early Cretaceous) or older ocean crust and highly extended continental crust (fig. 16). The Cretaceous and Tertiary strata likely represent distal

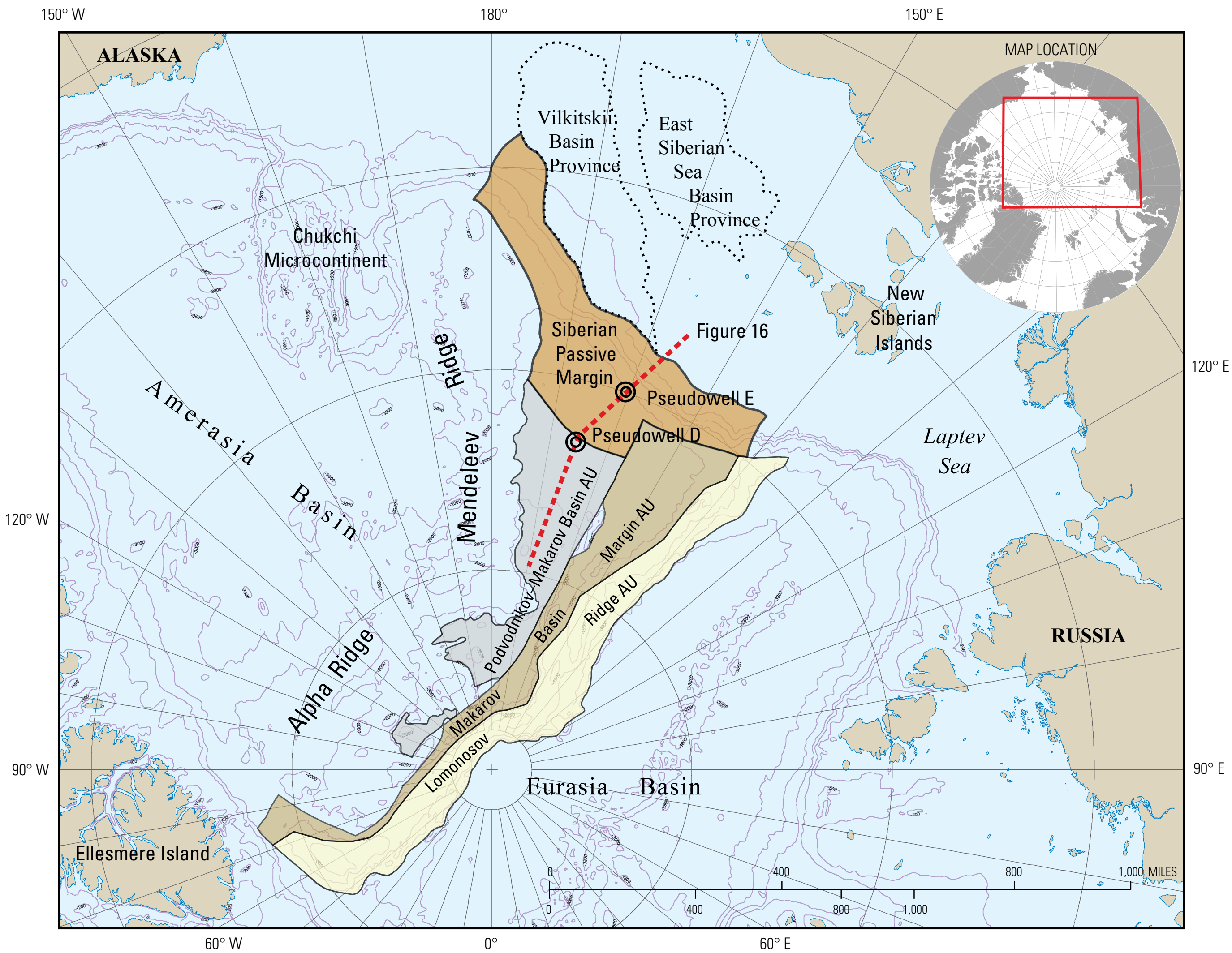


Figure 15. Location map showing the Podvodnikov-Makarov Basin and the Siberian Passive Margin Assessment Units (AU), other nearby AUs and provinces, cross section location (shown in fig. 16), and pseudowells D and E used in burial history modeling.

deep-marine facies of sediments derived from the Lomonosov Ridge and Siberian passive margins. Oil-prone source rocks known from the margins of the Amerasia Basin are hypothesized to be present in Lower Cretaceous, Upper Cretaceous, and Paleogene stratigraphic intervals. Maturation and petroleum generation commenced in parts of the AU where the succession exceeds 2 km in thickness under conditions of relatively high heat flow in the late Paleogene. Petroleum accumulations are hypothesized to have developed through expulsion of petroleum from the deep marine source rocks and updip migration into sandstone accumulations present in base-of-slope depositional settings. The primary exploration targets are therefore stratigraphic clastic reservoirs in the continental margin successions of the basin.

Geologic Analysis of Assessment Unit Probability

The probability that the Podvodnikov-Makarov Basin AU contains at least one undiscovered accumulation equal to or greater than the minimum prescribed accumulation size of 50 MMBOE was determined from its geologic and petroleum system characteristics as reviewed below.

Charge.— There is no direct evidence of a petroleum system in the Podvodnikov-Makarov Basin AU or in any of the adjacent assessment units. As described above and shown in figure 8, regional tectonic and paleogeographic reconstructions suggest that oil-prone condensed shale source rocks may be present throughout the AU. These include syn- and postrift Jurassic and Lower Cretaceous, Upper Cretaceous, and Paleogene strata (fig. 16). These hypothetical source rocks are classified together as a Cretaceous-Paleogene Composite Total Petroleum System (appendix 3). A model that assumes oceanic crust and a uniform heat flow of 75 mW/m^2 suggests that oil generation occurred only in the areas where source rocks are buried to depths exceeding 2 km (fig. 17*A*). Proximity to the Alpha-Mendeleev Igneous Province may have reduced the source rock character of coeval postulated mid-Cretaceous source rocks. For these reasons, a mildly unfavorable charge probability of 0.4 was assigned to this AU.

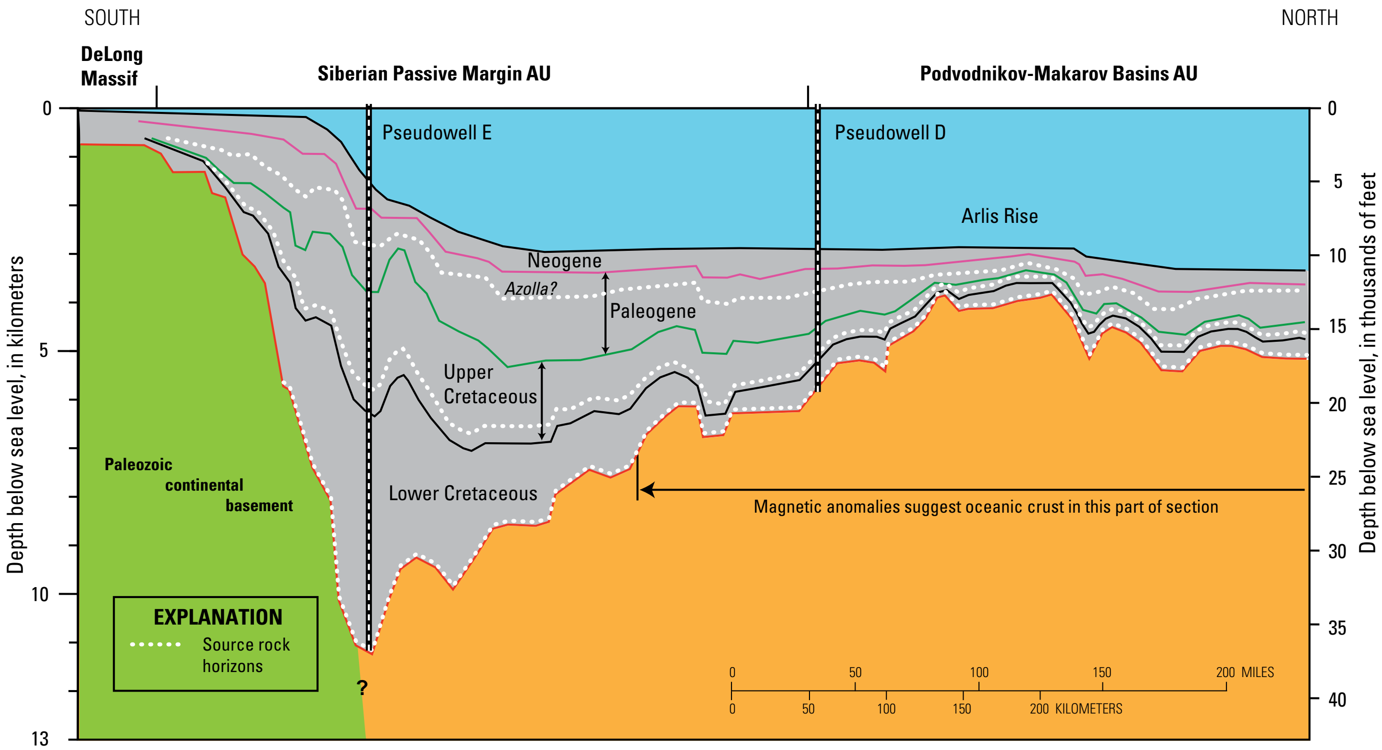


Figure 16. Cross section based on seismic data from the Siberian Passive Margin and Podvodnikov-Makarov Basins Assessment Units. Section adapted from Lebedeva-Ivanova and others (2006b, fig. 3). Stratigraphic horizon interpretations are derived mostly from Langinen and others (2006) and Sekretov (2001). See figure 15 for location of section and pseudowells.

Rocks.— As in the Canada Basin AU (Houseknecht and others, 2012c, this volume), Jurassic through Neogene strata may be prospective. Jurassic to Lower Cretaceous strata may occur in rift basins in highly extended continental crust in the outermost parts of the AU beyond the limit of oceanic crust. If present, their reservoir quality, and trap geometry are highly uncertain. Lower Cretaceous through Neogene strata probably are mostly distal hemipelagic facies associated with sediment dispersal systems emanating from the Lomonosov-Makarov and Siberian margins. Although sand-prone turbidite facies may be present in these strata, it is likely they are fine grained, and the probability that they occur in volume and quality sufficient to trap at least 50 MMBOE in an individual accumulation is considered low. In addition, the introduction of volcanic detritus from the Alpha-Mendeleev Igneous Province may have reduced porosity and permeability in mid-Cretaceous reservoir rocks. The AU probably contains mostly stratigraphic traps common in deep-water sediment-gravity flow and turbidite depositional systems. The presence of structural traps is unlikely. Because of the low likelihood of the presence of effective reservoirs in the AU, a rock probability of 0.1 is assigned.

Timing and Preservation.— Hydrocarbon generation might have begun as early as ~55 Ma (fig. 17*A*). Seismic interpretations (fig. 16) suggest that only Lower Cretaceous source rocks were buried sufficiently to generate petroleum in the AU. Because potential traps are mostly stratigraphic and are currently at maximum burial depth, the timing for entrapment and preservation of charge is favorable. Thus, a timing and preservation probability of 1.0 is assigned to this AU.

Overall Geologic Probability.— The geologic probability of the presence of an accumulation of the minimum size in the Podvodnikov-Makarov Basin AU, the product of the three geologic and petroleum system probabilities discussed above, is 0.04 (appendix 3). This level of probability suggests there is a 4 percent chance that at least one oil or gas accumulation of minimum size (50 MMBOE recoverable) exists in this AU. This probability, determined from the geology of the AU, was compared to the probabilities of other AUs evaluated by CARA to ensure internal consistency.

As in the Canada Basin AU in the southern Amerasia Basin, available evidence suggests a generally unfavorable probability (<10 percent) for the presence of at least one accumulation ≥50 MMBOE because the low probabilities for both charge and rocks indicate they are significant risk factors. Therefore no quantitative assessment of petroleum potential of this AU was conducted.

Siberian Passive Margin Assessment Unit

The Siberian Passive Margin AU contains no petroleum exploration wells and seismic data are extremely sparse in this area. This level of exploration places the Siberian Passive Margin into uncertainty category 4 on the scale used by the USGS for the Circum-Arctic Resource Appraisal (Charpentier and Gautier (2011) (appendix 4).

Table 1. Assessment results for the Lomonosov-Makarov Province (conventional undiscovered resources).

[MMBO, million barrels oil; BCFG, billion cubic feet gas; MMBNGL, million barrels natural gas liquid. Oil field sizes in MMBO; gas field sizes in BCFG. Results shown are fully risked estimates. Undiscovered gas resources are the sum of gas in oil fields and gas in gas fields. For gas fields, all liquids are included as NGL (natural gas liquids). F95 denotes a 95 percent chance of at least the amount tabulated; other fractiles are defined similarly. Numbers do not exactly add to the totals because totals were calculated by statistical aggregation. NA, not applicable. AU, assessment unit. AU probability is the chance of at least one accumulation of minimum size within the AU. Identities of analog AUs are found in Houseknecht and others (2012a, table 5)]

Assessment units (AU)	AU probability	Classes and numbers of analog AUs	Field type	Largest expected mean field size	Total undiscovered resources											
					Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
					F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Siberian Passive Margin AU[1]	0.42	Rifted passive margin; passive margin; growth fault traps (n=20)	Oil	307	0	0	4,027	984	0	0	6,592	1,538	0	0	179	42
			Gas	1,705	NA	NA	NA	NA	0	0	20,118	4,684	0	0	541	125
Makarov Basin Margin AU[2]	0.14	Rifted passive margin; passive margin; growth fault traps (n=20)	Oil	843	0	0	914	123	0	0	1,357	193	0	0	36	5
			Gas	1,967	NA	NA	NA	NA	0	0	5,492	741	0	0	146	20
Lomonosov Ridge AU[2]	0.072				Not quantitatively assessed											
Podvodnikov and Makarov AU[1]	0.040				Not quantitatively assessed											
Total conventional undiscovered petroleum resources					0	0	4,473	1,107	0	0	29,370	7,156	0	0	791	192
Total mean estimate of undiscovered resource expressed as oil equivalent (MMBOE)					2,491 MMBOE											

[1]Cretaceous-Paleogene composite total petroleum system.

[2]Lomonosov Ridge Mesozoic-Cenozoic composite total petroleum system.

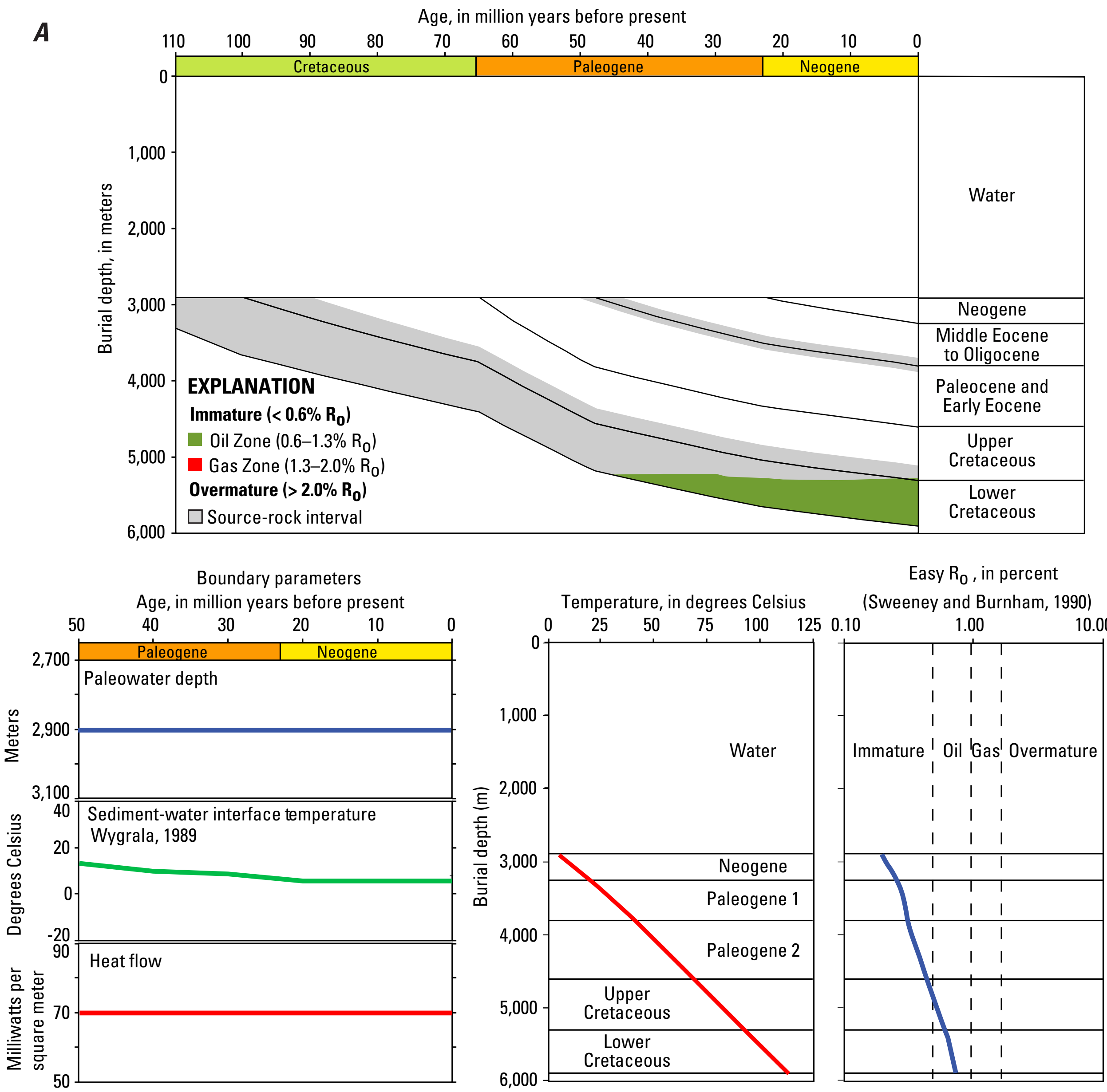


Figure 17. Burial history diagrams for pseudowells D and E. *A*, Burial history for pseudowell D in the Podvodnikov-Makarov Basins assessment unit. *B*, Burial history for pseudowell E in the Siberian Passive Margin assessment unit. Pseudowell locations shown in figure 15.

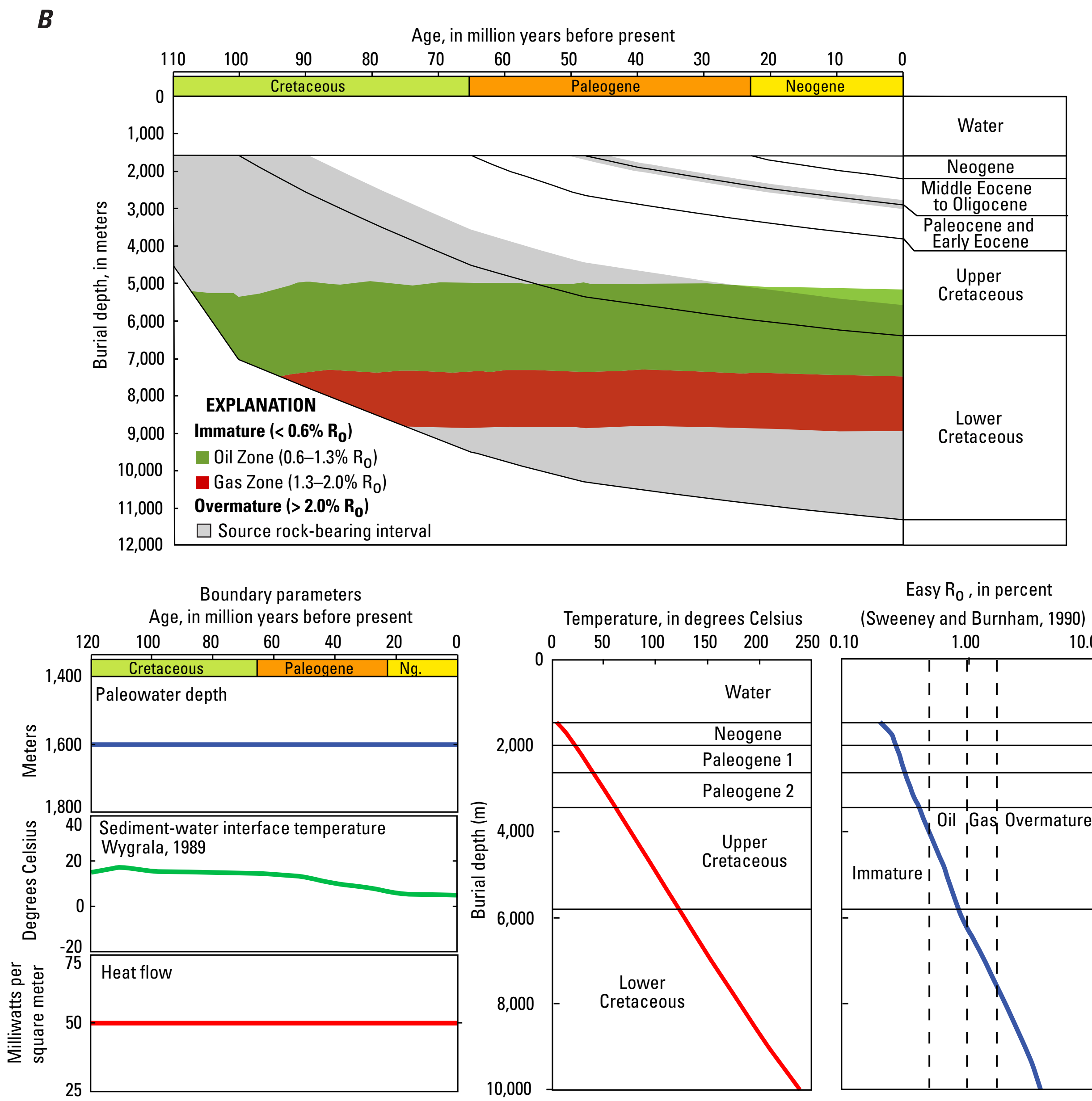


Figure 17.—Continued

AU Description

The Siberian Passive Margin AU covers an area of about 220,000 km^2 that encompasses the outer part of the Siberian continental shelf, the adjacent slope, and that part of the Podvodnikov Basin where sediment thickness is greater than 3 km (fig. 15). The AU is bordered on its continent-ward side by the DeLong Massif and the Vilkitskii Basin provinces, along a boundary that likely approximates the hingeline of the rift shoulder, and by the Alpha-Mendeleev Ridge LIP, Makarov-Podvodnikov AU, and Makarov Basin Margin AU to the north in the Amerasia Basin.

The structure and stratigraphy of this AU is constrained by only one highly generalized regional seismic profile (Lebedeva-Ivanova and others, 2006b) and two nearby higher resolution seismic profiles of limited extent nearby (Sekretov, 2001). The Siberian Passive Margin AU mostly lies outboard of a probable rift-shoulder hinge line fault zone on extended continental or transitional crust that was attenuated during Jurassic to Early Cretaceous rift opening of the Amerasia Basin. The seismic profiles (fig. 16) show that basement lies at depths of as much as 11 km and that the AU is characterized by a thick succession of strata of inferred Cretaceous and Cenozoic age. The greater thickness of Cretaceous strata shown here compared to thicknesses of Cretaceous strata in other margins of the Amerasia Basin is likely the result of proximity to major provenance areas in the Brooks Range and in Chukotka and other orogenic belts of the Russian Far East (fig. 2).

Geologic Model for Assessment

The geologic model for the Siberian Passive Margin AU is similar in many respects to models for the other margins of the Amerasia Basin (for example, Houseknecht and others, 2012a, this volume). Source rocks are hypothesized in syn- and postrift Jurassic and Lower Cretaceous, Upper Cretaceous, and Paleogene strata based on correlation with the other margins of the Amerasia Basin. A variety of stratigraphic traps and growth-fault traps are expected throughout the thick passive margin succession in continentally derived sediments. Oil generation probably began in inboard positions along the continental margin and migrated outward to the north as thick progressively offlapping sequences were deposited. Timing is excellent because traps are syndepositional. Overpressured reservoirs are likely.

Geologic Analysis of Assessment Unit Probability

The probability that the Siberian passive margin AU contains at least one undiscovered accumulation equal to or greater than the minimum accumulation size of 50 MMBOE prescribed by CARA methodology was determined from its geologic and petroleum system characteristics as reviewed below.

Charge.— There is no direct evidence of a petroleum system in the Siberian Passive Margin AU. As described above and shown in figure 8, regional tectonic and paleogeographic reconstructions suggest that oil-prone condensed shale source rocks may be present throughout the AU. The source rocks include deposits in syn- and postrift Jurassic and Lower Cretaceous strata, Upper Cretaceous strata, and Paleogene strata. The source rocks are classified together here in the Cretaceous-Paleogene Composite Total Petroleum System (appendix 4). A burial history model that assumes mostly continental crust and a uniform heat flow of 50 mW/m^2, suggests that oil generation occurred only in the areas where source rocks are buried to depths exceeding 3 km (fig. 17*B*). Although Cretaceous source rocks are buried to these depths, the Paleogene rocks are not (fig. 16). Proximity to the Alpha-Mendeleev Igneous Province may have reduced the source rock character of coeval postulated mid-Cretaceous source rocks. For these reasons, a charge probability of 0.6 is assigned to this AU.

Rocks.— With few seismic lines, an absence of wells, and outcrop information limited to exposures on islands on the Siberian shelf (for example, Kos'ko and Trufanov, 2002), there is considerable uncertainty about rock characteristics and structures in this AU. Although seismic records from drifting ice islands (Lebedeva-Ivanova and others, 2006b) display gross structural and stratigraphic features, multichannel data from ships (Sekretov, 2001) reveal considerably greater detail. Based on the seismic records from Sekretov (2001), it is postulated that the Cretaceous and Paleogene succession in this AU is as much as 10 km thick and may have a growth-faulted, overpressured depositional and tectonic style similar to that of the Alaska Passive Margin AU (for example, Houseknecht and others, 2012c, this volume). Regional relations suggest that the East Siberian Passive Margin AU is composed of mostly mudstone and sandstone that includes good reservoir-quality sandstone and seal-quality mudstone. The presence of Cenozoic Siberian shelf basins (East Siberian Sea and Vilkitskii), however, may have functioned as sediment traps, thereby reducing the amount and coarseness of potential Cenozoic sandstone reservoirs in this AU. Potential traps may consist of large-displacement (hundreds of meters) growth-fault systems; smaller potential traps may include low-stand, shelf-margin truncations, and channelized facies in both deep- and shallow-water facies. A rock probability of 0.7 is assigned based on these considerations.

Timing and Preservation Probability.—Burial history models (fig. 17) based on seismic interpretations suggest hydrocarbon generation might have begun as early as ~105 Ma for Lower Cretaceous source rocks and as late as about 40 Ma for Upper Cretaceous source rocks. Cenozoic source rocks were probably never buried deeply enough to cause generation. Oil generation probably radiated outward to the north during the Cretaceous and Tertiary as thick, progressively offlapping sequences were deposited. Because potential traps in the AU are postulated to be syndepositional, structural, and (or) stratigraphic, and at maximum burial, the timing for entrapment and preservation of charge is favorable. Thus, a timing and preservation probability of 1.0 is assigned to this AU.

Overall Geologic Probability.— The geologic probability of the presence of an accumulation of the minimum size in the Siberian Passive Margin AU, the product of the three geologic and petroleum system probabilities discussed above, is 0.42 (appendix 4). This level of probability suggests there is a 42 percent chance that the proper conditions to form at least one oil or gas accumulation of the minimum size (50 MMBOE recoverable) exists in this AU. This level of overall probability is greater than the 10 percent minimum necessary for a quantitative assessment. Accordingly, the sizes and numbers of undiscovered accumulations, the petroleum composition, and other properties for this AU were evaluated and are discussed below.

Quantitative Assessment of Siberian Passive Margin Assessment Unit

The analog-based assessment methodology described in Charpentier and Gautier (2011; this volume) was used to produce an assessment of the undiscovered hydrocarbon deposits of the Siberian Passive Margin AU (appendix 4).

Analogs Used in this Assessment

The USGS World Analog Database (Charpentier and others, 2008) was used to estimate numbers and sizes of undiscovered oil and gas accumulations in the Siberian

Passive Margin AU. The analog AUs selected for use in this assessment consist of the same suite of analogs employed by Houseknecht and others (2012a, this volume) for the assessments of the Alaska Passive Margin and Canada Passive Margin AUs of the Amerasia Basin Province. This analog suite includes those AUs having rifted passive margin and passive margin architecture plus those having gravity-induced growth fault trapping systems. Houseknecht and others (2012a, this volume) culled the passive margin analog set of AUs containing salt structures, basement-related normal faulting, carbonate reservoirs and other geologic parameters not appropriate for clastic continental margin successions in the Arctic, including the Siberian Passive Margin AU. See Houseknecht and others (2012a, table 5) for a list of the analog AUs used in this assessment.

Numbers of Undiscovered Oil and Gas Accumulations

The number of undiscovered accumulations was estimated from the discovered and undiscovered accumulations in the analog AUs normalized by area (i.e., accumulation densities) and multiplied by the area of the Siberia Passive Margin AU. Because this AU is similar in age, stratigraphic thickness, and geologic history to the Alaska and Canada passive margins of the Amerasia Basin, the accumulation densities calculated for those areas were assumed to apply to this AU. The minimum number of accumulations was set at 1 because of the paucity of information about the Siberia passive margin. The median number of accumulations was set at 30 and the maximum number at 120. These values were calculated by using the accumulation densities determined for the Canada Passive Margin AU. Although lower than in the Alaska Passive Margin AU (Houseknecht and others, 2012c), the accumulation densities assumed for this AU seem appropriate for an unexplored and very poorly known area.

Although the likely source rocks are thought to be oil-prone marine strata, the factors controlling the ratio of oil and gas in the province are highly uncertain. Therefore the minimum, median, and maximum values for oil/gas mix were set at 0.1, 0.7, and 0.9, values adopted from the Canada Passive Margin AU (Houseknecht and others, 2012c, this volume). From this distribution, estimates for the minimum, median, and maximum numbers of undiscovered accumulations in the Siberia Passive Margin AU consisting mainly of oil are 1, 16, and 108, respectively. Estimates for the minimum, median, and maximum numbers of undiscovered accumulations consisting mainly of gas are 1, 12, and 108, respectively.

Sizes of Undiscovered Oil and Gas Accumulations

The sizes of undiscovered oil and gas accumulations in the AU were estimated from sizes of the selected analogs in the analog database (Charpentier and others, 2008). The minimum field size was set at the CARA minimum field size limit of 50 MMBO (Charpentier and Gautier, 2011; Charpentier, 2016, this volume) and the median oil accumulation size was estimated to be 100 MMBO by comparison with the distribution of field sizes reported in Charpentier and others (2008). The maximum oil accumulation size was estimated to be 800 MMBO on the basis of the sizes of the largest known accumulations in the analog database. The maximum oil accumulation size was adjusted using the province geologist's estimate of the largest oil field size expected in the AU (300 MMBO), which takes into account the geology of the AU. Using an equivalence factor of 6, the minimum, median, and maximum gas accumulation size was set at 300, 600, and 4,800 BCFG, respectively.

Coproduct Ratios and Ancillary Data

Coproduct ratios (gas/oil, NGL/oil, liquids/gas) were estimated from the global averages determined from Charpentier and others (2008). Median gas/oil ratio for undiscovered accumulations was estimated to be 1000 CFG/BO; median NGL/gas ratio was estimated to be 25 BNGL/MMCFG; and median liquids/gas ratio in undiscovered gas accumulations was estimated to be 25 BBL/MMCFG. Based on available seismic data, drilling depths for undiscovered oil accumulations range from a minimum of 500 m to a maximum of 4,000 m and have a median depth of 2,000 m. The same range of drilling depths was estimated for undiscovered gas accumulations. Estimates of water depths were based on publicly available bathymetric maps and determined to range from a minimum of 100 m to a maximum of 2,800 m with a median of 2,000 m.

Results

Probabilistic estimates of volumes of undiscovered, technically recoverable hydrocarbons for the Siberian Passive Margin AU are summarized in table 1. These results include mean estimates of undiscovered resources of 984 MMB of oil, 1,538 BCF of gas and 42 MMB of natural gas liquids in oil fields, and 4,684 BCF of gas and 125 MMB of natural gas liquids in gas fields. The mean largest expected oil field size is about 300 MMBO and the mean largest expected nonassociated gas field size is nearly 2 TCF.

Summary of Assessment Results

The combined results for the Lomonosov-Makarov Province are listed in table 1. Estimated hydrocarbon resources are provided for the Siberian Passive Margin and the Makarov Basin Margin AUs; the Lomonosov Ridge and Podvodnikov and Makarov AUs were not quantitatively assessed owing to their low probabilities of containing resources. These results represent fully risked, undiscovered, technically recoverable, conventional petroleum resources.

The total risked mean undiscovered oil resource for the province is 1.1 BBO, the total mean undiscovered gas resource is nearly 7.2 TCF, and the total mean undiscovered natural gas liquids is 192 MMB. These results indicate that the predominant petroleum resource in the province is gas. Expressing the results as oil equivalents (MMBOE), the total mean estimate of undiscovered resource for the province is 2,491 MMBOE. The median (F50) results of 0 for oil, gas and natural gas liquids shows that the province has less than a 50 percent chance of containing any petroleum resources at or above the minimum accumulation size of 50 MMBOE. Despite the low probability of there being petroleum resources equal to or greater than the minimum accumulation size in the province, the F5 results (that is, the best 5 percent chance) indicate there is a small possibility of large amounts of petroleum resources being present, particularly gas resources (almost 30 TCF). Much of this resource would be expected to occur in the Siberia Passive Margin AU (20 TCF).

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Appendixes

Appendixes are available online only, and may be accessed at https://doi.org/10.3133/pp1824CC

Appendix 1. Input data for Lomonosov Ridge Assessment Unit
Appendix 2. Input data for Makarov Basin Margin Assessment Unit
Appendix 3. Input data for Podvodnikov-Makarov Basin Assessment Unit
Appendix 4. Input data for Siberian Passive Margin Assessment Unit

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