Geology and Assessment of Undiscovered Oil and Gas Resources of the East Greenland Rift Basins Province, 2008

Chapter K of
The 2008 Circum-Arctic Resource Appraisal

Professional Paper 1824

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COVER

Fishing boat in the Ilulissat Icefjord, Disko Bay, West Greenland, about 250 kilometers north of the Arctic Circle. The fjord is notable for its prolific iceberg production; the fast-moving tidal glacier Sermeq Kujalleq (also called Jakobshavn Isbrae) is a major outlet of the Greenland ice sheet. Photo by Flemming G. Christiansen, Geological Survey of Denmark and Greenland.

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Edited by T.E. Moore and D.L. Gautier

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North America

Greenland

North Atlantic Ocean

Eurasia

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Contents

Appendixes

[Available for download at https://doi.org/10.3133/pp1824K]

Figures

Tables

Chapter K

Geology and Assessment of Undiscovered Oil and Gas Resources of the East Greenland Rift Basins Province, 2008

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Abstract

In 2007 the U.S. Geological Survey (USGS) completed an assessment of undiscovered, technically recoverable oil and gas resources in the East Greenland Rift Basins Province of Northeast Greenland. The province was selected as the prototype for the U.S. Geological Survey Circum-Arctic Resource Appraisal (CARA). In collaboration with the Geological Survey of Denmark and Greenland (GEUS), the province was subdivided into nine geologically distinctive areas. Seven of these were defined as Assessment Units (AUs), of which five were quantitatively assessed. These are: North Danmarkshavn Salt Basin, South Danmarkshavn Basin, Thetis Basin, Northeast Greenland Volcanic Province, and Liverpool Land Basin. Jameson Land Basin and the Jameson Land Basin Subvolcanic Extension were defined as AUs but were not quantitatively assessed.

Onshore studies by GEUS and other organizations suggest that at least four stratigraphic intervals may contain potential source rocks for petroleum. The geological history of related areas in western Norway and burial history modeling suggest that Upper Jurassic strata are most likely to contain petroleum source rocks. A wide variety of possible trapping mechanisms are expected within the province. Potential traps in the North Danmarkshavn Salt Basin AU are dominated by structures formed through salt tectonics; those in the South Danmarkshavn Basin and the Northeast Greenland Volcanic Province are characterized by extensional structures and by stratigraphic traps in submarine fan complexes. Prospective inversion structures of Tertiary age are present along the western margin of South Danmarkshavn Basin AU, and the large horst block structures that separate the Danmarkshavn and Thetis Basins may provide numerous opportunities for traps in fault blocks and along various facies-related permeability barriers. Possible reservoirs include shallow marine to nonmarine sandstones of Middle Jurassic age, sandstones in Upper Jurassic synrift deposits, Cretaceous sandstones in submarine fan complexes, sandstones in Paleogene progradational sequences, and in Upper Carboniferous to Lower Permian warm-water carbonate sequences, especially in northern Danmarkshavn Basin. Marine shales are expected to provide the main sealing lithologies in most AUs.

Most of the undiscovered oil, gas, and natural gas liquids are likely to be in the offshore areas of the province and are inferred to belong to an Upper Jurassic Composite Total Petroleum System. The USGS estimated that the East Greenland Rift Basins Province contains approximately (mean) 31,400 million barrels oil equivalent (MMBOE) of oil, natural gas, and natural gas liquids. Of the five assessed AUs, North Danmarkshavn Salt Basin and the South Danmarkshavn Basin are estimated to contain most of the undiscovered petroleum.

Introduction and Province Description

Geological features of northeast Greenland suggest the possibility of large petroleum potential, as well as high uncertainty and risk. The area was the prototype for development of methodology used in the U.S. Geological Survey (USGS) Circum-Arctic Resource Appraisal (CARA), and the Northeast Greenland Rift Basins Province (fig. 1) was the first province to be evaluated. The new study was deemed necessary because of information made available through collaboration with the Geological Survey of Denmark and Greenland (GEUS), which significantly changed the geological understanding of the area. In collaboration with GEUS the province was subdivided into nine geologically distinct areas. From those, seven assessment units (AUs) were formally defined, five of which were quantitatively assessed. The CARA study superseded a previous USGS assessment of northeast Greenland completed in 2000 (Ahlbrandt and others 2005), from which it differs in several important respects: oil estimates were reduced and natural gas estimates were increased to reflect revised understanding of offshore geology. Despite the reduced oil estimates, the CARA indicates that northeast Greenland could be an important future petroleum province.

The East Greenland Rift Basins Province extends for more than 1,200 kilometers (km) from south of the Blosseville

Kyst Basin near 66° N to Kronprins Christian Land near 82º N (fig. 1), an area of approximately 500,000 km^2, most of which lies beneath less than 500 meters (m) of water. The northern and northeastern boundary of the province is set along the approximate southern trace of the Greenland Fracture Zone/ Trolle Land Fault Zone, thus excluding the Wandel Sea Basin (fig. 2). The province is as wide as 600 km; its western boundary follows the approximate limit of sedimentary rocks onshore and its eastern boundary tracks the continent-ocean transition. The province encompasses the sedimentary basins of northeastern Greenland, including Jameson Land Basin (Christiansen and others, 1992; Mathiesen and others, 1995; Stemmerik and others, 1993), and the less well known offshore basins of the northeast Greenland shelf: Danmarkshavn Basin, Thetis Basin (Hamann and others, 2005), Liverpool Land Basin (Larsen, 1990) and the Blosseville Kyst Basin (Larsen, 1985) (fig. 2). The Tertiary volcanic rocks found offshore between 67° and 75° N are included in the province and are presumed to cover thick sedimentary successions.

The Caledonian deformational belt (fig. 2), which formed as a consequence of the closing of the proto-Atlantic Ocean and the collision of the Laurentia and Baltica continents, is known to include more than 4,000 m of intensely folded and faulted sedimentary rocks of Cambrian to Devonian age. For the purposes of this study, deformed Caledonian rocks are assumed to be economic basement; the oldest strata considered in this assessment are Middle to Upper Devonian continental deposits (fig. 3), which accumulated during the crustal relaxation and extensional faulting that followed the Caledonian orogeny. Since the Caledonian collision, northeastern Greenland has been the site of numerous episodes of multi-phase lithospheric extension, the most prominent of which were in the late Permian to Triassic, Late Jurassic to Early Cretaceous, and in mid-Cretaceous time (Surlyk, 1990; Blystad and others, 1995; Doré and others, 1999; Brekke, 2000; Surlyk, 2003), culminating in crustal separation during the Paleocene. The outer (easternmost) part of the shelf has been a passive margin since the early Eocene (Tsikalas and others, 2005).

The petroleum potential of northeast Greenland has long been postulated (Ulmishek, 1984; Haimilia and others, 1990) on the basis of (1) the plate tectonic model of the opening of the North Atlantic Ocean Basin (Kay, 1969; Talwani and Eldholm, 1977; Hinz and others, 1987); (2) investigations of outcrops onshore (Stemmerik and others, 1993; and (3) the geologic similarity of northeastern Greenland and the petroliferous basins of northwestern Europe (Hinz and Schlüter 1980, Larsen 1984). As of 2011, with the exception of a few shallow research cores, the sedimentary basins of the province remain undrilled owing largely to their remote location and the possibility of sea ice any month of the year. The northeast Greenland shelf is of particular interest; potential field data have been used to identify major northeast-trending structural features (Larsen 1984, 1990) and, more recently, these features have been examined in greater detail following analysis of the proprietary KANUMAS seismic data (Hamann and others, 2005). South of Shannon Island, thick Tertiary volcanic rocks of the East Greenland Volcanic Province largely cover the shelf. The Koldewey Platform, on the westernmost part of the shelf, is an area of relatively shallow (2 to 5 km) Caledonian rocks, overlain by a thin sedimentary cover thought to include upper Carboniferous to Permian carbonate rocks and lower Carboniferous siliciclastic sequences (fig. 4). In the eastern part of the Koldewey Platform, the Paleozoic section is overlain by various thicknesses of discontinuous and incompletely preserved Mesozoic strata. In some places, such as on Store Koldewey, Mesozoic rocks directly overlie Caledonian basement.

North-trending en echelon faults separate the Koldewey Platform from the Danmarkshavn Basin, which is a large, deep, northeast-trending sedimentary basin that is bounded by the Koldewey Platform on the west and by Danmarkshavn Ridge on the east (fig. 4). South of Store Koldewey the basin is limited by the Shannon High, a basement horst that probably extends southward beneath the volcanic field. The basin is at least 400 km long in a northeast-southwest dimension, 50 km wide in the south, and 100 km wide at about 78° N. The central axis and principal depocenter of the basin is thought to contain a largely conformable section, more than 13 km thick, of (probable) Devonian to Holocene age sedimentary rocks. Numerous unconformities increase in significance and the sedimentary strata thin and unconformities increase in magnitude northward and westward of the central Danmarkshavn Basin.

Interpretation of the KANUMAS seismic data and unpublished research seismic data acquired by the Alfred Wegener Institute has led to the identification of a major salt province in the northern part of Danmarkshavn Basin (Hamann and others, 2005; W. Jokat, written commun., 2007). The salt is inferred to be of late Carboniferous or possibly earliest Permian age (fig. 3) based upon regional paleogeographic reconstructions (Stemmerik, 2000). The evaporite sequence is, therefore, a likely equivalent to the lower part of the carbonate succession found onshore in North Greenland (Stemmerik, 2000), closely related to similar salt accumulations in Tromsø and Nordkapp Basins in the Barents Sea, and related to the Sverdrup Basin of northern Canada (Larssen and others, 2002). The salt is believed to have accumulated in a rapidly subsiding sag basin along the rift axis between Norway and Greenland (Gudlaugsson and others, 1998).

Danmarkshavn Ridge is a northeast-trending complex of westward dipping fault blocks, which separates Danmarkshavn Basin from Thetis Basin to the east (fig. 4). Known from potential field data and from the KANUMAS seismic records, Danmarkshavn Ridge is 10 to 60 km wide and extends for more than 80 km from a well-defined basement high beneath Tertiary volcanic rocks in the south to a gentle platform at 78° N. The principal controlling fault of Danmarkshavn Ridge, which bounds its eastern margin, has a heave of more than 10 km and a throw of at least 7 km. Hamann and others (2005) estimated that 2 to 3 km of upper Paleozoic and Mesozoic rocks were eroded from the top of the ridge prior to deposition of a Tertiary sedimentary succession that may be as old as Paleocene.

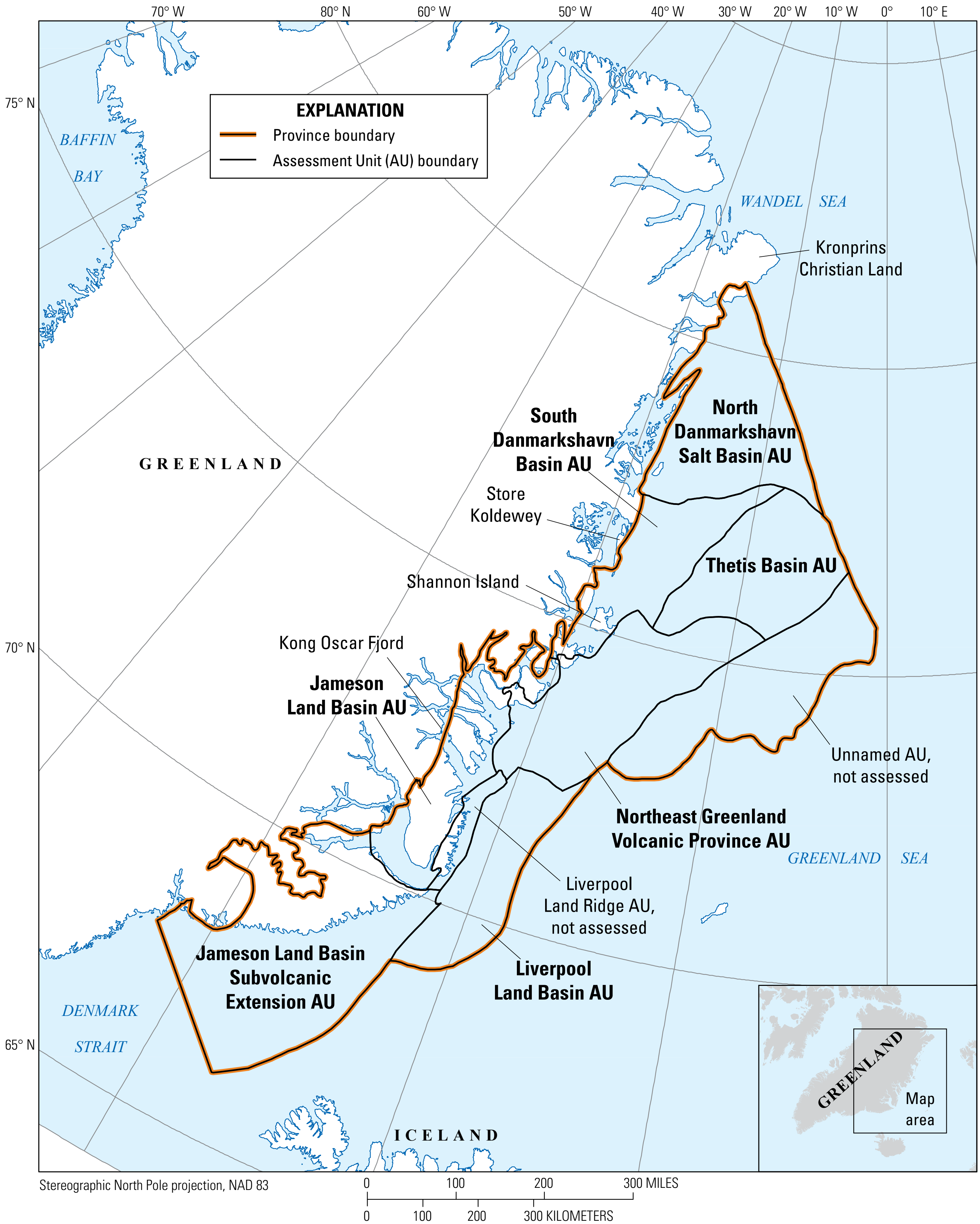


Figure 1. Map showing location of East Greenland Rift Basins Province and its constituent assessment units.

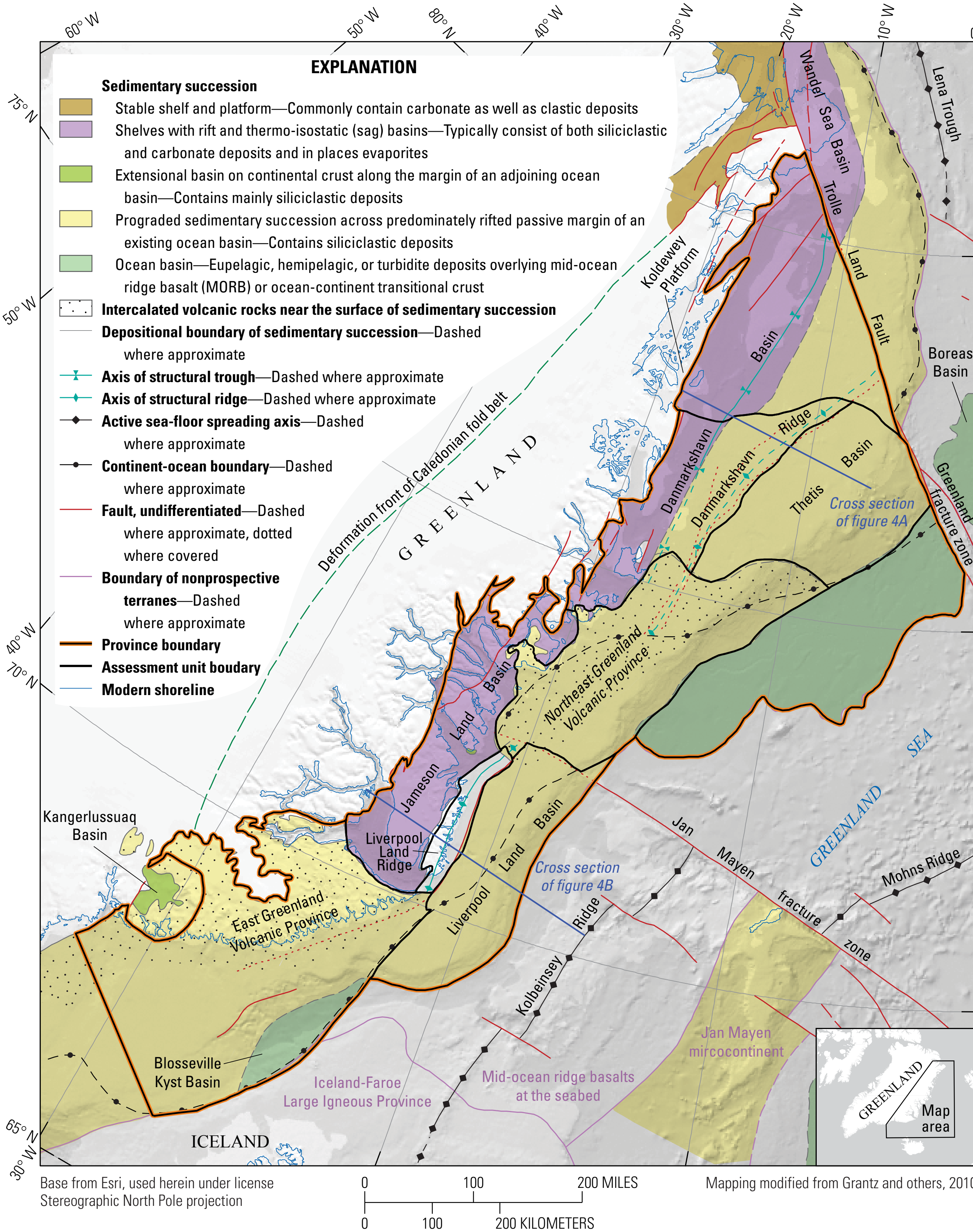


Figure 2. Generalized geologic map of East Greenland Rift Basins Province and surrounding regions (modified from Grantz and others, 2010).

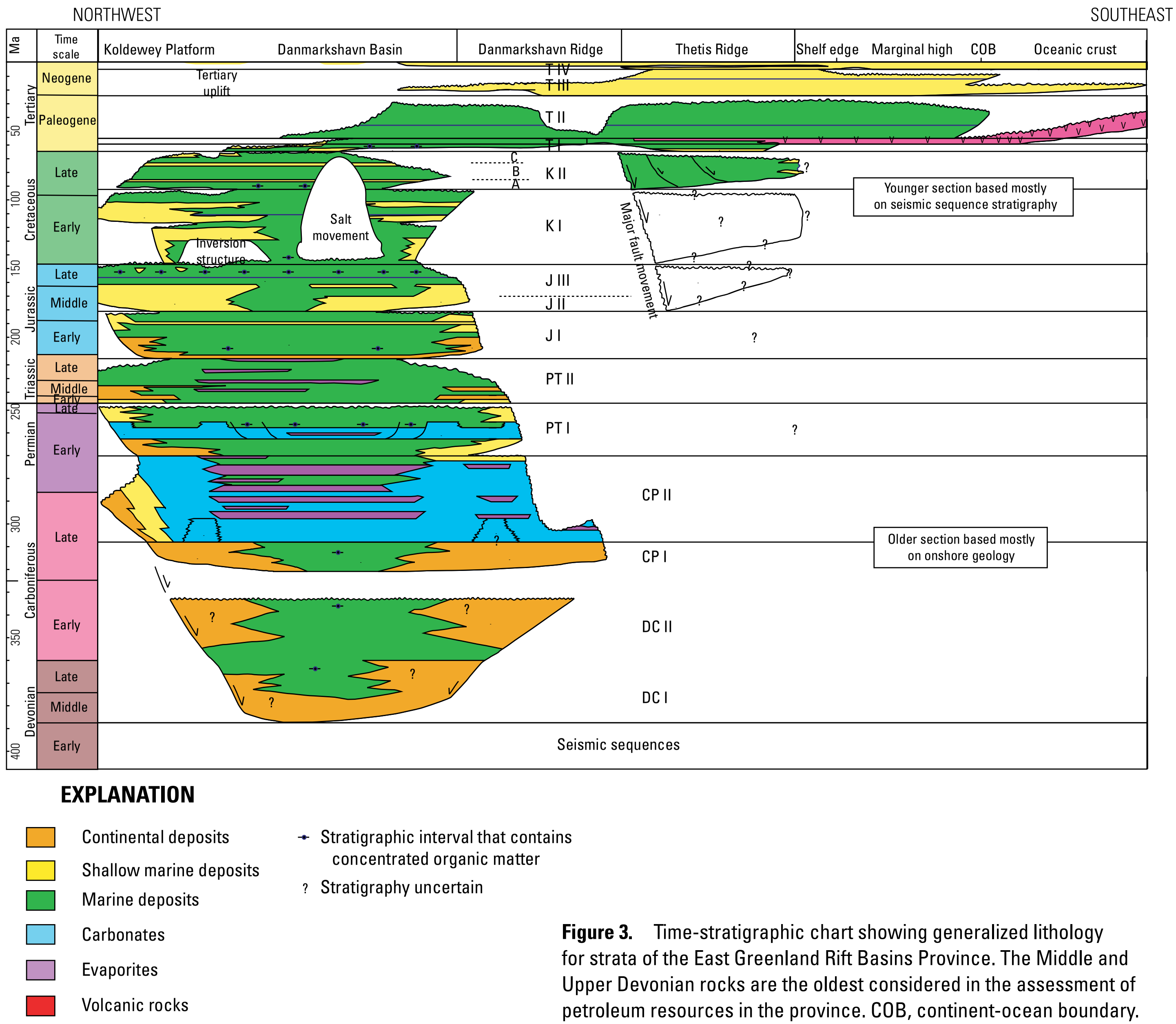


Figure 3. Time-stratigraphic chart showing generalized lithology for strata of the East Greenland Rift Basins Province. The Middle and Upper Devonian rocks are the oldest considered in the assessment of petroleum resources in the province. COB, continent-ocean boundary. Modified from Hamann and others (2005).

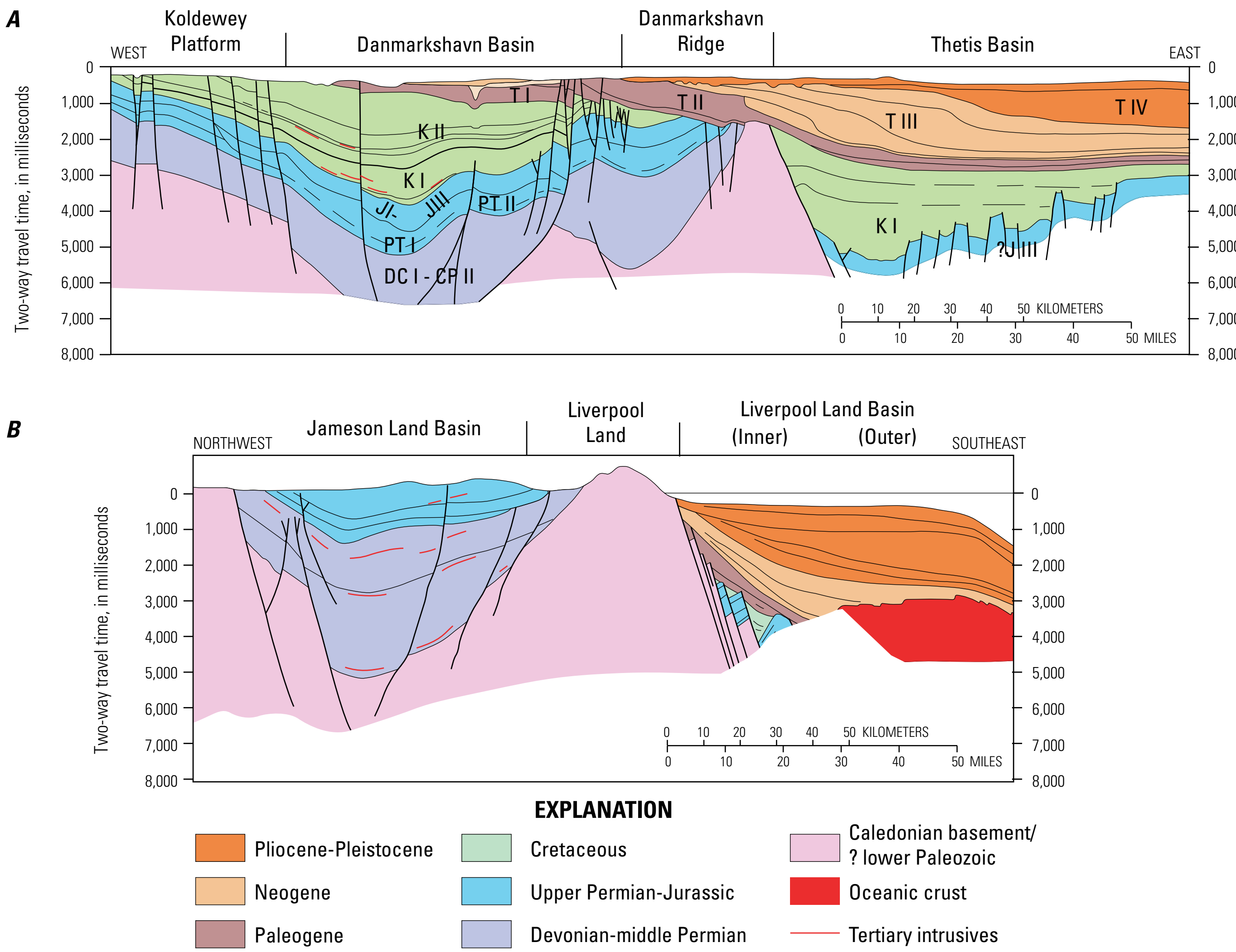


Figure 4. Two simplified cross sections through the northeast Greenland shelf showing the relative thickness of rocks of various ages in basins discussed in the text. Locations of cross sections are shown in figure 2. Stratigraphic intervals (TI, KII, and so on) are identified in the stratigraphic chart in figure 3 and in table 1. Modified from Hamann and others (2005).

Immediately east of Danmarkshavn Ridge, the Thetis Basin (fig. 4) comprises a thick succession of Cretaceous and Tertiary strata that accumulated as rift-sag basin and passive-margin deposits, respectively. Although older sedimentary rocks are probably present, thick Cretaceous age strata fill the basin to the acoustic basement. Thetis Basin is geologically similar in structure and stratigraphic relationships to the Vøring and Møre Basins on the Norwegian continental margin (Scheck-Wenderoth and others, 2007).

South and east of Thetis Basin, the continental shelf is marked by an area of high relief named the “Marginal High” by Hamann and others (2005). The Marginal High is believed to consist of Tertiary volcanic rocks extruded during the initial opening of the Atlantic Basin at the end of the Paleocene (Hinz and others, 1993). South of about 75°30’ N, extrusive rocks of probable Tertiary age inferred from aeromagnetic and seismic data (Larsen, 1990) are interpreted to overlie thick pre-Tertiary sedimentary sequences similar to those north of the volcanic field. Offshore and south of the volcanic field, thick sedimentary rocks have been recognized in seismic data to the east of Liverpool Land. The sedimentary section of Liverpool Land Basin is thickest where it overlies continental crust, thinning to the east across the continent-ocean boundary; the upper 6 km of strata in the Liverpool Land Basin form a prograding sedimentary wedge of Paleogene and Neogene age. South of Liverpool Land Basin, more than 4 km of post-middle Eocene sedimentary rocks overlie Paleogene volcanic rocks, which, in turn, probably rest on Mesozoic and Paleocene sedimentary strata.

For purposes of assessment, the East Greenland Rift Basins Province was subdivided into nine geologically distinctive areas, seven of which were designated as assessment units, of which five were quantitatively assessed. The seven designated assessment units are: (1) Northern Danmarkshavn Salt Basin, (2) Southern Danmarkshavn Basin, (3) Thetis Basin, (4) Northeast Greenland Volcanic Province, (5) Liverpool Land Basin, (6) Jameson Land Basin, and (7) the Jameson Land Basin Subvolcanic Extension (figs. 1, 2).

Petroleum System Elements

Onshore studies suggest that at least four stratigraphic intervals may contain source rocks for liquid petroleum (Christiansen and others, 1992). In consideration of the closely related geological history of western Norway, of outcrops of Jurassic strata in eastern Greenland (Surlyk, 2003), and of the origin and distribution of world petroleum (Ahlbrandt and others, 2005), Upper Jurassic strata in northeastern Greenland are inferred to contain particularly promising source rocks (fig. 5); burial history modeling of postulated Jurassic source rocks in northeast Greenland Shelf is further discussed below.

Possible trapping mechanisms are expected to vary widely across the province. Potential traps in the North Danmarkshavn Salt Basin AU are dominated by structures formed through salt tectonics; those in the South Danmarkshavn Basin and the Northeast Greenland Volcanic Province AU are probably characterized by extensional structures and by stratigraphic traps in submarine fan complexes (Surlyk, 1978). Potentially prospective inversion structures of Tertiary age are present along the western margin of South Danmarkshavn Basin AU; the large horst blocks of the Danmarkshavn Ridge, which separates the Danmarkshavn and Thetis Basins, may provide numerous opportunities for traps, as does the unconformity between Cretaceous and Paleogene strata, and various facies-related permeability barriers. For the purposes of this assessment, Danmarkshavn Ridge, west of its major bounding fault, is included in the South Danmarkshavn Basin AU.

Possible reservoirs are considered most likely within shallow marine to nonmarine sandstones of Middle Jurassic age, in Upper Jurassic syn-rift deposits, in Cretaceous sandstones of the submarine fan complexes, within progradational sequences of Paleogene age, and in upper Carboniferous to lower Permian warm-water carbonate strata, especially in the northern Danmarkshavn Basin. Marine shales are expected to provide the main sealing lithologies in most AUs.

Burial History Modeling

The burial history of potential source rocks in northeast Greenland was analyzed using the commercial burial history modeling software Petromod, version 10, by Integrated Exploration Systems (now owned by Schlumberger Limited). One-dimensional models were built for various selected localities in the Northeast Greenland Rift Basins Province. One of these localities, at the intersection of two KANUMAS seismic lines in the south Danmarkshavn Basin, was selected to model the burial history of the province (fig. 6); input data for the burial history model are given in table 1.

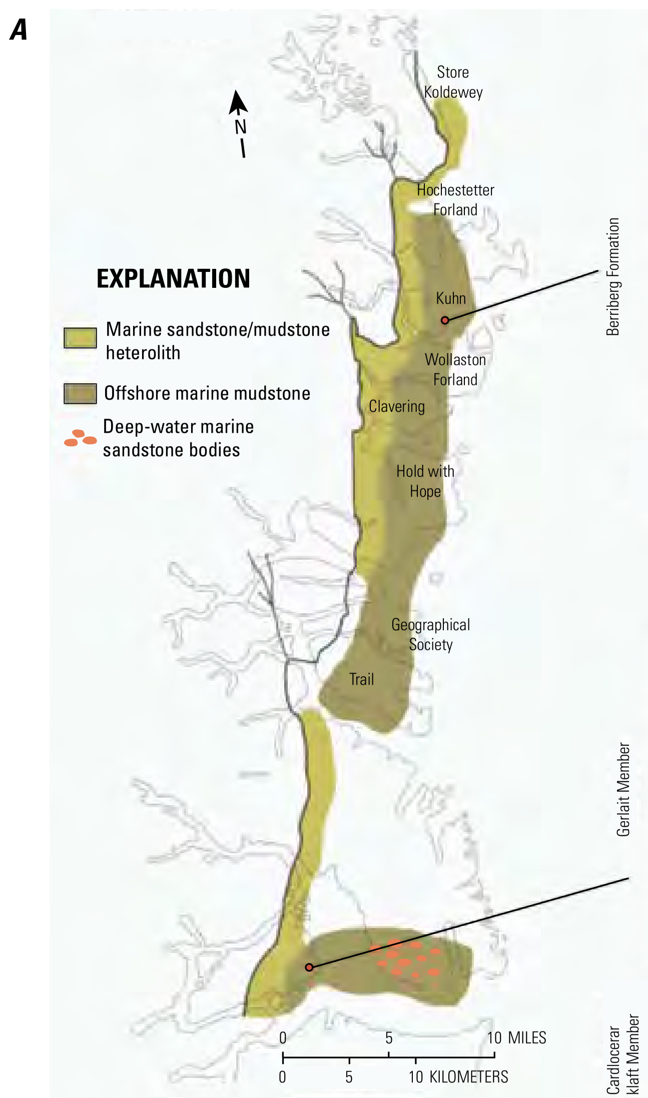
In collaboration with GEUS scientists, approximate time-stratigraphic boundaries were identified on the KANUMAS seismic lines and time-depth relations were estimated using time-depth models from various parts of the Arctic including the Beaufort Sea, the Barents Sea, and the Norwegian Sea. A subsurface geologic model was developed (fig. 7), which incorporated known stratigraphic relations from onshore outcrops in Greenland and from western and northern Norway, which is the conjugate transatlantic margin of northeastern Greenland. Heat flow history was reconstructed from the interpreted tectonic/geological history of the southern Danmarkshavn Basin, and the heat flow model was then compared to and calibrated with interpreted thermal histories from the Norwegian Sea provided by the Norwegian Petroleum Directorate (NPD). Additional inputs for the burial history model include interpretations of episodes of erosion, water depth, and sediment/water interface temperature, and kerogen reaction rates (kinetics).

The burial history model was used to estimate the range of possible thermal maturity to be expected in stratigraphic intervals that have potential source rocks. Particular attention was paid to the interpreted burial and thermal history of postulated Jurassic strata. A map of present day depths to the top of the postulated Jurassic strata was developed in collaboration with GEUS scientists, who have access to the proprietary KANUMAS seismic data, and using publicly available potential field data (fig. 5). When combined with the inferred burial history, the map provides an important tool for interpreting thermal maturity of postulated source rocks at various locations on the northeast Greenland Shelf.

From the burial history model (fig. 6), postulated source rocks of Late Jurassic age are interpreted to have been buried to the oil window over wide areas of the northeast Greenland shelf, and to have been buried to a time-temperature regime of supermaturity with respect to oil generation at any locality deeper than approximately 5 km. Maturation may have occurred as early as the Late Cretaceous in the depocenters of the South Danmarkshavn Basin. In North Danmarkshavn Salt Basin and in areas of South Danmarkshavn Basin that have thinner post-Jurassic sediment, oil maturation probably did not occur until Paleocene time or later.

Summary of Province Assessment Results

Five AUs were included in the assessment of the petroleum potential in the East Greenland Rift Basins Province: North Danmarkshavn Salt Basin, South Danmarkshavn Basin, Northeast Greenland Volcanic Province, Thetis Basin, and Liverpool Land Basin. Assessment Unit boundaries are shown in figures 1 and 2. The Jameson Land Basin and the Jameson Land Basin Subvolcanic Extension AUs were considered to have less than a 10 percent chance of containing a technically recoverable hydrocarbon accumulation larger than the minimum size of 50 million barrels of oil-equivalant oil, gas, and natural gas liquids (50 MMBOE). The high risk was assigned because onshore studies of Jameson Land geology and exploratory drilling in the basin decades ago suggest that possible source rock intervals are relatively poor in concentrated



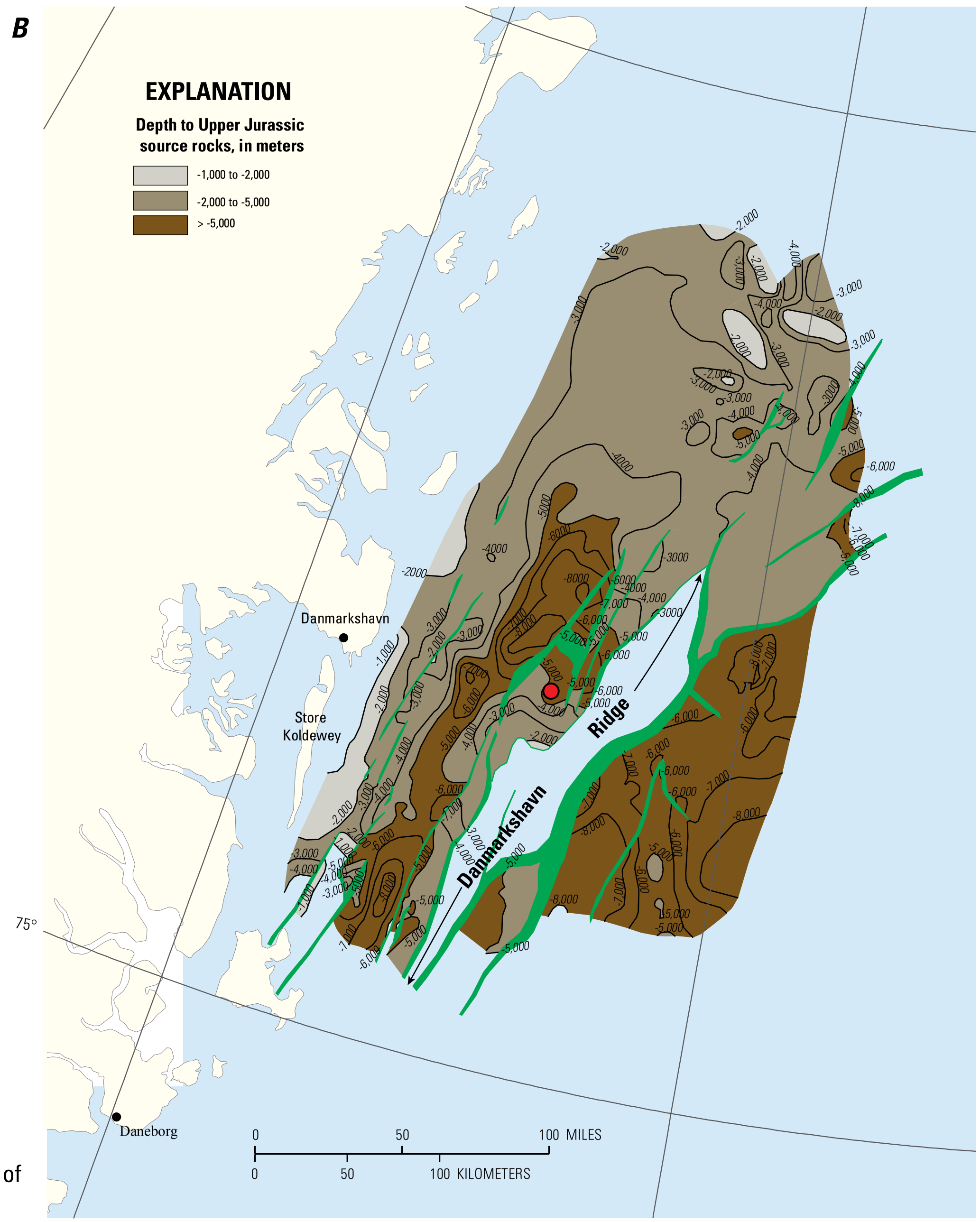


Figure 5. Onshore outcrop facies map (*A*) and depth to top of postulated Upper Jurassic source rocks offshore in the Danmarkshavn and Thetis Basins (*B*). Prepared in cooperation with the Geological Survey of Denmark and Greenland (GEUS). Location of the burial history model illustrated in figure 6 is shown by a red dot.

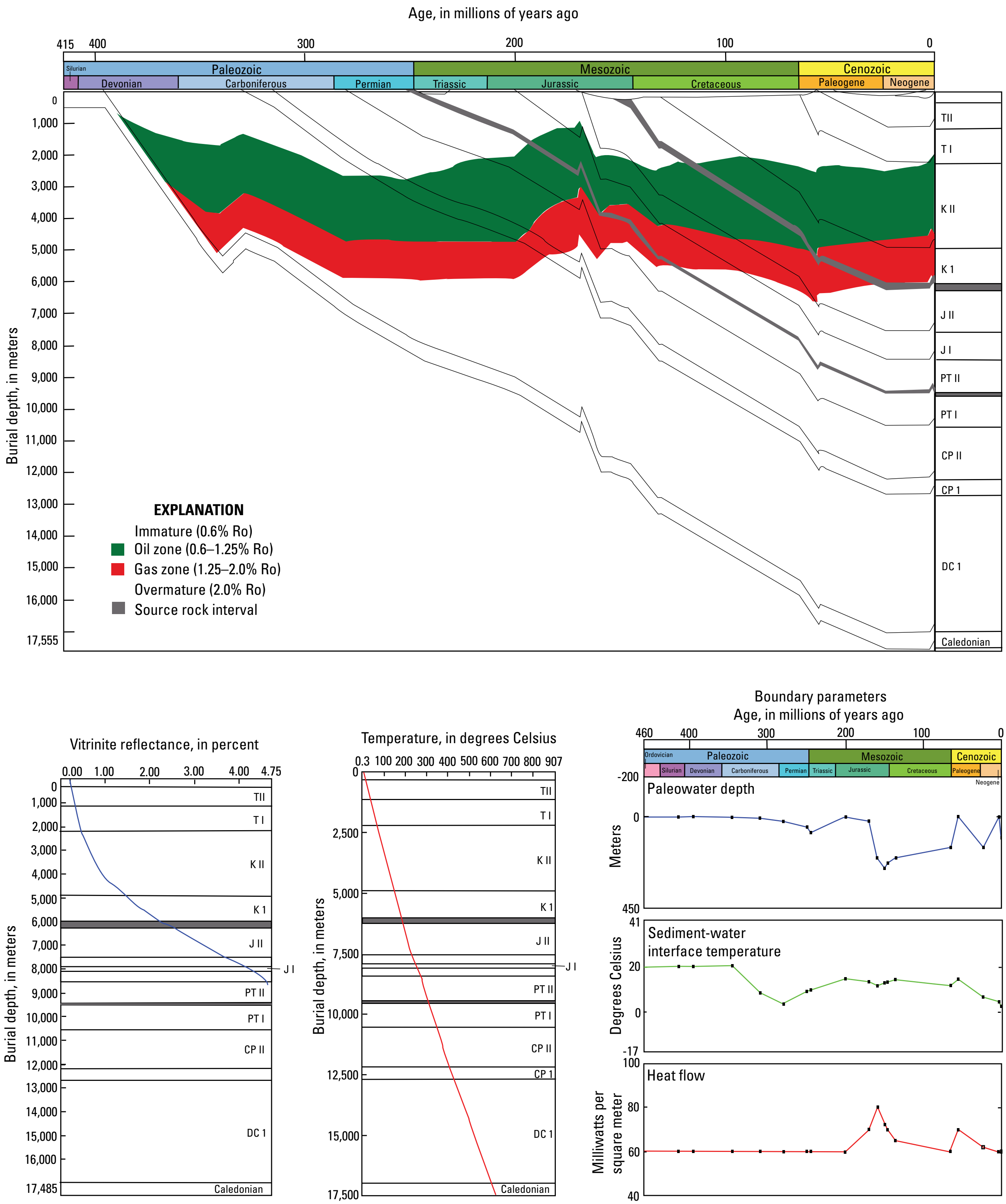


Figure 6. Burial history model and plots showing depths and vitrinite reflectance values (in percent Ro) interpreted for strata in a depocenter in the southern Danmarkshavn Basin. Location of the modeled site is shown on figure 5. Input data for the model are summarized in table 1.

Table 1. Input data for burial history model of Danmarkshavn Basin (shown in fig. 6).

[T, Tertiary; K, Cretaceous; J, Jurassic; PT Permian-Triassic; CP, Carboniferous; DC, Devonian; Ma, million years ago; wt%, weight percent; mgHC/gTOC, milligrams hydrocarbon per gram total organic carbon]

Stratigraphic interval	Top depth, in meters	Bottom depth, in meters	Thick-ness, in meters	Strata eroded, in meters	Begin deposition, Ma	End deposition, Ma	Begin erosion, Ma	End erosion, Ma	Principal lithologies	Petroleum system element	Total organic carbon, in weight percent	Petromod kinetic model	Hydrogen index, in mg HC/g TOC
Sediment surface			0										
T IV	0	330	330		1	0			Silty sandstone	Overburden	0	None	0
TIII	330	330	0	200	23	3	3	2	Sandstone and shale	Reservoir	0	None	0
TII	330	1,130	800	100	55	23	2	1	Sandstone and siltstone	Overburden	0	None	0
TI	1,130	2,210	1,080	100	65	56	56	55	Silty sandstone	Overburden	0	None	0
KII	2,210	4,910	2,700		131	65			Sandstone and siltstone	Reservoir	0	None	0
KI	4,910	6,035	1,125		146	132			Sandstone and conglomerate	Reservoir	0	None	0
JIII	6,035	6,135	100		150	146			Shale	Seal	0	None	0
JIIS	6,135	6,235	100		155	150			Shale	Source	5	Ungerer (1990) (Spekk)-CS	390
JII	6,235	7,535	1,300		169	160			Sandstone and conglomerate	Reservoir	0	None	0
JI	7,535	8,435	900	300	200	170	170	169	Coal and silt-stone	Source	2	Ungerer(1990) T3Åre_CS	150
PTII	8,435	9,435	1,000		245	200			Shale and sand-stone	Reservoir	0	None	0
PTIIS	9,435	9,535	100		250	245			Shale and lime-stone	Source	5	Behar etal(1997)_ T2-CS	350
PTI	9,535	10,535	1,000		280	250			Limestone	Reservoir	0	None	0
CPII	10,535	12,185	1,650		315	280			Limestone and evaporite	Underbur-den	0	None	0
CP1	12,185	12,685	500		329	315			Siltstone	Underbur-den	0	None	0
DC1	12,685	16,985	4,300	700	396	340	340	329	Silstone and shale	Underbur-den	0	None	0
Caledonian	16,985	17,485	500		460	415			Basement rocks	Underbur-den	0	None	0

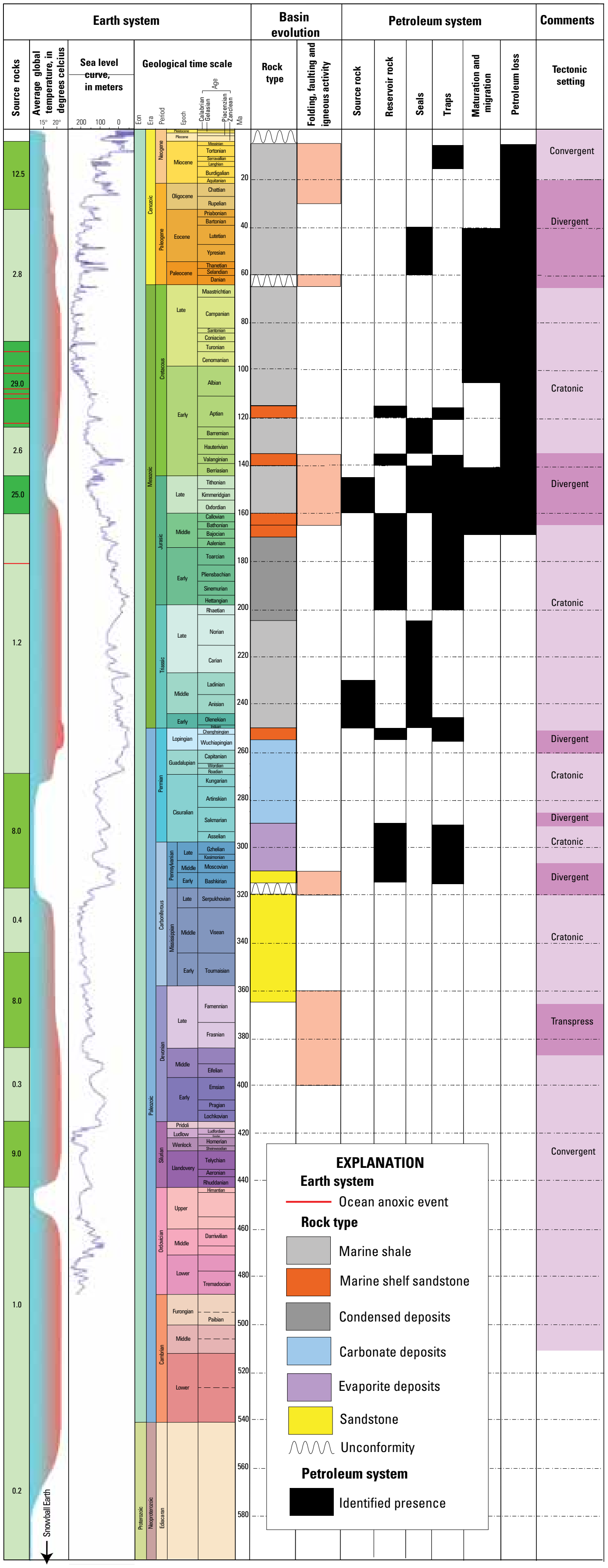


Figure 7. Lithostratigraphic column and total petroleum system events chart showing petroleum system elements for the East Greenland Rift Basins Province. Developed using data from and in collaboration with the Geological Survey of Denmark and Greenland (GEUS). Source rocks column shows the percent of the world's total petroleum reserves generated by source (modified from Ulmishek and Klemme, 1990). Average global temperature data is from Frakes and others (1992) and Barrett (2003). Sea level curve is from Golonka and Kiessling (2002) and Hardenbol and others (1998). Geologic time scale is that of Gradstein and others (2004).

oil-prone organic matter, and have had burial histories that are not conducive to oil generation and preservation. The Jameson Land Basin Subvolcanic Extension AU is probably geologically similar to Jameson Land and therefore shares its geological risks, but has the additional uncertainty of essentially hidden geology, which, in this case, adds to the risk. Following the CARA methodological protocols they were therefore not quantitatively assessed.

Descriptions of the assessed AUs are given in the text below. The probabilistic results of individual AU assessments and the aggregated province assessment of conventional oil and gas accumulations larger than 50 MMBOE are summarized in table 2.

North Danmarkshavn Salt Basin

Assessment Unit Description.—Stratigraphically, the AU includes the entire sedimentary section from the Caledonian basement to the seafloor. Geographically, the AU is bounded by the coast of northeast Greenland on the west; by the eastern boundary fault of Danmarkshavn Ridge on the east; by the southern limit of significant salt deformation on the south, and by the Wandel Sea Basin on the north (figs. 1, 2).

Geological Analysis of Assessment Unit Probability.—The likelihood that the North Danmarkshavn Salt Basin AU contains at least one accumulation greater than the minimum field size of 50 MMBOE is considered to be approximately 60 percent (0.57) based on an interpretation of the principal petroleum system/AU elements, which are discussed below.

Charge.—Regional studies indicate that numerous stratigraphic intervals in northeast Greenland contain organic carbon-rich strata (fig. 3). But for the purposes of assessment, only two intervals, the Lower to Middle Triassic and the Upper Jurassic, were included in the burial history model (fig. 6). The well-known importance of Upper Jurassic source rocks to petroleum generation in the Norwegian Sea and the North Sea suggests that the Upper Jurassic is the most likely petroleum source rock in northeast Greenland as well. Interpretation of regional seismic data and one-dimensional modeling indicates that Upper Jurassic strata have probably entered the oil window in most of North Danmarkshavn Basin; petroleum generation may have begun in the Late Cretaceous. Migration pathways are highly complex due to salt-induced deformation; oil may also have entered the province from the south. A probability of 0.9 was assigned for charge sufficiency in this AU.

Reservoir Rocks, Traps, and Seals.—Fluvio-deltaic sandstones of Middle Jurassic age, equivalent to the Pelion Member of the Vardekløft Formation onshore (Surlyk, 2003), are postulated to be the most important reservoirs in the AU. Other reservoir intervals may include submarine fans of Cretaceous age, Lower Jurassic marine sandstones, and carbonate rocks of late Carboniferous and early Permian age. In addition, reservoir lithologies may include Triassic sandstones and progradational sandstones of Tertiary age. Structural trapping is expected to be predominantly controlled by diapiric salt-induced structures. Also, unconformities and fault traps associated with Late Jurassic extension, inversion anticlines, platform margin stratigraphic and fault block traps related to Paleocene continental breakup, and various stratigraphic traps are anticipated. Seals are expected to be provided by evaporites of late Carboniferous or early Permian age and by marine shales of Jurassic, Cretaceous, and Tertiary age. A probability of 0.9 was assigned for adequacy of reservoirs, traps and seals in this AU.

Timing of Generation of Hydrocarbons and Preservation of Accumulations.—On the basis of initial one-dimensional modeling, oil generation is inferred to have begun in Late Cretaceous time and to have continued episodically until the present in various parts of the AU. Structures that formed prior to migration may have been available for charge. Salt structures formed subsequent to migration may provide traps for remigrated hydrocarbons but may also destroy previously formed accumulations. Significant preservation risk is postulated, owing to (1) complex effects of salt deformation; (2) uncertainty in seal integrity of shale intervals; (3) possible post-oil-window maturity in deeper areas; and (4) gas expansion and oil displacement due to regional late Tertiary uplift. Accordingly, a probability of 0.7 was assigned to adequacy of timing and preservation of fields greater than the minimum size within this AU.

Analogs Used in Assessment

Numbers of Fields.—Interpretation of the proprietary KANUMAS seismic survey and of unpublished seismic sections collected by the Alfred Wegener Institute (W. Jokat, written commun.) suggests that the structural style of North Danmarkshavn Salt Basin is controlled primarily by episodic salt deformation that began as early as Permian time and continued into the Holocene. Therefore, estimation of field density (number of accumulations >50 MMBOE per 1,000 km^2) relied upon the analog field densities of all 18 AUs in the USGS Analog Database (Charpentier and others, 2008) that are classified as having dominant salt-induced structures. This analog set exhibits a nearly uniform distribution across the range of field densities.

Field Size Distribution.—The minimum field size required for a full assessment under the Circum-Arctic Resource Appraisal is 50 MMBOE. The median field size (about 115 MMBOE) is similar to the median field size of the 18 AUs in the USGS Analog Database that report a predominance of salt-induced structures. The low-probability maximum field size truncation point of 20 billion BOE (barrels of oil equivalent) reflects the largest value from the analog set, excluding one outlying value judged to be inappropriate for this AU because it occupies a structure larger than any known subsurface feature in this area of Greenland.

Estimated Maximum Field Size.—The province geologist recommended an expected maximum field size of 2 to 3 billion BOE, based on the distribution of maximum field sizes

Table 2. Estimated volumes of undiscovered petroleum resources in the East Greenland Rift Basins Province.

[Estimates are for risked, undiscovered, technically recoverable resources. F95 represents a 95-percent chance of at least the amount tabulated; other fractiles are defined similarly. Std. dev., standard deviation; N/A, not assessed]

Assessment unit name	Assessment unit probability
North Danmarkshavn Salt Basin	0.648
South Danmarkshavn Basin	0.72
Northeast Greenland Volcanic Province	0.256
Thetis Basin	0.486
Liverpool Land Basin	0.288
Jameson Land Basin	0.072
Jameson Land Basin Subvolcanic Extension	0.042

Assessment unit name	F95	F50	F5	Mean	Std. dev.
Oil, in million barrels (MMBO)					
North Danmarkshavn Salt Basin	0.00	1,989.17	11,793.38	3,274.31	4,236.50
South Danmarkshavn Basin	0.00	3,228.45	13,995.75	4,384.12	4,822.34
Northeast Greenland Volcanic Province	0.00	0.00	2,757.09	497.30	1,024.28
Thetis Basin	0.00	0.00	2,095.35	537.01	775.99
Liverpool Land Basin	0.00	0.00	1,122.37	209.38	453.16
Jameson Land Basin	N/A	N/A	N/A	N/A	N/A
Jameson Land Basin Subvolcanic Extension	N/A	N/A	N/A	N/A	N/A
Associated/dissolved gas, in billion cubic feet (BCFG)					
North Danmarkshavn Salt Basin	0.00	3,827.38	26,779.18	7,255.43	11,198.91
South Danmarkshavn Basin	0.00	6,325.41	32,081.29	9,700.31	12,848.42
Northeast Greenland Volcanic Province	0.00	0.00	6,212.23	1,105.14	2,467.25
Thetis Basin	0.00	0.00	4,907.85	1,184.23	1,910.65
Liverpool Land Basin	0.00	0.00	2,528.33	463.98	1,146.87
Jameson Land Basin	N/A	N/A	N/A	N/A	N/A
Jameson Land Basin Subvolcanic Extension	N/A	N/A	N/A	N/A	N/A
Natural gas liquids, in million barrels (MMBNGL)					
North Danmarkshavn Salt Basin	0.00	264.24	2,123.16	569.91	1,042.78
South Danmarkshavn Basin	0.00	448.63	2,603.36	761.06	1,183.48
Northeast Greenland Volcanic Province	0.00	0.00	492.13	86.98	224.85
Thetis Basin	0.00	0.00	397.48	92.86	169.52
Liverpool Land Basin	0.00	0.00	199.66	36.67	106.04
Jameson Land Basin	N/A	N/A	N/A	N/A	N/A
Jameson Land Basin Subvolcanic Extension	N/A	N/A	N/A	N/A	N/A

Table 2. Estimated volumes of undiscovered petroleum resources in the East Greenland Rift Basins Province.—Continued.

Assessment unit name	F95	F50	F5	Mean	Std. dev.
Nonassociated gas, in billion cubic feet (BCFG)					
North Danmarkshavn Salt Basin	0.00	23,820.21	107,408.66	32,755.65	37,472.29
South Danmarkshavn Basin	0.00	19,343.89	83,621.43	26,251.49	28,802.63
Northeast Greenland Volcanic Province	0.00	0.00	16,550.52	3,002.67	6,168.58
Thetis Basin	0.00	0.00	12,488.54	3,206.45	4,631.31
Liverpool Land Basin	0.00	0.00	6,739.63	1,254.71	2,689.12
Jameson Land Basin	N/A	N/A	N/A	N/A	N/A
Jameson Land Basin Sub-volcanic Extension	N/A	N/A	N/A	N/A	N/A
Liquids, in million barrels (MMBL)					
North Danmarkshavn Salt Basin	0.00	2,283.61	10,729.86	3,237.32	3,855.86
South Danmarkshavn Basin	0.00	1,843.72	8,362.22	2,598.15	3,002.90
Northeast Greenland Volcanic Province	0.00	0.00	1,650.81	297.05	621.12
Thetis Basin	0.00	0.00	1,251.14	317.40	472.30
Liverpool Land Basin	0.00	0.00	672.21	124.18	276.72
Jameson Land Basin	N/A	N/A	N/A	N/A	N/A
Jameson Land Basin Sub-volcanic Extension	N/A	N/A	N/A	N/A	N/A
Largest oil, in MMBL					
North Danmarkshavn Salt Basin	255.82	1,265.79	7,394.35	2,163.88	2,550.58
South Danmarkshavn Basin	348.86	1,524.42	8,102.34	2,468.80	2,679.85
Northeast Greenland Volcanic Province	167.95	451.69	1,522.42	590.02	448.71
Thetis Basin	106.55	293.52	1,073.00	399.39	334.64
Liverpool Land Basin	87.61	233.98	909.46	329.63	297.70
Jameson Land Basin	N/A	N/A	N/A	N/A	N/A
Jameson Land Basin Sub-volcanic Extension	N/A	N/A	N/A	N/A	N/A
Largest nonassociated gas, in BCFG					
North Danmarkshavn Salt Basin	2,733.71	11,648.60	57,222.01	18,000.58	18,155.41
South Danmarkshavn Basin	2,071.86	9,249.21	49,214.88	14,947.77	16,382.29
Northeast Greenland Volcanic Province	1,005.38	2,704.66	9,038.30	3,525.18	2,675.45
Thetis Basin	635.96	1,761.72	6,385.82	2,381.27	1,978.15
Liverpool Land Basin	524.04	1,399.48	5,436.25	1,974.23	1,792.23
Jameson Land Basin	N/A	N/A	N/A	N/A	N/A
Jameson Land Basin Sub-volcanic Extension	N/A	N/A	N/A	N/A	N/A

from the analog set. This size is consistent with the largest field in the geologically related Central Graben of the North Sea (Ekofisk oil field), which also has salt-induced structures.

Oil Versus Gas Fields, Ancillary Properties, and Coproduct Ratios.—As there are no direct data concerning the distribution of oil, gas, and related properties in northeastern Greenland, the assessment relied on global statistical averages from the USGS Analog Database (Charpentier and others, 2008) and from the specific analog of the oil and gas fields of the Halten Terrace AU in the Norwegian conjugate margin of the North Atlantic Basin, the geographically closest assessment unit to northeastern Greenland.

South Danmarkshavn Basin

AU Description.—Stratigraphically, the South Danmarkshavn Basin AU includes the entire sedimentary section from the Caledonian basement to the seafloor. Geographically, the AU is bounded by the coast of northeast Greenland on the west; by the eastern boundary fault of Danmarkshavn Ridge on the east; by the southern limit of extensive salt deformation on the north, and by the northern limit of volcanic cover on the south (see figs. 1, 2).

Geological Analysis of Assessment Unit Probability.—The likelihood that the South Danmarkshavn Basin AU contains at least one accumulation greater than the minimum field size of 50 MMBOE is considered to be approximately 70 percent (0.729) on the basis of interpretation of principal petroleum system/AU elements, which will be discussed below.

Charge.—Source rocks may include upper Carboniferous lacustrine shales, upper Permian marine marls, Lower Jurassic lacustrine shales, and Upper Jurassic marine shales. Interpretation of regional seismic data and one-dimensional modeling indicates that Upper Jurassic strata have probably entered the oil window in all areas of the AU except on the western margin, on and adjacent to the Koldewey Platform. In some parts of the AU, the Upper Jurassic rocks may have entered the oil window as early as the Late Cretaceous. In the deeper parts of the AU, especially where the Upper Jurassic strata are deeper than 5,000 m, it is likely that these source rocks have passed through the oil window and are now supermature with respect to oil generation. KANUMAS seismic data and 1-D modeling indicate that Upper Jurassic strata are buried through the oil window in the deepest part of Danmarkshavn Basin; oil generation began in the Late Cretaceous. Elsewhere, the Upper Jurassic strata entered the oil window at various times from the Late Cretaceous through the Neogene. Principal migration pathways are upward and westward toward the Koldewey Platform and upward and eastward toward Danmarkshavn Ridge. A probability of 0.9 was assigned for charge sufficiency in this AU.

Reservoir Rocks, Traps, and Seals.—Fluvio-deltaic sandstones of Middle Jurassic age are postulated to be the most important reservoirs in this AU. Other reservoir intervals may include submarine fans of Cretaceous age, Lower Jurassic marine sandstones, and carbonate rocks of Late Carboniferous and early Permian age. In addition, reservoir lithologies may include Triassic sandstones and progradational sandstones of Tertiary age. Unconformities and fault traps associated with Late Jurassic extension, inversion anticlines along the western margin of the AU, and platform margin stratigraphic and fault-block traps (especially on the western flank of Danmarkshavn Ridge), are related to Paleocene continental breakup. Stratigraphic traps associated with channelized sandstones in fans and progradational sequences are to be expected. Seals are anticipated to be provided by marine shales of Jurassic, Cretaceous or Tertiary age. A probability of 0.9 was assigned for adequacy of reservoirs, traps and seals in this AU.

Timing of Generation of Hydrocarbons and Preservation of Accumulations.—The likelihood of Late Jurassic source rocks and oil generation in Cretaceous and later time suggests a timing risk for pre-Jurassic reservoirs, except in structurally high positions on Koldewey Platform and on the flanks of Danmarkshavn Ridge. Significant preservation risk to some reservoirs and traps reflects (1) uncertainty in the seal integrity of shale intervals; (2) post-oil-window maturity that affects hydrocarbon phase and reservoirs in deeper areas; and (3) gas expansion and oil displacement resulting from Cenozoic uplift on Koldewey Platform. Nevertheless, a probability of 0.9 was assigned to adequacy of timing and preservation of one or more fields greater than the minimum size within this AU.

Analogs Used in Assessment

Numbers of Fields.—Interpretation of the proprietary KANUMAS seismic survey and work on outcrops onshore suggest that the structures controlling field size distribution derive principally from various episodes of tectonic extension and rift/sag subsidence, which accommodated the deposition of thick Cretaceous submarine fan complexes and formation of the Danmarkshavn Ridge. The estimated minimum number of accumulations in the South Danmarkshavn Basin AU is derived from the full range of field densities of the 32 rift/sag basin AUs in the USGS Analog Database (Charpentier and others, 2008). The maximum field densities in the analog set are consistent with those observed in the Central Graben and Viking Graben of the North Sea, which, together with the Halten Terrace, are the geologically most similar basins known to the assessors.

Field Size Distribution.—The minimum field size required for a full assessment under the Circum-Arctic Resource Appraisal is 50 MMBOE. The median value reflects the approximate midpoint in the median sizes of the 32 rift/sag basin AUs in the USGS Analog Database. The low-probability upper truncation of the log normal distribution was selected such that the largest of the inversion structures on the western margin of the AU would exhibit four-way closure and be filled to spill point (approximately 35 billion BOE).

Estimated Maximum Field Size.—In the province geologist's judgment, the geological setting of the South Danmarkshavn AU, being a rift/sag basin filled largely by

Cretaceous-age submarine fan deposits, suggests the presence of an accumulation of similar size to the Forties oil field of the Central Graben in the North Sea (Wills, 1991). Therefore, the province geologist expects that, if charged, there is a 50 percent chance of an accumulation of approximately 4 billion BOE.

Oil Versus Gas Fields, Ancillary Properties, and Coproduct Ratios.—The input values relied upon global statistical averages from the USGS Analog Database (Charpentier and others, 2008) and the specific analog of the oil and gas fields from the Halten Terrace AU of the Norwegian Sea, which were believed to have the most similar source-rock burial history of any previously studied AUs.

Northeast Greenland Volcanic Province

Assessment Unit Description.—Stratigraphically, the Northeast Greenland Volcanic Province AU includes the entire sedimentary section from the basement to the seafloor. Geographically, the AU is bounded by the Greenland Platform on the west, by the continent-ocean boundary on the east, by the north limit of pervasive volcanic rocks on the north, and by the south limit of volcanic cover near Kong Oscar Fjord on the south (figs. 1, 2).

Geological Analysis of Assessment Unit Probability.—The likelihood that South Danmarkshavn Basin extends, uninterrupted, beneath the Paleocene volcanic rocks was judged to be about 0.5. If present, the likelihood that the extended South Danmarkshavn Basin AU contains at least one accumulation greater than the minimum field size of 50 MMBOE is considered to be approximately 70 percent (0.729). Therefore, the combined probability for the existence of at least one accumulation of the minimum size is approximately 0.365.

Analogs Used in Assessment.—South Danmarkshavn Basin AU is used as an internal analog; the assessment of the Northeast Greenland Volcanic Province is based upon the scenario that the geological properties of the South Danmarkshavn Basin AU extend beneath the Paleocene volcanic cover of the Northeast Greenland Volcanic Province.

Thetis Basin

Assessment Unit Description.—Stratigraphically, the Thetis Basin AU is defined to include all strata from at or below the acoustic basement to the seafloor. Geographically, the AU extends from the main boundary fault of Danmarkshavn Ridge on the west to the continent-ocean boundary or ocean-continental transition zone on the east, and from the southern limit of significant salt deformation on the north to the northeastern limit of volcanic cover on the south and southwest (figs. 1, 2).

Geological Analysis of Assessment Unit Probability.—The overall likelihood that the Thetis Basin AU contains at least one accumulation of 50 MMBOE or greater is judged to be approximately 45 percent (0.448) based on an interpretation of principal petroleum system/AU elements, which are discussed below.

Charge.—Source rocks may include deeply buried Upper Jurassic marine shales, as well as marine shales of Cretaceous or Tertiary age. Lower Cretaceous and older strata probably entered the oil window in Paleocene time. Late Cretaceous and Paleogene strata may have entered the oil window during the Neogene; most Mesozoic strata have been buried through the oil window and are now supermature with respect to oil generation. Postulated migration pathways are upward into overlying Tertiary progradational sequences and westward to the margin of Danmarkshavn Ridge or eastward to the Marginal Uplift. A probability of 0.8 was assigned for charge adequacy for this AU.

Reservoir Rocks, Traps, and Seals.—Channelized sandstones and fans in eastward-advancing Tertiary progradational strata and sandstones in Cretaceous submarine fan complexes deposited in the pre-Paleogene rift/sag basin are postulated to be the principal reservoir rocks of this AU. Trapping geometries are mainly stratigraphic traps associated with the Tertiary progradational strata and the rift/sag basin fill of Mesozoic age. In addition, the possibility exists for traps in fault blocks along the margin of Danmarkshavn Ridge and for unconformity traps along the eastern marginal high. Seals are intraformational within the stratigraphic traps, and ultimate top seals are provided by shales of Tertiary age. A probability of 0.8 was assigned to the adequacy of reservoir lithologies and trap geometries sufficient to contain at least one accumulation of the minimum size within the AU.

Timing of Generation of Hydrocarbons and Preservation of Accumulations.—In comparison with other AUs in the East Greenland Rift Basins Province, hydrocarbon generation and migration in the Thetis Basin would have been relatively late in the burial history. Late generation as a result of progradation of thick Cretaceous and Tertiary strata is considered beneficial to timing and preservation. Preservation of oil is extremely unlikely in Mesozoic strata because of their high temperature exposure due to deep burial during the Cenozoic. Siliciclastic strata may be insufficient to provide effective seals for gas accumulations. For this reason a probability of 0.7 was assigned for adequacy of timing and preservation of one accumulation of minimum size within the AU.

Analogs Used in Assessment

Numbers of Fields.—The USGS Analog Database (Charpentier and others, 2008) was searched for analogs in slope, clinoform, and turbidite depositional settings and in rifted passive margins. The full distribution of field densities from those analogs was used to estimate the range of numbers of undiscovered fields within the AU.

Field Size Distribution.—Field sizes in the USGS Analog Database (Charpentier and others, 2008) from slope, clinoform, and turbidite depositional settings and from the rifted-passive-margin tectonic settings were considered, as were several specific analogs from the margins of the Atlantic basin, including the Vøring and Møre Basins. The minimum field size required for a full assessment under the Circum-Arctic Resource Appraisal is 50 MMBOE; the median value was chosen from the central tendency of the analog sets. The truncation point of the log-normal field size distribution was set at approximately 8 billion BOE, consistent with the absolute maximum field size in the analog set.

Estimated Maximum Field Size.—The maximum field size was estimated based on review of the limited geological information available for Thetis Basin, including its distal setting compared to Southern Danmarkshavn Basin, the great thickness and exceedingly deep burial of much of the Cretaceous rift/sag basin fill, and the uncertain lithologies of the Tertiary progradational strata. The province geologist estimated a probability of 0.5 that an accumulation of 800 MMBOE or more might be present within the AU. This size is the median of maximum field sizes among the analog basins used in assessment of the Thetis Basin.

Oil Versus Gas Fields, Ancillary Properties, and Coproduct Ratios.—These parameters were estimated in reference to the specific analog of hydrocarbon fill observed in fields of the Halten Terrace on the Norwegian conjugate margin, as discussed above, and from global statistical averages.

Liverpool Land Basin

Assessment Unit Description.—Stratigraphically, the Liverpool Land Basin AU includes all strata from the acoustic basement to the seafloor. Geographically, the AU extends from the Liverpool Land uplift on the west, to the continent-ocean boundary on the east and southeast. The Liverpool Land Basin AU extends northward to the Northeast Greenland Volcanic Province (see figs. 1, 2).

Geological Analysis of Assessment Unit Probability.—The overall likelihood that the Liverpool Land Basin AU contains at least one accumulation of 50 MMBOE or greater is judged to be approximately 20 percent (0.224) on the basis of an interpretation of the principal petroleum system and AU elements, which are discussed below.

Charge.—Source rocks are speculated to include now deeply buried Upper Jurassic marine shales, as well as shales of Cretaceous or Tertiary age. Initial one-dimensional modeling suggests that Cretaceous and older strata probably entered the oil window in the Neogene. Upper Cretaceous and Paleogene strata may also have entered the oil window during the Neogene; most Mesozoic strata have been buried through the oil window and are now supermature with respect to oil generation. Postulated migration pathways are upward into overlying Cenozoic progradational sequences and westward to the margin of Liverpool Land and eastward beyond the continent-ocean boundary. Because of the doubtful presence of Upper Jurassic strata, a probability of 0.4 for charge adequacy was assigned to this AU.

Reservoir Rocks, Traps, and Seals.—Channelized sandstones and fans in eastward-advancing Tertiary progradational strata are postulated to be the principal reservoir rocks of this AU. Trapping geometries are mainly stratigraphic traps associated with the Tertiary progradational strata. In addition, the possibility exists for traps in fault blocks along the margin of Liverpool Land and for unconformity traps along the eastern transition to the continent-ocean boundary. Seals are intraformational within the stratigraphic traps, and ultimate top seals are provided by shales of Neogene age. A probability of 0.7 was assigned to the adequacy of reservoir lithologies and trap geometries sufficient to contain at least one accumulation of the minimum size within the Liverpool Land Basin AU.

Timing of Generation of Hydrocarbons and Preservation of Accumulations.—Generation and migration is believed to have taken place as late as Neogene time, as a result of burial beneath thick Tertiary progradational strata. However, the siliciclastic strata of the Neogene succession may be insufficient to provide effective seals for gas accumulations. For this reason a probability of 0.8 was assigned for adequacy of timing and preservation of one accumulation of minimum size within the AU.

Analogs Used in Assessment

Numbers of Fields.—The USGS Analog Database (Charpentier and others, 2008) was searched for analogs in slope, clinoform and turbidite depositional settings and in rifted passive margins. The full distribution of field densities from those analogs was used to estimate the range of numbers of undiscovered fields within the AU.

Field Size Distribution.—Field sizes of analog AUs having similar slope, clinoform, and turbidite depositional systems within rifted passive margin tectonic settings were considered, as were several specific analogs from the margins of the Atlantic Ocean Basin, including the Vøring and Møre Basins. The minimum field size necessary for assessment was set by the CARA protocol; the median value was chosen from the central tendency of the analog sets. The truncation point of the log-normal field size distribution was set at approximately 8 billion BOE, consistent with the absolute maximum field size in the analog set.

Estimated Maximum Field Size.—The maximum field size was estimated from the extremely limited geological information available for Liverpool Land Basin; it has a distal setting compared to Southern Danmarkshavn Basin, exceedingly deep burial of pre-Tertiary strata, and uncertain lithologies of the progradational systems. The province geologist estimated a probability of 0.5 that an accumulation of 800 MMBOE or more might be present within the AU. This size is the median value for maximum field sizes within the searched analog sets.

Oil Versus Gas Fields, Ancillary Properties, and Coproduct Ratios.—These parameters were estimated by analogy of hydrocarbon fill in fields of the Halten Terrace on the Norwegian conjugate margin and from global statistical averages.

Results

Although the risks and uncertainties are high, northeast Greenland may contain large quantities of recoverable petroleum. The entire East Greenland Rift Basins Province is estimated to contain about 31.4 BBOE oil, gas, and natural gas liquids, thus ranking fourth among the 25 assessed CARA provinces with quantitatively assessed resources. The undiscovered, technically recoverable oil and gas resources are estimated to be almost entirely offshore and concentrated in two assessment units: (1) South Danmarkshavn Basin, with a mean estimate of 4.4 BBO and 26.3 TCF of gas, and (2) the North Danmarkshavn Basin, with a mean estimate of 3.3 BBO and 32.7 TCF of gas. Much smaller resource volumes are estimated in the other quantitatively assessed AUs.

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Appendixes

Appendixes are available online only, and may be accessed at https://doi.org/10.3133/pp1824K

Appendix 1. Input data for the North Danmarkshavn Salt Basin Assessment Unit
Appendix 2. Input data for the South Danmarkshavn Basin Assessment Unit
Appendix 3. Input data for the Northeast Greenland Volcanic Province Assessment Unit
Appendix 4. Input data for the Thetis Basin Assessment Unit
Appendix 5. Input data for the Liverpool Land Assessment Unit
Appendix 6. Input data for the Jameson Land Basin Assessment Unit
Appendix 7. Input data for the Jameson Land Basin Subvolcanic Extension Assessment Unit

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