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Geology and Assessment of Undiscovered Oil and Gas Resources of the Vilkitskii Basin Province, 2008

Chapter Z of
The 2008 Circum-Arctic Resource Appraisal

Professional Paper 1824

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

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

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

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DAVID BERNHARDT, Acting Secretary

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Chapter Z

Geology and Assessment of Undiscovered Oil and Gas Resources of the Vilkitskii Basin Province, 2008

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Abstract

The Vilkitskii Basin is a separate petroleum province that lies beneath the continental shelf of the East Siberian Sea east of the New Siberian Islands and northwest of Wrangel Island. It is a basin known only on the basis of gravity data and three seismic profiles. A small, southern part of the basin overlies the Brooks Range–Chukotka late Mesozoic-early Paleogene orogenic belt, but most of the basin lies north of that belt. Its regional setting suggests that it may have similarities to other post-orogenic (successor) basins on the East Siberian Shelf as well as to foreland, rift-sag, and passive margin basins lying north of the orogenic belt such as the North Slope, North Chukchi and Podvodnikov Basins.

Although the basin's petroleum potential is poorly known, extremely thick sediments, diapiric structures, and gas plumes interpreted from a seismic profile are considered favorable features for petroleum presence and imply that there may be an active petroleum system. An overall probability of about 30 percent of at least one petroleum accumulation >50 MMBOE (million barrels of oil equivalent) was determined based on estimated probabilities of the occurrence of petroleum source, adequate reservoir, trap and seal, and favorable timing. A single assessment unit (AU) was defined and assessed, resulting in mean estimates of undiscovered, technically recoverable resources that include about 100 million barrels of oil and 5,500 billion cubic feet of nonassociated gas.

Introduction

The Vilkitskii Basin is one of seven sedimentary basins situated on the continental shelf of the East Siberian and western Chukchi Sea (fig. 1). It lies east of the New Siberian Islands between the East Siberian Sea Basin and the Wrangel Foreland-North Chukchi Basins and northwest of Wrangel Island and Long Strait Basin. It has an elongate northwesterly-tapering trend with maximum dimensions of 250 by 900 km and covers an area of 167,000 km^2. It is located entirely offshore in 25- to 400-m water depths and lies well north of the Arctic Circle (fig.1). For purposes of this assessment, the Vilkitskii Basin is designated as both a province and assessment unit (AU).

Geologic Setting and Stratigraphy

Limited geologic and geophysical evidence indicates that Vilkitskii Basin is a hybrid basin. Its southern quarter, overlying the Brooks Range-Chukotka orogenic belt, is believed to be a successor or intermontane basin. The larger northern part of the basin lies inboard (southwest) from the Podvodnikov Prograded (passive) Margin and the rifted North Chukchi Basin, and adjacent to the Wrangel Foreland Basin and the high-standing volcanic plateau of De Long Massif (fig. 2). Accordingly, this part of the basin probably has some combination of passive-margin, rift-sag, and foreland-basin characteristics.

The Brooks Range-Chukotka orogenic belt, part of the Arctic Alaska-Chukotka Microplate, is bounded on the south by the South Anyui suture and on the north by western extent of the Herald Arch-Lisburne Hills–Brooks Range thrust front (fig. 1). The northern boundary of the orogenic belt may be as young as early Paleogene (~60 Ma) if timing is similar to that on the Alaskan North Slope. The orogenic belt, in particular its eastern part, is postulated to have been a Cretaceous highland (Tigara Uplift) and major contributor of the enormous volumes of clastic debris filling the North Slope foreland and North Chukchi basins (Molenaar, 1985; Grantz and others, 1990; Lothamer, 1994). The Cretaceous highland may have contributed sediment to the Vilkitskii Basin as well.

The origin of Vilkitskii Basin is uncertain but the limited observations of structural and stratigraphic features and its regional setting are generally compatible with an early episode (Jurassic-Cretaceous) of crustal extension related to opening of the Amerasia Basin coincident with the Brooks Range–Chukotka orogeny and northward sediment dispersal followed by pervasive, but poorly understood, Cenozoic extensional (strike-slip?) faulting of northwest and northeast trend that appears to affect the entire East Siberian-western Chukchi Sea region (for example, Filatova and Khain, 2007; Franke and others, 2004; Kos'ko and others, 1993; Tolson, 1987).

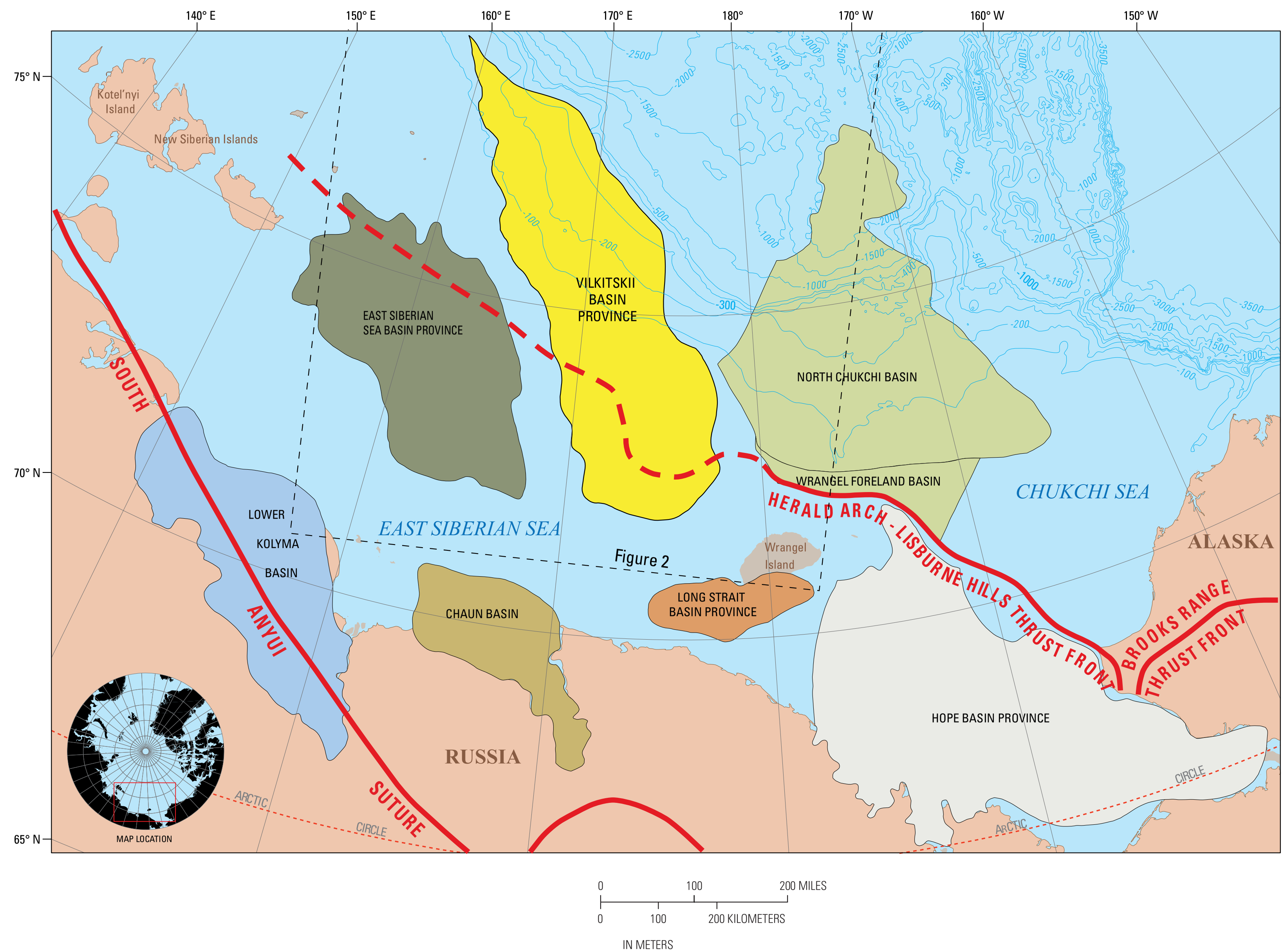

Figure 1. Map showing Vilkitskii Basin in relation to other sedimentary basins of the East Siberian and Chukchi Seas that lie within and adjacent to the Arctic Alaska-Chukotka orogenic belt, defined as the area between the South Anyui Suture and the Herald Arch-frontal Brooks Range thrust trend. Map and basin outlines derived from Grantz and others (2009). Bathymetric contour labels are in meters.

The most revealing, albeit limited, views of the basin are provided by the three seismic profiles shown in the map in figure 2. In the absence of information from drilling, the age of seismic reflectors is inferred from outcrop geology, Arctic region tectonics, and global eustatic sea level. The two profiles in the northwestern part of the basin cross the very narrow (<30 km wide) northern tip of the basin so it is unknown how representative they are of the whole basin. As interpreted by Sekretov (2001), these lines (fig. 3) show a northeastward-expanding sedimentary succession resting on down-faulted acoustic basement. His five "key reflectors," which range from 10.5 Ma to 120–125 Ma indicate that the sedimentary succession is Cretaceous and Cenozoic and has volcanic rocks represented by relatively high interval velocities (4.7–4.8 km/s) in its lower (Cretaceous) parts. The sedimentary cover thickens from <1–2 km on the high-standing De Long Massif to 2–6 km in the Vilkitskii Basin and nearly 10 km in the Podvodnikov Prograded Margin. In this area, the Vilkitskii Basin seems to part of the overall Siberian passive margin.

To the south, a proprietary seismic profile spans the entire 240-km width of the basin (fig. 2). It shows relatively unfaulted acoustic basement that slopes westward from less than 2 km (<2-s two-way traveltime) at the eastern margin of the basin to more than 12 km (>6.5-s two-way traveltime) at the Herald Arch-Lisburne Hills thrust front where it is uplifted to about 3.5 km (~2.5-s two-way traveltime) across a poorly resolved reverse fault. From there, acoustic basement shallows westward to about 1 km (~1-s two-way traveltime) at the edge of the basin and is even shallower in the area between Vilkitskii and East Siberian Sea basin. The basin fill is composed of four unconformity-bounded sequences, all of which are thickest in the basin center and thin by onlap toward the basin margins. Extensional (transtensional?) faults cut all but the youngest sequence (fig. 4) in the basin.

The oldest and thickest sequence, nearly 10 km (~4-s two-way traveltime) thick, is only present northeast of the Herald Arch-Lisburne Hills thrust front. Adjacent to the thrust front this old, thick sequence displays three diapiric structures, the easternmost of which is illustrated in figure 4. The sequence is undeformed farther east and thins by sedimentary onlap and convergence to less than 1 km (0.5-s two-way traveltime) at the basin margin. The sequence is clearly older than the bounding fault, which could be as young as early Paleogene (~60 Ma) if timing is similar to that on the Alaskan North Slope. Considering this and its regional setting, the sequence is provisionally assigned a Cretaceous age (120–65 Ma) for burial history modeling but recognizing that it could include Jurassic strata as well. By analogy with the north Alaskan (Colville) foreland basin and the North Chukchi Basin, this sequence probably consists of marine and nonmarine strata. The diapirs are inferred to be shale-cored and derived from the deepest parts of the basin (fig. 4), which implies an early shale-dominated (marine) basin fill that was probably overpressured.

The beds overlying the oldest and thickest sequence consist of a thin (0.5 km, 0.25-s two-way traveltime) interval of high amplitude reflectors that overlaps the bounding fault and thickens toward the basin center. On seismic profiles in the East Siberian Sea Basin, a thin, highly reflective sequence overlying acoustic basement, as shown in figure 5, has been related to the stratigraphic succession on the New Siberian Islands. Different investigators have considered this sequence equivalent to a mid-Cretaceous (Aptian-Turonian) coal-bearing clastic and volcanic succession (Kos'ko and Trufanov, 2002) or to a younger sequence composed of Paleocene-Eocene coal-bearing clastic and shallow marine rocks (Franke and others, 2004). Given the overlap of the bounding fault and the possible early Paleogene age of the fault, this sequence has been assigned a provisional age of 65–32 Ma for burial history modeling.

The next higher sequence is as thick as 2.5 km (1.5-s two-way traveltime). Changes in stratal thickness across faults (fig. 5) and folds related to the diapirs (fig. 4) indicate deformation during deposition of this sequence. Extensional faults are truncated at an unconformity at the top of the sequence or extend just above the unconformity. These observations of deformation relative to the overlying (youngest) sequence are similar to those in the East Siberian Sea Basin, where this sequence has been interpreted as Oligocene-mid-Miocene (33–10 Ma) by Franke and others (2004); they interpret it as shallow-marine Oligocene strata that grade upsection into nonmarine Miocene rocks.

The youngest sequence in the basin is virtually undeformed and is as thick as 1 km (1-s two-way traveltime). In the East Siberian Sea Basin, Franke and others (2004) interpret this sequence as late Miocene to recent shallow marine to nonmarine clastic sediments.

A critical question related to Vilkitskii Basin's petroleum potential is the regional extent of the thick (Cretaceous) basin fill observed on the proprietary seismic profile. Using stacking velocities, a total basin fill of more than 12 km is indicated, nearly 10 km of which is estimated to be Cretaceous. In other basins of the Chukchi-East Siberian Sea region, inspection shows fair to good agreement between location of basin fill observed on seismic profiles and negative gravity anomalies, for example in Hope, Long Strait, North Chukchi, and East Siberian Sea Basin Provinces (fig. 2*B*). In the southern Vilkitskii Basin, however, only a very minor gravity low, covering a relatively small area of the basin, is observed where the seismic data suggest that lower gravity anomaly values would be present. Perhaps the observed Cretaceous basin is only of limited thickness or extent, or Cretaceous strata are higher density, or intra-basement density variations are causes of this discrepancy. It is also possible that negative gravity anomalies in other basins may only be indicative of low-density Cenozoic strata. In the East Siberian Sea Basin north of the Herald Arch-Lisburne Hills thrust front (fig. 2, star symbol), Drachev and others (2001) interpret the seismic profile LARGE 89001 as showing one of the deepest and oldest (Albian?) parts of the basin (>3.5-s two-way traveltime), but, like the situation in southern Vilkitskii Basin, the gravity anomaly in this area is near zero (fig. 2*B*).

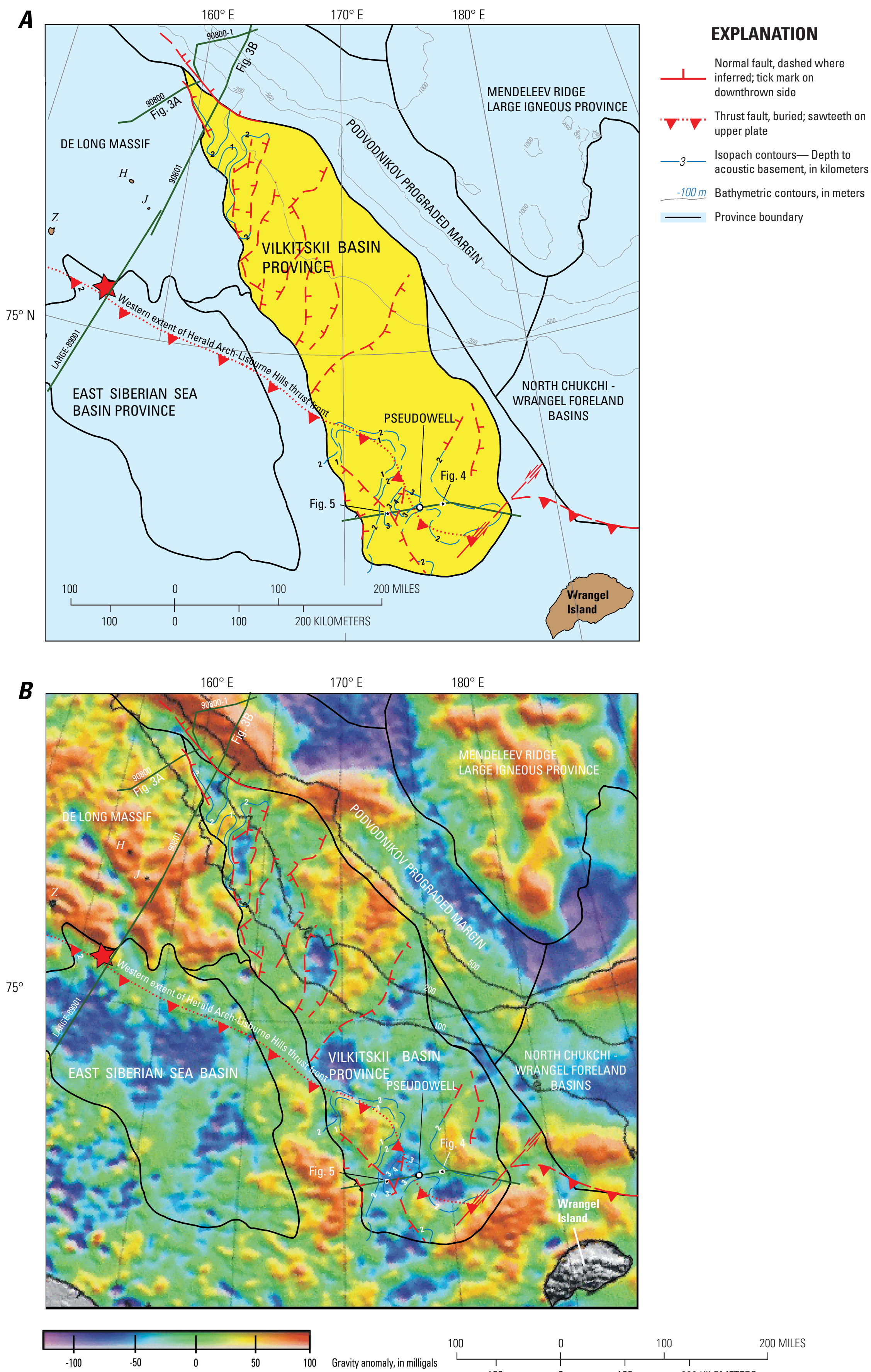

Figure 2. Map of the Vilkitskii Basin and nearby geologic features adapted from Grantz and others (2009). *A*, Vilkitskii Basin (yellow) with interpreted faults (red lines), isopachs (in kilometers) on acoustic basement within the basin, reflection seismic profiles (green lines), the pseudowell used in burial history analysis, and bathymetry in meters. Star symbol, segment of Drachev and others (2001) seismic profile discussed in text. Islands in the De Long Massif area: H, Henrietta; J, Jeannette; Z, Zokhov. *B*, Features of map *A* superimposed on free-air gravity anomaly map adapted from Mazarovich and Sokolov (2003) showing relation of basin outlines, faults and isopachs to gravity anomalies.

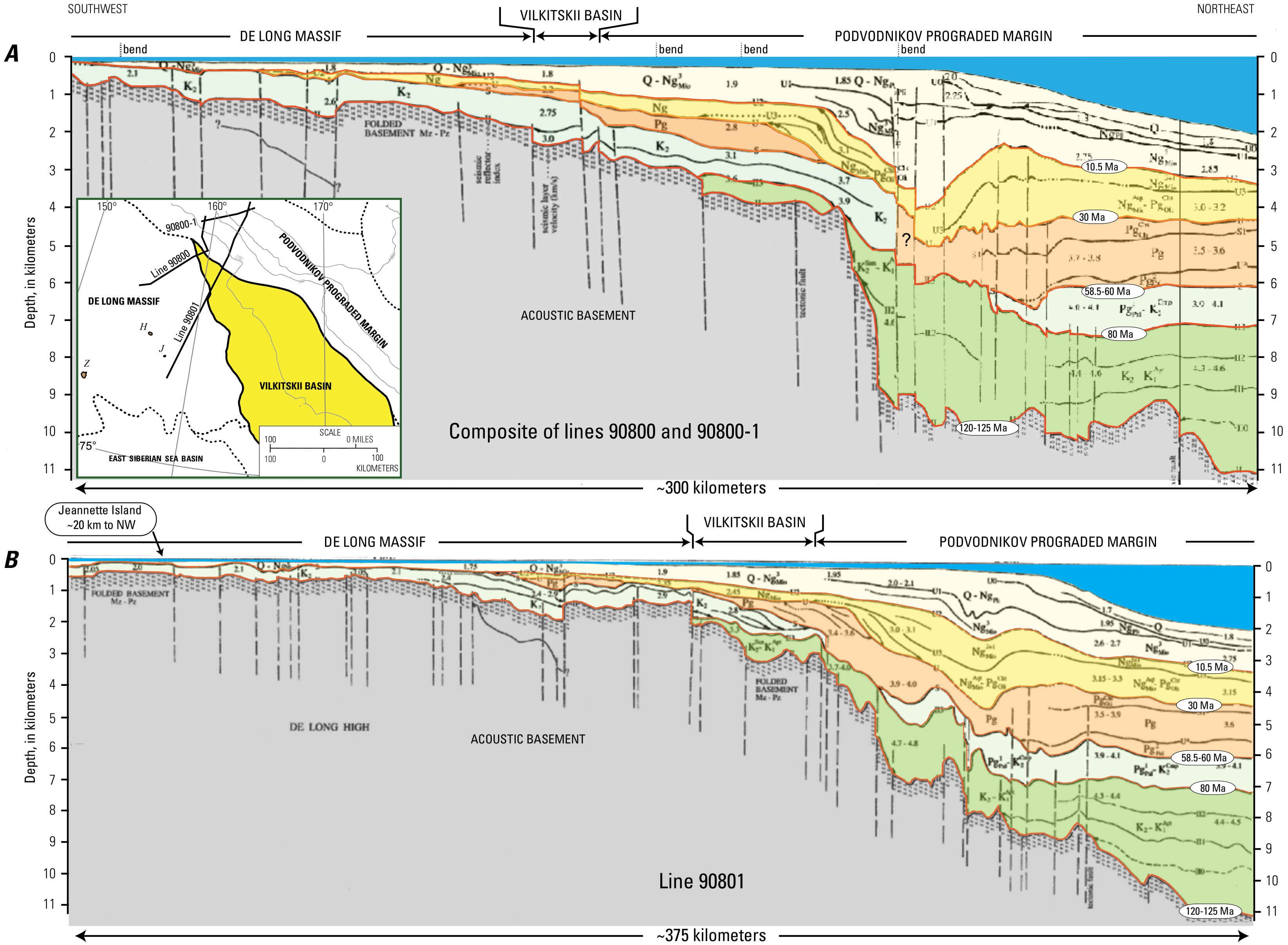

Figure 3. Interpreted geometry and ages in millions of years before present (Ma) of unconformity-bounded sedimentary and volcanic packages overlying acoustic basement (from Sekretov, 2001) interpreted from seismic profiles that trend northeasterly from the De Long Massif across the northwesternmost Vilkitskii Basin and into the Podvodnikov Prograded Margin. Islands in the De Long Massif area: H, Henrietta; J, Jeannette; Z, Zokhov.

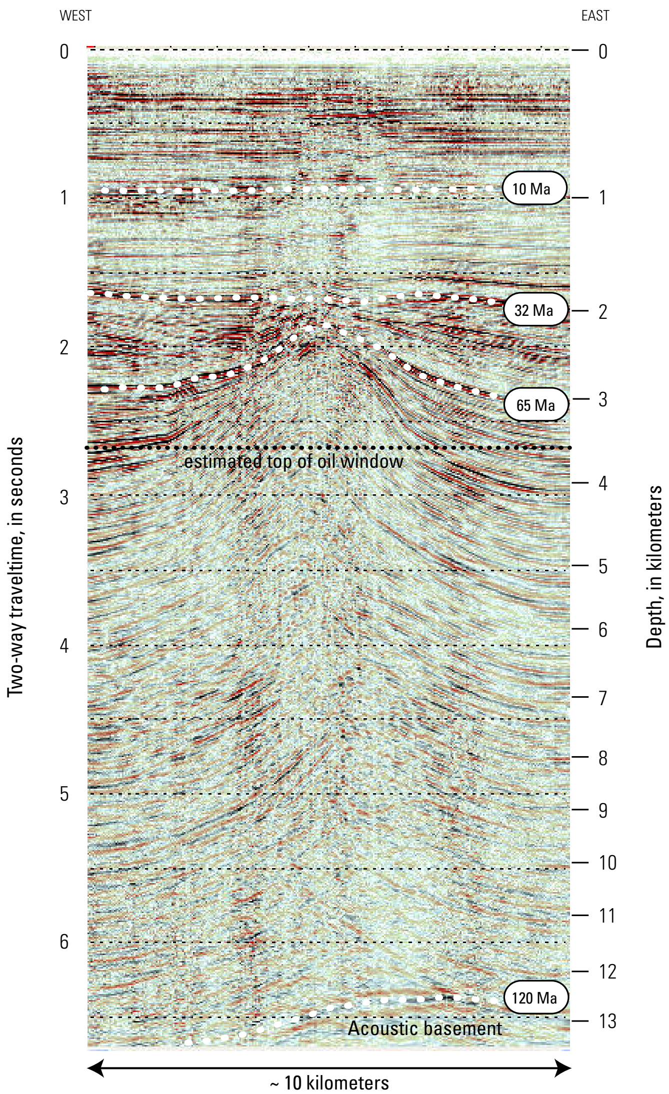

Figure 4. A segment of proprietary seismic profile in southern Vilkitskii Basin east of the Herald Arch-Lisburne Hills thrust front (fig. 2) showing the easternmost of three diapiric structures. Conversion of time to depth using stacking velocities indicates total sediment thickness exceeds 12 kilometers. Age of identified horizons is speculative and is based on regional considerations and comparison to seismic profiles in nearby East Siberian Sea Basin and North Chukchi-Wrangel Foreland Basin. Ages shown (in millions of years before present, Ma) are those used in burial history analysis (fig. 6). Top of the oil window at 2.7 seconds (~3,600 meters) is derived from that analysis. Image courtesy of Wavetech Geophysical, Inc., and Dalmorneftegeophysika.

Petroleum Systems

Reflector fade-outs and velocity sags in the proprietary seismic profile in the southern part of the basin (figs. 4, 5), interpreted as gas indicators, suggest one or more petroleum systems are active in the Vilkitskii Basin. No other hydrocarbon indicators are known from the basin. Likely source rocks are Cretaceous marine shale in the deep basin and coal, carbonaceous shale, and shallow marine mudstone in the Cenozoic section. The *Azolla* interval, identified in the New Siberian Islands (Brinkhuis and others, 2006, table S-1), is probably present. The possibility of Paleozoic and early Mesozoic source rocks within the acoustic basement cannot be ruled out, but, if present, their original thickness, distribution, organic richness, and thermal maturity are unknown.

Burial history of a pseudowell located in the deepest known part of the basin, on the proprietary seismic profile about 30 km west of the diapir in figure 4, was modeled to estimate thermal maturity and timing of petroleum generation (fig. 6). This analysis, using a constant heat flow of 50 milliwatts per square meter (mW/m^2) (derived from the Popcorn well in the U.S. Chukchi Sea, 800 km to the east) and the interpreted sequence ages and depths, suggests that onset of petroleum generation would occur at about 3.6 km of burial, as early as Albian (~105 Ma). In modeled depocenters, postulated source rocks as young as Paleogene would lie within the oil window at maximum burial. If the free air gravity anomalies in the basin (fig. 2*B*) give reliable estimates of Cenozoic sediment thickness, then just a few relatively small areas of the basin would have mature Cenozoic strata. Thus, mature source rocks at any particular part of Vilkitskii basin are more likely to occur in the underlying Mesozoic succession, assuming it is present.

Vilkitskii Basin Assessment Unit

Assessment Unit Description.—The Vilkitskii Basin assessment unit encompasses the entire basin, about 167,000 km^2 (fig. 2). Knowledge of the basin is limited to information derived from gravity data, magnetic data, three reflection seismic profiles, and regional geologic relations. It appears that the basin is geologically complex and has an undetermined mix of characteristics of foreland, rift-sag, passive margin, and successor basins (figs. 3–5). Basin fill, locally greater than 12 km thick, is composed of at least 4 unconformity-bounded sequences, the ages of which are uncertain because of an absence of well penetrations (fig. 4). Regional tectonic considerations, combined with seismic interpretations in nearby areas/basins, suggest that the oldest and thickest sequence is probably marine Cretaceous and the three overlying sequences are Cenozoic. The Cenozoic sequences show seismic reflection characteristics (fig. 5) similar to those observed to the west in the East Siberian Sea Basin (see, for example, Franke and others, 2004), which suggests a similar lithologic succession and similar ages. Those sequences are inferred to be composed predominantly of coal-bearing nonmarine clastic sediments with probable shallow marine intervals from parts of the Eocene, Oligocene, Pliocene, and Pleistocene based on outcrop geology projections from the New Siberian Islands (for example, Kos'ko and Trufanov, 2002). Volcanic rocks are known in the late Early Cretaceous and Pliocene-Pleistocene parts of

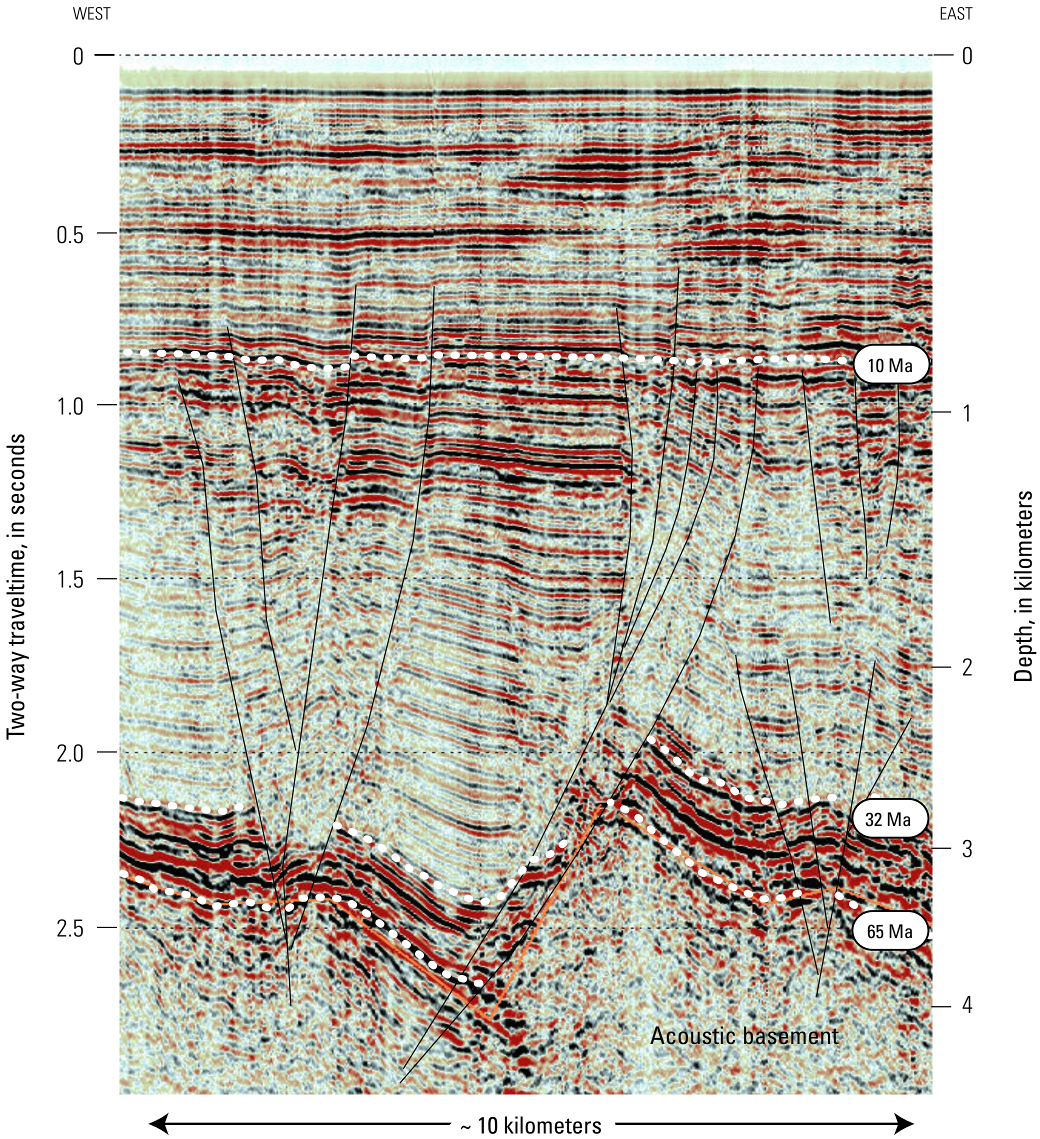

Figure 5. A segment of proprietary seismic profile in southern Vilkitskii Basin approximately 40 kilometers west of the Herald Arch-Lisburne Hills thrust front (fig. 2) showing faulting, reflective character, and possible gas indications (reflector "fade outs" in faulted areas). Age of identified horizons (in ovals) is speculative and is based on regional considerations and comparison to seismic profiles in nearby East Siberian Sea Basin. Seismic section courtesy of Wavetech Geophysical, Inc., and Dalmorneftegeophysika.

the succession that outcrop in the New Siberian Islands, but these rocks were not identified with certainty on the seismic sections. On profile 90801 (fig. 3), Sekretov (2001) identified a probable Cretaceous volcanic interval characterized by high amplitude reflections and interval velocities of 4.7–4.8 km/s in the Podvodnikov Prograded Margin Province adjacent to the northernmost part of Vilkitskii Basin. In the southern Vilkitskii Basin west of the Herald Arch-Lisburne Hills thrust front, the seismic interval characterized by high amplitude reflections and directly overlying acoustic basement (shown in figure 5) may owe its character to a combination of volcanic and coal-bearing strata, similar to the Albian section reported on Kotel'nyi Island (Kos'ko and Trufanov, 2002; Kuzmichev, 2009).

The proprietary reflection seismic profile in the southern part of the basin shows three separate diapiric structures (one of which is illustrated in figure 4) that have apparent gas plumes (fade-out zones and sags in reflectors). These structures show sediment onlap relations that indicate diapir growth during deposition was followed by extensional faulting (fig. 5) that involved all but the youngest sequence. The youngest sequence, generally about 1 km thick, unconformably overlies the older sequences and forms a relatively undisturbed cap. Stratal thickening in sags and grabens and across faults indicate the various structures were forming mostly during the second sequence, provisionally 33–10 Ma.

Petroleum source rocks may be marine shale, coal, carbonaceous shale, and shallow marine mudstone, and, thus, are expected to be predominantly gas prone. The Eocene *Azolla* interval, reported in the New Siberian Islands (Brinkhuis and others, 2006, table S-1), is likely present, but its organic-carbon richness, aerial extent, and burial depth are unknown. Petroleum source rocks of Paleozoic and Mesozoic age may also be present in the acoustic basement, but nothing is known of their thickness, distribution, or source characteristics. Analysis of the burial history suggests that only the part of the basin that has greater than about 3.6 km of fill is capable of petroleum generation.

Geological Analysis of Assessment Unit Probability.—Considering data limitations, the probability that the Vilkitskii Basin AU contains at least one undiscovered accumulation >50 MMBOE is considered to be about 29 percent (table 1).

Charge.—A probability of 0.6 was estimated for charge sufficiency in this AU. Cenozoic and late Mesozoic source rocks of unknown quality and thickness were considered.

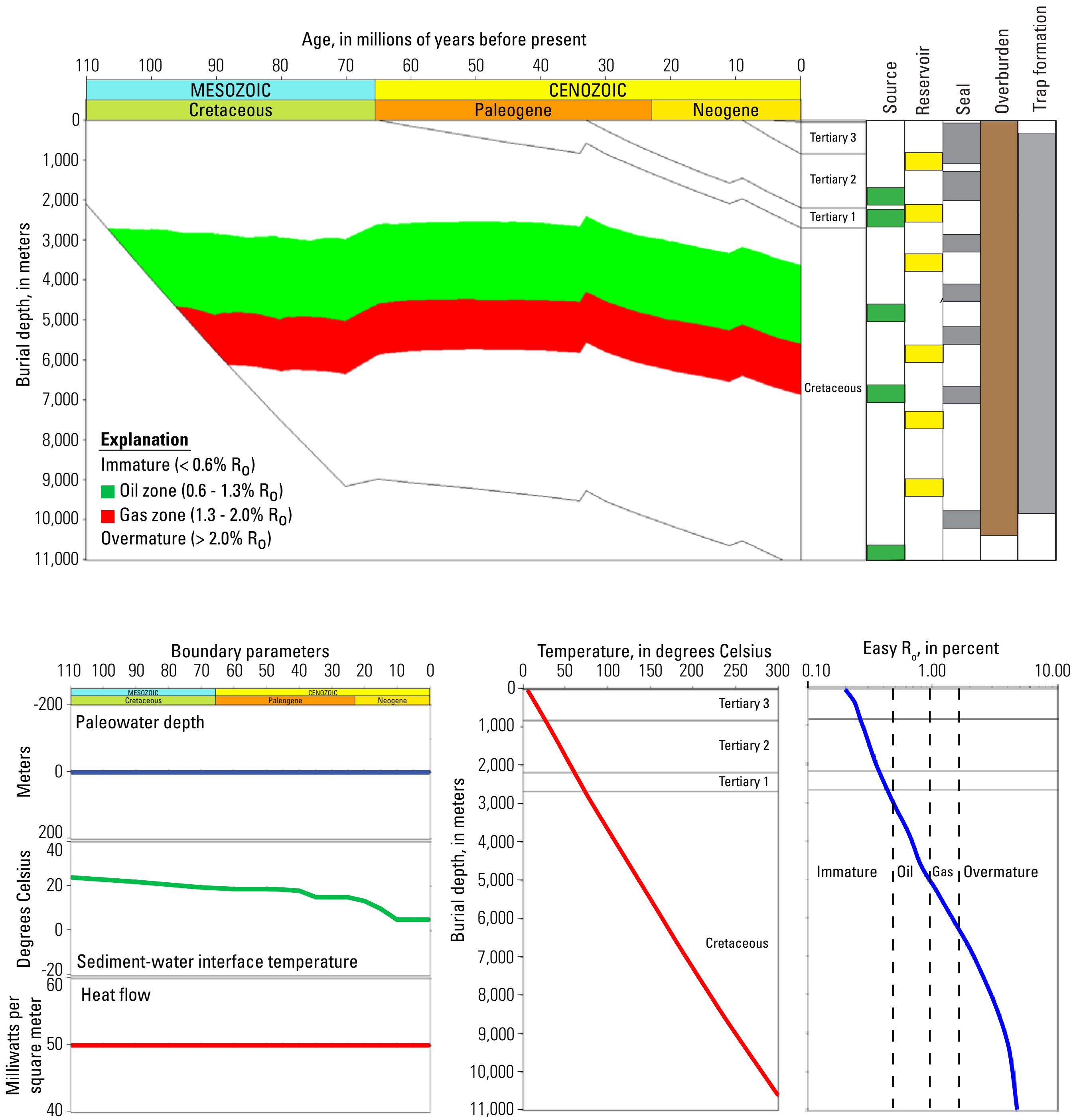

Figure 6. Burial history analysis of pseudowell located in the southern part of the Vilkitskii Basin, just east of the Herald Arch-Lisburne Hills thrust front (fig. 2). Age of horizons in the pseudowell and the petroleum system components shown are speculative. Ro, vitrinite reflectance, in percent (%). PetroMod references: Wygrala (1989), Sweeney and Burnham (1990), and Integrated Exploration Systems (2008).

Table 1. Assessment results for the Vilkitskii Basin Province (conventional undiscovered resources).

[AU, assessment unit; BCF; billion cubic feet; MMB, million barrels. Results shown are fully risked estimates. For gas fields, all liquids are included under the natural gas liquids category. F95, 95-percent probability of at least the amount tabulated, and so on for F50 and F5. Fractiles are additive under the assumption of perfect positive ocrrelation. N/A, not applicable]

Total petroleum system and AU	AU probability	Field type	Oil (MMB)				Gas (BCF)				Natural gas liquids (MMB)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Vilkitskii Basin Province—Mesozoic-Cenozoic composite total petroleum system														
Vilkitskii Basin AU	0.228	Oil	0	0	530	98	0	0	1,043	198	0	0	19	4
		Gas	N/A	N/A	N/A	N/A	0	0	29,850	5,544	0	0	528	98

Cenozoic coal and shallow marine carbonaceous mudstones are likely present throughout the basin. The Eocene *Azolla* interval is probably present and may have source potential in the eastern and northern parts of the basin that are presumed to be distal from clastic sediment influx. Late Mesozoic (Cretaceous and possibly Jurassic) marine source rocks are likely to be present north of the Herald Arch-Lisburne Hills thrust front (fig. 2) in the extremely thick succession shown on the seismic profile (fig. 4). But in the absence of gravity or magnetic anomalies, there is no way of knowing the aerial extent and thickness of these strata beyond the observed seismic sections. The onset of thermal maturity at a depth of about 3.6 km at the pseudowell (fig. 6), indicated by burial history modeling, suggests that Cenozoic source rock strata are mature only in local depocenters whereas significant parts of the thick Cretaceous and older(?) source rocks are likely mature and overmature.

Rocks.—A probability of 0.8 was estimated for adequacy of reservoirs, traps and seals in this AU. Sandstone reservoirs deposited in a variety of settings appear likely to be present. Cenozoic fluvial and shallow marine sandstones and late Mesozoic turbidites and shallow marine deposits are probably present. Diapiric folds, faults, and unconformity trap geometries are observed on available seismic images. The seismic sections indicate that folding, faulting, and diapiric deformation were most active during the second-youngest sequence, provisionally dated to 33–10 Ma. The youngest seismic sequence (<10 Ma) forms an unconformable, overlapping, generally unfaulted cap on the underlying strata that is as much as 1 km thick and may constitute a sealing unit. The presence of adequate mudstone and fault seals are considered a significant risk.

Timing and Preservation.—With the basin currently at maximum burial and a history of relatively continuous subsidence, a favorable probability of 0.6 was assigned to adequacy of timing and preservation of accumulations greater than the minimum size of 50 MMBOE within this AU.

Analogs.—The USGS World Analog Database (Charpentier and others, 2008) was searched for the following basin features or types: extensional structural setting, continental crustal system, rifted passive margin, rift-sag architecture, and basement-involved block fault structures or extensional grabens. This is the same analog set that was used in the Arctic Platform assessment unit (Houseknecht and others, 2012).

Numbers of Accumulations.—Based on the set of analogs searched, the total number of petroleum accumulations >50 MMBOE was set to minimum, median, and maximum values of 1, 15, and 70.

Oil/Gas Mix.—Based on the inferred kerogen types, thermal history, and common gas indications on the seismic profile, the minimum, median, and maximum values for oil/gas mix were set at 0, 0.1, and 0.3 (table 1).

Accumulation Size Distribution.—The median and maximum oil accumulation size was set to 70 and 4,000 MMBO, and the median and maximum gas accumulation size was estimated to be 600 and 40,000 BCFG.

Estimated Maximum Field Size.—Maximum accumulation sizes of 500 MMBO and 9 TCFG were selected based on the interpretation that some very large traps are probably present, but that maximum accumulation size may be constrained by limited hydrocarbon charge and possibly by seal integrity.

Ancillary properties and coproduct ratios used are world averages in analogs from the USGS World Analog Database (Charpentier and others, 2008).

Results

Probabilistic estimates of volumes of undiscovered, technically recoverable hydrocarbons in the Vilkitskii Basin AU are summarized in table 1. These results include mean estimates of about 100 MMBO and 5,500 BCF nonassociated gas.

Acknowledgments

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Appendix. Input Data for the Vilkitskii Basin Assessment Unit

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