

Circum-Arctic Resource Appraisal Project

# **Assessment of Undiscovered Petroleum Resources of the Arctic Alaska Petroleum Province**



Scientific Investigations Report 2012–5147

**Cover.** Northwestward view across the southern foothills of the Brooks Range along Akmagolik Creek, approximately 150 miles southwest of Prudhoe Bay. Exposed rocks are part of the Mississippian–Pennsylvanian Lisburne Group and include a thrust-fault ramp at left. This area is included in the Arctic Alaska fold-and-thrust belt assessment unit discussed in text. Photo includes two helicopters for scale, a blue-and-white one near the center and a red one at center-right at creek level.

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

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## Conversion Factors

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
Area		
square kilometer (km <sup>2</sup> )	247.1	acre
square kilometer (km <sup>2</sup> )	0.3861	square mile (mi <sup>2</sup> )
Volume		
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m <sup>3</sup> )
cubic foot (ft <sup>3</sup> )	28.32	cubic decimeter (dm <sup>3</sup> )
cubic foot (ft <sup>3</sup> )	0.02832	cubic meter (m <sup>3</sup> )

# Assessment of Undiscovered Petroleum Resources of the Arctic Alaska Petroleum Province

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## Abstract

The Arctic Alaska Petroleum Province encompasses all lands and adjacent continental shelf areas north of the Brooks Range-Herald arch tectonic belts and south of the northern (outboard) margin of the Alaska rift shoulder. Even though only a small part is thoroughly explored, it is one of the most prolific petroleum provinces in North America, with total known resources (cumulative production plus proved reserves) of about 28 billion barrels of oil equivalent.

For assessment purposes, the province is divided into a platform assessment unit, comprising the Alaska rift shoulder and its relatively undeformed flanks, and a fold-and-thrust belt assessment unit, comprising the deformed area north of the Brooks Range and Herald arch tectonic belts. Mean estimates of undiscovered, technically recoverable resources include nearly 28 billion barrels of oil and 122 trillion cubic feet of nonassociated gas in the platform assessment unit and 2 billion barrels of oil and 59 trillion cubic feet of nonassociated gas in the fold-and-thrust belt assessment unit.

## 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 geological framework and resource estimates for specific Arctic provinces (Bird and Houseknecht, 2011; Gautier and others, 2011b; Houseknecht and Bird, 2011; Klett and Pitman, 2011; Klett and others, 2011; Moore and Pitman, 2011; Moore and others, 2011; Schenk, 2011a, b; Sørensen and others, 2011). In addition, the procedures and methods used in conducting the Circum-Arctic Resource Appraisal have been documented by Charpentier and Gautier (2011). The purpose of this report is to provide a synthesis of the geology of the Arctic Alaska Province and to present input parameters and results of the resource assessment.

The Arctic Alaska Petroleum Province extends from the northern margin of the Brooks Range and Herald arch tectonic belts on the south and southwest to the northern margin of the Alaska rift shoulder (Houseknecht and Bird, 2011) on the north, and from the axis of the Chukchi platform on the northwest to the western margin of the Mackenzie delta on the east (fig. 1). The province is about 1,400 km long (west-east) and ranges in width (south-north) from about 500 km in the west to about 50 km in the east. The province includes the Alaska North Slope, the Alaska and Canada Brooks Range foothills, part of the Alaska and Canada Beaufort shelf, and most of the U.S. Chukchi shelf. The province is divided into two units, the platform and the fold-and-thrust belt, for assessment purposes.

## Geologic Setting and Stratigraphy

The most notable geologic features of the province are the Alaska rift shoulder, the Colville foreland basin, and the Brooks Range and Herald arch fold-thrust belts (figs. 1, 2). The Alaska rift shoulder formed during the Jurassic–Early Cretaceous opening of the Canada Basin (Grantz and May, 1982; Lawver and Scotese, 1990; Grantz and others, 1990, 2011; Embry, 1990, 2000; Lane, 1997; Lawver and others, 2002, 2011; Houseknecht and Bird, 2011). The Arctic Alaska microplate (including Arctic Alaska and the Chukchi shelf) rifted from Arctic Canada, perhaps by counterclockwise rotational opening of the Canada Basin or alternative motions. The rift shoulder is defined by high-standing acoustic basement, whose upper surface generally dips southward beneath Arctic Alaska and the Chukchi shelf and steps northward over a short distance across normal faults to great depths beneath the Beaufort shelf (fig. 2). This abrupt northern boundary of the rift shoulder defines the Alaska (Beaufort) hinge (fig. 2). The current structural crest of the rift shoulder is commonly known as the Barrow arch (fig. 2) and is tens of kilometers south of the hinge. This structural geometry is the result of several geological processes, including thermal contraction and sedimentary loading of the northern margin of the rift shoulder, sediment loading of the southern flank of the rift shoulder by Colville basin strata, and perhaps flexural uplift

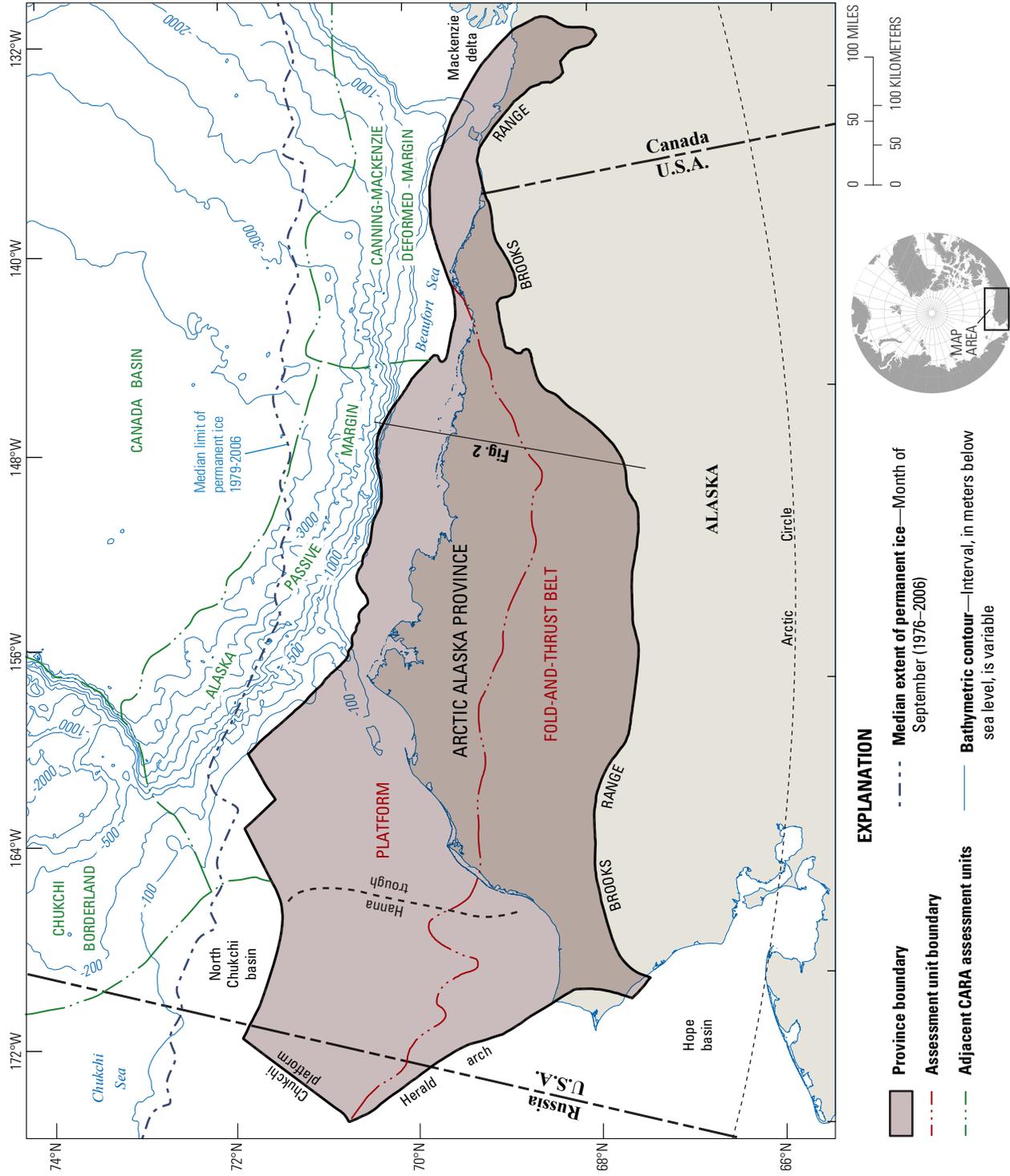
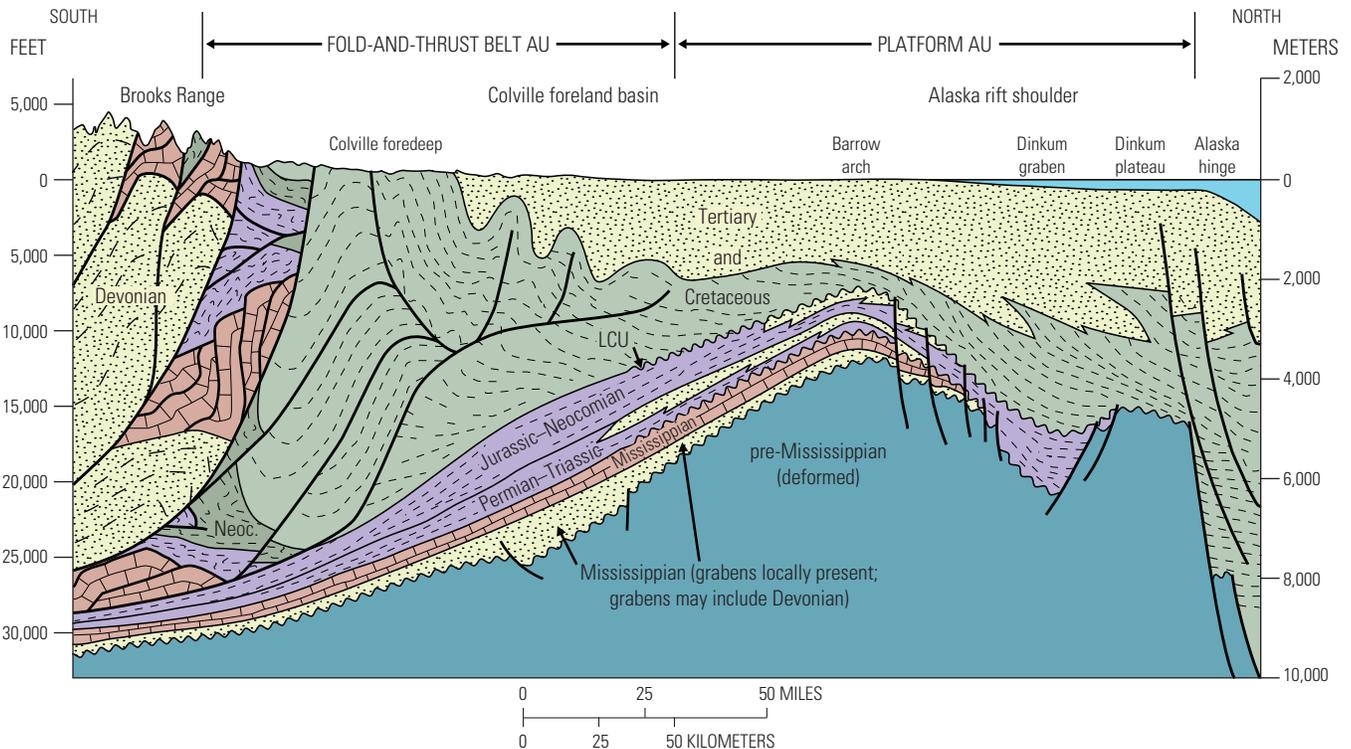


Figure 1. Map of Arctic Alaska Province (outlined in black) showing boundaries of the platform and fold-and-thrust belt assessment units in red. Location of cross section in fig. 2 is shown by thin black line. Blue lines, bathymetry in meters; green lines, boundaries of adjacent Circum-Arctic Resource Appraisal (CARA) assessment units.



**Figure 2.** Generalized cross section showing stratigraphic and structural relations from the Brooks Range to the northern margin of the Alaska rift shoulder, central North Slope of Alaska. Note that Alaska rift shoulder in this area includes the Dinkum graben and plateau. AU, assessment unit; LCU, Lower Cretaceous unconformity. Location of cross section is shown in fig. 1. Modified from Bird and Bader (1987).

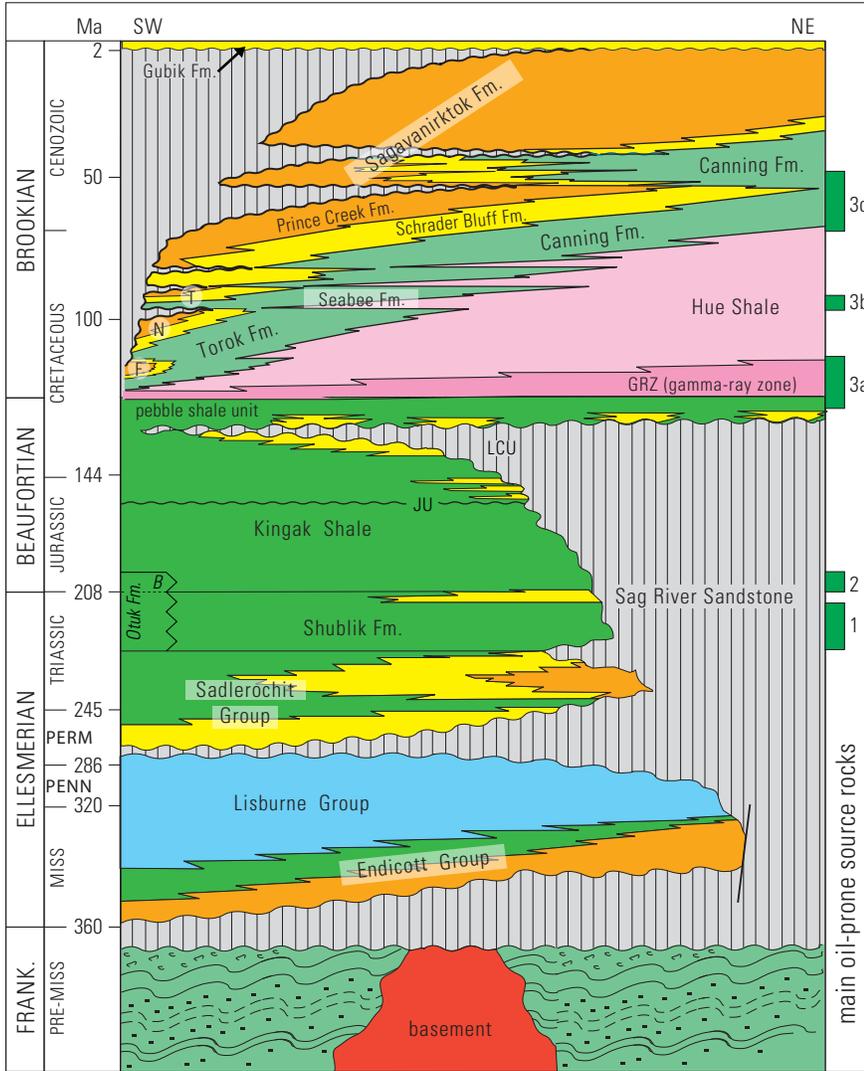
of the Barrow arch by tectonic loading of the Arctic Alaska microplate by the Brooks Range. Acoustic basement of the Arctic Alaska microplate is thought to consist mostly of pre-Mississippian low-rank metamorphic rocks known as the Franklinian sequence (fig. 3), which was broadly deformed during the Ellesmerian orogeny (Late Devonian–Early Mississippian; Balkwill and others, 1983; Moore and others, 1994; Dumoulin, 2001), although aeromagnetic and gravity data suggest a much more heterogeneous basement (see, for example, Saltus and others, 2006).

Franklinian basement in Arctic Alaska is overlain by Mississippian–Cretaceous strata (fig. 3) deposited before (Ellesmerian sequence) and during (Beaufortian sequence) rift opening of the Canada Basin. The older part of the Ellesmerian sequence, which in places may be as old as Devonian, locally includes thick graben-filling successions, and the younger part comprises passive-margin deposits (Bird, 2001; Sherwood and others, 2002; Bird and Houseknecht, 2011). The Beaufortian sequence and, in many areas, the Ellesmerian sequence are truncated progressively northward beneath the Lower Cretaceous unconformity (fig. 2, LCU), considered to represent the climax of rift-shoulder uplift, perhaps accentuated as a forebulge in response to tectonic loading, and Franklinian basement subcrops the LCU in areas of maximum uplift (fig. 4A, B). Overlying the LCU, Lower Cretaceous–Tertiary foreland basin strata (Brookian sequence) generally thicken

southward into the foredeep of the Colville basin and thin northward by onlap against the rift shoulder (Bird and Molenaar, 1992; Houseknecht and others, 2009a, b). The thickest part of the foreland-basin succession grades in age from Early Cretaceous beneath the western Alaska North Slope (ANS) to Tertiary beneath the eastern ANS, and the Alaska rift shoulder was progressively overstepped and buried from west to east by foreland-basin depositional systems (Molenaar, 1983; Bird and Molenaar, 1992; Houseknecht and others, 2009a, b, 2012b).

Although the Chukchi shelf is stratigraphically similar to the ANS, the Hanna trough—a Paleozoic failed rift filled by a thick succession of the Ellesmerian sequence—is a distinguishing feature (Sherwood and others, 2002; Thurston and Theiss, 1987). Ellesmerian strata in the Hanna trough thin eastward and grade into the passive-margin succession of the ANS and thin westward to an onlap pinchout against the Chukchi platform, an ancestral ridge of Franklinian basement whose axis lies near the U.S.-Russia maritime boundary (fig. 1). The Beaufortian sequence beneath the Chukchi shelf is similar to that of the ANS, except that it is punctuated by several unconformities (for example, Jurassic unconformity; fig. 3) that appear to be more significant than those to the east (Sherwood and others, 1998). The Brookian sequence beneath the Chukchi shelf comprises Lower Cretaceous (mostly Aptian–Albian) and Tertiary successions separated by a Paleocene unconformity (Sherwood and others, 1998). The

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**Figure 3.** Generalized chronostratigraphy for the Arctic Alaska Petroleum Province, based on the Alaska North Slope. Tectonostratigraphic sequence names shown in all caps at left. Oil-prone source-rock systems discussed in text are indicated at right: 1, Triassic source-rock system, comprising the Shublik Formation and Triassic part of the Otuk Formation; 2, Jurassic source-rock system, comprising the lower Kingak Shale and Blankenship Member (B) of the Otuk Formation; and 3, Cretaceous–Paleogene source-rock system, comprising (3a) the Lower Cretaceous pebble shale unit and gamma-ray zone (GRZ), (3b) the Upper Cretaceous Seabee Formation, and (3c) lower Paleogene organic-rich tongues of the Canning Formation. LCU, Lower Cretaceous unconformity; JU, Jurassic unconformity; F, Fortress Mountain Formation; N, Nanushuk Formation; T, Tuluva Formation. Oblique labels (*Otuk Formation* and *B*, Blankenship Member) indicate units that crop out in the Brooks Range frontal thrust belt and that represent southern distal facies equivalents of formations present beneath the Alaska North Slope. Arctic Alaska stratigraphy modified from Lerand (1973), Bird (1985, 2001), Hubbard and others (1987), and Mull and others (2003); ages from Gradstein and others (2004).

Lower Cretaceous succession displays a regional geometry suggesting influences of both a sag basin developed above the Hanna trough and a foreland basin related to the Herald arch and western Brooks Range. Lower Cretaceous strata grade eastward into foreland basin deposits of the ANS (Moore and others, 2002; Houseknecht and others, 2009a, b). The Tertiary succession, in contrast, is thickest in syndepositional grabens that open northward into the North Chukchi basin (fig. 1; Sherwood and others, 1998; Houseknecht and Bird, 2011).

South of the rift shoulder, no apparent stratigraphic continuity exists between the Tertiary successions beneath the Chukchi shelf and the eastern ANS. Evidence suggests broad uplift of the western ANS during this time (Burns and others, 2007; Houseknecht and Bird, 2011; Houseknecht and others, 2011), segmenting the foreland into a Chukchi depocenter influenced by wrench tectonics and an eastern ANS depocenter influenced by contractional tectonics associated with the eastern Brooks Range.

## Source-Rock Systems

Multiple petroleum systems have been identified in Arctic Alaska, and many oil accumulations appear to be mixtures of oil expelled from two or more source rocks (Magoon and others, 2003; Peters and others, 2008). The regional source-rock potential of Arctic Alaska is considered within a framework of three source-rock systems: Triassic, Jurassic, and Cretaceous–Paleogene. The Triassic source-rock system includes the Shublik Formation and its southern distal equivalent, the Triassic part of the Otuk Formation, which crops out in the frontal thrust belt of the Brooks Range (Mull and others, 1982; Kupecz, 1995; Masterson, 2001; Parrish and others, 2001a, b; Peters and others, 2006). The Jurassic source-rock system includes the lower Kingak Shale and its southern distal equivalent, the Jurassic Blankenship Member of the Otuk Formation, which crops out in the frontal thrust belt of the Brooks Range (Seifert and others, 1980; Mull and others, 1982; Masterson, 2001; Houseknecht and Bird, 2004; Peters and others, 2006). Although both the Shublik and Kingak source rocks may be present in grabens along the northern margin of the province, it is unlikely that either is present north of the hingeline because the Amerasia Basin was not yet open when those source rocks were deposited (Houseknecht and others, 2012b). The Cretaceous–Paleogene source-rock system includes the Hauterivian pebble shale unit, the Lower Cretaceous gamma-ray zone (GRZ) of the Hue Shale, the Upper Cretaceous (mostly Turonian) Seabee Formation, and Paleogene organic-rich beds in the Canning Formation (fig. 3; Mull and others, 2003; Macquaker and Keller, 2005; Peters and others, 2006; Houseknecht and Bird, 2011; Houseknecht and others, 2012b).

The present character of these source-rock systems has been documented in the most heavily explored part of the Arctic Alaska Petroleum Province (see, for example, Claypool and Magoon, 1985; Creaney and Passey, 1993; Lillis and others, 1999; Magoon, 1994; Magoon and Bird, 1988; Magoon and Claypool, 1985; Magoon and others, 1987, 1999; Masterson, 2001; Threlkeld and others, 2000), and the original (prematuration) character has been inferred for the same area (Peters and others, 2006). However, the source-rock quality across much of the province remains poorly known because of limited data. Outcrop samples from the Brooks Range frontal thrust belt (Dow and Talukdar, 1995; Dow, 1998; Mull, 2000, 2009) indicate that the Triassic and Jurassic source rocks originally were rich (higher total organic carbon content) and oil-prone (higher hydrogen index values). In contrast, thrust-belt outcrop samples of the pebble shale and GRZ display highly variable character; they tend to be lean and gas-prone across much of the thrust belt but locally are rich and oil-prone (Dow and Talukdar, 1995; Dow, 1998; Mull, 2000, 2009).

Highly generalized maps depicting the original character of these three source-rock systems are shown in figure 4. The Triassic and Jurassic source-rock systems were deposited on a south-facing (present coordinates) passive continental margin

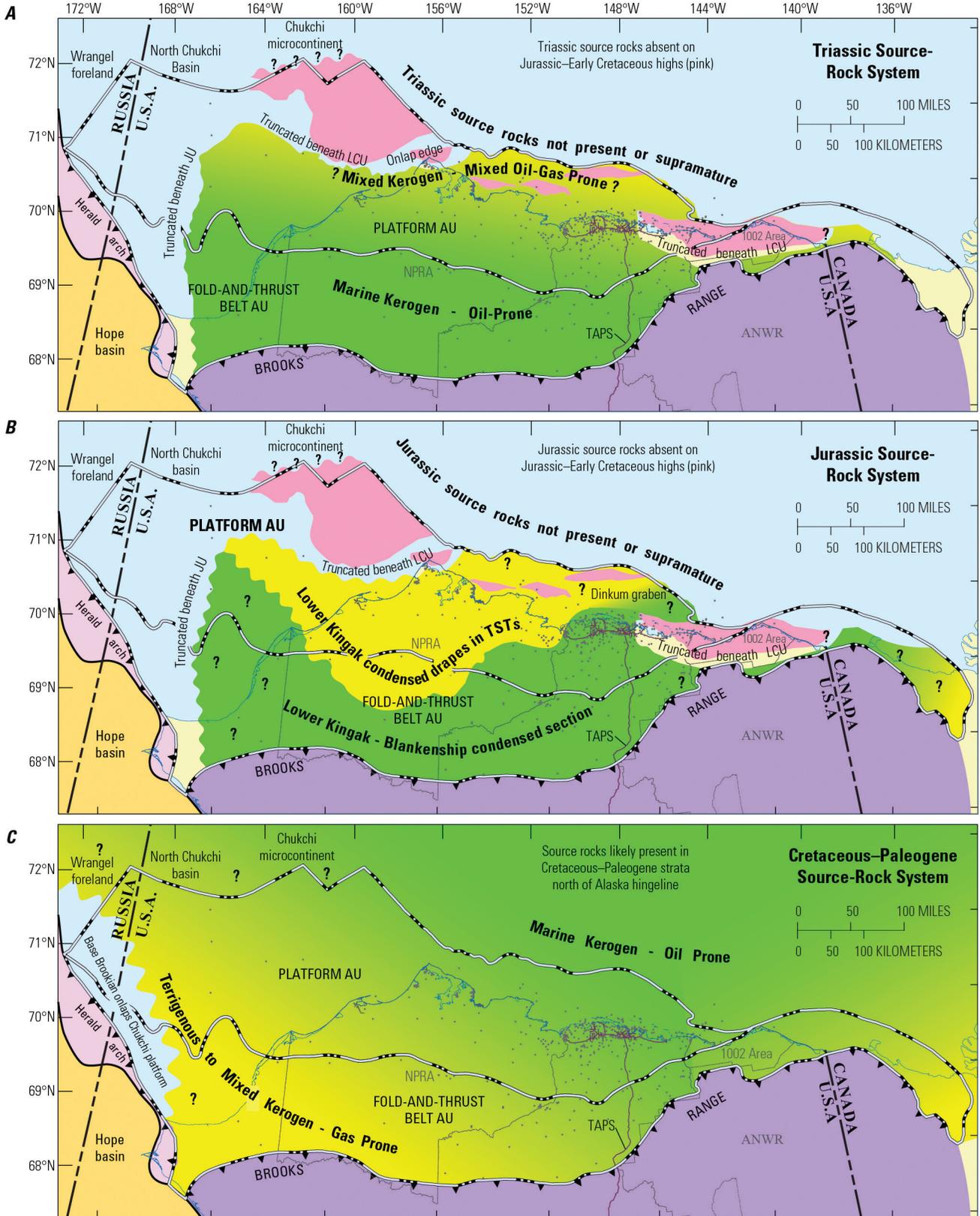
and, when the character of outcrop samples from the Brooks Range frontal thrust belt are considered, they appear originally to have graded southward to facies that are richer (higher total organic carbon content) and more oil-prone (higher hydrogen index values) (fig. 4A, B; Dow and Talukdar, 1995; Kupecz, 1995; Dow, 1998; Mull, 2000, 2009; Masterson, 2001; Parrish and others, 2001a, b; Peters and others, 2006). The Lower Cretaceous pebble shale unit and GRZ, deposited during and after the opening of the Canada Basin and the onset of Brooks Range tectonism and foreland basin development, appear originally to have been richer and more oil-prone towards the east and north (fig. 4C; Dow and Talukdar, 1995; Dow, 1998; Mull, 2000, 2009; Peters and others, 2006). However, organic-rich and oil-prone source rocks also have been documented locally in outcrops of the pebble shale unit and GRZ along the western part of the Brooks Range frontal thrust belt (C.G. Mull, Alaska Division of Geological and Geophysical Surveys, written commun., 2009)<sup>1</sup>, so exceptions to the generalized regional trends have been documented. Although not confirmed by drilling, the potential exists for rich and oil-prone Cretaceous and Paleogene source rocks in the Canada Basin, north of the Alaska rift shoulder (Houseknecht and Bird, 2011; Houseknecht and others, 2012b), and this potential is reflected in figure 4C.

In addition to the major source-rock systems discussed above, oil-prone source rocks are known to occur in the upper part of the upper Paleozoic Lisburne Group (fig. 3), and several Arctic Alaska oil accumulations are inferred to have been partly charged from Lisburne source rocks (Magoon and others, 2003; Dumoulin and others, 2008a, b, 2011). Moreover, gas-prone mudstones and local coals occur in strata ranging in age from Mississippian (Endicott Group) to Paleogene (Canning, Prince Creek, and Sagavanirktok Formations) (fig. 3).

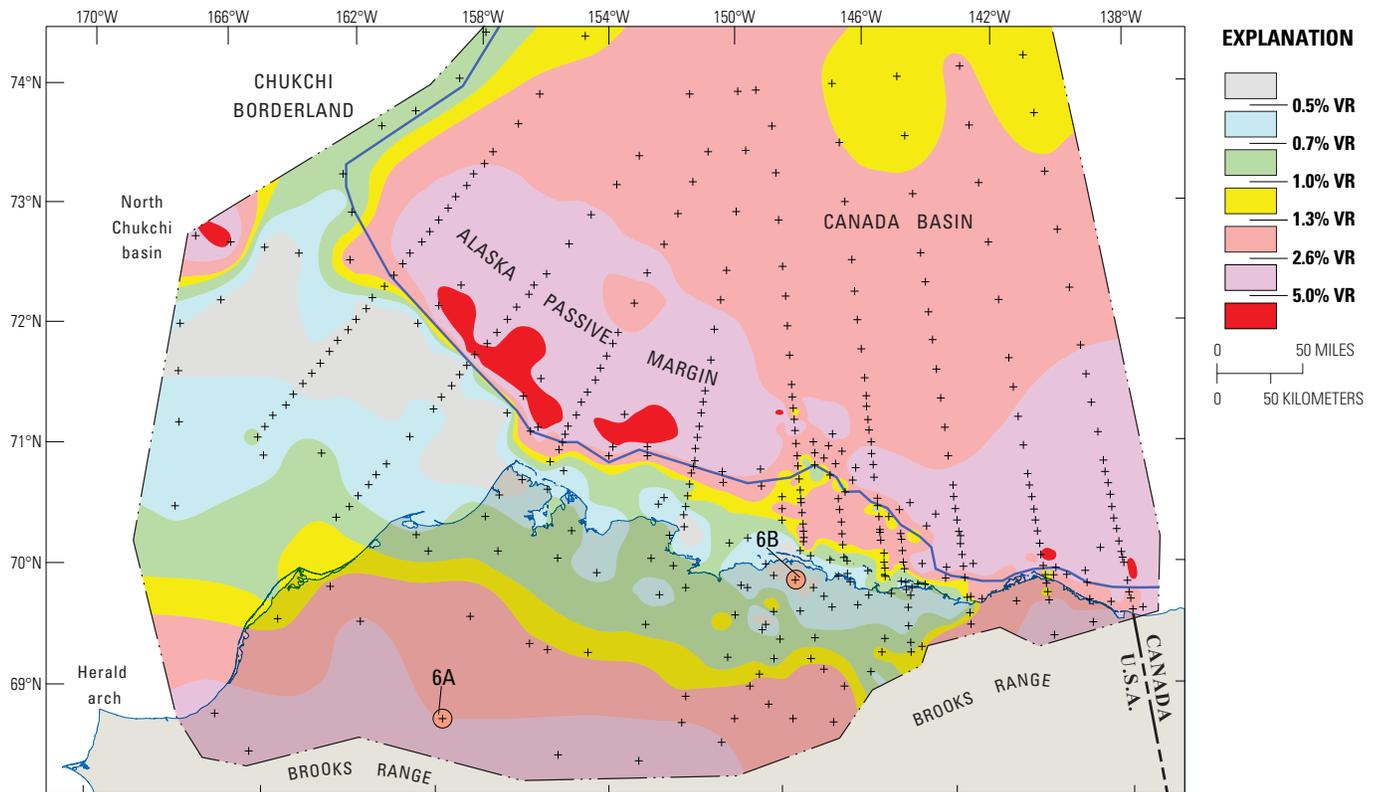
Thermal maturity of these source rocks generally reflects the distribution and thickness of Cretaceous and younger foreland-basin and Beaufort passive-margin deposits (fig. 5). All source rocks in the foredeep are overmature with respect to the oil window, are mostly mature on the northern flank of the foreland basin, and are mostly early-mature to immature on the rift shoulder (figs. 5, 6). Modeling of burial history and hydrocarbon generation indicates that most oil generation occurred during the Early to middle Cretaceous in the western to central part of the province and during the Paleogene in the eastern part of the province; these maturation dates correspond to times when the thickest foreland basin successions were deposited (Houseknecht and others, 2012b). In the Canada Basin, maturation of all source rocks generally occurred during the Paleogene–Neogene, except in a depocenter immediately north of the Alaska rift shoulder along the northeast Chukchi margin where maturation of the oldest source rocks may have occurred during the Early Cretaceous (Houseknecht and others, 2012b).

<sup>1</sup> Notes regarding source-rock character of the Otuk Formation, the pebble shale unit, and the GRZ in outcrops of the Brooks Range frontal thrust belt, based on work conducted by the Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys.

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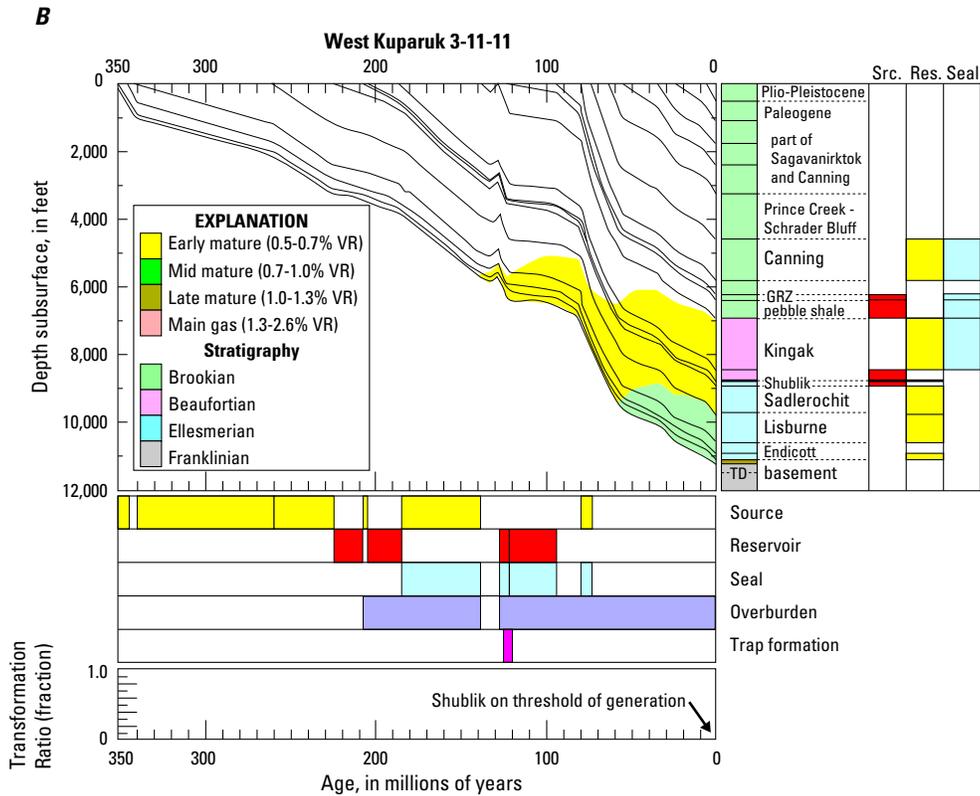
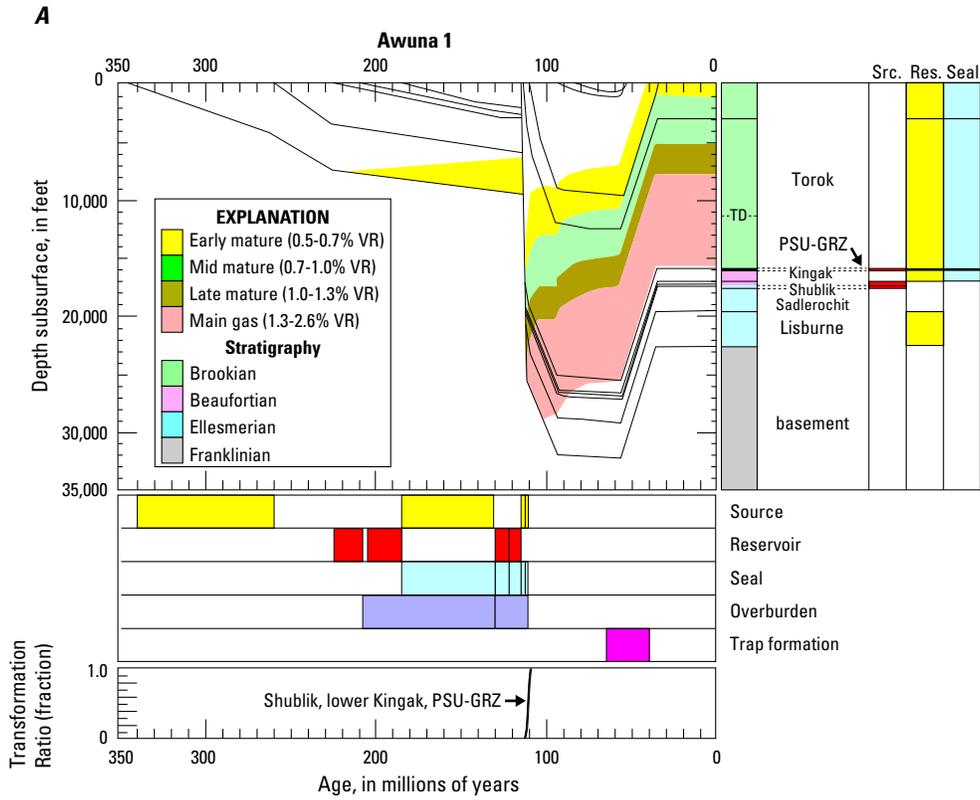


**Figure 4 (at left).** Maps showing the three main oil-prone source-rock systems in the Arctic Alaska Province, with colors depicting the inferred original distribution of predominantly oil-prone (green) and gas-prone (yellow) kerogen. Maps are highly generalized and based on published information (see text) and paleogeographic reconstructions (Parrish and others, 2001a, b; Houseknecht and Bird, 2004, 2011). *A.* Triassic source-rock system, comprising the Shublik Formation across most of the map area and the Triassic part of the Otuk Formation in the southernmost part of the map area (frontal thrust belt of the Brooks Range). *B.* Jurassic source-rock system, comprising primarily the lower Kingak Shale across most of the map area and the Jurassic Blankenship Member of the Otuk Formation in the southernmost part of the map area (frontal thrust belt of the Brooks Range). The abrupt yellow-to-green boundary occurs at the shelf margin of the lower Kingak depositional sequence (Houseknecht and Bird, 2004). *C.* Cretaceous–Paleogene source-rock system, comprising primarily the pebble shale unit, gamma-ray zone (GRZ), and Seabee Formation south of the Alaska hinge and Cretaceous and Paleogene condensed mudstones north of the Alaska hinge (Houseknecht and Bird, 2011; Houseknecht and others, 2012b). Pink shading in *A* and *B* shows areas of greatest uplift of rift shoulder during Jurassic–Early Cretaceous; Triassic and Jurassic source rocks are absent by erosion in those areas. Note that Triassic and Jurassic source rocks are probably absent or buried to extreme depths north of the Alaska hinge. Presence of Cretaceous–Paleogene source rocks north of Alaska hinge is inferred on the basis of paleogeographic reconstructions (Houseknecht and Bird, 2011). AU, assessment unit; JU, Jurassic unconformity; LCU, Lower Cretaceous unconformity; TAPS, Trans Alaska Pipeline System; TST, Transgressive Systems Tract (Houseknecht and Bird, 2004).



**Figure 5.** Map of thermal maturity at the base of the Brookian sequence across the Arctic Alaska Province and the southern Canada Basin. This map is derived from thermal history modeling and honors empirical vitrinite reflectance data from 97 exploration wells in the Arctic Alaska Province. Crosses are exploration wells and pseudowells used for modeling. Petroleum systems plots for circled wells with labels are shown in fig. 6. Maturity values greater than 3 percent vitrinite reflectance (VR) are approximate because those values exceed the validity range of kinetics used for calculation. Location of the Alaska hinge is shown by the heavy blue line. Most empirical data from the compilation of Johnsson and others (1993); vitrinite reflectance calculated by using kinetics of Burnham and Sweeney (1989). Modified from Houseknecht and others (2012b).

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**Figure 6 (at left).** Petroleum systems plots for two wells in the Arctic Alaska Province. *A.* Husky Awuna 1, representative of burial and thermal maturation history in the fold-and-thrust belt assessment unit. Stratigraphy below total depth of well (TD in stratigraphic column) was estimated from seismic data. Timing of indicated trap formation reflects Paleogene deformation and does not include development of stratigraphic traps and pre-Paleogene structural traps. Note rapid and nearly simultaneous oil generation in all three main source-rock systems, as expressed by plot of time versus transformation ratio. *B.* Mobil West Kuparuk 3-11-11, representative of burial and thermal maturation history in the platform assessment unit. Well penetrated entire stratigraphic section and reached total depth (TD) in Franklinian basement. Timing of indicated trap formation reflects development of the Lower Cretaceous unconformity truncation trap (main trap at Prudhoe Bay) and does not include other stratigraphic and structural trap development. Note that none of the main oil-prone source rocks has generated oil at this location, as indicated by the plot of time versus transformation ratio. In the stratigraphic column of both plots, only major stratigraphic units are named, whereas burial history plots include more detailed subdivision of strata. Well locations are shown in figs. 5, 7, and 8. GRZ, gamma-ray zone; PSU, pebble shale unit.

Throughout the history of hydrocarbon generation, the Alaska rift shoulder remained a structurally high focus for migration of hydrocarbons generated both in the Arctic Alaska Province and in the southern Canada Basin. Most discovered oil accumulations (including the giant Prudhoe Bay field) and many discovered gas accumulations occur along the rift shoulder and its flanks.

## Arctic Alaska Platform

The Arctic Alaska platform assessment unit (AU) (USGS assessment code 50010201) contains numerous discovered accumulations that have been produced (Houseknecht and Bird, 2006; Alaska Division of Oil and Gas, 2007). This level of exploration places the platform AU into uncertainty category 1 on the scale used by the USGS for the Circum-Arctic Resource Appraisal. That scale of uncertainty places each AU into one of five categories based on data density and degree of exploration, as follows: 1, producing fields; 2, discovered accumulations; 3, exploration wells; 4, seismic data; and 5, no seismic data (Charpentier and Gautier, 2011).

### Assessment Unit Description

The Arctic Alaska platform AU extends from the northern limit of the Brooks Range foothills fold-and-thrust belt on the south to the northern margin of the Alaska rift shoulder on the north and from the axis of the Chukchi platform (near the U.S.-Russia maritime boundary) on the west to a wedge-out on the east where the Brooks Range tectonic front has overridden the rift shoulder (fig. 7; Dietrich and Lane, 1992). The AU encompasses an area of 193,000 km<sup>2</sup>.

The AU includes the Alaska rift shoulder (whose crest is the Barrow arch) and the Arctic-Chukchi platform, including much of the Chukchi shelf. The tectonic history of the AU includes a late Paleozoic through early Mesozoic phase characterized by a south-facing passive continental margin transected in the west by a Devonian(?)–Mississippian failed rift (fig. 1, Hanna trough), an episode of extension and rifting (mostly along the northern margin of the AU) in the Jurassic through early Cretaceous, and development of a foreland basin

during the Cretaceous and Tertiary related to tectonism along the Chukotka and Brooks Range belts (Moore and others, 1994; Houseknecht and Bird, 2011). Petroleum prospective strata are mostly Mississippian and younger, although postulated lower Paleozoic strata in the Northeast Chukchi basin (Sherwood and others, 1998) also are included.

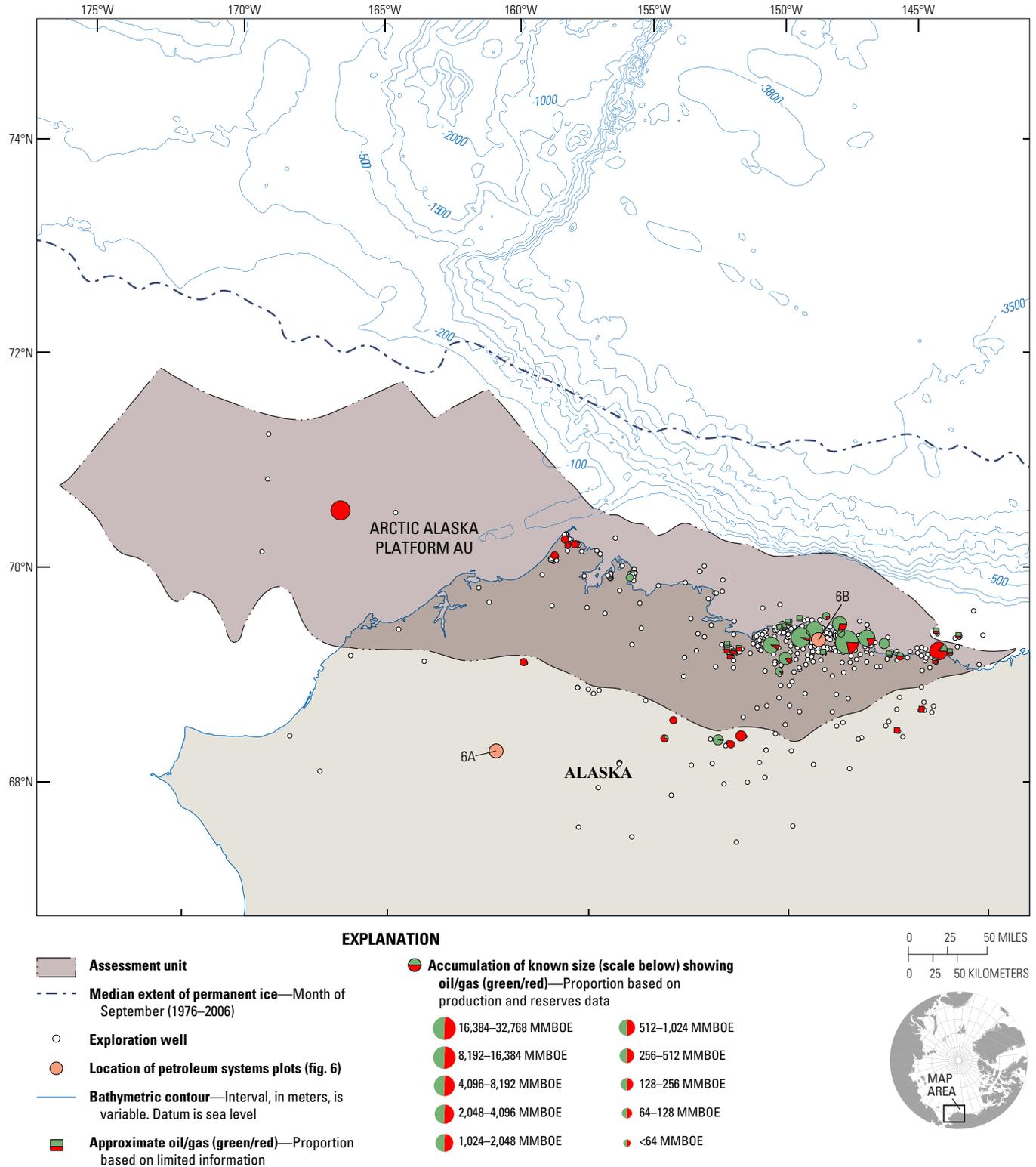
The AU contains several oil-prone source-rock systems that have been demonstrated to have charged discovered oil and gas accumulations (Masterson, 2001; Magoon and others, 2003; Peters and others, 2006, 2008). The main oil source rocks include the Triassic Shublik Formation, Jurassic lower Kingak Shale, and Lower Cretaceous pebble shale unit and GRZ (fig. 3). Additional oil-prone source rocks are locally present in upper Paleozoic and perhaps in Paleogene strata. Gas-prone source rocks are present in several formations spanning upper Paleozoic through Paleogene strata.

More than 2 dozen accumulations have been discovered in the AU, including at least 15 oil and 2 gas accumulations larger than 50 million barrels of oil equivalent (MMBOE) plus numerous smaller oil and gas accumulations (Jamison and others, 1980; Carman and Hardwick, 1983; Melvin and Knight, 1984; Hohler and Bischoff, 1986; Masterson and Paris, 1987; Werner, 1987; Wicks and others, 1991; Masterson and Eggert, 1992; Jameson, 1994; Gingrich and others, 2001; Craig and Sherwood, 2004; Houseknecht and Bird, 2006; Hudson and others, 2006). Through 2005, about 15 billion barrels of oil (BBO) have been produced with reserves of 6.7 BBO and 35 trillion cubic feet of gas (TCFG).

### Geological Analysis of Assessment Unit Probability

Although this AU is the most intensely explored in Arctic Alaska, most exploration has been concentrated in a relatively small part of the AU, onshore and nearshore along the trend of the rift shoulder (fig. 7). Considering the history of discovery in this AU and the vast area that is lightly explored, the probability that the Arctic Alaska platform AU contains at least one undiscovered accumulation of at least 50 MMBOE is considered to be 100 percent (table 1). At the time of this assessment, the AU contained 10 producing fields, including the largest conventional oil field in North America (Prudhoe Bay), and several additional discoveries larger than 50 MMBOE.

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**Figure 7.** Map of Arctic Alaska platform assessment unit showing locations of exploration wells and known accumulations of oil and gas. Known accumulation bubbles are scaled to show estimated total known resource (produced plus reserves) and are divided to show proportion of liquid (crude oil plus condensate) and gas. Reserves data are from Houseknecht and Bird (2006) and Alaska Division of Oil and Gas (2007).

**Table 1.** Summary of assessment unit probabilities and key input parameters for numbers and sizes of undiscovered, conventional accumulations for the Arctic Alaska platform assessment unit.

<b>Assessment-Unit Probabilities:</b> (Adequacy for at least one undiscovered field of minimum size)	
<u>Attribute</u>	<u>Probability of occurrence (0–1.0)</u>
1. <b>CHARGE:</b> Adequate petroleum charge:	<b>1.0</b>
2. <b>ROCKS:</b> Adequate reservoirs, traps, and seals:	<b>1.0</b>
3. <b>TIMING OF GEOLOGIC EVENTS:</b> Favorable timing:	<b>1.0</b>
<b>Assessment-Unit GEOLOGIC Probability</b> (Product of 1, 2, and 3):	<b>1.0</b>

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<b>UNDISCOVERED ACCUMULATIONS</b>			
<b>Number of Undiscovered Accumulations:</b> How many undiscovered accumulations exist that are at least the minimum size? (uncertainty of fixed but unknown values)			
Total Accumulations:	minimum (>0)	<b>25</b>	median <b>150</b> maximum <b>300</b>
Oil/Gas Mix:	minimum (>0)	<b>0.3</b>	mode <b>0.6</b> maximum <b>0.8</b>
X	# of oil accumulations / # of total accumulations		
_____	# of oil accumulations / # of gas accumulations		
_____	# of gas accumulations / # of oil accumulations		
Oil Accumulations:	minimum (>0)	<b>8</b>	median <b>85</b> maximum <b>240</b>
Gas Accumulations:	minimum (>0)	<b>5</b>	median <b>60</b> maximum <b>200</b>
<b>Sizes of Undiscovered Accumulations:</b> What are the sizes ( <b>grown</b> ) of the above accumulations? (variations in the sizes of undiscovered accumulations)			
Oil in Oil Accumulations (mmbo):	minimum	<b>50</b>	median <b>150</b> maximum <b>8,000</b>
Gas in Gas Accumulations (bcfg):	minimum	<b>300</b>	median <b>900</b> maximum <b>50,000</b>

## Charge

Demonstrated source rocks that occur within this AU, as well as in the fold-and-thrust belt AU to the south, include the Triassic Shublik Formation, Jurassic lower Kingak Shale, and Lower Cretaceous pebble shale unit and GRZ. Mixing of oil from these source rocks is common in this AU (Magoon and others, 2003; Peters and others, 2008). Regional seismic, well, and outcrop data and burial history modeling indicate that petroleum generation was controlled by burial related to filling of the Colville foreland basin, which began in the southwest in the Early Cretaceous (about 120–110 Ma) and progressed eastward to the middle Paleogene (about 45 Ma). As foreland basin fill prograded northward across the subsiding rift shoulder, petroleum generation occurred north of the rift shoulder, where a thick prism of Brookian sediment was deposited (fig. 5). Generally, regional migration pathways likely fol-

lowed stratigraphic bedding and unconformities updip toward the Barrow arch, but local pathways are postulated to be controlled by faults in the entire stratigraphic section and by clinoforms in the Beaufortian and Brookian sequences. Moreover, Paleogene uplift in the northwestern part of the AU and regional tilting of the Barrow arch, probably induced by tectonic loading by the Brooks Range in the east, resulted in spilling and remigration in several areas (Jones and Spears, 1976; Wallace and Hanks, 1990; O'Sullivan and others, 1993; Masterson, 2001; Potter and others, 2004; Houseknecht and others, 2011).

## Rocks

The dominant reservoir lithology in this AU is sandstone, although upper Paleozoic carbonate reservoirs (Lisburne

Group) are locally important. Nearly every sandstone unit is known to contain hydrocarbons somewhere in the AU. The greatest volumes of known petroleum resources (cumulative production plus reserves) are reseroired in fluvial-deltaic sandstone of the Ivishak and Kekiktuk Formations (Triassic and Mississippian, respectively; Melvin and Knight, 1984; Shanmugam and Higgins, 1988; Crowder, 1990), the shallow marine sandstone of the Kuparuk Formation and stratigraphically equivalent units (Early Cretaceous; Carman and Hardwick, 1983; Masterson and Paris, 1987; Werner, 1987; Masterson and Eggert, 1992), and the Upper Jurassic part of the Kingak Shale (Houseknecht and Bird, 2004). The largest known accumulations (Prudhoe Bay, Kuparuk, Point Thomson, Burger) occur in combination structural-stratigraphic traps related to rifting, but an increasing number of accumulations are known to occur in purely stratigraphic traps in both deep marine facies (Meltwater, Tarn, Nanuq) and shallow marine facies (Alpine, Fiord, Rendezvous, Moose's Tooth, Tabasco) (Gingrich and others, 2001; Houseknecht and Schenk, 2007). Seals are provided by marine shale.

## Timing and Preservation

Oil generation began in the southern and western parts of the Arctic Alaska Province in the Early Cretaceous (fig. 6A) and progressed eastward and northward through the Tertiary (Houseknecht and others, 2012b). Onshore, generation probably ended during the late Eocene (about 45 Ma) but may still be ongoing offshore in the eastern part of the AU where sedimentation continues on the shelf of the Beaufort Sea (Houseknecht and others, 2012b).

There was potential for loss of trapped hydrocarbons during the Paleogene, when the Barrow arch tilted downward to the east, apparently as the result of tectonic loading by the northward advance of the northeast Brooks Range. This regional tilting caused spilling of oil from the giant Prudhoe Bay accumulation and remigration of that oil to shallower traps (Jones and Spears, 1976; Masterson, 2001). Some of those traps are so shallow that the oil has been biodegraded, resulting in multibillion-barrel accumulations of heavy oil in the Prudhoe Bay-Kuparuk area. Also during the Paleogene, the western part of the Alaska rift shoulder was uplifted (Houseknecht and others, 2011), likely resulting in both oil displacement from traps by gas expansion and regional updip migration of dry gas from the foredeep. It is unknown whether tilting of the Barrow arch and uplift of the western part of the rift shoulder share a common geologic cause.

## Analogues Used for Assessment

Assessment input was influenced strongly by the geology, sizes, and numbers of discovered accumulations in the AU and by the assessments of undiscovered resources conducted by the USGS and U.S. Department of the Interior, Minerals Management Service (MMS), which were largely based on the

mapping of favorable trap geometries from reflection seismic data (ANWR Assessment Team, 1999; Bird and others, 2005; Minerals Management Service, 2006; Houseknecht and others, 2010). In those assessments a total of 69 plays were identified and assessed within the area considered in the Arctic Alaska platform AU. From those assessments, the mean value of undiscovered resources and number and sizes of undiscovered pools larger than 50 MMBOE were tabulated and used as a consideration for completing the assessment input. Because of the unique tectonic history of the Arctic Alaska platform AU (rift shoulder and foreland basin overlap in time and space), analogs were difficult to identify in the USGS World Analog Database (Charpentier and others, 2008). A search of extensional structural setting plus continental crustal system, culled to remove AUs with compressional, thrust-fault, wrench-fault, and salt-related structures, provided additional guidance for constraining possible numbers and sizes of accumulations. The resulting analog set (table 2) contains 34 AUs in which the predominant trap system is basement-involved block structures.

## Assessment Inputs

### Number of Accumulations

Considering that this AU is one of the most prolific oil Provinces in North America, that only a small part of the AU has been explored, and that numerous potential traps have been identified in seismic data, values of 25, 150, and 300 were selected for the minimum, median, and maximum number of undiscovered accumulations of at least 50 MMBOE (table 1). These inputs equate to densities that are within the distribution of the analog set.

### Oil-to-Gas Mix

The minimum, median, and maximum values for the oil-to-gas ratio were set at 0.3, 0.6, and 0.8 (table 1) based on the ratio of oil-to-gas accumulations in the discovered population (larger than 50 MMBOE) and the spatial distribution of oil- versus gas-prone source rocks and thermal maturity across the AU.

### Accumulation Size Distribution

The median and maximum oil accumulation sizes were set at 150 and 8,000 MMBO, respectively (table 1). The median value was based on the sizes of discovered accumulations in the AU and the sizes of potential traps identified in seismic data. The maximum value was set to approximately half the size of the Prudhoe Bay accumulation. These input values are within the analog distributions, although they fall in the upper parts of those distributions. Median and maximum input values of 0.9 and 50 TCF (table 1) were set for gas accumulation sizes based mostly on the range of sizes of potential

**Table 2.** Analog assessment units used to constrain input parameters for the Arctic Alaska platform assessment unit. Analog data from Charpentier and others (2008).

[AU, assessment unit; TPS, total petroleum system]

<b>AU Code</b>	<b>AU name</b>	<b>TPS name</b>	<b>Province name</b>
10080101	Northwest Izhma-Pechora Depression	Domanik-Paleozoic	Timan-Pechora Basin
10090102	Devonian Synrift	Dnieper-Donets Paleozoic	Dnieper-Donets Basin
20040101	Ma'Rib-Al Jawf/Shabwah/Masila	Madbi Amran/Qishn	Ma'Rib-Al Jawf/Masila Basin
20230101	Horst/Graben-Related Oil and Gas	Paleozoic Qusaiba/Akkas/Abba/Mudawwara	Widyan Basin-Interior Platform
20230201	Platform Horst/Graben-Related Oil	Jurassic Gotnia/Barsarin/Sargelu/Najmah	Widyan Basin-Interior Platform
20430101	Southeast Sirte Clastics	Sirte-Zelten	Sirte Basin
20430102	Central Sirte Carbonates	Sirte-Zelten	Sirte Basin
20430104	Southeast Sirte Hypothetical	Sirte-Zelten	Sirte Basin
31270101	Tertiary Lacustrine	Shahejie-Shahejie/Guantao/Wumishan	Bohaiwan Basin
31270102	Pre-Tertiary Buried Hills	Shahejie-Shahejie/Guantao/Wumishan	Bohaiwan Basin
31440102	Anticlinal	Qingshankou-Putaohua/Shuertu	Songliao Basin
31440201	Structural Traps	Jurassic Coal-Denglouku/Nongan	Songliao Basin
38220102	Mergui	Bampo-Cenozoic	North Sumatra Basin
38240101	Sunda/Asri	Banuwati-Oligocene/Miocene	Northwest Java Basin
38240201	Ardjuna	Jatibarang/Talang Akar-Oligocene/Miocene	Northwest Java Basin
39100101	Barnett	Milligans-Carboniferous/Permian	Bonaparte Gulf Basin
39100202	Vulcan Graben	Keyling/Hyland Bay-Permian	Bonaparte Gulf Basin
39130101	Late Jurassic/Early Cretaceous-Mesozoic	Late Jurassic/Early Cretaceous-Mesozoic	Browse Basin
40170101	Halten Terrace-Trondelag Platform	Upper Jurassic Spekk	Vestford-Helgeland
40170102	Mid-Norway Continental Margin	Upper Jurassic Spekk	Vestford-Helgeland
40250101	Viking Graben	Kimmeridgian Shales	North Sea Graben
40250102	Moray Firth	Kimmeridgian Shales	North Sea Graben
40480101	Greater Hungarian Plain Basins	Greater Hungarian Plain Neogene	Pannonian Basin
40480201	Zala-Drava-Sava Basins	Zala-Drava-Sava Mesozoic/Neogene	Pannonian Basin
40480301	Danube Basin	Danube Neogene	Pannonian Basin
40480401	Transcarpathian Basin	Transcarpathian Neogene	Pannonian Basin
40600201	Thermal Triassic	Meride/Riva di Solto	Po Basin
60550103	Dorsal de Neuquen Structure	Neuquen Composite	Neuquen Basin
60580101	San Jorge Extensional Structures	D-129	San Jorge Basin
60600101	North Falklands Basin	Neocomian Lacustrine	Falklands Plateau
60600201	South Falklands Basin	Lower Cretaceous	Falklands Plateau
60630101	Malvinas Extensional Structures	Lower Cretaceous Marine	Malvinas Basin
60980202	Orinoco Delta and Offshore	Upper Cretaceous/Tertiary	East Venezuela Basin
80430101	Eocene-Miocene Bombay Shelf	Eocene-Miocene Composite	Bombay

traps identified on seismic data. The only known gas accumulations in this AU whose sizes are well constrained are those associated with large oil accumulations (for example, Prudhoe Bay), and the sizes of nonassociated gas accumulations are poorly known (Houseknecht and Bird, 2006).

## Province Geologist's Estimated Maximum Accumulation Size

Maximum accumulation sizes of 1 to 2 BBO and 12 to 15 TCFG were selected based on the size distribution of discovered accumulations and the largest accumulation sizes assessed by MMS and USGS using a large seismic database to constrain trap sizes. These maximum sizes, which did not enter directly into the volumetric calculations, were used to judge the reasonableness of the results of statistical analysis.

## Ancillary Properties and Co-Product Ratios

Data from discovered pools in this AU and from geochemistry of source rocks were used to establish input values for these parameters.

## Results

Probabilistic estimates of volumes of undiscovered, technically recoverable hydrocarbons for the Arctic Alaska platform AU are summarized in table 3. These results include mean estimates of nearly 28 BBO, more than 37 TCF associated gas, and more than 120 TCF nonassociated gas.

## Arctic Alaska Fold-and-Thrust Belt

The fold-and-thrust belt AU (USGS assessment code 50010202) has been lightly explored but includes oil and gas discoveries larger than the minimum considered in the CARA. This level of exploration places the Arctic Alaska fold-and-thrust belt into uncertainty category 2 on the scale used by the USGS for the Circum-Arctic Resource Appraisal (Charpentier and Gautier, 2011).

### Assessment Unit Description

The Arctic Alaska fold-and-thrust belt AU extends from the northern margin of the Brooks Range and Herald arch on the south to the northern limit of significant detachment folding that marks the boundary with the Arctic Alaska platform AU (fig. 8). The eastern quarter of the AU, where the Brooks Range tectonic front has overridden the Alaska rift shoulder, is bounded on the north by growth-faulted and contractionally deformed Tertiary strata deposited north of the rift shoulder (part of the Canning-Mackenzie deformed margin AU of the

Amerasia Basin Province; Houseknecht and others, 2012a). The AU encompasses an area of 156,000 km<sup>2</sup>.

As defined, the AU includes the southern parts of the Chukchi shelf, Hanna trough, and Colville foreland basin, plus the entire frontal thrust belt of the Brooks Range in northeastern Alaska and northwestern Canada (fig. 8). This AU is characterized by detachment folds and thrust faults related to Brooks Range tectonism. The detachment level generally steps down the stratigraphic section southward toward the Brooks Range, from Cretaceous–Tertiary foreland basin strata in the north, through upper Mesozoic–Lower Cretaceous rift-related strata, and into lower Mesozoic–upper Paleozoic passive margin strata in the south (Moore and others, 1994, 2004; Potter and others, 2004). Petroleum prospective strata span the stratigraphic section from upper Paleozoic through Tertiary.

The AU contains several oil-prone source-rock systems that have been shown to have charged discovered oil and gas accumulations (Magoon and others, 2003; Peters and others, 2008). The main oil-prone source rocks include the Triassic Shublik Formation, the Jurassic lower Kingak Shale, and the Lower Cretaceous pebble shale unit and GRZ (fig. 3). The Triassic–Lower Jurassic Otuk Formation—the distal stratigraphic equivalent of the Shublik Formation and lower Kingak Shale—is an important component of the source-rock system in the southern part of the AU where it is present on thrust sheets. Source-rock facies gradational between the Shublik Formation and lower Kingak Shale on the north and the Otuk Formation in the south may be present in autochthonous positions deeply buried beneath the disturbed belt of the frontal Brooks Range. Locally, the Otuk Formation in outcrop occurs at levels of thermal maturity that are in the oil window (Dow and Talukdar, 1995; Dow, 1998; Mull, 2000, written commun., 2009). Additional oil-prone source rocks are locally present in upper Paleozoic strata, most notably the Kuna Formation of the Lisburne Group. Gas-prone source rocks are present in several formations spanning upper Paleozoic through Tertiary strata.

Several gas accumulations and one oil accumulation have been discovered in the AU (Houseknecht and Bird, 2006). Only the Gubik gas accumulation (about 600 BCF) and the Umiat oil accumulation (about 70 MMBO) are larger than the minimum size considered in this assessment. However, most of the discovered gas accumulations are too poorly characterized to determine their size. No commercial production has occurred in this AU, although about 40,000 barrels of oil was produced for local consumption and testing at Umiat prior to 1953 (Molenaar, 1982).

### Geological Analysis of Assessment Unit Probability

The likelihood that the Arctic Alaska fold-and-thrust belt AU contains at least one undiscovered accumulation of at least 50 MMBOE is considered to be 100 percent (table 4) based on the occurrence of two discoveries greater than the minimum

**Table 3.** Summary of results for risked, undiscovered, technically recoverable petroleum resources for the Arctic Alaska Province, including results for the platform assessment unit and the fold-and-thrust belt assessment unit.

[F95 represents a 95-percent chance of at least the amount tabulated; other fractiles are defined similarly. Std. dev., standard deviation]

Assessment unit name		Assessment unit probability			
	Platform	1.000			
	Fold- and-thrust belt	1.000			
Assessment unit name	F95	F50	F5	Mean	Std. dev.
Oil, in millions of barrels (MMBO)					
Platform	13,866.70	26,207.02	47,425.71	27,851.06	10,450.85
Fold-and-thrust belt	587.64	1,761.86	4,814.48	2,109.89	1,402.14
Associated/Dissolved Gas, in billions of cubic feet (BCFG)					
Platform	17,176.27	34,742.05	68,535.20	37,692.85	16,215.51
Fold-and-thrust belt	640.54	2,255.62	7,047.29	2,846.06	2,190.90
Natural Gas Liquids, in millions of barrels (MMBNGL)					
Platform	454.91	928.94	1,856.99	1,011.71	447.97
Fold-and-thrust belt	16.51	59.86	191.90	76.42	60.64
Nonassociated Gas, in billions of cubic feet (BCFG)					
Platform	53,122.97	112,562.12	222,711.73	121,860.59	53,452.97
Fold-and-thrust belt	24,272.55	52,465.41	115,798.60	58,998.09	29,620.91
Liquids, in millions of barrels (MMBL)					
Platform	1,391.94	2,993.27	5,989.52	3,245.45	1,449.80
Fold-and-thrust belt	640.60	1,395.64	3,107.19	1,571.39	795.92
Largest Oil, in millions of barrels (MMBO)					
Platform	1,264.08	2,904.98	6,603.05	3,280.92	1,619.33
Fold-and-thrust belt	150.55	384.26	1,138.93	476.29	318.23
Largest Nonassociated Gas, in billions of cubic feet (BCFG)					
Platform	6,136.18	15,403.31	38,866.11	17,864.13	9,928.09
Fold-and-thrust belt	2,475.42	5,194.98	11,160.75	5,763.17	2,617.91

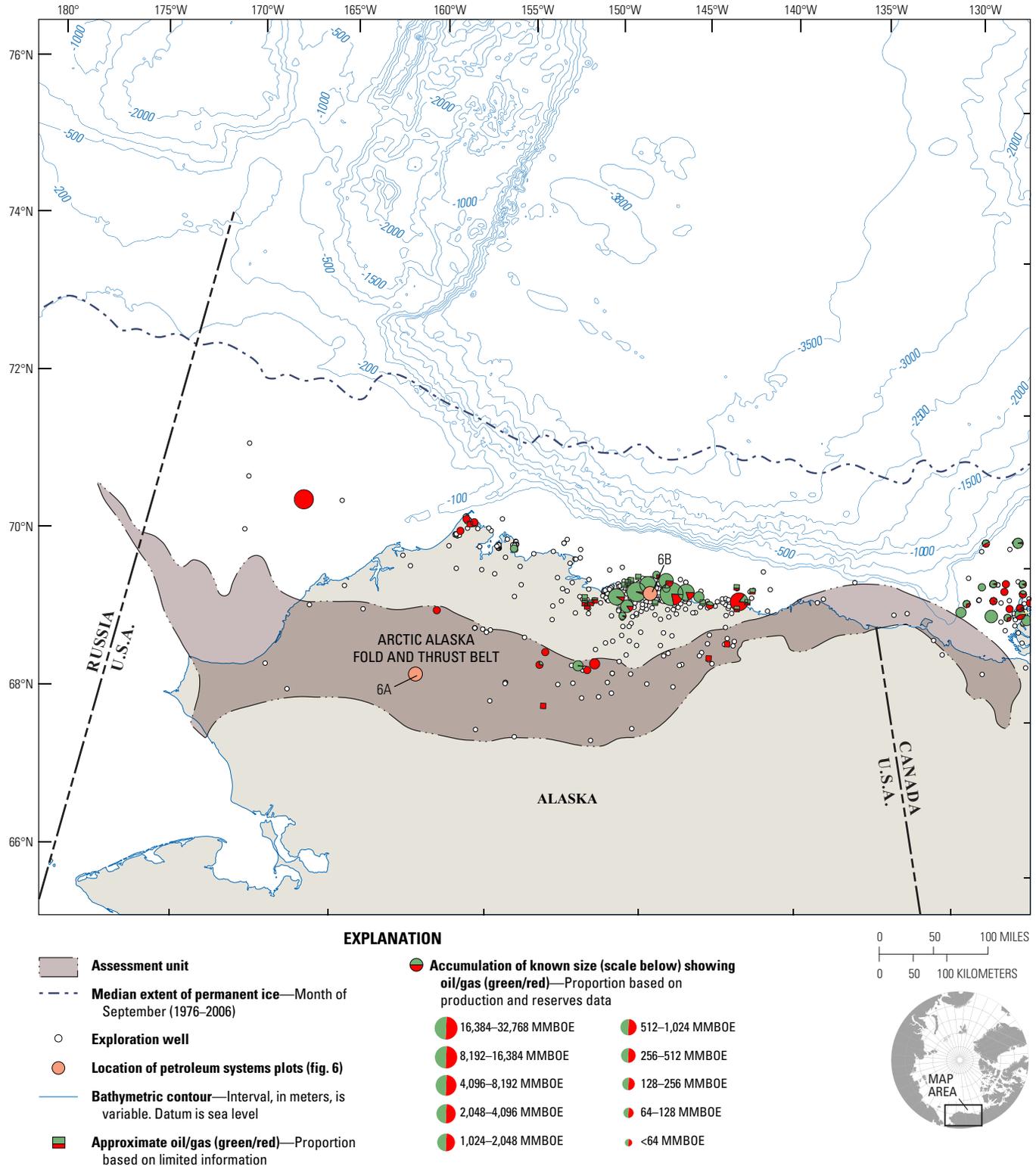
size, the large number of prospects that are evident in seismic data and surface geologic map patterns, and the underexplored status of the AU. Many untested prospects involve anticlines, including relatively simple detachment anticlines and more complex thrust-faulted anticlines (see, for example, Oldow and others, 1987; Bird, 1988; Moore and others, 2004; Potter and others, 2004). Stratigraphic traps and combination structural-stratigraphic traps also are likely to occur (see, for example, Houseknecht and Schenk, 2007).

## Charge

Demonstrated source rocks that occur within this AU include the Mississippian Kuna Formation in the upper part of the Lisburne Group, the Triassic Shublik Formation, the Jurassic lower Kingak Shale, the Triassic–Jurassic Otuk Formation, and the Lower Cretaceous pebble shale unit and GRZ (fig. 3). Regional seismic, well, and outcrop data and burial history modeling indicate that petroleum generation was controlled by sedimentary and tectonic burial. Initial hydrocarbon generation induced by sedimentation in the western Colville foredeep began about 120–110 Ma (fig. 6A) and progressed eastward

and northward until about 90 Ma, with relatively modest additional generation occurring during the Late Cretaceous and Paleogene as the result of additional sedimentary burial and, near the mountain front, tectonic burial (Houseknecht and others, 2012b). This timing reflects the progressive filling of the foredeep and the broader foreland basin from southwest to northeast (Bird and Molenaar, 1992; Houseknecht and others, 2009a, b; Houseknecht and Bird, 2011). Migration pathways in this AU likely were controlled by stratal geometry (for example, clinoforms), unconformities, and faults. Geochemical evidence from oil-stained rocks in outcrop in this AU indicates widespread mixing of oil from two or more source rocks. In addition, gas generation in the foredeep during Tertiary structural burial and gas expansion related to Tertiary uplift likely caused remigration of some accumulated oil. Gas also may have been generated from thermal cracking of oil accumulations and from bitumen that did not migrate from source rocks during oil generation. Consideration of kerogen composition in the three major source-rock systems (fig. 4) and thermal maturity (figs. 5, 6A) indicates that the AU is significantly gas-prone, although the potential for oil is demonstrated by the discovered Umiat accumulation, which is thought to have been sourced from the GRZ (Magoon and others, 2003).

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**Figure 8.** Map of Arctic Alaska fold-and-thrust belt assessment unit showing locations of exploration wells and known accumulations of oil and gas. Known accumulation bubbles are scaled to show estimated total known resource (produced plus reserves) and are divided to show proportion of liquid (crude oil plus condensate) and gas. Reserves data for Alaska are from Houseknecht and Bird (2006) and Alaska Division of Oil and Gas (2007) and for Canada are from Osadetz and others (2005), except for a new discovery reported by Johnston (2007).

**Table 4.** Summary of assessment unit probabilities and key input parameters for numbers and sizes of undiscovered, conventional accumulations for the Arctic Alaska fold-and-thrust belt assessment unit.

<b>Assessment-Unit Probabilities:</b> (Adequacy for at least one undiscovered field of minimum size)	
<u>Attribute</u>	<u>Probability of occurrence (0–1.0)</u>
1. <b>CHARGE:</b> Adequate petroleum charge:	<u>1.0</u>
2. <b>ROCKS:</b> Adequate reservoirs, traps, and seals:	<u>1.0</u>
3. <b>TIMING OF GEOLOGIC EVENTS:</b> Favorable timing:	<u>1.0</u>
<b>Assessment-Unit GEOLOGIC Probability</b> (Product of 1, 2, and 3):	<u>1.0</u>

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<b>UNDISCOVERED ACCUMULATIONS</b>			
<b>Number of Undiscovered Accumulations:</b> How many undiscovered accumulations exist that are at least the minimum size? (uncertainty of fixed but unknown values)			
Total Accumulations:	minimum (>0) <u>10</u>	median <u>60</u>	maximum <u>250</u>
Oil/Gas Mix:	minimum (>0) <u>0.1</u>	mode <u>0.2</u>	maximum <u>0.3</u>
X	# of oil accumulations / # of total accumulations		
_____	# of oil accumulations / # of gas accumulations		
_____	# of gas accumulations / # of oil accumulations		
Oil Accumulations:	minimum (>0) <u>1</u>	median <u>12</u>	maximum <u>75</u>
Gas Accumulations:	minimum (>0) <u>7</u>	median <u>50</u>	maximum <u>225</u>
<b>Sizes of Undiscovered Accumulations:</b> What are the sizes ( <b>grown</b> ) of the above accumulations? (variations in the sizes of undiscovered accumulations)			
Oil in Oil Accumulations (mmbbl):	minimum <u>50</u>	median <u>100</u>	maximum <u>2,000</u>
Gas in Gas Accumulations (bcfg):	minimum <u>300</u>	median <u>700</u>	maximum <u>14,000</u>

**Rocks**

The dominant reservoirs in this AU are sandstone, although late Paleozoic carbonate reservoirs (Lisburne Group) also are viable, especially in thrust sheets close to the Brooks Range (Hanks and others, 1997). Oil and gas shows are common in this AU. The best known reservoir potential has been documented in Cretaceous and Tertiary fluvial-deltaic (topset) sandstone (Fortress Mountain, Nanushuk, Tuluvaq, Schrader Bluff, and Sagavanirktok Formations) and coeval slope and basin-floor turbidite sandstone (Torok, Seabee, and Canning Formations; fig. 3). The largest known accumulations (Umiat oil accumulation and Gubik gas accumulation) occur in sandstone reservoirs of topset seismic facies in detachment-anticline traps. Stratigraphic traps in both deep marine and shallow marine sandstone are likely (see, for example, Moleenaar, 1988; Houseknecht and Schenk, 2007). There also is

significant potential for low-permeability sandstone reservoirs, especially in association with overpressured gas accumulations (Nelson and others, 2006). Seals are provided by marine shale and mudstone.

**Timing and Preservation**

Oil generation began in the southern and western parts of the AU in the Early Cretaceous and progressed eastward and northward (Houseknecht and others, 2012b). Onshore, generation probably ended in late Eocene (about 45 Ma) but may be ongoing offshore in the eastern part of the AU where sedimentation and contractional deformation continue. An important consideration regarding charge in this AU is the inference that the fold-and-thrust belt formed as the result of two major phases of contractional deformation—one during the Early Cretaceous and the second during the Tertiary

(Moore and others, 2004). Hydrocarbon generation modeling (Houseknecht and others, 2012b) suggests that—except for the eastern offshore part of the AU—most oil generation, primary migration, and initial accumulation in traps occurred during the Cretaceous, either contemporaneous with or immediately after the first major phase of deformation. Thus, the second phase of deformation occurred after oil accumulation in traps across much of the AU. The subsequent phase of deformation in the Tertiary may have disrupted traps and caused seal failure that may have resulted in remigration, and perhaps leakage to the surface, of oil and gas. In fact, it is likely that the Umiat oil accumulation, which is trapped in a structure that formed during the Paleogene (O’Sullivan, 1999) in an area where oil was generated during the early Cretaceous (Houseknecht and others, 2012b), is the result of remigration of oil from an older stratigraphic or combination trap (perhaps similar to that described by Houseknecht and Schenk, 2007) that failed during Paleogene deformation. In addition, gas generation during structural burial in the Colville foredeep and gas expansion related to uplift of parts of the fold-and-thrust belt during Paleogene deformation likely caused remigration of hydrocarbons that accumulated during generation and primary migration.

## Analogous Used for Assessment

Assessment input was influenced by the geology, sizes, and numbers of discovered accumulations in the AU and by the assessments of undiscovered resources conducted by the USGS and MMS, which were largely based on the mapping of favorable trap geometries from 2-D seismic data. In those assessments, a total of 23 plays were identified and assessed within the area considered in the Arctic Alaska fold-and-thrust belt AU. From those assessments, the mean value of undiscovered resources and number and sizes of undiscovered pools larger than 50 MMBOE were tabulated and used as a consideration for completing the assessment input.

The USGS World Analog Database was used to help constrain assessment input parameters, especially the density of accumulations larger than 50 MMBOE and the median and maximum sizes of accumulations. A search of compressional structural setting, plus continental crustal system, plus foreland architecture returned 43 potential analogs. These were culled to remove 16 AUs with transtensional and transpressional trap systems, extensional grabens and other structures related to normal faults, and salt-induced structures. The remaining 27 AUs (table 5) were considered as a population that may provide reasonable constraints on assessment input parameters.

## Assessment Inputs

### Number of Accumulations

Previous MMS and USGS assessments estimated 58 accumulations of at least 50 MMBOE at the mean, which yields a density of 0.31 accumulations per 1,000 km<sup>2</sup>. With a focus on the previous assessments, a minimum of 10 to a maximum of 250 accumulations and a median value of 60 was used (table 4).

### Oil-to-Gas Mix

The minimum, median, and maximum values for the oil-to-gas ratio were set at 0.1, 0.2, and 0.3 (table 4) based on the ratio of oil/gas accumulations in the discovered population, empirical and modeled thermal maturity considerations, and the distribution of oil- versus gas-prone source rocks.

### Accumulation Size Distribution

The median and maximum gas accumulation sizes were set at 700 and 14,000 BCF (table 4), based on the sizes of seismically mapped structural closures and known reservoir parameters. Inputs for oil accumulation sizes were scaled downward (median, 100 MMBO; maximum, 2,000 MMBO; table 4) relative to gas because of the poor timing for charging structural traps with oil and the overall gas-prone nature of the AU, primarily due to high levels of thermal maturity.

### Province Geologist’s Estimated Maximum Accumulation Size

Maximum accumulation sizes of 5 TCFG and 400–500 MMBO were selected considering the sizes of seismically mapped structural closures, regional reservoir character, and sizes of discovered accumulations. These maximum sizes, which did not enter directly into the volumetric calculations, were used to judge the reasonableness of the results of statistical analysis.

### Ancillary Properties and Co-Product Ratios

Data from discovered pools in this AU and from geochemistry of source rocks were used to establish input values for these parameters.

## Results

Probabilistic estimates of volumes of undiscovered, technically recoverable hydrocarbons for the Arctic Alaska fold-and-thrust belt AU are summarized in table 3. These results include mean estimates of 2 BBO, nearly 3 TCF associated gas, and 59 TCF nonassociated gas.

**Table 5.** Analog assessment units used to constrain input parameters for the Arctic Alaska fold-and-thrust belt assessment unit. Analog data from Charpentier and others (2008).

[AU, assessment unit; TPS, total petroleum system]

AU Code	AU name	TPS name	Province name
10080103	Foredeep Basins	Domanik-Paleozoic	Timan-Pechora Basin
10150201	Permian Reefs/Thrust Folds	Belsk Basin	Volga-Ural Region
11090101	Foldbelt-Foothills	Terek-Caspian	Middle Caspian Basin
11090102	Terek-Sunzha Subsalt Jurassic	Terek-Caspian	Middle Caspian Basin
11540103	Murgab Depression Suprasalt	Amu-Darya Jurassic-Cretaceous	Amu-Darya Basin
11540104	Murgab Depression Subsalt	Amu-Darya Jurassic-Cretaceous	Amu-Darya Basin
20190101	Cretaceous Reservoirs in Northwest Desert Anticlines	Cretaceous Thamama/Wasia	Rub Al Khali Basin
20190103	Mesozoic/Tertiary Foredeep Fold and Thrust	Cretaceous Thamama/Wasia	Rub Al Khali Basin
20190201	Jurassic Reservoirs in Northwest Desert Anticlines	Jurassic Hanifa/Diyab-Arab	Rub Al Khali Basin
20190302	Paleozoic Reservoirs	Silurian Qusaiba	Rub Al Khali Basin
20300101	Cretaceous Reservoirs	Zagros-Mesopotamian Cretaceous-Tertiary	Zagros Fold Belt
20300102	Tertiary Reservoirs	Zagros-Mesopotamian Cretaceous-Tertiary	Zagros Fold Belt
20300201	Northern Qatar Arch Extension	Paleozoic-Permian/Triassic	Zagros Fold Belt
20580501	Tanezzuft-Benoud Structural/Stratigraphic	Tanezzuft-Benoud	Grand Erg/Ahnet Basin
31150201	Jurassic/Tertiary Fluvial and Lacustrine Sandstone	Jurassic Coal-Jurassic/Tertiary	Junggar Basin
31420101	Southeastern Fold Belt	Maokou/Longtang-Jialingjiang/Maokou/Huanglong	Sichuan Basin
31420102	Northwestern Depression/Foldbelt	Maokou/Longtang-Jialingjiang/Maokou/Huanglong	Sichuan Basin
31420201	Jurassic Lacustrine	Daanzhai-Daanzhai/Lianggaoshan	Sichuan Basin
31420402	Lower Paleozoic of Southeastern Fold Belt	Cambrian/Silurian Marine Shale-Dengying/Lower Paleozoic	Sichuan Basin
31540102	Kuche (Northern) Foldbelt	Ordovician/Jurassic-Phanerozoic	Tarim Basin
31540103	Southwest Foldbelt	Ordovician/Jurassic-Phanerozoic	Tarim Basin
40470201	Deformed Belt	Mesozoic/Paleogene Composite	North Carpathian Basin
40600101	Neogene Flysch Gas	Porto Garibaldi	Po Basin
52430201	Leduc Gas	Duvernay-Leduc	Alberta Basin
52430301	Exshaw-Rundle Gas	Exshaw-Rundle	Alberta Basin
52430302	Exshaw-Rundle Oil and Gas	Exshaw-Rundle	Alberta Basin
52430401	Combined Triassic/Jurassic Gas	Combined Triassic/Jurassic	Alberta Basin

## Summary and Conclusions

The Arctic Alaska Petroleum Province is part of a displaced continental fragment, the Arctic Alaska microplate, which rifted from the Canada Arctic margin during opening of the Canada Basin. Petroleum prospective rocks in the province, mostly Mississippian and younger, record a sequential geologic evolution through passive margin, rift, and foreland basin tectonic stages. Significant petroleum source and reservoir rocks were formed during each tectonic stage, but it

was the foreland basin stage that provided sufficient burial for widespread hydrocarbon generation.

Three major source-rock systems (Triassic, Jurassic, and Cretaceous–Paleogene) contribute to the overall richness of the province, although details of regional source-rock quality remain poorly known because of limited data. Relative to levels of thermal maturity appropriate for the generation and preservation of oil, these source rocks grade northward from overmature in the Colville foredeep to early mature to immature on the rift shoulder. Burial history and hydro-

carbon generation modeling indicates that peak oil generation occurred mostly during the Cretaceous in the foredeep. Thermal maturity abruptly grades northward from immature to mature, and even overmature, along the northernmost margin of the province where strata thicken into the Amerasia Basin Petroleum Province. Although it is unlikely that the Triassic and Jurassic source rocks are present beyond the hingeline because the Amerasia Basin was not yet open at the time of deposition, oil generated in younger source rocks may have migrated southward into the Arctic Alaska Province during Cretaceous through Paleogene generation.

The majority of known petroleum resources in the province occur in combination structural-stratigraphic traps formed as a consequence of rifting and located along the rift shoulder. Most exploration activity in the province has been focused on either combination or structural traps, although oil discoveries during the past 20 years have increased the emphasis on stratigraphic traps.

The Arctic Alaska Petroleum Province was divided into two AUs for appraisal of undiscovered petroleum resources in conventional accumulations. The platform AU includes the Alaska rift shoulder and its relatively undeformed flanks, and the fold-and-thrust belt AU includes the deformed areas north of the Brooks Range and Herald arch tectonic belts.

The Arctic Alaska platform AU includes at least 15 oil and 2 gas accumulations larger than 50 MMBOE, including the largest oil field in North America at Prudhoe Bay. Considering that a relatively small proportion of the AU has been explored, the potential for discovery of additional accumulations is considered high. Mean estimates for undiscovered, technically recoverable resources in conventional accumulations include nearly 28 BBO, more than 37 TCF of associated gas, and more than 120 TCF of nonassociated gas.

The Arctic Alaska fold-and-thrust belt AU is lightly explored and includes multiple oil and gas discoveries, including at least one oil and one gas accumulation that exceed the 50-MMBOE threshold for the CARA. Exploration in this AU has been limited by the absence of a market for natural gas and the perception that it is a gas-prone region. The potential for discovery of additional accumulations is considered high. Mean estimates for undiscovered, technically recoverable resources in conventional accumulations include 2 BBO, nearly 3 TCF of associated gas, and 59 TCF of nonassociated gas.

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