Chapter 2

Geologic Assessment of Undiscovered, Technically Recoverable Coalbed-Gas Resources in Cretaceous and Tertiary Rocks, North Slope and Adjacent State Waters, Alaska

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By Stephen B. Roberts

Chapter 2 of
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Compiled by Stephen B. Roberts

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Publishing support provided by:
Denver Publishing Service Center
Manuscript approved for publication October 17, 2008

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Suggested citation:
Roberts, S.B., 2008, Geologic Assessment of undiscovered, technically recoverable coalbed-gas resources in Cretaceous and Tertiary rocks, North Slope, and adjacent State waters, Alaska, *in* Roberts, S.B., compiler, Geologic assessment of undiscovered, technically recoverable coalbed-gas resources in Cretaceous and Tertiary rocks, North Slope and adjacent State waters, Alaska: U.S. Geological Survey Digital Data Series DDS–69–S, chap. 2, 95 p., 2 pls.

ISBN 1-4113-2138-0

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Geologic Assessment of Undiscovered, Technically Recoverable Coalbed Gas Resources in Cretaceous and Tertiary Rocks, North Slope and Adjacent State Waters, Alaska

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Abstract

Natural gas resources are present in coal beds that are widely distributed across the North Slope of Alaska. In order to address the potential for this resource, the U.S. Geological Survey (USGS) completed an assessment of undiscovered, technically recoverable coalbed-gas resources in Cretaceous and Tertiary rocks underlying the North Slope and adjacent Alaskan State waters. The assessment is based on the total petroleum system (TPS) concept, which combines the principal geologic elements relating to hydrocarbon accumulation, source rock characteristics (maturity, hydrocarbon generation and migration), the characteristics of the reservoir rocks, and trap and seal formation. In the case of coalbed gas, coal beds serve as both the primary source rock and reservoir. USGS concepts and operational procedure for assessing continuous petroleum accumulations using a cell-based approach were applied in this assessment. Continuous accumulations, which include coalbed gas, basin-center gas, and oil and gas in fractured shale, are characterized by a large volume of rock that is pervasively charged with oil or gas; these accumulations do not depend upon the buoyancy of oil and gas in water in order to exist. A continuous accumulation consists of a collection of petroleum-containing cells, and each cell has dimensions related (in part) to the drainage area of wells actually producing from the accumulation or producing from analogous accumulations with similar geologic characteristics.

Four Cretaceous and Tertiary coal-bearing formations were assessed for coalbed-gas potential at depths within 6,000 feet of the ground surface; coal beds at greater depths were not considered due to the potential decrease in permeability with increasing depth. Also, because of the uncertainty as to the permeability of coal beds in ice-bearing permafrost and the degree to which cold temperatures within the permafrost zone might affect gas flow from coals, this assessment focused on potential gas resources in coal beds below permafrost.

The Brookian Coalbed Gas Composite TPS was defined to include that area of the North Slope and adjacent State waters underlain by Cretaceous and Tertiary strata interpreted to contain coal deposits having the potential for generation and retention of coalbed gas. The TPS encompasses about 50,000 square miles, and includes most of the National Petroleum Reserve in Alaska and a limited area in the Arctic National Wildlife Refuge, as well as significant areas of Alaskan State Lands and Native Lands. Assessment units (AUs) within the TPS are defined as follows (oldest to youngest); the Nanushuk Formation Coalbed Gas AU, the Prince Creek and Tuluvak Formations Coalbed Gas AU, and the Sagavanirktok Formation Coalbed Gas AU. Because there is no production of coalbed gas from the North Slope, all AUs are categorized as hypothetical.

The Nanushuk Formation Coalbed Gas AU encompasses about 40,000 square miles in the western and central parts of the North Slope. Discontinuous outcrops of the formation contain coal beds as much as 20 feet thick. In the subsurface, depth to the top of the coal-bearing interval ranges from less than 50 feet to almost 3,400 feet; in most wells, the top of coal is less than 600 feet deep. Cumulative coal thicknesses below permafrost exceed 100 to 150 feet. The apparent coal rank ranges from lignite A to high-volatile A bituminous, and apparent ranks are higher in coals underlying foothills areas of the AU. R_o values measured from coal outcrop samples range from 0.44 to 0.96 percent.

The Prince Creek and Tuluvak Formations Coalbed Gas AU encompasses about 15,000 square miles in the central part of the North Slope. The Tuluvak and Prince Creek Formations were assessed jointly for undiscovered coalbed-gas resources because coal-bearing strata in both formations share a similar geographic area. The formations are separated by the Schrader Bluff Formation, a dominantly marine unit composed of sandstone and shale that can be as thick as 2,500 feet. Coal outcrops are sporadic and the complete coal-bearing section in either formation is not present at any single locality. In the subsurface, depth to the top of the coal-bearing interval ranges from about 20 feet to as much as 1,300 feet, and the maximum cumulative coal thickness inclusive of all coal beds below permafrost in both formations is 35 feet; the maximum individual coal-bed thickness measured in the subsurface is 16 feet. R_o values measured from Prince Creek Formation coal

outcrop samples range from 0.40 to 0.59 percent.

The Sagavanirktok Formation Coalbed Gas AU encompasses about 8,700 square miles in the central and eastern parts of the North Slope. Coal beds in the southern part of the AU are exposed sporadically over a distance of about 50 miles. In outcrops, coal beds vary from less than 1.0 foot thick to as much as 23 feet thick in zones typically associated with carbonaceous shale. In subsurface data, depth to the top of the coal-bearing interval ranges from less than 200 feet to as much as 6,848 feet. Cumulative coal thickness values below permafrost exceed 100 to 150 feet over a large part of the AU; the maximum individual coal-bed thickness measured in well logs was 37 feet. The main coal-bearing interval in the Sagavanirktok Formation is within the Staines Tongue, or in laterally equivalent strata within the main body of the formation where the Staines Tongue is not present. The apparent coal rank of outcrop samples from the southern part of the AU varies from lignite A to subbituminous B; most coals are subbituminous C. R_o values measured from coal outcrop samples range from 0.28 to 0.48 percent, and R_o values based on downhole reflectance profiles projected to the lowest coal bed in the formation range from 0.33 to 0.52 percent.

The combined, mean total estimate of undiscovered coalbed-gas resources in the three AUs within the Brookian Coalbed Gas Composite TPS is 18 trillion cubic feet (TCF). About 84 percent (15 TCF) is estimated to be in the Nanushuk Formation, 12 percent (2.2 TCF) in the Sagavanirktok Formation, and 4 percent (0.8 TCF) in the Prince Creek and Tuluvak Formations.

Introduction

Alaska's North Slope is a vast, tundra-covered region that lies north of the Brooks Range, extending from the Chukchi Sea eastward to the Canadian border (fig. 1). This area is known for its wealth of petroleum resources; to date, some 15 billion barrels of oil have been produced and more than 35 trillion cubic ft (TCF) of gas have been discovered (Houseknecht and Bird, 2005). Mean estimates of undiscovered, technically recoverable petroleum resources in conventional accumulations underlying the North Slope and adjacent State waters indicate the potential for another 24 billion barrels of oil and 119 TCF of gas (Houseknecht and Bird, 2005). An additional, enormous volume of gas may also exist within permafrost-associated gas hydrates. Mean estimates of in-place resources indicate that some 590 TCF of gas may be present in these accumulations (Collett, 1996, 2004).

Within this framework of overwhelming gas potential, additional natural gas resources may be present in coal beds that are widely distributed across the North Slope. Estimates of hypothetical coal resources indicate a total coal volume at or near 4 trillion short tons (Tailleur and Brosgé, 1975; Merritt and Hawley, 1986; Flores and others, 2004). Earlier geologic studies touched on the potential for gas in North Slope coals (for example, Tailleur and Brosgé, 1975; Sable and Stricker, 1987). The successful production of coalbed gas in the conterminous United States and elsewhere in the world, coupled with the large estimated volume of North Slope coal

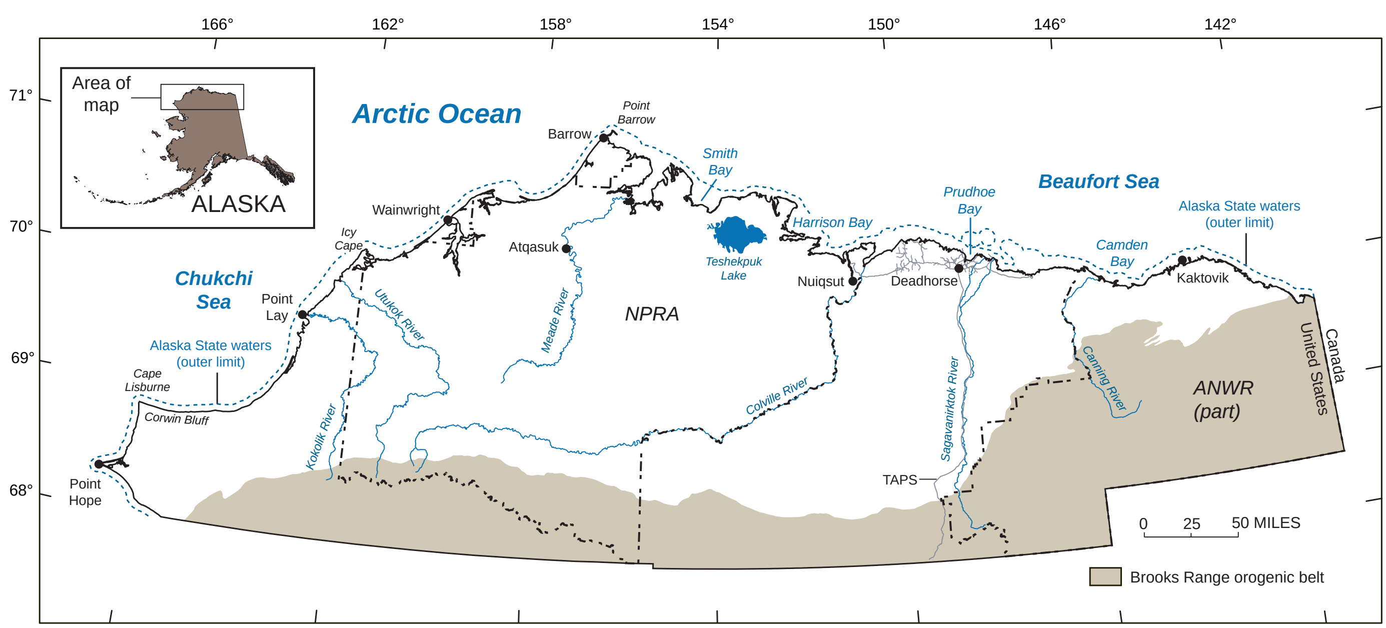


Figure 1. Index map showing the North Slope and State waters boundary in northern Alaska. The North Slope includes lands lying north of the Brooks Range orogenic belt in an area extending from the Chukchi Sea on the west to the Canadian border on the east. TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

has helped to stimulate more recent interest in this potential gas resource (Smith, 1995; Tyler and others, 2000; Barker and others, 2002; Flores and others, 2004).

The present assessment of undiscovered, technically recoverable coalbed-gas resources underlying the North Slope of Alaska and adjacent State waters is the first to be conducted by the USGS. The assessment is based on the total petroleum system (TPS) concept (Magoon and Dow, 1994), which combines geologic elements relating to hydrocarbon accumulation, source rock characteristics (maturity, hydrocarbon generation and migration), the characteristics of the reservoir rocks, and trap and seal formation. In the case of coalbed gas, the coal beds serve as both the primary source rock and reservoir, although the gas resource potential within the coals can also be enhanced by the entrapment of migrated gas from other source rocks.

USGS concepts and operational procedures for assessing continuous petroleum accumulations were applied in this assessment as per guidelines detailed in Schmoker (2005) and Klett and Schmoker (2005). Continuous accumulations (for example, coalbed gas, basin-center gas, and oil and gas in fractured shale) are characterized by a large volume of rock that is pervasively charged with petroleum; these accumulations do not depend upon the buoyancy of oil or gas in water in order to exist (Schmoker, 2005). The assessment methodology utilizes a cell-based approach in which each continuous accumulation within a TPS is considered to consist of a collection of petroleum-containing cells. Each cell has areal dimensions related to the drainage area of wells producing from the accumulation. If there is no production from the accumulation, cell dimensions are derived from the drainage area of wells producing from other continuous accumulations with analogous geologic characteristics (analog areas). Each continuous accumulation within the TPS is assigned to an assessment unit (AU). Key input data required for the assessment of continuous accumulations include (1) the area per cell of untested cells having potential for additions to reserves, (2) the percentage of the untested AU area that has the potential for additions to reserves, and (3) the total recovery of petroleum per cell for untested cells having the potential for additions to reserves. These data are discussed in detail in subsequent sections of this report. The area per cell of untested cells is generally equated to the drainage area of wells as described previously. Estimates of the percentage of the untested AU area with the potential for additions to reserves are based on geologic characteristics within the AU that might critically influence the petroleum resource potential, either positively or negatively. Estimates of the total recovery of petroleum per cell for untested cells are based on estimated ultimate recoveries (EURs) from producing wells within the AU or from producing wells in analog areas.

The coalbed-gas potential was assessed in four Cretaceous and Tertiary coal-bearing formations (fig. 2) at depths estimated to be within 6,000 ft of the ground surface. Coal beds at depths exceeding 6,000 ft were not considered due to the potential decrease in permeability with increasing depth, which could affect coalbed-gas recovery. Other Cretaceous and Tertiary formations with minor coal deposits, as well as coal-bearing strata of Mississippian age were not assessed for coalbed-gas resources, but are discussed briefly within the report. Also, because of the uncertainty as to the permeability of coal beds in ice-bearing permafrost and the degree to which cold temperatures within the permafrost might affect gas flow from coals (Smith, 1995; Tyler and others, 2000), the assessment focused on potential coalbed-gas resources interpreted to be below the permafrost interval. The term ‘permafrost’ as used in this study designates the subsurface interval of cold temperatures and potentially ice-bearing rock that might inhibit coalbed-gas production for the reasons previously stated. Reported permafrost depths are based primarily on data from 123 oil and gas exploration wells and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost as determined from geophysical well log interpretations by Collett and others (1989) or interpretations by the author as part of this study, (2) the depth from the ground surface to the base of the ice-rich layer as derived from down-hole temperature profiles (for example, Lachenbruch and others, 1987), or (3) the depth from the ground surface to a subsurface temperature of 0˚C as measured in borehole temperature logs (for example, Lachenbruch and others, 1987). The actual measured depth to the base of the ice-bearing permafrost was not available in all drill holes, so permafrost depth in certain cases had to be inferred from factors 2 or 3 above. Based on the data available for this study, the depth to 0˚ C exceeded the depth to the base of the ice-bearing permafrost by an average of about 300 ft, and exceeded the depth to the base of the ice-rich layer by an average of about 150 ft. Depths to the base of ice-bearing permafrost and the base of the ice-rich layer were generally within 100 ft of one another, although there was no consistency as to which occurred at the greater or lesser depth. In oil and gas exploratory wells with no permafrost data, the estimated depth to the base of ice-bearing permafrost was based on the nearest well(s) with those data available. Additionally, although coal beds and coalbed-gas resources interpreted to be below permafrost are emphasized in the assessment, information on the distribution and thickness of coal beds within the permafrost is also provided in discussions for each of the assessment units.

Cretaceous stratigraphic nomenclature used here follows the revised nomenclature for Cretaceous rocks on the North Slope as described in Mull and others (2003) (figs. 2, 3). Within their scheme, coal-bearing formations previously included within the Nanushuk Group (Corwin and Chandler Formations) are now assigned to the Nanushuk Formation; Nanushuk Group terminology is not applied. Upper Cretaceous coal-bearing strata previously assigned to the Tuluvak Tongue of the Prince Creek Formation in the Colville Group are now included in the Tuluvak Formation, and coal-bearing rocks previously included in the Kogosukruk Tongue of the Prince Creek Formation (Colville Group), as well as coal-bearing rocks previously assigned to the lower part of

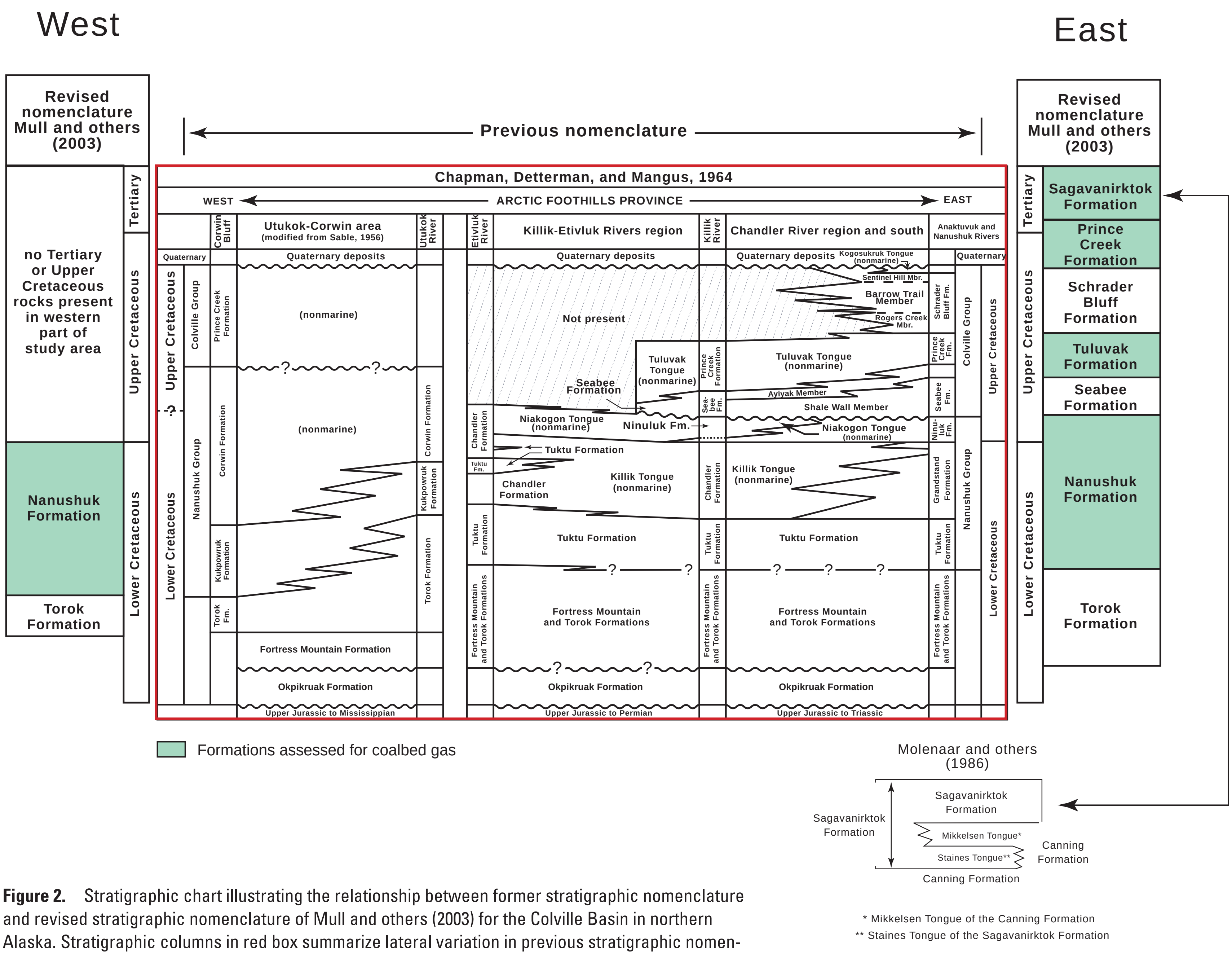


Figure 2. Stratigraphic chart illustrating the relationship between former stratigraphic nomenclature and revised stratigraphic nomenclature of Mull and others (2003) for the Colville Basin in northern Alaska. Stratigraphic columns in red box summarize lateral variation in previous stratigraphic nomenclature for Cretaceous strata from west to east across the western and central foothills of the Brooks Range, as presented by Chapman and others (1964). Chart modified from Mull and others (2003).

the Sagwon Member of the Sagavanirktok Formation, are now included in the Prince Creek Formation; Colville Group terminology is not used.

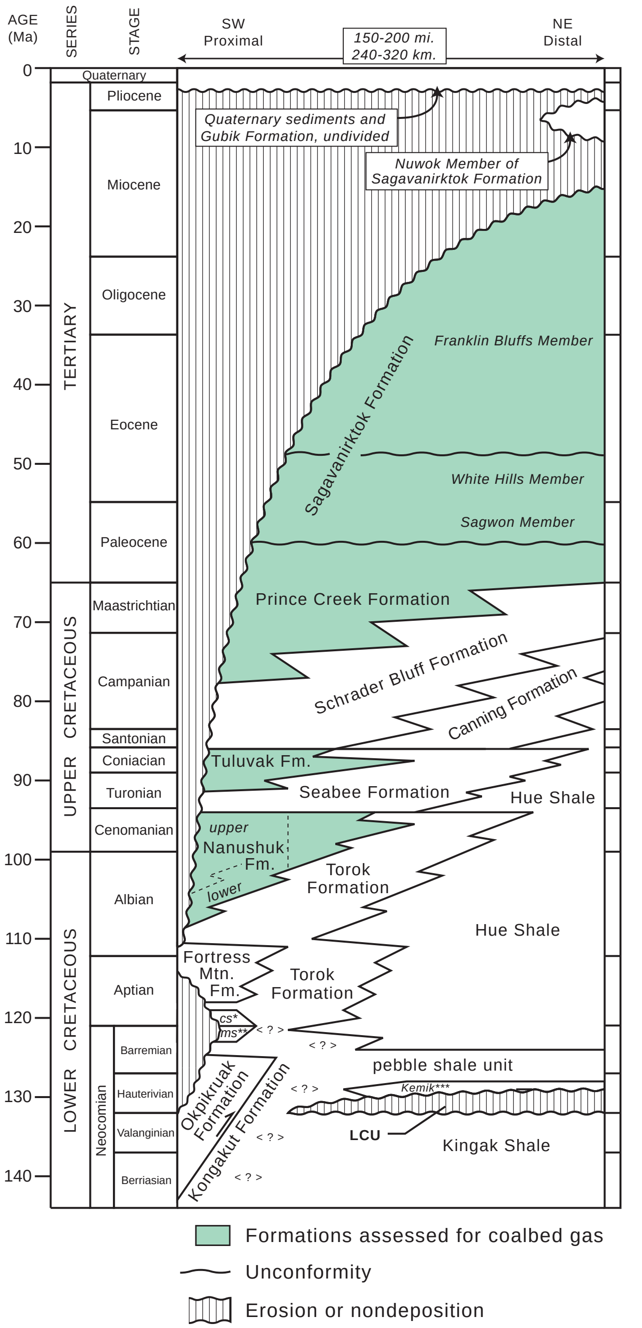


Figure 3. Chronostratigraphic column for the Colville Basin, northern Alaska, showing revised stratigraphic nomenclature and ages of units based on Mull and others (2003). Abbreviations or symbols are as follows: <?>, uncertain relationship; cs*, cobblestone sandstone of Fortress Mountain Formation (informal unit of Mull and others, 2003); ms**, manganiferous shale unit (informal term); Kemik***, Kemik Sandstone (formation) as revised by Molenaar and others (1987); Fm., Formation; Mtn., Mountain; LCU, Lower Cretaceous unconformity. Geologic time scale from Gradstein and Ogg (1996). Column modified from Mull and others (2003).

Stratigraphic nomenclature of Mull and others (2003) for Tertiary strata in the Sagavanirktok Formation also includes revisions to previous definitions and terminology of Gryc and others (1951) and Detterman and others (1975) for this formation. In Mull and others (2003) revised terminology, the Sagavanirktok Formation includes three members in ascending order: the Sagwon Member (revised definition), White Hills Member (newly defined), and the Franklin Bluffs Member (revised definition) (fig. 3). Many (or most) of these revisions are based on outcrop studies, and the identification of the individual members in the subsurface using geophysical well logs can be difficult. For this reason, this study applies subsurface terminology of Molenaar and others (1986; 1987) for the Sagavanirktok Formation rather than using Mull and others' (2003) nomenclature because most interpretations of coal distribution and extent in the formation are derived from geophysical well logs. In Molenaar and others' (1986, 1987) definition, the Sagavanirktok Formation includes a "main body" of the formation, and a lower tongue of nonmarine to shallow marine rocks designated the Staines Tongue (fig. 2). The Staines Tongue is overlain by a marine shale tongue (Mikkelsen Tongue) of the Canning Formation, which separates the Staines Tongue from the main body of the Sagavanirktok Formation. Figure 4 compares terminology of Mull and others (2003) and Molenaar and others (1986; 1987) in geophysical well logs from the West Kadleroshilik well. Although in most cases the revised terminology is applied, discussions of coal geology in subsequent sections of this report may refer to earlier terminology for Cretaceous and Tertiary coal-bearing rocks.

The Brookian Coalbed Gas Composite TPS is defined here to include that area of the North Slope and adjacent State waters underlain by Cretaceous and Tertiary strata interpreted to contain coal deposits having the potential for generation and retention of coalbed gas (fig. 5). The TPS includes a large part of the National Petroleum Reserve in Alaska (NPRA), and limited lands in the Arctic National Wildlife Refuge (ANWR), as well as significant areas of Alaskan State Lands and Native Lands. The term Brookian refers to the Lower Cretaceous through Tertiary "mega sequence" of basinal, basin-slope, shallow marine and nonmarine rocks derived primarily from source areas in the ancestral Brooks Range and source areas farther west beneath the present-day Chukchi Sea (for example, see Lerand, 1973; Molenaar and others, 1987; Bird and Molenaar, 1992; Houseknecht, 2003). This succession of strata was deposited in an asymmetrical foreland basin (Colville Basin; fig. 6) that developed to the north of thrust-faulted rocks in the ancestral Brooks Range. East- to northeast-prograding depositional systems that prevailed from the Cretaceous through the Tertiary filled the basin and ultimately distributed Brookian sediments across the North Slope. Peat-accumulating environments associated with deltaic and coastal plain depositional settings (Ahlbrandt and others, 1979; Roehler and Stricker, 1979; Molenaar, 1983; Huffman and others, 1985; Roehler, 1987) resulted in the widespread distribution of coal deposits in progressively younger strata from west to east across the North Slope.

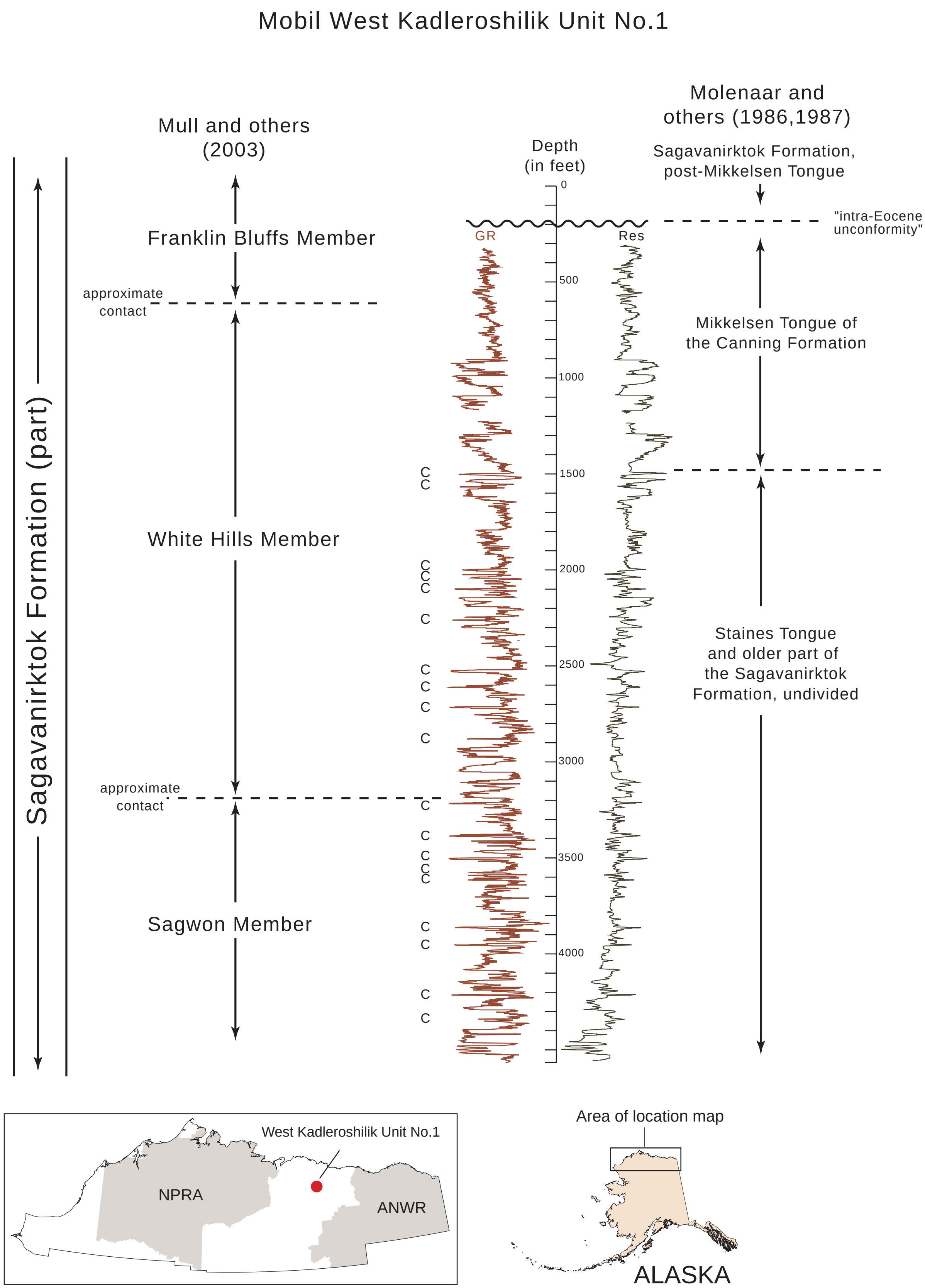


Figure 4. Geophysical logs from the West Kadleroshilik Unit No. 1 oil and gas exploration well, east-central North Slope, Alaska, comparing Sagavanirktok Formation stratigraphic terminology from outcrop studies by Mull and others (2003) with subsurface nomenclature of Molenaar and others (1986; 1987). C, coal bed; GR, gamma ray log; Res, resistivity log. Modified from Mull and others (2003).

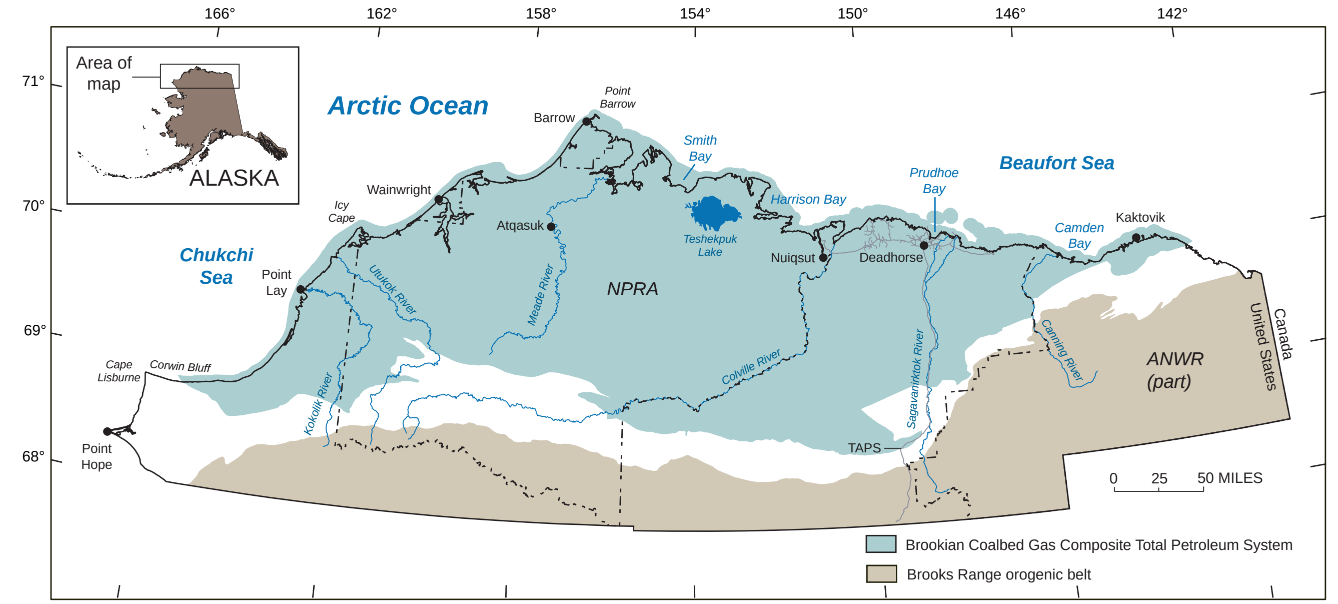


Figure 5. Map showing the extent of the Brookian Coalbed Gas Composite Total Petroleum System (TPS), North Slope and adjacent State waters, Alaska. TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

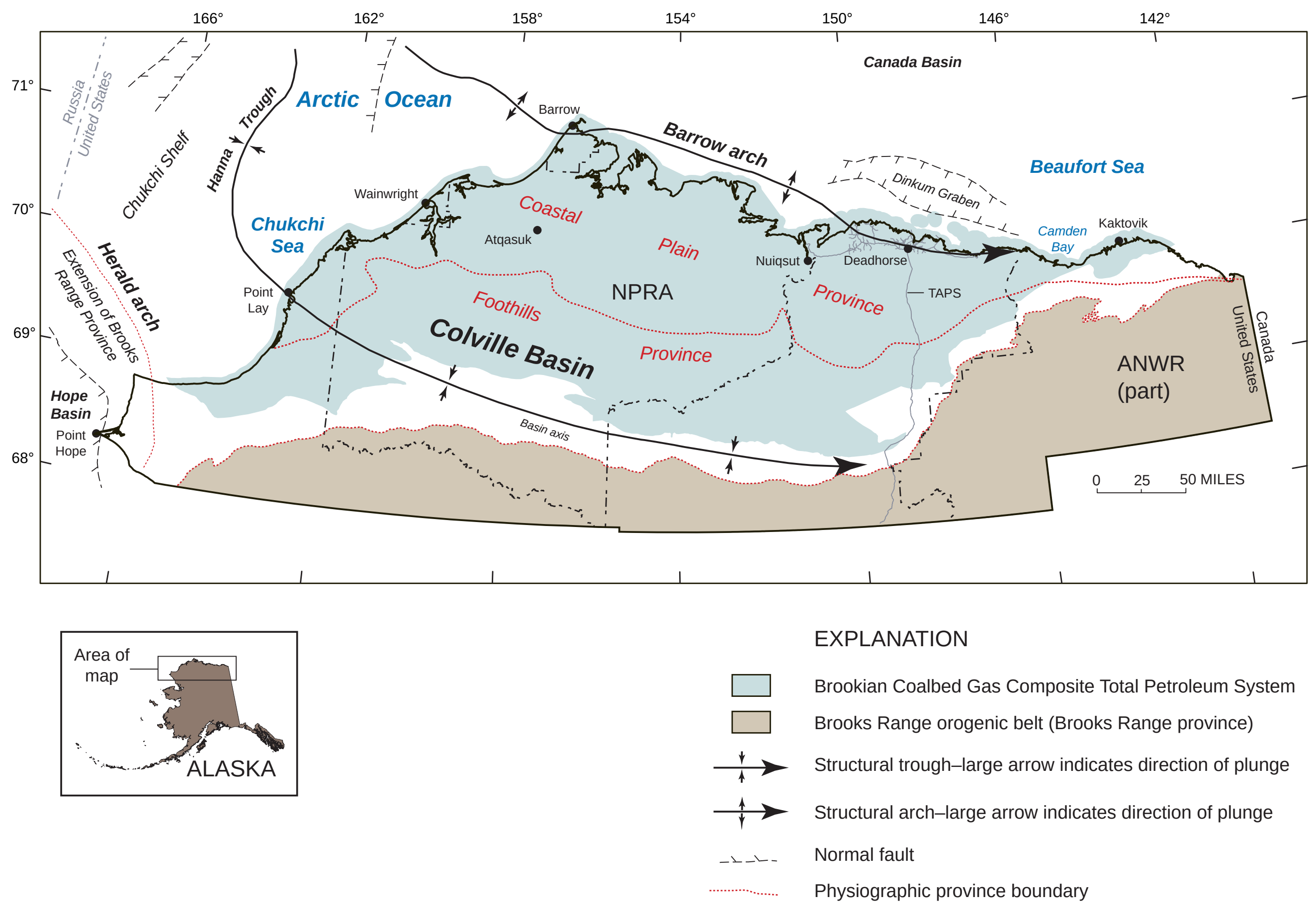


Figure 6. Map showing physiographic provinces and major structural features in northern Alaska and adjacent offshore areas. Geologic structures based on Bird (1985), Grantz and others (1982), and Grantz and May (1983). Physiographic province boundaries modified from Payne and others (1951). TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

The petroleum system encompasses about 50,000 mi^2 and essentially all onshore areas in the TPS contain permafrost (fig. 7). The onshore boundary is defined primarily by (1) the mapped extent of Cretaceous continental deposits (Beikman, 1980), (2) the southern limit of the Brookian Topset Play of Houseknecht (2003) in the National Petroleum Reserve in Alaska (NPRA), (3) the eastern limits (in part) of topset AUs in the central North Slope area (Bird and others, 2005; Garrity and others, 2005), (4) the Topset Play (U.S. Geological Survey, ANWR Assessment Team, 1999) in the 1002 area of the Arctic National Wildlife Refuge (ANWR), and (5) the mapped extent of undifferentiated upper Tertiary rocks (Beikman, 1980). Figure 8 shows the relation of USGS topset plays or AUs from previous assessments to the Brookian Coalbed Gas TPS. Oil and gas exploration and development well data helped to delimit part of the south and southeast boundaries in areas with no outcrop control. Offshore limits of the TPS extend to the boundary of Alaskan State waters.

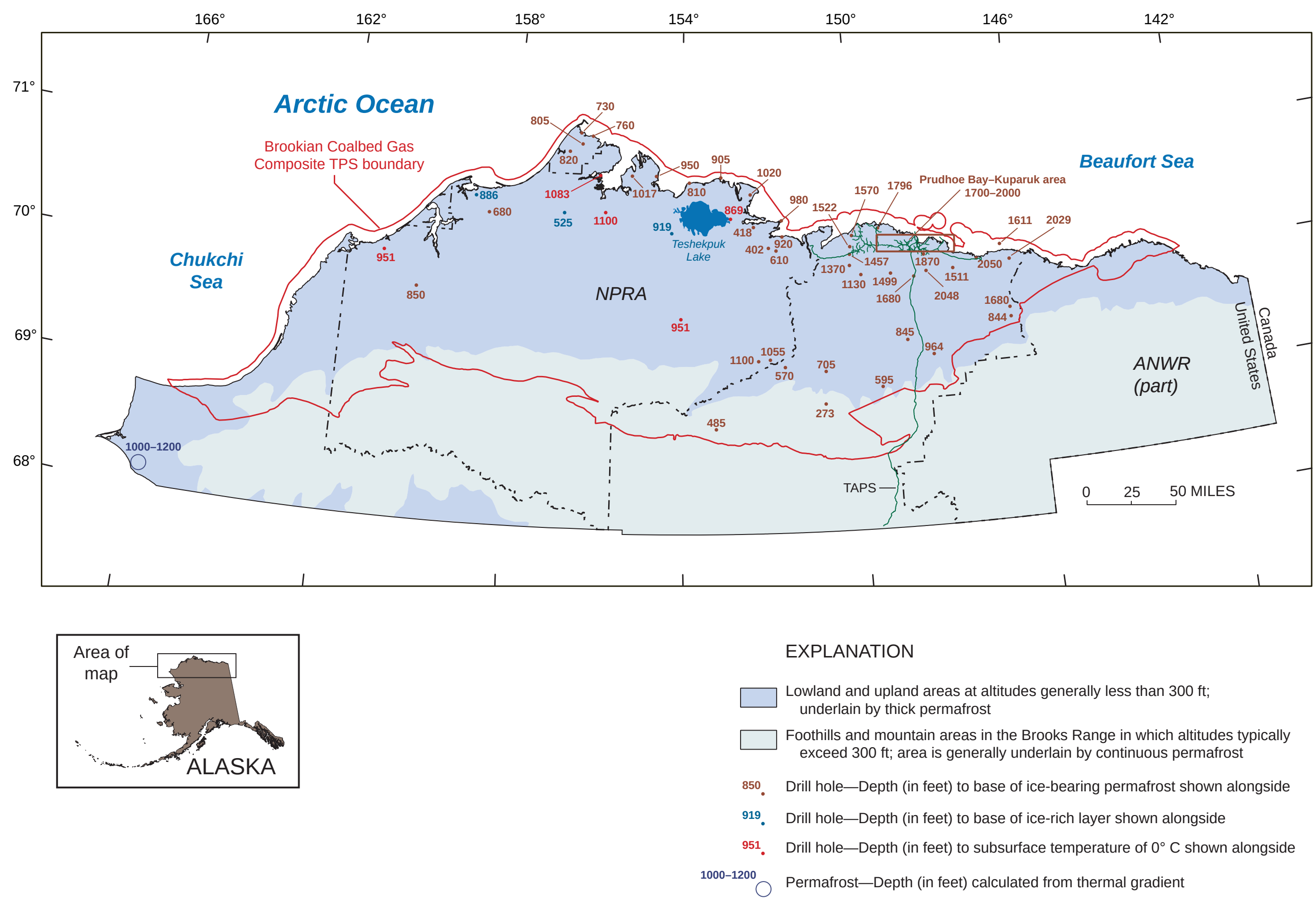


Figure 7. Map showing generalized distribution and characteristics of permafrost in upland areas of the Brooks Range and on the North Slope, Alaska, and the estimated depth to the base of permafrost in the Brookian Coalbed Gas Composite Total Petroleum System. Permafrost depths are based on data from selected oil and gas exploration wells and represent either (1) depth from kelly bushing to base of ice-bearing permafrost as identified in geophysical logs of oil and gas wells, (2) depth from ground surface to base of the ice-rich layer as derived from down-hole temperature profiles, or (3) depth from the ground surface to subsurface temperature of 0°C as measured in borehole temperature logs. Depth to base of permafrost calculated from thermal gradients and measured in drill holes is also shown. Permafrost data based on MacCarthy (1952) Brewer (1958), Ferrians, Jr. (1965), Osterkamp and Payne (1981), Lachenbruch and others (1982; 1987), and Collett and others (1989). TPS, total petroleum system; TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

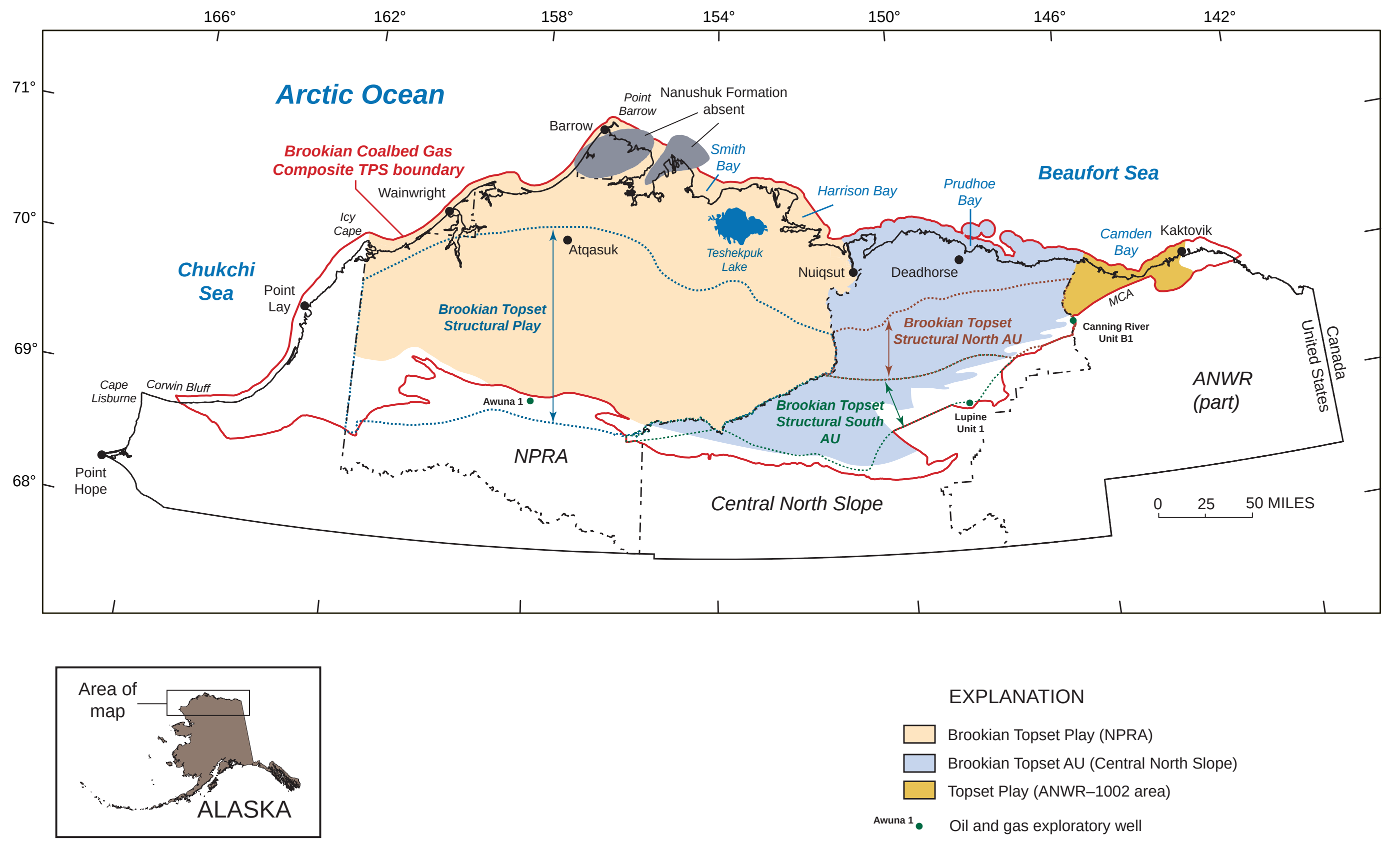


Figure 8. Map showing boundary of the Brookian Coalbed Gas Composite Total Petroleum System (TPS), North Slope and adjacent State waters areas, Alaska. Elements used to define the TPS boundary include boundaries of conventional oil and gas plays or assessment units from previous USGS assessments, and drill-hole data from oil and gas exploration wells. Conventional play and assessment unit boundaries from U.S. Geological Survey, ANWR Assessment Team (1999), Houseknecht (2003), Potter and Moore (2003), and Garrity and others (2005). TPS, total petroleum system; AU, assessment unit; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge; MCA, Marsh Creek anticline..

Assessment units defined within the TPS are (oldest to youngest): the Nanushuk Formation Coalbed Gas AU (fig. 9), the Prince Creek and Tuluvak Formations Coalbed Gas AU (fig. 10), and the Sagavanirktok Formation Coalbed Gas AU (fig. 11). Interpreted coal depocenters in the Prince Creek and Tuluvak Formations share a similar geographic distribution, and for this reason, these formations are assessed in a single AU. Because there is no production of coalbed gas from the North Slope and only limited testing of the coals for gas, all assessment units are hypothetical.

This report provides a summary of the geologic criteria and data that were used to estimate undiscovered, technically recoverable coalbed-gas resources in the three AUs. Key geologic considerations that are discussed for each AU relate primarily to specific aspects of coal geology, such as coal thickness, stratigraphic and areal distribution, and coal quality (specifically, thermal maturity). Pertinent aspects of the structural geologic setting that might relate to coalbed-gas potential are also described in the text or depicted within the figures.

Acknowledgments

This study benefited greatly from data compiled by numerous workers involved with USGS petroleum studies on the North Slope. I would like to thank Ken Bird and Dave Houseknecht for their assistance and thoughtful comments through the assessment process, and for the wealth of published and unpublished studies pertaining to North Slope geology, seismic stratigraphy, and petroleum resources that were of great value in establishing the framework for coalbed-gas studies. I would also like to thank Joyce Kibler (retired, USGS) and Phil Nelson for providing digital logs of oil and gas wells that were critical for subsurface coal interpretations,

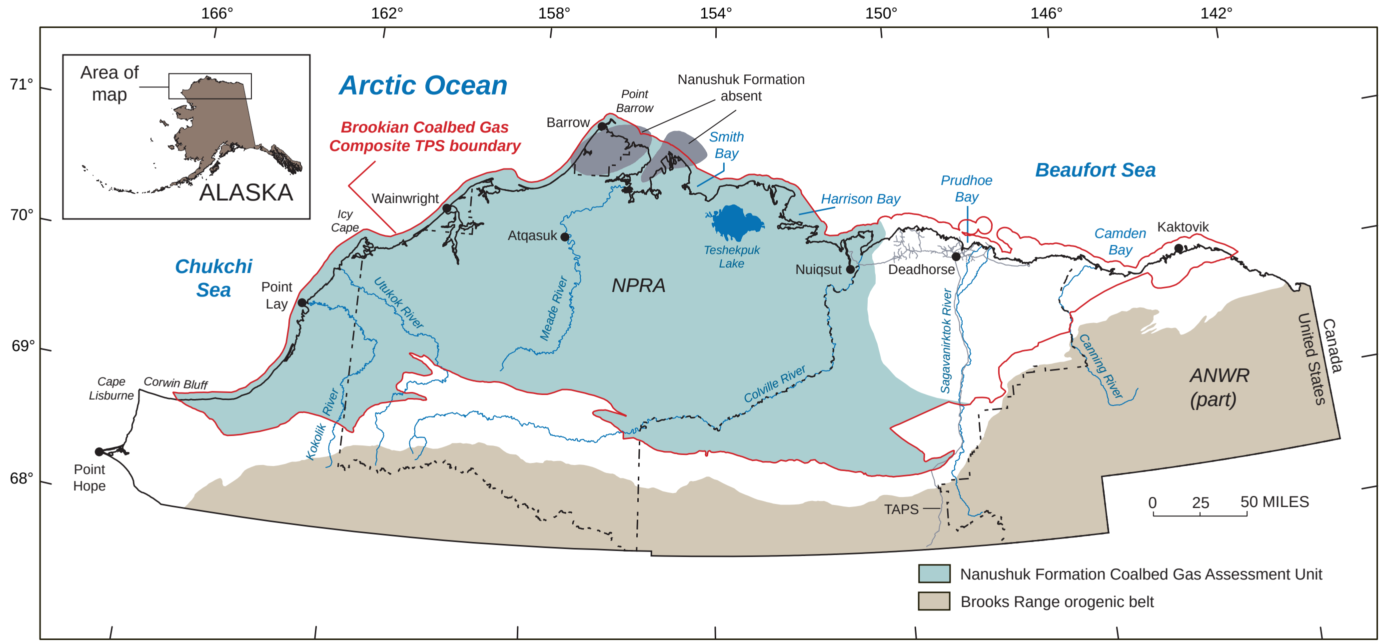


Figure 9. Map showing location and extent of the Nanushuk Formation Coalbed Gas Assessment Unit, North Slope and adjacent State waters, Alaska. TPS, total petroleum system; TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

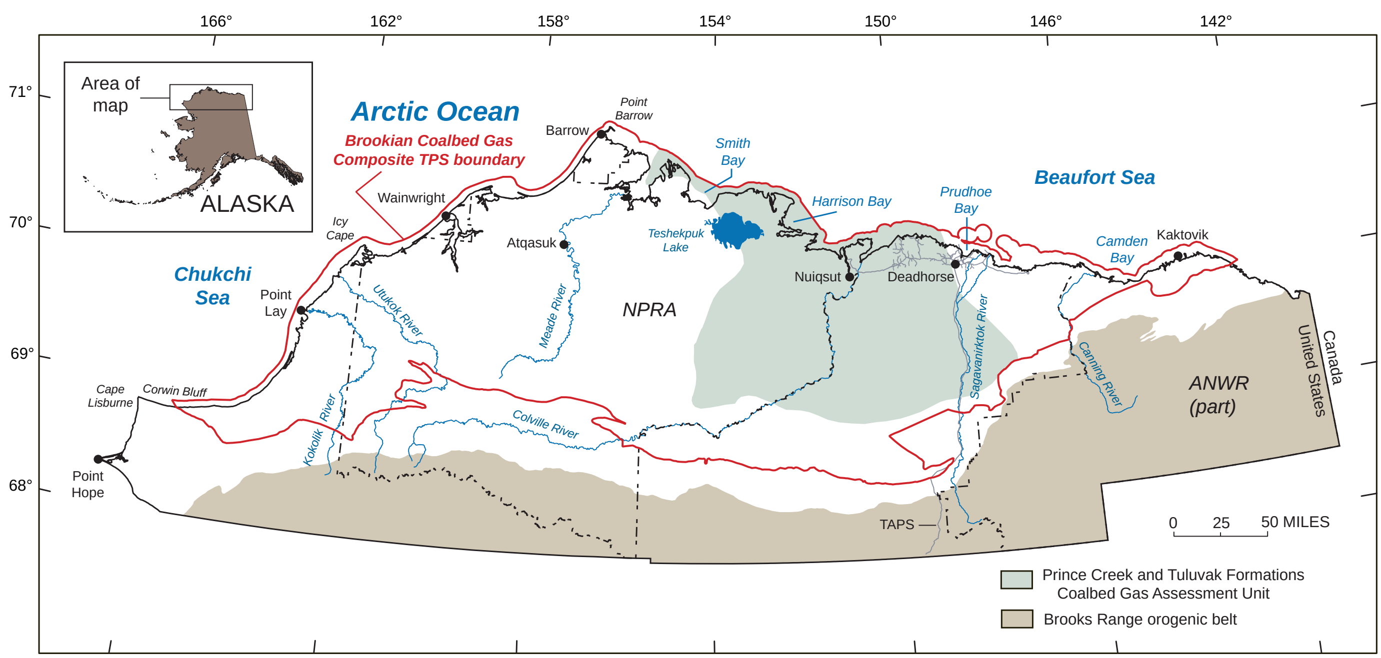


Figure 10. Map showing location and extent of the Prince Creek and Tuluvak Formations Coalbed Gas Assessment Unit, North Slope and adjacent State waters, Alaska. TPS, total petroleum system; TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

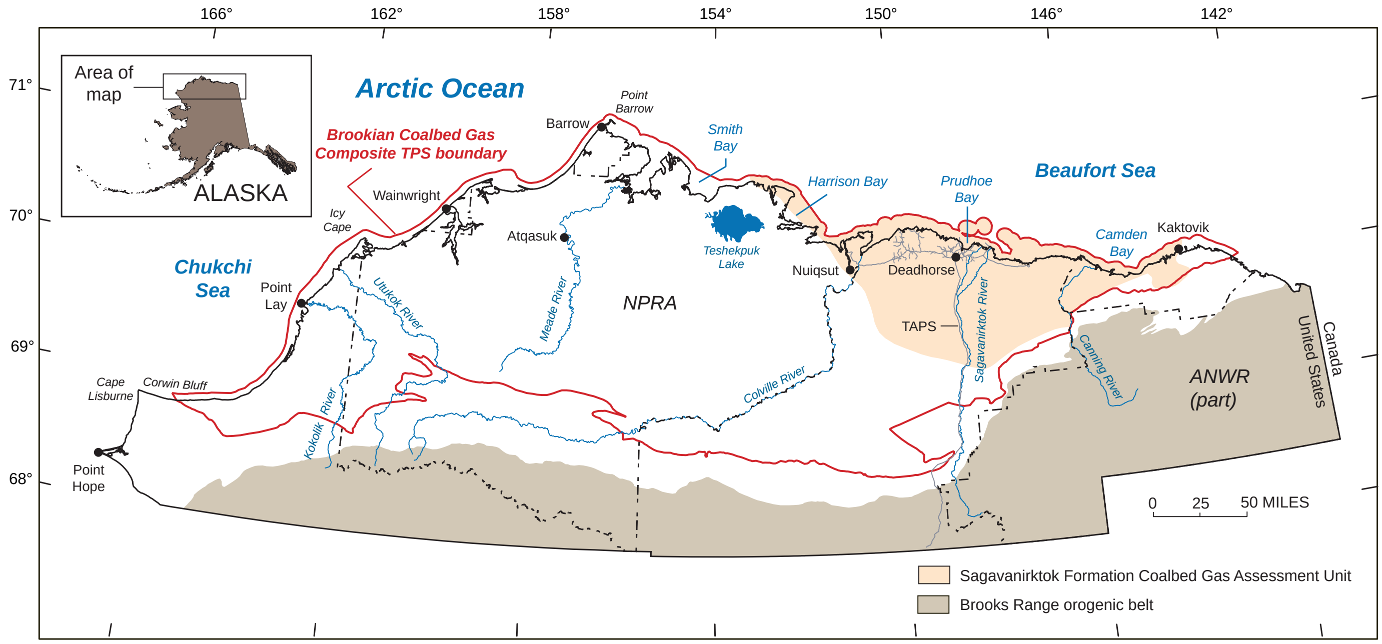


Figure 11. Map showing location and extent of the Sagavanirktok Formation Coalbed Gas Assessment Unit, North Slope and adjacent State waters, Alaska. TPS, total petroleum system; TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

Dan Hayba and Matthew Burns for providing data related to gas occurrences and basin modeling, and Chris Garrity and Chris Anderson (contract employee) for their assistance in compiling digital coverages for GIS development. During the assessment process, excellent comments and criticisms were provided by the USGS Assessment Methodology Team of Chris Schenk, Ron Charpentier, Rich Pollastro, Tim Klett, Tom Ahlbrandt, and Troy Cook, who also furnished key production data from coalbed-gas wells used as analogs in the assessment. This manuscript was vastly improved through reviews by Ken Bird, Tim Collett, Dick Keefer, and Doug Nichols (Scientist Emeritus, USGS). I greatly appreciate their efforts in this regard. I would also like to thank Charles Barker (Scientist Emeritus, USGS) for sharing his expertise in North Slope coalbed-gas geology and geochemistry, and for his aid in facilitating funds and field studies that were extremely valuable toward the completion of this assessment.

Unassessed Coal-Bearing Formations

Although the formations addressed in the three coalbed gas assessment units contain the majority of coal resources on the North Slope, additional coal is present in several other formations. These formations are listed and described briefly in the following sections.

Kapaloak Formation and Kekiktuk Conglomerate

Mississippian age coal is present in outcrops in the Cape Lisburne region (fig. 12) (Collier, 1906; Chapman and Sable, 1960; Tailleur, 1965; Barnes, 1967a; Sable and Stricker, 1987), and in the deep subsurface in NPRA and the Prudhoe Bay area (Sable and Stricker, 1987; Woidneck and others, 1987; Magoon and others, 1988). Coal outcrops in the Cape Lisburne area are included in the Kapaloak Formation (for example, see Eakins, 1986; Merritt and Hawley, 1986), whereas age-equivalent coal-bearing rocks underlying NPRA and the Prudhoe Bay area are included in the Kekiktuk Conglomerate (Sable and Stricker, 1987; Woidneck and others, 1987).

Coal beds in outcrops of the Kapaloak Formation tend to be moderately or steeply dipping and overturned locally. In a 2,200-ft-thick measured section, Tailleur (1965) reported coal beds ranging in thickness from a few inches to as much as 11 ft; at least 13 exceed 2.5 ft in thickness. Individual coal beds persist for a few hundred feet laterally, but intense deformation and limited exposures restrict coal-bed continuity. Based on as-received analyses of coal outcrop samples, the apparent rank is interpreted to be low-volatile bituminous (Tailleur, 1965). Because of the structural complexity, limited surface exposures, and lack of subsurface data for coals in the Kapaloak Formation, no assessment of coalbed-gas potential was completed for this formation.

Minor coal is present in Kekiktuk Conglomerate outcrops in the Brooks Range (Smith, 1995), and in northern NPRA, coal beds as thick as 5 ft are reported in the formation in deep oil and gas exploration wells (Sable and Stricker,

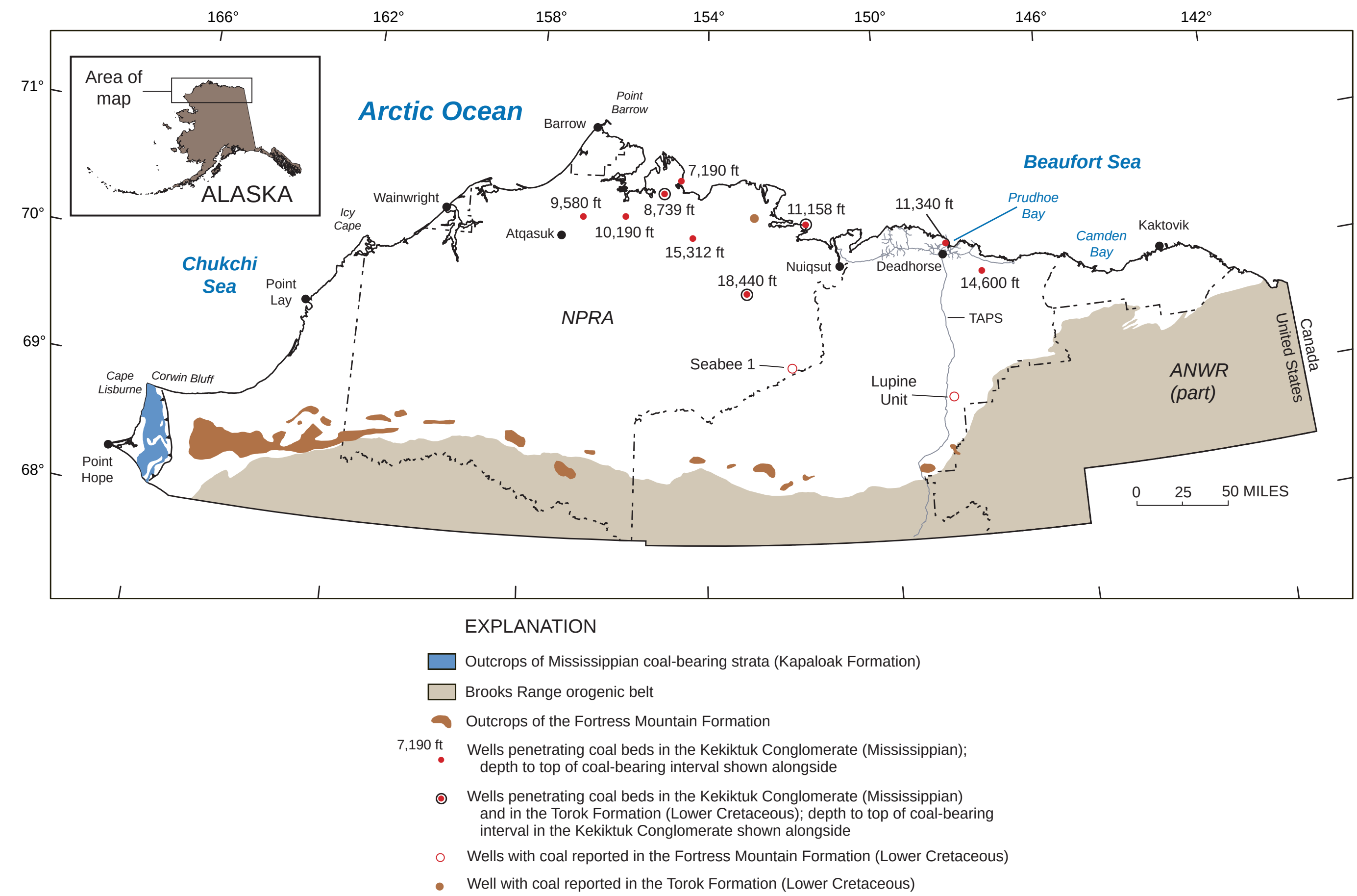


Figure 12. Map showing distribution of coal-bearing outcrops in the Kapaloak Formation (Mississippian), and outcrops of the Fortress Mountain Formation (Lower Cretaceous), North Slope, Alaska. Depth to coal in wells penetrating the coal-bearing Kekiktuk Conglomerate (Mississippian) and selected wells penetrating Lower Cretaceous rocks in the Fortress Mountain and Torok Formations are also shown. Geology based on Beikman (1980) and Mull (1985). Depth to coal in the Kekiktuk Conglomerate based on Sable and Stricker (1987) and Woidneck and others (1987). TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

1987). Coal beds as thick as 10 ft at depths exceeding 9,500 ft are in the formation in the Prudhoe Bay area (Woidneck and others, 1987; Smith, 1995). Overall depth to the top of the coal-bearing interval ranges from about 7,200 ft to more than 18,000 ft (fig. 12). Although coal within the Kekiktuk Conglomerate may be fairly widespread across the North Slope, the limited number of deep wells penetrating this formation precludes a complete understanding of the subsurface distribution of the coal-bearing facies. Also, given that the depth to Kekiktuk coal exceeds the 6,000-ft-depth cutoff applied to potential coalbed-gas resources in this study, no assessment of undiscovered coalbed-gas resources was completed for this formation.

Fortress Mountain and Torok Formations

The Fortress Mountain Formation (figs. 2, 3) consists primarily of conglomerate, sandstone, and shale deposited in marine (shallow to deep water) and nonmarine environments (for example, see Crowder, 1987; Molenaar and others, 1988). Discontinuous outcrops of the formation are present in an east-west-trending belt just north of the Brooks Range (fig. 12). The Torok Formation (figs. 2, 3) is a thick (up to 19,000+ ft; Sable and Stricker, 1987) succession of mainly offshore and deep water marine shale, siltstone, and minor sandstone that crops out in the Brooks Range foothills and is widespread in the subsurface across much of the North Slope (Molenaar, 1985). The lower part of the Torok Formation in areas north of the Brooks Range mountain front is considered to be the fine-grained equivalent (in part) of the coarse clastic deposits that characterize the Fortress Mountain Formation (Crowder, 1987; Molenaar, 1985; Molenaar and others, 1988), and Fortress Mountain strata become finer grained toward the north (basinward) where they intertongue with shale in the Torok Formation. Because of this close genetic relation, it can be difficult to separate these formations in the subsurface.

Nonmarine facies in the Fortress Mountain Formation, which may be a relatively minor component, include coal beds in outcrops, most of which are only a few inches thick or less; rarely, coal beds are as thick as 2 or 3 ft, and most coal beds include carbonaceous shale (Marwan Wartes, Alaska Department of Natural Resources, written commun., 2005). In the subsurface, numerous thin coal beds were reported to be present in the lower part of the Fortress Mountain Formation at depths between 10,700 ft and 13,005 ft in the Seabee 1 well (fig. 12) (Husky Oil NPR Operations, Inc., 1983; Sable and Stricker, 1987; Magoon and others, 1988), and in the Lupine Unit well, nine coal beds as thick as 5 ft were reported in the undifferentiated Fortress Mountain and Torok Formations at depths between 5,400 and 6,400 ft (Magoon and others, 1988). Thin beds of coal and carbonaceous shale have also been observed in outcrops of the Torok Formation and reported in several drill holes penetrating the formation in NPRA (Sable and Stricker, 1987).

These formations were not assessed for coalbed-gas potential because of the limited occurrence of nonmarine, coal-bearing facies in both formations, and the lack of definitive data needed to fully understand coal abundance and distribution in much of the subsurface. Additionally, solid bitumen hydrocarbon occurrences are fairly common in outcrops of both formations (Marwan Wartes, Alaska Department of Natural Resources, written commun., 2005; D.W. Houseknecht, U.S. Geological Survey, oral commun. 2005), and it could be possible to confuse these solid hydrocarbons with coal in drill cuttings from wells penetrating this type of deposit in the subsurface. This might be the case for reported coal in the Seabee 1 and Lupine Unit wells, which are both located in areas where nonmarine, coal-bearing facies in either formation are not expected to be present (Marwan Wartes, Alaska Department of Natural Resources, written commun., 2005); reported coal from these wells might, instead, represent cuttings from deposits of solid hydrocarbon (for example, see Sable and Stricker, 1987).

Jago River Formation

Minor coal is also reported in Upper Cretaceous–lower Tertiary strata in the Jago River Formation, which is present in outcrops on the coastal plain in ANWR, about 30 miles south of the village of Kaktovik (fig. 1) (Buckingham, 1987). However, because the reported coals are “thin” and the formation itself is only present in a limited area, no assessment of coalbed-gas potential was attempted.

Nanushuk Formation Coalbed Gas Assessment Unit

The Nanushuk Formation Coalbed Gas AU encompasses just over 26 million acres (about 40,000 mi^2) in the western and central parts of the North Slope (fig. 9). Most of the AU boundary is coincident with the Brookian Coalbed Gas TPS, except for the east boundary, which represents the limit of marine shelf-margin facies (Nanushuk depositional zero edge) as interpreted from seismic data for the Nanushuk-Torok depositional succession (D.W. Houseknecht, U.S. Geological Survey, written commun., 2006); the Nanushuk is not recognized in the subsurface east of this boundary. The west and north margins of the AU extend offshore to the limit of Alaskan State waters. In the broad sense, the assessment unit boundary is designed to coincide with the areal extent of topset seismic facies in the Nanushuk Formation. The AU is within the Foothills and Coastal Plain physiographic provinces, and includes a large portion of NPRA (fig. 13). Available drill-hole data indicate that the depth to the base of permafrost varies from less than 300 ft to as much as 1,100 ft (fig. 14).

Geologic Setting

The Nanushuk Formation, Albian to Cenomanian in age (fig. 3), is exposed discontinuously in an outcrop belt about 20 to 30 mi wide that extends for nearly 400 mi from west to east in the Foothills Province north of the Brooks Range orogenic belt (for comparison, see Huffman and others, 1985). The formation overlies the predominantly marine Torok Formation. In the subsurface, the Nanushuk extends across the coastal plain, covering much of the western and central parts of the North Slope and adjacent offshore areas. The maximum preserved thickness is more than 15,000 ft in outcrops near Point Hope at Corwin Bluff (type section of the Corwin Formation; Chapman and Sable, 1960), and the thickest section in the subsurface is 6,150 ft in the Tunalik 1 well (fig. 13) (K.J. Bird, U.S. Geological Survey, written commun., 2007). The formation thins to the north and northeast of the Corwin Bluff area, due in large part to erosion of the upper part. Except for in the eastern one-third of NPRA, the upper contact is an erosional surface underlying Pleistocene deposits (Molenaar, 1985; Bird, 1988).

Variations in the structural setting within the Nanushuk Formation Coalbed Gas AU coincide roughly with the physiographic provinces; that is, east-west-trending detachment folds characterizing the Foothills Province give way northward to a frontal welt comprised of several broad, low-amplitude anticlines that have gently warped Nanushuk strata in the Coastal Plain province (for example, see Mull, 1985; Kirschner and Rycerski, 1988; Potter and Moore, 2003). The northern limit of this frontal welt corresponds to the interpreted northern limit of Tertiary deformation (fig. 15) (Potter and Moore, 2003). Detachment folds in the foothills are generally long and narrow, with steep northern flanks and complexly folded cores of Torok Formation shale (Kirschner and Rycerski, 1988). Structure contour maps on the tops of the Nanushuk Formation and the Torok Formation (base of the Nanushuk Formation) in coastal plain areas north of the foothills fold-belt (figs. 16 and 17, respectively), indicate that Nanushuk rocks dip gently southward in west-central and western parts of the AU, and shift to east or southeasterly dips in the eastern part (Bird, 1988).

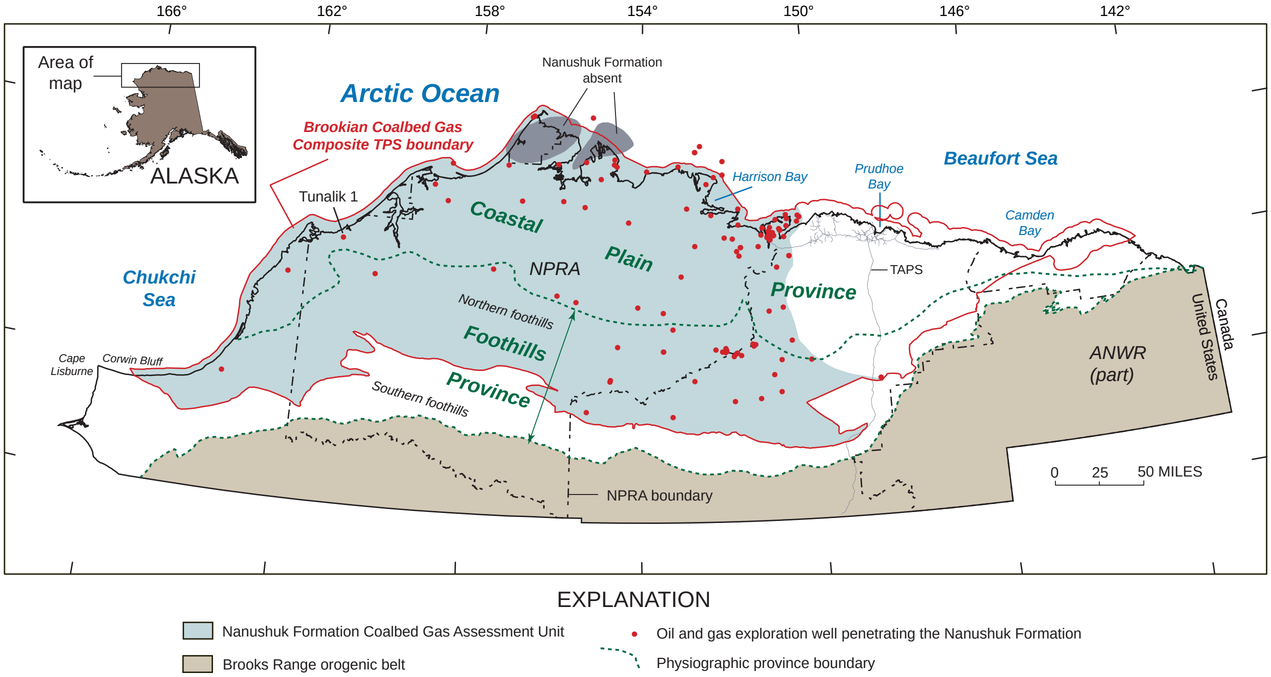


Figure 13. Map showing locations of oil and gas exploration wells penetrating the Nanushuk Formation, and extent of the Nanushuk Formation Coalbed Gas Assessment Unit in the Coastal Plain and a part of the Foothills physiographic provinces, North Slope and adjacent State waters, Alaska. Physiographic province boundaries modified from Payne and others (1951). TPS, total petroleum system; TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

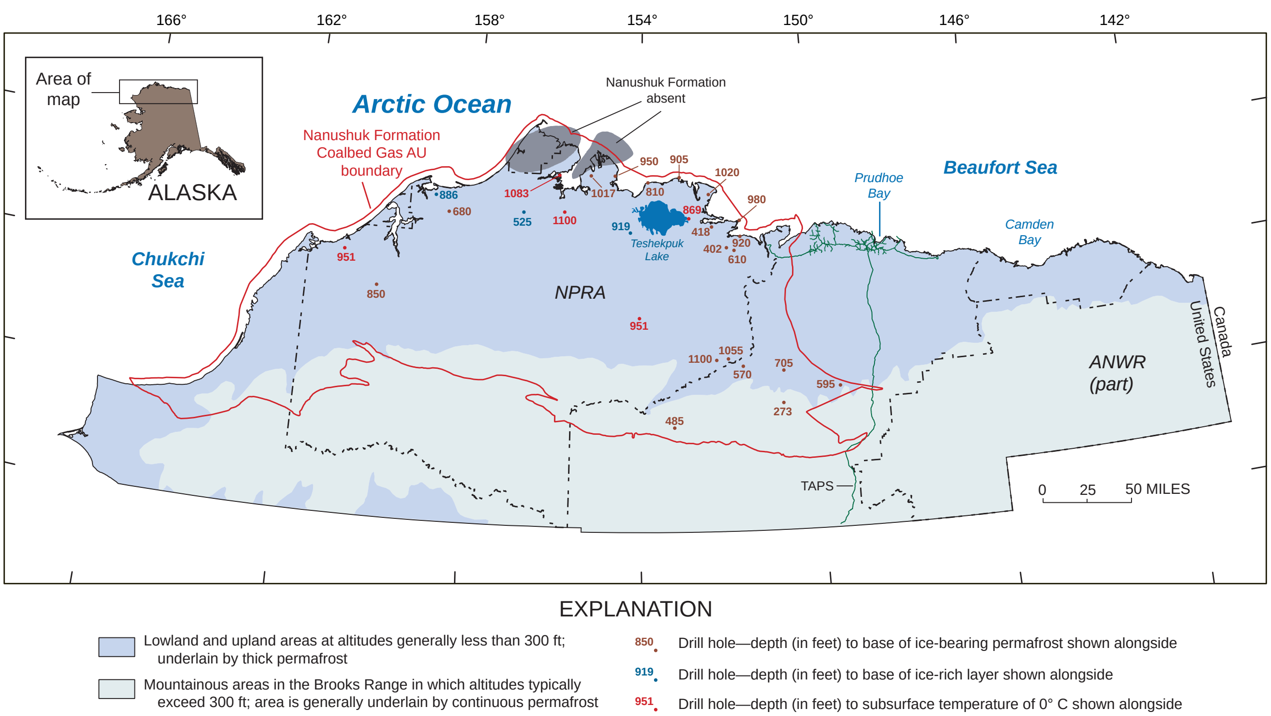


Figure 14. Map showing generalized distribution and characteristics of permafrost in upland areas of the Brooks Range and on the North Slope, Alaska, and the estimated depths to the base of permafrost in the Nanushuk Formation Coalbed Gas Assessment Unit (AU). Permafrost depths are based on data from selected oil and gas exploration wells and represent either (1) depth from the kelly bushing to base of ice-bearing permafrost, (2) depth from the ground surface to base of the ice-rich layer, or (3) depth from the ground surface to subsurface temperature of 0˚C as measured in boreholes. Permafrost data based on MacCarthy (1952) Brewer (1958), Ferrians, Jr. (1965), Osterkamp and Payne (1981), Lachenbruch and others (1982; 1987), and Collett and others (1989). TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

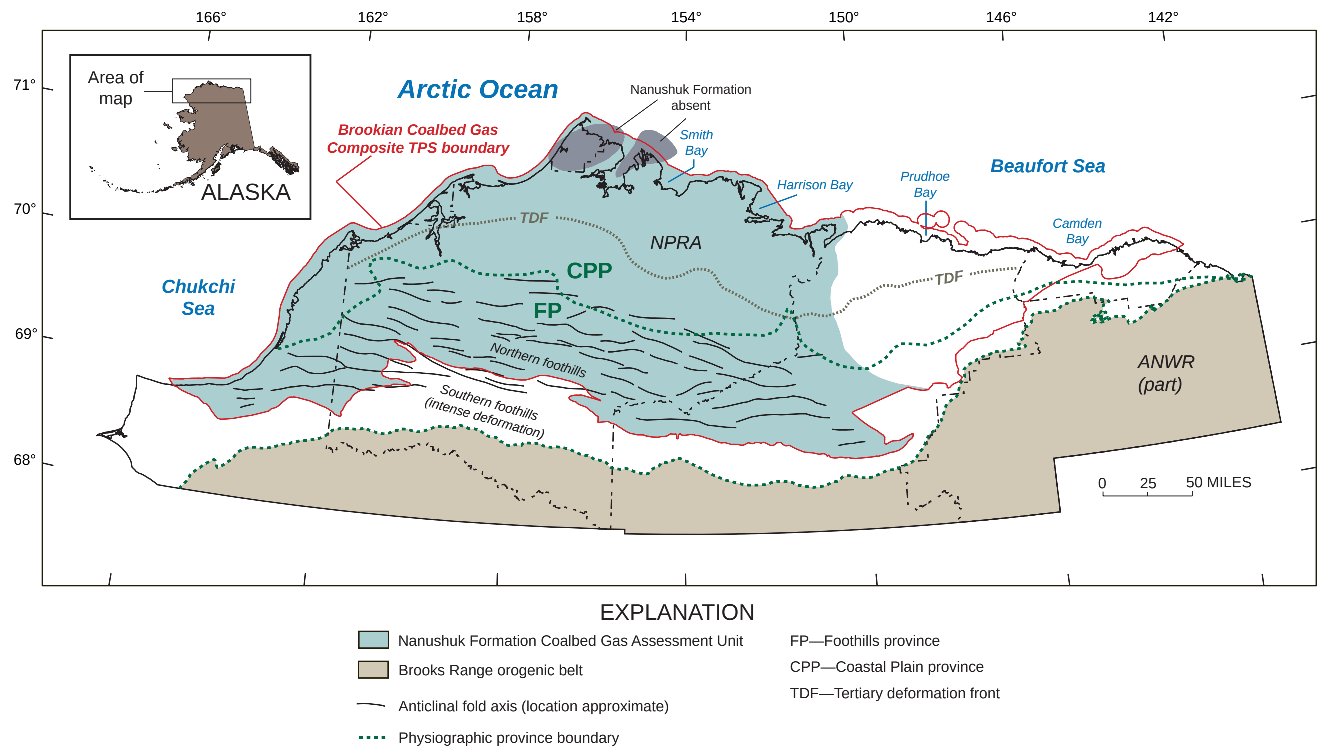


Figure 15. Map showing physiographic province boundaries, detachment (anticlinal) fold axes, and the northern limit of Tertiary-age deformation in the Nanushuk Formation Coalbed Gas Assessment Unit, North Slope, Alaska. Fold axes locations are highly generalized and are based on Mull (1985) and Kirschner and Rycerski, (1988). Physiographic province boundaries modified from Payne and others (1951). TPS, total petroleum system; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

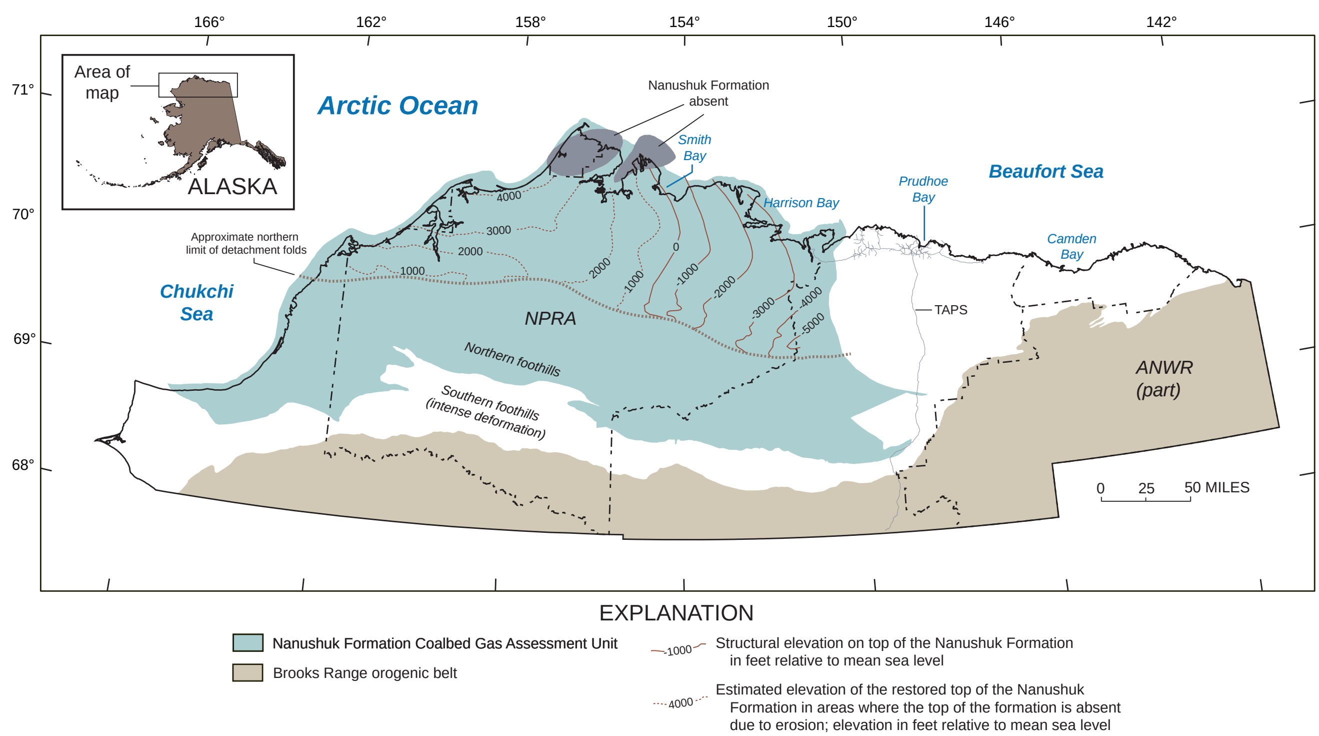


Figure 16. Structure contour map on top of the Nanushuk Formation in the northern part of the Nanushuk Formation Coalbed Gas Assessment Unit, North Slope, Alaska. Dashed contours represent elevation to the restored top of the Nanushuk in areas where the top of the formation is eroded. Contour interval 1,000 ft. Structure contours modified from Bird (1988). TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

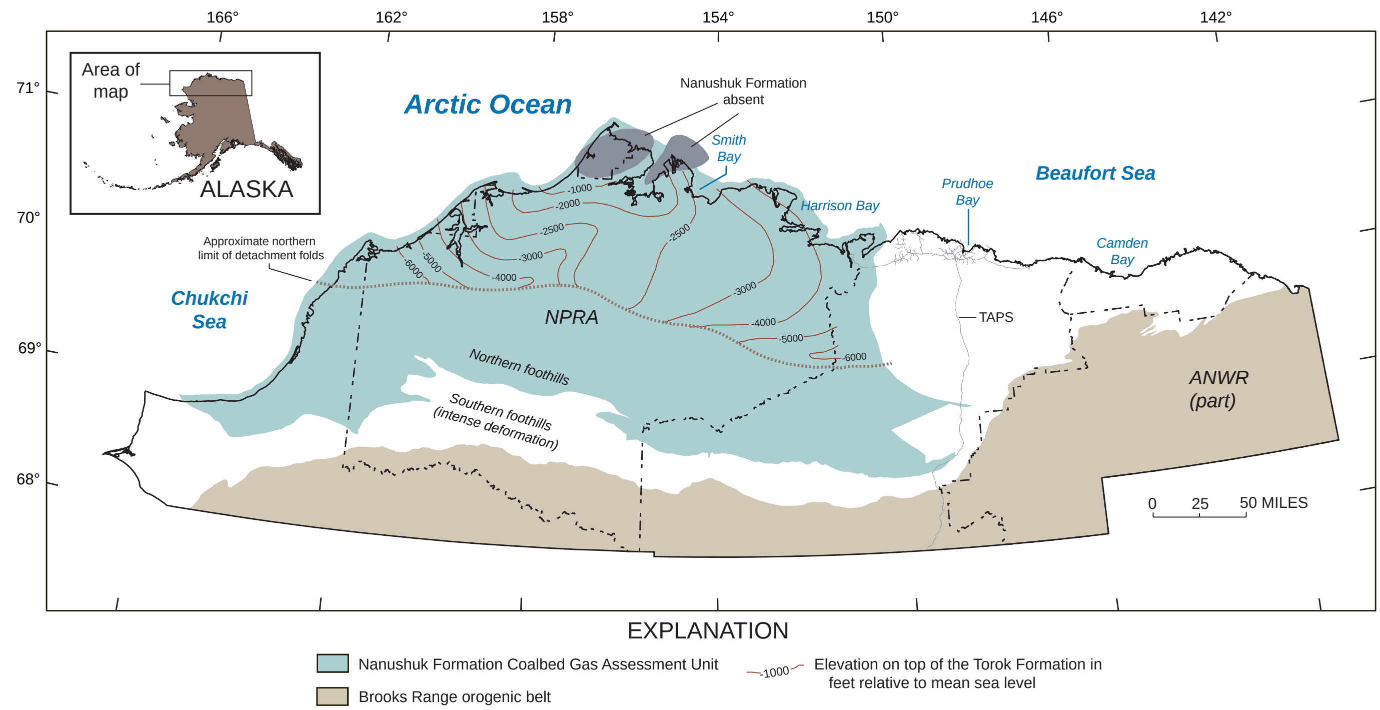


Figure 17. Structure contour map on top of the Torok Formation in the northern part of the Nanushuk Formation Coalbed Gas Assessment Unit, North Slope, Alaska. Contour interval variable. Structure contours modified from Bird (1988). TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

Coal Geology

The preponderance of coal in the Nanushuk Formation has fostered numerous studies pertaining to the depositional setting and coal resources of the formation (Collier, 1906; Barnes, 1967a and b; Tailleur and Brosgé, 1975; Martin and Callahan, 1978; Ahlbrandt and others, 1979; Roehler and Stricker, 1979; Callahan and Martin, 1980; Huffman and others, 1985; Merritt, 1986; Merritt and Hawley, 1986; Roehler, 1987; Sable and Stricker, 1987; Clough and Roe, 1990; Flores and others, 2004); the reader is referred to these studies and the additional references listed in those reports for coal information not specifically addressed in this report. Key geologic parameters considered in the assessment of coalbed-gas resources relate mainly to coal thickness (thickness of individual beds and cumulative coal thickness), stratigraphic and areal distribution of the coal, and thermal maturity based on vitrinite reflectance data.

Coal-bearing strata in the Nanushuk Formation extend continuously across most of the Nanushuk Formation Coalbed Gas AU, as indicated by both surface and subsurface data (fig. 18). In the southwestern part of the AU, coal-bearing rocks (Corwin Formation equivalents) are restricted to broad, en echelon synclines or basins (figs. 18, 19) that are separated by a complex of tightly folded anticlines (Chapman and Sable, 1960). There appears to be little or no coal in the Nanushuk Formation in the extreme eastern and northern parts of the AU.

Because coal outcrops are sporadic and incomplete, the entire coal-bearing section of the Nanushuk Formation is generally not present at any single locality. The thickest measured section is at Corwin Bluff (type section of the Corwin Formation; Chapman and Sable, 1960) (figs 18 and 19), where more than 15,000 ft of coal-bearing strata are exposed. At this locality, there are about 124 coal beds ranging in thickness from less than 1 ft-thick to as much as 9 ft; however, over 75 percent of the coal beds in this interval are 2 ft thick or less. Total (cumulative) coal thickness is about 195 ft. East and north of Corwin Bluff, Chapman and Sable (1960) reported coal beds ranging from a few inches to 13 ft thick in outcrops along the Kukpowruk River south of Point Lay (fig. 19). G.D. Stricker (U.S. Geological Survey, oral commun., 2007) observed a 20-ft-thick coal bed in this same general area. Measured stratigraphic sections by Roehler and Stricker (1979) along the Utukok River and areas southwest of the river (fig. 18), indicate the presence coal beds as thick as 14 ft. In the southeastern part of the AU, Chapman and others (1964) reported coal beds from 1 to 3 ft thick in Nanushuk Formation outcrops (Chandler Formation equivalent) along the Colville River; locally, beds in this area are as thick as 8 ft (D.W. Houseknecht, U.S. Geological Survey, written commun., 2005).

Because of the incomplete nature of coal outcrop data, subsurface information from oil and gas exploration wells was critical to understanding Nanushuk coal geology. Interpretations of geophysical logs from 96 oil and gas exploration wells within the AU (fig. 13) were completed as part of this study to gain

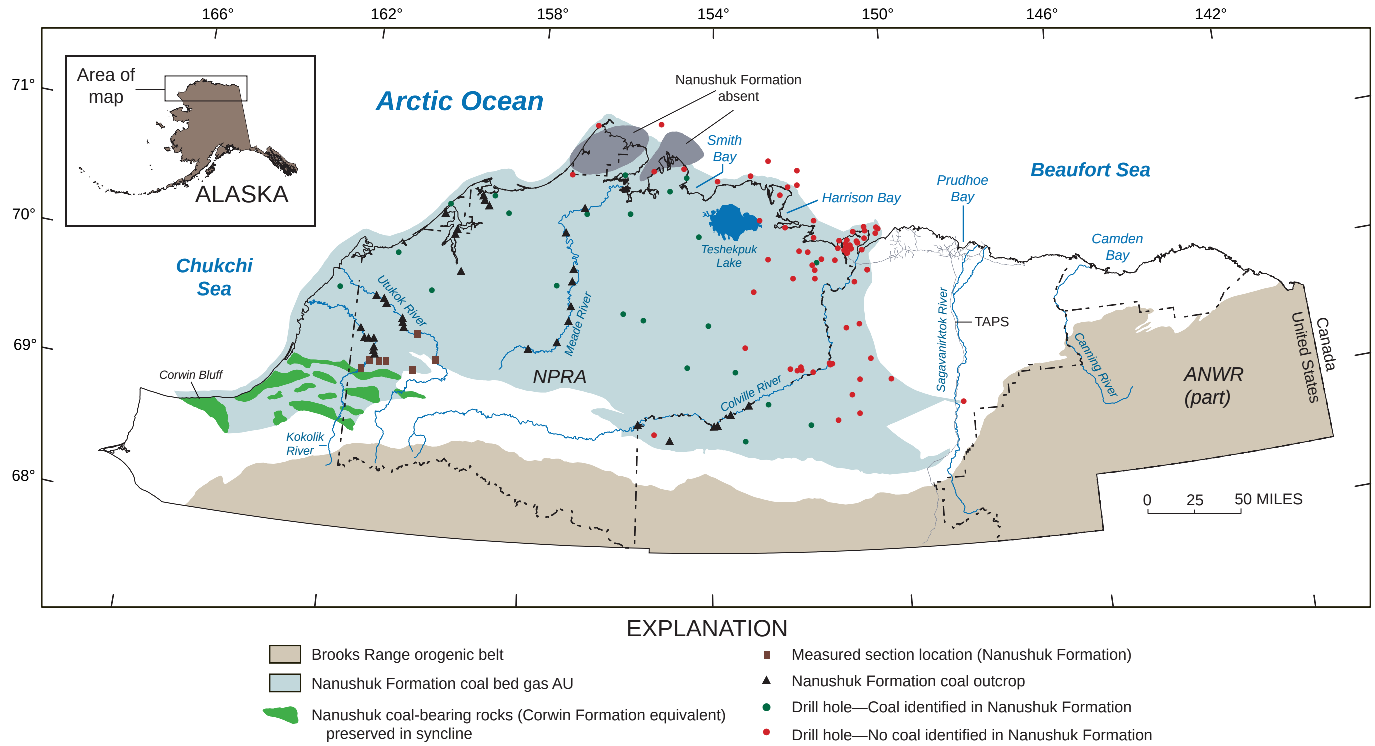
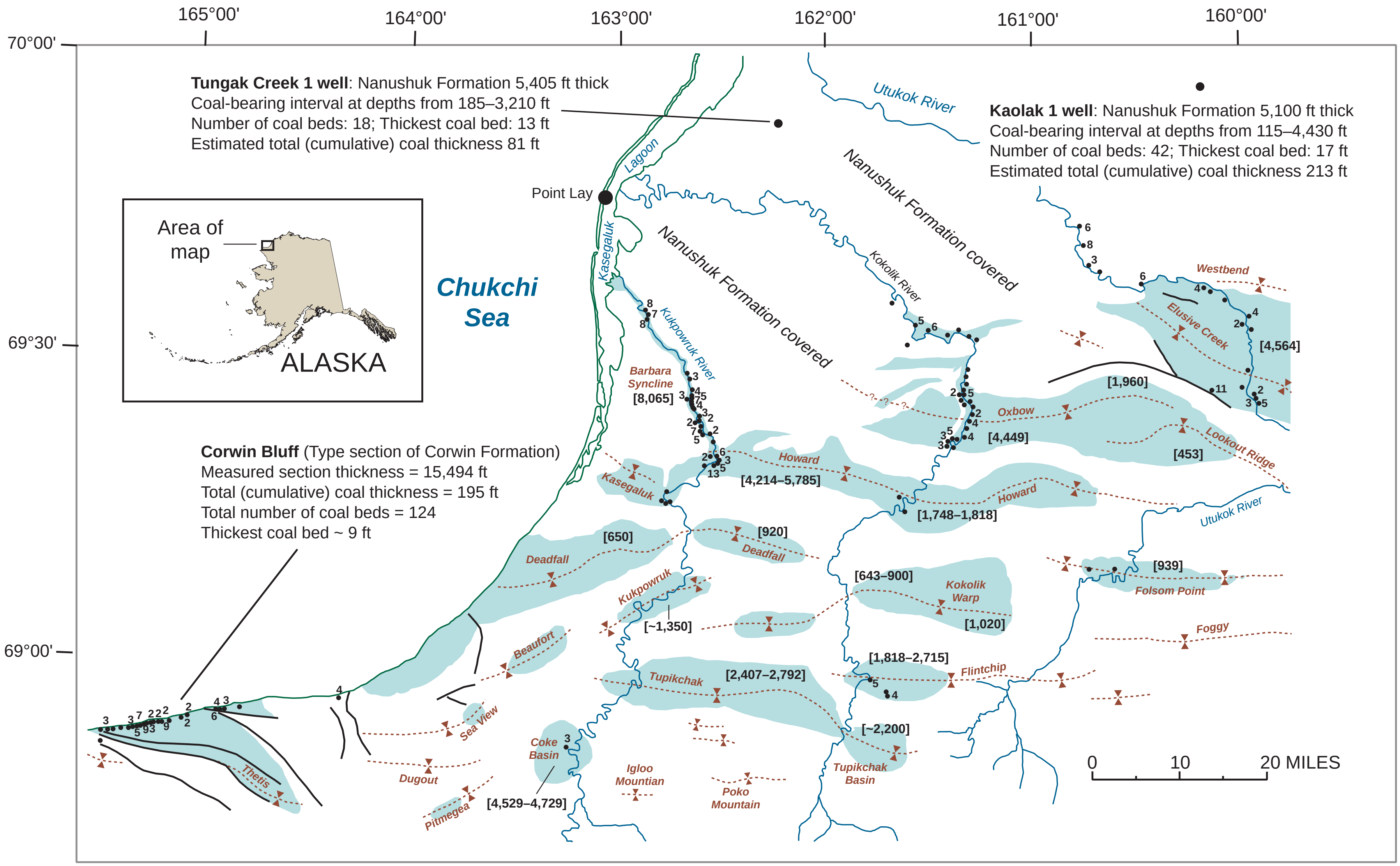


Figure 18. Map showing locations of selected drill holes, coal outcrops, and measured sections used in evaluation of Nanushuk Formation coal thickness and distribution, North Slope, Alaska. Coal outcrop locations from Martin and Callahan (1978). Measured section locations from Roehler and Stricker (1979). TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

further insight into Nanushuk coal thickness and stratigraphic distribution in the subsurface. Coal was identified in 22 of these wells (fig. 18), and graphic displays of geophysical logs and coal-bed thickness from 20 of these wells are shown in Appendix 1; coal thickness and depth interpretations for 8 of the wells are from Magoon and others (1988).

Geophysical log type varied among the wells, ranging from a relatively basic log suite including spontaneous potential (SP) and resistivity logs (for example, Kaolak 1 well; Appendix 1, fig. 1–6) to log suites including gamma ray, resistivity, bulk density, and sonic logs (for example, Tunalik 1 well; Appendix 1, fig. 1–19). Interpretations of coal-bed distribution and thickness were hampered in wells with only SP and resistivity logs because it is extremely difficult to identify coals with those particular logs. In wells with gamma ray, sonic, and bulk density logs, coals could be identified and measured with greater certainty as these log types are particularly useful for coal interpretations (for example, see Wood and others, 1983). Lithologic logs based on drill-cuttings samples were available for most wells and were useful for identifying the overall coal-bearing interval within the well; however, these logs were not considered reliable for determining individual coal-bed thickness and depth.

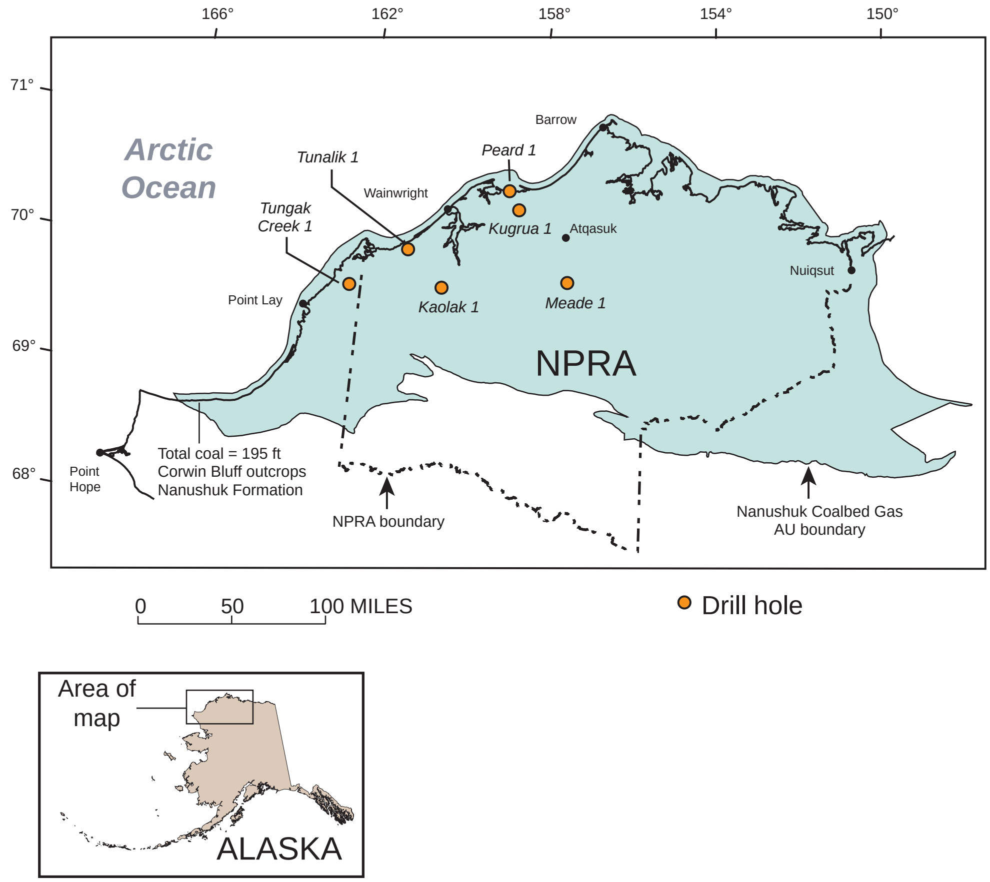
Cumulative coal thicknesses as determined in this study for certain key wells within the AU differ from previous reports; these differences (and some similarities) are summarized in figures 20 and 21. The most pronounced differences relate to the Kaolak 1 and Meade 1 wells, possibly because these wells only have lithologic, SP, and resistivity logs for coal thickness evaluation. However, even with a more complete suite of geophysical logs such as the density, sonic, and gamma ray logs for the Tunalik 1 and Tungak Creek 1 wells, interpretations vary widely, so that interpretive maps derived from these different data also vary. Figure 21 illustrates this fact by comparing a cumulative (total) coal isopach map generated for the present assessment with previously published total coal isopach maps from Tyler and others (2000) and Flores and others (2004). The marked differences are due primarily to variations in interpreted coal thickness in the Meade 1, Kaolak 1, Tunalik 1, and Tungak Creek 1 wells, and these differences serve to highlight the degree of uncertainty in identifying coals in drill holes. It should be noted, however, that each map depicts a generally similar "fairway" or trend of thick coal accumulation extending eastward from Point Lay to central areas of the NPRA. Also, an area of thick coal accumulation in the southeastern part of NPRA was identified during the present study (fig. 21), but was not included in previous interpretations of Tyler and others (2000) and Flores and others (2004).
In summary, coal isopach trends can highly interpretive, especially where there are only relatively few data points distributed over an extremely large area, which is certainly the



EXPLANATION

[1,020]	Nanushuk Formation (Corwin Formation equivalent) preserved in syncline; estimated maximum thickness (in feet) of preserved Nanushuk (Corwin Formation) in brackets
4 •	Coal bed in outcrop; thickness (in feet) shown alongside
•	Coal bed in outcrop; thickness not known
	Fault
	Synclinal axis

Figure 19. Map showing named synclines containing coal-bearing rocks in the Nanushuk Formation and locations and thicknesses of coal beds in outcrops between Corwin Bluff and the Utukok River, North Slope, Alaska. Modified from Chapman and Sable (1960).



Total (cumulative) coal thickness (in feet)

	Kaolak 1	Meade 1	Tunalik 1	Tungak Creek 1	Kugrua 1	Peard 1
This study	213	220	180	81	62	59
Flores and others (2004)*	> 400	380–390	190–200	> 300	50	< 50
Tyler and others (1998)	—	—	300	89	57	92
Magoon and others (1988)	179	120	195	—	72	69
Sable and Stricker (1987)**	255	130	76	—	5	37
Pasternak (1981)	196	—	—	—	—	—
Martin and Callahan (1978)***	519	334	—	—	—	—
Barnes (1967a)	350	260	—	—	—	—

* Total coal thickness estimated from isopach map; where a range of values is used, the total coal thickness lies between the two values

** Total coal thickness derived from summed thickness of coal beds greater than 5 ft thick; thinner coal beds not included in total

*** Total coal thickness calculated from the estimated percentage of coal relative to the total thickness of the Nansuhuk Formation in the well

Dashes indicate no data

Figure. 20. Tabulated total (cumulative) coal thickness values for selected wells penetrating the Nanushuk Formation coal in the Nanushuk Formation Coalbed Gas Assessment Unit (AU), North Slope, Alaska. NPRA, National Petroleum Reserve in Alaska.

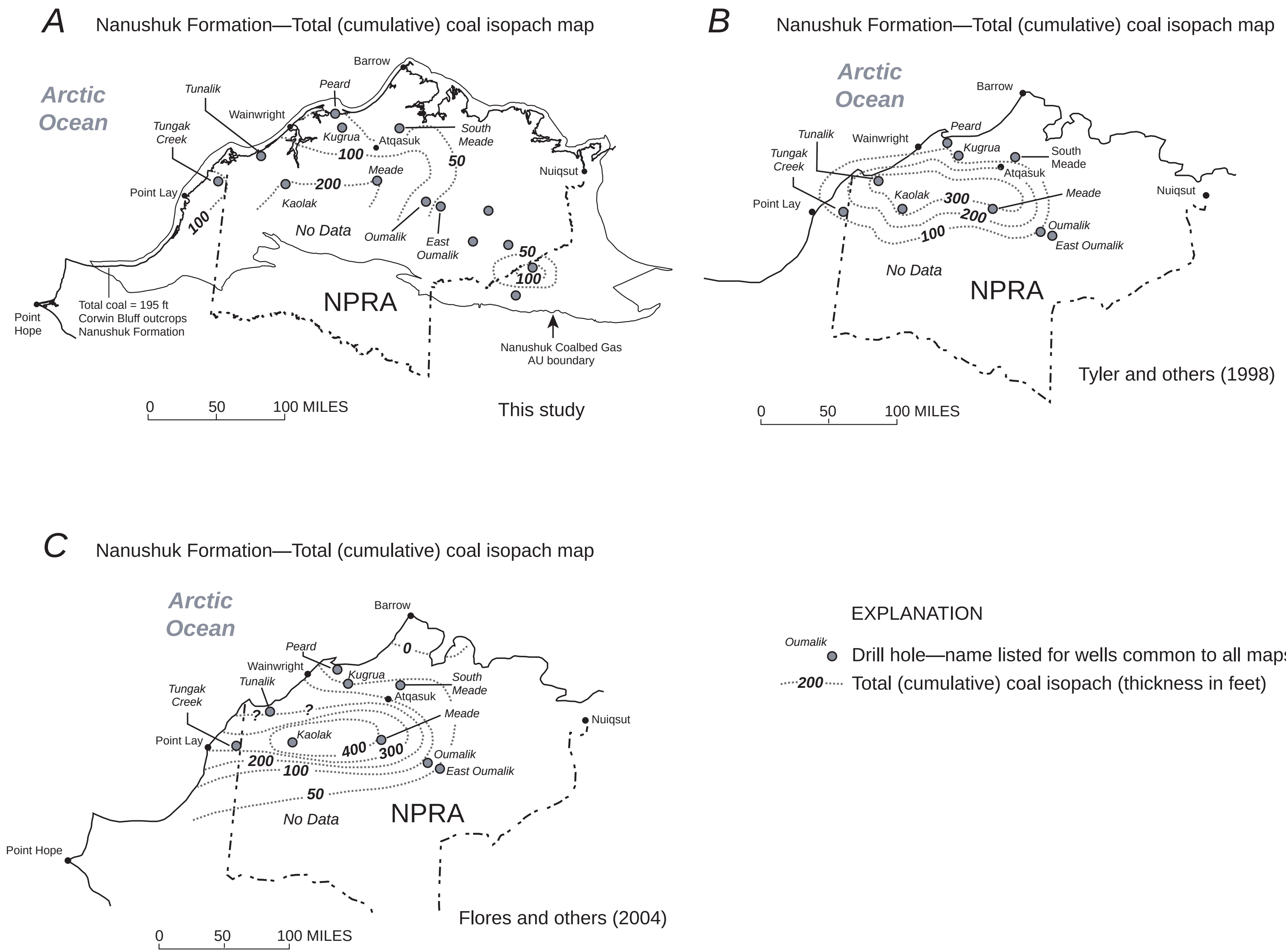


Figure 21. Isopach maps comparing estimated total (cumulative) coal in the Nanushuk Formation, North Slope, Alaska. Map *A* is from this study, map *B* is modified from Tyler and others (1998), and map *C* is modified from Flores and others (2004). NPRA, National Petroleum Reserve in Alaska.

case for the Nanushuk Formation.

Maps showing the locations of drill holes used in this study for coal thickness evaluations and total (cumulative) coal thickness isopachs for all coal beds in the Nanushuk Formation, and for only those coal beds identified in the formation below the permafrost zone are shown in figures 22 and 23, respectively. As mentioned previously, because of gas flow and permeability uncertainties in frozen coal beds, this assessment focused on coals below permafrost in order to help define prospective areas for coalbed-gas potential. Both isopach maps (figs. 22, 23) indicate a major depocenter of thick coal accumulation in areas east of the village of Pont Lay and south of Atqasuk, and a second depocenter of limited areal extent in the southeastern part of NPRA. Coal trends in the latter area are based almost solely on interpretations of the formation density and sonic logs from a single well (Little Twist 1; Appendix 1; figs. 1–10), and these interpretations could not be corroborated from other wells in the area because of poor or incomplete logs or because the wells did not penetrate equivalent intervals of coal-bearing strata.

In drill holes, depth to the top of the coal-bearing interval in the Nanushuk Formation ranges from less than 50 ft to as much as 3,380 ft, although in most wells depth to the top of coal is less than 600 ft. Depth to the base of coal ranges from about 100 ft to as much as 4,430 ft. The maximum subsurface thickness of the coal-bearing interval (interval from the uppermost to lowermost coal bed), including coal beds in permafrost, is more than 4,300 ft in the Kaolak 1 well; this value decreases to about 3,500 ft when coals in permafrost are excluded. Total (cumulative) coal thickness exceeds 200 ft for all coal in the Kaolak 1 well, and this value decreases to about 188 ft when only coals below permafrost are considered. Although total coal thicknesses below permafrost are diminished relative to values including all coal beds, the general trend of thick coal is roughly the same and total coal values below permafrost are still significant, exceeding 100 ft over a fairly large area (fig. 23). The maximum individual coal-bed thickness measured in well logs was 31 ft for all coals, and 30 ft for coals below permafrost. The maximum number of coal beds in a single well varied from 37 (inclusive of coal in permafrost) to 31 when only coals below permafrost were considered.

The apparent rank of Nanushuk Formation coals ranges from lignite A to high–volatile A bituminous; apparent ranks are higher in coals underlying foothills areas of the Nanushuk Formation Coalbed Gas AU relative to coal underlying the coastal plain (Martin and Callahan, 1978; Affolter and Stricker, 1987). The coals tend to be low in total sulfur content, with as-received values ranging from 0.1 to 2.0 percent and averaging about 0.3 percent (Flores and others, 2004). Heat-of-combustion values (as-received) range from 9,100 to 12,700 Btu/lb, averaging 12,300 Btu/lb (Flores and others, 2004, *after* Alaska Division of Geological and Geophysical Surveys, 1993).

Vitrinite reflectance (R_o) values measured from Nanushuk Formation coal outcrop samples range from 0.44 to 0.96 percent (Rao, 1980; Rao and Smith, 1983; Johnsson and others, 1999). As with the apparent coal rank, R_o values increase to the south and are highest in foothills areas east of Corwin Bluff. Reflectance values from coals in the Corwin Bluff outcrops range from 0.49 to 0.74 percent, and 19 of the 24 coals sampled had values of less than 0.70 percent. Figure 24 is a map showing the locations of outcrop samples with R_o measurements and estimated values at the base of the coal-bearing interval based on R_o profiles from oil and gas exploratory wells. The positions of the 0.50 and 0.70 percent isoreflectance lines are approximate and based on measured values from coal outcrop samples. The quality of the reflectance profiles used to estimate R_o values in oil and gas wells was highly variable and these estimates are considered less reliable than the direct reflectance readings from coal outcrop samples.

Assessment Data Input and Analogs

Although the Nanushuk Formation Coalbed Gas AU is considered hypothetical due to the lack of coalbed-gas production, gas in Nanushuk Formation coal beds has been documented in a shallow core hole (total depth 1,613 ft) drilled in the village of Wainwright (fig. 1) in June, 2007. Preliminary desorption data of samples taken from 19 coal beds indicate raw gas contents ranging from less than 10 to more than 180 standard cubic feet (SCF) per ton (A.C. Clark, U.S. Geological Survey, oral commun., 2007); gas content increases with increasing depth. In addition, well-log data from numerous oil and gas exploration wells penetrating Nanushuk coal-bearing strata elsewhere in the AU indicate the presence of gas in close association with coal beds, and available records of these gas shows are included with geophysical logs in Appendix 1. Collins (1958) also reported gas associated with coal beds in the Meade 1 and Kaolak 1 test wells (fig. 20).

The basic input data used for the assessment of Nanushuk Formation coalbed gas are shown in table 1. Because there is no production of coalbed gas within this AU, wells producing gas from subbituminous coal beds in the Paleocene Fort Union Formation in the Powder River Basin, Wyoming, and bituminous coal (high-volatile A to high-volatile B) in the Ferron Sandstone Member of the Upper Cretaceous Mancos Shale in the Wasatch Plateau (Drunkard's Wash and Helper fields), Utah, were used as analogs for estimates of drainage area and total recovery per cell of untested cells (table 1). Powder River Basin coal-bed analogs are restricted to the Anderson and Canyon coal beds, which commonly range from 20 to 30 ft in thickness. The average thickness of coal beds in the Ferron Sandstone Member is reported to be about 13 ft; where beds coalesce, coal thickness can be as much as 25 ft (Adams and Kirr, 1984, *after* Doelling and others, 1979). Reported gas contents for Fort Union Formation coal in the Powder River Basin vary from 6 to more than 75 standard cubic ft/ton (scf/ton) and are commonly in the range of 20 to

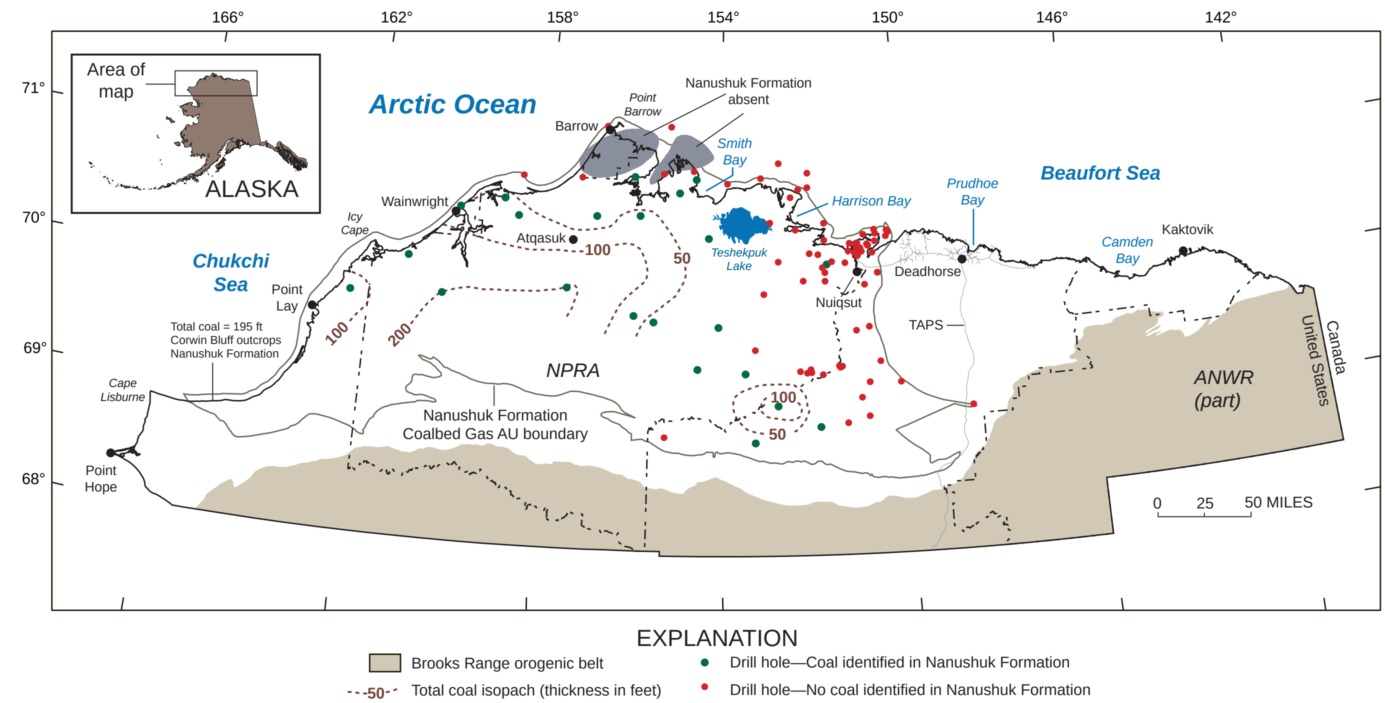


Figure 22. Map showing locations of drill holes used to evaluate coal-bed thickness and distribution and total (cumulative) coal isopachs for all coal identified in the Nanushuk Formation in the Nanushuk Formation Coalbed Gas Assessment Unit (AU), North Slope and adjacent State Waters, Alaska. TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

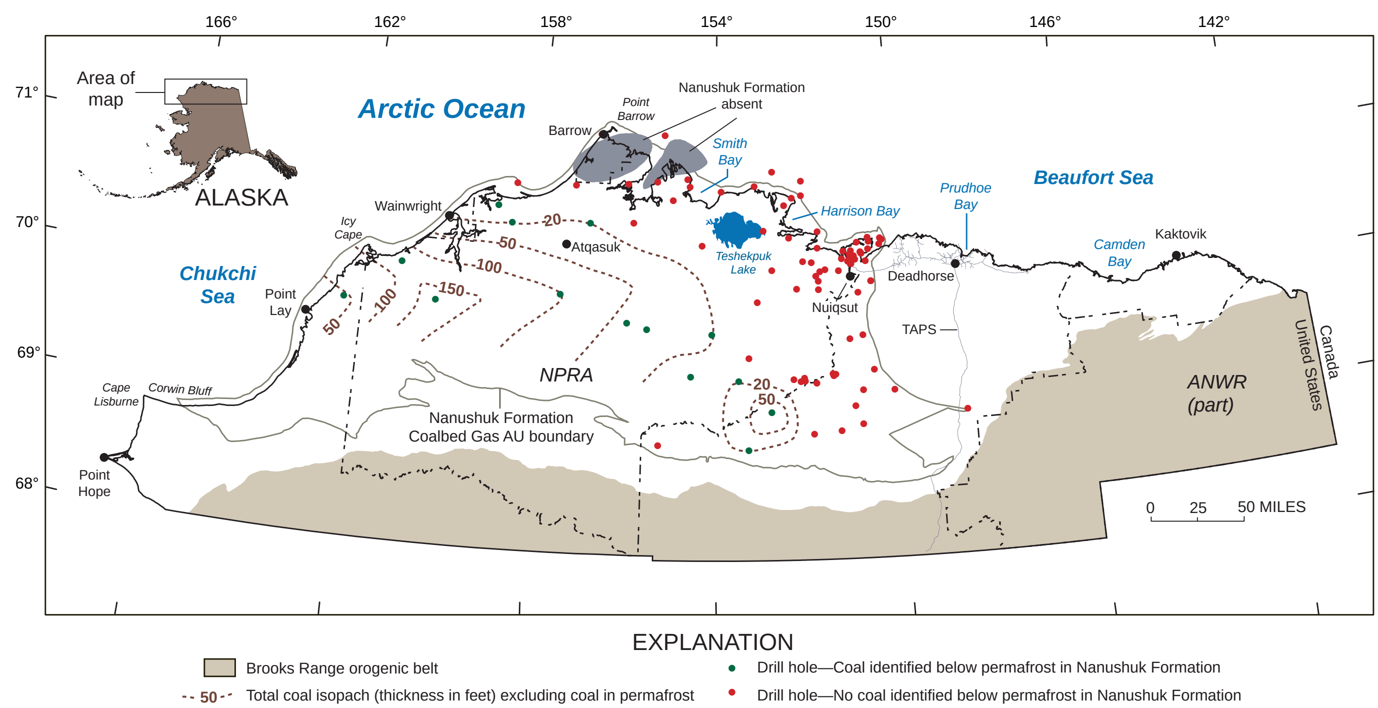


Figure 23. Map showing locations of drill holes used to evaluate coal-bed thickness and distribution and total (cumulative) coal isopachs for coal beds below the base of permafrost in the Nanushuk Formation in the Nanushuk Formation Coalbed Gas Assessment Unit (AU), North Slope and adjacent State Waters, Alaska. TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

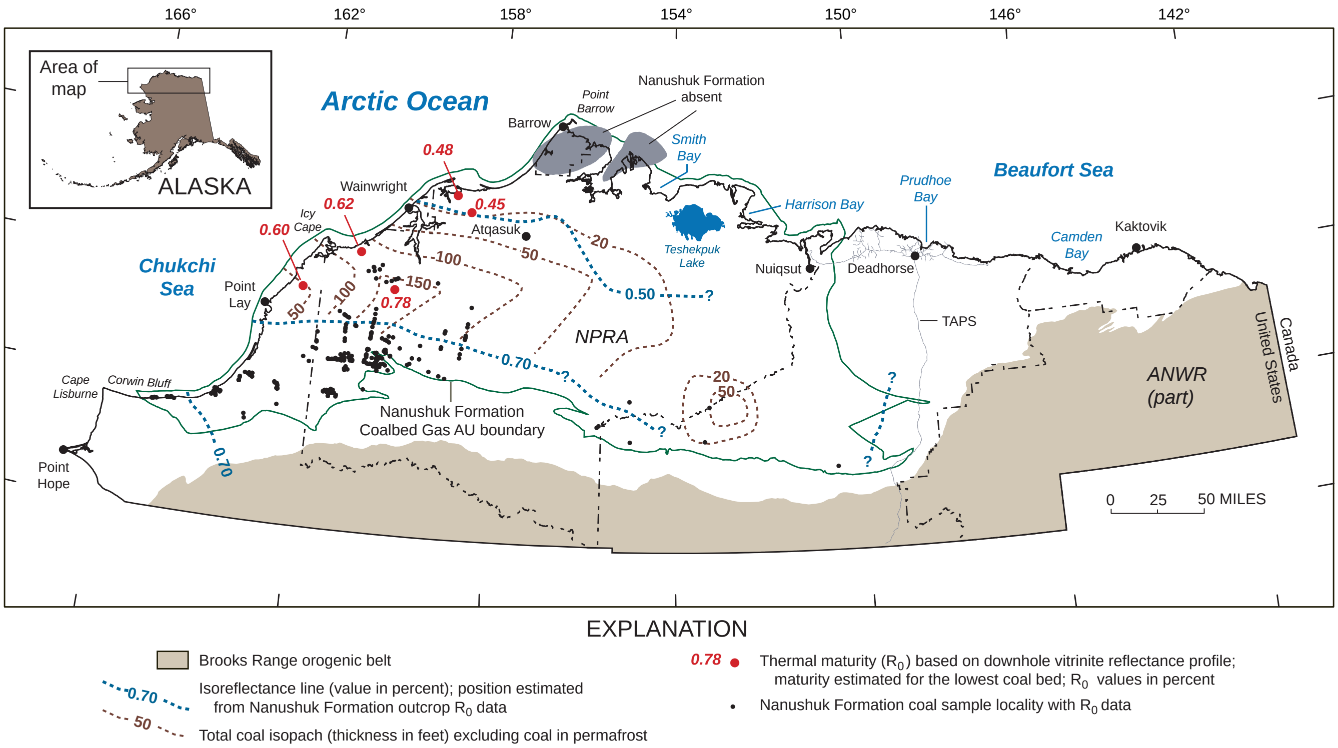


Figure 24. Map showing locations of coal outcrops sampled for vitrinite reflectance (R_0) measurements and total (cumulative) coal isopachs for coal beds interpreted to be below the base of permafrost in the Nanushuk Formation in the Nanushuk Formation Coalbed Gas Assessment Unit (AU), North Slope and adjacent State Waters, Alaska. R_0 values estimated from reflectance profiles in oil and gas exploratory wells are labeled in red. Coal outcrop sample locations from data compiled in Johnsson and others (1999) from studies by Rao (1980) and Rao and Smith (1983). TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

40 scf/ton (for example, see Stricker and others, 2000). Gas contents for Ferron coals range from 12 to 457 scf/ton (ash-free basis) (Lamarre, 2003). Based on gas isotopic analyses, coalbed gas in Fort Union Formation coal beds is exclusively biogenic (microbial) (Flores, 2004) and coalbed gas in the Ferron coals is a mix of biogenic and thermogenic gases (for example, see Lamarre, 2003). Thermal maturities (R_o values) for coal beds in the Fort Union Formation (Tongue River Member) range from 0.31 percent to 0.47 percent, and R_o values for Ferron coals range from 0.53 to 0.74 percent (Lamarre, 2003; Flores, 2004).

The range in thermal maturity of Nanushuk Formation coal (R_o from about 0.40 to almost 1.0 percent) would allow for the generation and accumulation of either biogenic (microbial) or thermogenic gas or both; significant thermal gas generation in coal (Type–III organic matter) is thought to occur at R_o levels above 0.73–0.80 percent (for example, see Law, 1984; Meissner, 1984; Johnson, 1989). Deeply buried coal beds within the trend of thick coal accumulation east of Point Lay and in areas to the south may have achieved maturity levels adequate for thermogenic gas generation and accumulation in foothills areas (fig. 24). Regional structural trends to the north of the detachment folds (figs. 16, 17) are favorable for updip (northerly) migration of these gases if permeability conditions are favorable (for comparison, see Tyler and others, 2000). There is also the potential for accumulation of gas that has migrated from older, non-coal source rocks lying stratigraphically below the Nanushuk Formation, based on a model proposed by Houseknecht (2003) for entrapment of petroleum in Brookian topset facies inclusive of the Nanushuk Formation (fig. 25). Coal beds as well as sandstones within these topset intervals would provide excellent reservoirs for the accumulation of gas migrating from deeper source rocks. Mechanisms for trapping could include a combination of stratigraphic and structural traps similar to models proposed by Lamarre (2003) for coalbed-gas fields in east-central Utah (fig. 26). Stratigraphic traps might form updip from deep basin areas where coal beds pinch out in relatively impermeable rocks surrounding the coal. In foothills areas with numerous detachment folds, migrated gas could be trapped at or near the apex of folds. Impermeable lithologies overlying and underlying coal beds could help to seal gas within fractures and coal cleats. The retention of gas in coalbed reservoirs may also depend to some degree on "hydrologic" traps, whereby contained water and associated hydrostatic pressure within the coal prohibits desorption and leakage of gas.

Depending on coal-bed continuity, cleat development, and natural fracturing, effective reservoir drainage areas for individual coalbed-gas wells can be highly variable. Based

Table 1. Basic input data form for the Nanushuk Formation Coalbed Gas Assessment Unit, North Slope and adjacent State waters, Alaska.

***FORSPAN* ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 9, 2-10-03)**

IDENTIFICATION INFORMATION

Assessment Geologist:	S.B. Roberts	Date:	6/6/2006
Region:	North America	Number:	5
Province:	Northern Alaska	Number:	5001
Total Petroleum System:	Brookian Coalbed Gas Composite	Number:	500101
Assessment Unit:	Nanushuk Formation Coalbed Gas	Number:	50010181
Based on Data as of:	2004 Tops File (Bird)		
Notes from Assessor:	Analogs: Ferron coals (Helper area); Upper Fort Union coal (Powder River Basin, excluding Wyodak coal bed)		

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo), incl. disc. & pot. additions: Gas

What is the minimum total recovery per cell? 0.02 (mmbo for oil A.U.; bcfg for gas A.U.)

Number of tested cells: 0

Number of tested cells with total recovery per cell ≥ minimum: 0

Established (discovered cells): ______ Hypothetical (no cells): X

Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)

1st 3rd discovered ______ 2nd 3rd ______ 3rd 3rd ______

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an untested cell with total recovery ≥ minimum.	1.0
2. **ROCKS:** Adequate reservoirs, traps, seals for an untested cell with total recovery ≥ minimum.	1.0
3. **TIMING:** Favorable geologic timing for an untested cell with total recovery ≥ minimum.	1.0

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3): 1.0

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES

1. Total assessment-unit area (acres): (uncertainty of a fixed value)

calculated mean	minimum	mode	maximum
26,241,000	23,617,000	26,241,000	28,865,000

2. Area per cell of untested cells having potential for additions to reserves (acres): (values are inherently variable)

calculated mean	minimum	mode	maximum
140	40	100	280

uncertainty of mean: minimum 90 maximum 190

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)

calculated mean	minimum	mode	maximum
100	100	100	100

Table 1. Basic input data form for the Nanushuk Formation Coalbed Gas Assessment Unit, North Slope and adjacent State waters, Alaska.—Continued

Assessment Unit (name, no.)
Nanushuk Formation Coalbed Gas 50010181

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES (Continued)

4. Percentage of untested assessment-unit area that has potential for additions to reserves (%):
(a necessary criterion is that total recovery per cell ≥ minimum; uncertainty of a fixed value)

calculated mean 15.3 minimum 0.5 mode 7.5 maximum 38

Geologic evidence for estimates:
Minimum area: Area where total coal values estimated at > 100 ft (10% success ratio)
Modal area: Minimum area plus areas where coal thermal maturity estimated > 0.70% (50% success ratio)
Maximum area: All areas where total coal estimated at > 20 ft (90% success ratio)

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves:
(values are inherently variable; mmbo for oil A.U.; bcfg for gas A.U.)

calculated mean 0.54 minimum 0.02 median 0.25 maximum 12

AVERAGE COPRODUCT RATIOS FOR UNTESTED CELLS, TO ASSESS COPRODUCTS
(uncertainty of fixed but unknown values)

	minimum	mode	maximum
Oil assessment unit:			
Gas/oil ratio (cfg/bo)			
NGL/gas ratio (bngl/mmcfg)			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)	0	2	5

Table 1. Basic input data form for the Nanushuk Formation Coalbed Gas Assessment Unit, North Slope and adjacent State waters, Alaska.—Continued

Assessment Unit (name, no.)
Nanushuk Formation Coalbed Gas 50010181

SELECTED ANCILLARY DATA FOR UNTESTED CELLS
(values are inherently variable)

Oil assessment unit:	minimum	mode	maximum
API gravity of oil (degrees)			
Sulfur content of oil (%)			
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum

Gas assessment unit:	minimum	mode	maximum
Inert-gas content (%)	0.01	0.20	2.00
CO_2 content (%)	0.01	0.20	2.00
Hydrogen sulfide content (%)	0.00	0.00	0.00
Heating value (BTU)	850	950	1050
Depth (m) of water (if applicable)	0	10	20

Drilling depth (m)

minimum	F75	mode	F25	maximum
300	733	800	1188	1800

Success ratios:	calculated mean	minimum	mode	maximum
Future success ratio (%)	50	10	50	90

Historic success ratio, tested cells (%) ____________

Completion practices:

1. Typical well-completion practices (conventional, open hole, open cavity, other) ____________
2. Fraction of wells drilled that are typically stimulated ____________
3. Predominant type of stimulation (none, frac, acid, other) ____________
4. Fraction of wells drilled that are horizontal ____________

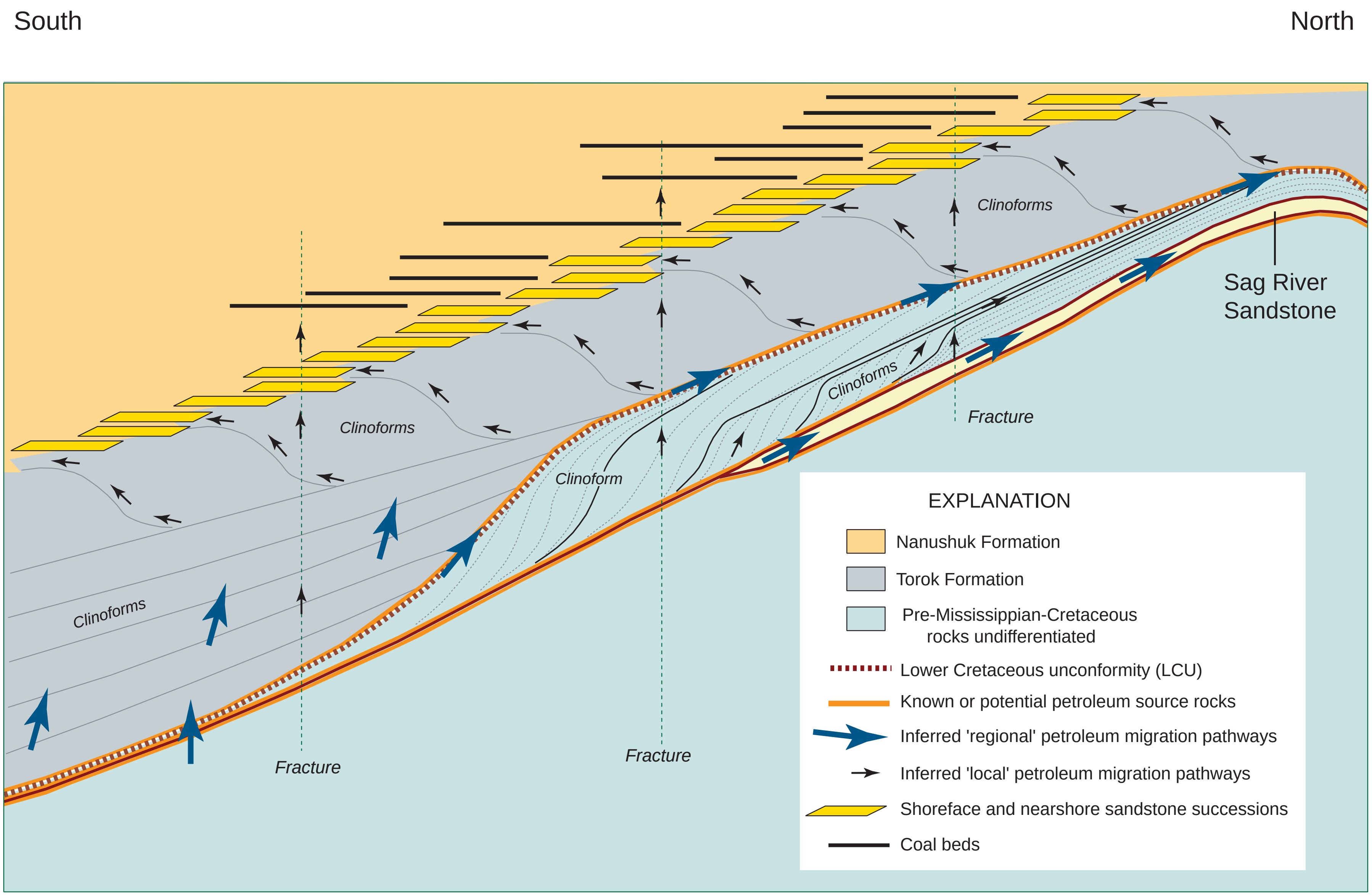


Figure 25. Schematic south-north cross section showing major source rocks and potential pathways for migration of hydrocarbons (especially gas) to coal beds in the Nanushuk Formation, North Slope, Alaska. Diagram based on concepts of hydrocarbon migration and accumulation in Brookian topset strata in Houseknecht (2003).

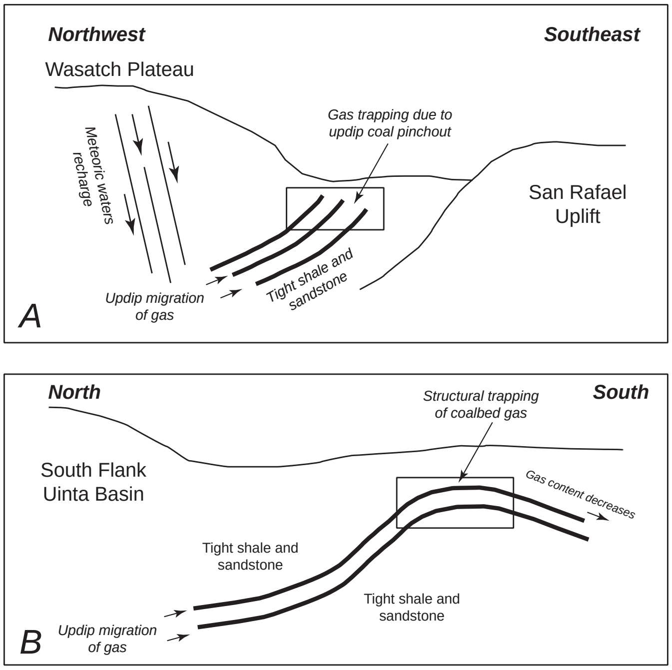


Figure 26. Schematic diagram depicting scenarios for updip migration and entrapment of coalbed gas (biogenic and thermogenic) in folded strata in the Wasatch Plateau (*A*) and Uinta Basin (*B*) areas, Utah. Models based on Lamarre (2003).

on comparable data from Powder River Basin and Wasatch Plateau coalbed-gas wells, areas per cell of untested cells having potential for additions to reserves in the Nanushuk Formation Coalbed Gas AU are estimated at a minimum of 40 acres, a mode of 100 acres, and a maximum of 280 acres (table 1). A 40-acre cell size was used as the minimum because of strong evidence for interference between coalbed-gas wells producing at less than 40-acre spacing in the Powder River Basin (R.M. Flores, U.S. Geological Survey, oral commun., 2003). The 100-acre cell size applied to the mode estimate is considered optimal in regard to gas volume and recovery, dewatering considerations, and reduction (or omission) of interference between adjacent wells. This cell-size estimate is comparable to mode estimates of cell size for Fort Union and Ferron coalbed-gas wells, which range from 80 to 120 acres. The maximum estimate of 280 acres accounts for increased drainage areas in continuous and highly permeable coal beds.

Estimates for the percentage of the untested areas within the AU that have the potential for additions to reserves are a minimum of 0.5 percent, a mode of 7.5 percent, and a maximum of 38 percent (table 1). The minimum percentage focuses on coal thickness trends and represents that area of the AU where total coal accumulation in the Nanushuk Formation (exclusive of coal in permafrost) is estimated to be greater than 100 ft (fig. 27). This area seems to best represent the main fairway of thick coal accumulation and is in general agreement with previous interpretations of thicker coal accumulation (Tyler and others, 2000; Flores and others, 2004) (fig. 21), although absolute coal thickness values vary significantly. This area also includes the northern part of the detachment fold belt where structural trapping of gas could be enhanced, and extends into the coastal plain where stratigraphic traps (updip coal pinchout) (fig. 26) may play a larger role. The mode estimate includes the minimum area coupled with foothills areas within the AU where R_o values are 0.70 percent or greater. This area of higher thermal maturity has the potential for generation and accumulation of thermogenic gas within the coals as well as the potential for increased gas contents due to the higher coal rank.

In that area of the foothills where the Nanushuk Formation is restricted to isolated synclinal troughs south of the Howard syncline (fig. 19), the coalbed-gas potential may be compromised by gas leakage from outcrops along fold margins and the limited preservation of Nanushuk coal-bearing strata within the synclines. However, because of the lack of data and the resulting geologic uncertainty as to the characteristics of the Nanushuk Formation within each syncline, part of the mode estimate (about 1 to 2 percent) allows for undiscovered coalbed-gas resources in this area of the AU. The maximum estimate includes all areas previously discussed, and also incorporates remaining areas within the AU where total coal thickness in the Nansuhuk Formation (below permafrost) is estimated to be 20 ft or greater.

It is assumed in this study that because coal beds in the Nanushuk Formation are of similar rank and maturity as the analog Ferron and Fort Union coals, estimated ultimate recoveries (EURs) applied to untested cells in the Nanushuk Formation Coalbed Gas AU might be comparable to wells producing coalbed gas in Utah and Wyoming. However, EURs from Fort Union wells (fig. 28) are significantly different than EURs from Ferron wells (fig. 29). The median EUR for Fort Union coalbed-gas wells ranges from 0.13 (Anderson coal bed) to 0.17 billion cubic feet (BCF) of gas (Canyon coal bed), whereas wells producing gas from Ferron coal beds in the Helper and Drunkard's Wash fields have median EURs ranging from 0.5 to 1.9 BCF, respectively. Maximum EURs are about 1 BCF for wells producing from the Fort Union coal beds, and range from about 3 to 20 BCF for wells producing from Ferron coal beds. Because the Nanushuk Formation Coalbed Gas AU includes coal beds that share similar characteristics with coal beds in both analog areas, total cell-recovery (EUR) estimates applied to the Nanushuk Formation (table 1) should fall somewhere between the lower EURs from Powder River Basin wells and the higher EURs characteristic of wells in the Wasatch Plateau area.

A minimum EUR of 0.02 BCF was applied to untested cells in the Nanushuk Formation Coalbed Gas AU (table 1). This value is generally considered to be the minimum gas recovery required for a successful well. A median EUR of 0.25 BCF was applied to untested cells in the AU. This median estimate is skewed slightly toward Powder River Basin median EURs because thermal maturities in Nanushuk Formation coal beds throughout much of the AU (fig. 24) may not be sufficient to generate thermogenic gas in many areas. This

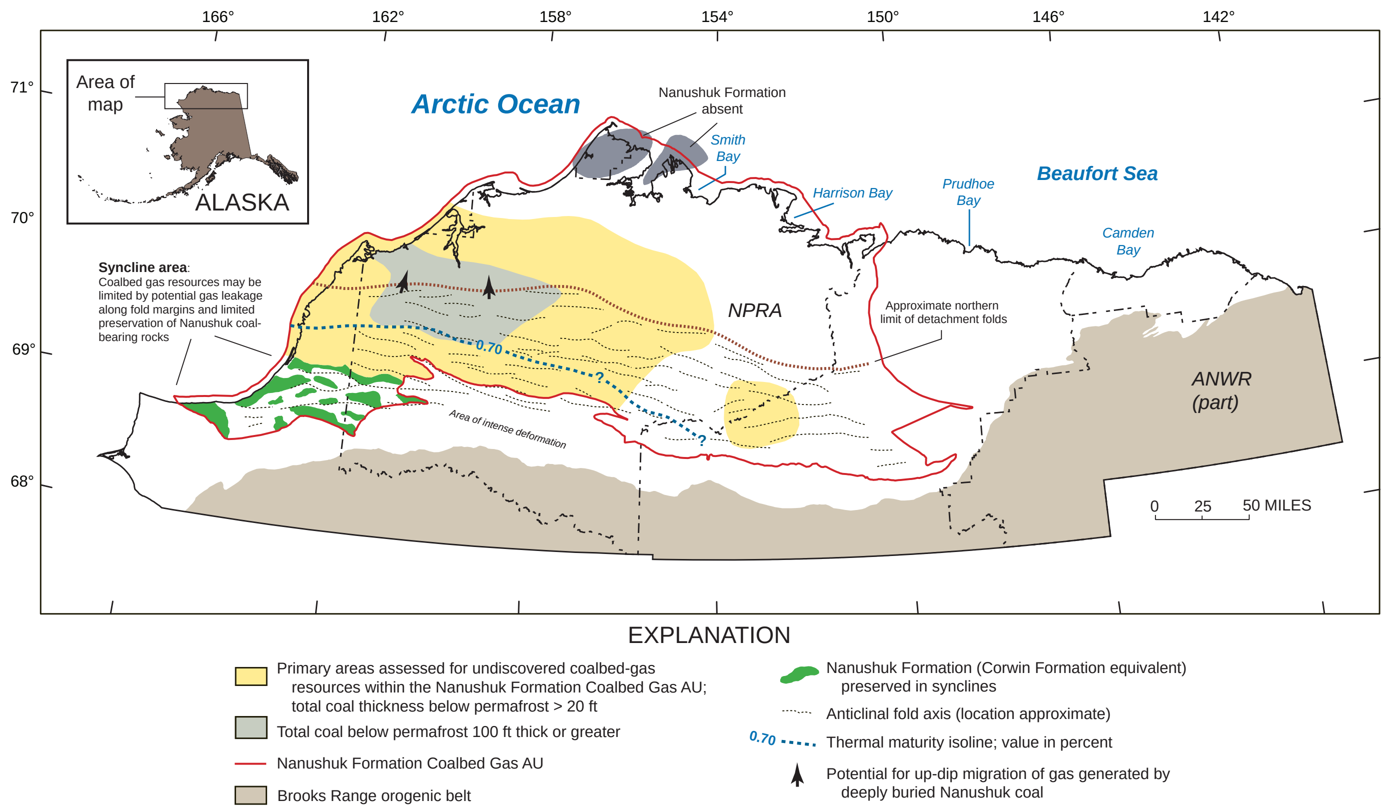


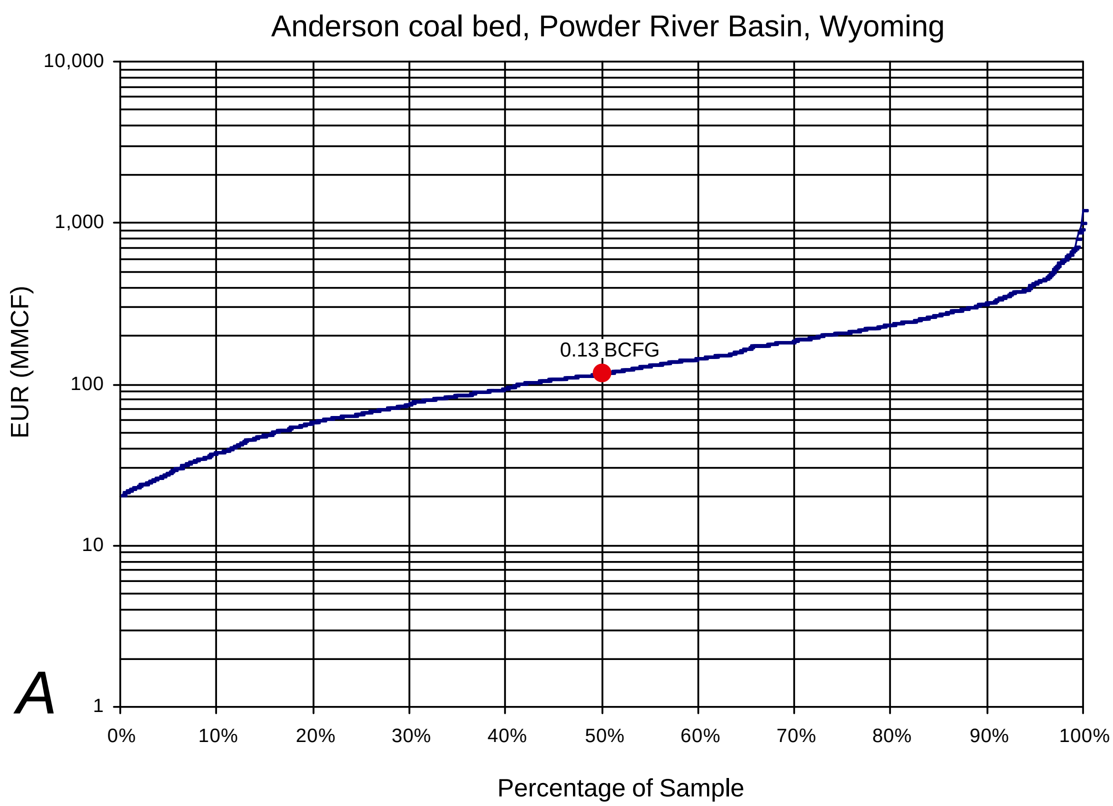
Figure 27. Map showing maximum extent of coal-bearing areas assessed for coalbed-gas potential in the Nanushuk Formation Coalbed Gas AU, North Slope and adjacent State waters, Alaska. Fold axes locations based on Mull (1985) and Kirschner and Rycerski, (1988). Syncline locations and extent based on Chapman and Sable (1960). TPS, total petroleum system; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

factor might reduce the potential for median recoveries at the level of EURs in wells producing from Ferron coal beds that contain a significant component of thermogenic gas mixed with biogenic gas. The maximum EUR of 12 BCF, however, is more strongly influenced by maximum EURs from the Wasatch Plateau fields in Utah (fig. 29) because coal beds with higher thermal maturities in a similar structural setting in the foothills area of the Nanushuk Formation Coalbed Gas AU might include a significant component of thermogenic gas and overall higher gas contents, resulting in recovery potentials on the level of some Ferron coalbed-gas wells.

Prince Creek and Tuluvak Formations Coalbed Gas Assessment Unit

The Prince Creek and Tuluvak Formations Coalbed Gas AU encompasses more than 9.6 million acres (about 15,000 mi^2) in the central and east-central part of the North Slope (fig. 10). The western boundary of the AU is the estimated depositional limit of the informally designated "sandstone of the Colville Group," which is a previously defined stratigraphic unit that includes rocks equivalent to both Tuluvak and Prince Creek Formations (for example, see Bird, 1988). Although strata also interpreted to be equivalent to the Prince Creek or Tuluvak Formation have been reported in outcrops as far west as the Utukok River region near Corwin Bluff (fig. 1) (Chapman and Sable, 1960; Mull and others, 2006), the AU was not extended to that area because neither formation has been identified in oil and gas exploration wells west of the boundary as defined here (K.J. Bird, U.S. Geological Survey, written commun., 2007). The east boundary represents the limit of marine shelf margin facies (Prince Creek Formation depositional zero edge) as defined seismically (D.W. Houseknecht, U.S. Geological Survey, written commun., 2006), and the south boundary is the estimated subsurface limit of the Tuluvak Formation based on data from a few oil and gas exploration wells in the area (fig. 30). The AU is mainly within the Coastal Plain physiographic province, and includes the easternmost portion of the NPRA. Available drill-hole data indicate that the depth to the base of permafrost within the AU varies from about 400 ft to nearly 1,800 ft (fig. 31).

The Tuluvak and Prince Creek Formations (figs 2, 3) were assessed jointly for undiscovered coalbed-gas resources. As discussed previously, coal-bearing rocks within the Tuluvak Formation were previously assigned to the Tuluvak Tongue of the Prince Creek Formation (Gryc and others,



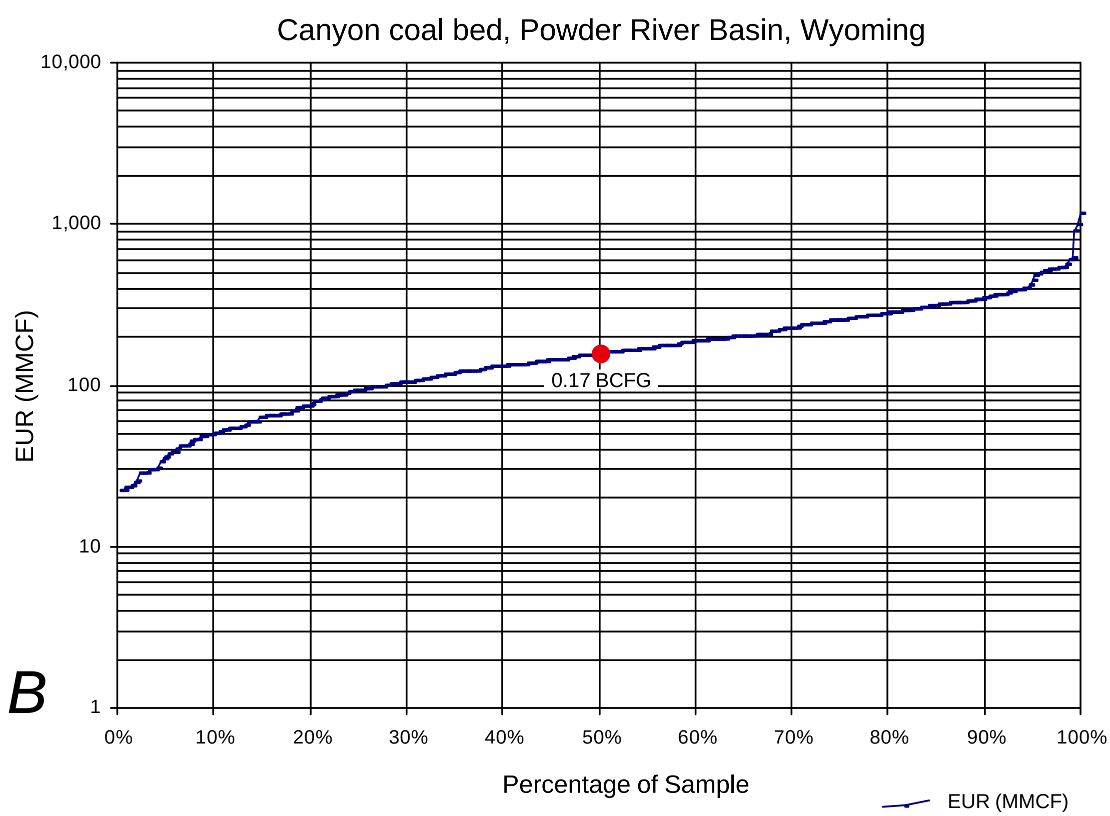
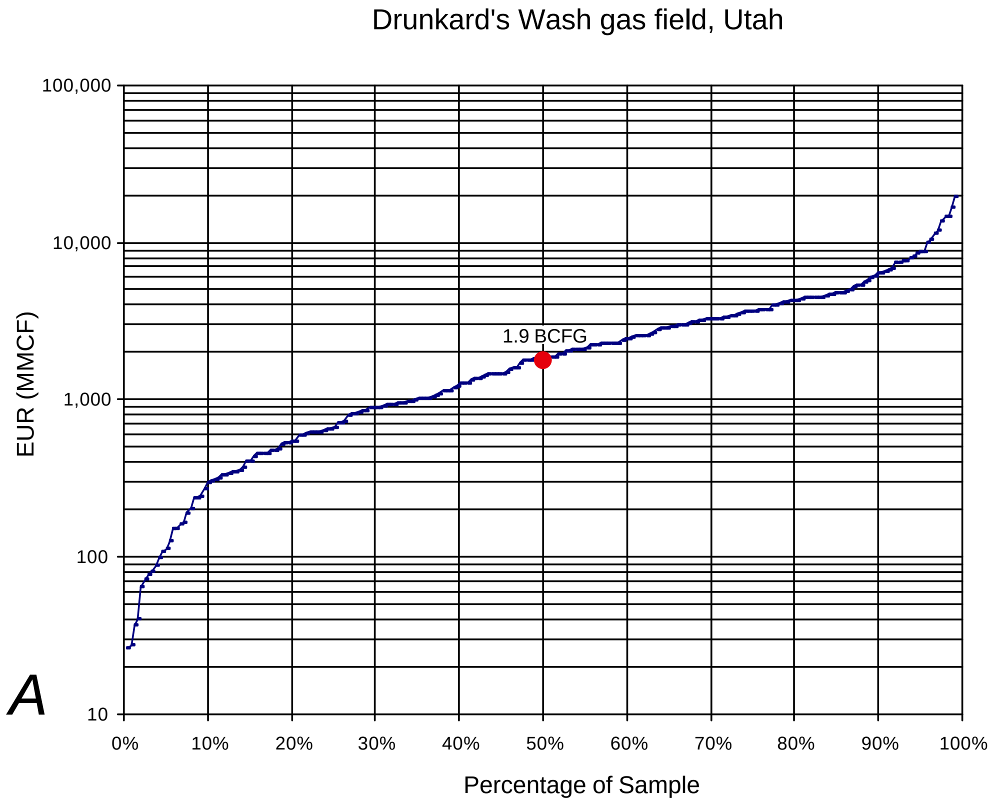


Figure 28. Graph showing distribution of estimated ultimate recoveries (EURs) for coalbed-gas wells producing from the Anderson (*A*) and Canyon (*B*) coal beds in the Powder River Basin, Wyoming. Red dot represents the median EUR in each graph. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas are represented by the graph. MMCF, million cubic feet; BCFG, billion cubic feet of gas. Production data used in EUR distributions from IHS Energy Group (2005).



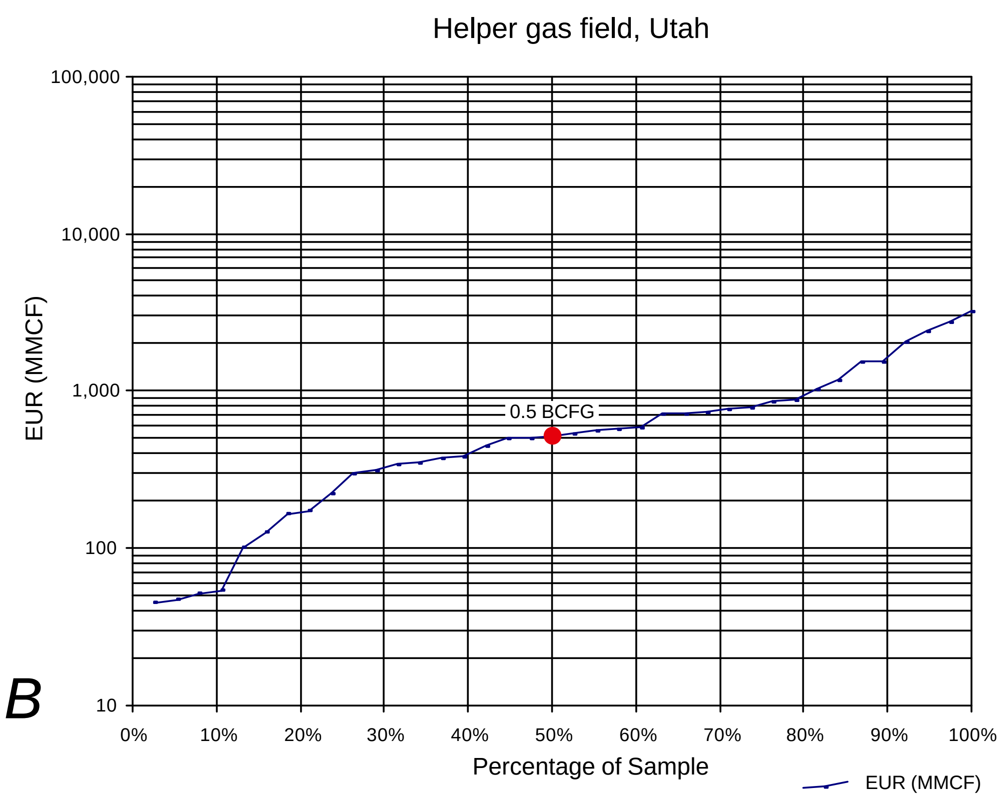


Figure 29. Graph showing the distribution of estimated ultimate recoveries (EURs) for coalbed-gas wells producing from coal beds in the Drunkard's Wash (A) and Helper gas fields (B) in the Wasatch Plateau area, Utah. Red dot represents the median EUR in each graph. Only wells with minimum EURs exceeding 0.02 billion cubic feet of gas are represented by the graph. MMCF, million cubic feet; BCFG, billion cubic feet of gas. Production data used in EUR distributions from IHS Energy Group (2000).

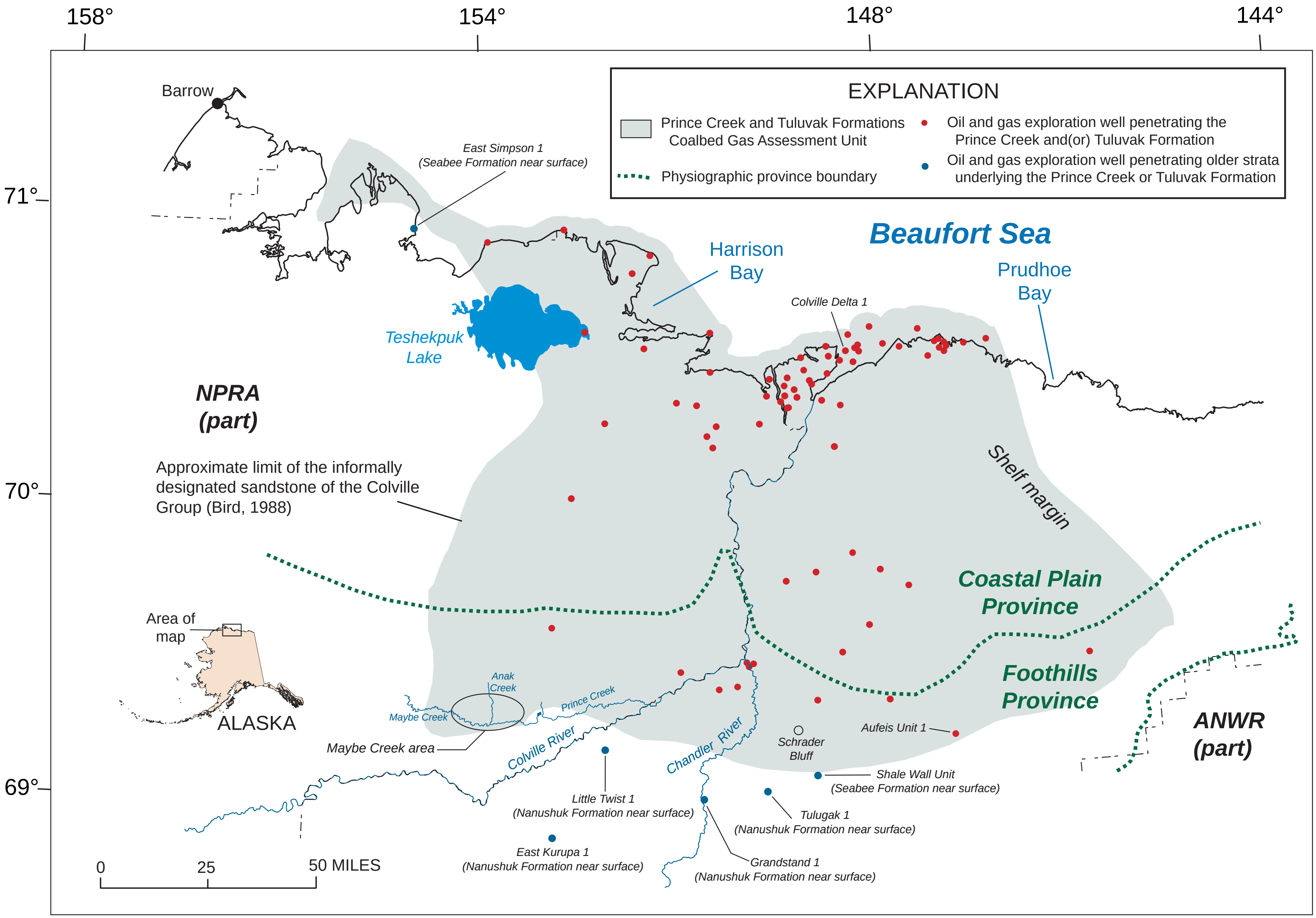


Figure 30. Map showing boundaries of the Prince Creek and Tuluvak Formations Coalbed Gas Assessment Unit (AU) and locations of drill holes penetrating one or both of these formations, central North Slope and adjacent State Waters, Alaska. Physiographic province boundaries modified from Payne and others (1951). NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

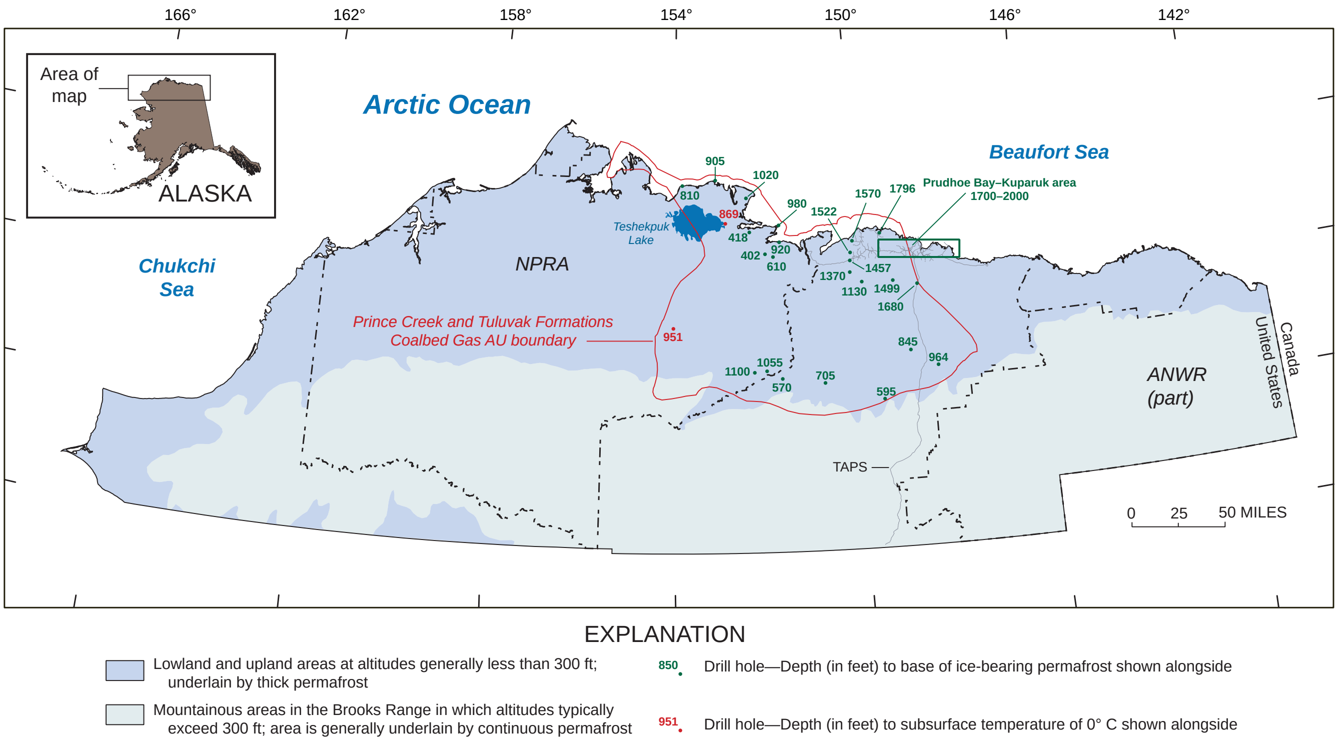


Figure 31. Map showing generalized distribution and characteristics of permafrost in upland areas of the Brooks Range and on the North Slope, Alaska, and estimated depths to the base of permafrost in the Prince Creek and Tuluvak Formations Coalbed Gas Assessment Unit (AU). Permafrost depths are based on data from selected oil and gas exploration wells and represent either (1) depth from the kelly bushing to base of ice-bearing permafrost, (2) depth from the ground surface to base of the ice-rich layer, or (3) depth from the ground surface to subsurface temperature of 0°C as measured in boreholes. Permafrost data based on Ferrians, Jr. (1965), Osterkamp and Payne (1981), Lachenbruch and others (1982, 1987), and Collett and others (1989). TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

1951). In the revised definition (Mull and others, 2003), the Tuluvak Formation includes the Tuluvak Tongue as well as underlying rocks previously assigned to the Ayiyak Member of the Seabee Formation (Detterman, 1956). The Prince Creek Formation has also been redefined to include coal-bearing rocks previously assigned to the Kogosukruk Tongue of the Prince Creek Formation (Gryc and others, 1951) as well as younger coal-bearing rocks that were included in the lower part of the Sagwon Member of the Sagavanirktok Formation (Detterman and others, 1975). The Tuluvak and Prince Creek Formations are separated by the Schrader Bluff Formation, a dominantly marine unit composed of sandstone and shale that can be as thick as 2,500 ft (Mull and others, 2003).

Geologic Setting

The Tuluvak Formation is Turonian-Coniacian in age (fig. 3) and outcrops generally consist of conglomerate, sandstone, shale, carbonaceous shale, and coal; lithologies vary in relative abundance depending on location. At Schrader Bluff (fig. 30), 575 ft of the formation is exposed (Tuluvak Tongue; Detterman and others, 1963) and sandstone constitutes one-half of the section. In some areas, conglomerates are a more prominent constituent, although they generally thin to the east and become finer grained, indicating an overall eastward progradation of the Tuluvak clastic wedge toward a shelf margin (Mull and others, 2003). The Tuluvak Formation is only partially exposed at any given outcrop locality, but subsurface data indicate that thicknesses range from about 140 ft in the Colville Delta 1 well to as much as 1,450 ft in the Aufeis Unit 1 well (fig. 30) (K. Bird, U.S. Geological Survey, written commun., 2007).

The Prince Creek Formation is Campanian through Paleocene in age (fig. 3), and is characterized in outcrops by interbedded conglomerate, sandstone, mudstone, carbonaceous shale, and coal. Sandstones are typically very fine- to fine-grained, although beds of medium- to coarse-grained conglomeratic sandstone are present locally in the lower part of the formation (Mull and others, 2003). No complete section is present in any of the exposed areas. The formation overlies and intertongues with the Schrader Bluff Formation and, because of the intertonguing relation, the two formations are generally difficult to separate in the subsurface. The aggregate thickness of the undifferentiated Prince Creek and Schrader Bluff Formations ranges from about 100 ft to almost 5,000 ft.

The overall structural characteristics of the AU are similar to those described for the Nanushuk Coalbed Gas AU in that east-west-trending detachment folds characterize the foothills region, whereas in the coastal plain strata are only slightly disturbed and dipping gently eastward (fig. 32). Many of the anticlines within the foothills may actually represent the structural expression of north-vergent thrust faults (Mull and others, 2004).

Coal Geology

Coals in the Tuluvak and Prince Creek Formations have been studied far less than Nanushuk Formation coal; consequently, data detailing the characteristics of the coal (stratigraphic distribution, thickness and quality) are rather sparse throughout much of the AU. As with the Nanushuk Formation, coal outcrops are sporadic and complete coal-bearing sections in the Prince Creek and Tuluvak Formations are not exposed at any single locality. In outcrops in the Maybe Creek area (fig. 30), Brosgé and Whittington (1966) reported a 6.5-ft-thick coal bed in the Tuluvak Formation (Tuluvak Tongue) at exposures along Banshee Creek, an 11-ft-thick interval of coal and bentonite near Baby Creek, and an 8- to 12-ft-thick interval of coal and bentonite between Anak and Maybe Creek. In outcrops of the Prince Creek Formation (Kogosukruk Tongue) along the Chandler River, Detterman and others (1963) described it as “mainly a coal, clay shale, and bentonitic unit” that includes nine coal beds with an aggregate thickness of 23 ft within the basal 75 ft of the section; the thickest individual coal bed is 5 ft. Prince Creek coal beds ranging from 6 to 12 ft in thickness have also been reported at additional sites along the Chandler River and on the Colville River (D.W. Houseknecht, U.S. Geological Survey, written commun., 2005).

Interpretations of geophysical logs from 58 oil and gas exploration wells within the Prince Creek and Tuluvak Formations Coalbed Gas AU (fig. 33) were completed to gain insight into thicknesses and stratigraphic distribution of coals in the subsurface; coal was identified in 10 of these wells (fig. 33), and graphic displays of geophysical logs and coal-bed thicknesses for these wells are included in Appendix 2. In the Colville Unit 1 well (fig. 33), geophysical logs were not available for the interval from ground surface to a depth of 1,100 ft, so the total coal thickness in that well is considered to be a minimum value. Most interpretations of coal-bed thickness are based on this study, although in 4 wells coal thickness and depths are based on Magoon and others (1988). Coal appears to be absent from the northernmost and eastern parts of the AU, although in the latter area well data are extremely sparse; consequently, no attempt was made to generate total coal isopach maps.

Maps with drill-hole locations and total (cumulative) coal thickness values for the Tuluvak and Prince Creek Formations, one for all coal beds identified in these formations and another for coal beds identified below permafrost are shown in figures 33 and 34, respectively. Based on limited subsurface data—SP and resistivity logs for some wells (for example, Gubik 1 well; Appendix 2, fig. 2–4) and more complete log suites for other wells (for example, Hunter A well; Appendix 2, fig. 2–6)—depth to the top of the coal-bearing interval ranges from about 20 ft to as much as 1,300 ft, and depth to the base of coal ranges from about 455 ft to 2,550 ft. The maximum combined thickness of all coal beds in the Tuluvak-Prince Creek interval is 76 ft (fig. 33); the maximum thickness decreases to 35 ft when only coal below permafrost is considered (fig. 34). The maximum individual coal-bed thickness measured in well logs was 16 ft when all coals were considered, and 12 ft for coals below permafrost. The maximum number of coal beds in a single well varied from 17 (inclusive of coal in permafrost) to 12 when only coals below permafrost were considered.

Based on as-received analyses from three outcrop samples of Prince Creek Formation coal, heat-of combustion values range from 7,286 to 8,257 Btu/lb, ash yields range from 15.34 to 27.31 percent, and total sulfur varies from 0.21 to 0.23 percent (U.S. Geological Survey, unpub. data). Apparent rank based on these limited samples is subbituminous B (G.D. Stricker, U.S. Geological Survey, oral commun., 2007). Vitrinite reflectance (R_o) values measured from Prince Creek Formation coal outcrop samples range from 0.40 to 0.59 percent (fig. 35) (D.W. Houseknecht, U.S. Geological Survey, written commun., 2005).

Assessment Data Input and Analogs

Basic input data used for assessing Prince Creek and Tuluvak Formations coalbed-gas potential are shown in table 2. Wells producing gas from subbituminous coal beds in the Paleocene Fort Union Formation in the Powder River Basin, Wyoming, were used as analogs for estimates of drainage area and total recovery per cell of untested cells. These analogs are restricted to the Anderson or Canyon coal beds, which commonly range from 20 to 30 ft in thickness; these thicknesses are significantly greater than those reported for Prince Creek or Tuluvak coal beds, which are as thick as 15 ft but generally less than 10 ft thick.

Limited gas shows are reported in coal-bearing strata of the Tuluvak and Prince Creek Formations (Gubik 1 and 2 wells and the Inigok 1 well; Appendix 2), far less numerous than shows in Nanushuk Formation coaly successions. Thermal maturities appear too low for significant thermal gas generation from Prince Creek or Tuluvak Formation coal beds (R_o less than 0.60 percent; fig. 35), but there may be some limited potential for entrapment of migrated gas from deeper source rocks, either through mechanisms as proposed by Houseknecht (2003) (fig. 25) or via vertical migration in fractures, particularly on anticlinal structures. In large part, however, it is anticipated that coalbed-gas potential within this AU will rely mainly on the accumulation of biogenic gas generated by the coals.

Based on comparable data from Powder River Basin coalbed-gas wells, the area per cell of untested cells (drainage areas) having the potential for additions to reserves in the

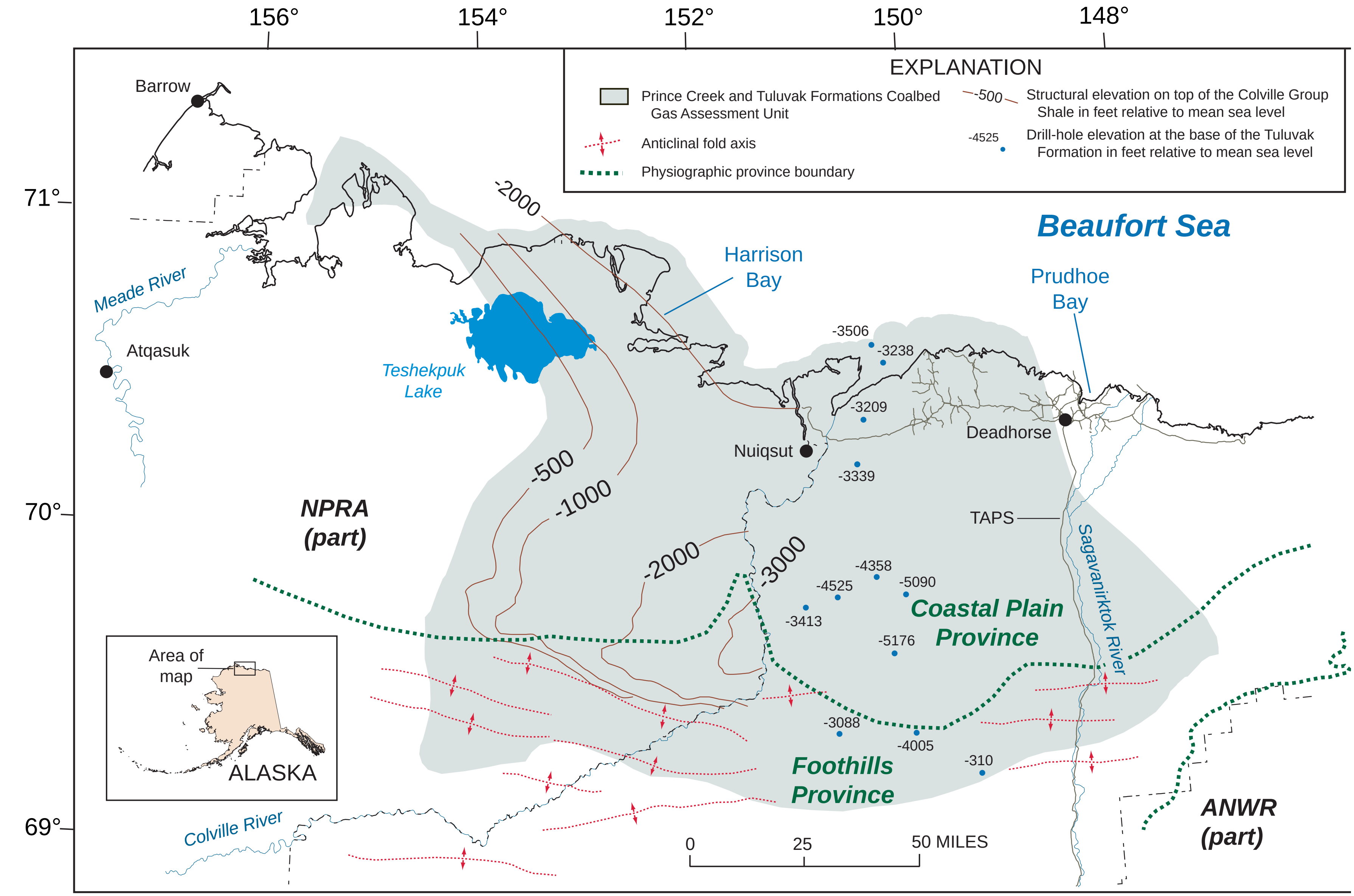


Figure 32. Map showing physiographic province boundaries, detachment (anticlinal) fold axes, elevation at base of the Tuluvak Formation, and structure contours on top of strata immediately underlying the Tuluvak Formation (Colville Group Shale) in the Prince Creek and Tuluvak Formations Coalbed Gas Assessment Unit, North Slope and adjacent State waters, Alaska. Structure contours modified from Bird (1988). Fold axes locations are highly generalized and based on Mull (1985) and Kirschner and Rycerski (1988). Physiographic province boundaries modified from Payne and others (1951). TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

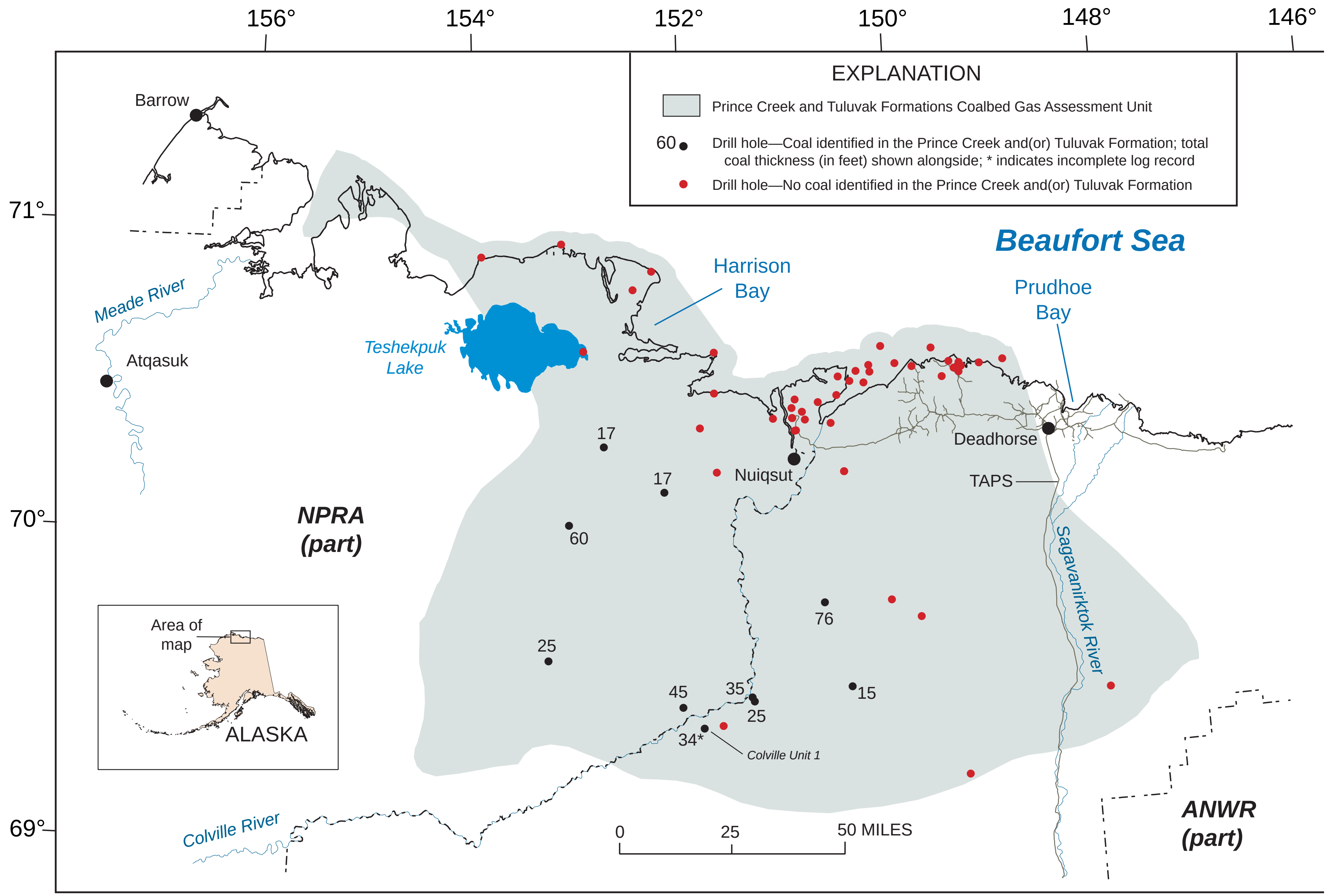


Figure 33. Map showing locations of drill holes used to evaluate coal-bed thickness and total (cumulative) coal thickness in the Prince Creek and Tuluvak Formations, central North Slope, Alaska. TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

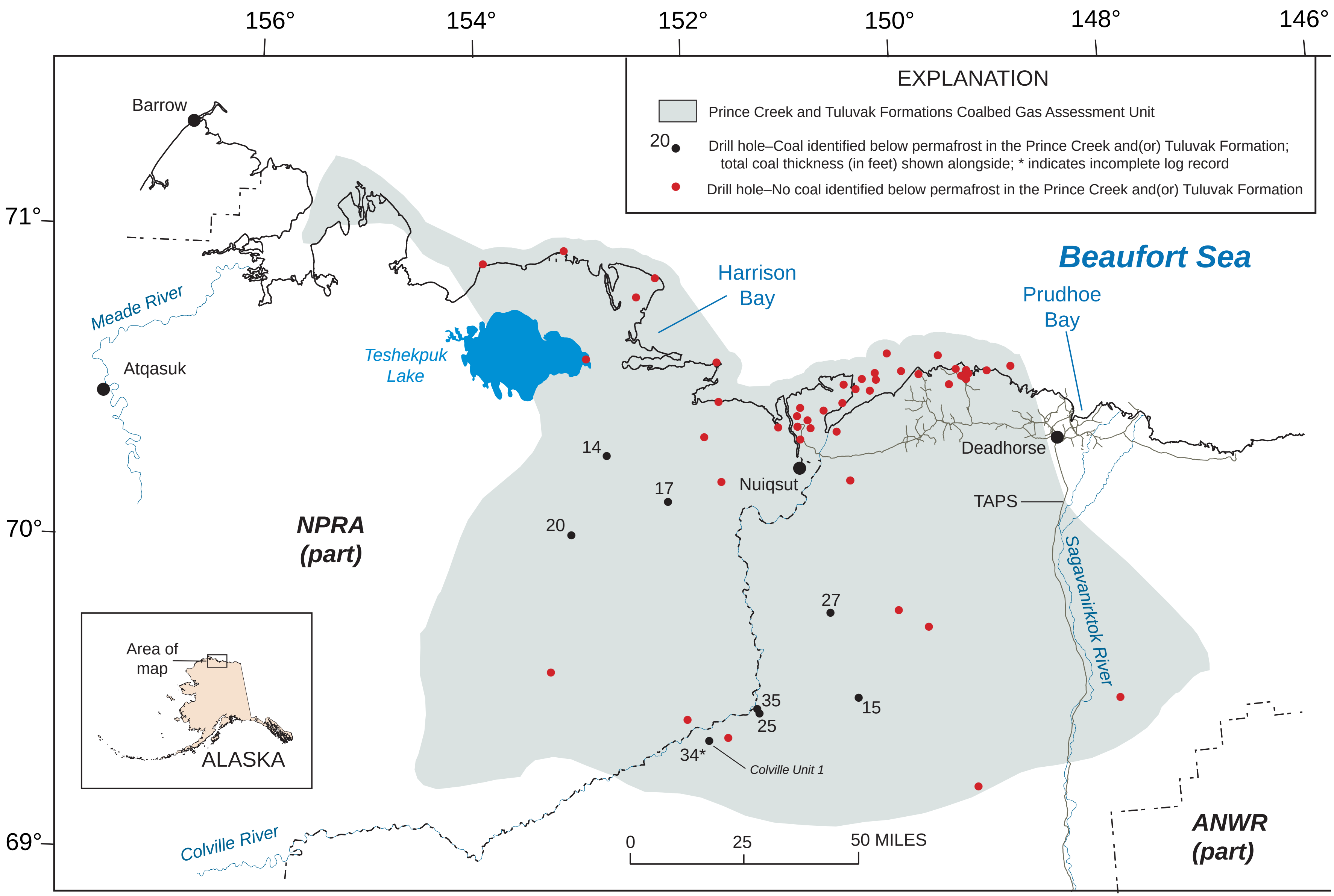


Figure 34. Map showing locations of drill holes used to evaluate coal-bed thickness and total (cumulative) coal thickness below the estimated base of permafrost in the Prince Creek and Tuluvak Formations, central North Slope, Alaska. TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

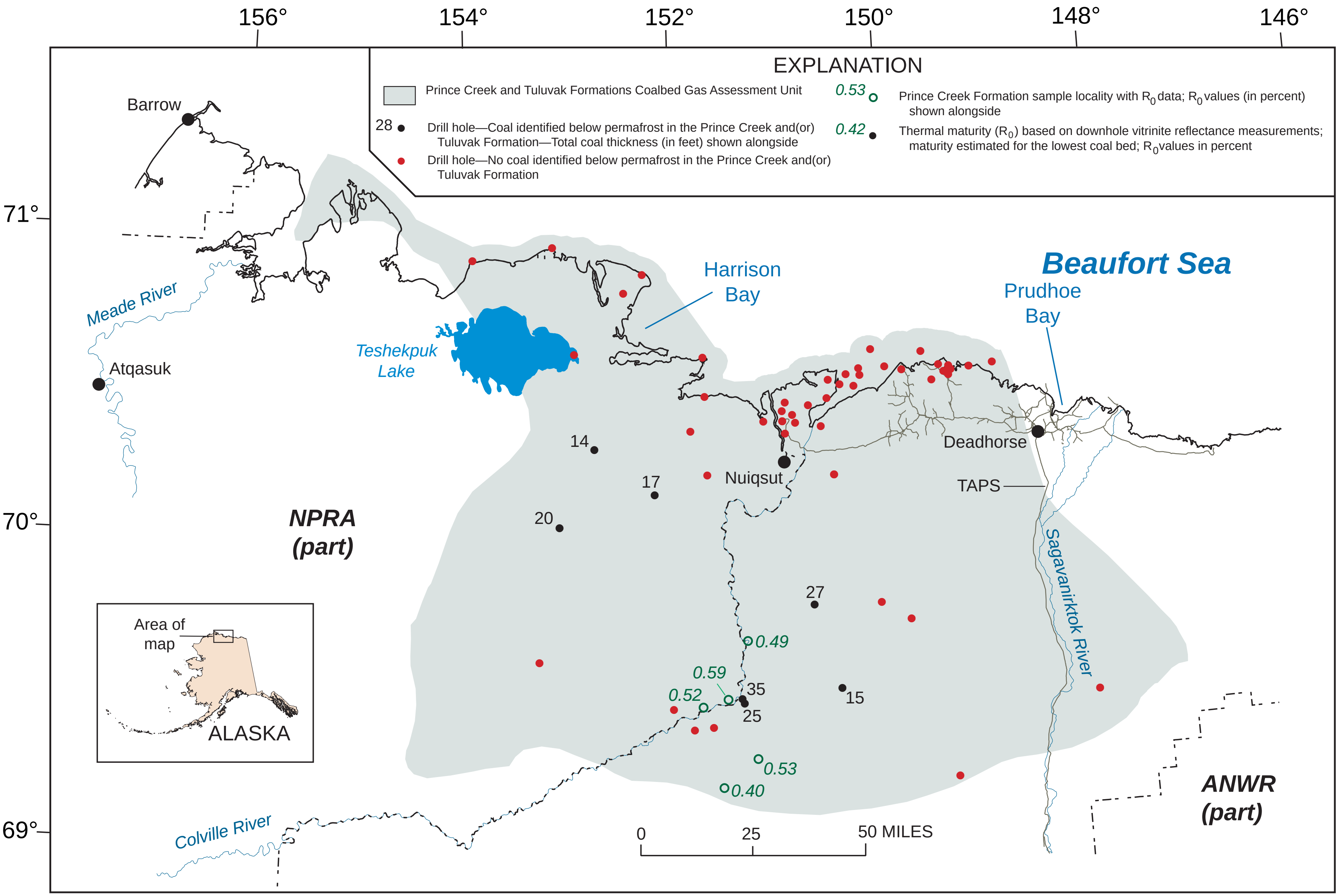


Figure 35. Map showing locations of drill holes used to evaluate coal-bed thickness and coal sample locations used for vitrinite reflectance (R_0) measurements in the Prince Creek and Tuluvak Formations Coalbed Gas Assessment Unit, North Slope and adjacent State Waters, Alaska. Coal sample locations and reflectance data from D.W. Houseknecht, U.S. Geological Survey (written commun., 2005). TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

Table 2. Basic input data form for the Prince Creek and Tuluvak Formations Coalbed Gas Assessment Unit, North Slope and adjacent State waters, Alaska.

FORSPAN **ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 9, 2-10-03)**

IDENTIFICATION INFORMATION

Assessment Geologist:	S.B. Roberts	Date:	6/6/2006
Region:	North America	Number:	5
Province:	Northern Alaska	Number:	5001
Total Petroleum System:	Brookian Coalbed Gas Composite	Number:	500101
Assessment Unit:	Prince Creek-Tuluvak Formations Coalbed Gas	Number:	50010182
Based on Data as of:	2004 Tops File (Bird)		
Notes from Assessor:	Analogs: Upper Fort Union coal (Powder River Basin, excluding Wyodak coal bed)		

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo), incl. disc. & pot. additions: Gas

What is the minimum total recovery per cell? 0.02 (mmbo for oil A.U.; bcfg for gas A.U.)

Number of tested cells: 0

Number of tested cells with total recovery per cell ≥ minimum: 0

Established (discovered cells): ______ Hypothetical (no cells): X

Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)

1st 3rd discovered ______ 2nd 3rd ______ 3rd 3rd ______

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an untested cell with total recovery ≥ minimum.	1.0
2. **ROCKS:** Adequate reservoirs, traps, seals for an untested cell with total recovery ≥ minimum.	1.0
3. **TIMING:** Favorable geologic timing for an untested cell with total recovery ≥ minimum.	1.0

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3): 1.0

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES

1. Total assessment-unit area (acres): (uncertainty of a fixed value)

   calculated mean 9,619,000 minimum 8,657,000 mode 9,619,000 maximum 10,581,000

2. Area per cell of untested cells having potential for additions to reserves (acres): (values are inherently variable)

   calculated mean 113 minimum 40 mode 100 maximum 200

   uncertainty of mean: minimum 60 maximum 160

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)

   calculated mean 100 minimum 100 mode 100 maximum 100

Table 2. Basic input data form for the Prince Creek and Tuluvak Formations Coalbed Gas Assessment Unit, North Slope and adjacent State waters, Alaska.—Continued

Assessment Unit (name, no.)
Prince Creek-Tuluvak Formations Coalbed Gas 50010182

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES (Continued)

4. Percentage of untested assessment-unit area that has potential for additions to reserves (%):
(a necessary criterion is that total recovery per cell ≥ minimum; uncertainty of a fixed value)

calculated mean 6.4 minimum 0.2 mode 5 maximum 14

Geologic evidence for estimates:
Minimum area: Structurally folded area with total coal > 20 ft (10% success ratio)
Modal area: Minimum area plus remaining area south of Brookian deformation front (40% success ratio)
Maximum area: All areas where total coal estimated at > 20 ft (70% success ratio)

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves:
(values are inherently variable; mmbo for oil A.U.; bcfg for gas A.U.)

calculated mean 0.145 minimum 0.02 median 0.1 maximum 1.5

AVERAGE COPRODUCT RATIOS FOR UNTESTED CELLS, TO ASSESS COPRODUCTS
(uncertainty of fixed but unknown values)

	minimum	mode	maximum
Oil assessment unit:			
Gas/oil ratio (cfg/bo)			
NGL/gas ratio (bngl/mmcfg)			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)	0	0	0

Table 2. Basic input data form for the Prince Creek and Tuluvak Formations Coalbed Gas Assessment Unit, North Slope and adjacent State waters, Alaska.—Continued

Assessment Unit (name, no.)
Prince Creek-Tuluvak Formations Coalbed Gas 50010182

SELECTED ANCILLARY DATA FOR UNTESTED CELLS
(values are inherently variable)

Oil assessment unit:	minimum	mode	maximum
API gravity of oil (degrees)			
Sulfur content of oil (%)			
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum

Gas assessment unit:	minimum	mode	maximum
Inert-gas content (%)	0.01	0.20	2.00
CO_2 content (%)	0.01	0.20	2.00
Hydrogen sulfide content (%)	0.00	0.00	0.00
Heating value (BTU)	850	950	1050
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum
300	600	750	835	1100

Success ratios:	calculated mean	minimum	mode	maximum
Future success ratio (%)	40	10	40	70

Historic success ratio, tested cells (%) ______

Completion practices:
1. Typical well-completion practices (conventional, open hole, open cavity, other) ______
2. Fraction of wells drilled that are typically stimulated ______
3. Predominant type of stimulation (none, frac, acid, other) ______
4. Fraction of wells drilled that are horizontal ______

Prince Creek and Tuluvak Formations Coalbed Gas AU is estimated at a minimum of 40 acres, a mode of 100 acres, and a maximum of 200 acres (table 2). Minimum and mode acreages are identical to those applied to the Nanushuk Formation Coalbed Gas AU and reflect the potential for well interference at cell sizes less than 40 acres, as well as more optimal conditions with regard to gas recovery, dewatering considerations, and reduction (or omission) of interference between adjacent wells at a 100-acre spacing; these values are closely comparable to Powder River Basin coalbed-gas wells. The maximum estimate of 200 acres accounts to some degree for an increased drainage area if the coal beds are exceptionally continuous and permeable. Although this value is significantly less than the maximum drainage area estimates for wells producing from Ferron coals (250–280 acres), it was applied because of the potentially higher ash yields and more interbedded shale or clay (bentonite) in Prince Creek and Tuluvak coal-bearing strata (for example, see Brosgé and Whittington, 1966) that might reduce permeability relative to the Ferron coal beds.

Estimates for the percentage of the untested areas within the AU that have the potential for additions to reserves are a minimum of 0.2 percent, a mode of 5 percent, and a maximum of 14 percent (table 2). The minimum percentage focuses on the southern area of the AU, where detachment folds are present and total coal thickness below permafrost exceeds 25 ft; a small, poorly constrained area surrounding the Colville Unit 1 well (fig. 36) is included in this estimate. The minimum estimate restricts coalbed-gas potential to folded areas where structure might enhance the potential for coalbed-gas accumulation comparable to mechanisms proposed by Lamarre (2003) (fig. 26); fracture systems associated with folds might provide conduits for vertical migration of any deeply sourced gas into coal beds in the overlying rocks. The mode area includes the minimum area and additional areas extending northward to the Tertiary deformation front (limit of deformed Brookian strata; Potter and Moore, 2003) (fig. 36). Accumulation of coalbed gas might also be enhanced by subtle folds within this area. The maximum estimate for untested areas with the potential for additions to reserves includes all areas in the AU where total coal thickness below permafrost is estimated to be greater than 20 ft.

Because of low thermal maturity and the assumption that most of the coalbed-gas potential in the Prince Creek and Tuluvak Formations Coalbed Gas AU relates primarily to biogenic gas generation, estimates for the total recovery per cell of untested cells are derived solely from comparisons to EURs from coalbed-gas wells producing from the Anderson and Canyon coal beds in the Powder River Basin. A minimum EUR of 0.02 BCF was applied to untested cells, as this value is generally considered representative of the minimum gas recovery required for a successful coalbed-gas well. A median EUR of 0.1 BCF was estimated for untested cells in the AU, which is slightly less than Powder River Basin median EURs (fig. 28) based on the decreased coal-bed thickness in the Prince Creek and Tuluvak Formations compared to the Powder River Basin coals. Although no direct correlation has been made between coal thickness, gas content, and enhanced production, greater coal volumes associated with thicker coal beds should result in a greater volume of coalbed gas per unit area of land (for example, see Choate and others, 1984). Thus, volumes of gas per unit of acreage and corresponding ultimate recovery for individual wells might be less in the Prince Creek and Tuluvak Formations Coalbed Gas AU than in Powder River Basin analogs, assuming all other factors (gas content, water content, permeability, and so on) are comparable. The maximum estimate of 1.5 BCF is consistent with maximum EURs from the analog Powder River Basin wells (fig. 28).

Sagavanirktok Formation Coalbed Gas Assessment Unit

The Sagavanirktok Formation Coalbed Gas AU encompasses just over 5.6 million acres (about 8,700 mi^2) in the east-central part of the North Slope (fig. 11). The west and south boundaries represent the estimated limit of the Sagavanirktok Formation based on drill-hole data and limited outcrops (fig. 37). The northeast limit coincides with the Topset Play boundary from the USGS oil and gas assessment of ANWR (U.S. Geological Survey, ANWR Assessment Team, 1999), and the northern limit extends offshore to the boundaries of Alaskan State waters. The AU is within the Foothills and Coastal Plain physiographic provinces, and includes part of the ANWR coastal plain area. Available drill-hole data indicate that depth to the base of permafrost varies from about 900 ft to more than 2,000 ft (fig. 38).

Geologic Setting

The Sagavanirktok Formation is Paleocene–Pliocene (maybe Pleistocene; Molenaar and others, 1987) in age, and generally consists of conglomerate, sandstone, mudstone, carbonaceous shale, and abundant coal. The formation was deposited in an east- to northeast-prograding deltaic system (Molenaar, 1983) and becomes younger from southwest to northeast across the AU. Gryc and others (1951) named the Sagavanirktok Formation for exposures of coal-bearing rocks along the Sagavanirktok River at Franklin Bluffs (fig. 37), and Detterman and others (1975) later subdivided the formation into three members, in ascending order the Sagwon, Franklin Bluffs, and Nuwok Members. Mull and others (2003) revised the definition of the Sagwon Member, incorporated a newly defined White Hills Member, and revised the definition of the Franklin Bluffs Member; Nuwok Member terminology is no longer applied. As discussed previously, subsurface

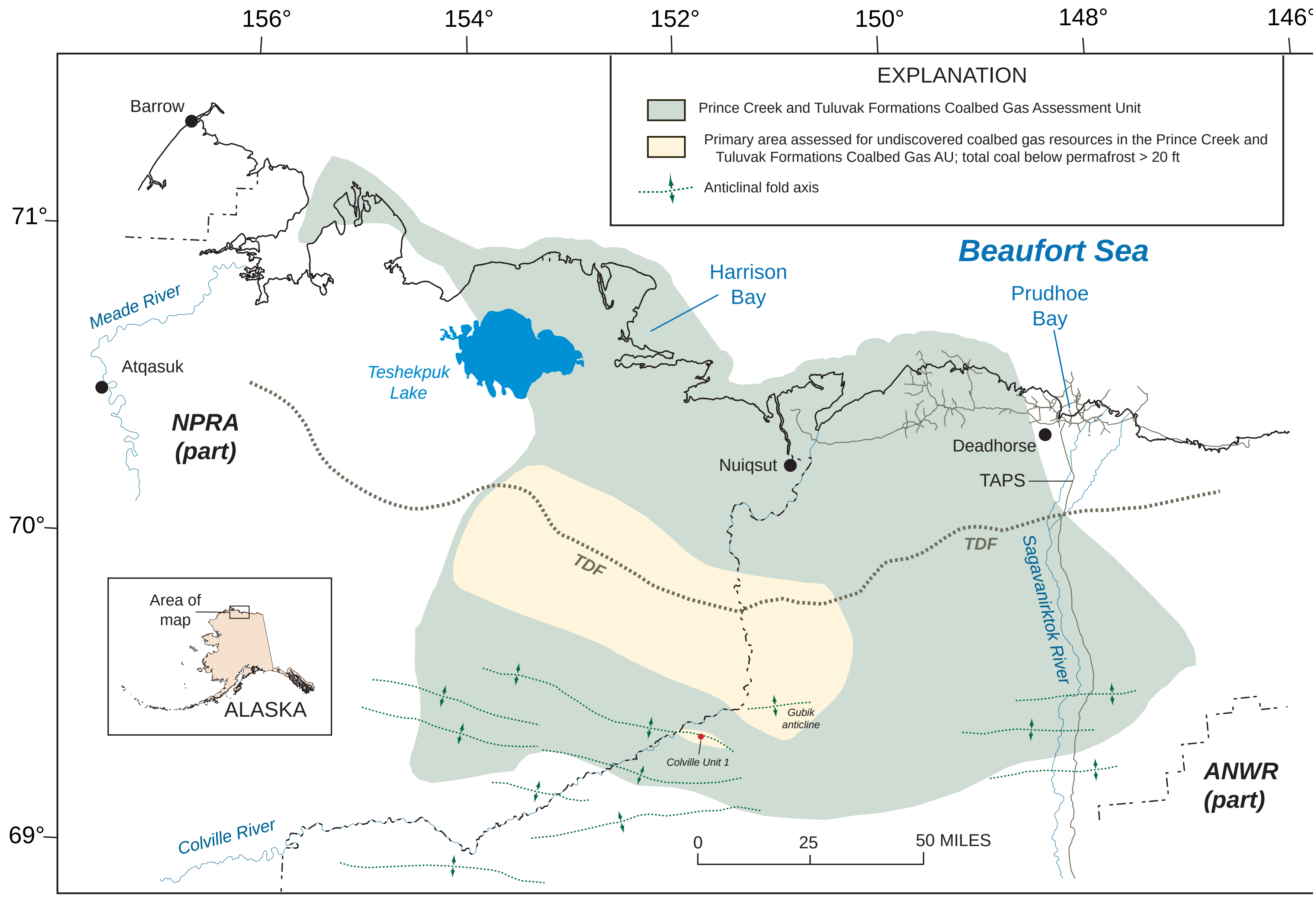


Figure 36. Map showing maximum extent of coal-bearing area assessed for coalbed-gas potential in the Prince Creek and Tuluvak Formations Coalbed Gas Assessment Unit (AU), North Slope and adjacent State waters, Alaska. Fold axes locations based on Mull (1985). TDF, Tertiary deformation front; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

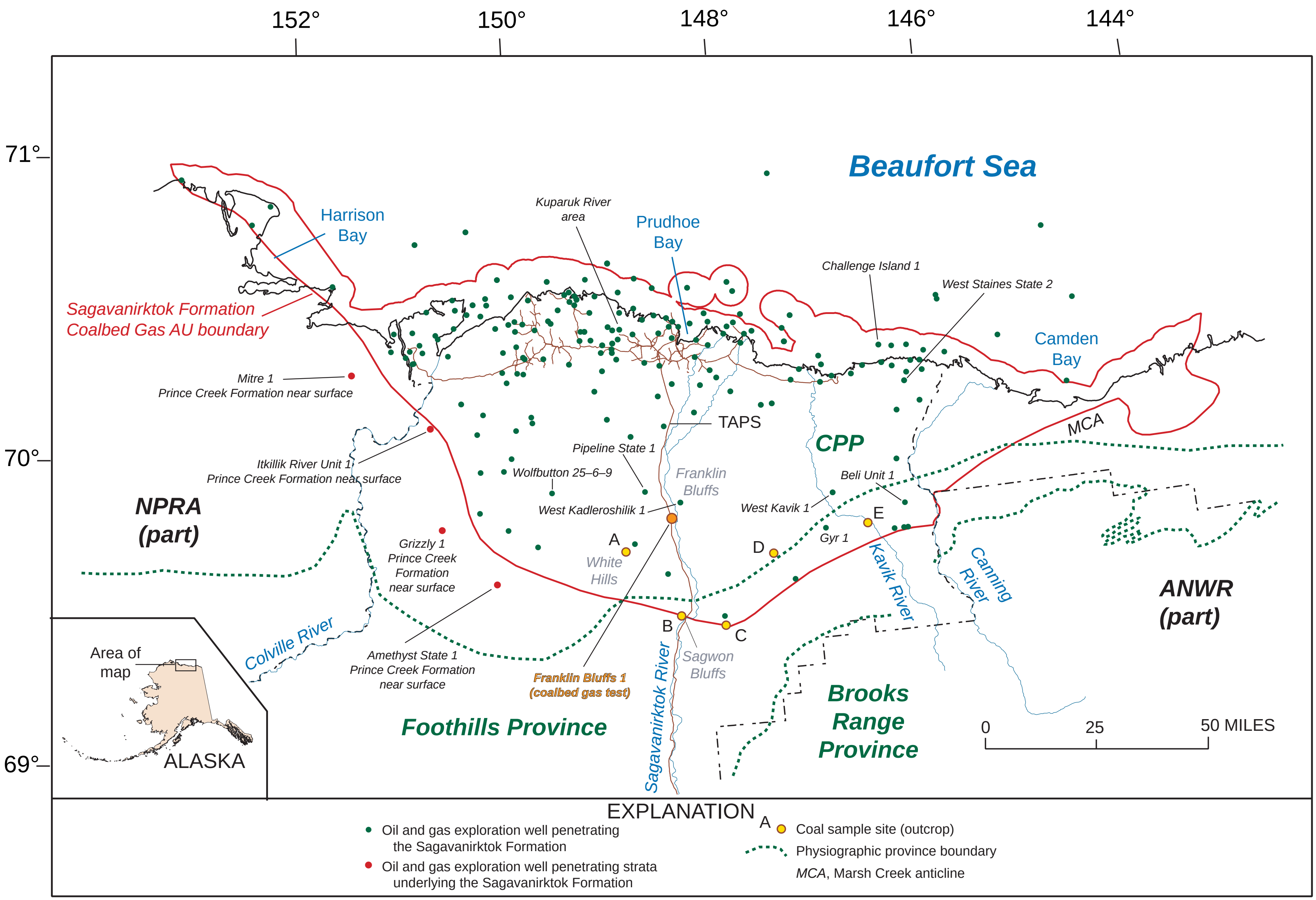


Figure 37. Map showing drill-hole locations and coal sample sites in the Sagavanirktok Formation Coalbed Gas Assessment Unit (AU), North Slope and adjacent State waters, Alaska. Physiographic province boundaries modified from Payne and others (1951). CPP, Coastal Plain Province; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

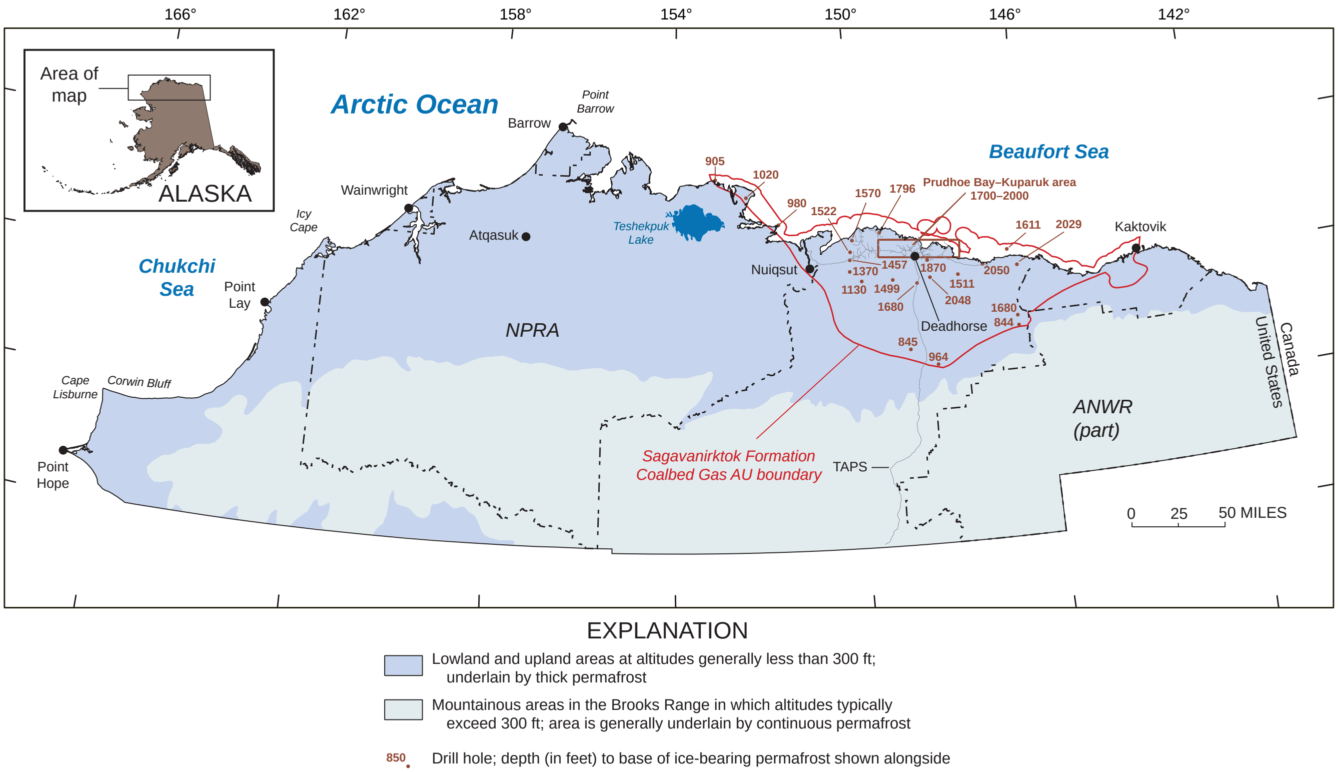


Figure 38. Map showing generalized distribution and characteristics of permafrost in upland areas of the Brooks Range and on the North Slope, Alaska, and estimated depths to the base of permafrost in the Sagavanirktok Formation Coalbed Gas Assessment Unit (AU). Permafrost depths are based on data from selected oil and gas exploration wells and represent depth from kelly bushing to base of ice-bearing permafrost. Permafrost data based on Osterkamp and Payne (1981), and Collett and others (1989). TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

nomenclature of Molenaar and others (1986, 1987) for the Sagavanirktok Formation, which subdivides the formation into a "main body" and a lower, predominantly nonmarine tongue named the Staines Tongue (inset, fig. 2), is applied in this assessment because most coal interpretations are based on subsurface data from oil and gas exploration wells. The Staines Tongue was defined in the West Staines State 2 well (fig. 37) where it is 880 ft thick (Molenaar and others, 1987). Based on available drill-hole data, the Staines Tongue ranges from about 180 ft thick in the Challenge Island 1 well to a maximum of 4,750 ft in the Pipeline State 1 well (fig. 37) (K.J. Bird, U.S. Geological Survey, written commun., 2007). The unit thickens southward and westward to where it grades laterally into the main body of the Sagavanirktok Formation. The maximum thickness of the formation, (including one or more tongues of the Canning Formation) is about 9,000 ft (Bird and Molenaar, 1987).

Structurally, most of the AU lies north of the detachment folds characteristic of the Foothills province, although some coal-bearing strata in the Sagavanirktok Formation are exposed on the limbs of anticlines along the southeast AU boundary. Generalized structure contours on top of the Staines Tongue indicate a gentle east to northeast regional dip (fig. 39). In the Kuparuk River and Prudhoe Bay areas, the Sagavanirktok Formation is cut by faults that are generally downthrown to the east, with displacements from 50 to 200 ft (Werner, 1987).

Coal Geology

The Sagavanirktok Formation contains a large volume of coal, with estimated hypothetical resources exceeding 600 billion tons (Roberts and others, 1990). The coal deposits are widespread throughout much of the central North Slope between NPRA and ANWR, extending from the Prudhoe Bay area south to Sagwon Bluffs (fig. 37). Sporadic exposures in the southern part of the AU extend over a distance of about 50 mi between the White Hills and the Kavik River. Coal beds in outcrops vary from less than 1.0 ft thick to as much as 23 ft thick and are in zones typically associated with carbonaceous shale (Roberts and others, 1991). The entire coal-bearing interval within the formation is not completely exposed at any single outcrop locality.

Coal thicknesses and depths in the subsurface were measured on geophysical logs from 133 oil and gas exploration wells within the AU; cross sections including graphic displays of geophysical logs and coal-bed thicknesses from selected wells are presented in plates 1 and 2. In general, the quality of geophysical logs used for

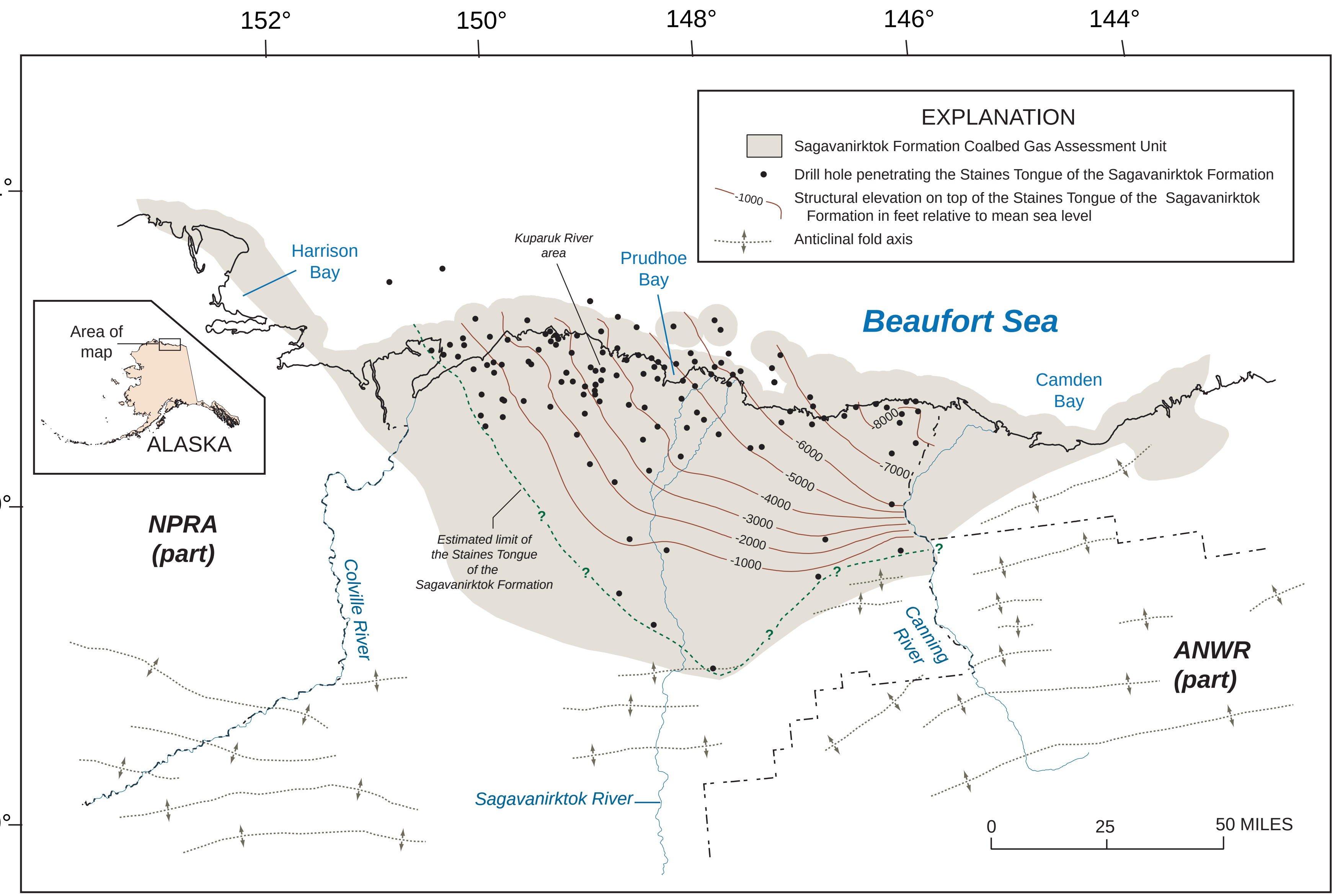


Figure 39. Map showing detachment (anticlinal) fold axes, and generalized structure contours on top of the Staines Tongue of the Sagavanirktok Formation in Sagavanirktok Formation Coalbed Gas Assessment Unit (AU), North Slope and adjacent State waters, Alaska. Fold axes locations are generalized and based on Mull (1985) and Kirschner and Rycerski, (1988). NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

interpretations of Sagavanirktok Formation coal was good, with log suites typically including bulk density and sonic logs that were particularly useful for interpreting coal depths and thicknesses. The main coal-bearing strata are within the Staines Tongue and in laterally equivalent strata within the main body of the formation where the Staines Tongue is not present (Roberts, 1991). In the southeastern part of the AU, coal is also present in a lower, unnamed tongue of the Sagavanirktok Formation that is stratigraphically below the Staines Tongue in the West Kavik 1, Gyr 1, and Beli Unit 1 wells (fig. 37) (Molenaar and others, 1986; Roberts and others, 1991); the areal extent of this tongue is not well known due to limited drill-hole data. Although coal in minor amounts has been reported throughout the upper part of the formation above the Mikkelsen Tongue of the Canning Formation (for example, Molenaar and others, 1986), no coal beds could be identified on geophysical well logs recorded through this interval. The Staines Tongue deepens to the northeast (fig. 39) and becomes thin (< 200 ft thick), approaching pinchout or erosional truncation (for comparison, see Bird and Molenaar, 1987; Houseknecht and Schenk, 1999) near the Arctic coast or just offshore; coal accumulation decreases in similar fashion with little or no coal present in the Staines Tongue along the coast or offshore in areas east of Prudhoe Bay (plate 1).

Based on drill-hole data, depth to the top of the coal-bearing interval in the Sagavanirktok Formation ranges from less than 200 ft to as much as 6,848 ft, and depth to the base of coal ranges from about 600 ft to as much as 7,054 ft. The maximum subsurface thickness of the coal-bearing interval (interval from the uppermost to lowermost coal bed), including coal beds in permafrost, is more than 3,700 ft in the Gyr 1 well (fig. 36); this value decreases to about 3,100 ft when coals in permafrost are excluded. In general, the coals are present at depths exceeding 2,000 ft throughout much of the AU, so permafrost impact is minimal in most areas. The maximum individual coal-bed thickness measured in well logs was 37 ft for all coals (Wolfbutton 25–6–9), and 34 ft for coals below permafrost (Pipeline State 1) (fig. 37). The maximum number of coal beds decreased from 33 in Gyr 1 (inclusive of coal in permafrost) to 31 in West Kavik 1 when only coals below permafrost were considered.

Generalized maps in figures 40 and 41 show, respectively, total (cumulative) coal thickness for all coal beds in the Sagavanirktok Formation and for only those coal beds identified in the formation below permafrost. Total coal accumulation is thickest in the central and south-central parts of the AU, but total coal decreases to the west, north, and east; lack of data to the south precludes the mapping of thickness trends in that area.

Analyses (equilibrium moisture basis) of coal samples collected from outcrops in the southern part of the AU (fig. 37) show that (1) the apparent rank of the coal varies from lignite A to subbituminous B (most coals are subbituminous C); (2) ash yields range from 1.2 to 47.1 percent and average about 10.9 percent; (3) total sulfur contents range from 0.08 to 2.16 percent and average about 0.39 percent; and (4) heat-of-combustion values range from 3,340 to 9,740, averaging about 7,780 Btu/lb (Roberts and others, 1988, 1991). R_o values measured from Sagavanirktok Formation coal at these same outcrops range from 0.28 to 0.48 percent (fig. 42). R_o values based on downhole reflectance profiles projected to the lowest coal bed in the Sagavanirktok Formation range from 0.33 to 0.52 percent.

Assessment Data Input and Analogs

Although there is no production of coalbed gas from the Sagavanirktok Formation, there has been limited testing for gas. In July, 2005, a shallow well (total depth 1,825 ft) was drilled west of the Sagavanirktok River near the southern end of Franklin Bluffs (fig. 37). The well included 3 cored intervals of the Staines Tongue(?) at depths from 500–722 ft, 975–1,341 ft, and 1,488–1,617 ft. Coal samples for gas desorption were recovered from each interval, and a total of ten samples were analyzed for gas content. The coal beds were typically interbedded with carbonaceous shale; the thickest coal bed sampled was 11 ft thick. Preliminary estimates of the raw gas contents were low, generally less than 5 to 10 scf/ton (C.E. Barker, U.S. Geological Survey, written commun., 2007). However, the drill hole was terminated before anticipated coals at greater depths (2,000 to 2,500 ft) could be tested, so it is not known whether (or if) higher gas contents would be encountered in the deeper coals. Lithologic logs from the Pipeline State 1 well (fig. 37), north and structurally downdip from the Franklin Bluffs 1 well indicate gas shows throughout much of the Staines Tongue coal-bearing interval, with more significant gas shows at a depth of about 3,500 ft within the lowermost coal beds in that part of the formation (plate 2).

Thermal maturities for lignite and subbituminous coal beds in the Sagavanirktok Formation (R_o values from 0.33 to 0.52 percent) are comparable to thermal maturities from Fort Union coal beds in the Powder River Basin (R_o values from 0.31 to 0.47 percent; Flores, 2004); consequently, wells producing gas from Fort Union Formation coal were again used as the primary analogs for estimates of drainage area and total recovery per cell of untested cells. As with the previous AUs, use of the Powder River Basin coal-bed analogs was restricted to the Anderson or Canyon coal beds, which commonly range from 20 to 30 ft in thickness; similar coal bed thicknesses are relatively common within the Sagavanirktok Formation. Given the low thermal maturity of Sagavanirktok coals, it is assumed that generation and retention of biogenic (microbial) gas was critical to the accumulation of coalbed-gas resources within much of the formation. However, potential for entrapment of thermogenic gas also exists in certain areas of the AU, as vertical migration of gas from source rocks at depth is evidenced by an interpreted thermogenic gas component within the interval of gas-hydrate stability in the Kuparuk River area (Collett and others, 1990) (fig. 37). Thermal maturities within the hydrate

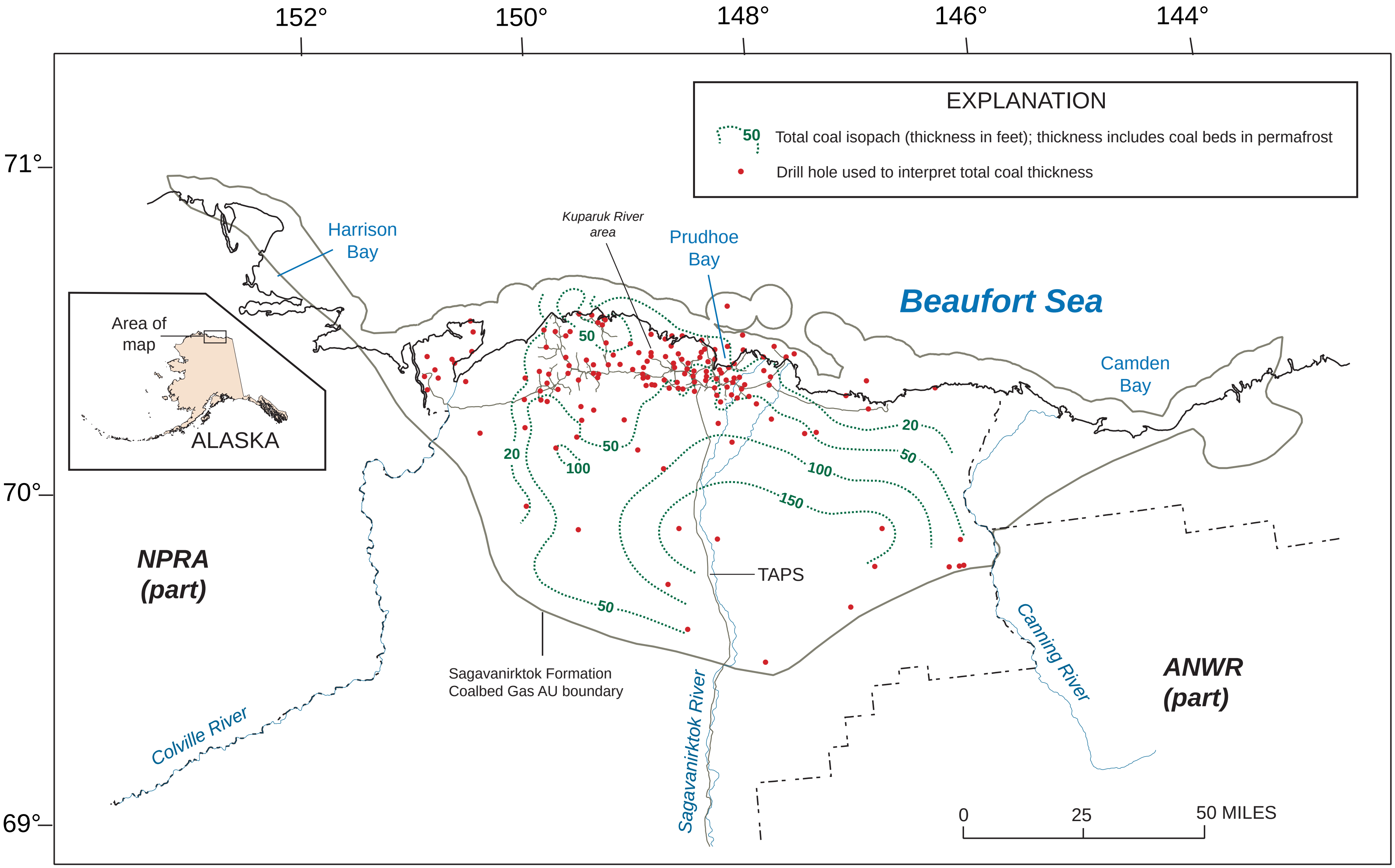


Figure 40. Map showing locations of drill holes used to evaluate coal-bed thickness and distribution and total (cumulative) coal isopachs for all coal identified in the Sagavanirktok Formation in the Sagavanirktok Formation Coalbed Gas Assessment Unit (AU), North Slope and adjacent State Waters, Alaska. TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

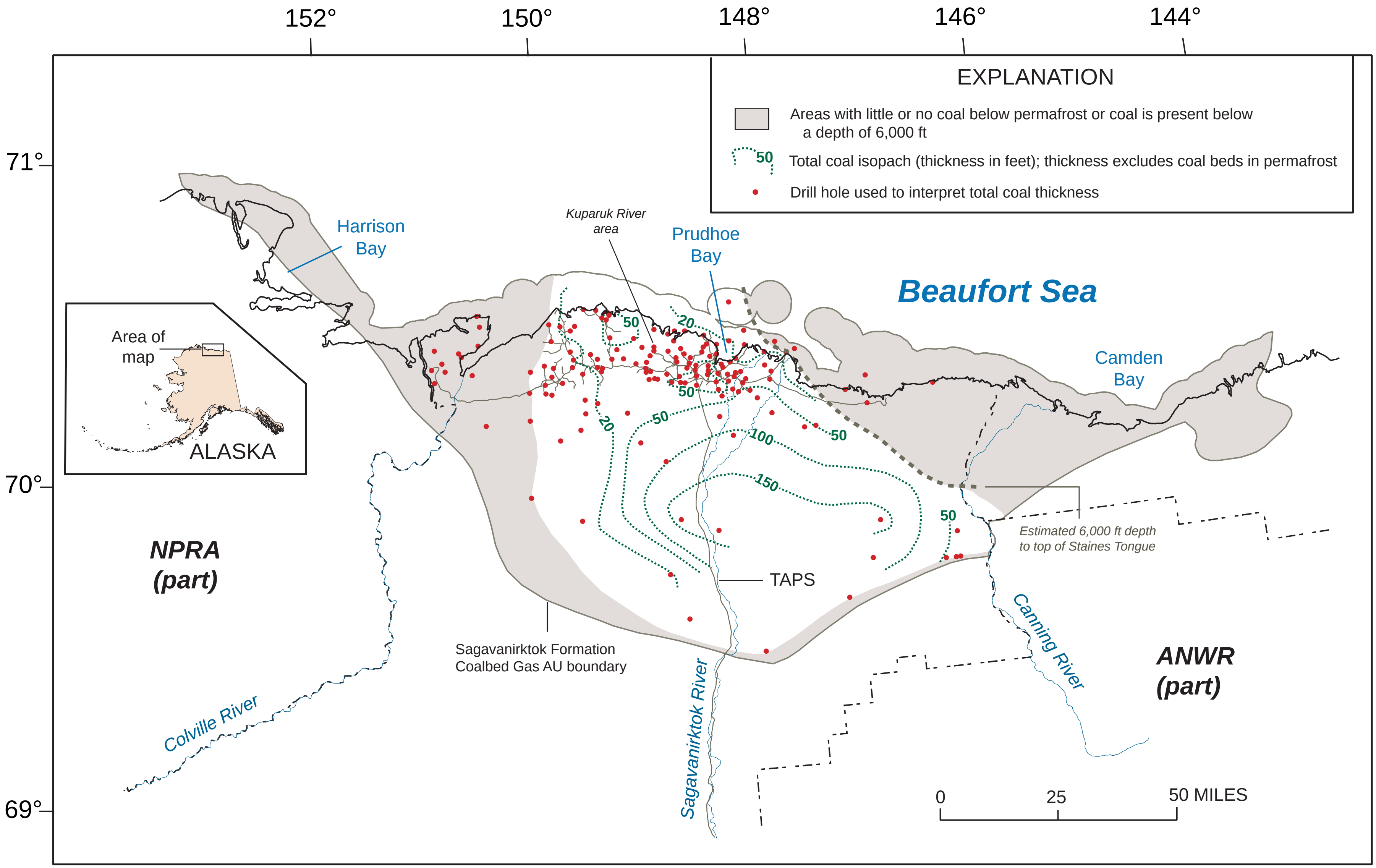


Figure 41. Map showing locations of drill holes used to evaluate coal-bed thickness and distribution and total (cumulative) coal isopachs for coal beds below base of permafrost in the Sagavanirktok Formation in the Sagavanirktok Formation Coalbed Gas Assessment Unit, North Slope and adjacent State Waters, Alaska. TAPS, Trans Alaska Pipeline System; NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

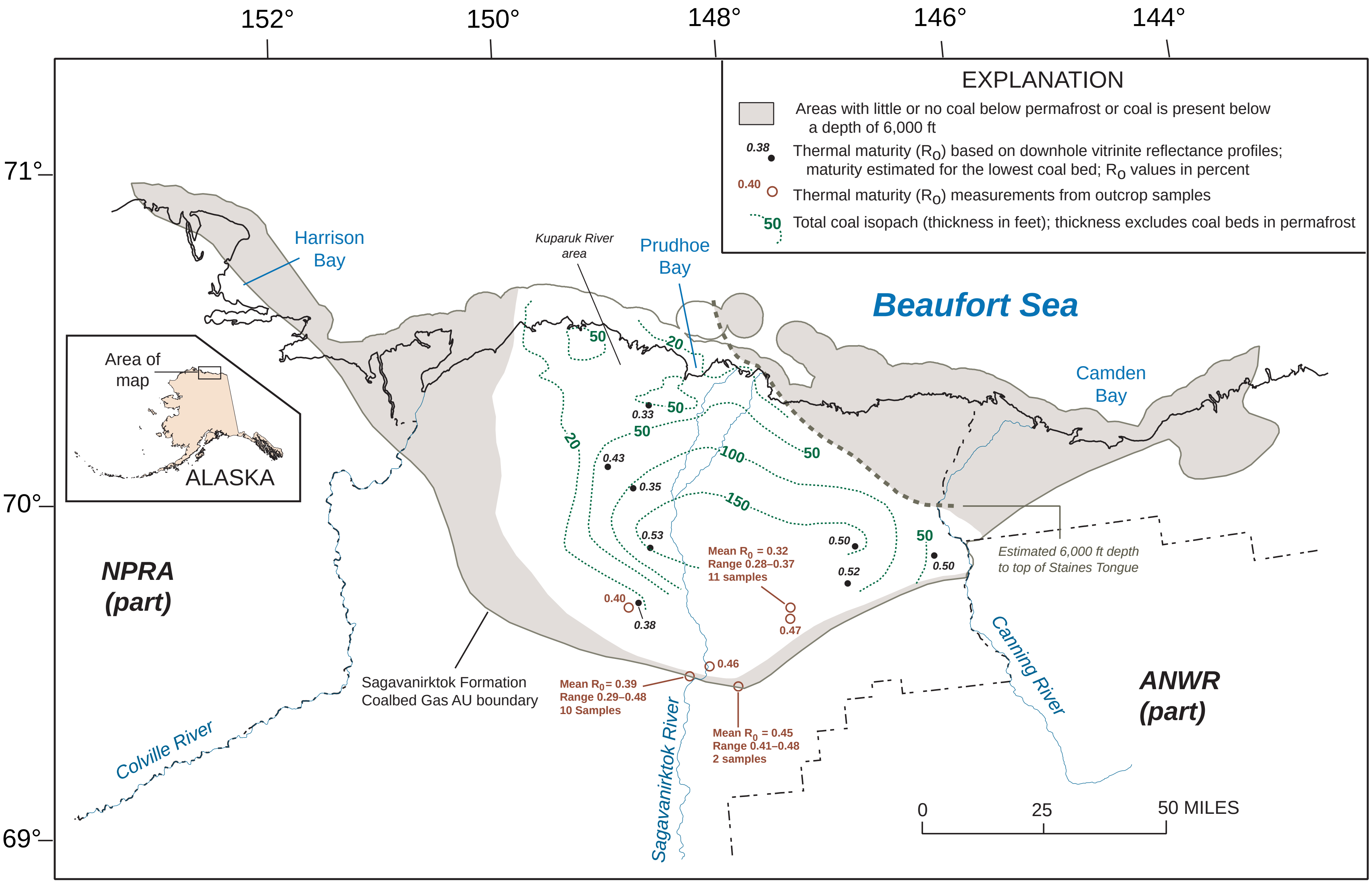


Figure 42. Map showing locations of coal outcrops sampled for vitrinite reflectance (R_0) measurements, oil and gas exploration wells with R_0 values estimated from downhole reflectance profiles, and total (cumulative) coal isopachs for coal beds below the base of permafrost in the Sagavanirktok Formation in the Sagavanirktok Formation Coalbed Gas Assessment Unit, North Slope and adjacent State Waters, Alaska. Coal outcrop sample locations and R_0 values are compiled in Johnsson and others (1999). NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

stability interval are considered too low for thermogenic gas generation and models invoking the migration of gas (and oil) from deeper source rocks through faults (fig. 43) have been proposed for petroleum accumulations in Tertiary strata in the Kuparuk River area (fig. 40) (Carman and Hardwick, 1983; Collett and others, 1990; Collett, 1993). Free gas accumulations that are trapped below the gas-hydrate stability zone have a strong probability of occurring within the Staines Tongue, which has total coal thickness values of 50 ft or more in this same area. Thus, given this potential for migration of thermogenic gas into Sagavanirktok Formation coal-bearing strata, coalbed-gas wells producing from Ferron coal beds in the Wasatch Plateau were also used as analogs, but emphasized to a lesser degree than wells producing from Fort Union coal beds.

The basic input data used for the assessment of undiscovered coalbed-gas resources in the Sagavanirktok Formation Coalbed Gas AU are shown in table 3. Based primarily on data from Powder River Basin coalbed-gas wells, the area per cell of untested cells (drainage areas) within the AU having the potential for additions to reserves are estimated at a minimum of 40 acres, a mode of 100 acres, and a maximum of 200 acres. Minimum and mode areas are identical to those applied to both the Nanushuk Formation

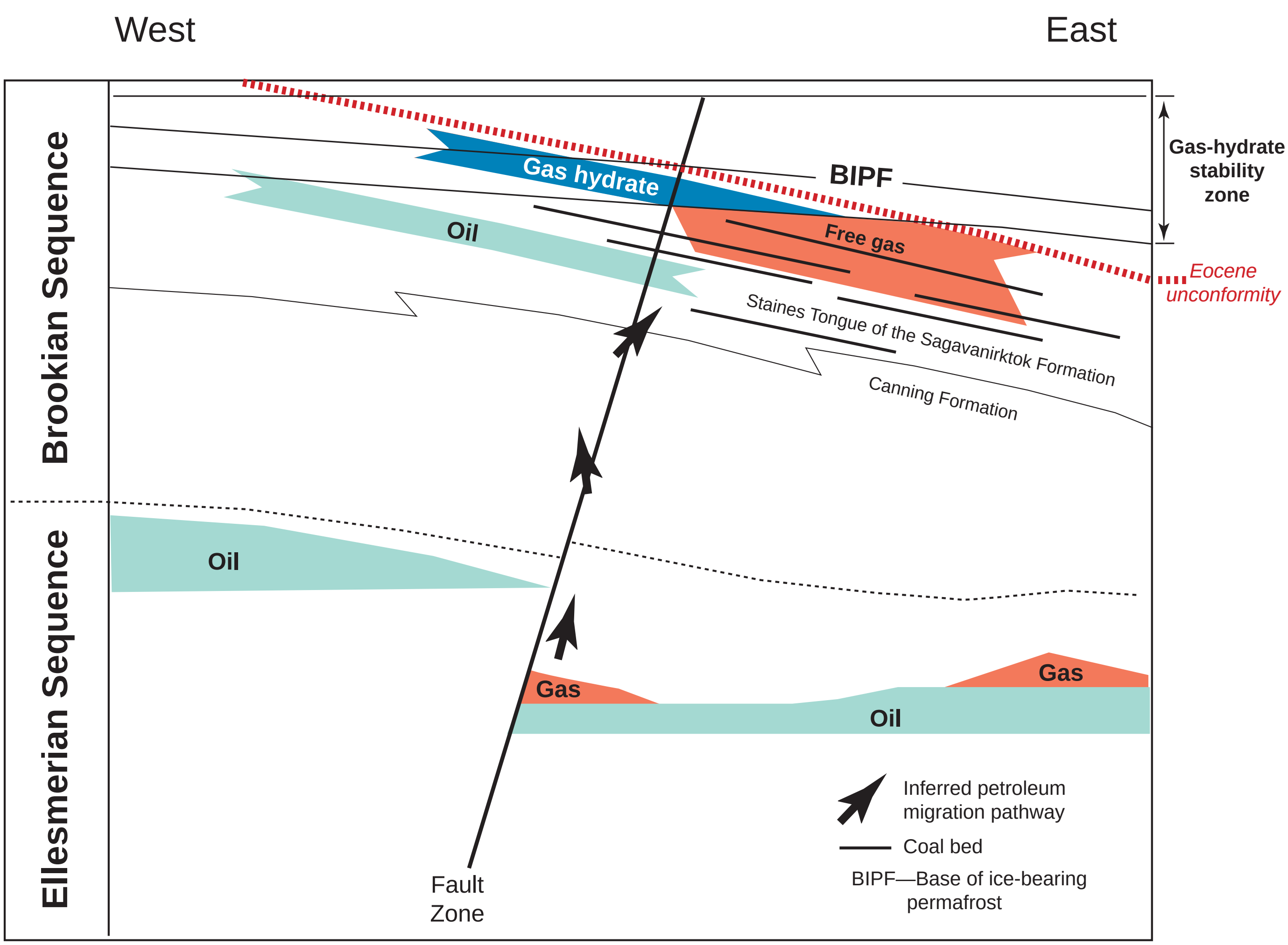


Figure 43. Schematic diagram depicting vertical migration of thermogenic gas from source rocks at depth to gas hydrate and potential coalbed-gas accumulations in the lower part of the Sagavanirktok Formation in the Kuparuk River area west of Prudhoe Bay, North Slope, Alaska. Diagram modified from Collett (1993) after Carman and Hardwick (1983).

Table 3. Basic input data form for the Sagavanirktok Formation Coalbed Gas Assessment Unit, North Slope and adjacent State waters, Alaska.

***FORSPAN* ASSESSMENT MODEL FOR CONTINUOUS ACCUMULATIONS--BASIC INPUT DATA FORM (NOGA, Version 9, 2-10-03)**

IDENTIFICATION INFORMATION

Assessment Geologist:	S.B. Roberts	Date:	6/6/2006
Region:	North America	Number:	5
Province:	Northern Alaska	Number:	5001
Total Petroleum System:	Brookian Coalbed Gas Composite	Number:	500101
Assessment Unit:	Sagavanirktok Formation Coalbed Gas	Number:	50010183
Based on Data as of:	2004 Tops File (Bird)		
Notes from Assessor:	Analogs: Upper Fort Union coal (Powder River Basin, excluding Wyodak coal bed) Limited use of Ferron analog in Milne Point and Eileen areas (potential migrated thermal gas)		

CHARACTERISTICS OF ASSESSMENT UNIT

Assessment-unit type: Oil (<20,000 cfg/bo) **or Gas** (≥20,000 cfg/bo), incl. disc. & pot. additions: Gas

What is the minimum total recovery per cell? 0.02 (mmbo for oil A.U.; bcfg for gas A.U.)

Number of tested cells: 0

Number of tested cells with total recovery per cell ≥ minimum: 0

Established (discovered cells): ______ Hypothetical (no cells): X

Median total recovery per cell (for cells ≥ min.): (mmbo for oil A.U.; bcfg for gas A.U.)

1st 3rd discovered ______ 2nd 3rd ______ 3rd 3rd ______

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an untested cell with total recovery ≥ minimum.	1.0
2. **ROCKS:** Adequate reservoirs, traps, seals for an untested cell with total recovery ≥ minimum.	1.0
3. **TIMING:** Favorable geologic timing for an untested cell with total recovery ≥ minimum.	1.0

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3): 1.0

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES

1. Total assessment-unit area (acres): (uncertainty of a fixed value)

   calculated mean 5,645,000 minimum 5,081,000 mode 5,645,000 maximum 6,210,000

2. Area per cell of untested cells having potential for additions to reserves (acres): (values are inherently variable)

   calculated mean 113 minimum 40 mode 100 maximum 200

   uncertainty of mean: minimum 60 maximum 160

3. Percentage of total assessment-unit area that is untested (%): (uncertainty of a fixed value)

   calculated mean 100 minimum 100 mode 100 maximum 100

Table 3. Basic input data form for the Sagavanirktok Formation Coalbed Gas Assessment Unit, North Slope and adjacent State waters, Alaska.—Continued

Assessment Unit (name, no.)
Sagavanirktok Formation Coalbed Gas 50010183

NO. OF UNTESTED CELLS WITH POTENTIAL FOR ADDITIONS TO RESERVES (Continued)

4. Percentage of untested assessment-unit area that has potential for additions to reserves (%):
(a necessary criterion is that total recovery per cell ≥ minimum; uncertainty of a fixed value)

calculated mean	minimum	mode	maximum
14.4	0.3	8	35

Geologic evidence for estimates:
Minimum area: Area with potential for migrated thermal gas (10% success ratio)
Modal area: Minimum area plus area where total coal > 100 ft thick (45% success ratio)
Maximum area: All areas where total coal estimated at > 20 ft (80% success ratio)

TOTAL RECOVERY PER CELL

Total recovery per cell for untested cells having potential for additions to reserves:
(values are inherently variable; mmbo for oil A.U.; bcfg for gas A.U.)

calculated mean	minimum	median	maximum
0.32	0.02	0.18	5

AVERAGE COPRODUCT RATIOS FOR UNTESTED CELLS, TO ASSESS COPRODUCTS
(uncertainty of fixed but unknown values)

Oil assessment unit:	minimum	mode	maximum
Gas/oil ratio (cfg/bo)			
NGL/gas ratio (bngl/mmcfg)			
Gas assessment unit:			
Liquids/gas ratio (bliq/mmcfg)	0	2	5

Table 3. Basic input data form for the Sagavanirktok Formation Coalbed Gas Assessment Unit, North Slope and adjacent State waters, Alaska.—Continued

Assessment Unit (name, no.)
Sagavanirktok Formation Coalbed Gas 50010183

SELECTED ANCILLARY DATA FOR UNTESTED CELLS
(values are inherently variable)

Oil assessment unit:	minimum	mode	maximum
API gravity of oil (degrees)			
Sulfur content of oil (%)			
Depth (m) of water (if applicable)			

Drilling depth (m)

minimum	F75	mode	F25	maximum

Gas assessment unit:	minimum	mode	maximum
Inert-gas content (%)	0.01	0.20	2.00
CO_2 content (%)	0.01	0.20	5.00
Hydrogen sulfide content (%)	0.00	0.00	0.00
Heating value (BTU)	850	950	1050
Depth (m) of water (if applicable)	0	10	50

Drilling depth (m)

minimum	F75	mode	F25	maximum
350	776	850	1213	1800

Success ratios:	calculated mean	minimum	mode	maximum
Future success ratio (%)	45	10	45	80

Historic success ratio, tested cells (%) ________

Completion practices:

1. Typical well-completion practices (conventional, open hole, open cavity, other) ________
2. Fraction of wells drilled that are typically stimulated ________
3. Predominant type of stimulation (none, frac, acid, other) ________
4. Fraction of wells drilled that are horizontal ________

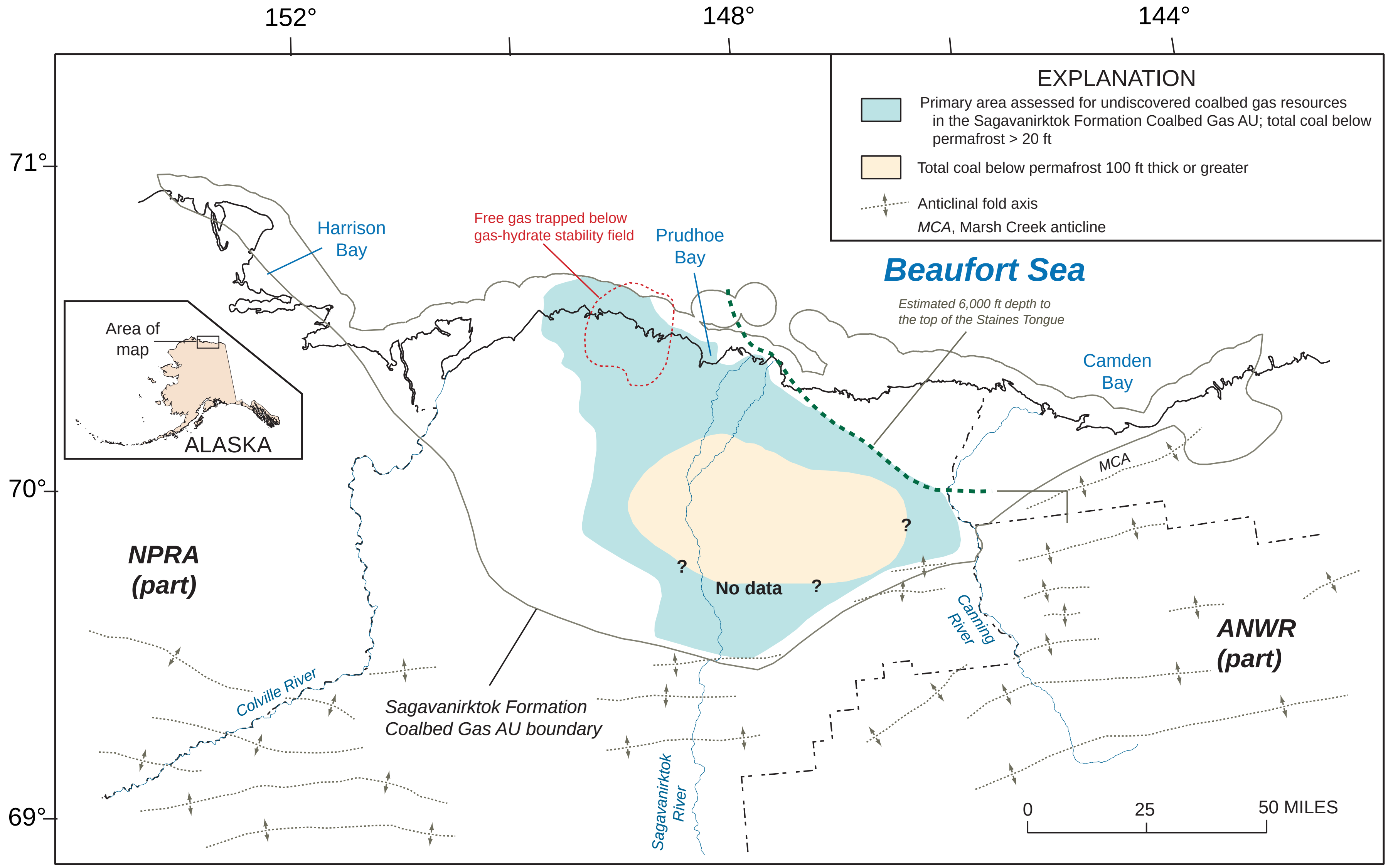


Figure 44. Map showing maximum extent of coal-bearing area assessed for coalbed-gas potential in the Sagavanirktok Formation Coalbed Gas Assessment Unit (AU), North Slope and adjacent State waters, Alaska. Fold axes locations based on Mull (1985). NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

and Prince Creek and Tuluvak Formations Coalbed Gas AUs and reflect (1) the potential for well interference at cell sizes of less than 40 acres; and (2) more optimal conditions with regard to gas recovery, dewatering considerations, and reduction (or omission) of interference between adjacent wells at a 100-acre spacing. The maximum estimate of 200 acres is less than mode drainage area estimates for wells producing from Ferron coals (250–280 acres) because, similar to coal beds in the Tuluvak and Prince Creek Formations, coal beds in the Sagavanirktok Formation as observed in outcrops and limited cores commonly are in zones including carbonaceous shale; this factor could effectively reduce drainage areas relative to wells producing from Ferron coals.

Estimates for the percentage of the untested areas within the AU that have the potential for additions to reserves are a minimum of 0.3 percent, a mode of 8 percent, and a maximum of 35 percent (table 3). The minimum percentage focuses on the Kuparuk River area where faults might provide conduits for vertical migration of thermogenic gas to free gas accumulations associated with coal-bearing strata in the Staines Tongue below the gas-hydrate stability zone (fig. 44). The mode area includes the minimum area and additional areas where total coal thickness below permafrost in the Sagavanirktok Formation exceeds 100 ft. The maximum estimate for untested areas with the potential for additions to reserves includes all areas in the AU where total coal thickness below permafrost is estimated to be greater than 20 ft.

Estimates of total recovery per cell in the Sagavanirktok Formation Coalbed Gas AU are also based largely on Powder River Basin analog wells. A minimum EUR of 0.02 BCF was applied to untested cells (table 3), which is generally considered representative of the minimum gas recovery required for a successful well. A median EUR of 0.18 BCF was applied to untested cells in the AU; this estimate is skewed toward Powder River Basin median EURs because thermal maturities in Sagavanirktok Formation coal beds (fig. 42) are not sufficient to generate significant thermogenic gas. This factor might reduce the potential for median recoveries at the overall level of EURs in wells producing from Ferron coal beds that contain a significant component of thermogenic gas. The maximum EUR of 5 BCF, however, is higher than maximum EURs for Powder River Basin wells (fig. 28), and relates more closely to maximum EURs from Ferron coalbed-gas wells (Helper Field, Utah) (fig. 29) because of the potential for thermogenic gas in coal beds in the Staines Tongue in the Kuparuk River area as described in the previous section.

Assessment of Coalbed Gas Resources—Summary of Results

Tabulated estimates of undiscovered coalbed gas and natural gas liquid resources for assessment units in the Brookian Coalbed Gas Composite TPS are shown in table 4. Because of the greater potential for a wetter and heavier thermogenic gas component within the Nanushuk and Sagavanirktok Formation Coalbed Gas AUs, volumes of natural gas liquids have been calculated. Conversely, coalbed-gas potential within the Prince Creek and Tuluvak Formations Coalbed Gas AU is presumed to relate primarily to biogenic gas generation and retention, and no estimates of natural gas liquid volumes are included in the tabulated resources. The combined, mean total estimate of undiscovered coalbed-gas resources in the three AUs is 18 trillion cubic feet (TCF). About 84 percent (15 TCF) is estimated to be in the Nanushuk Formation, about 12 percent (2.2 TCF) is in the Sagavanirktok Formation, and about 4 percent (0.8 TCF) is in the Prince Creek and Tuluvak Formations (table 4).

The potential for coalbed-gas resources in the Nanushuk Formation is enhanced by the widespread distribution and large volume of coal within the formation, and the fact that coal-bed thermal maturities are high enough (R_o = 0.70 percent or greater) for the generation of thermogenic as well as biogenic (microbial) gas over a fairly large area, including the foothills fold belt where structure could aid in trapping gas. In addition, testing for coalbed gas in the Nanushuk Formation in the village of Wainwright has verified the presence of gas in coal beds, at least locally, with raw gas contents at levels comparable to or even exceeding gas contents in coal beds in the Powder River Basin in Wyoming. Although the Sagavanirktok Formation also includes a significant volume of coal, the generally low thermal maturity of the coal beds (R_o < 0.60 percent) likely precludes the potential generation of thermogenic gas within the formation. Thus, it would seem that much of the Sagavanirktok Formation coalbed-gas potential relies on biogenic gas generation, with some possibility of a thermogenic gas component that has migrated into coal beds from older and more deeply buried non-coal source rocks in the Kuparuk River area to the west of Prudhoe Bay. The potential for coalbed-gas resources in the Prince Creek and Tuluvak Formations is lessened by having low thermal maturity and significantly smaller accumulations of coal, particularly below permafrost, relative to the Nanushuk and Sagavanirktok Formations.

Table 4. Alaska North Slope: Coalbed gas resource assessment results.

Results shown are fully risked estimates. F95 denotes a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. TPS, total petroleum system; AU, assessment unit; CBG, coalbed gas. BCFG, billion cubic feet of gas; MMBL, million barrels of natural gas liquids.

Total Petroleum Systems (TPS) and Coalbed Gas Assessment Units (AU)	Field type	Total undiscovered resources: Gas (BCFG)				Total undiscovered resources: Liquids (MMBL)			
		F95	F50	F5	Mean	F95	F50	F5	Mean
Brookian Coalbed Gas Composite TPS									
Nanushuk Formation AU	CBG	5,834	13,279	30,225	15,047	10	28	83	35
Prince Creek-Tuluvak Formations AU	CBG	350	709	1,436	778	0	0	0	0
Sagavanirktok Formation AU	CBG	889	1,981	4,416	2,231	1	4	12	5
Total Undiscovered Oil and Gas Resources		**7,073**	**15,969**	**36,077**	**18,056**	**11**	**32**	**95**	**40**

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Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).

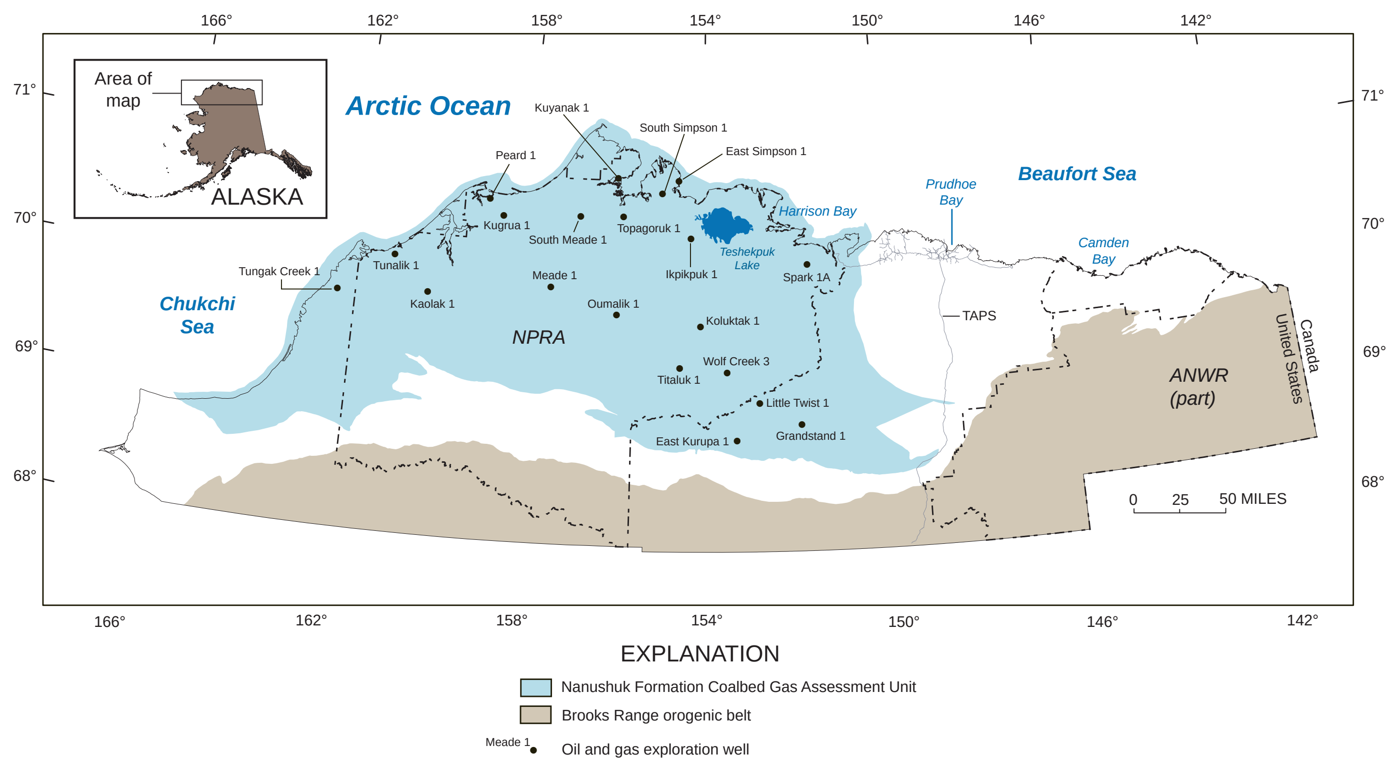

Figure 1–1. Map showing locations of oil and gas exploration wells used in total (cumulative) coal thickness interpretations for the Nanushuk Formation, North Slope, Alaska. NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

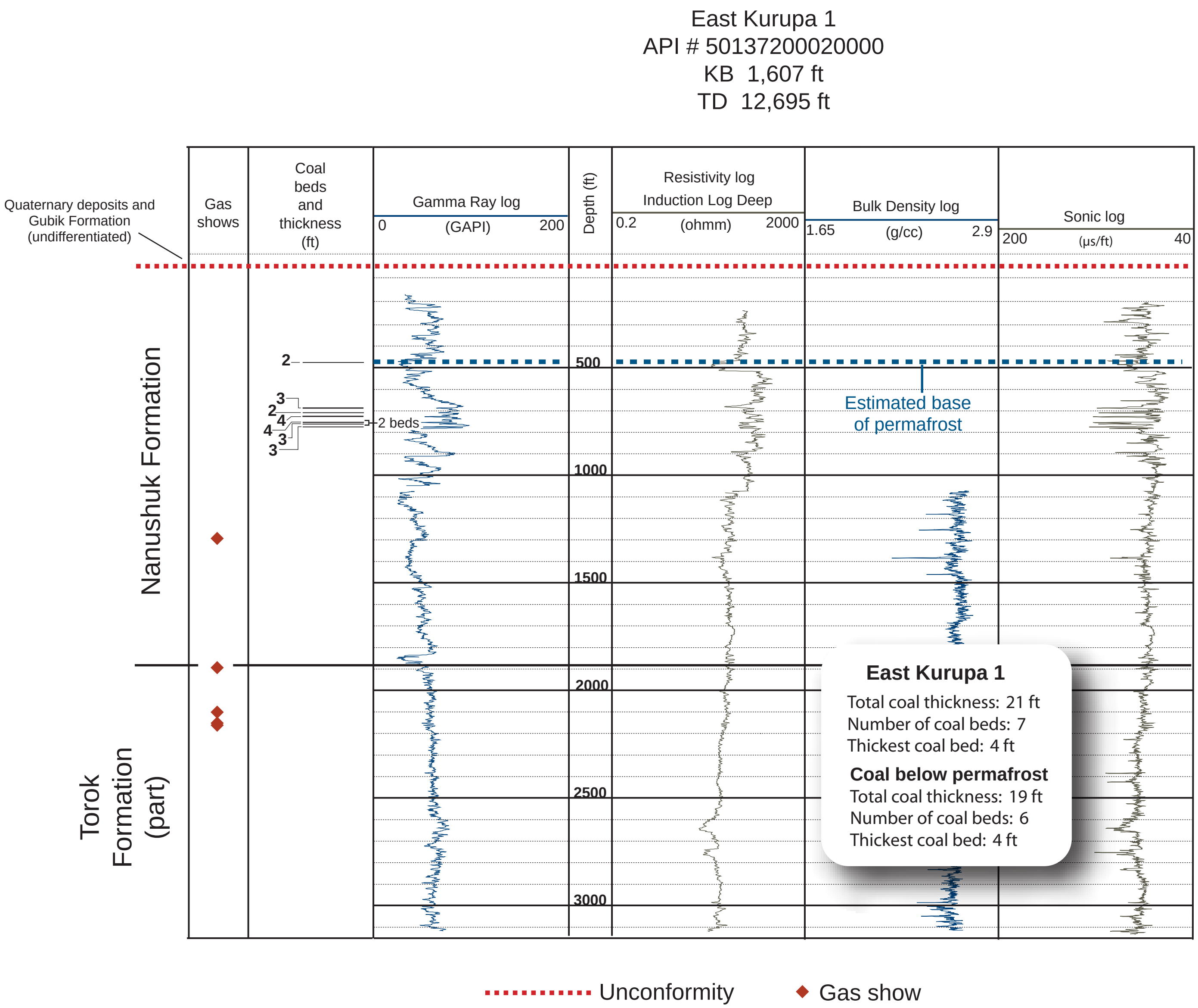

Figure 1–2. Geophysical log traces, net coal thickness (in feet), permafrost depth, and gas shows in the Nanushuk and Torok Formations in the upper part of the East Kurupa 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 1–1. Permafrost depth is from Collett and others (1989), and represents the depth from the kelly bushing to the base of ice-bearing permafrost. KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; g/cc, grams per cubic centimeter, µs/ft, microseconds per foot.

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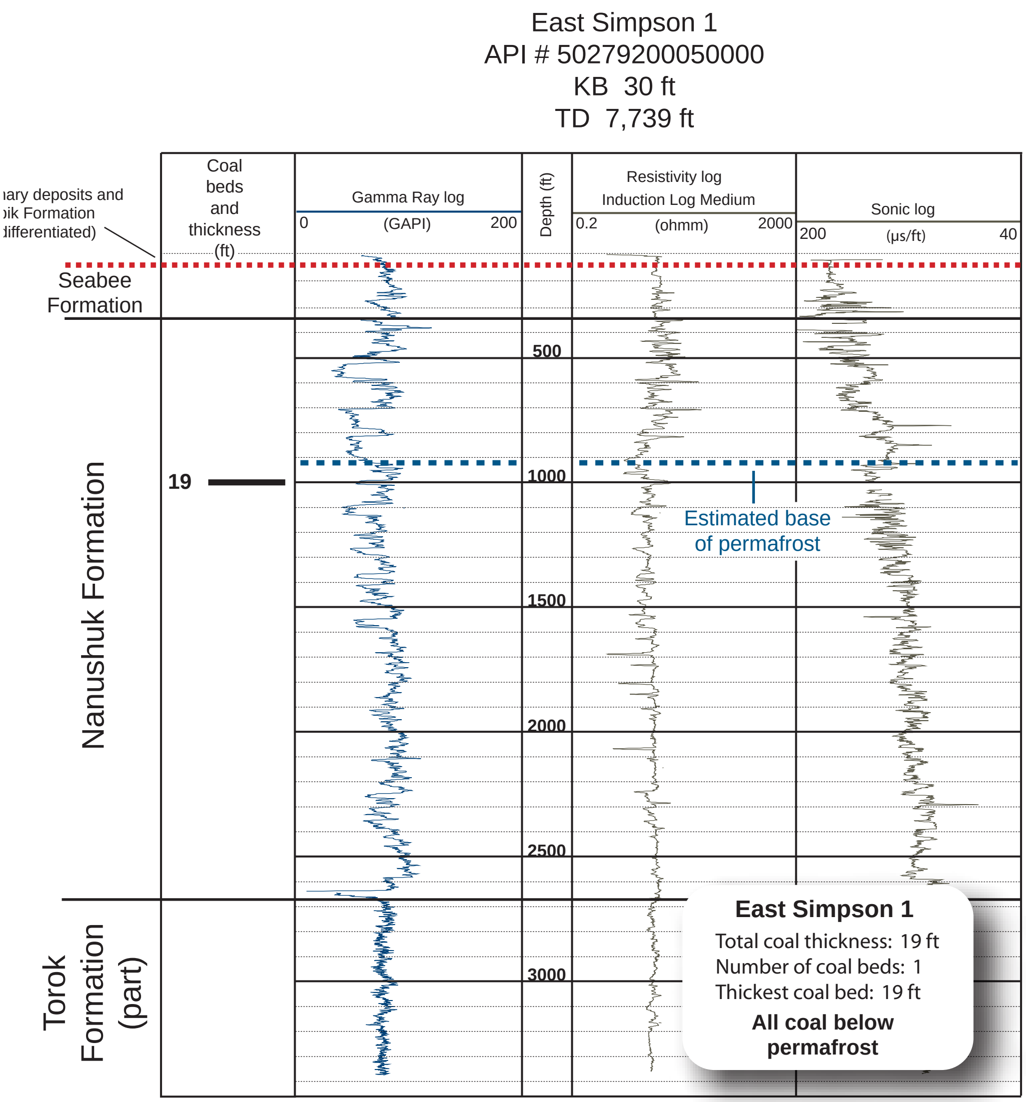

Figure 1–3. Geophysical log traces, net coal thickness (in feet), and permafrost depth in the Nanushuk Formation in the upper part of the East Simpson 1 oil and gas exploration well, North Slope, Alaska. Permafrost depth is from Lachenbruch and others (1987), and represents the depth from the ground surface to the base of the ice-rich layer. Coal interpretations from Magoon and others (1988). Location of well shown in figure 1–1. KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; µs/ft, microseconds per foot.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

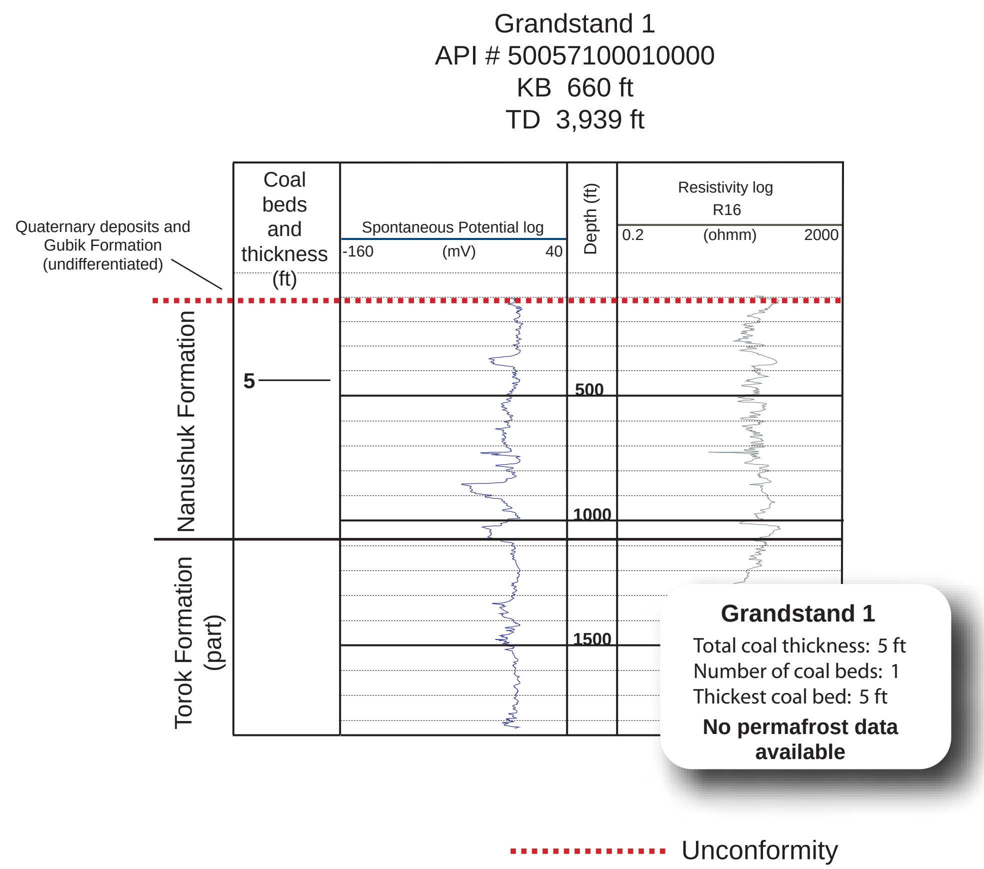

Figure 1–4. Geophysical log traces and net coal thickness (in feet) in the Nanushuk Formation in the upper part of the Grandstand 1 oil and gas exploration well, North Slope, Alaska. Coal interpretations from Magoon and others (1988). Location of well shown in figure 1–1. KB, kelly bushing; TD, total depth; mV, millivolts; ohmm, ohm-meters.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

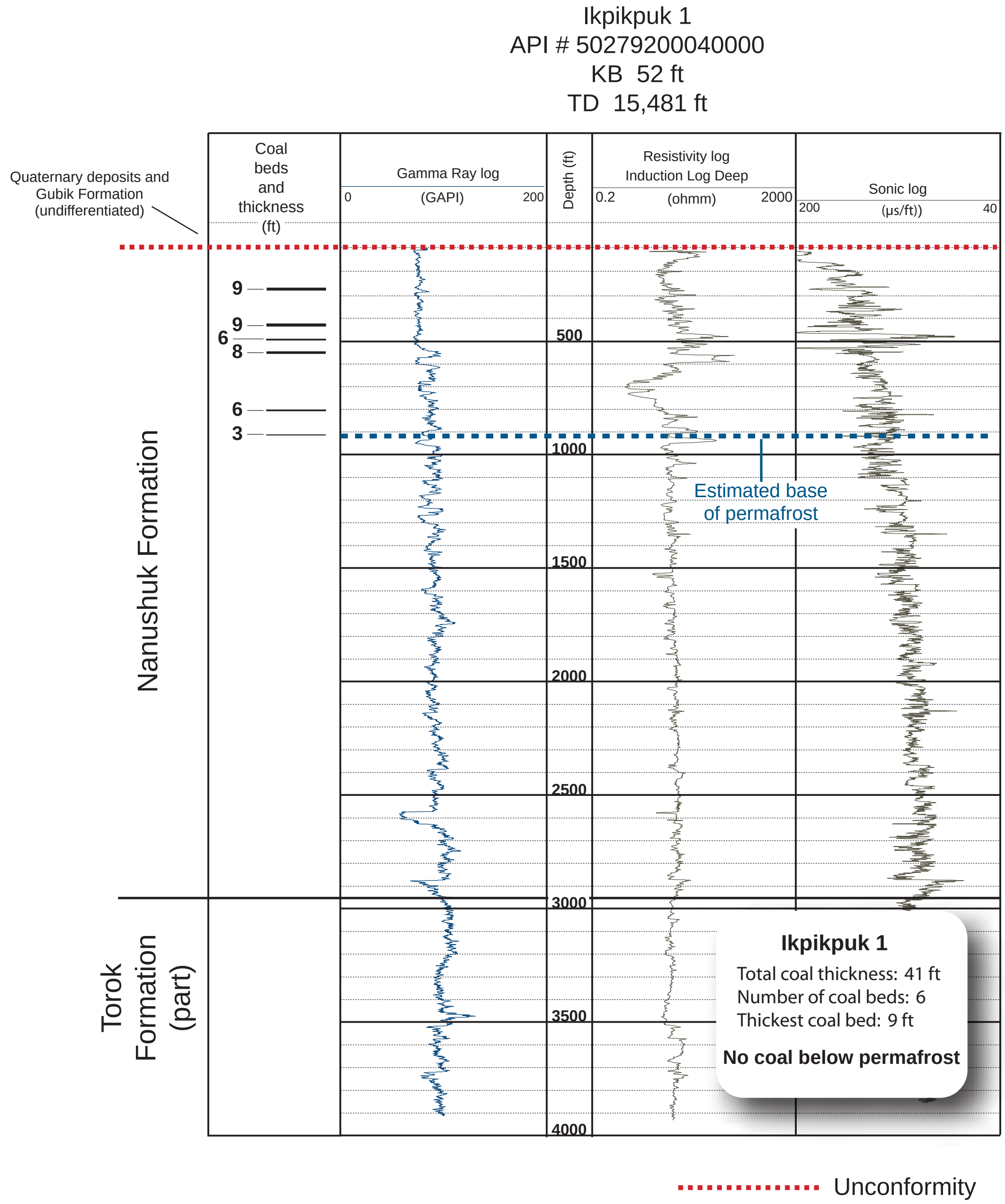

Figure 1–5. Geophysical log traces, net coal thickness (in feet), and permafrost depth in the Nanushuk Formation in the upper part of the Ikpikpuk 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 1–1. Permafrost depth is from Lachenbruch and others (1987), and represents the depth from the ground surface to the base of the ice-rich layer. KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; µs/ft, microseconds per foot.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

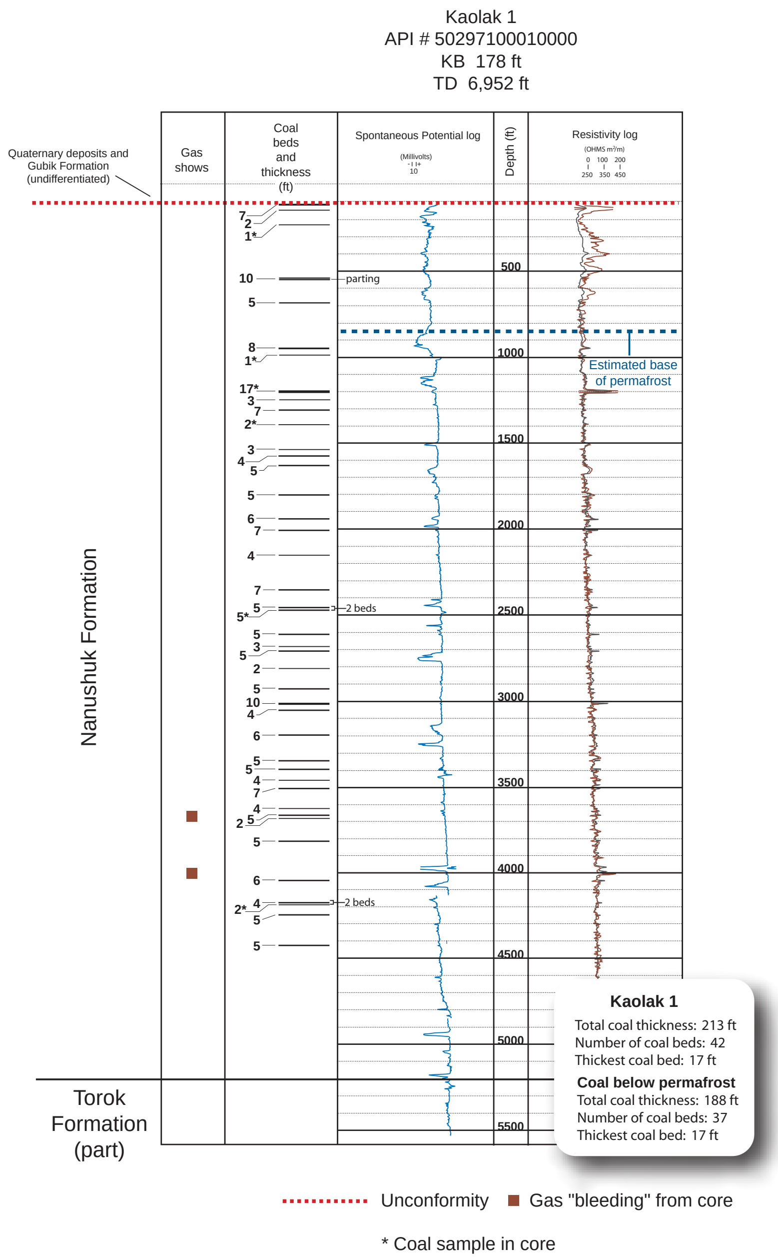

Figure 1–6. Geophysical log traces, net coal thickness (in feet), permafrost depth, and cored interval with evidence of gas in the Nanushuk Formation in the Kaolak 1 oil and gas exploration well, North Slope, Alaska. Permafrost depth based on Ferrians, Jr. (1965) and Osterkamp and Payne (1981), and represents the depth from the kelly bushing to the base of ice-bearing permafrost. Location of well shown in figure 1–1. KB, kelly bushing; TD, total depth.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

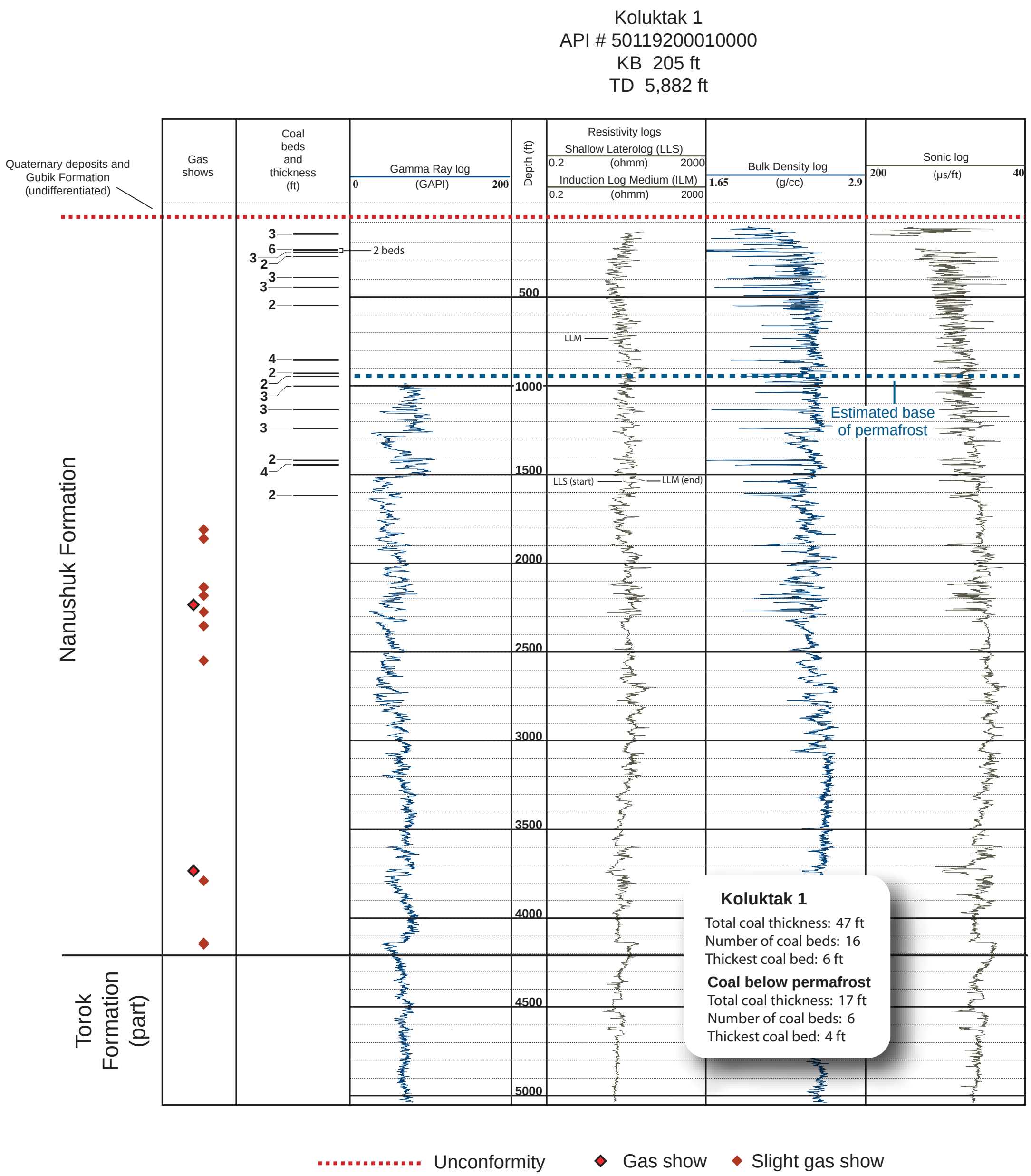

Figure 1–7. Geophysical log traces, net coal thickness (in feet), permafrost depth, and gas shows in the Nanushuk Formation in the upper part of the Koluktak 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 1–1. Permafrost depth is from Lachenbruch and others (1987), and represents the depth from the ground surface to a temperature of 0°C. KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; g/cc, grams per cubic centimeter, µs/ft, microseconds per foot.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0˚C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

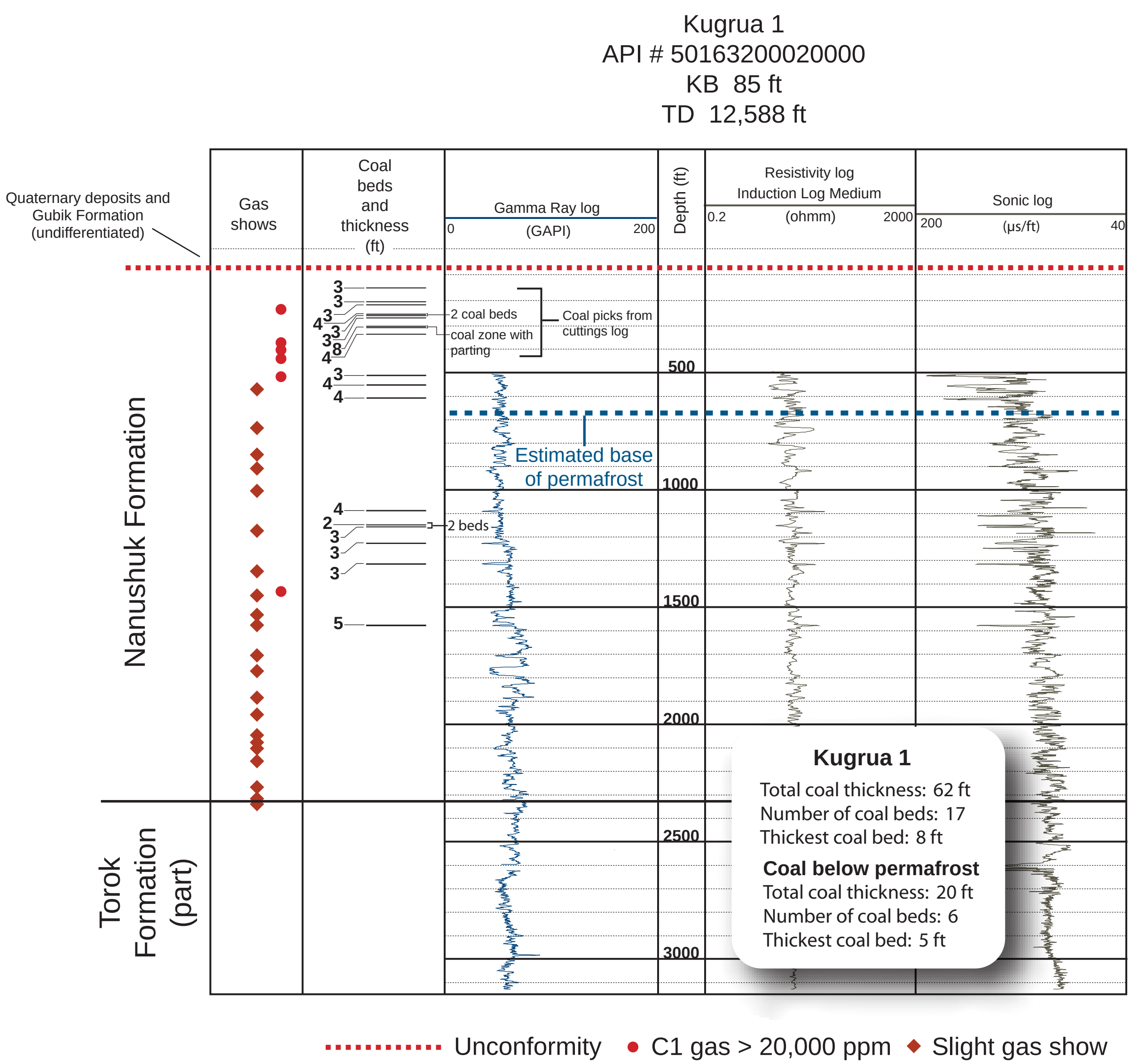

Figure 1–8. Geophysical log traces, net coal thickness (in feet), permafrost depth, and gas shows in the Nanushuk Formation in the upper part of the Kugrua 1 oil and gas exploration well, North Slope, Alaska. Permafrost depth based on Osterkamp and Payne (1981) and Lachenbruch and others (1987), and represents the estimated depth from the kelly bushing to the base of ice-bearing permafrost. Location of well shown in figure 1–1. C1, methane gas; ppm, parts per million; KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; µs/ft, microseconds per foot.

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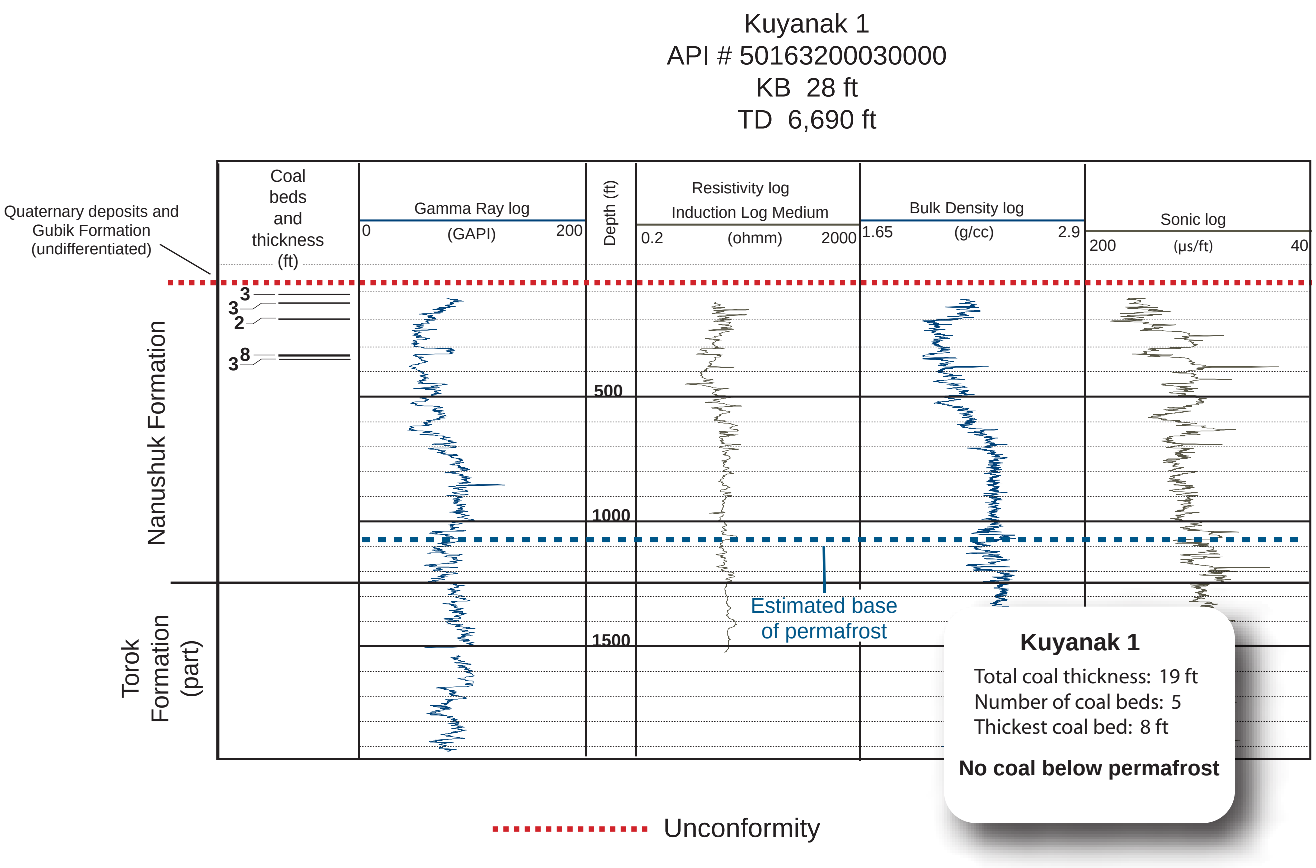

Figure 1–9. Geophysical log traces, net coal thickness (in feet), and permafrost depth in the Nanushuk Formation in the upper part of the Kuyanak 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 1–1. Permafrost depth from Lachenbruch and others (1987), and represents the depth from the ground surface to a temperature of 0°C. KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; g/cc, grams per cubic centimeter, µs/ft, microseconds per foot.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

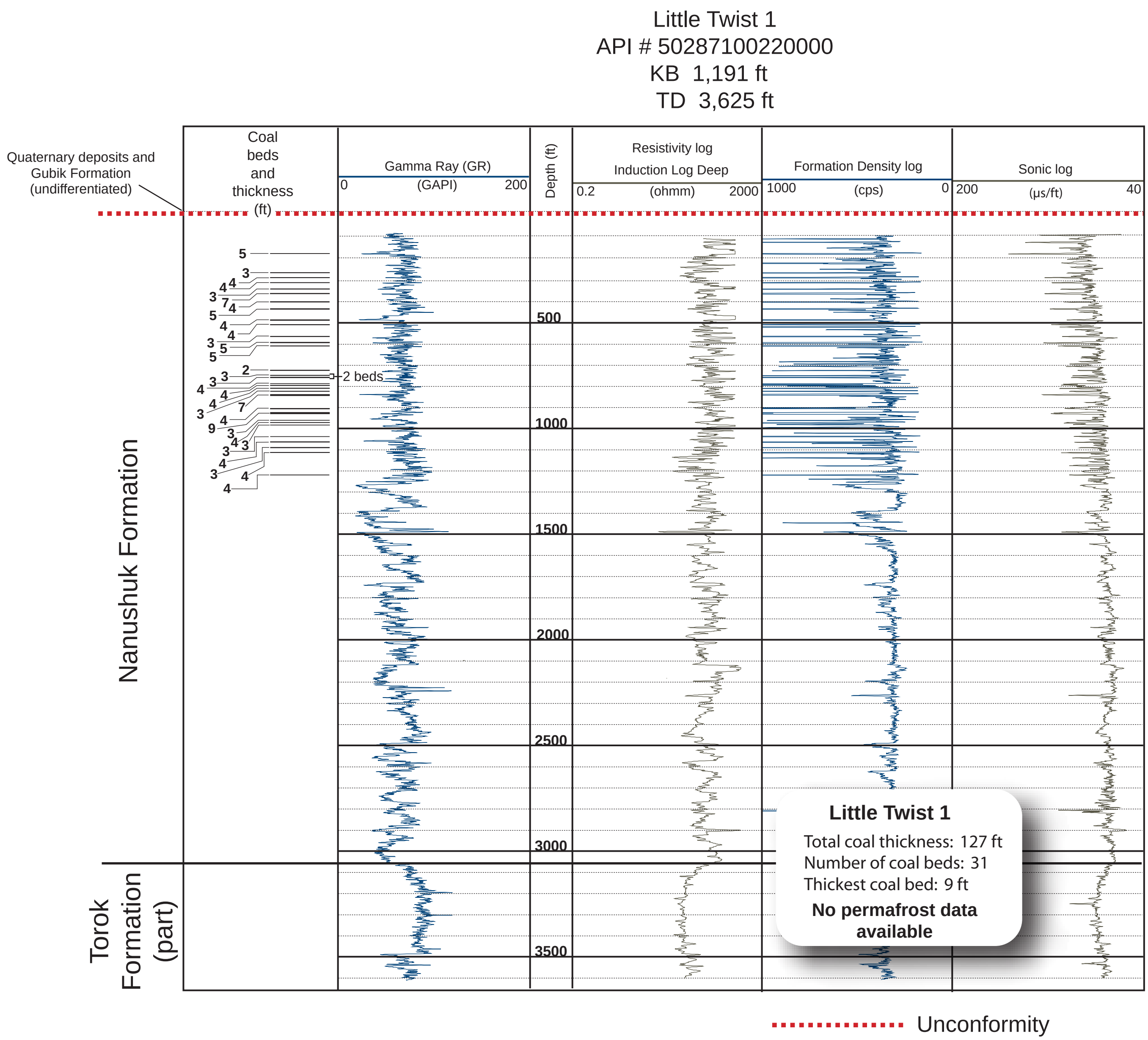

Figure 1–10. Geophysical log traces and net coal thickness (in feet) in the Nanushuk Formation in the upper part of the Little Twist 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 1–1. KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; cps, counts per second, µs/ft, microseconds per foot.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

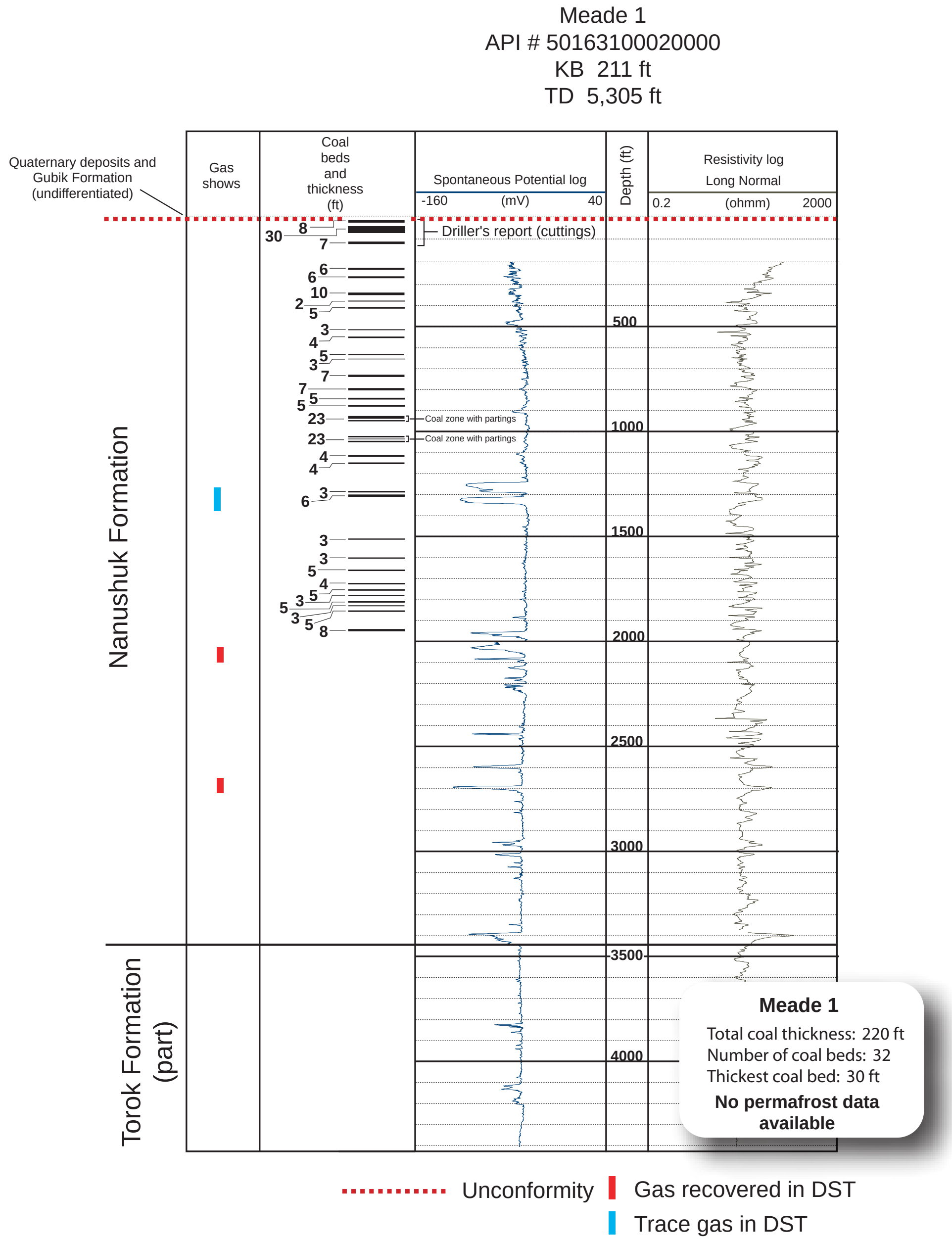

Figure 1–11. Geophysical log traces, net coal thickness (in feet), and gas shows in the Nanushuk Formation in the upper part of the Meade 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 1–1. KB, kelly bushing; TD, total depth; mV, millivolts; ohmm, ohm-meters; DST, drill-stem test.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0˚C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

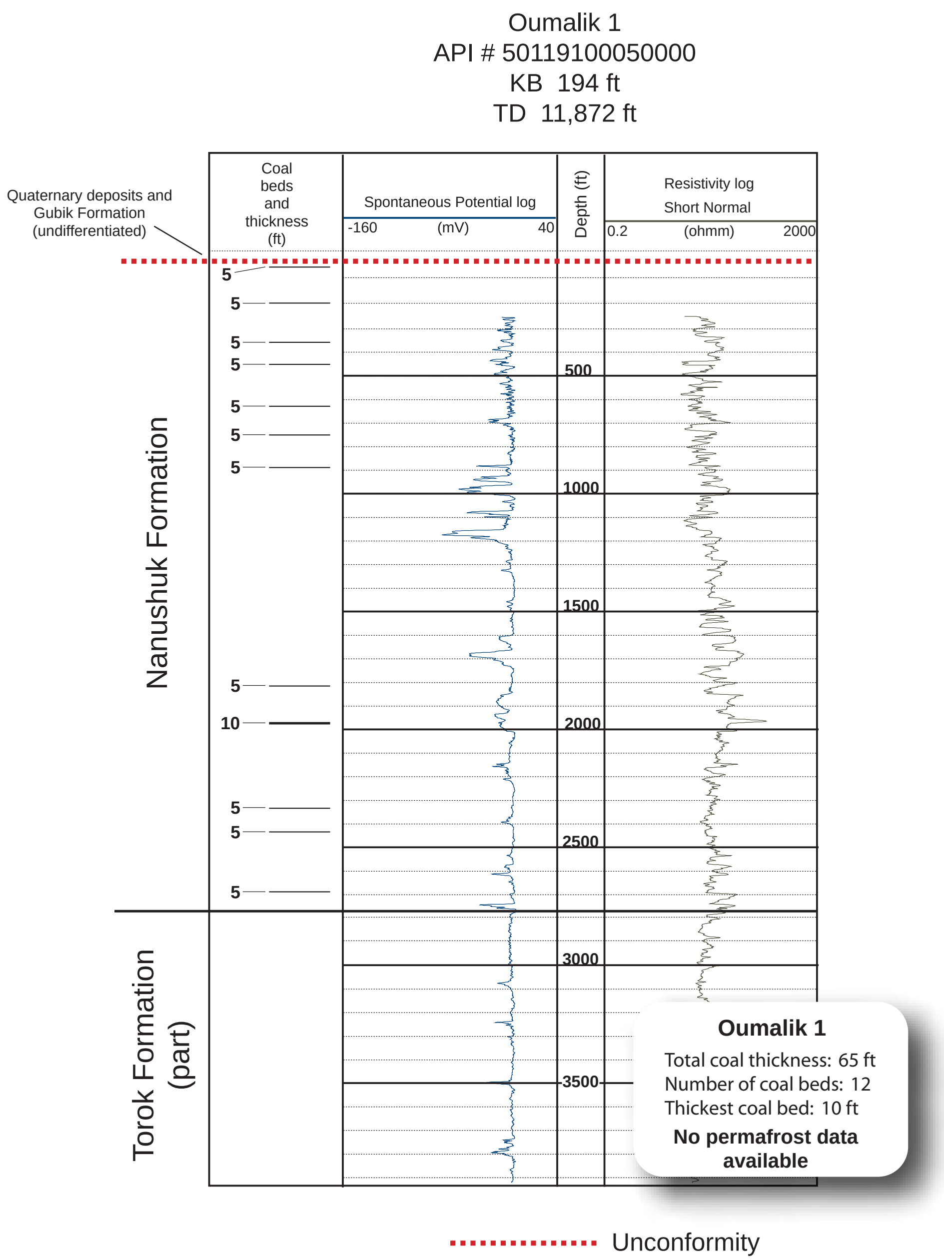

Figure 1–12. Geophysical log traces and net coal thickness (in feet) in the Nanushuk Formation in the upper part of the Oumalik 1 oil and gas exploration well, North Slope, Alaska. Coal interpretations from Magoon and others (1988). Location of well shown in figure 1–1. KB, kelly bushing; TD, total depth; mV, millivolts; ohmm, ohm-meters.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

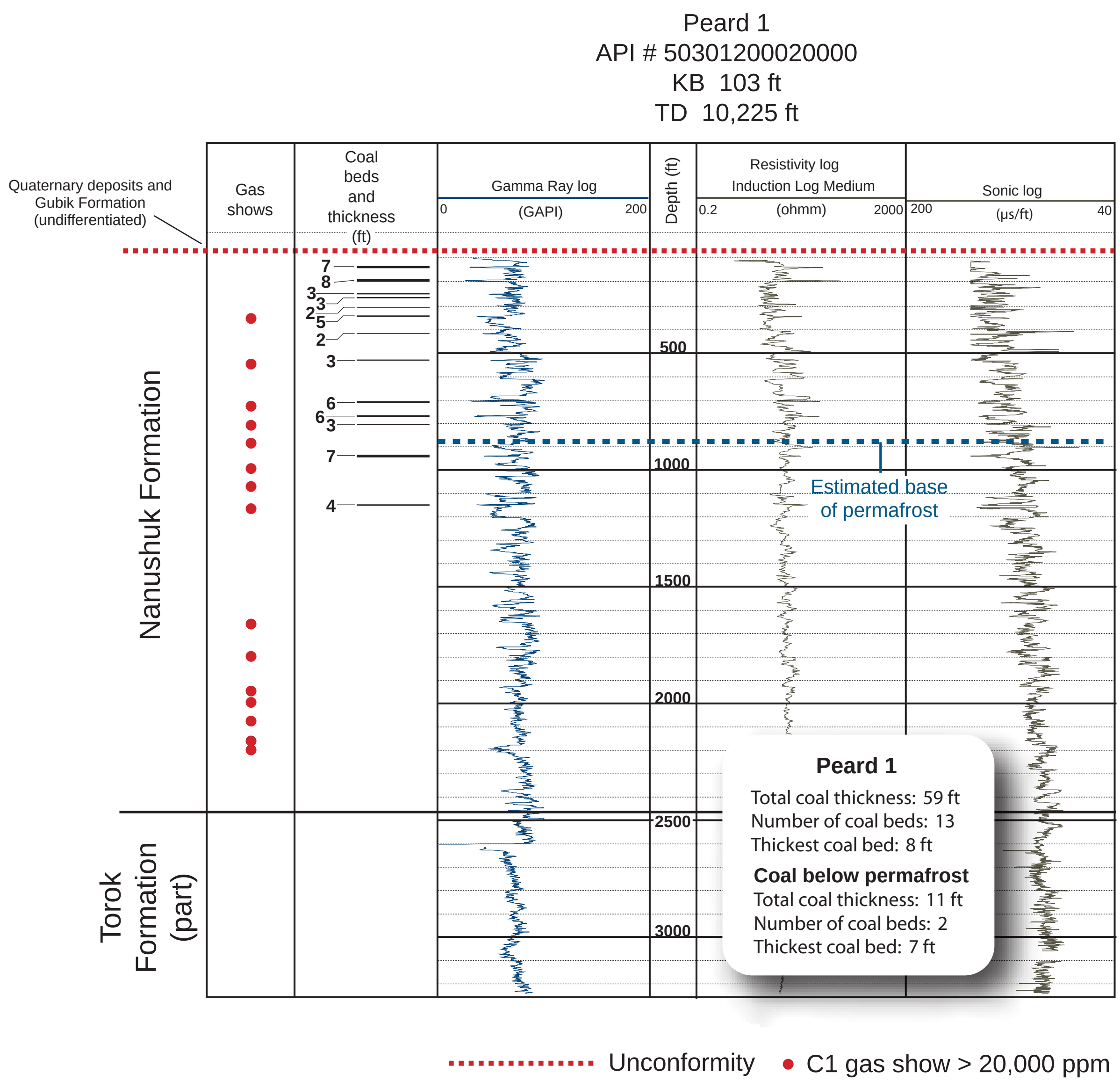

Figure 1–13 Geophysical log traces, net coal thickness (in feet), permafrost depth, and gas shows in the Nanushuk Formation in the upper part of the Peard 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 1–1. Permafrost depth from Lachenbruch and others (1987), and represents the depth from the ground surface to the base of the ice-rich layer. C1, methane gas; ppm, parts per million; KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; µs/ft, microseconds per foot.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

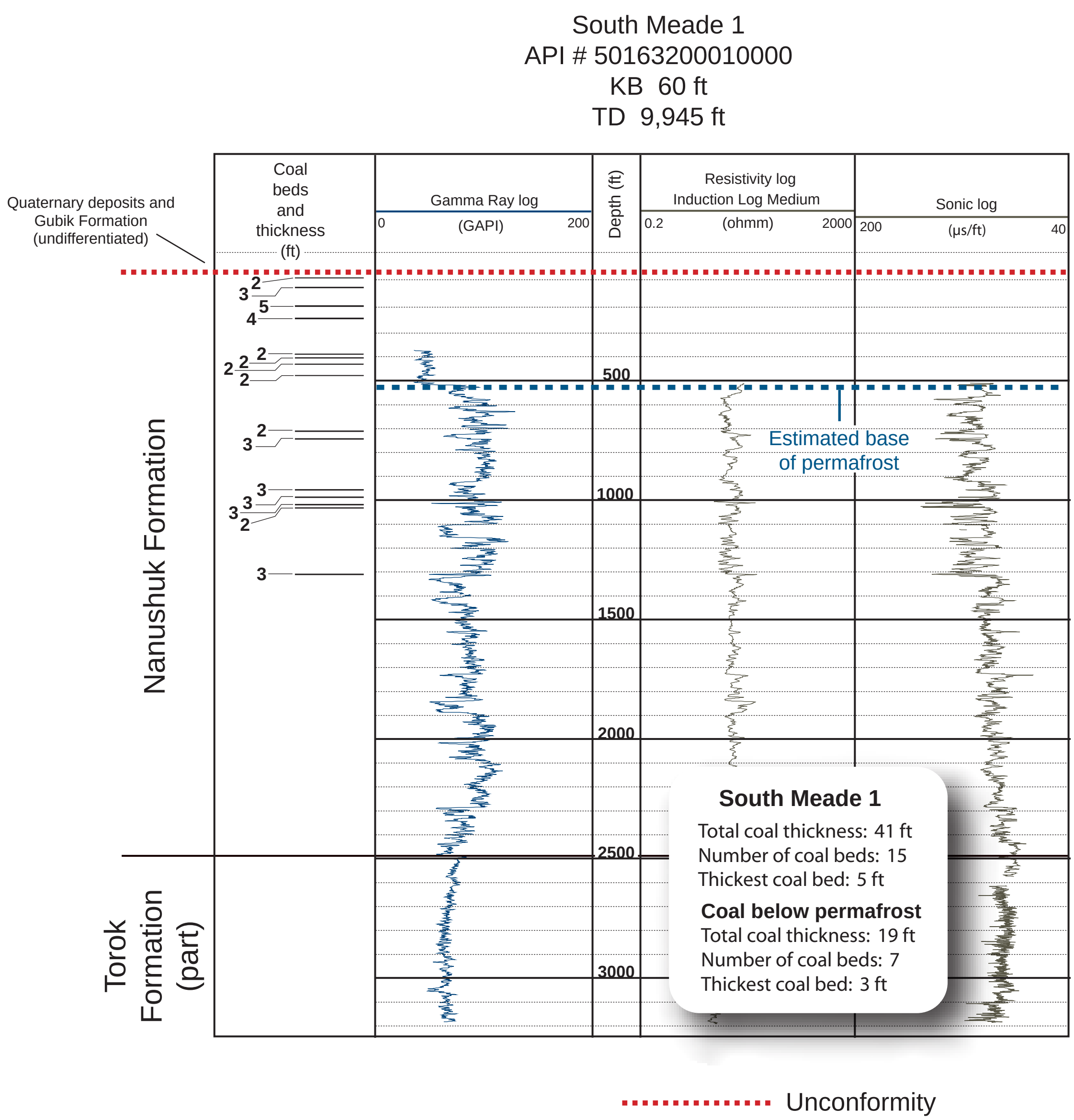

Figure 1–14. Geophysical log traces, and net coal thickness (in feet), and permafrost depth in the Nanushuk Formation in the upper part of the South Meade 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 1–1. Permafrost depth from Lachenbruch and others (1987), and represents the depth from the ground surface to the base of the ice-rich layer. KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; us/ft, microseconds per foot.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

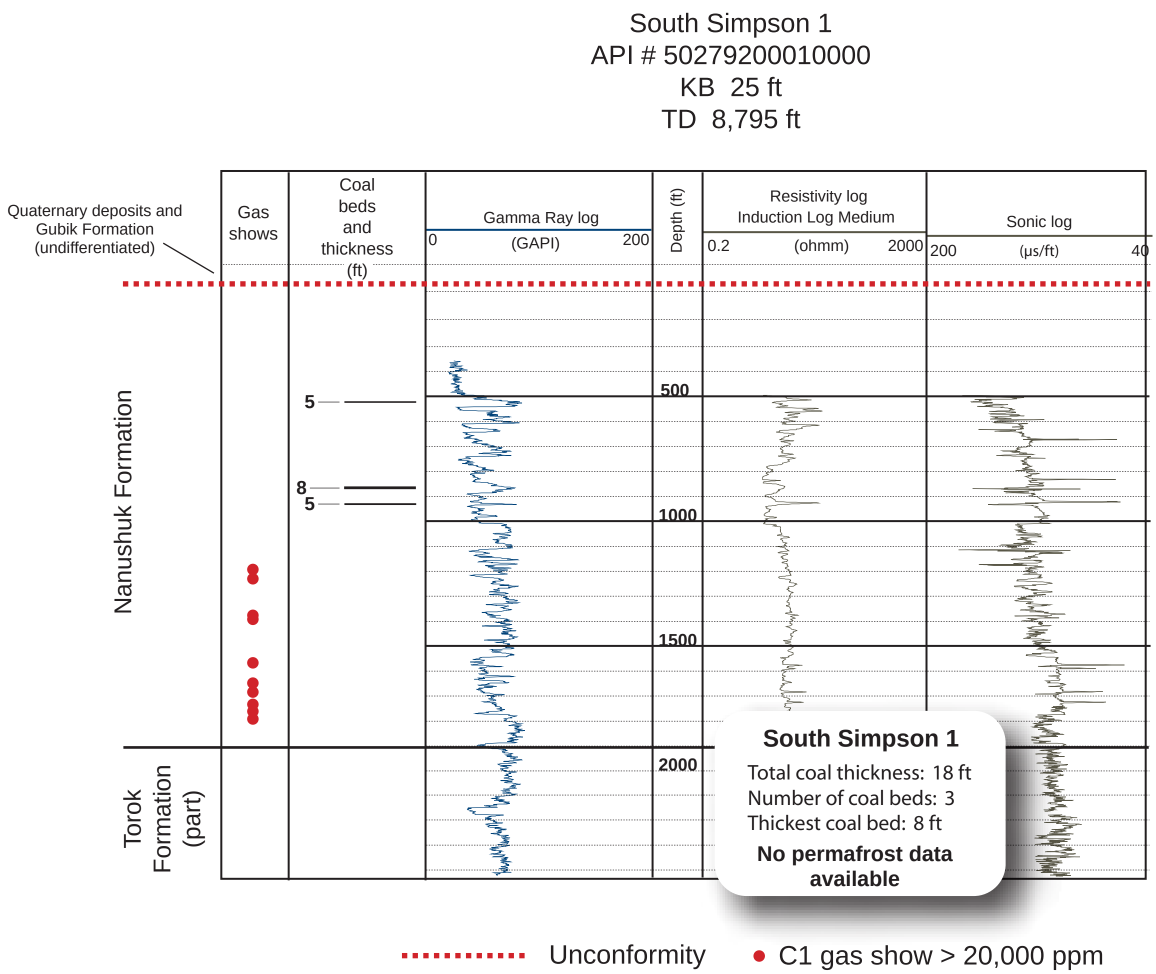

Figure 1–15. Geophysical log traces, net coal thickness (in feet), and gas shows in the Nanushuk Formation in the upper part of the South Simpson 1 oil and gas exploration well, North Slope, Alaska. Coal interpretations from Magoon and others (1988). Location of well shown in figure 1–1. C1, methane gas; ppm, parts per million; KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; us/ft, microseconds per foot.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0˚C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

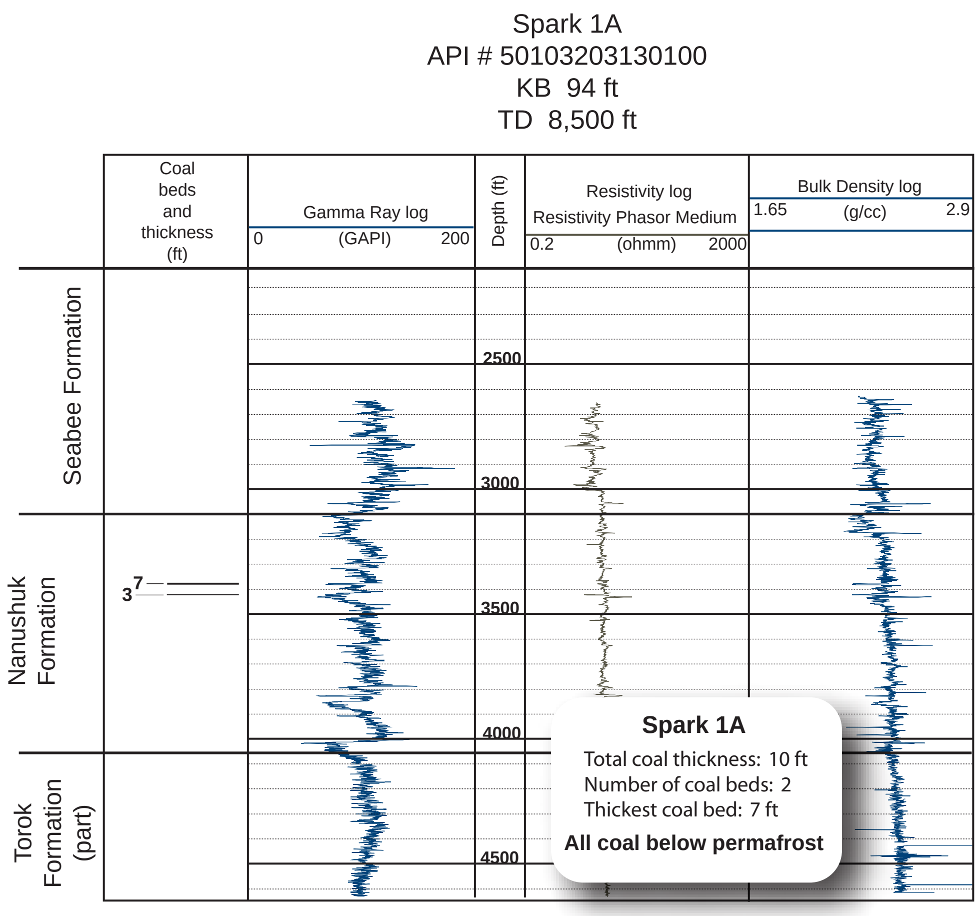

Figure 1–16. Geophysical log traces and net coal thickness (in feet) in the Nanushuk Formation in the upper part of the Spark 1A oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 1–1. KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; g/cc, grams per cubic centimeter.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

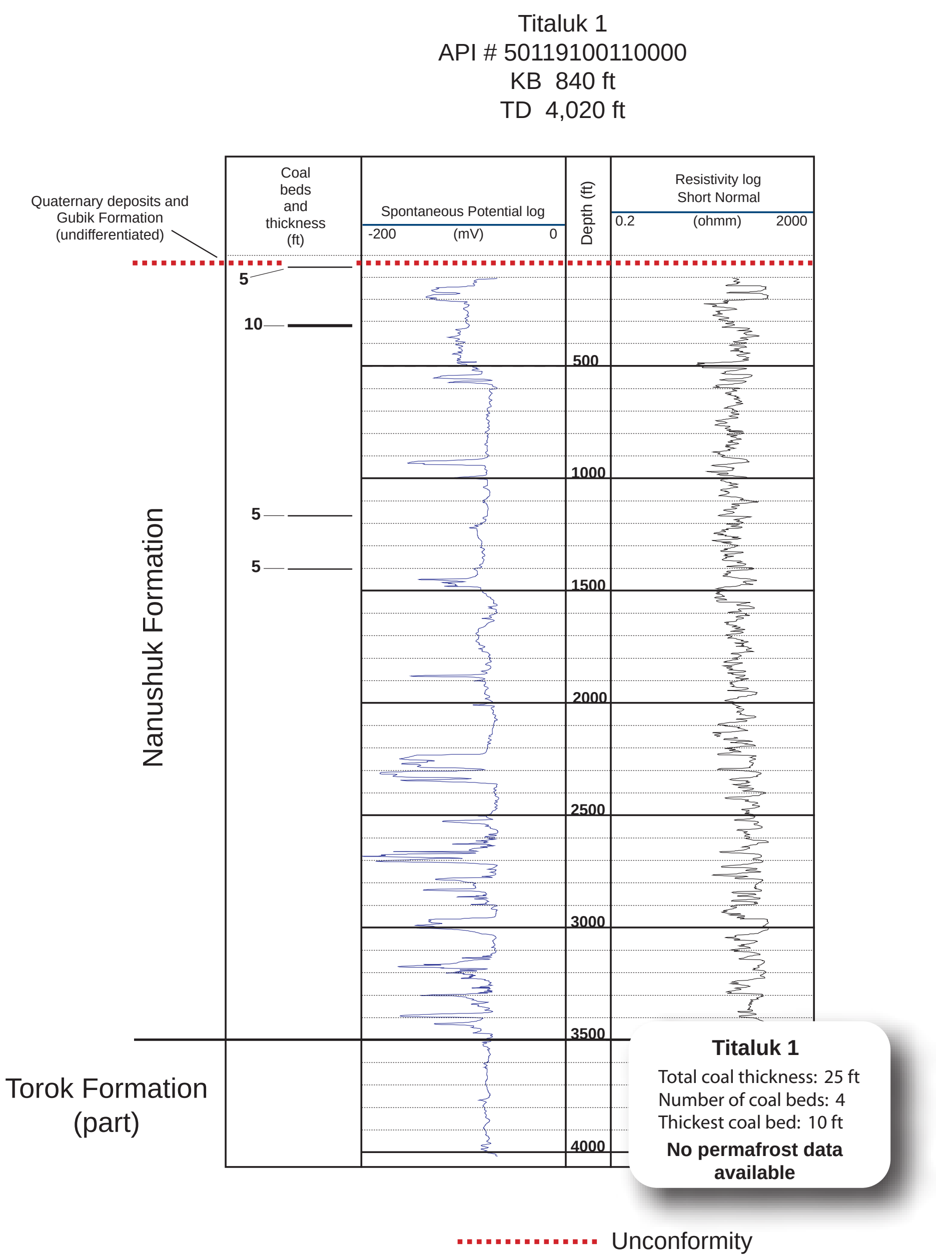

Figure 1–17. Geophysical log traces and net coal thickness (in feet) in the Nanushuk Formation in the Titaluk 1 oil and gas exploration well, North Slope, Alaska. Coal interpretations from Magoon and others (1988). Location of well shown in figure 1–1. KB, kelly bushing; TD, total depth; mV, millivolts; ohmm, ohm-meters.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

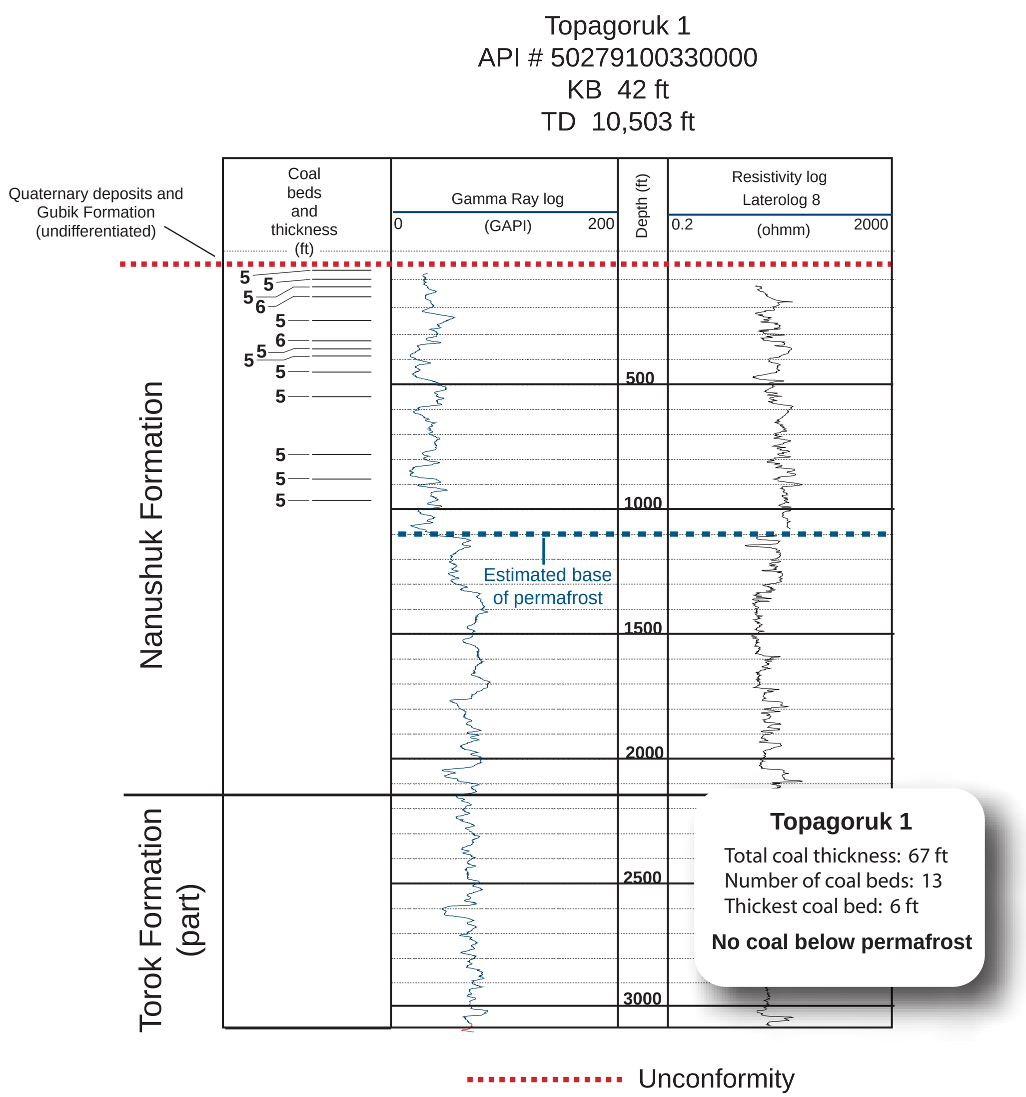

Figure 1–18. Geophysical log traces and net coal thickness (in feet) in the Nanushuk Formation in the upper part of the Topagoruk 1 oil and gas exploration well, North Slope, Alaska. Coal interpretations from Magoon and others (1988). Location of well shown in figure 1–1. KB, kelly bushing; TD, total depth; mV, millivolts; ohmm, ohm-meters.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0˚C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

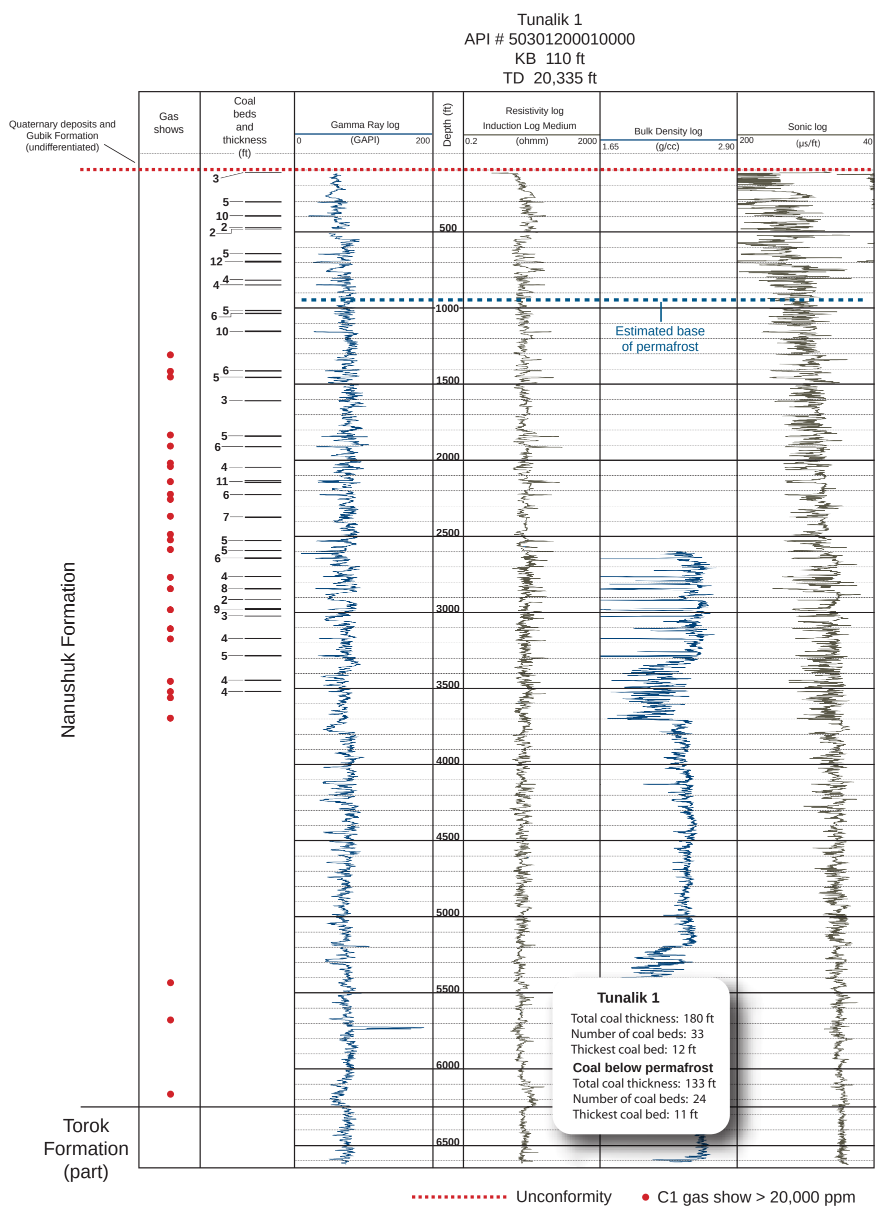

Figure 1–19. Geophysical log traces, net coal thickness (in feet), permafrost depth, and gas shows in the Nanushuk Formation in the upper part of the Tunalik 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 1–1. Permafrost depth from Lachenbruch and others (1987), and represents the depth from the ground surface to a temperature of 0˚C. C1, methane gas; ppm, parts per million; KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; g/cc, grams per cubic centimeter, µs/ft, microseconds per foot.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0˚C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

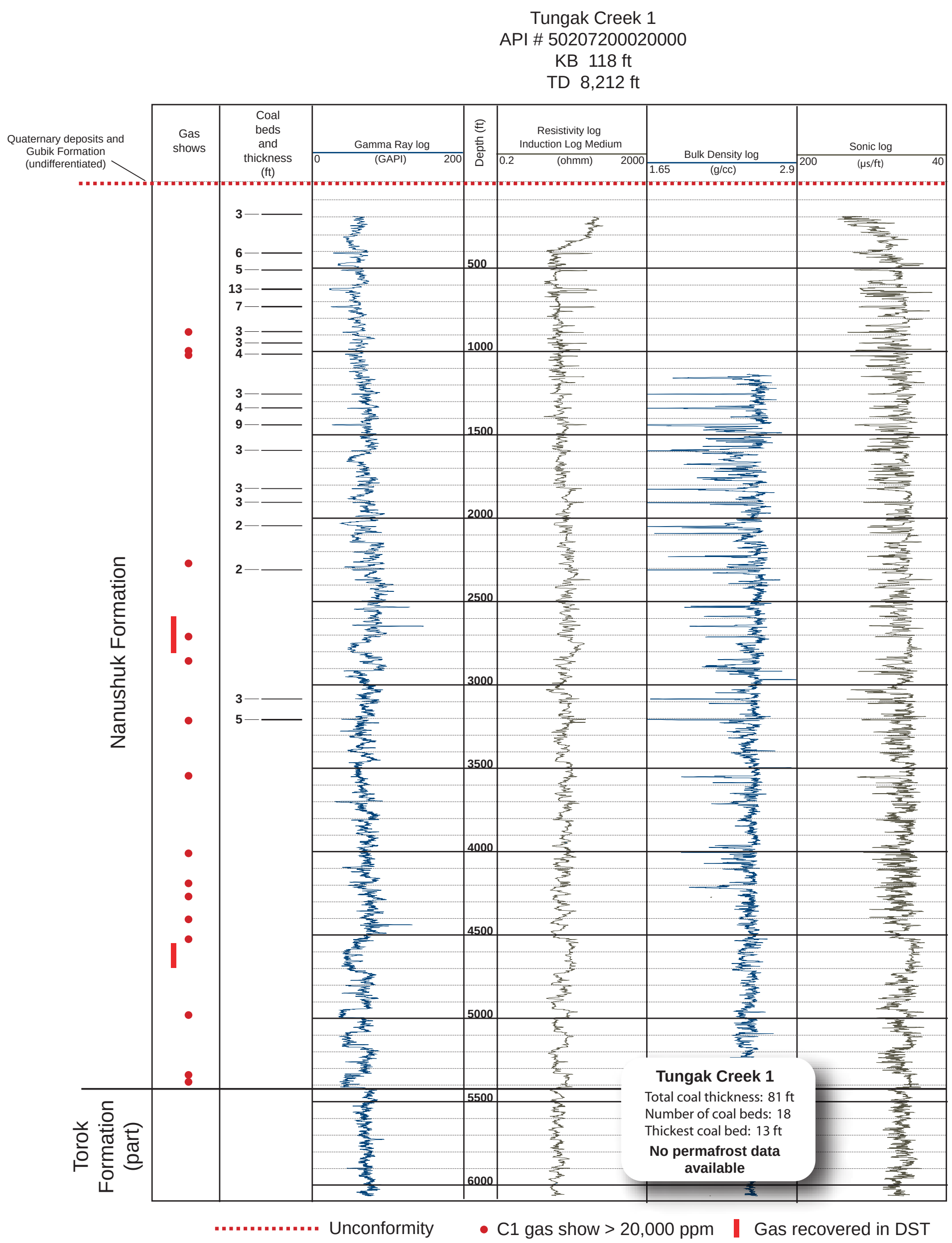

Figure 1–20. Geophysical log traces, net coal thickness (in feet), and gas shows in the Nanushuk Formation in the upper part of the Tungak Creek 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 1–1. C1, methane gas; ppm, parts per million; KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; g/cc, grams per cubic centimeter; μs/ft, microseconds per foot; DST, drill-stem test.

Appendix 1. Appendix 1 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, permafrost depths, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Nanushuk Formation, North Slope, Alaska. Permafrost depths are based on Ferrians, (1965), Lachenbruch and others (1987), Osterkamp and Payne (1981), and Collett and others (1989), and represent either (1) the depth from the kelly bushing to the base of ice-bearing permafrost, (2) the depth from the ground surface to the base of the ice-rich layer, or (3) the depth from the ground surface to a temperature of 0°C. Coal interpretations are based on (1) geophysical and drill cuttings log analyses completed as part of this study, (2) coal geologic studies reported in Collins (1958) for the Kaolak 1 and Mead 1 wells and in Husky Oil NPR Operations, Inc. (1982) geological reports for Kugrua 1 and Peard 1 test wells, and (3) coal thickness interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D.O. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded. Formation contacts are from Ken Bird (U.S Geological Survey, written commun., 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Digital geophysical logs as shown were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

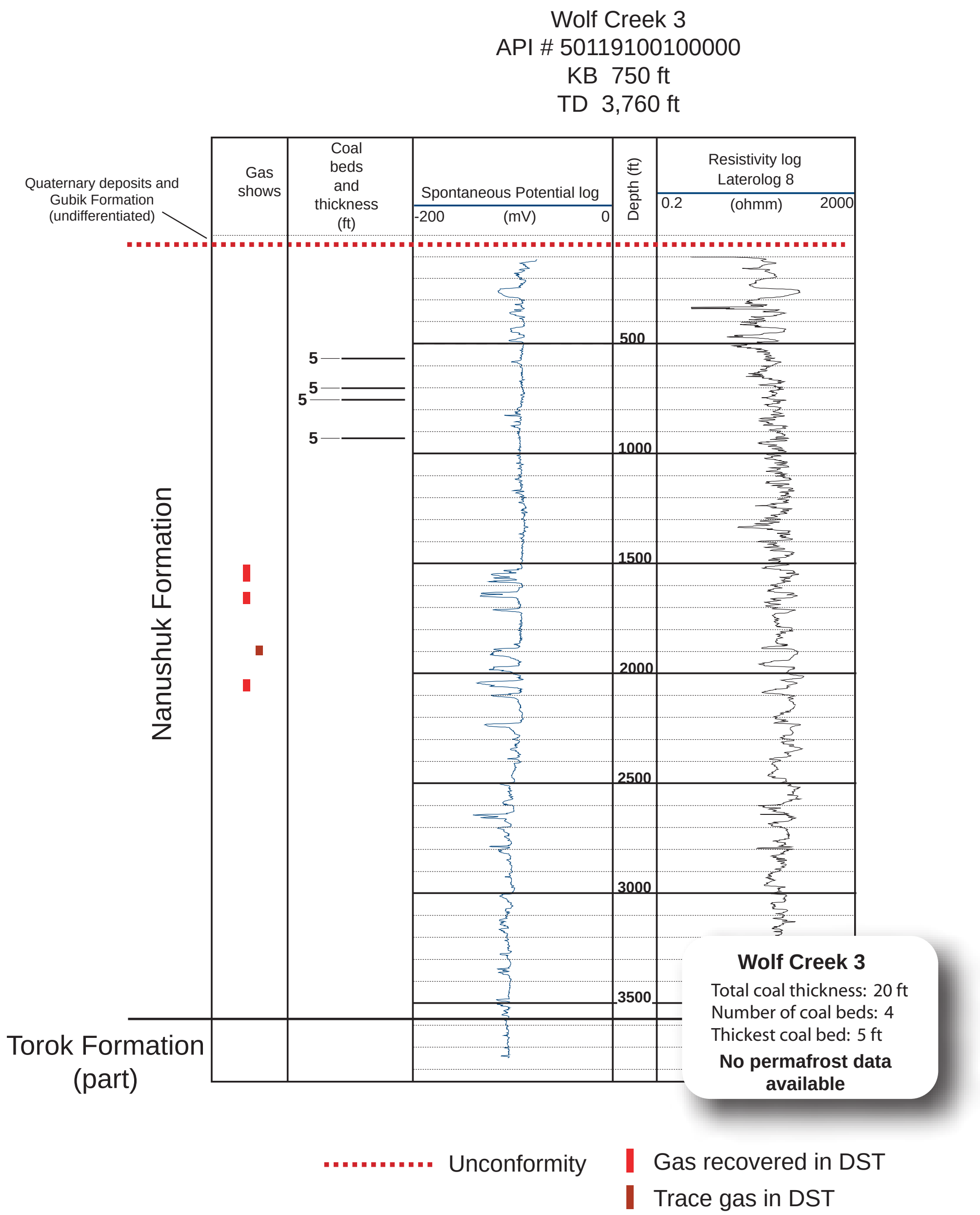

Figure 1–21. Geophysical log traces, net coal thickness (in feet), and intervals where gas was recovered in drill-stem tests in the Nanushuk Formation in the Wolf Creek 3 oil and gas exploration well, North Slope, Alaska. Coal interpretations from Magoon and others (1988). Location of well shown in figure 1–1. KB, kelly bushing; TD, total depth; mV, millivolts; ohmm, ohm-meters; DST, drill-stem test.

Appendix 2. Appendix 2 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Prince Creek and Tuluvak Formation, North Slope, Alaska. Coal interpretations are based on geophysical and drill cuttings log analyses completed as part of this study and lithologic interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded from coal zone values. Formation contacts are from Ken Bird (U.S Geological Survey, written commun. 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Permafrost depth in the Umiat 11 well based on Ferrians, (1965), and represents the depth from the ground surface to a temperature of 0°C. Digital geophysical log displays were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).

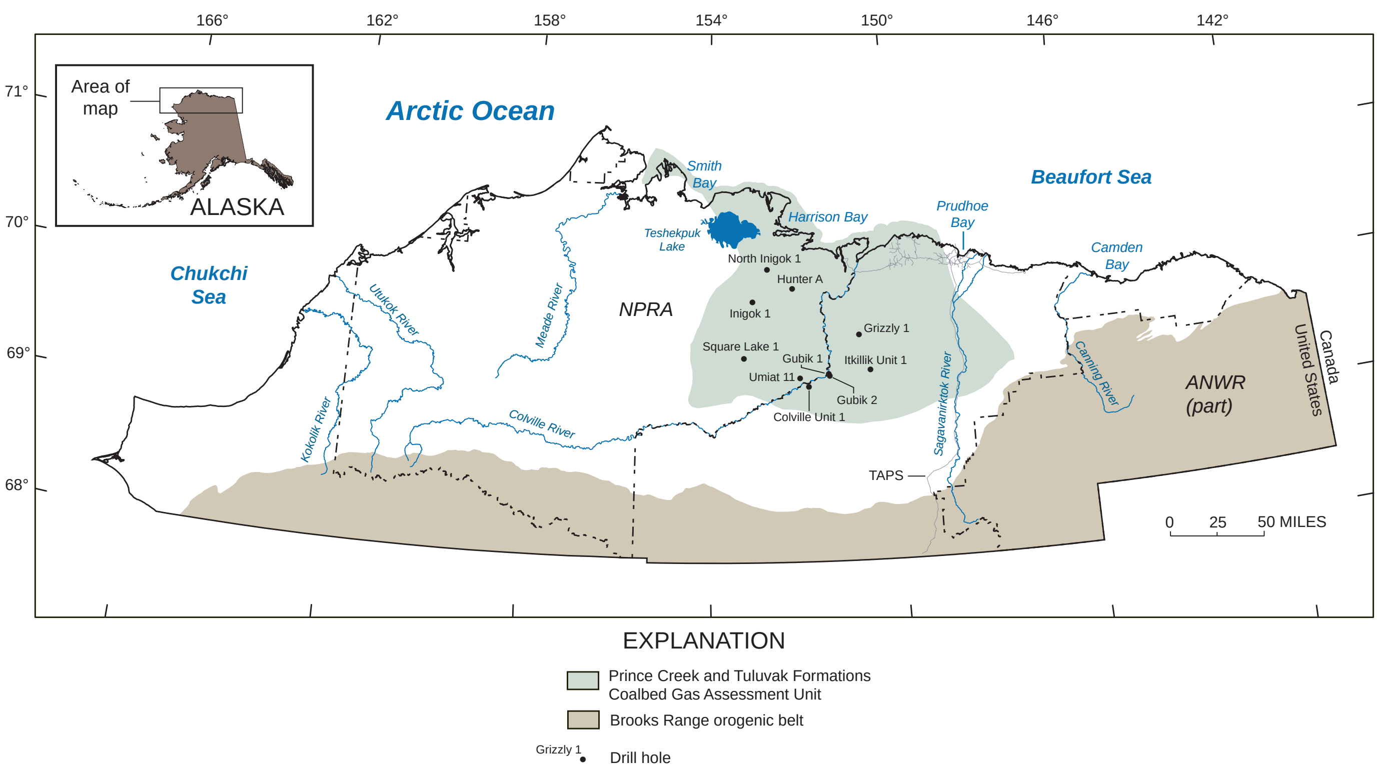

Figure 2–1. Map showing locations of oil and gas exploration wells used in total (cumulative) coal thickness interpretations for the Prince Creek and Tuluvak Formations, North Slope, Alaska. NPRA, National Petroleum Reserve in Alaska; ANWR, Arctic National Wildlife Refuge; TAPS, Trans Alaska Pipeline System.

Appendix 2. Appendix 2 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Prince Creek and Tuluvak Formation, North Slope, Alaska. Coal interpretations are based on geophysical and drill cuttings log analyses completed as part of this study and lithologic interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded from coal zone values. Formation contacts are from Ken Bird (U.S Geological Survey, written commun. 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Permafrost depth in the Umiat 11 well based on Ferrians, (1965), and represents the depth from the ground surface to a temperature of 0°C. Digital geophysical log displays were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

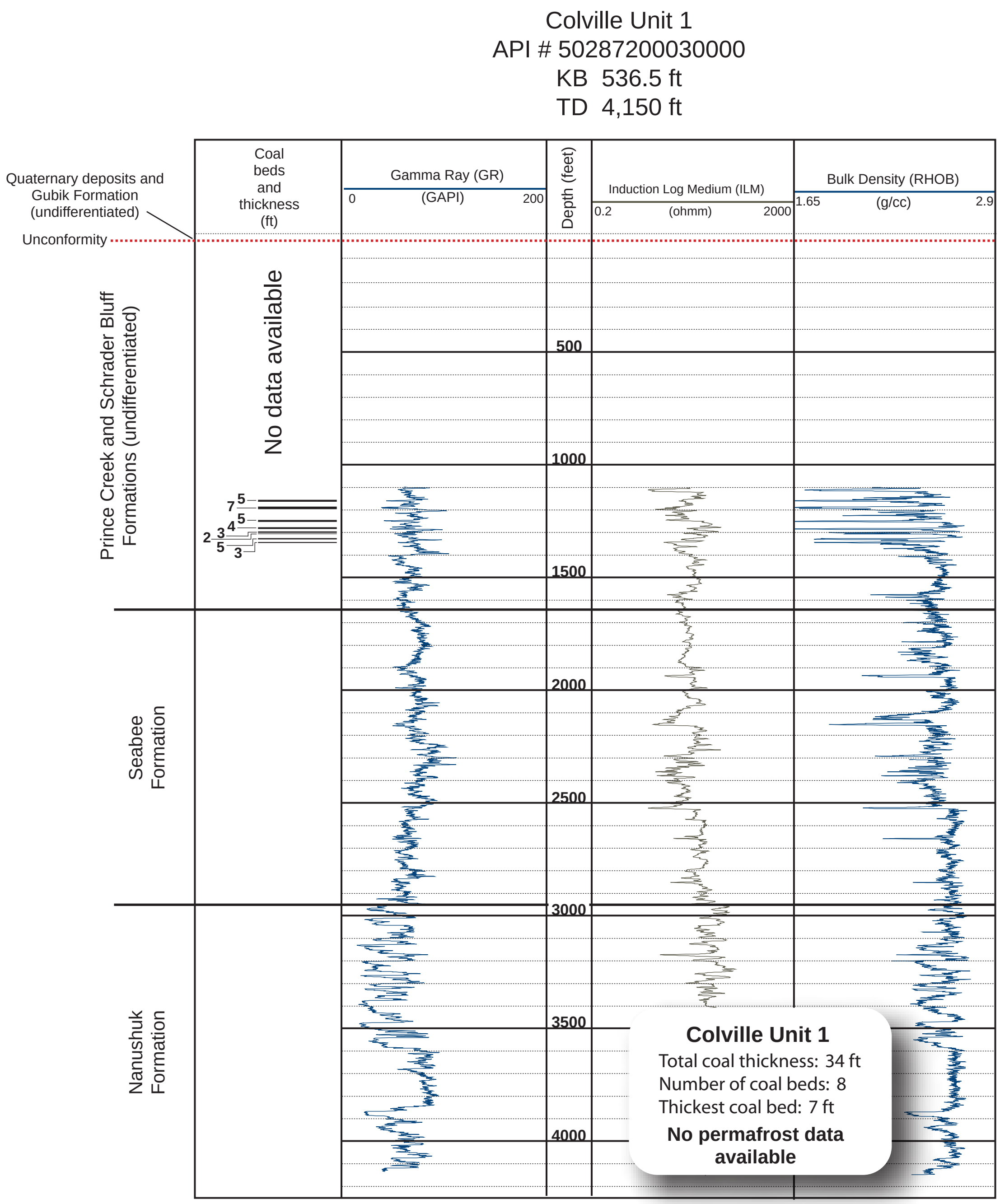

Figure 2–2. Geophysical log traces and net coal thickness (in feet) in the undifferentiated Prince Creek and Schrader Bluff Formations in the Colville Unit 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 2–1. KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; g/cc, grams per cubic centimeter.

Appendix 2. Appendix 2 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Prince Creek and Tuluvak Formation, North Slope, Alaska. Coal interpretations are based on geophysical and drill cuttings log analyses completed as part of this study and lithologic interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded from coal zone values. Formation contacts are from Ken Bird (U.S Geological Survey, written commun. 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Permafrost depth in the Umiat 11 well based on Ferrians, (1965), and represents the depth from the ground surface to a temperature of 0˚C. Digital geophysical log displays were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

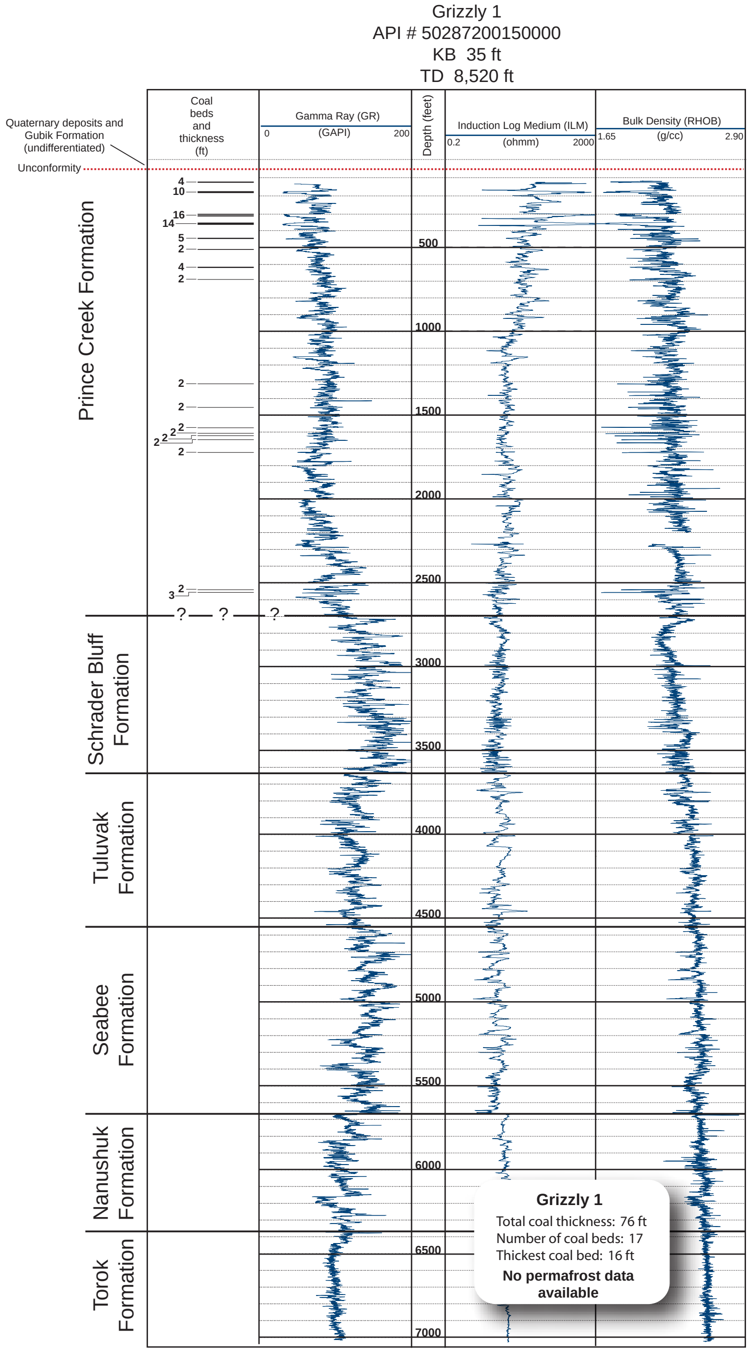

Figure 2–3. Geophysical log traces and net coal thickness (in feet) in the Prince Creek Formation in the upper part of the Grizzly 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 2–1. Contact between the Prince Creek and Schrader Bluff Formations is queried and based primarily on the assumption that coal beds are restricted to the Prince Creek Formation. KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; g/cc, grams per cubic centimeter.

Appendix 2. Appendix 2 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Prince Creek and Tuluvak Formation, North Slope, Alaska. Coal interpretations are based on geophysical and drill cuttings log analyses completed as part of this study and lithologic interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded from coal zone values. Formation contacts are from Ken Bird (U.S Geological Survey, written commun. 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Permafrost depth in the Umiat 11 well based on Ferrians, (1965), and represents the depth from the ground surface to a temperature of 0°C. Digital geophysical log displays were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

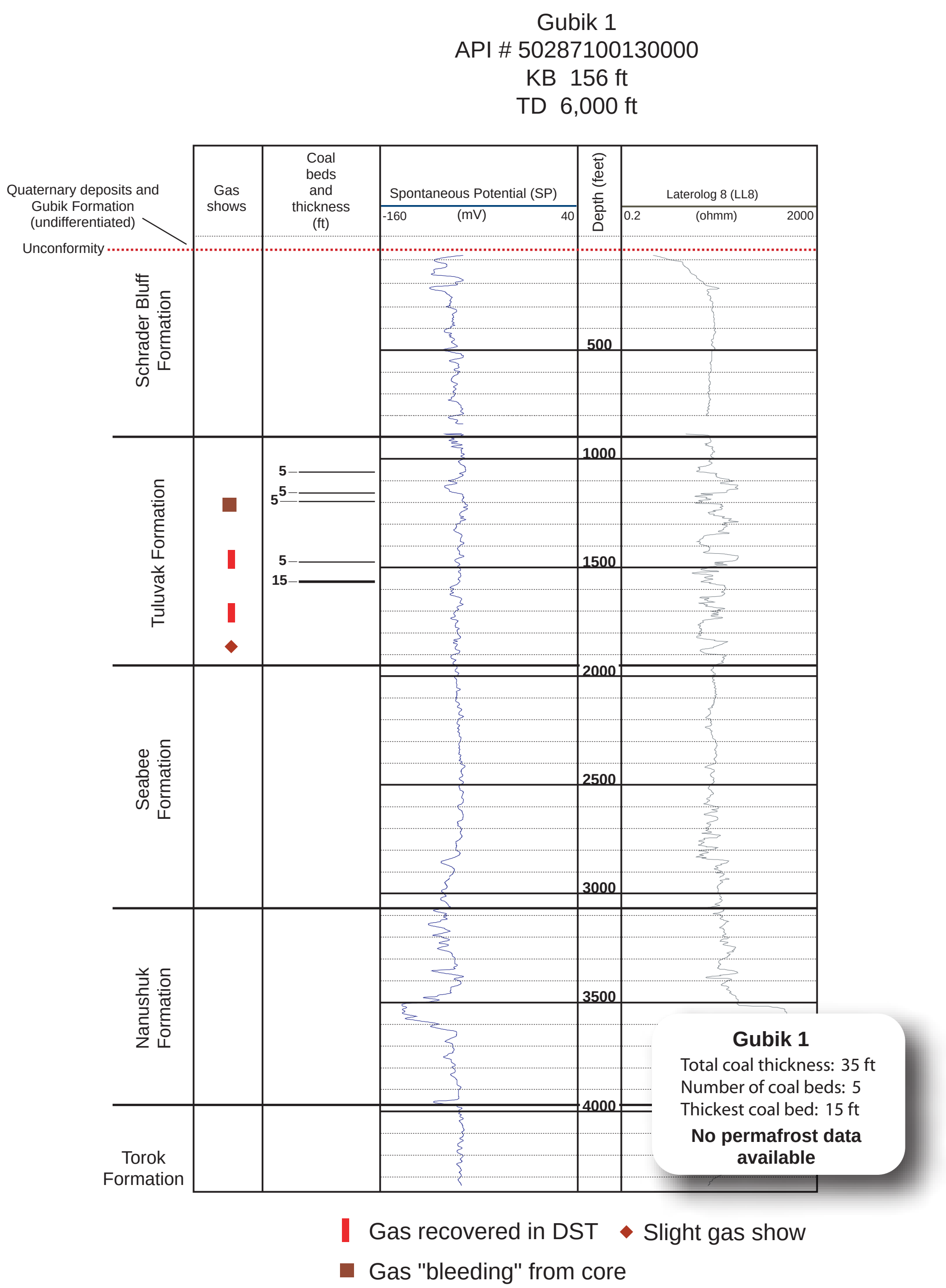

Figure 2–4. Geophysical log traces, net coal thickness (in feet), and gas shows in the Tuluvak Formation in the upper part of the Gubik 1 oil and gas exploration well, North Slope, Alaska. Coal interpretations from Magoon and others (1988). Location of well shown in figure 2–1. DST, drill-stem test; KB, kelly bushing; TD, total depth; mV, millivolts; ohmm, ohm-meters.

Appendix 2. Appendix 2 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Prince Creek and Tuluvak Formation, North Slope, Alaska. Coal interpretations are based on geophysical and drill cuttings log analyses completed as part of this study and lithologic interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded from coal zone values. Formation contacts are from Ken Bird (U.S Geological Survey, written commun. 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Permafrost depth in the Umiat 11 well based on Ferrians, (1965), and represents the depth from the ground surface to a temperature of 0°C. Digital geophysical log displays were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

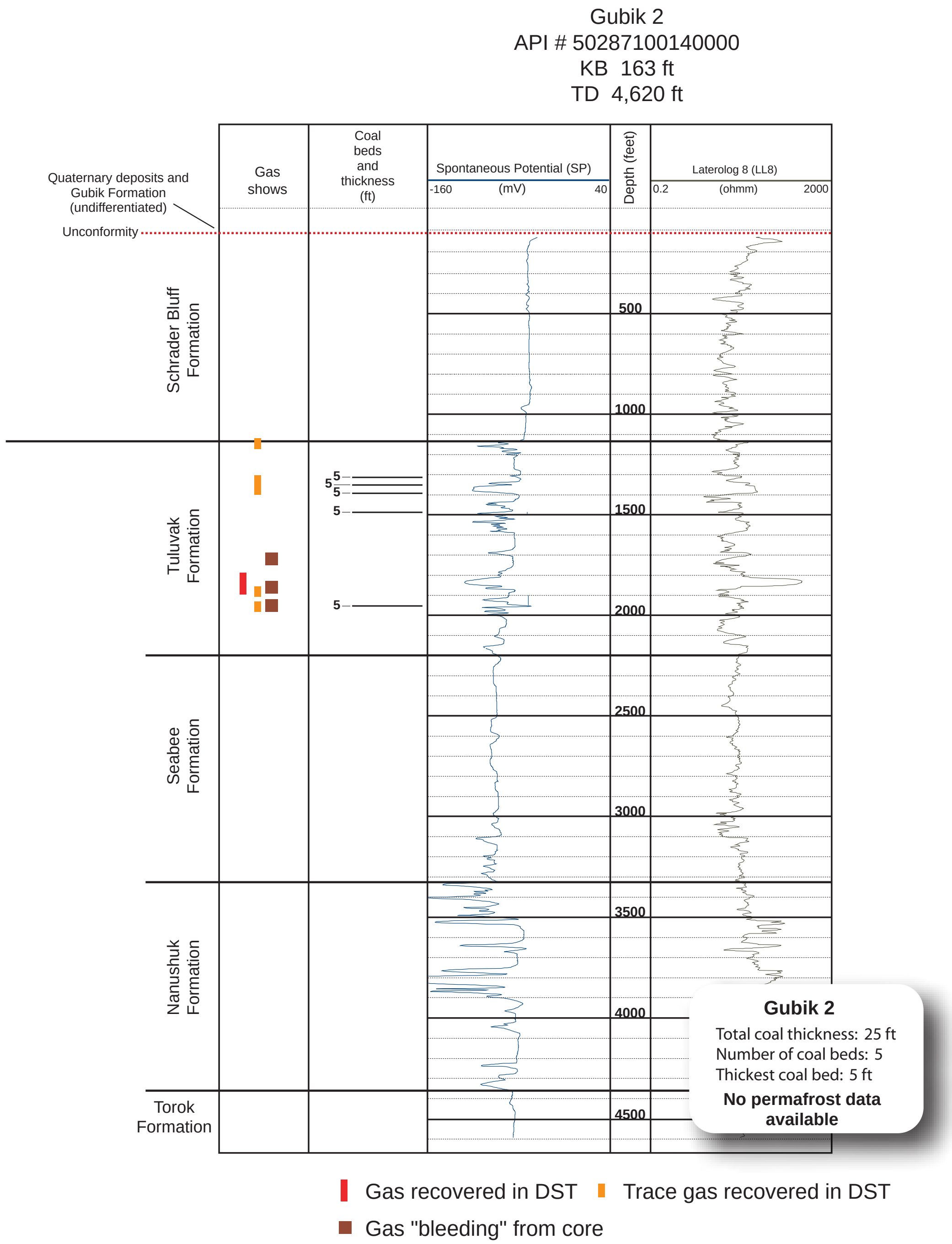

Figure 2–5. Geophysical log traces, net coal thickness (in feet), and gas shows in the Tuluvak Formation in the upper part of the Gubik 2 oil and gas exploration well, North Slope, Alaska. Coal interpretations from Magoon and others (1988). Location of well shown in figure 2–1. DST, drill-stem test; KB, kelly bushing; TD, total depth; mV, millivolts; ohmm, ohm-meters.

Appendix 2. Appendix 2 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Prince Creek and Tuluvak Formation, North Slope, Alaska. Coal interpretations are based on geophysical and drill cuttings log analyses completed as part of this study and lithologic interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded from coal zone values. Formation contacts are from Ken Bird (U.S Geological Survey, written commun. 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Permafrost depth in the Umiat 11 well based on Ferrians, (1965), and represents the depth from the ground surface to a temperature of 0°C. Digital geophysical log displays were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

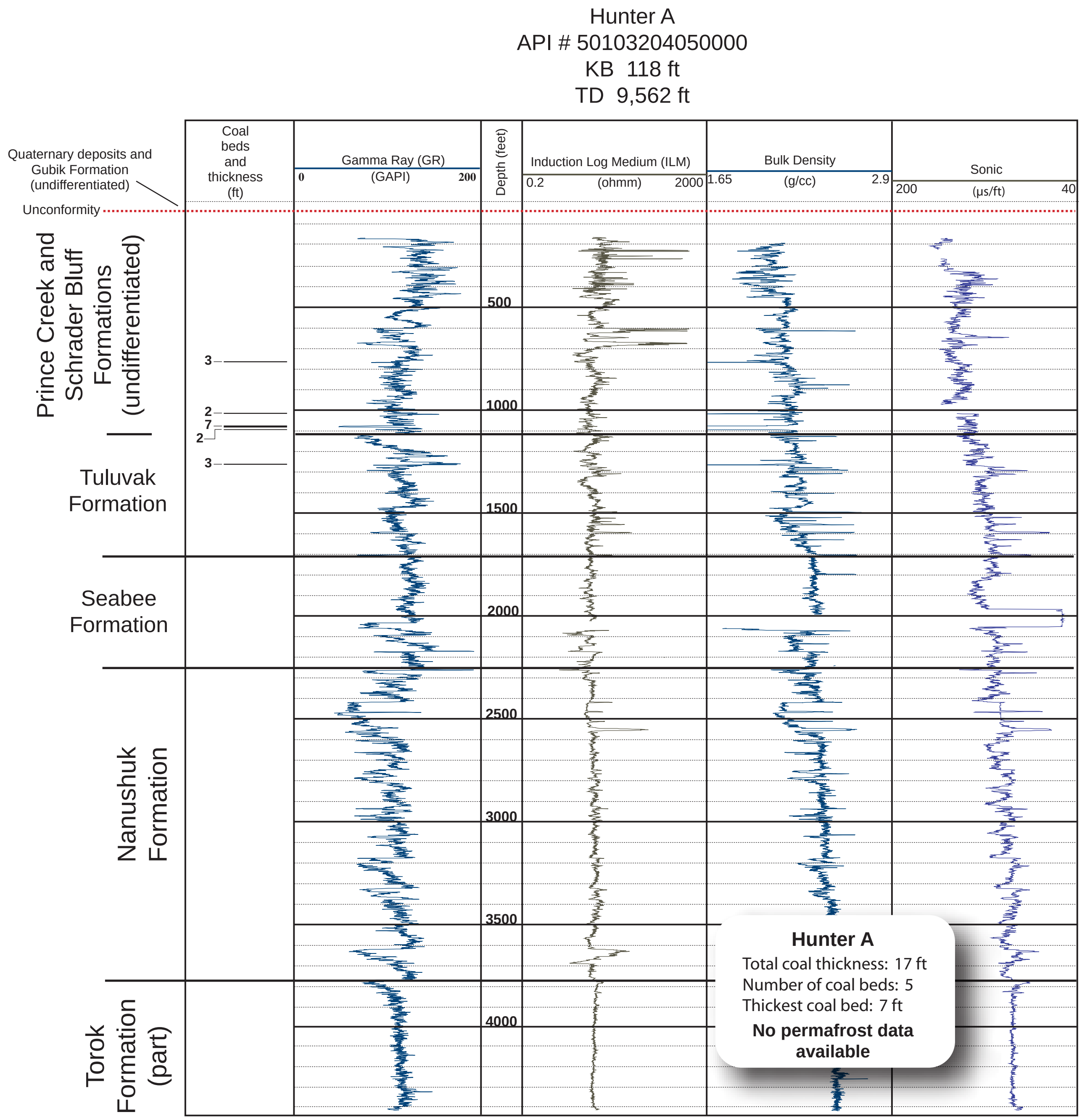

Figure 2–6. Geophysical log traces and net coal thickness (in feet) in the undifferentiated Prince Creek and Schrader Bluff Formations and in the Tuluvak Formation in the upper part of the Hunter A oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 2–1. KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; g/cc, grams per cubic centimeter; µs/ft, microseconds per foot.

Appendix 2. Appendix 2 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Prince Creek and Tuluvak Formation, North Slope, Alaska. Coal interpretations are based on geophysical and drill cuttings log analyses completed as part of this study and lithologic interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded from coal zone values. Formation contacts are from Ken Bird (U.S Geological Survey, written commun. 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Permafrost depth in the Umiat 11 well based on Ferrians, (1965), and represents the depth from the ground surface to a temperature of 0°C. Digital geophysical log displays were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

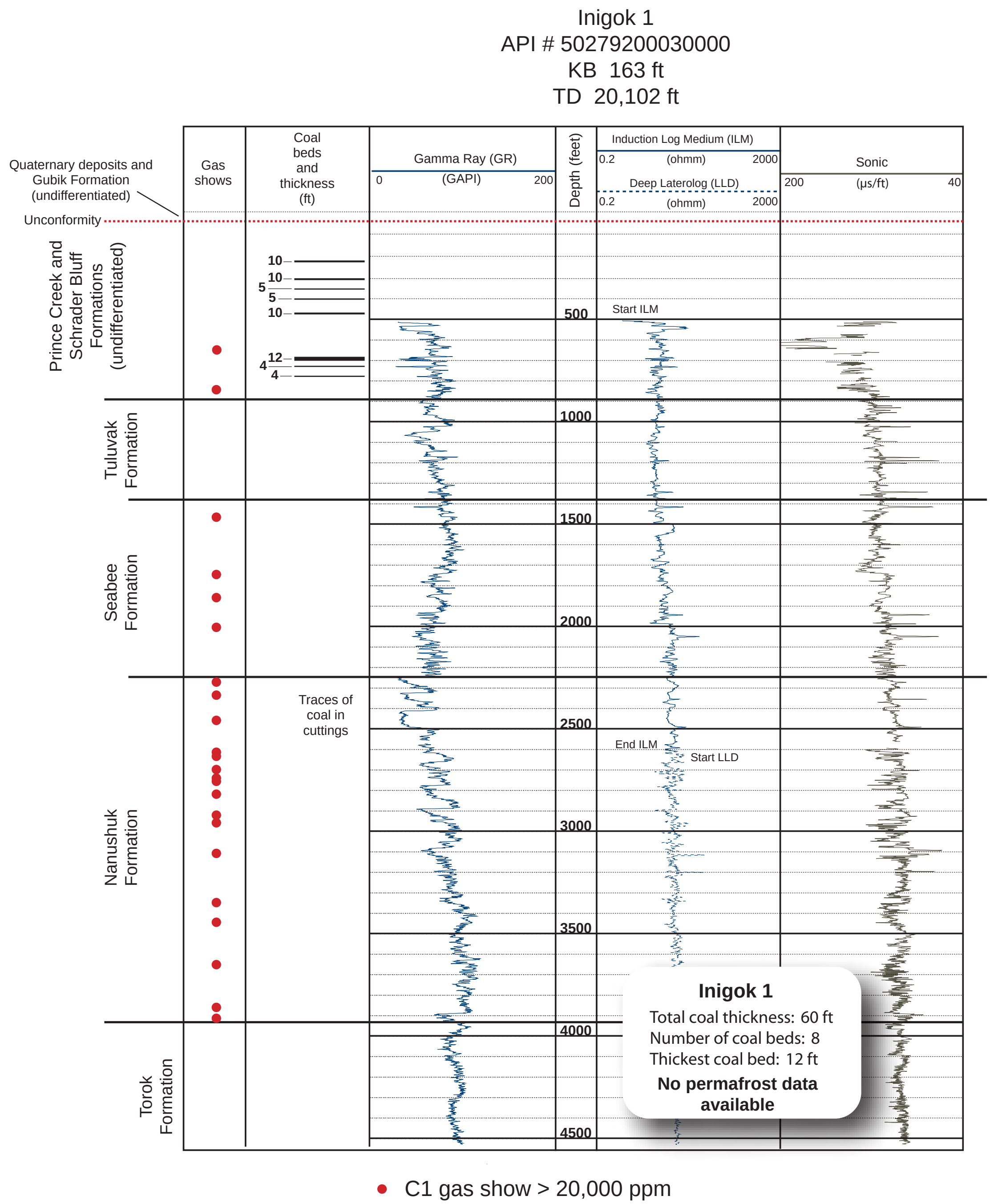

Figure 2–7. Geophysical log traces, net coal thickness (in feet), and gas shows in the undifferentiated Prince Creek and Schrader Bluff Formations and in the Seabee and Nanushuk Formations in the upper part of the Inigok 1 oil and gas exploration well, North Slope, Alaska. Coal interpretations from Magoon and others (1988). Location of well shown in figure 2–1. C1, methane gas; ppm, parts per million; KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; μs/ft, microseconds per foot.

Appendix 2. Appendix 2 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Prince Creek and Tuluvak Formation, North Slope, Alaska. Coal interpretations are based on geophysical and drill cuttings log analyses completed as part of this study and lithologic interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded from coal zone values. Formation contacts are from Ken Bird (U.S Geological Survey, written commun. 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Permafrost depth in the Umiat 11 well based on Ferrians, (1965), and represents the depth from the ground surface to a temperature of 0°C. Digital geophysical log displays were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

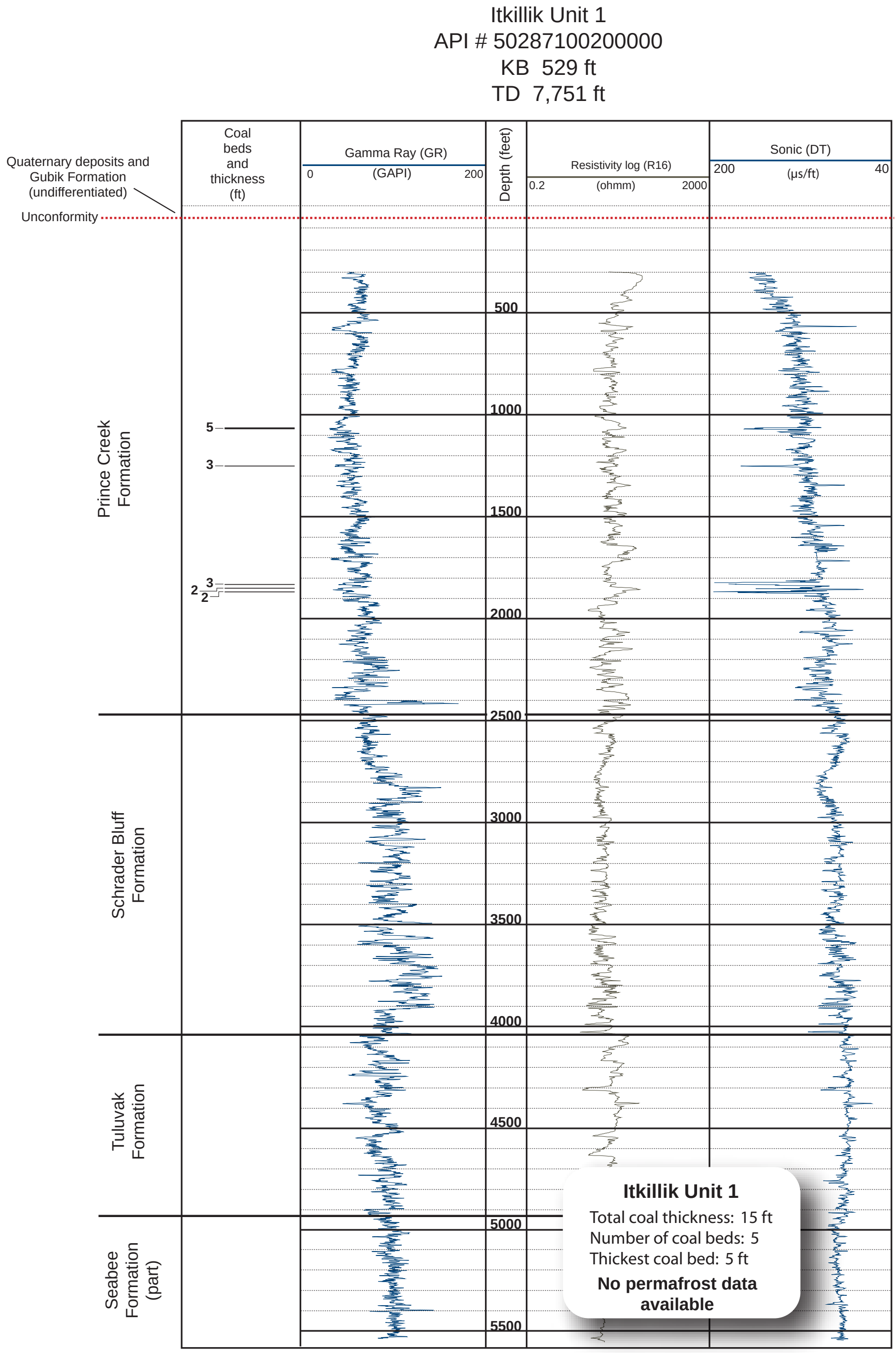

Figure 2–8. Geophysical log traces and net coal thickness (in feet) in the Prince Creek Formation in the upper part of the Itkillik Unit 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 2–1. KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; µs/ft, microseconds per foot.

Appendix 2. Appendix 2 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Prince Creek and Tuluvak Formation, North Slope, Alaska. Coal interpretations are based on geophysical and drill cuttings log analyses completed as part of this study and lithologic interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; noncoal parting thickness is excluded from coal zone values. Formation contacts are from Ken Bird (U.S Geological Survey, written commun. 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Permafrost depth in the Umiat 11 well based on Ferrians, (1965), and represents the depth from the ground surface to a temperature of 0˚C. Digital geophysical log displays were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

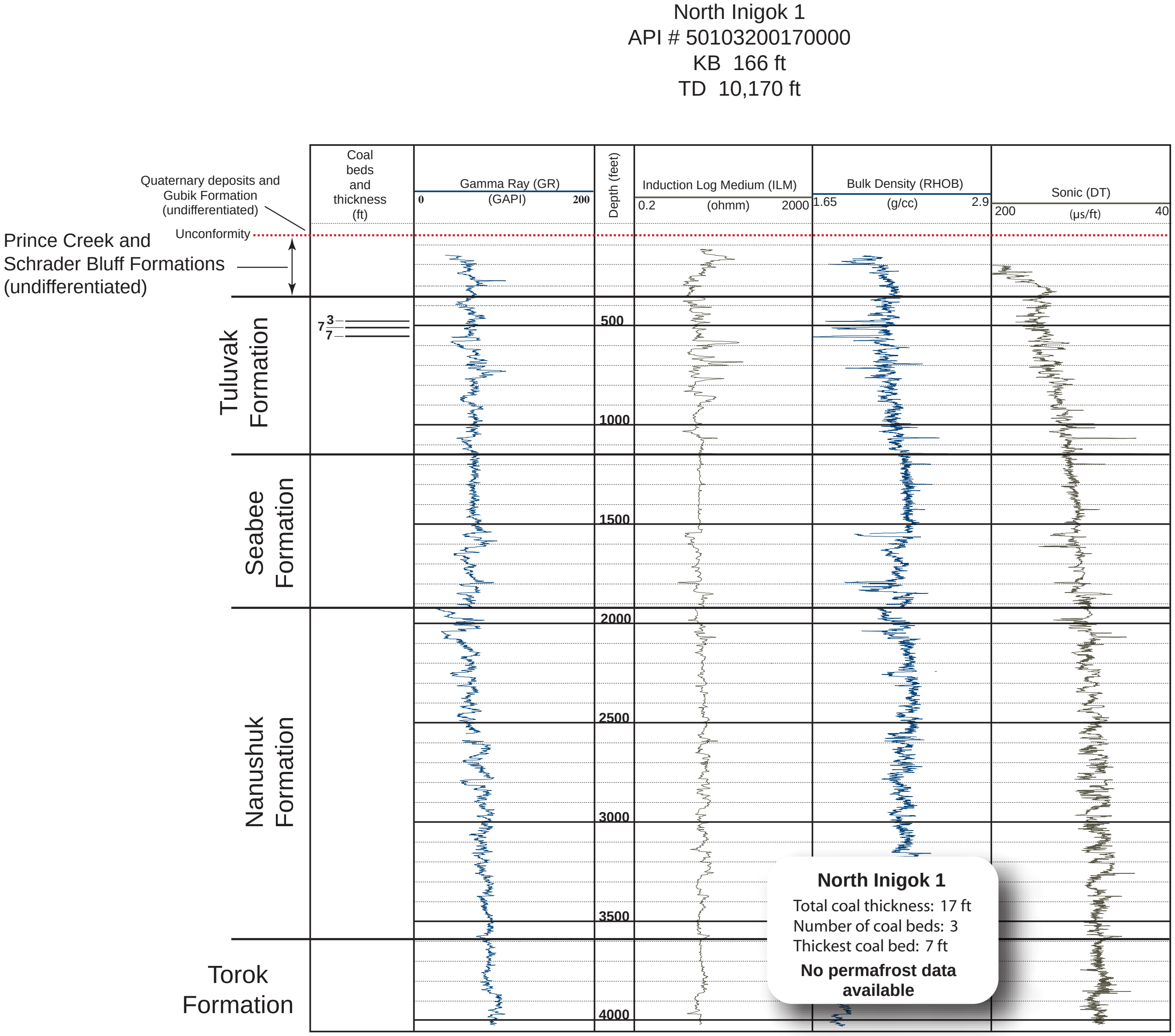

Figure 2–9. Geophysical log traces and net coal thickness (in feet) in the Tuluvak Formation in the upper part of the North Inigok 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 2–1. KB, kelly bushing; TD, total depth; GAPI, Gamma API units; ohmm, ohm-meters; g/cc, grams per cubic centimeter; μs/ft, microseconds per foot.

Appendix 2. Appendix 2 includes displays of geophysical logs, coal thickness and stratigraphic distribution, gas shows, and stratigraphic contacts in selected wells penetrating coal-bearing strata in the Prince Creek and Tuluvak Formation, North Slope, Alaska. Coal interpretations are based on geophysical and drill cuttings log analyses completed as part of this study and lithologic interpretations from Ken Bird (U.S. Geological Survey; NPRA studies from 1974–1982) published in Magoon and others (1988) and compiled in spreadsheet format by D. Hayba (U.S. Geological Survey, 2002). Coal thickness as depicted in the figures represents net coal thickness; non-coal parting thickness is excluded from coal zone values. Formation contacts are from Ken Bird (U.S Geological Survey, written commun. 2007), and gas show data were compiled by Dan Hayba (U.S. Geological Survey, written commun., 2001). Permafrost depth in the Umiat 11 well based on Ferrians, (1965), and represents the depth from the ground surface to a temperature of 0°C. Digital geophysical log displays were formatted and compiled by Phil Nelson (U.S. Geological Survey) and Joyce Kibler (U.S. Geological Survey).—Continued

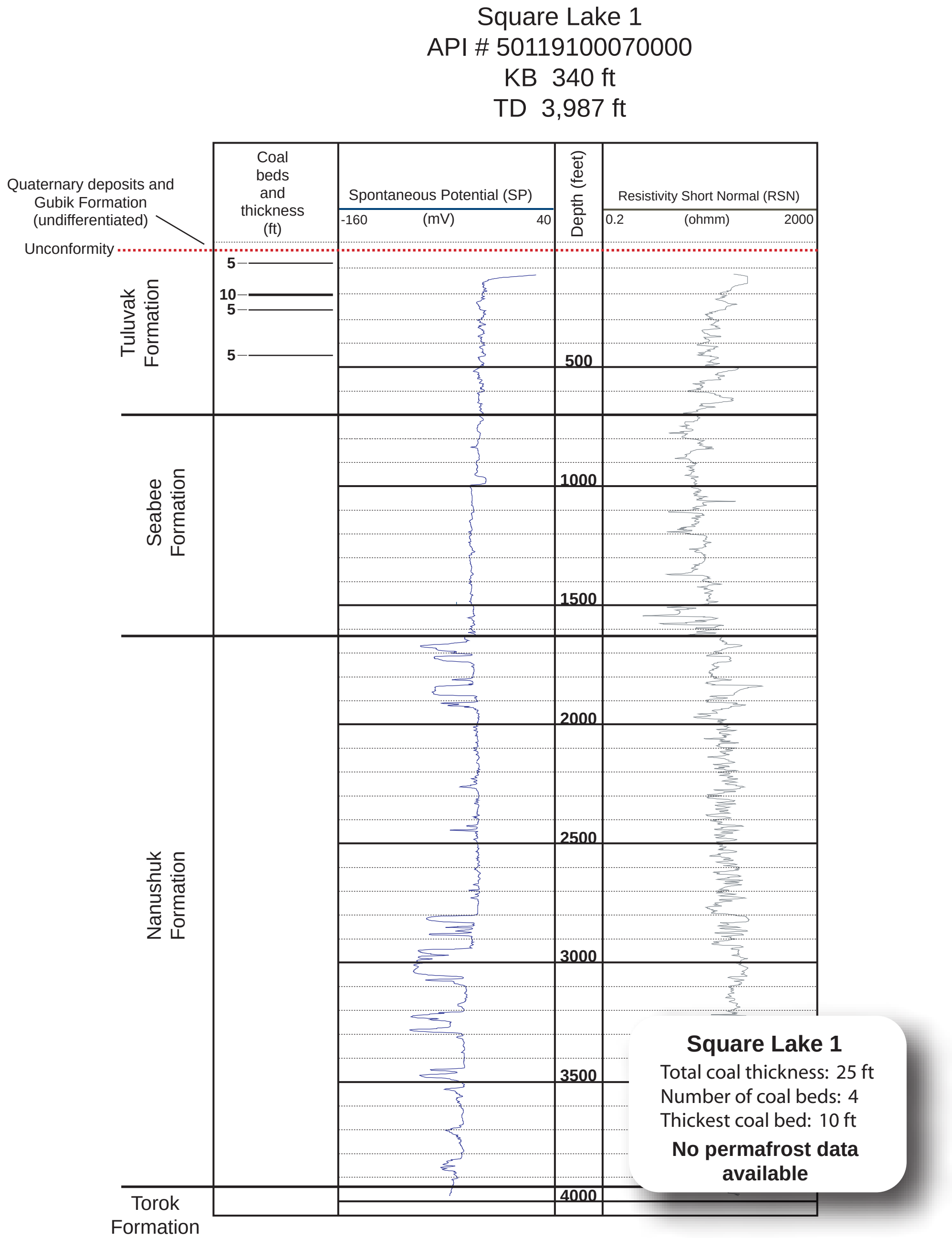

Figure 2–10. Geophysical log traces and net coal thickness (in feet) in the Tuluvak Formation in the upper part of the Square Lake 1 oil and gas exploration well, North Slope, Alaska. Location of well shown in figure 2–1. KB, kelly bushing; TD, total depth; mV, millivolts; ohmm, ohm-meters.

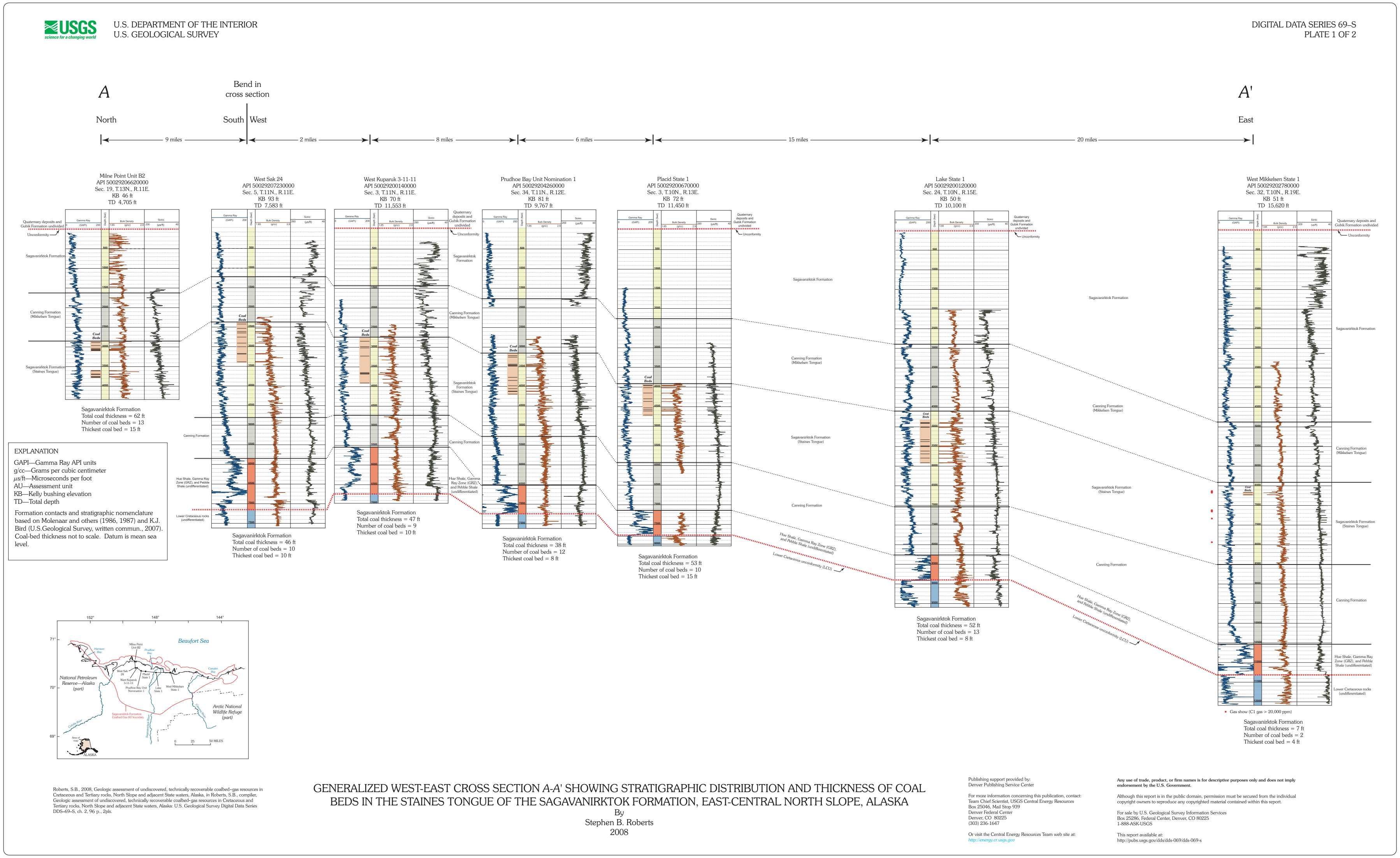

Plate 1. Generalized west-east cross section A-A' showing stratigraphic distribution and thickness of coal beds in the Staines Tongue of the Sagavanirktok Formation, East-Central North Slope, Alaska. (Click on image above to view and print full size plate).

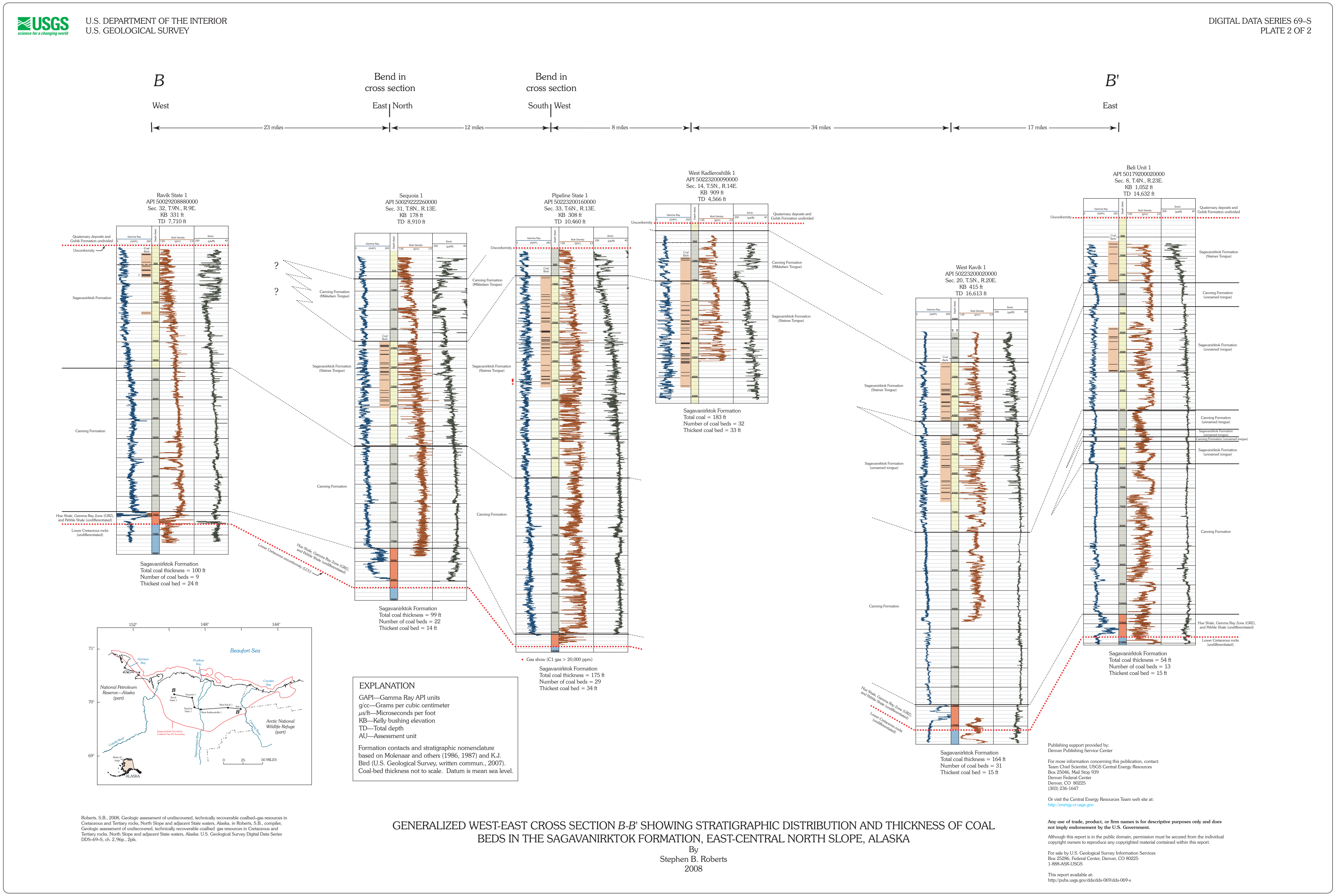

Plate 2. Generalized west-east cross section B-B′ showing stratigraphic distribution and thickness of coal beds in the Sagavanirktok Formation, East-Central North Slope, Alaska. (Click on image above to view and print full size plate).

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