Division of Geological & Geophysical Surveys

PRELIMINARY INTERPRETIVE REPORT 2000-2

COALBED METHANE POTENTIAL AND EXPLORATION TARGETS FOR RURAL ALASKA COMMUNITIES

by

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February 2000

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STATE OF ALASKA
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FINAL REPORT

COALBED METHANE POTENTIAL AND EXPLORATION TARGETS FOR RURAL ALASKAN COMMUNITIES

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prepared for the State of Alaska
under Agreement No. UTA97-0042

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August 1998

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EXECUTIVE SUMMARY

As part of a cooperative agreement between the Bureau of Economic Geology (BEG), The University of Texas at Austin, and the Division of Geological and Geophysical Surveys (DGGS), Department of Natural Resources, State of Alaska, a producibility model was applied to rural Alaskan coal provinces, basins, and villages to define and target the coalbed methane resource potential. The BEG coalbed methane producibility model indicates that tectonic/structural setting, depositional systems and coal distribution, coal rank, gas content, permeability, and hydrodynamics are critical controls on coalbed methane producibility and resource assessment in rural Alaska (fig. 1). High productivity in rural Alaskan basins will be governed by (1) thick, laterally continuous coals of high thermal maturity; (2) adequate permeability; (3) basinward flow of ground water through coals of high rank and gas content orthogonally toward no-flow boundaries (structural hingelines, fault systems, facies changes, and/or discharge areas); (4) possible generation of secondary biogenic gases; and (5) conventional and hydrodynamic trapping along those boundaries to provide additional gas beyond that generated during coalification (fig. 2).

All coal-bearing rural Alaskan basins have the potential for coalbed methane resource development. Preliminary research and development targeting of coalbed methane provinces, basins, and villages have been accomplished. On the basis of geologic and hydrologic criteria, the Northern Alaska Province (Colville Basin), Upper Yukon Province (Yukon Basin), and Alaska Peninsula Province (Chignik Basin) are considered of greatest importance in making a significant economic contribution to the rural Alaskan gas supply (fig. 3). The Yukon-Koyukuk Province (Kobuk, Upper Koyukuk, and Lower Koyukuk Basins) and Nenana Province (Minchumina Basin) are thought to have secondary economic importance (fig. 3). We have prioritized the basin exploration and development program, in decreasing order of coalbed methane potential, to include the Colville, Yukon, Chignik, Upper Koyukuk, Lower Koyukuk,

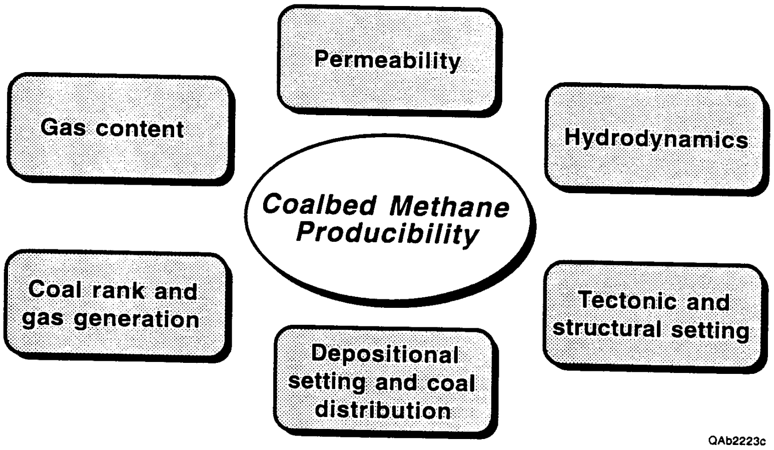


Figure 1. Geologic and hydrologic controls critical to coalbed methane producibility. Synergistic interplay among these controls and their spatial relations governs producibility (Kaiser and others, 1994; Scott and others, 1995; Tyler and others, 1997a, b).

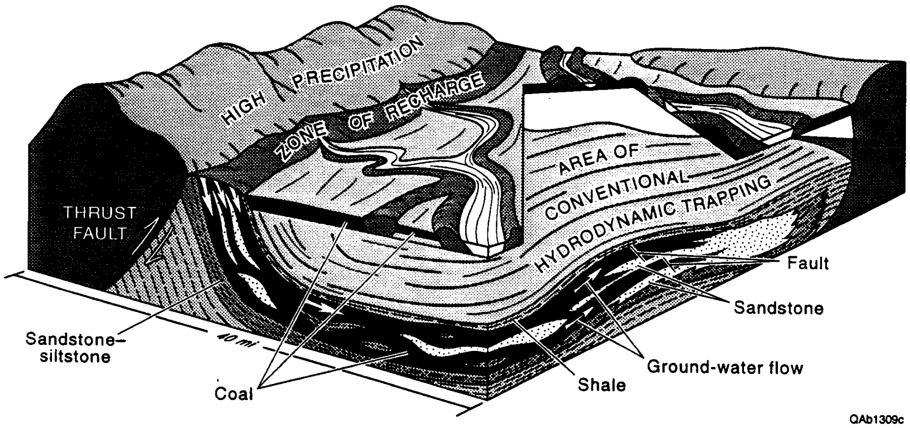


Figure 2. Model for high coalbed gas producibility based on the prolific producing San Juan Basin and marginally producing Sand Wash and Piceance Basins. Exceptionally high productivity is governed by (1) thick, laterally continuous coals of high thermal maturity; (2) adequate permeability; (3) basinward flow of ground water through coals of high rank and gas content orthogonally toward no-flow boundaries (structural hingelines, fault systems, facies changes, and/or discharge areas); (4) generation of secondary biogenic gases; and (5) conventional trapping along those boundaries to provide additional gas beyond that generated during coalification. Modified from Kaiser and others (1994); Scott and others (1995); and Tyler and others (1997a, b).

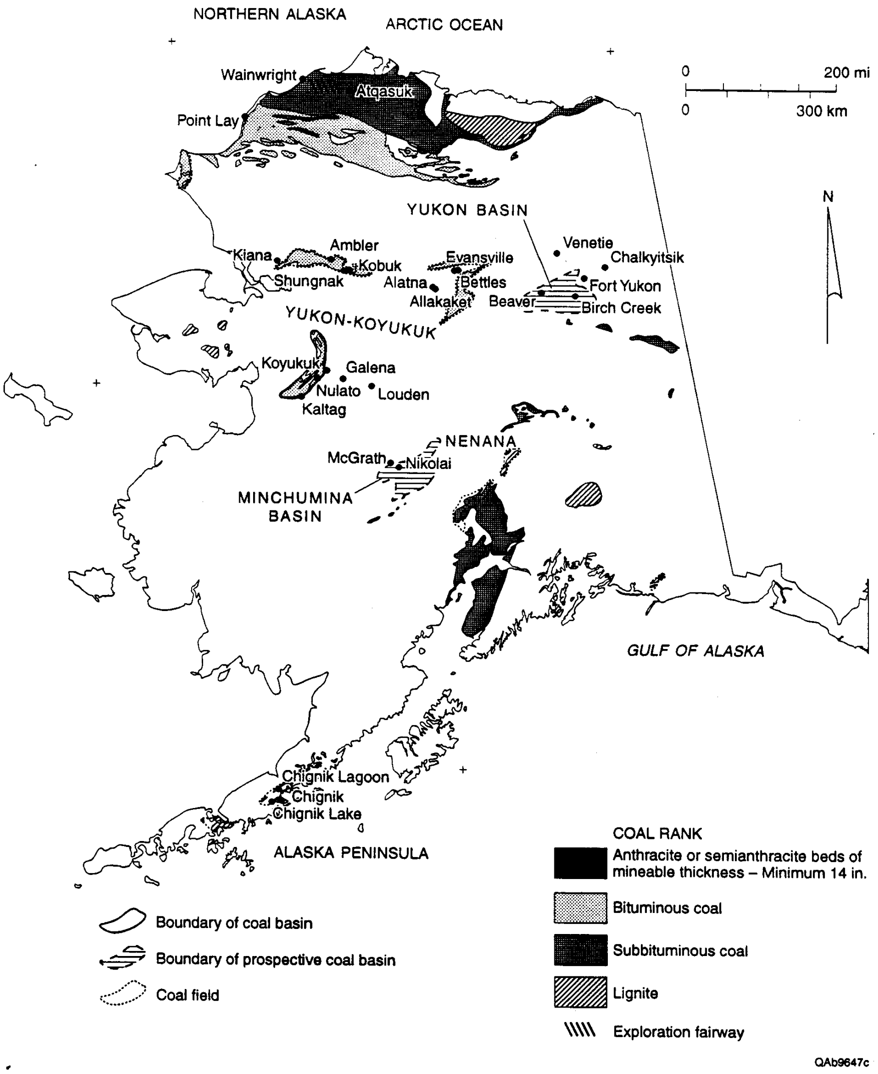


Figure 3. Coal rank and prioritized coalbed methane provinces, basins, and villages of rural Alaska (Modified from Merritt and Hawley, 1986). As a result of this evaluation, an exploration fairway is defined between the villages of Wainwright and Atqasuk and an area 30 mi (48 km) south of these towns. Coal ranks in Alaska range from lignite to anthracite.

and Kobuk Basins. Additionally we recommend that more data be collected in the highest ranked basins before undertaking an advanced drilling and exploration program. In order of decreasing importance, a summary of the coalbed methane potential in each basin follows.

Application of the coalbed methane producibility model shows that the North Slope has the highest potential for coalbed methane resource development of all rural Alaskan coal basins. Along the western North Slope and within the Colville Basin, the mechanism for coalbed methane resource development is conventional trapping. The traps are postulated to be both stratigraphic and structural, and an exploration fairway has been defined between the villages of Wainwright and Atqasuk and an area 30 mi (48 km) south of these villages. Stratigraphic traps are related to updip (northeast) pinch out of the coal beds behind the progradational shoreline sequences of the coal-bearing Nanushuk Group on the south flanks of the Barrow Arch and west flank of the Meade Arch. Structural traps within this area consist of fault-cored anticlines related to the Rocky Mountain Foreland (Brooks Range and Barrow Arch) orogenesis and gas traps formed against smaller-displacement faults. Moreover, traps supplied by the updip migration of thermogenic gases within the thick, laterally continuous coal beds and traps containing migrated gases beneath permafrost layers (clathrate development) are important exploration targets in addition to conventional trapping of coalbed resources within the exploration fairway. Coal rank in the Colville Basin supports coalbed methane resource development, approaching the high-volatile A bituminous coal ranks at depths of less than 6,000 ft (<1,829 m). Evidence of some saline water beneath the permafrost suggests that meteoric recharge from the Brooks Range may not have penetrated this far north and, therefore, gases in this area could be predominantly thermogenic and migrated thermogenic. Secondary biogenic gases may, however, be present locally. Additional analysis of subsurface hydrodynamics and water geochemistry should be undertaken to establish the extent of the saline aquifer development and to characterize ground-water attributes.

The coalbed methane resource potential of the Yukon Basin remains unknown because of inadequate data. Characterization of structural setting and depositional systems are tentative because of the absence of both surface and subsurface data. Coal rank documented from the shallow parts of the basin are too low for thermogenic gas generation, but in the deeper parts of the basin, where there is no data, coal rank may reach the thermal maturity level necessary to generate methane. The presence of gas escaping from lignites in the 1994 U.S. Geological Survey test well in the Yukon Basin is encouraging because it indicates the possible presence of active biogenic gas generation or migration of biogenic gas to this area. Although gas-content data were not collected, migration and accumulation of coal gas often results in higher-than-expected gas contents in lower rank coals. Coals in the Yukon Basin appear to be relatively thick (>21 ft [>6 m]) and gassy in this area, but it is possible that their thickness, lateral extent, and/or gas content are insufficient to support significant coal-gas production. Exploration and development of potentially shallow coalbed methane resources in the Yukon Basin, which could be similar to that developed in the Powder River Basin, Wyoming, should therefore only be undertaken when additional subsurface data have been processed and additional well data have been obtained.

The coalbed methane potential of the Alaskan Peninsula (Chignik area) may be limited because of structural and stratigraphic complexity. Coalbed methane resource development at depths greater than 4,000 ft (>1,210 m) is favored because coals in the area are either approaching or have reached the threshold of thermogenic gas generation and have significant mud-log-gas shows in oil exploration wells. The presence of water in an abandoned coal mine, moreover, indicates that at least some coal beds are permeable, and, therefore, secondary biogenic gas generation is a possibility. The area is structurally very complex, however, with potentially high in situ stresses that may significantly reduce or eliminate permeability in subsurface coal beds. Additionally, dewatering of permeable coal beds may prove to be uneconomical because of the high annual precipitation rates and proximity to the ocean. Exploration and development for coalbed methane should, therefore, only be undertaken after an advanced and extensive stratigraphic and structural study of the Chignik area is completed.

The coalbed methane potential of the Minchumina Basin remains unknown because of inadequate data. If the low coal ranks observed at the surface persist at depth, then the coalbed methane potential may be low, particularly if the coals do not crop out in the elevated margins of the basin. Convergent and upward flow potential may occur along the Kuskokwim River near the town of McGrath, suggesting that coal gases may accumulate in this area. However, the migrated gases will move out of the system if there are no or inadequate permeability barriers associated with the upward flow potential. The apparently low coal ranks near the surface suggest that if coal gases are found in this area, they may be dominantly secondary biogenic in origin. The town of Nikolai may be more favorably located for higher coalbed methane potential because of potentially thicker Tertiary fill. Additionally, present-day ground water flows to the northwest at an oblique angle to the assumed net coal trends (north and northeast), possibly enhancing the trapping of migrating coal gases.

The coalbed methane potential of the Upper Koyukuk area also remains unknown because of the lack of data. Additional surface and subsurface data will be required before coalbed methane development can occur in the Minchumina Basin. Although there are some favorable hydrogeologic attributes in this basin, the overall coalbed methane potential is questionable because of the absence of thick coal beds. Ground water flows southward from the Brooks Range toward the towns of Bettles and Evansville in the Upper Koyukuk area, but the Malamute Fault, located on the south margin of the Brooks Range, may inhibit basinward flow of ground water. A thin (<1-mi [<1.6-km]) outcrop of potentially coal-bearing rocks is however, exposed immediately south of this fault system (north of Bettles and Evansville), and these rocks generally dip to the south (Patton and Miller, 1973), suggesting favorable orientation for recharge. If coals are present in the subsurface and if they are aquifers, then meteoric recharge will enter the coals north of the two villages and possibly turn upward at the South Fork Fault located approximately 1 mi (~1.6 km) south of Bettles and Evansville. Although this suggests that the towns Bettles and Evansville are in a favorable position for the accumulation of coal gases, the relatively small area of recharge, discontinuity, or absence of coal beds in the area and apparent high levels of thermal maturity around this area may limit the coalbed methane potential. The apparent absence of coal-bearing rocks in the Alatna and Allakaket areas suggests that coalbed methane is absent in this area. The Upper Koyukuk Basin is given a very low coalbed methane exploration and development priority.

The high level of thermal maturity of the Lower Koyukuk Basin coupled with steeply dipping beds (structural complexity), the presence of only thin and discontinuous coal beds, discontinuous permafrost (general absence of vertical permeability barriers), and limited meteoric recharge basinward toward Galena limit the coalbed methane potential of this area. Thicker coal beds have, however, been reported near Louden, and secondary biogenic and/or migrated thermogenic coal gases may accumulate locally. Coal gas from bituminous coals may therefore occur along the Lower Koyukuk and Yukon Rivers if migration and trapping of gases have occurred and if viable drilling targets can be delineated (Smith, 1995). The Lower Koyukuk is given a very low coalbed methane exploration and development priority.

Detailed field studies have not been performed in the Kobuk Basin to evaluate coal resources fully in the Kobuk coal region, and outdated and sparsely published reports indicate the presence of only minor coal beds in the area, most of which are generally less than 3 ft (<1 m) thick. Additionally, surface vitrinite-reflectance values of Cretaceous coal-bearing rocks north and south of the Kobuk Basin are very high (1.3 to more than 5.0 percent), indicating that the coals may have already passed through the hydrocarbon-generating window. Cretaceous sedimentary rocks in the area are characterized by very low permeability, suggesting that if the coals have developed cleat and are permeable, they may be potential aquifers. If the coals are laterally continuous, moreover, then there may be potential for secondary biogenic gas generation and accumulation. However, accumulation of coal-gas resources will depend on local coalbed geometry and the presence of permeability barriers and/or seals for trapping the coal gases. The Kobuk Basin is assigned a very low coalbed methane potential because of very high thermal maturity, the presence of only thin coal beds (according to available data), and the lack of adequate surface and, especially, subsurface data to fully evaluate coal and coalbed methane resources.

The next phase in the development of coalbed methane resources of rural Alaska will be drilling and testing of the exploration fairway defined in the prioritized North Slope Province–Colville Basin in conjunction with advanced basin analysis. According to data available and application of the producibility model to the prioritized basin, drilling and testing of the coalbed methane fairway should be undertaken between the villages of Wainwright and Atqasuk and an area 30 mi (48 km) south of these villages. Detailed and advanced coalbed methane resource evaluation, including outcrop, geologic, and hydrologic coal reservoir characterization, should be undertaken close to the prioritized villages. The North Slope fairway has the highest priority, followed by possible wildcat prospects near the villages of Fort Yukon and Chignik Lake. Obtaining additional data, including geophysical logs from old wells and advanced geologic and hydrologic reservoir characterization, are a prerequisite for resource development in the Yukon and Alaskan Peninsula coal provinces. Recompletion of existing exploration well bores may offset some of the drilling costs in these areas.

It is hypothesized that the first (one or two) wells drilled in the rural Alaskan exploration program will be key to the future of coalbed methane development in the state. Fairways should therefore be targeted in the basin having the most available data (North Slope-Colville Basin) and the highest probability of penetrating thick, laterally continuous and gassy coal beds. Drilling a dry hole having little or no coal, or low gas contents, during early exploration attempts may severely retard future coalbed methane exploration and development in rural Alaska. The drilling program should proceed with the cooperation of local operators familiar with drilling in permafrost regions and with local organizations that can provide additional data and information for complete evaluation of the coalbed methane potential.

INTRODUCTION

The Bureau of Economic Geology (BEG), The University of Texas at Austin, has developed a basin-scale producibility model for defining areas of prolific coalbed methane production based on over a decade of research performed in the Rocky Mountain Foreland, Western United States. As part of a cooperative agreement between the BEG and the Division of Geological and Geophysical Surveys (DGGS), Department of Natural Resources, State of Alaska, this producibility model was applied to the evaluation of coalbed methane resources in rural Alaskan coal provinces and basins. The cooperative agreement evaluated the coalbed methane resources of rural Alaska by selecting coalbed methane exploration basins and fairways for the purpose of drilling and testing their potential as an alternative rural energy source to be used for local electrical power generation and home heating. Although Alaska's potential for coalbed methane resources may be as high as 1,000 trillion cubic feet (28 Tm^3) (Smith, 1995), the actual number of methane-bearing coal basins and resources is still mostly unknown and the extent and magnitude of producible gas remains untested.

The BEG coalbed methane producibility model that was applied to rural Alaskan coal basins considered all available geologic and hydrologic criteria and data. Importantly, coalbed methane producibility and resource assessment in rural Alaska is governed by six critical factors: tectonic/structural setting, depositional systems and coal distribution, coal rank, gas content, permeability, and hydrodynamics (fig. 1). Coal beds are both the source and the reservoir for methane, indicating that their distribution and occurrence within a basin is critical in establishing a coalbed methane resource. Exceptionally high productivity within a basin will be governed by (1) thick, laterally continuous coals of high thermal maturity, (2) adequate permeability, (3) basinward flow of ground water through high-rank coals and high gas content orthogonally toward no-flow boundaries (regional hingelines, fault systems, facies changes, and/or discharge areas), (4) generation of secondary biogenic gases, and (5) conventional trapping along those boundaries to provide additional gas beyond that generated in situ during coalification (fig. 2).

We believe that the coalbed methane exploration and development program in rural Alaska has progressed to the point where basin analysis that is, understanding the dynamic interaction among these key geologic and hydrologic factors, can be used to define exploration fairways that potentially may have high coalbed methane producibility.

As part of the cooperative agreement, we considered all rural coal-bearing Alaskan basins to have the potential for coalbed methane resource development. The rural coal basins assessed in this evaluation were distant to any existing infrastructure (roads and railway lines) as required by development and exploratory constraints recommended by DGGS in the cooperative agreement. Moreover, the villages for coalbed methane resource development and evaluation were selected based on economic constraints defined by the DGGS using the DCRA Community Database (1997). On the basis of our initial geologic and hydrologic assessment, the Northern Alaska Province (Colville Basin), Upper Yukon Province (Yukon Basin), Alaska Peninsula Province (Chignik Basin), Yukon-Koyukuk Province (Kobuk, Upper Koyukuk, and Lower Koyukuk Basins) and Nenana Province (Minchumina Basin) were considered important in making an economic contribution to the rural Alaskan gas supply (fig. 3).

HISTORICAL BACKGROUND TO COALBED METHANE RESOURCE DEVELOPMENT

Methane produced from coal beds is an important energy source in the United States and continued exploration and development of this resource in Alaska will be of economic significance and benefit to the state and particularly the rural Alaskan population. To date, exploration of coalbed methane resources in Alaska has been limited to the Cook Inlet. Successful exploitation in the Lower 48 States has been restricted to the Rocky Mountain Foreland and Appalachian Basins. What has not been widely recognized about the Lower 48 states experience is that whereas coalbed methane resources in some basins have been successfully exploited, other basins with seemingly similar geologic and hydrologic attributes have proven to be relatively poor to moderate coalbed methane producers. Understanding the reasons for these production contrasts through detailed basin analysis and drilling are vital for coalbed methane exploration and development in rural Alaska.

Our understanding of the controls on coalbed methane producibility in Alaska is based on a decade of comprehensive and comparative geologic and hydrologic research and development of the San Juan, Greater Green River (Sand Wash), and Piceance Basins, and reconnaissance studies of several other producing and prospective coal basins in the western United States (Tyler and others, 1991, 1994, 1995a, b, 1997b; fig. 4). The San Juan Basin is the world's most prolific coalbed methane basin, with cumulative production exceeding 1 Tcf (>28 Bcm). Our basin-scale model for coalbed methane producibility has evolved out of a comparison of the San Juan Basin and the marginally producing Sand Wash and Piceance Basins. The comparison is appropriate because although these basins share similar geologic and hydrologic attributes, the dynamic interaction among these key attributes varies in each basin. Prior to research and development efforts, the Sand Wash and Piceance Basins were viewed as being potentially very productive, but subsequent drilling and production efforts showed them to be poor to moderate producers. To date, Sand Wash Basin coals have yielded large volumes of water and little gas, and Piceance Basin coals have produced little water and limited gas.

Additional sources of gas are required to achieve high gas contents that are found in many frontier basins for consequent high productivity (Scott and others, 1994a). These additional sources of gas are generally conventionally and hydrodynamically trapped migrated gases, in-situ-generated secondary biogenic gases, and/or solution gases. To delineate the presence and origin of these additional sources of gas in Alaska requires a detailed basin analysis that includes an understanding of the interplay among tectonic and structural setting, depositional systems and coal distribution, coal rank, gas content, and hydrodynamics. This research should be followed by a program of drilling, well and coal data acquisition, and exploration. The objectives of the cooperative agreement are to: (1) evaluate geologic and hydrologic controls on coalbed methane producibility in selected rural Alaskan coal basins; (2) encourage and promote additional exploration and development of coalbed methane in rural Alaskan coal basins; and

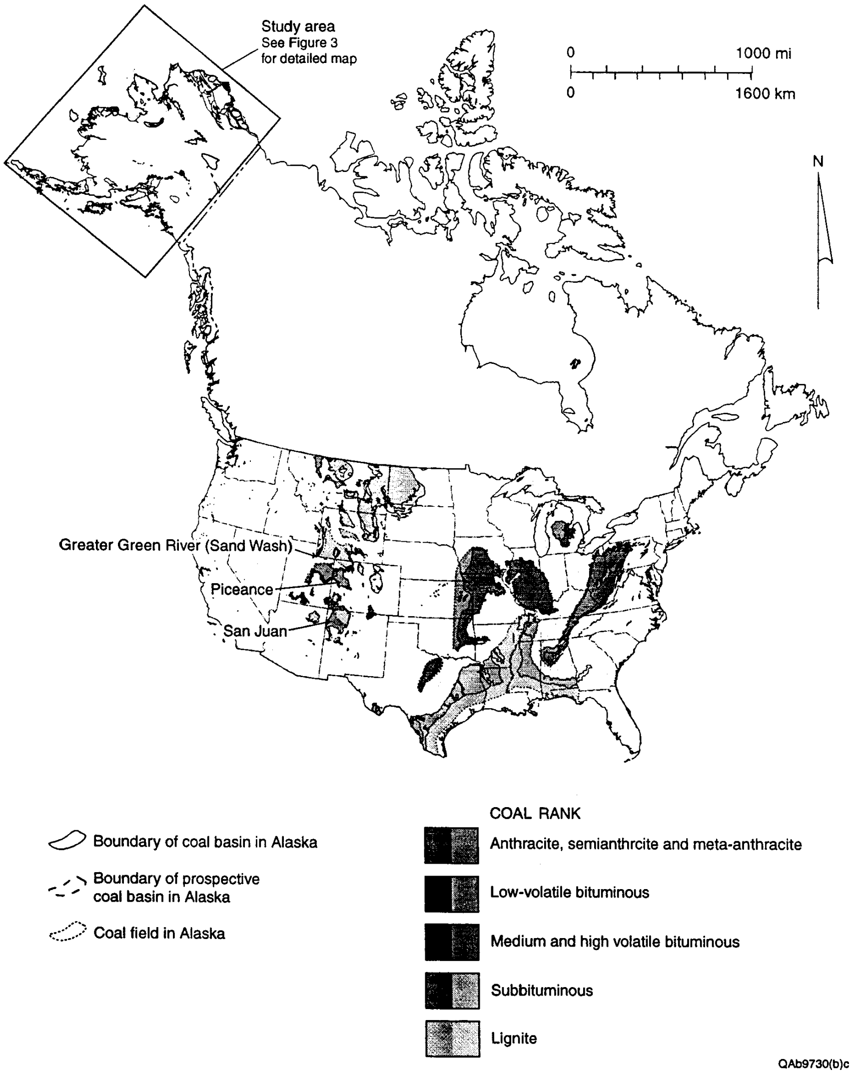


Figure 4. Coal basins and coalbed methane resources of the United States of America. Total coalbed methane resources are estimated to exceed 675 Tcf (18.9 Tm^3) in the lower 48 States (Scott and others, 1994) and over 1,000 Tcf (28 Tm^3) in Alaska (Smith, 1995). Our understanding of the controls on coalbed methane producibility is based on comprehensive geologic and hydrologic studies of the San Juan, Greater Green River (Sand Wash), and Piceance Basins in the western United States (Modified from Wood and Bour, 1988).

(3) communicate the coalbed methane potential in the state in order to create a momentum for future exploration and development of coalbed methane resources in rural Alaska.

BENEFITS OF DEVELOPING RURAL ALASKAN COALBED METHANE RESOURCES

The benefits of exploring and developing a coalbed methane program in rural Alaska will be the profitable recovery of a local source of gas. Coalbed methane is a an alternative, environmentally friendly source of energy (gas and/or electricity) that can be used in the rural villages as an alternative to more expensive and potentially environmentally damaging diesel fuel. Coalbed methane may be the opportunity for both the State of Alaska and rural Alaskans to economically recover and possibly profit from coalbed methane production. By using technologies available from the Lower 48 states, the State of Alaska and its rural communities may capture significant quantities of the methane present in many coal basins. The exploitation of coalbed methane in rural Alaska may (1) create jobs within the local villages, (2) capture clean-burning energy that is currently being under exploited, and (3) reduce emissions of methane, a greenhouse gas that is about 20 times more damaging to the atmosphere than carbon dioxide. Moreover, if the State of Alaska could provide timely information about the benefits of coalbed methane by initiating technology transfer and an extensive drilling program, then companies and local communities may be encouraged to develop energy resources that are currently under exploited in Alaska. However, mechanisms to attract other investors and to raise the awareness of profitable coalbed methane recovery opportunities in Alaska must first be developed by communicating the value of coalbed methane recovery to other organizations (for example: the North Slope Borough, Arctic Slope Regional Corp., etc.) and relevant government agencies (for example: the United States Department of Energy, Environmental Protection Agency, etc.), so as to create the momentum for development. This report is the initial State of Alaska investment in a plan that may ultimately lead to the drilling, exploration, and development of coalbed methane in rural Alaskan settlements in an attempt to offset the increasing costs of transporting diesel fuel to these communities.

THE COALBED METHANE PRODUCIBILITY MODEL: DEFINING GEOLOGIC AND HYDROLOGIC CONTROLS ON EXPLORATION AND DEVELOPMENT

Detailed studies in the San Juan, Greater Green River (Sand Wash), and Piceance Basins and several other United States coal basins (fig. 4) show that tectonic and structural setting, coal distribution and rank, gas content, permeability, and hydrodynamics control the producibility of coalbed methane (fig. 1). Coal beds are the source and reservoir for methane, indicating that their distribution within a basin is critical in establishing a significant coalbed methane resource. Coal distribution is closely tied to the tectonic, structural, and depositional settings because peat accumulation and preservation requires a delicately balanced subsidence rate that maintains optimum water-table levels but excludes disruptive clastic sediment influx. The depositional systems define the substrate upon which peat growth is initiated and within which the peat swamps proliferate. Knowledge of depositional framework enables predication of coalbed thickness, geometry, and continuity and, therefore, areas of potential coalbed methane resources.

Coals must also reach a certain threshold of thermal maturity (vitrinite reflectance values between 0.8 and 1.0 percent; high-volatile A bituminous) before large volumes of thermogenic gases can be generated (Scott and Kaiser, 1996). The amount and types of coal gases generated during coalification are a function of burial history, geothermal gradient, maceral composition, and coal distribution within the thermally mature parts of a basin. Although higher rank coals generally have higher gas contents, gas content is not determined by coal rank alone; gas content is not fixed but changes when equilibrium conditions within the reservoir are disrupted (Scott and Kaiser, 1996). Gas content of coals can be enhanced, either locally or regionally, by generation of secondary biogenic gases or by diffusion and long-distance migration of gases to no-flow boundaries such as structural hingelines or faults for eventual resorption and conventional trapping (Scott and others, 1994a; Scott and Kaiser, 1996).

Permeability and ground-water flow are additional controls critical to methane producibility. They are intimately related to coal distribution, and depositional and tectonic/structural setting because basinward flow of ground water through coal beds requires recharge of laterally continuous permeable coals at the structurally defined basin margins. Permeability in coal beds is determined by its fracture (cleat) system, which in turn is largely controlled by the tectonic/structural and paleostress regime. Cleats are the permeability pathways for migration of gas and water to the producing well head, and cleats may either enhance or retard the success of the coalbed methane completion. The coals, therefore, act not only as conduits for gas migration but also are commonly ground-water aquifers having permeabilities that are orders of magnitude larger than associated sandstones.

However, simply knowing the characteristics of the geological and hydrological controls will not lead to a conclusion about coalbed methane producibility because it is the complex interplay among these controls and their spatial relationships that governs producibility; high coalbed methane productivity requires a synergistic interplay among these controls. That synergism is evident in a comparison of the prolific San Juan Basin and marginally producing Greater Green River (Sand Wash) and Piceance Basins (Kaiser and others, 1994; Tyler and others, 1995a, b). In the San Juan Basin, ground water flows through laterally continuous, high-rank, high-gas-content coals orthogonally toward lower rank coals at a no-flow boundary or flow barrier along a structural hingeline (Ayers and others, 1991; Ayers and Kaiser, 1994). At this point in the basin, flow turns upward and coalbed wells typically produce >1,000 Mcf/d (>28 Mm^3/d) and small volumes of water. A combination conventional and hydrodynamic trap is postulated to exist along the hingeline. Coal gases in the high productivity fairway are a combination of secondary biogenic and migrated thermogenic and biogenic gases (Scott and others, 1994a, b). In the Sand Wash Basin, a subbasin within the Greater Green River Basin, flow is through low-rank, low-gas-content coals toward areas of higher thermal maturity (Kaiser and others, 1993, 1994). The absence of seals and permeability contrasts limit the potential for conventional trapping of gas in the Sand Wash Basin. In the Piceance Basin, net coal is thickest in a north-south trending belt, behind west-east prograding shoreline sequences (Tyler and others, 1991, 1995a). Depositional setting and thrust faults cause coals along the Grand Hogback and in the subsurface to be in modest to poor reservoir and hydraulic communication (McMurry and Tyler, 1996; Scott, 1996). Meteoric recharge and flow basinward is thus restricted; permeability of coals and sandstone in the basin are generally in the microdarcy range, indicating that meteoric recharge is limited to basin margins. Moreover, extraordinary coalbed methane production is precluded by the absence of dynamic ground-water flow. The best potential for coalbed methane production in the Piceance Basin may lie in conventional traps basinward of where outcrop and subsurface coals are in good hydraulic communication (Tyler and others 1995a, b; 1997a, b).

Out of a geologic and hydrologic comparison between the San Juan, Greater Green River (Sand Wash), and Piceance Basins (fig. 4), the basin-scale coalbed methane producibility model evolved (Kaiser and others, 1994; Tyler and others, 1995a, b; Scott and others, 1995), and was applied to the rural Alaskan coal basins. The model's essential elements for high coalbed methane resource production in rural Alaska are (1) ground-water flow basinward through coals of high rank and high gas content orthogonally toward no-flow boundaries or flow barriers (structural hingelines, fault systems, facies changes, and/or discharge areas) accompanied by generation of secondary biogenic gas and (2) conventional trapping of migrated and solution gases along those barriers (fig. 2). Gas gathered by lateral flow, either dissolved or entrained, is swept basinward ahead of an advancing flux of meteoric water for conventional and hydrodynamic trapping. When flow direction is orthogonal to flow boundaries, the largest possible area of flow is intercepted, thus maximizing the opportunity for resorption and conventional trapping of gas, which plays a much more important role in coalbed methane production than is generally recognized. In rural Alaska, there is subsequent to basin uplift and cooling a need for additional sources of gas beyond that initially sorbed on the coal surface to achieve higher gas. Those additional sources of gas are migrated thermogenic, conventionally trapped, secondary biogenic, and solution gases. Understanding the reasons for these contrasts in producibility is applicable and vital to Alaskan coalbed methane exploration development.

THE APPLICATION OF THE COALBED METHANE PRODUCIBILITY MODEL IN DEFINING EXPLORATION FAIRWAYS WITHIN RURAL ALASKAN COAL BASINS

The initial screening of rural Alaskan coal basins considered all basins as frontier exploration targets with the potential for coalbed methane exploration and development. Initial screening involved the reviewing of the existing regional data base at the DGGS including literature, technology, economics, and resources available. Multiple Alaskan coal provinces (5), basins (7), and towns/villages (26) were selected as potential sites for focused and more detailed screening and evaluation (figs. 3 and 5). These basins included the Northern Alaska Province (Colville Basin), Yukon-Koyukuk Province (Kobuk, Upper Koyukuk, and Lower Koyukuk Basins), Upper Yukon Province (Yukon Basin), Nenana Province (Minchumina Basin), and Alaska Peninsula Province (Chignik Basins) (fig. 3). Towns and villages included Atqasuk, Point Lay, Wainwright, Ambler, Kiana, Kobuk, Shungnak, Alatna, Allakaket, Bettles, Evansville, Beaver, Birch Creek, Chalkyitsik, Fort Yukon, Venetie, Galena, Kaltag, Koyukuk, Louden, Nulato, Nikolai, McGrath, Chignik, Chignik Lake, and Chignik Lagoon (fig. 5).

A regional data base was then established, in which data obtained from the DGGS and literature (including geologic and hydrologic attributes, production engineering, and economic criteria) were evaluated, compared, and ranked. This task involved basin analysis and reservoir characterization of the 7 basins and 26 towns selected for advanced coalbed methane exploration, research, and development. This included a more in-depth geologic and hydrologic basin analysis, with new insights and interpretations that described the controls critical to coalbed methane producibility and resource assessment, primarily in the three higher-ranked rural Alaskan coal basins (Colville, Yukon, and Chignik). These prioritized basins were considered to be of greater importance to the development of the rural Alaskan gas supply, based on project economics and the available data supplied. In these basins, original and interpretive tectonic and

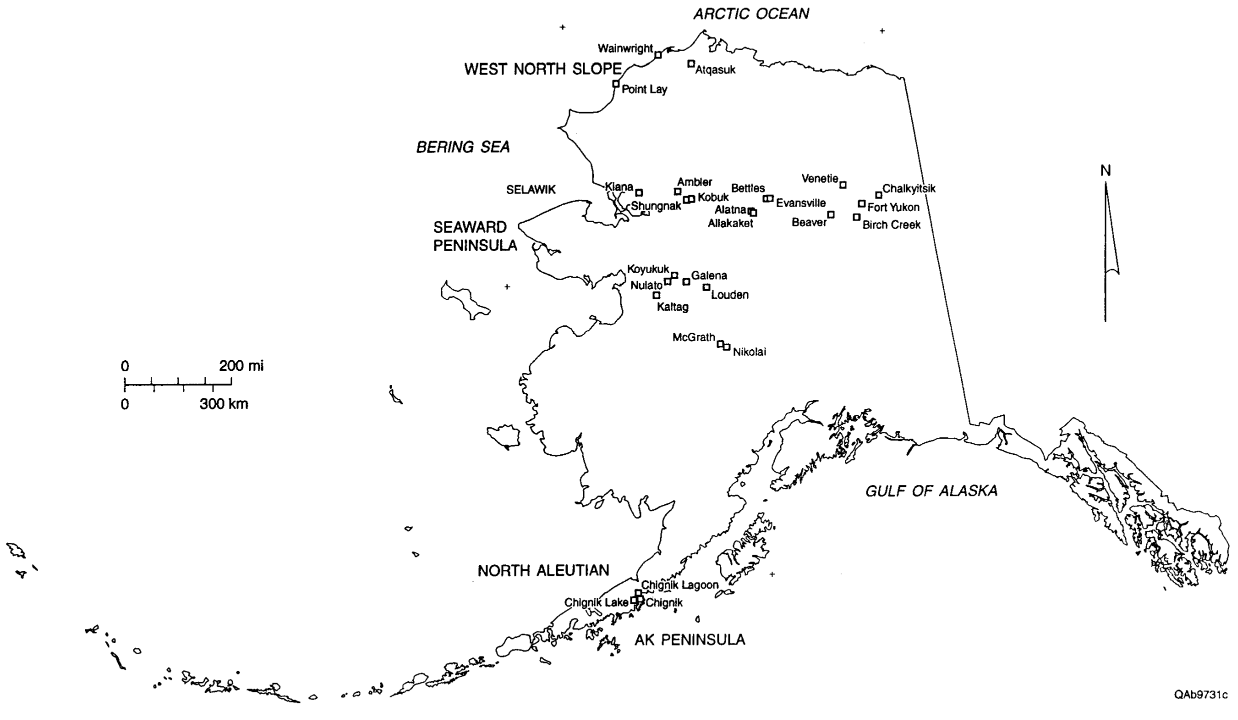


Figure 5. The 26 prioritized rural villages were selected based on economic constraints defined by the DGGS using the DCRA Community Database (1997).

structural, stratigraphic, coalification and burial history, ground-water flow, and production analyses were undertaken to the extent to which data were available. An improved data base was created where possible, followed by new interpretations of the controls on reservoir conditions and coalbed methane producibility. Using the producibility model, these controls were synergistically combined to define exploration fairways. Importantly, all data were integrated for prospect development using the producibility model to identify exploration fairways that are proximal to rural villages that need gas resources and that have coal deposits occurring at depths of less than 3,000 ft (914 m) (as requested by DGGS in the cooperative agreement).

The evaluation of each basin was configured to terminate at any point during the project or to proceed to successively with more sophisticated levels of analysis depending on available data. Each decision was reached on the basis of an integrated geologic and hydrologic evaluation. The sections below document in more detail the methods and procedures used in selecting a basin, village and/or exploration fairway for future coalbed methane exploration and development in rural Alaska.

Regional Basin Analysis Framework

The exploration and development program, performed in cooperation with the DGGS, the University of Alaska, individual operators, and local inhabitants, has concentrated on selected frontier coalbed methane basins for exploration and development within rural Alaska. In collaboration with the DGGS, our initial investigation favored testing of the coalbed methane producibility model in all rural Alaskan coal provinces and basins. Based on discussions with the DGGS (James G. Clough, October, 1996), total coal resource estimates available (fig. 6), current data available (tables 1 through 9), town and village economics, and the need to be distant from any existing infrastructure such as roads, pipelines, and major cities, the Northern Alaska Province (Colville Basin), Yukon-Koyukuk Province (Kobuk, Upper Koyukuk, and Lower Koyukuk Basins), Upper Yukon Province (Yukon Basin), Nenana Province (Minchumina

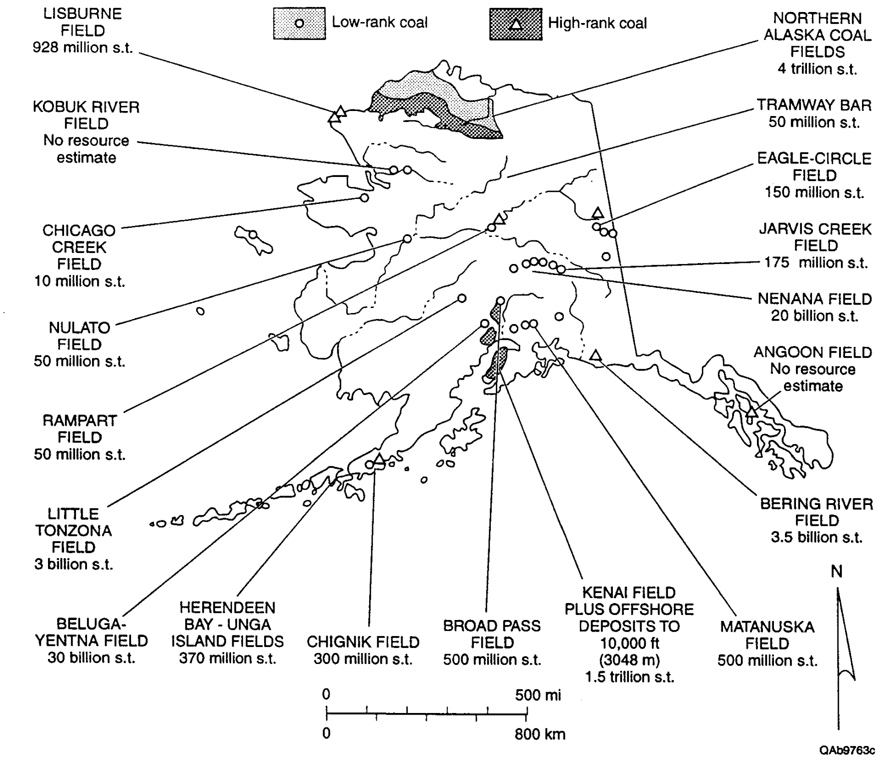


Figure 6. Coal resources (in short tons) of Alaska coal basins as defined by Rao and Walsh (1991). (short ton = 0.9078 metric tons).

Table 1. Summary of coal provinces, fields, and villages evaluated for coalbed methane potential.

Basins	**Colville (North Slope)**	**Kobuk**	**Upper Koyukuk**	**Lower Koyukuk**	**Yukon**	**Minchumina**	**Alaska Peninsula**
PROVINCE	Northern Alaska	North Alaska/ Yukon-Koyukuk	Yukon-Koyukuk	Yukon-Koyukuk	Yukon-Koyukuk	Nenana Province	Alaska Peninsula
FIELDS	Wainwright Kukpowruk	West Kobuk East Kobuk	Tramway Bar	Nulato		Little Tonzona	Chignik Lake
VILLAGES	Atqasuk Point Lay Wainwright	Ambler Kiana Kobuk Shungnak	Alatna Allakaket Bettles Evansville	Galena Kaltag Koyukuk Louden Nulato	Beaver Birch Creek Chalkyitsik Fort Yukon Venetie	Nikolai McGrath	Chignik Chignik Lake Chignik Lagoon

Table 2. Economic attributes of villages and basins.

ECONOMIC ATTRIBUTES	Colville (North Slope)	Kobuk	Upper Koyukuk	Lower Koyukuk
Number of towns	3	4	4	5
Populations	994	1,048	246	1,245?
Regional corporation	Arctic Slope Regional Corp.	NANA Regional Corp.	Doyon Limited	Doyon Limited
Village corporation	Atqasuk Village Cully Corporation (Point Lay) Olgoonik Corporation (Wainwright)	None	Evansville, Inc. (Evansville)	None
Distance to port (mi)	very close, summer only	>50	>50	>50
Distance to major road (mi)	>50	>50	<40	>50
Distance to rail (mi)	>50	>50	<40	>50
Distance to pipeline (mi)	N/D	N/D	N/D	N/D
Landing strip	Yes	Yes	Yes (Bettles)	Yes

Table 2 (cont.).

ECONOMIC ATTRIBUTES	**Yukon**	**Minchumina**	**Alaska Peninsula**
Number of towns	5	2	3
Populations	1,046	604	360
Regional corporation	Doyon Limited	Doyon Limited	Bristol Bay Native Corp.
Village corporation	Beaver Kwit'chin C Tihteet'all, Inc (Birch Creek) Chalkyitsik Native Corp. Gwitchyaa Zhee Corp. (Fort Yukon)	MTNT Limited (McGrath)	Far West, Inc. (Chignik) Chignik Lagoon Native Corp. Chignik River Limited (Chignik Lake)
Distance to port (mi)	>50	>50	very close
Distance to major road (mi)	>50	>50	>50
Distance to rail (mi)	>50	>50	>50
Distance to pipeline (mi)	N/D	N/D	N/D
Landing strip	Yes	Yes	Yes

Table 3. Summary of resources in basins evaluated for coalbed methane potential.

RESOURCES	Colville (North Slope)	Kobuk	Upper Koyukuk	Lower Koyukuk
Area (mi^2)	60,000 (83,000 km^2)	772 (2,000 km^2)	N/D	3,475 (9,000 km^2)
Coal resources (billions of short tons)	150	N/D	>15	>0.05
Potential resources (billions of short tons)	4,000	1,080	>1,135	N/D
Coal rank	Lig to lvb	Hvb to lvb	Hvb	High vol. bit
Gas content (Scf/ton)	N/D	N/D	N/D	N/D
Gas in place (Tcf)	N/D	N/D	N/D	N/D
Age of coals	Low Cret./Tert.	Upper Cret./Tert.	Upper Cret./Tert.	Upper Cret./Tert.
Name, Group/Formation	Lisburne-Nanushuk-Colville	Bergman/Kaltag	Bergman/Kaltag	Bergman/Kaltag

RESOURCES	Yukon	Minchumina	Alaska Peninsula
Area (mi^2)	8,500 (22,000 km^2)	7,722 (20,000 km^2)*	10,000 (25,900 km^2)
Coal resources (billions of short tons)	Unknown	<1.5	200
Potential resources (billions of short tons)	>1,000	>3,000*	3,000
Coal rank	Subbit. High vol. bit	Subbit. High vol. bit	Lig., high-low vol. bit.
Gas content (Scf/ton)	N/D	N/D	N/D
Gas in place (Tcf)	N/D	N/D	N/D
Age of coals	Upper Cret./ Tert.	Olig./ Mioc. (Tert.)	Upper Cret./Tert.
Name, Group/Formation	Bergman/Kaltag	Usibelli	Chignik/Herendeen Coal Valley

* Nenana Coal Province

Table 4. Structural characteristics of basins evaluated for coalbed methane potential.

STRUCTURE	Colville (North Slope)	Kobuk	Upper Koyukuk	Lower Koyukuk
Structural relations	Complex	Half-graben	Low lands/half-graben	Low lands/half-graben
Thrusted/elevated margins	Yes, relaxed tectonic regime to extensional fault/fold	Dips >40°; folds/faults	Steep dips	Complex-to-severe deform
Intrabasin uplifts	Yes	Possible	Structurally Complex	Dips >60°
Cleat occurrence	Open (good cleat)	N/D	N/D	N/D
Cleat orientation	NW and NE	N/D	N/D	Abundant brecciation
Structure dip changes	Many faults NW, NE	Numerous	Numerous	Numerous
Stress regime (in-situ)	Low-to-medium stress	Intense deformation	Intense deformation	Intense deformation
Lineaments	Not mapped	N/D	N/D	N/D
Geophysical (aeromag, gravity)	Abundant	N/D	N/D	N/D
Structural cross-section	Abundant	N/D	N/D	N/D

STRUCTURE	Yukon	Minchumina	Alaska Peninsula
Structural relations	Low lands/half-graben	Low lands/half-graben	Complex-considerable uplift
Thrusted/elevated margins	Complex graben-steep dip	Steep dips	Moderate-to-complex faults/folds
Intrabasin uplifts	Near vertical south and west margin	Possible to vertical	
Cleat occurrence	Poor to moderate	Good blocky cleat	Uplift could enhance cleat spacing
Cleat orientation	Highly fractured (Drew Mine)	N/D	
Structure dip changes	Abundant on margins	Abundant	Anticline through field
Stress regime (in-situ)	High on margins	Yes	Very high stress
Lineaments	Some	Some	Some
Geophysical (aeromag, gravity)	Yes	N/D	N/D
Structural cross-section	Yes (proprietary)	N/D	N/D

Table 5. Depositional styles of basins evaluated for coalbed methane potential.

DEPOSITIONAL SETTING	**Colville (North Slope)**	**Kobuk**	**Upper Koyukuk**	**Lower Koyukuk**
Group/Formation Name	Lisburne-Nanushuk-Colville	Bergman/Kaltag	Bergman/Kaltag	Bergman/Kaltag
Net coal thickness (ft)	255 ft (78 m)	Thin coal	Thin coal	Thin coal
Maximum coal thickness (ft)	Cret. up to 20 ft./Tert. up to 50 ft	<6 ft (1.8 m)	up to 18 ft (5 m)	<11 ft (3.3 m)
Typical coal thickness (ft)	5-10 ft (1.5 - 3 m)	2-3 ft (0.6 - 0.9 m)	3-12 ft (0.9 - 4 m)	<4 ft (1.2 m)
Depth to coal (ft)	Surface to >6000 ft (18 - 9 m)	N/D	N/D	N/D
Coal seam continuity	Very good	Very discontinuous	Very discontinuous	Very discontinuous
Depositional system	Fluvial-deltaic (prograding NE)	Deltaic (?)	Deltaic (?)	Deltaic (?)
Coal interval thickness (ft)	4,500 -7,000 ft (1372 - 2134 m)	10,000 ft (?) (3048 m)	10,000 ft (?) (3048 m)	10,000 ft (?) (3048 m)
Stratigraphic cross-section	Thins to 900 ft (Barrow)	West progradational	West progradational	West progradational
Depth/Notes	>10,000 ft (3048 m)	Abrupt deposition	Abrupt deposition	Abrupt deposition

DEPOSITIONAL SETTING	**Yukon**	**Minchumina**	**Alaska Peninsula**
Group/Formation Name	Bergman/Kaltag	Usibelli	Chignik-Herendeen
Net coal thickness (ft)	Thin coal	228 ft (69 m)	Up to 28 ft (8.5 m)
Maximum coal thickness (ft)	Up to 30 ft (9 m)	Up to 38 ft (12 m)	<8 ft (24 m)
Typical coal thickness (ft)	<5 ft (1.5 m)	20 ft (6 m)	3-5-16 ft (0.9 - 1.5 - 5 m)
Depth to coal (ft)	N/D	N/D	<9,000 ft (2743 m)
Coal seam continuity	Laterally discontinuous	Problematic mapping	Laterally discontinuous
Depositional system	Fluvial	Fluvial/Coastal Plain	Flood plain-paludal-lacustrine
Coal interval thickness (ft)	N/D	6,000 ft* (1829 m)	1,200 ft ? (366 m)
Stratigraphic cross-section	N/D	West progradational	SE progradational
Depth/Notes	N/D	Abrupt deposition	<9,000 ft (2743 m)

* Nenana Coal Province

Table 6. Hydrogeologic characteristics of basins evaluated for coalbed methane potential.

HYDROLOGY	Colville (North Slope)	Kobuk	Upper Koyukuk
Predicted pressure regime	Underpressure to overpressure	Normal to underpressure; local overpressure	Normal to underpressure; local overpressure
Chlorinity at depth	Brackish-to-saline water	Possible fresh to brackish	N/D
Permeability (md)	<1 md (sand)	<1 md (sand)	N/D
Pressure transition	Probably present	Limited/unknown	N/D
Convergent flow/barrier	Probably present	Present; Kobuk River	Probable fault zone
Predicted flow direction	Probably north	Probably south and north toward Kobuk River	South from Brooks range
Precipitation (in)	6" (15 cm) rain/18" (46 cm) snow	16" (41 cm) rain/69" (175 cm) snow	13" (33 cm) rain/75" (191 cm) snow
Permafrost geometry	Thick and continuous	Probably continuous south; discontinuous along Kobuk River	Variable; generally continuous mountains; becomes moderate-to-thin and discontinuous near rivers
Permafrost thickness (ft)	600 to 1,300+ ft (183 m - 396 m)	moderate - thin; max 600 ft (183 m)	200+ ft (61 m) mountains; moderate-to-thin or absent near rivers
Fresh-water springs	Brackish-to-saline water below permafrost	Possible fresh-to-brackish below permafrost	N/D
Gas seeps	Seeps in lakes near Wainwright	N/D	N/D
Water resources	Surface; thawed zones in permafrost	Unfrozen alluvial aquifers	Unfrozen alluvial aquifers

Table 6 (cont.).

HYDROLOGY	Lower Koyukuk	Yukon	Minchumina	Alaska Peninsula
Predicted pressure regime	Normal to underpressure	Normal to underpressure locally overpressure	Normal to underpressure; local overpressure possible	Dominantly normal to underpressure; possibly local overpressure
Chlorinity at depth	Fresh water below permafrost	N/D; possibly fresh	N/D	probably fresh to saline
Permeability (md)	N/D	N/D	N/D	Probably low sands; moderate coal(?)
Pressure transition	N/D	N/D	N/D	N/D
Convergent flow/barrier	Present Yukon River	Present Yukon River	Yes/possible facies, faulting(?)	Yes(?)/possible facies, faulting(?)
Predicted flow direction	Southwest; locally southeast from Nulato Hills	Toward Yukon River	Northwest from Alaska Range; southeast from Kuskokwim Range	Highly variable
Precipitation (inches)	14" (36 cm) rain/67" (170 cm) snow	6" (15 cm) rain/43" (109 cm) snow	4" (10 cm) rain/86" (218 cm) snow	127" (323 cm) rain/58" (147 cm) snow
Permafrost geometry	Generally continuous; discontinuous/absent south and along Yukon River	Discontinuous permafrost; permafrost may be absent locally	Discontinuous; numerous isolated masses of permafrost	No permafrost
Permafrost thickness (ft)	Highly variable, zero to 400+ ft (122 m); mod.- thin north	<60 to 320+ ft (18 m - 98 m)	Generally thin, <100 ft (30 m); max thickness <600 ft (183 m)	No permafrost
Fresh-water springs	Fresh water below permafrost	Fresh water below permafrost	N/D	Probable
Gas seeps	N/D	N/D	N/D	N/D
Water resources	Unfrozen alluvial aquifers	Unfrozen alluvial, flood-plain and terrane aquifers	Unfrozen alluvial, flood-plain and terrane aquifers	Surface water; shallow wells

Table 7. Summary of thermal maturity and coal-gas origins for basins evaluated for coalbed methane potential.

THERMAL MATURITY	**Colville (North Slope)**	**Kobuk**	**Upper Koyukuk**
Outcrop coal rank (VR%)	0.5 to 0.8%; rank decreases northeast toward Wainwright	<0.4 Tertiary 1.3 to 5.0% Cretaceous	Coal HvBb; 1.3 to 2.0% north of Bettles
Subsurface coal rank (VR%)	0.7% (8,200 ft) (2499 m)	very high	unknown; probably high
Gas composition	Possibly wet to very dry	N/D	N/D
Carbon dioxide content	N/D	N/D	N/D
Sulfur content (%)	0.2 to 0.4% (avg. 0.3%)	0.3 to 0.9% (avg. 0.50%)	poorly defined; probably low
Ash content (%)	8 to 27% (avg. 16%)	8 to 49% (avg. 24%)	poorly defined; possibly high
Predicted gas origins	Thermogenic; local biogenic; migrated thermogenic; hydrates(?)	Biogenic; possible thermogenic	Biogenic; possible thermogenic

THERMAL MATURITY	**Lower Koyukuk**	**Yukon**	**Minchumina**	**Alaska Peninsula**
Outcrop coal rank (VR%)	2.0 to 5.0% in mountains; Nulato coals 0.4 to 1.07%	Lig. to sub. (0.3 to 0.5%)	0.5 to 1.3%; Paleozoic rocks >2.0% in mountains	0.58 to 1.76%; generally less than 1.0%
Subsurface coal rank (VR%)	4.5 (12,000 ft) (3658 m)	HvCb to HvAb(?)	probably low to moderate	probably low to moderate
Gas composition	N/D	Gas dryness index near unity	N/D	N/D
Carbon dioxide content	N/D	Probably low	N/D	N/D
Sulfur content (%)	0.64 to 1.42% (avg. 0.73%)	Low; <0.35%	0.44 to 8.19%	0.28 to 4.79% (avg. 1.36%)
Ash content (%)	2.0 to 26.0% (avg. 19%)	4.0 to 15.0%	4.0 to 26.0%	4.2 to 30.6% (avg. 11.6%)
Predicted gas origins	Probably thermogenic; possible biogenic, migrated	Dominantly biogenic; migrated biogenic	Biogenic and thermogenic;	Biogenic and thermogenic; migrated biogenic/thermogenic

Table 8. Summary of available data in basins evaluated for coalbed methane potential.

AVAILABLE DATA BASE	Colville (North Slope)	Kobuk	Upper Koyukuk	Lower Koyukuk
Geophysical logs	2,500 (7 in area)	Lack well/seismic	Lack well/seismic	1 well to 12,000 ft (3638 m)
Core	Abundant	N/D	N/D	Poor coal section
Coal core	Minor	N/D	N/D	N/D
Water wells	yes	minimum 4	yes	15+
DST's	Limited	N/D	N/D	N/D
SIP's	N/D	N/D	N/D	N/D
Vitrinite reflectance	Abundant surface; limited subsurface; 5 wells	Surface; limited subsurface	Very limited surface VR and conodont; no subsurface	Limited surface; one well subsurface
Proximate/ultimate data	Relatively abundant	Limited surface data	Very limited	Limited

AVAILABLE DATA BASE	Yukon	Minchumina	Alaska Peninsula
Geophysical logs	1 shallow well	No subsurface control	Several wells (4 in area)
Core	N/D	N/D	N/D
Coal core	N/D	N/D	N/D
Water wells		21+	2+
DST's	N/D	N/D	N/D
SIP's	N/D	N/D	N/D
Vitrinite reflectance	Very limited surface; no subsurface	Limited surface; no subsurface; distant well data	Some surface; only distant subsurface
Proximate/ultimate data	Very limited	Limited	Limited to moderate

Table 9. Summary of production data in basins evaluated for coalbed methane potential.

PRODUCTION	Colville (North Slope)	Kobuk	Upper Koyukuk	Lower Koyukuk	Yukon	Minchumina	Alaska Peninsula
Cumulative gas (Mmcf)	Yield 23 Tcf (0.644 Tm^3)	N/D	N/D	N/D	N/D	N/D	Some
Cumulative oil (Mmbbl)	Yield 2 billion (318 Tm^3)	N/D	N/D	N/D	N/D	N/D	N/D
IP gas (Mcf/d)	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Cumulative water (Mmbbl)	N/D	N/D	N/D	N/D	N/D	N/D	N/D
IP water (Mcf/d)	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Average TD (ft)	>10,000 ft (3048 m)	N/D	N/D	N/D	N/D	N/D	10,000 ft (3048 m)

Basin), and Alaska Peninsula Province (Chignik and Herendeen Basins) were selected as coalbed methane resource development targets. Villages for coalbed methane resource assessment were selected based on economic constraints defined by the DGGS using the DCRA Community Database (1997). Many towns and villages were researched and the following were selected as potential sites for evaluation: Atqasuk, Point Lay, Wainwright, Ambler, Kiana, Kobuk, Shungnak, Alatna, Allakaket, Bettles, Evansville, Beaver, Birch Creek, Chalkyitsik, Fort Yukon, Venetie, Galena, Kaltag, Koyukuk, Louden, Nulato, Nikolai, McGrath, Chignik, Chignik Lake, and Chignik Lagoon. Operators, local boroughs, and native tribes that were contacted in these villages also discussed, requested, and/or justified coalbed methane exploration and development in these areas.

Due to the limited time period (9 months) of the cooperative agreement and funding constraints for the exploration and development of coalbed methane in rural Alaska, we focused our attention on the Colville, Kobuk, Upper Koyukuk, Lower Koyukuk, Yukon, Minchumina, and Alaska Peninsula Basins (fig. 3), and the 26 towns and villages within those basins (fig. 5). The remaining basins and towns/villages either lack data, are too close to an existing infrastructure, and/or the potential for coalbed methane exploration and development was considered of lessor economic importance at the time the evaluation was being conducted. Our initial basin (and village) selections and recommendations are conservative and based on our research and experience in the lower 48 States. The basins selected for more detailed evaluation should ideally have at least some subsurface coal data, evidence supporting the presence of gas in the form of positive geologic and hydrologic attributes, and/or statements taken from the literature discussing the development of coalbed methane resources at or near the rural Alaskan communities of interest. Importantly, all rural Alaskan coal provinces and basins are considered exploitable, and with additional subsurface data and advanced reservoir characterization these areas may become potential targets for coalbed methane resource development in the future.

GEOLOGIC AND HYDROLOGIC EVALUATION OF PRIORITIZED RURAL ALASKAN COAL BASINS

Detailed basin analysis was undertaken by describing the geologic and hydrologic controls on coalbed methane producibility near villages from the five provinces and seven basins of (1) Northern Alaskan Province, Colville Basin (Atqasuk, Point Lay, Wainwright), (2) Upper Yukon Province, Yukon Basin (Beaver, Birch Creek, Chalkyitsik, Ft. Yukon, and Venetie), (3) Alaska Peninsula Province (Chignik, Chignik Lake, and Chignik Lagoon), (4) Nenana Province, Minchumina Basin (Nikolai and McGrath), (5) Yukon-Koyukuk Province, Upper Koyukuk Basin (Alatna, Allakaket, Bettles, and Evansville), (6) Yukon-Koyukuk Province, Lower Koyukuk Basin (Galena, Kaltag, Koyukuk, Louden, and Nulato), and (7) Yukon-Koyukuk Province, Kobuk Basin (Ambler, Kiana, Kobuk, and Shungnak).

The basin evaluation included the application of the coalbed methane producibility model in defining exploration fairways in the prioritized rural Alaska basins. As part of the evaluation, the DGGS provided the BEG with all available data including public domain literature, geophysical logs, seismic surveys, coal rank, coal gas composition, isotopic, gas content data, water analyses, drill stem tests and/or pressure data, and other data to the extent that such data were available.

Alaska has a potentially enormous coal and coalbed methane resource base located principally in the North Slope Province and the Cook Inlet Province (fig. 6). Outside of these areas, little is known about the thickness and continuity of coals in the subsurface. In order to predict the subsurface coal attributes close to the villages of interest, data from the literature, outcrops (appendix A), mines, and a few geophysical logs were integrated into established geohydrologic characterization models of tectonic and structural setting, coal deposition and rank, gas content and generation, and hydrodynamics based on our experience and expertise in the Lower 48 States. The integration of regional coal-occurrence, structure, fracture-attribute, potentiometric-surface, pressure-gradient, hydrochemical, coal-rank, gas-composition, and production maps, where available, helped identify and rank potential exploration basins and targets for resource development. If the coalbed methane exploration and development program did not take into account the variability of as many of these controlling parameters as possible, then the risk exists that the exploration program could (1) condemn a resource that exists but was not correctly assessed because of a poorly chosen test basin or (2) achieve some success, but not the full potential, because an interpreted model for the small area did not fit the larger basin-scale setting.

Many benchmark papers were used in the integration. Notably, in the Alaskan coal basins, the following references were extensively used: Merritt (1986a), Sable and Stricker (1987), Huffmann and others (1988), The Geology of Alaska (Plafker and Berg; 1994), National Petroleum Reserve in Alaska (Gryc, 1988), and Smith (1995). Much of the following text is based on these benchmark papers and, as such, will be individually referenced. The coalbed provinces and basins targeted for resource development in rural Alaska, are discussed in decreasing order of importance as follows: Northern Alaska Province (Colville Basin), Yukon-Koyukuk Province (Kobuk, Upper Koyukuk, and Lower Koyukuk Basins), Upper Yukon Province (Yukon Basin), Nenana Province (Minchumina Basin), and Alaska Peninsula Province (Chignik Basin).

Northern Alaska Province: Colville Basin
(Atqasuk, Point Lay, and Wainwright)

Physiographic and Geologic Setting

The Northern Alaska Coal Province, including the National Petroleum Reserve in Alaska (NPRA), underlies an area of up to 58,000 mi^2 (150,220 km^2), and occurs north of the Brooks Range and, north and west of the lower Colville River, on the North Slope of Alaska (fig. 7). The major coal deposits of the Northern Alaska Coal Province are delineated mainly by the outcrop belt of the Nanushuk Group, which extends nearly continuously from the sea cliffs of Corwin Bluff on the west, some 400 mi (650 km) eastward to the Sagavanirktok River of the eastern Arctic Slope (Merritt, 1986a) (fig. 7). Based on the exploratory constraints defined by the

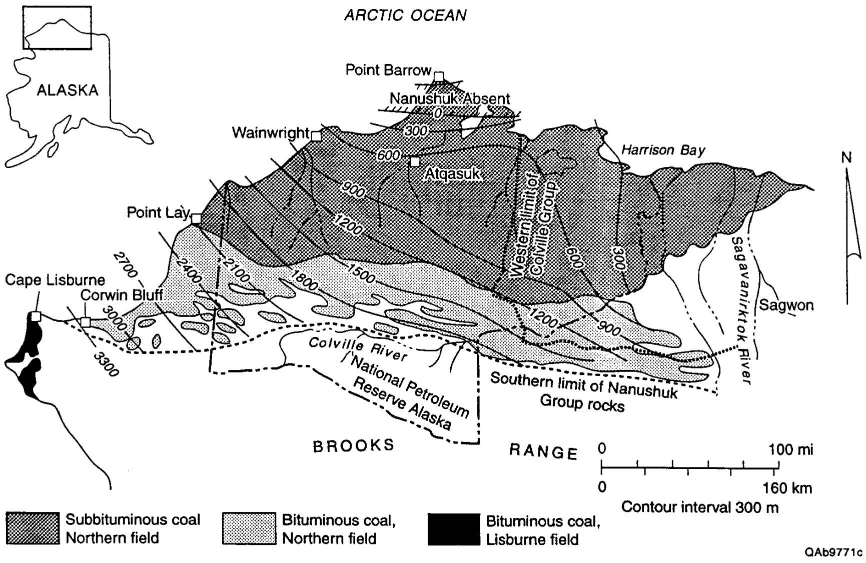


Figure 7. Distribution and extent of the coal-bearing rocks of the northern Alaskan coal province showing surface coal ranks and thickness of the Cretaceous Nanushuk Group, the prime coalbed methane target. Modified from Bird and Andrews, 1979.

DGGS, focus of the resource assessment along the North Slope is restricted to the western Colville Basin, close to the villages of Wainwright, Atqasuk, and Point Lay (figs. 7 and 8) (tables 1 through 9). Reconnaissance field work of the western North Slope indicated that the Nanushuk Group is typically better exposed in the western Colville Basin where several stream channels have locally incised through the coal-bearing section. The coal deposits mainly occur in two major physiographic provinces: (1) the Arctic Foothills belt, located north of the Brooks Range, in the northern part of which Nanushuk Group rocks are exposed, and (2) the Arctic Coastal Plain, which spans the remaining terrain to the Arctic Ocean (Merritt, 1986a) (figs. 9 and 10). The Arctic Foothills province is characterized by treeless rolling hills, ridges, and valleys generally aligned east to west and parallel to the mountain front, and cut by numerous north-flowing streams and rivers. It comprises a Southern Foothills section and a Northern Foothills section. The Southern Foothills section averages about 3,940 ft (1,200 m) altitude (Merritt, 1986a). The relief of the Northern Foothills section ranges from 200 to 980 ft (61 to 299 m), and altitudes average 591 ft (180 m). The Arctic Coastal Plain is an extensive, nearly featureless tundra plain with numerous lakes, marshes, and poorly developed streams (Martin and Callahan, 1978; Mull, 1979).

Tectonic and Structural Setting

The northern Alaskan coal province forms part of the northwestern limit of the Rocky Mountain Foreland and the Cretaceous Interior Seaway (fig. 11). The northern Alaskan coal province has similar tectonic, structural, and depositional settings to those of the San Juan, Piceance, and Greater Green River Basins in the Rocky Mountain Foreland, where Cretaceous coastal plain and Tertiary fluvial coal deposits predominate in foreland basins. About 150 coal beds of significant thickness, 5 to 28 ft, have been documented along the North Slope, and a few beds are as much as 40 ft thick. Most coal beds display dominant opening-mode fractures (face cleat), similar to those found in the San Juan Basin of New Mexico and Colorado. The face cleat

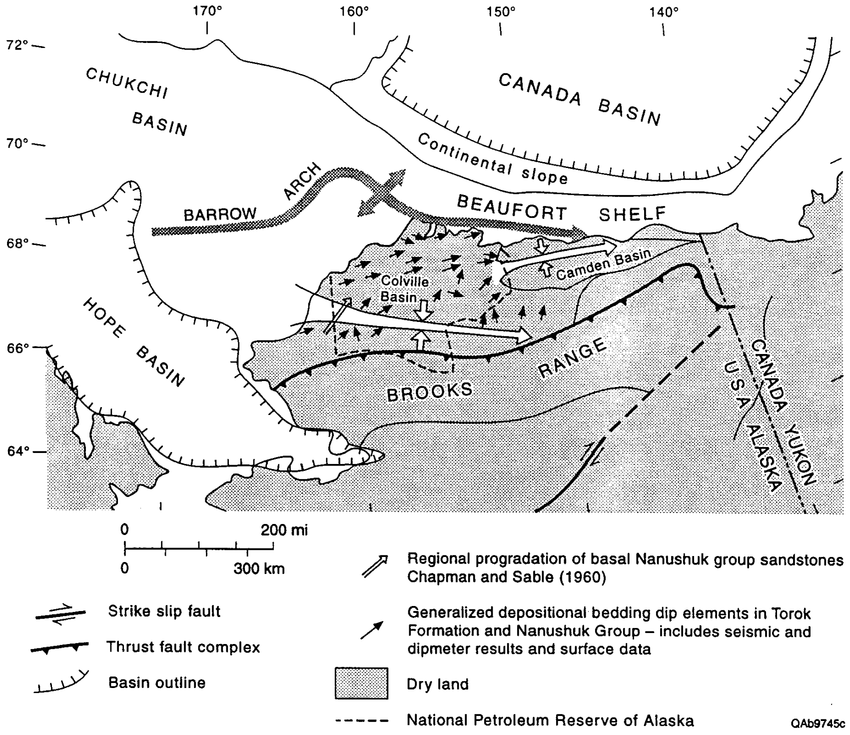


Figure 8. Structural elements of the northern Alaskan coal province (modified from Molenaar, 1985). The Colville Basin is a prime location for the development coalbed methane resources.

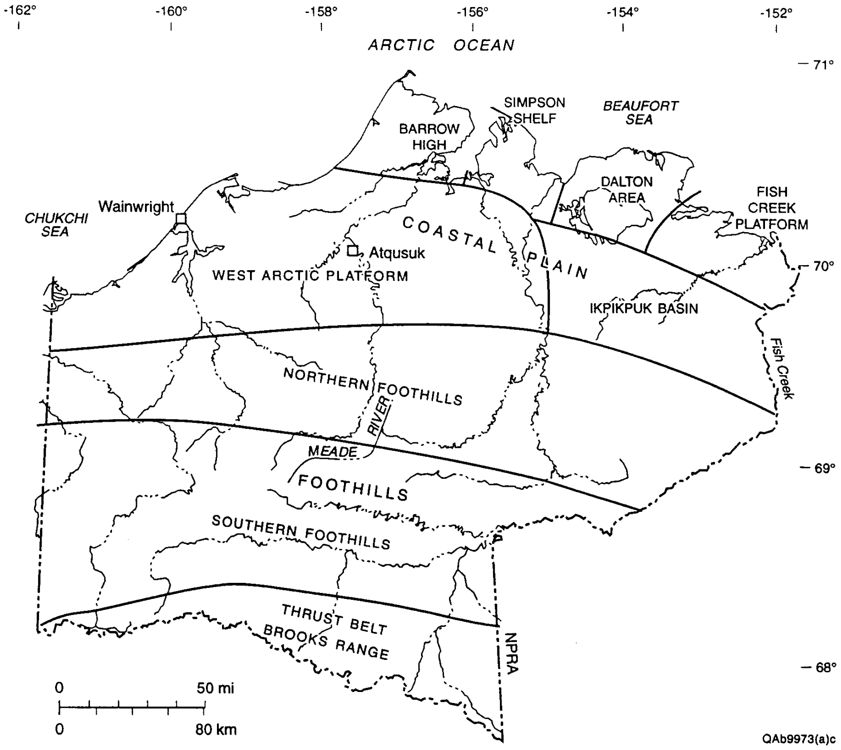


Figure 9. Geographic regions of the National Petroleum Reserve in Alaska (NPRA). Modified from Schindler (1988).

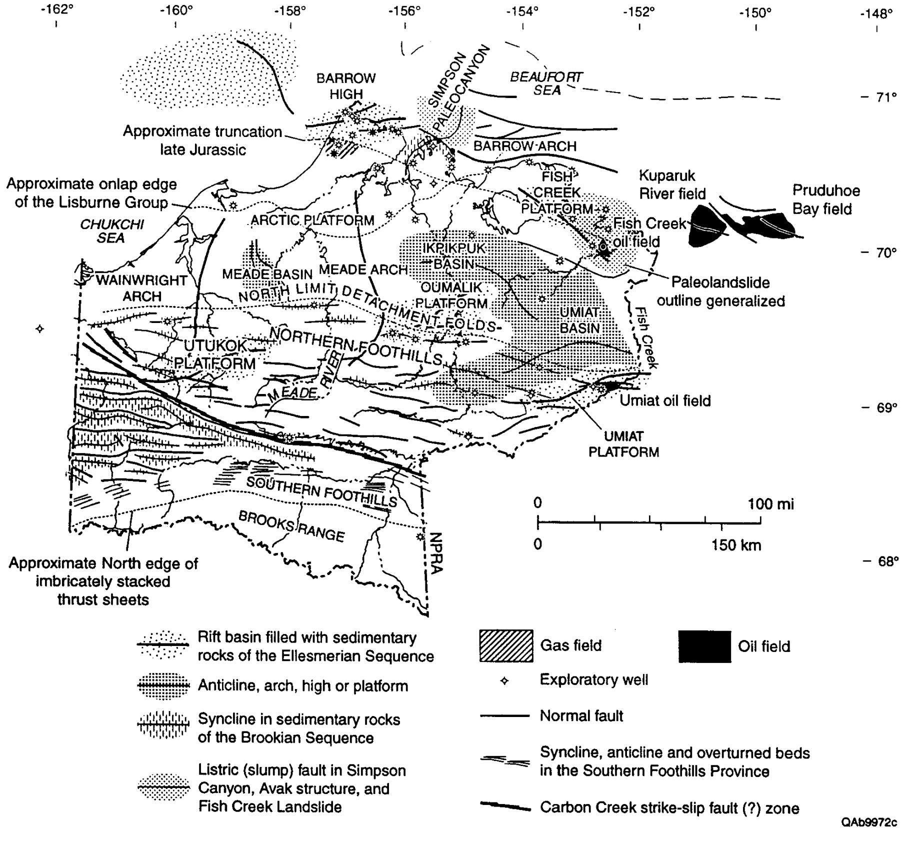


Figure 10. Structural provinces of the National Petroleum Reserve in Alaska (NPRA). Modified from Kirschner and Rycerski (1988).

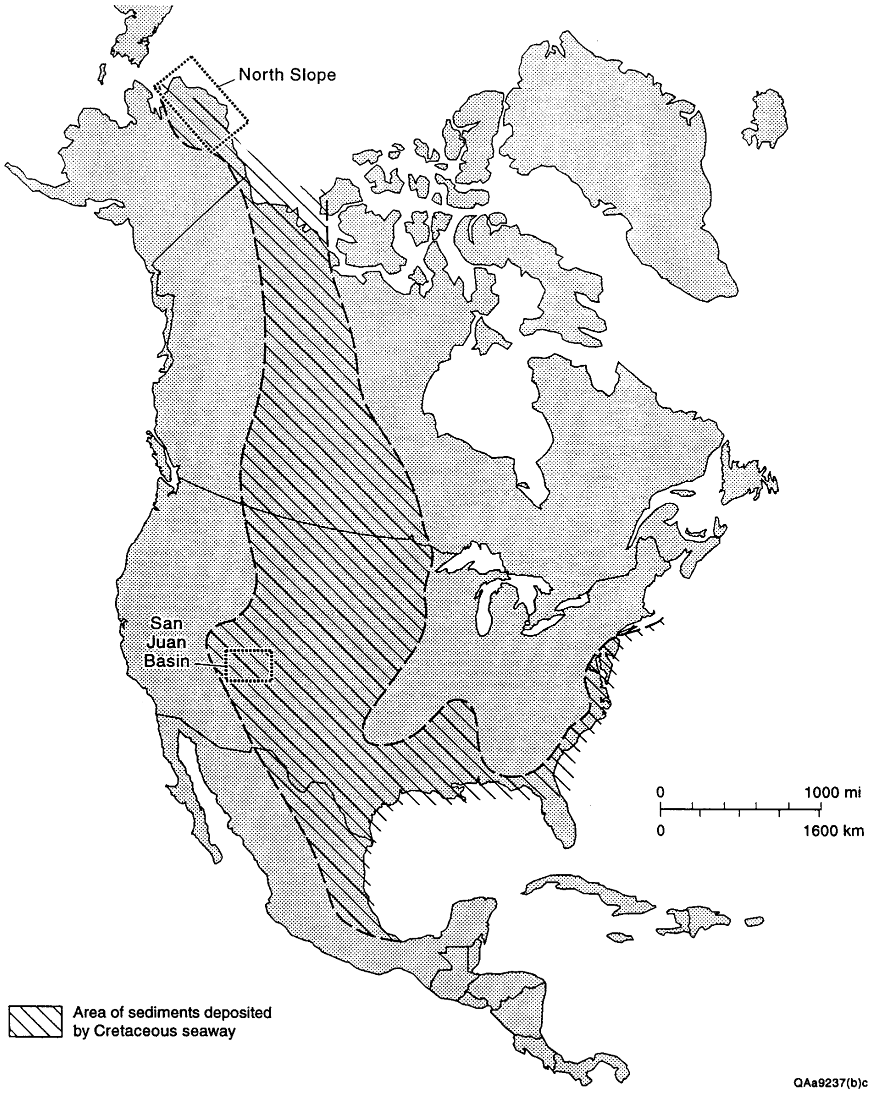


Figure 11. Structural setting and coal depositional systems for the San Juan and North Slope basins are predicted to be similar, as both of these basins are found along the flanks of the Western Cretaceous Interior Seaway. Using the North Slope as an analog to the lower 48 States coal basins within the Rocky Mountain Foreland, the North Slope structural style and depositional systems should be similar. The thickest coal-bearing zones will be found in coastal plain depositional environments, landward of the progradational shoreline sequences. Modified from Kauffman (1977).

strikes in bright coals cropping out along the Kukpowruk River, far western Colville Basin, are oriented at 320 degrees. The face cleat strikes along the Utukok River are oriented north-south. Butt cleats at both localities are orthogonal to face cleat strikes. Preliminary analysis indicates that the face cleats in the Colville Basin developed perpendicular to the Brooks Range Orogenic thrust fronts and are oriented parallel to maximum horizontal compressive paleostresses. Spacing of the primary cleat in outcrop ranges between 0.25 to 0.75 inches (0.6 to 2 cm). The surface fracture attributes are an indication that coal beds in the subsurface may be cleated and permeable, allowing the flow of gas and water to the wellbore, which will significantly contribute to the resource potential of the Colville Basin.

North Slope subsurface data includes more than 350 oil and gas exploratory wells, 2,500 development wells, and seismic data from near the Canadian border to the Chukchi Sea (Smith, 1995). These data, together with more that a dozen key wells close to selected villages in the Colville Basin, significantly contributed to the structural, stratigraphic, and resource evaluation. The structure of the coal-bearing Colville Basin is characterized by folding and faulting along roughly east-northeast and east-trending axes generally parallel to the Brooks Range (fig. 12). The intensity of foreland deformation decreases northward from the Brooks Range toward the Coastal Plain, where the uplifted Barrow Arch has resulted in the recent erosion of the shallower coal-bearing section (Merritt, 1986a) (fig. 10). The targeted Cretaceous strata (Brookian Sequence) exhibit a gentle homoclinal dip to the south in the Coastal Plain, but in the Foothills numerous broad but relatively simple synclinal basins are separated by tightly folded, east-trending anticlines (Merritt, 1986a) (figs. 10, 13, 14, and 15). Most of these anticlines in the southern Foothills are complicated by high-angle reverse faults or north-directed thrust faults (Martin and Callahan, 1978; Callahan and Martin, 1981) (fig. 13).

Cretaceous sedimentation on the North Slope reflects the uplift of the Brooks Range orogenic belt and attendant deposition into a marine basin along the north flank of the range (Merritt, 1986a). The Lower Cretaceous rocks of the western and central Brooks Range record an abrupt shift from dominant northern sources to southern and southwestern sources. The Brooks

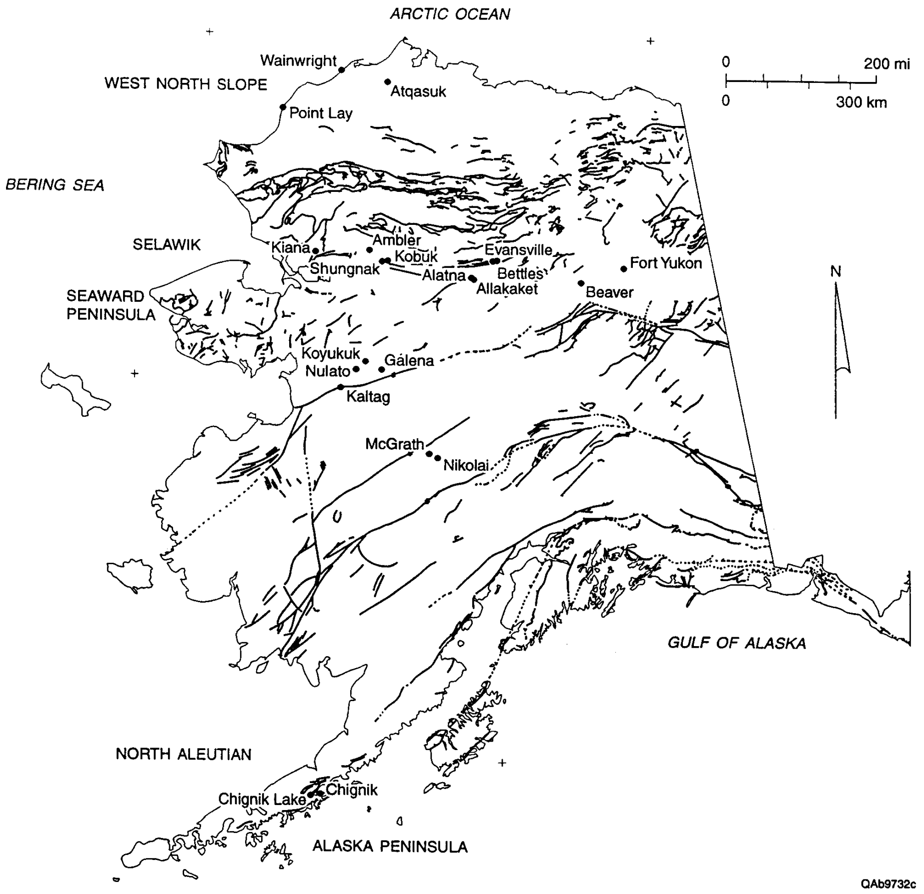


Figure 12. Major faults of Alaska. The North Slope coal province is on the north flanks of the Brooks Range. Structural complexity decreases away from the range. Modified from Beikman (1980).

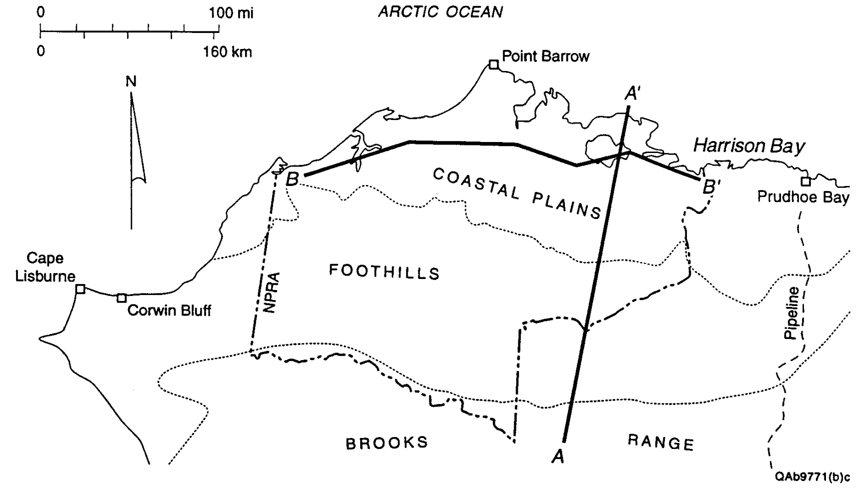


Figure 13. Location of the structural cross sections A–A′ and B–B′, North Slope coal province. Modified from Bird (1987).

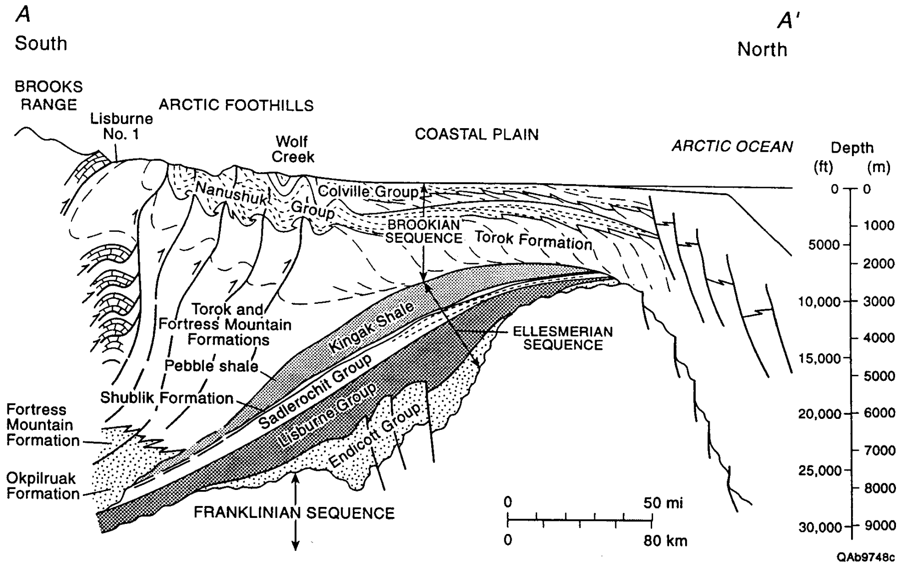


Figure 14. North-south structural cross section (A–A′) through the Brookian (Cretaceous) Nanushuk Group coal-bearing horizons, North Slope coal province. Modified from Bird (1991). The Nanushuk Group sandstones prograde to the north and east, showing several stacked sequences, pinching out into marine shales and against major fault systems. Location of cross section on figure 13.

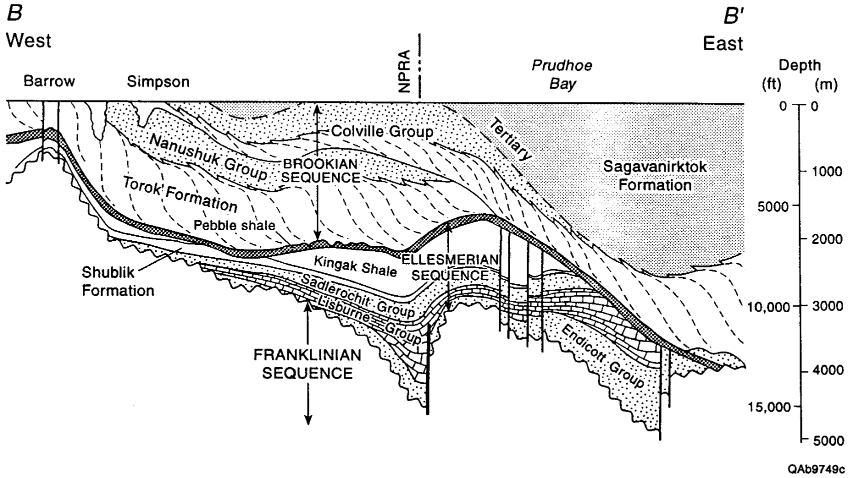


Figure 15. West-east structural cross section (B–B′) through the Brookian (Cretaceous) sequence, North Slope. Modified from Bird (1991). The Nanushuk Group sandstones prograde to the north and east, showing several stacked sequences, pinching out into marine shales. Location of cross section on figure 13.

Range orogenic belt consists of multiple major thrust sheets from which sediments of the Nanushuk Group were derived (Merritt, 1986a). The thrust sequences formed by under thrusting as a result of a counterclockwise rotation of the Arctic Alaska plate that moved relatively southward and was abducted by oceanic crust at a south-dipping subduction zone (Mull, 1979). The major structural elements that influenced deposition of the Cretaceous Nanushuk Group rocks and the present-day structure are shown in figures 8, 13, 14, and 15. The present-day structural configuration and thermal maturity of the rocks suggests greater depth of burial and/or heat flow, uplift, and erosion in the Foothills than in the Coastal Plain. To the north and south, parts of the Nanushuk Group rocks have been removed by erosion, especially in the Foothills belt and the northeastern Arctic Slope, respectively (Merritt, 1986a). Thus, regional tectonism has greatly affected the ultimate distribution and rank of coal beds between the Foothills and Coastal Plain on the Arctic Slope of northern Alaska (Carter and others, 1977; Martin and Callahan, 1978; Ahlbrandt, 1979).

Depositional Systems and Coal Distribution

The coal-bearing formations of the North Slope form part of the northern limit of the Cretaceous Interior Seaway, and the coastal-plain and fluvial-deltaic coal depositional systems are similar to those in the Lower 48 states. Coal has been documented to occur in five formations along the western and central North Slope and include the Kapaloak, Kukpowruk, Corwin, Colville, and Sagavanik Formations. Most of the coal and coalbed methane resources will be found in the Lower Cretaceous, Kukpowruk, Corwin, and Chandler Formations of the Nanushuk Group at optimum coalbed methane exploration depths of greater than 300 ft (>91 m) and less than 6,000 ft (<1,829 m) (fig. 16). Total Cretaceous coal thickness exceeds 300 ft (91 m) and is the prime target for resource development (table 5).

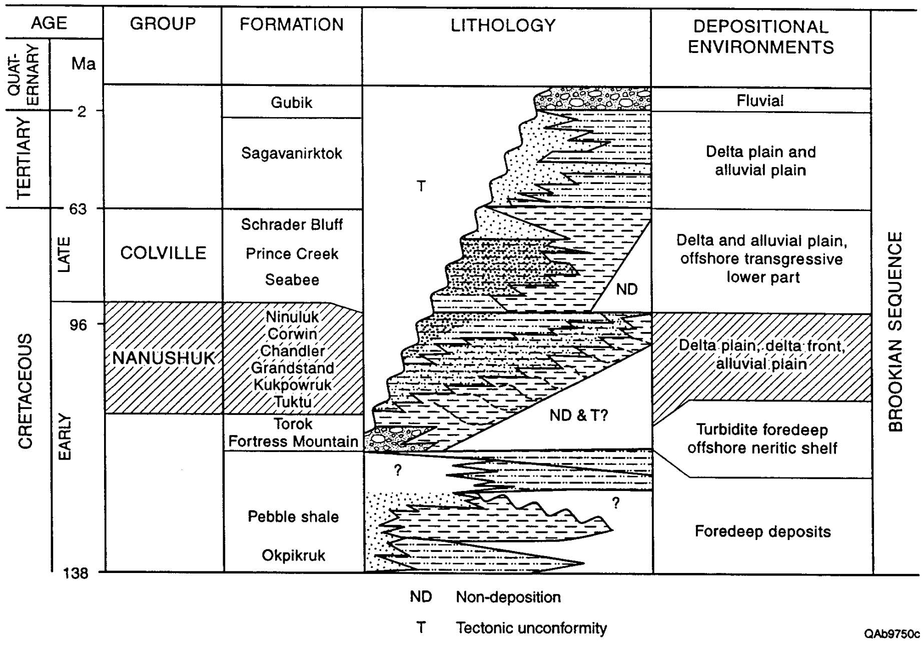


Figure 16. Schematic stratigraphic column and depositional environments of the Colville Basin. Modified from Bird (1987).

Kapaloak Formation. Lisburne Group, Mississippian Coal

Mississippian coals of the Kapaloak Formation are the oldest in Alaska, and they are found on the Lisburne Peninsula where outcrops occur over a 45-mi (72-km) north-south-trending belt. A minimum of 13 coal beds have been identified in outcrop along 2,200 feet (670 m) of measured section that is extensively faulted and folded (Smith, 1995). The Kapaloak Formation coals are typically low-volatile bituminous to semianthracite in rank (Merritt and Hawley, 1986). Because of the complex structure, depth, and distance to villages of consideration, the Kapaloak Formation coals are not considered targets for coalbed methane resource evaluation and development (Smith, 1995).

Kukpowruk and Corwin Formations, Nanushuk Group, Lower Cretaceous Coal, and Colville Group, Upper Cretaceous Coal

Based on the work of Merritt (1986a) and Sable and Stricker (1987), the Lower and Upper Cretaceous coals occur in two major sedimentary rock sequences: the Nanushuk Group (Lower Cretaceous) and the Colville Group (Upper Cretaceous) (fig. 16). Most of the coal and coalbed methane resources will be found in the Lower Cretaceous Nanushuk Group (Kukpowruk, Corwin, and Chandler Formations) (Sable and Stricker, 1987). The lower part of the Cretaceous succession is composed predominantly of marine shales, which exhibit an upward prograding shoreline sequences backed landward by coastal-delta-plain coal-bearing rocks of the Nanushuk and Colville Groups (fig. 16). The Nanushuk Group has been subdivided into formations based mainly on the marine and nonmarine character of the rocks (Merritt, 1986a) (fig. 16). In the Nanushuk Group, the Kukpowruk, Corwin, and Chandler Formations are dominantly nonmarine strata that were deposited in two separated, but simultaneous prograding, fluvial-deltaic systems (Corwin delta of western NPRA and Umiat delta of eastern NPRA) (Ahlbrandt, 1979) (figs. 17, 18, and 19). Progradation of the Corwin delta to the north and east resulted in thick coastal-plain coals being deposited and stacked behind the shoreline sequences.

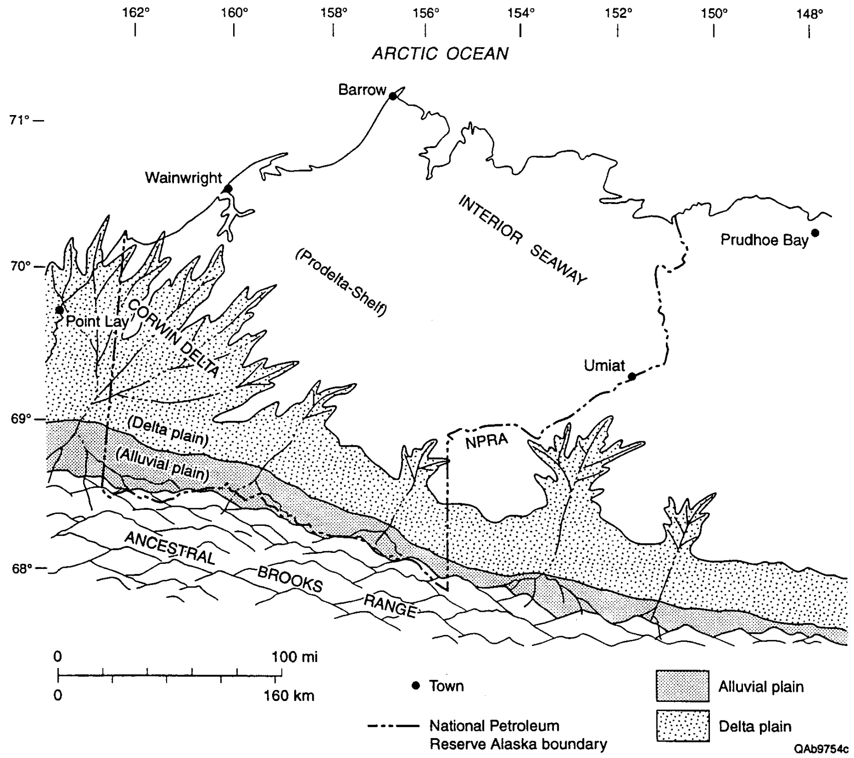


Figure 17. Western North Slope paleogeography during the early Nanushuk Group (middle Albanian) time. Modified from Roehler (1987).

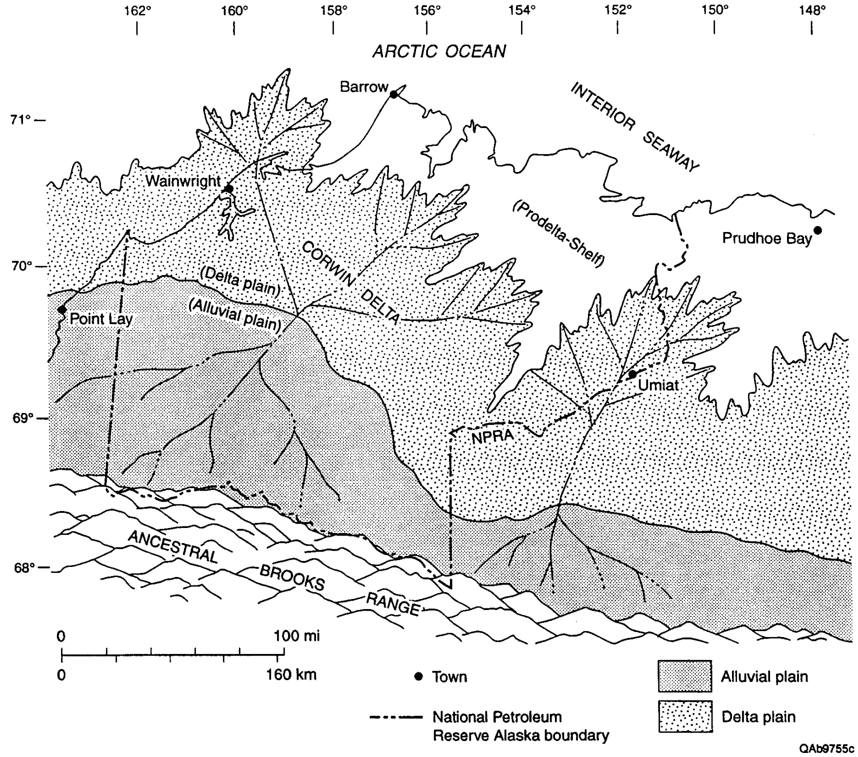


Figure 18. Western North Slope paleogeography during the late Nanushuk Group (late Albanian) time. Modified from Roehler (1987).

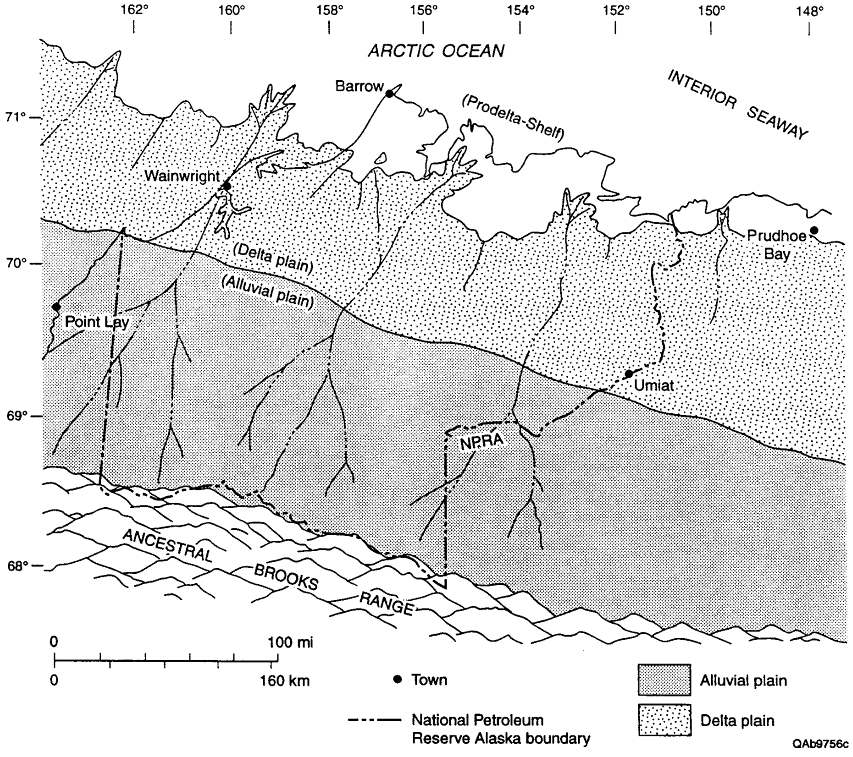


Figure 19. Western North Slope paleogeography during the Colville Group (Campanian) time. Modified from Roehler (1987).

Reconnaissance field work and limited access to NPRA oil and gas well data helped define the regional distribution and extent of coal beds of the Nanushuk Group in the Colville Basin and in the vicinity of selected rural villages. The Nanushuk Group forms a continuous subcrop beneath Pleistocene and Holocene deposits along the Coastal Plain, but in the Foothills, however, the outcrop area of nonmarine rocks is discontinuous and coal beds are exposed only in the cutbanks of the larger streams and along sea cliffs at Corwin Bluff (Callahan and Martin, 1981).

The Nanushuk Group sequence is more than 9,000 ft (2,743 m) thick in the southern part of the NPRA, but thins northward to about less than 3,000 ft (914 m) near Barrow (fig. 20). The Corwin Formation, the major coal-bearing horizon, composes the entire thickness of the Nanushuk Group measured at Corwin Bluff but decreases to about 4,000 ft (1,219 m) thick in west-central NPRA (Merritt, 1986a). The type section for the Corwin Formation is at Corwin bluff (Sable, 1956; Smiley, 1969), where coal beds less than 5 ft (1.5 m) thick are characteristic, but beds 15 to 22 ft (4.5 to 6.7 m) thick are common (Merritt, 1986a). In the northern NPRA, most stratigraphic sections represent only the lower part of the formation, as the upper part of the section has been eroded in Recent time.

From subsurface data, mainly from the Tungak, Tunalik, Peard, and Kugrua wells (fig. 21), the Kukpowruk and Corwin Formations contain abundant coal seams up to 20 feet (6 m) thick, that underlie most of western and central NPRA and extend farther west under the Chukchi Sea (Tailleur and Brosge, 1976). These coal seams have been documented in outcrop along the Kukpowruk River to the west of NPRA and in wells drilled in NPRA (Smith, 1995). The Tungak (T6N, R42W, sec. 12) penetrated over 3,000 ft (914 m) of coal-bearing section with total coal estimated at 89 ft (27 m) (fig. 22). Coal beds were recognized using the formation density, interval transit time, and gamma-ray log suites (fig. 22). The Tunalik (T10N, R36W, sec. 20) penetrated over 3,600 ft (1,097 m) of coal-bearing section with total coal estimated at more than 300 ft (91 m). Coal beds were recognized using the formation density, interval transit time, and gamma-ray log suites (fig. 23). The Peard (T16N, R28W, sec. 25) penetrated over 1,200 ft (366 m) of coal-bearing section with total coal estimated at 92 ft (28 m). Coal beds were

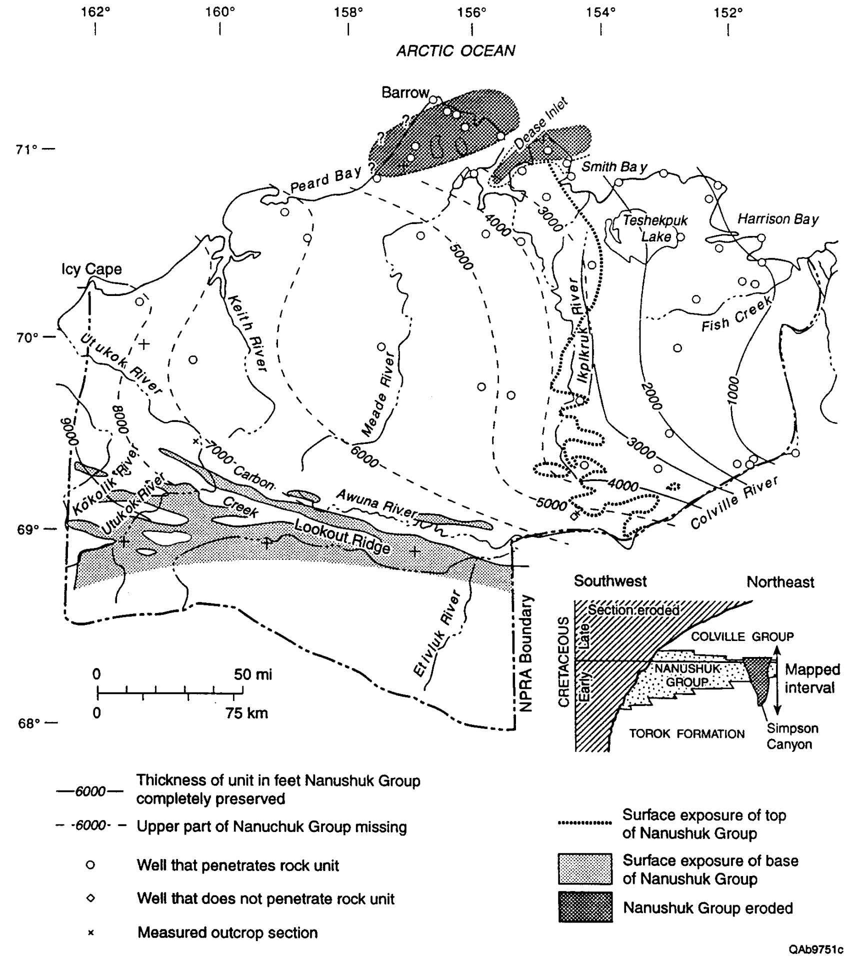


Figure 20. Isopach map of the Nanushuk Group in the National Petroleum Reserve in Alaska (NPRA). Modified from Bird (1988).

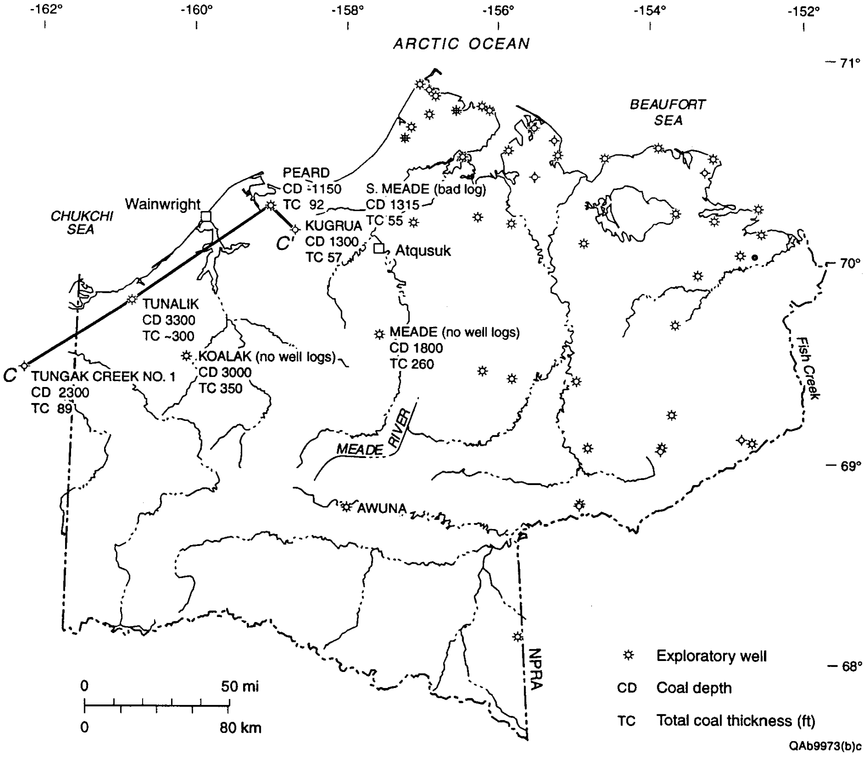


Figure 21. Subsurface well data used for the coalbed methane resource assessment and included many wells of the National Petroleum Reserve in Alaska (NPRA), Data obtained from these wells included total coal thickness, estimated coal depth, and stratigraphic cross section C–C′ (Refer to figure 27 and enlarged cross section in the pocket at the back of the report). Modified from Schindler (1988).

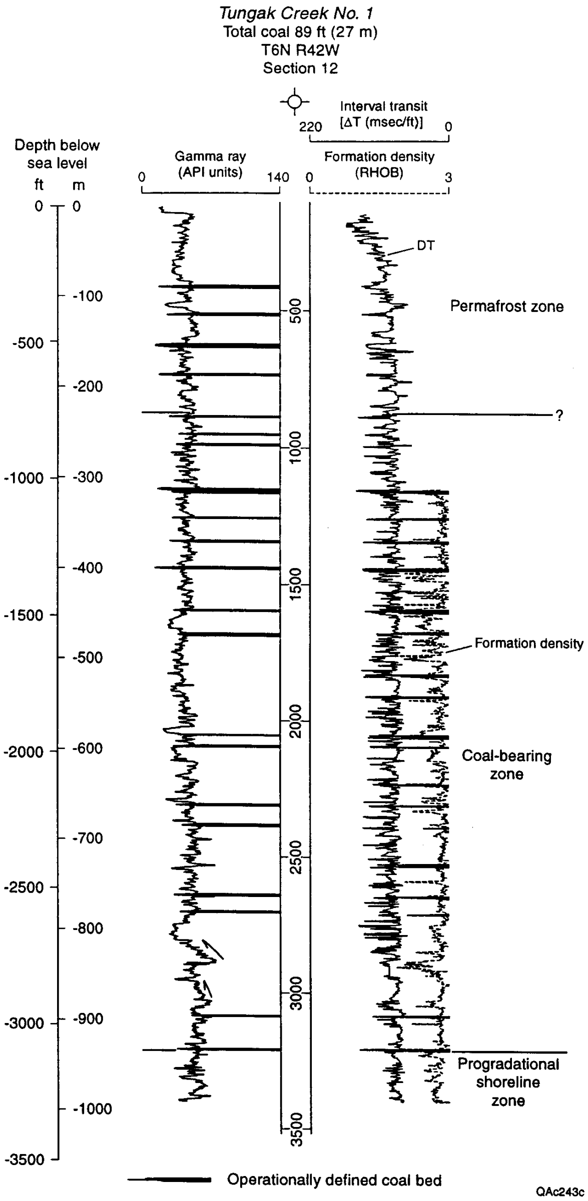


Figure 22. Type log Tungak Creek No. 1 well. North Slope coal province. Coal beds are operationally defined using the combination of formation density (delta D/RHOB), interval transit (delta T), and gamma-ray (GR) log suites. Total coal exceeds 89 ft (27 m).

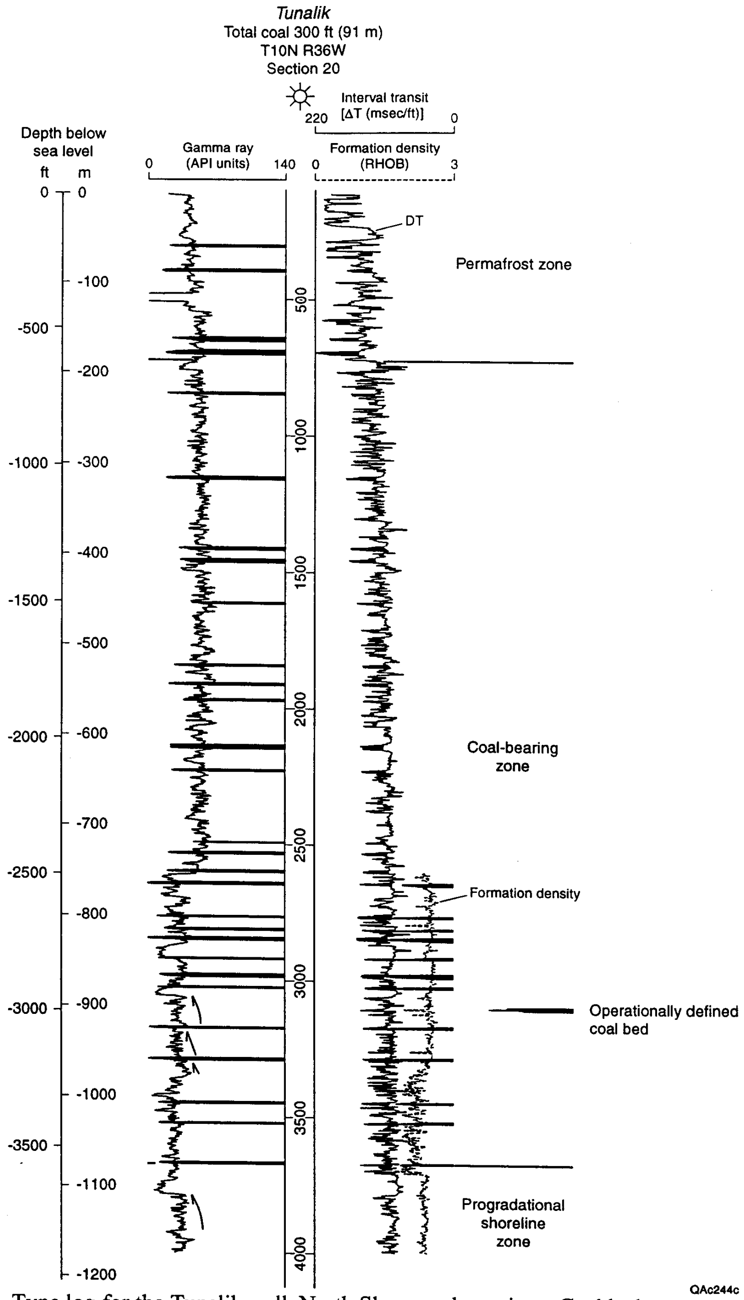


Figure 23. Type log for the Tunalik well, North Slope coal province. Coal beds are operationally defined using the combination of formation density (delta D/RHOB), interval transit (delta T), and gamma-ray (GR) log suites. Total coal exceeds 300 ft (91 m).

recognized using the interval transit time and gamma-ray log suites (fig. 24). Note the gas kicks on the mud logs associated with the coal-bearing zone, below the permafrost layers (fig. 24). The Kugrua (T14N, R26W, sec 8) penetrated over 1,500 ft (457 m) of coal-bearing section with total coal estimated at 57 ft (17 m). Coal beds were recognized using the interval transit time and gamma-ray log suites (fig. 25). Note the correlation of gas kicks on the mud log with the coal beds and the generally higher gas concentrations below the permafrost zone (fig. 25). The Kaolak -1 penetrated 255 feet (78 m) of coal in over 4,500 feet (1,370 m) of Nanushuk section and the Meade -1 encountered 130 feet (40 m) of coal in 2,000 feet (610 m) of Nanushuk Group section (Sable and Stricker, 1987). Individual coal beds in these wells reach 20 feet (6 m) with up to 26 coal beds exceeding 5 feet (1.5 m) thick (Sable and Stricker, 1987). For the western Colville Basin, total coal thickness, in the Wainwright, Atqasuk, and Point Lay area, exceeds 300 ft (91 m) and is considered the prime exploration fairway for rural Alaskan coalbed methane (fig. 26). A detailed stratigraphic cross section through the fairway shows the thick coal-bearing zone, possible depths to the base of the permafrost, and zones for exploration and development (fig. 27). Mapping by Sable and Stricker (1987), in the vicinity of the exploration fairway, shows that the depth of the coal-bearing interval lies between the surface and 6,000 feet (1,830 m) (fig. 28). South of Wainwright and Atqasuk, the depths to the Nanushuk coal-bearing interval is less than 3,000 ft (914 m). At Point Lay, depth to the base of the coal interval is greater than 6,000 ft (1,829 m). The thickness of the coal-bearing interval increases from 0 ft (0 m) in the northeast to more than 6,000 ft (1,829 m) near Point Lay (fig. 29). South of Wainwright the thickness of the coal-bearing interval exceeds 3,000 ft (914 m). Thicknesses of the Nanushuk Group marine and non-marine sequences display similar trends (figs. 30 and 31).

Ahlbrandt and others (1979) developed a fluvial-deltaic sedimentation model, later refined by Callahan and Martin (1981), to reconstruct depositional systems and facies represented by the coal-bearing Kukpowruk and Corwin Formations, Nanushuk Group. The Nanushuk Group clastic wedge is interpreted to have prograded to the north and northeast becoming thinner and increasingly more marine in character away from its sources. Huffman and others (1988)

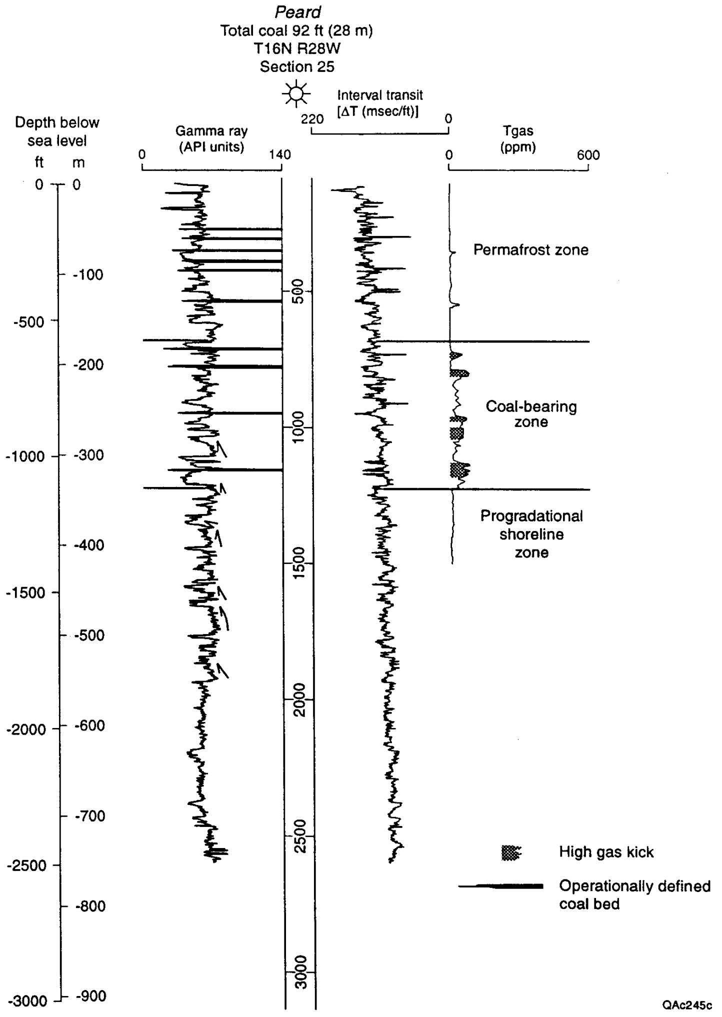


Figure 24. Type log Peard well, North Slope coal province. Coal beds are operationally defined using the combination of interval transit (delta T) and gamma-ray (GR) log suites. Total coal exceeds 92 ft (28 m). Note the gas kicks associated with the mud logs.

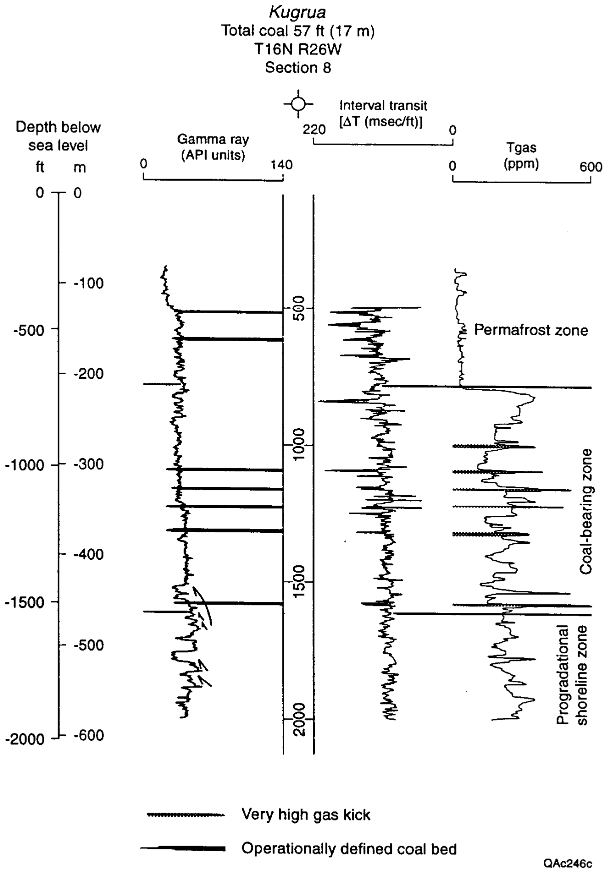


Figure 25. Type log Kugrua well, North Slope coal province. Coal beds are operationally defined using the combination of interval transit (delta T) and gamma-ray (GR) log suites. Total coal exceeds 57 ft (17 m). Note the very high gas kicks indicated on the mud logs are directly associated with the coal beds.

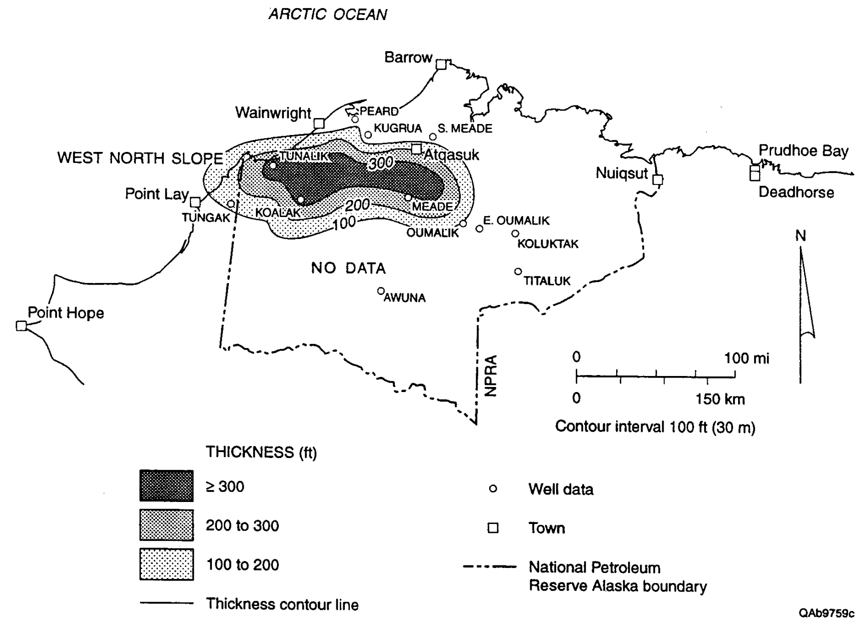
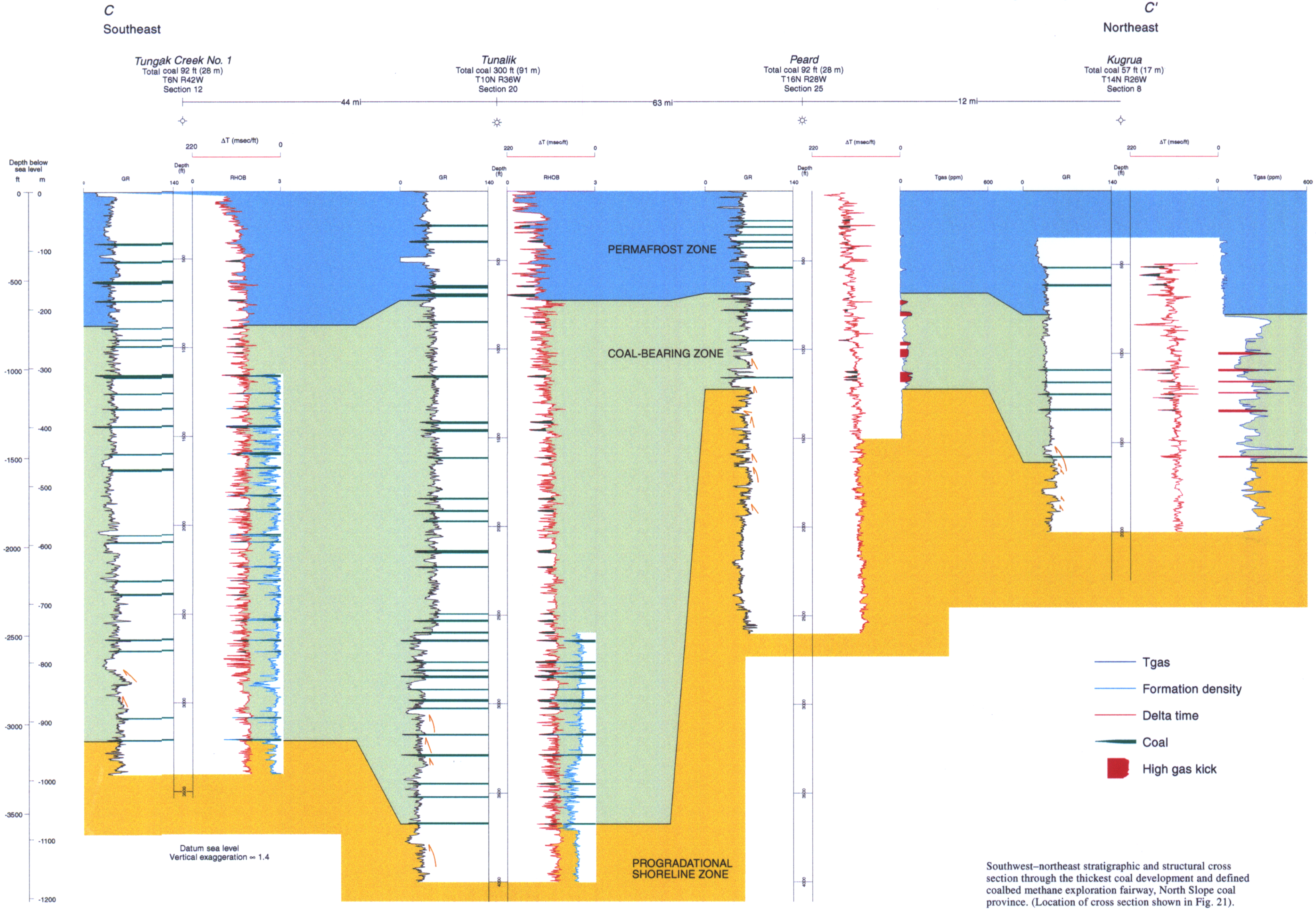


Figure 26. Total coal thickness of the Nanushuk Group, western Colville basin. Coal thickness exceeds 300 ft (91 m) south of the villages of Wainwright and Atqasuk.



Southwest–northeast stratigraphic and structural cross section through the thickest coal development and defined coalbed methane exploration fairway, North Slope coal province. (Location of cross section shown in Fig. 21).

FIGURE 27 EXPANDED: SOUTHWEST-NORTHEAST STRATIGRAPHIC AND STRUCTURAL CROSS SECTION THROUGH THE THICKEST COAL DEVELOPMENT AND DEFINED COALBED METHANE EXPLORATION FAIRWAY, NORTH SLOPE COAL PROVINCE

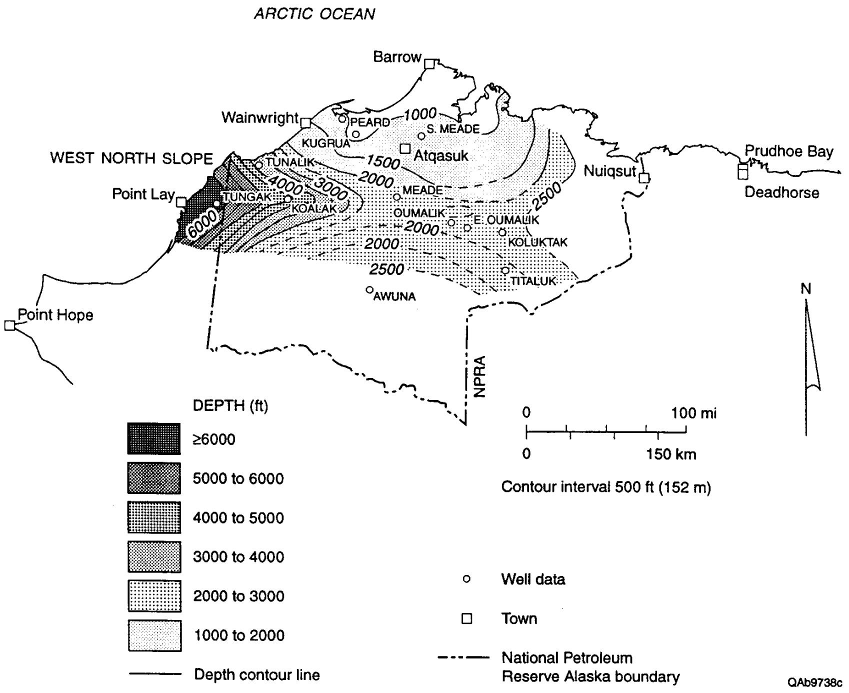


Figure 28. Depth to the base of the Nanushuk Group exploration fairway. Modified from Sable and Stricker (1987).

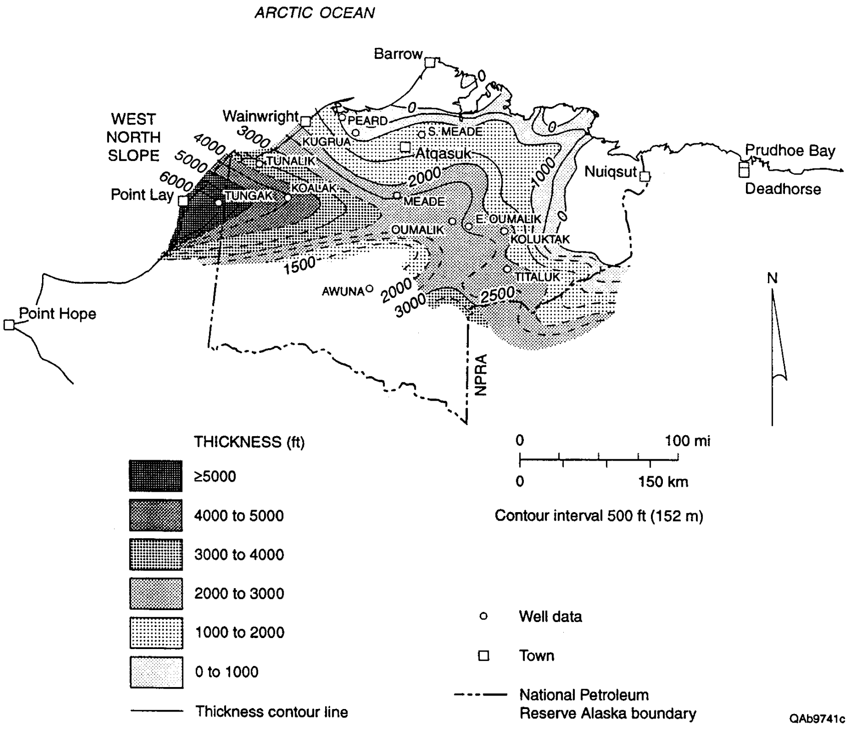


Figure 29. Thickness of the coal-bearing sequence within the Nanushuk Group exploration fairway. Modified from Sable and Stricker (1987).

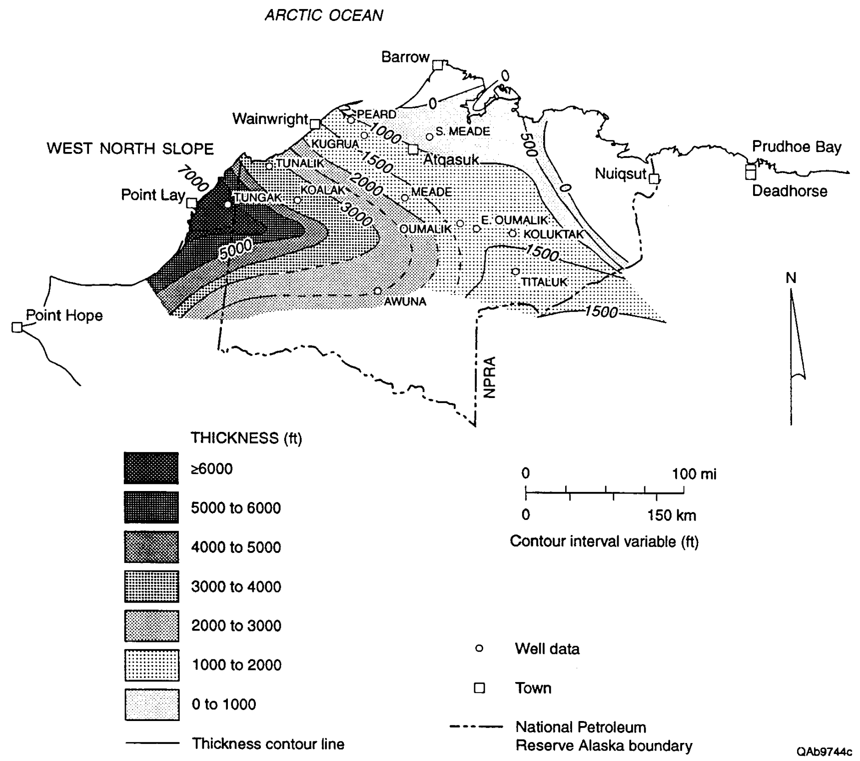


Figure 30. Thickness of the Nanushuk Group nonmarine sequence. Modified from Wahrhaftig and others (1994).

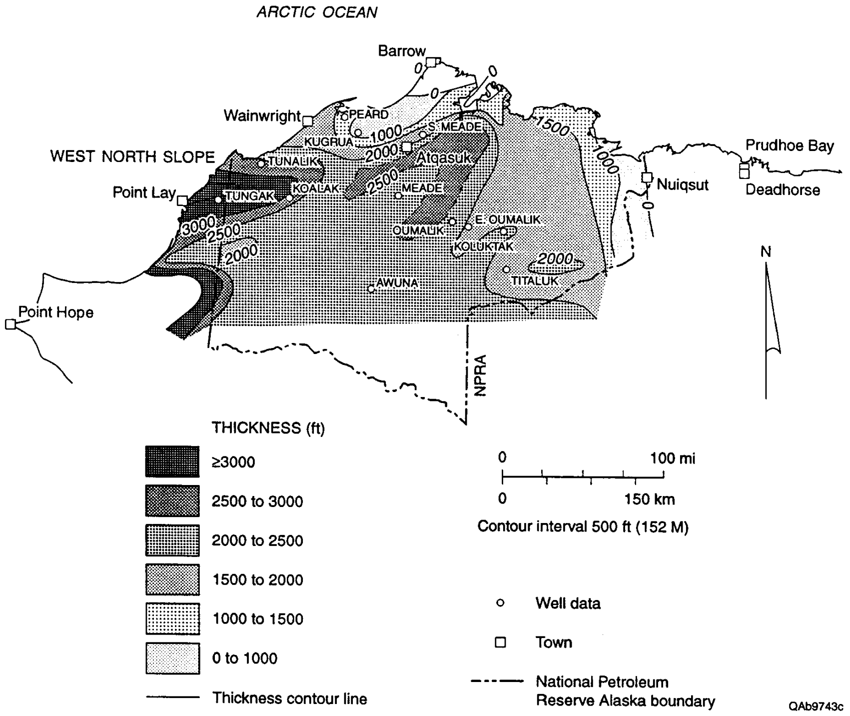


Figure 31. Thickness of the Nanushuk Group marine sequence. Modified from Wahrhaftig and others (1994).

interpreted that the Nanushuk Group (west of longitude 157° W) was deposited in the elongate river-dominated Corwin delta, which prograded to the east and northeast over shelf and prodelta muds and sands of the Aptian and Albian Torok Formations. The general shape of the Corwin delta is indicated by the contours of the sandstone percentage maps (fig. 32) and, combined with the paleotransport directions, indicates an elongate river-dominated system prograding to the north and east in two major lobes with a large deltaic subembayment between them (Huffman and others, 1988).

In mapping the sandstone trends of the Nanushuk Group, Huffman and others (1985) indicated that the thick sandstone percentages of the Nanushuk Group are oriented northwest; sandstone percentages exceed 30 and are interpreted to be part of the Corwin and Umiat delta systems (figs. 18 and 32). Based on analogs in the lower 48 States, we interpret the thick sandstone trends as associated with progradational shoreline sequences, behind which the coastal plain deposits are host to the thick coal beds (fig. 33). In the western Colville Basin, the Nanushuk Group essentially forms a progradational wedge where the thickest linear shoreline sandstones are found seaward (northeast) of the thickest coastal-plain coal depositional environments. The coastal-plain environment is backed landward (southwest) by the alluvial plain. The linear shoreline is fed by distributary channels located south of Point Lay (fig. 33). Available evidence suggests two sources for the development of the progradational sandstones of the Nanushuk Group: (1) from the Brooks Range to the south and (2) from a northwest-trending uplift in the area of Cape Lisburne and its offshore extension beneath the Chukchi Sea (Mull, 1979). Combining the coal distribution with depositional systems, the total coal thickness map indicates that a coalbed methane exploration fairway exists between the villages of Wainwright and Atqasuk and an area 30 miles (48 km) south of those villages (fig. 26).

In the eastern section of the Foothills and Coastal Plain (eastern NPRA), Nanushuk Group non-marine units are the coal-bearing Chandler and Niakogon Formations, which intertongue with marginal marine facies of the Tuktu, Grandstand, and Ninuluk Formations and the marine Torok Formation. Source areas include Corwin and Umiat delta sources and sources in the

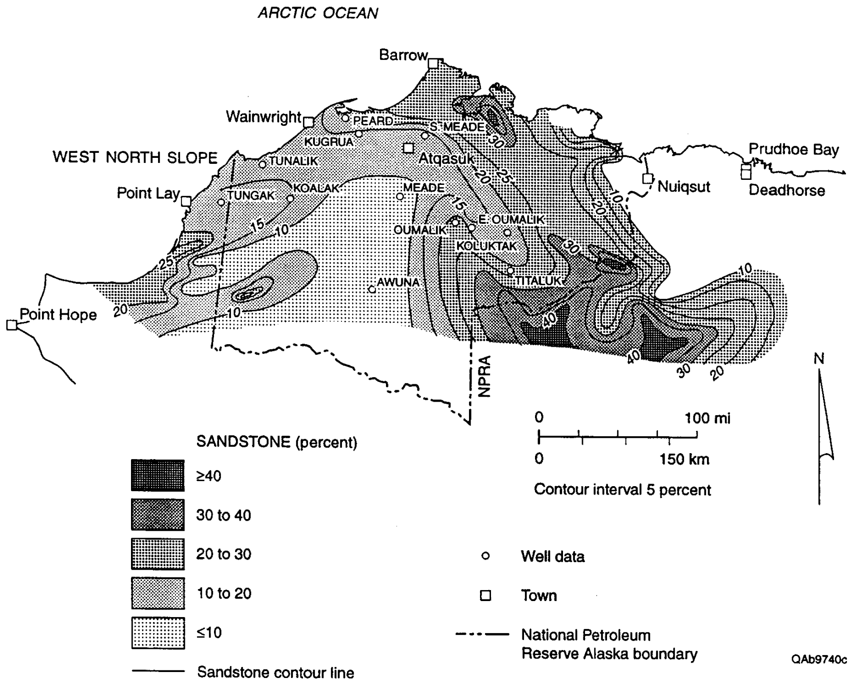


Figure 32. Sandstone percentages in the Nanushuk Group. Modified from Huffman and others (1985).

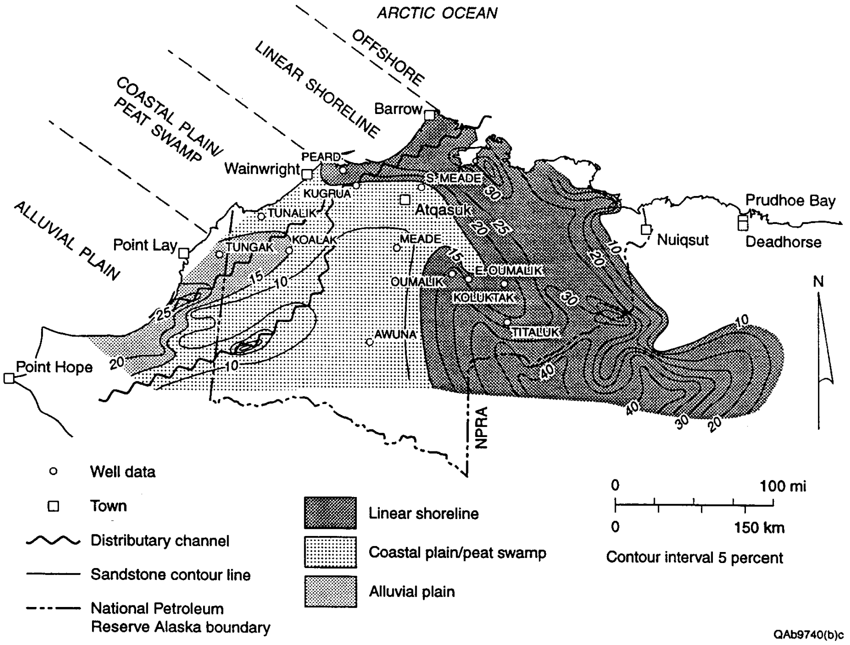


Figure 33. Depositional systems of the Nanushuk Group. Modified from Huffman and others (1985).

central Brooks Range to the south. The Nanushuk Group in eastern NPRA is as much as 5,000 ft thick (1,524 m); the nonmarine units range from zero to about 2,000 ft (610 m) thick. The Colville Group unconformably overlies the Nanushuk Group in eastern NPRA and reaches a maximum thickness of about 3,000 ft (914 m) (Brosgé and Tailleur, 1971; Callahan and Martin, 1981). In the eastern NPRA, the Chandler Formation contains abundant coals similar to those found in the Corwin Formation. However, the coal-bearing interval of the Chandler Formation is less than 2,000 ft (610 m) deep (Smith, 1995), and they are deposited some distance from the prioritized villages. They are not considered coalbed methane targets for exploration in this evaluation.

In summary, the primary coalbed methane target and potential exploration fairway, based on depth, coal thickness and depositional systems, occurs in the Cretaceous, Nanushuk Group coals within the western Colville Basin. The Nanushuk Group coals, extending from the eastern boundary of the National Petroleum Reserve of Alaska (NPRA) to the Chukchi Sea coast, have the highest potential for coalbed methane resource development of rural Alaska, based on available data. In this Rocky Mountain Foreland type of setting, coastal-plain coal is thick, laterally continuous, and highly cleated. At its thickest development (>300 ft net coal; 91 m), between Wainwright and Atqasuk and an area 30 mi (48 km) south of these villages, the potential for both coalbed methane and hydrate (clathrate) resource development may be high. Within this region, along the Alaskan Coastal Plain, the coals are found at depths suitable for exploration, in a relatively relaxed tectonic stress regime, and possibly draped over gently folded strata (Meade and Wainwright Arches), which could enhance coalbed methane permeability and overall producibility. Moreover, most of the Nanushuk Group coals in the Colville Basin, lying at depths averaging 2,000 ft (610 m), will be in or near the permafrost zone (Smith, 1995), where higher gas concentrations may occur. It remains uncertain, without additional subsurface data, what effects permafrost and cold temperatures will have on gas flow from these coals (Smith, 1995), but lower permeabilities in these frozen shallow zones are predicted. Importantly, permafrost may also act as a permeability barrier to the upward migration of thermogenic gas, thus forming conventional traps for exploration. The depths to the exploration targets should, therefore, be below the permafrost to depths not exceeding 6,000 ft (1,829 m), which is a pseudo floor for current coalbed methane activity in the lower 48 States.

Sagavanirktok Formation, Tertiary Coal

The Sagavanirktok Formation (Paleocene and Eocene) is a fluvial-deltaic sequence of poorly consolidated siltstone, sandstone, conglomerate, and lignite that forms an important eastern extension of the Northern Alaska coal fields (Detterman and others, 1975). Subsurface coal in the Sagavanirktok Formation underlie an area of more than 7,000 mi^2 (18, 130 km^2) in the east-central North Slope (Roberts and others, 1990). The coal-bearing units that crop out along a 50-mi (80 km) belt from the White Hills to the Kavik River and extend northward beyond the Arctic coastline (Roberts and others, 1990) are distant to the prioritized villages of importance. They are not considered potential targets in this cooperative agreement.

Coal Rank

The Upper Cretaceous and minor Tertiary coals that subcrop in the Colville Basin represent a large, low-rank coal resource that may contain a large gas reserve (Smith, 1995). Sable and Sticker (1987) mapped the coal distribution and rank of the Cretaceous coal beds through out the National Petroleum Reserve in Alaska (NPRA) (fig. 34). Sources of heat within the basin in the form of intrusives and volcanic complexes that could locally increase the surface coal rank close to the prioritized villages are nearly nonexistent in the western Colville Basin (fig. 35). Surface and near-surface vitrinite reflectance values in the Colville basin range from less than 0.5 to 1.3%, which corresponds to high-volatile C to medium-volatile bituminous coal ranks (Johnsson and Howell, 1996) (fig. 36). Coal rank increases southward towards the Brooks Range, where surface vitrinite reflectance values exceed 3.6%. In the area between Point Lay and Atqasuk, vitrinite reflectance values at 6,500 ft (1,982 m) range between 0.6 to 0.8% (high-volatile C to

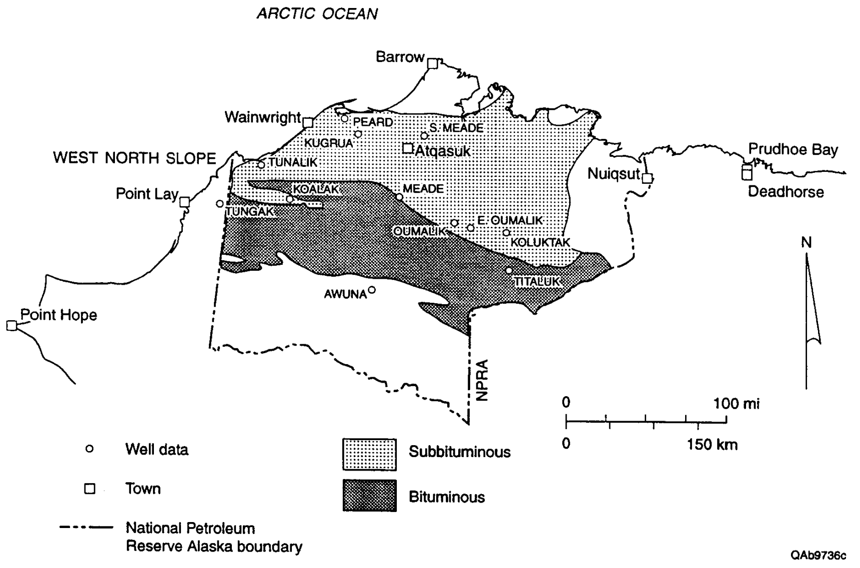


Figure 34. Surface coal distribution and rank for the Upper Cretaceous and Tertiary coals of the National Petroleum Reserve in Alaska. Modified from Sable and Stricker (1987).

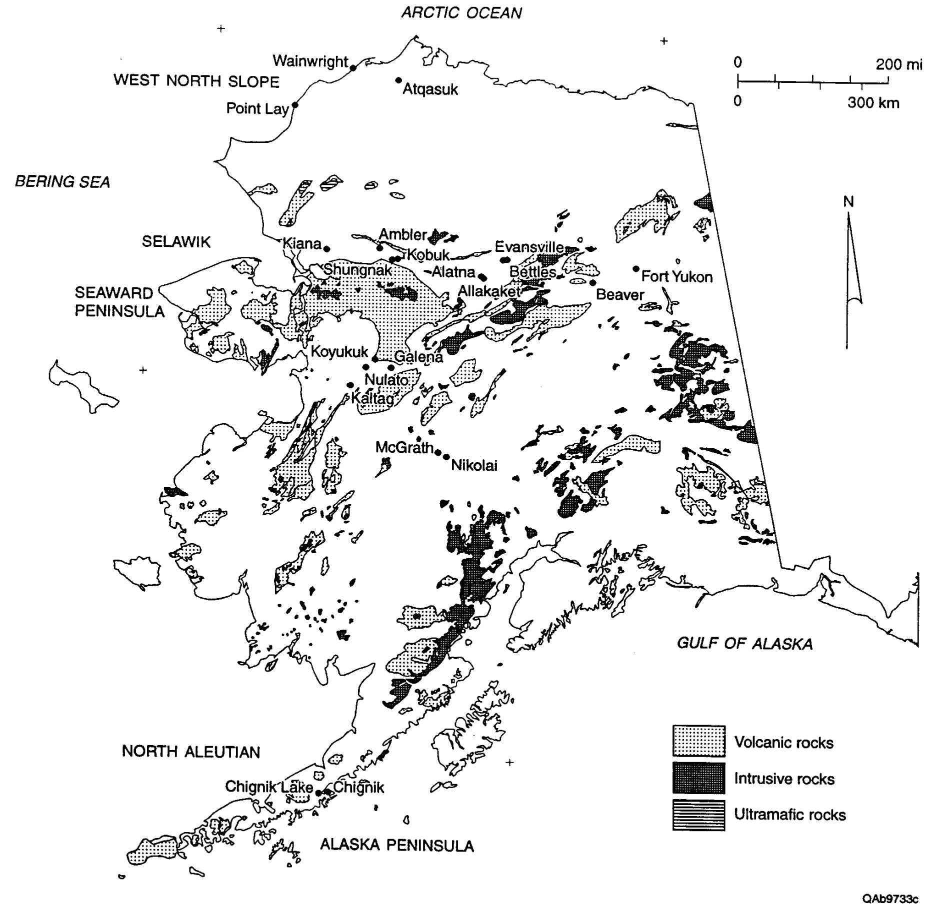


Figure 35. Intrusives and volcanic complexes of Alaska. The North Slope is generally devoid of local sources of heat. Modified from Beikman (1980).

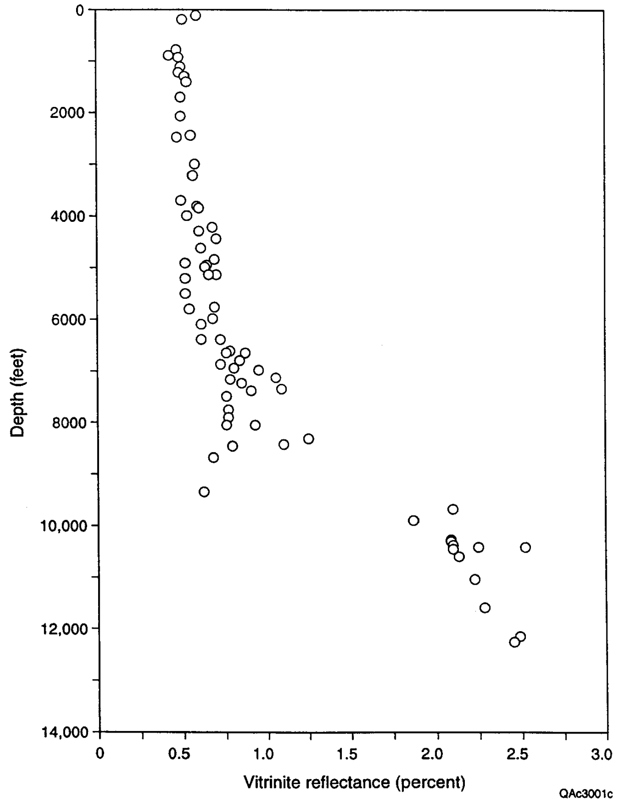


Figure 36. Thermal maturity profiles for the Meade Quadrangle, National Petroleum Reserve in Alaska. The threshold of thermogenic gas generation is not reached until approximately 7,000 ft (2,133 m). Vitrinite reflectance (VR) values range from less than 0.5 to more than 2.5% (subbituminous to anthracite). Modified from Magoon and Bird (1988).

A bituminous), suggesting that the coals have reached the thermal maturity level required to generate significant amounts of thermogenic methane (Johnsson and Howell, 1996) (fig. 37). Thermogenic gases generated at greater depths may migrate updip (northeast) to be trapped behind the progradational shoreline sequences, on structural traps, and/or beneath the impermeable permafrost, resulting in higher gas contents and better potential for coalbed methane resource development.

Hydrodynamics

In the northern and western Colville Basin, the surface coals represent a large, low-rank coal resource. However, because of the low rank of these coals and cold surface and subsurface temperatures, coals buried to a depth of less than 1,000 ft (305 m) are within the permafrost zone (fig. 38) (table 6). Coals shallowly buried and within the permafrost zone will therefore have low permeabilities and low potential for coalbed methane production (Smith, 1995). However, Williams (1970) showed that a water well drilled south of Wainwright on the Kaolak River reported no frozen ground and saline water to depths of 850 to 980 feet (259 to 299 m). In the subcrop, ground-water flow in the permafrost regions may flow as indicated by Cederstrom and others (1953) (fig. 39). Permeability may be enhanced where flow occurs associated with karst channels, faults, fractures in sandstone, and/or cleats in coal. It therefore remains uncertain what effects permafrost and cold temperatures will have on gas and water flow for these coals buried at depth greater than 1,000 ft (305 m), and additional subsurface data is necessary to evaluate permafrost attributes in the areas of the prioritized villages.

Importantly, permafrost may also act as a permeability barrier to the upward migration of fluids and thermogenic gas, thus forming conventional traps for exploration (fig. 40). Along the Alaskan Coastal Plain, the depth to the base of the Nanushuk Group coals generally exceeds 2,500 feet (760 m), placing a substantial portion of the coal section below permafrost (Smith, 1995). Close to Point Lay in the western Colville Basin, the depth to the base of the Nanushuk

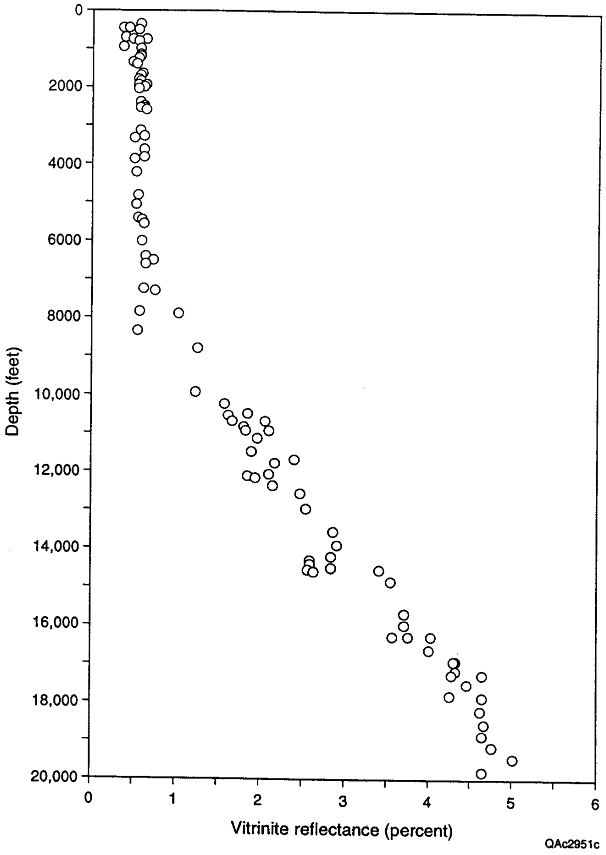


Figure 37. Thermal maturity profiles for the Junalik No. 1 well, National Petroleum Reserve in Alaska. Modified from Magoon and Bird (1988). At depths of 6,500 ft (1,982 m) vitrinite reflectance values have reached the thermal maturity level required to generate significant amounts of thermogenic methane.

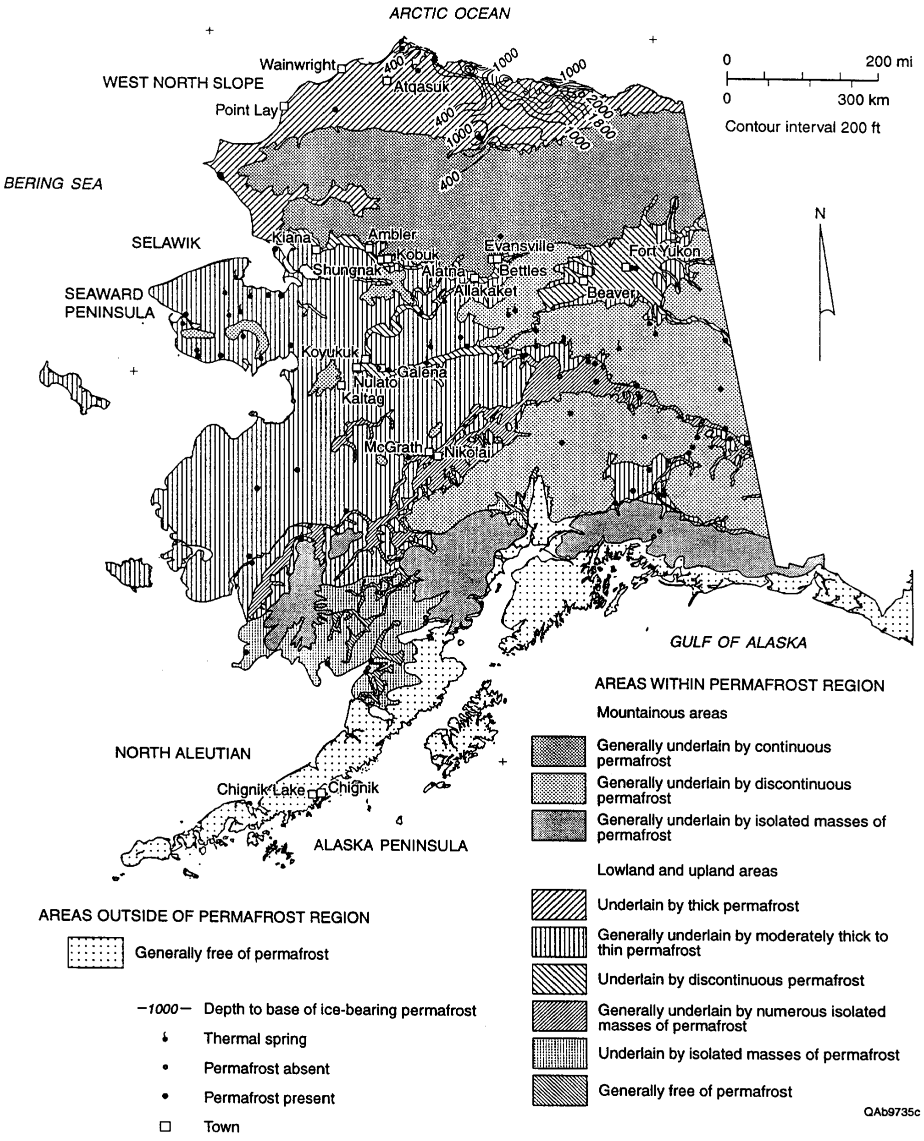


Figure 38. Permafrost regions of Alaska. The North Slope is generally underlain by thick, continuous permafrost. Modified from Ferrians (1965).

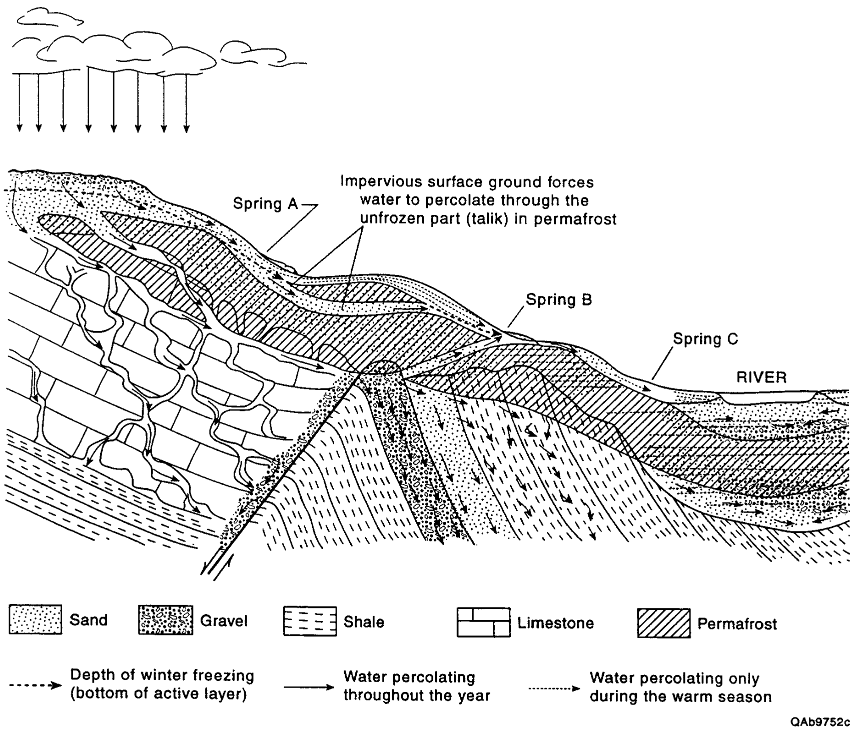


Figure 39. Schematic diagram showing occurrence of ground-water flow in permafrost regions (modified from Cederstrom and others, 1953). Ground-water flow may occur in solution (karst) channels, faults, porous sediments, fractures in sandstone, and cleats in coal.

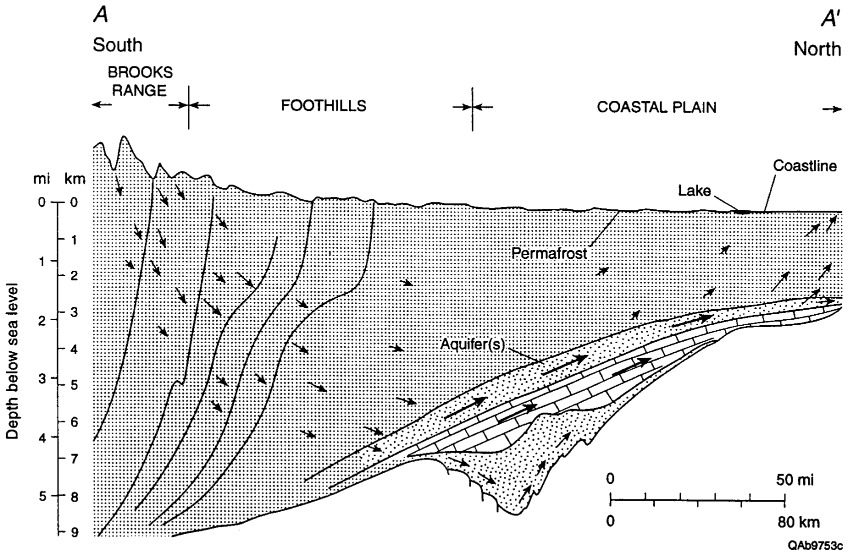


Figure 40. Conceptual hydrogeology model of regional ground-water flow of the North Slope of Alaska. Modified from Deming and others (1992). Location of cross section on figure 15. Flow is from the uplifted Brooks Range in the south, the elevated margins of the basin, down the hydrodynamic and topographic gradient toward areas of discharge (upward-flow potential) along the coastal plain.

Group coals exceeds 6,000 feet (1,829 m), placing a substantial portion of the coal section below the permafrost zone. In the deeper subsurface, the Nanushuk Group coal ranks are predicted to be higher, especially along the southern part of the Colville Basin, therefore having a higher potential for thermogenic gas generation. Based on the mapped total coalbed thickness, the deeper coal beds are suitably positioned for the migration of thermogenic coal gases updip (northeast) toward the Barrow Arch, if adequate permeability still exists in the well developed natural fractures (face cleats). This would result in the conventional and hydrodynamic trapping of migrated fluid and coal gases close to the villages of Wainwright and Atqasuk. Therefore, the hydrodynamic, conventional trapping model proposed for coalbed gas exploration in the Colville Basin is similar to that defined in the prolific producing San Juan Basin (Tyler and others, 1997b).

Subsurface Data and Production: Including Important Statements and Quotations Supporting Coalbed Methane Development along the North Slope

As part of the supporting evidence for selecting basins and/or fairways for advanced coalbed methane resource evaluation, a list of some of the more important statements and quotations made by several operators, authors, and researchers have been recorded. These are time sequentially listed below, with statements directly relevant to the future development of coalbed methane in the Colville Basin; underlined text highlighted by authors:

(1) Collins (1958), in discussing the formation test (4) of the Meade Test well No. 1 between 0-3,038 ft, the coal-bearing section of the Nanushuk Group, stated that the: "Critical flow prover measured 124,500 cu ft gas per day, at 74 psi, 74 degrees; and 301,000 cu ft gas per day at 39 psi, 54 degrees F. A second test recorded 718,000 cu ft per day at 110 psi, 42 degrees F; 1,900,000 cu ft per day at 70 psi, 42 degrees F; and 1,132,000 cu ft per day at 35 psi 38 degrees F". The Meade Well was subsequently designated as a gas field by Kirschner (1988). In examining the log suite, it is also noted that a prime dual completion or recompletion target could be the

interbedded sandstone and coal bed horizon between 1,240 ft to 1,350 ft. This zone appears to be gas charged and the SP response indicates some permeability. Collins (1958) further stated that: "A 30-foot coalbed was reported by the drillers between 40 and 70 ft." and "Only a few very faint shows of oil and gas were found during drilling, except for some gas associated with the coal beds." The coal bearing section record in the well includes 21 coal beds, 4 to 30 feet thick, within 2,000 ft of the surface and these are considered prime targets for coalbed methane exploration and development. (Note: The formation packers failed during formation testing).

(2) Collins (1958), in discussing the Kaolak Test well No. 1 stated that: "Several slight shows of oil and gas were noted in the hole, but the gas was methane associated with the coal beds" (between 800 to 2,200 ft); "17 ft black shiny coal, with blocky to shaly cleavage (blocky fracture) at 1, 183 to 1,203 ft." (This well log suite has a good resistivity response. Moreover, abundant coal is reported to depths of approximately 3,000 ft); "The (permafrost) anomalies in the electric log are abnormal from 113 to 850 ft. Below 980 ft the effects of permafrost cannot be recognized;" and "Collins identified 36 coal beds within 3,000 ft of the surface within coal beds ranging from 3 to 26 feet in thickness. Collins concluded that geophysical evidence indicates that the well may have been near the axis of a broad anticline with gentle dipping limbs." As part of the advanced reservoir characterization program to develop the coalbed methane potential of the North Slope it is recommended that the original log suites, not available during this evaluation, be obtained for the Kaolak and Meade wells so that accurate mapping of the coal thickness can be accomplished.

(3) Barnes (1967), stated that: "The greatest known concentration of coal beds in the area was revealed by the Kaolak Test well 1. A sequence of rock 4,600 ft thick contains 60 coal beds with an aggregate thickness of nearly 350 ft. Two 10-ft beds and 2 thinner ones are within 1,000 ft of the surface, and 32 beds ranging from 4 to 26 feet in thickness were reached between depths of 1,000 and 3,000 ft;" and the "Meade test

well 1 section includes 21 coal beds 4 to 30 ft thick, having an aggregate of 260 ft, within 2,000 ft of the surface."

(4) Tailleur and Brosgé (1976) stated: "Please note the location of the two wells - Kaolak and Meade - which appear to have penetrated an extraordinary concentration of coal" and "The additional potential energy source in gas generated by the coal bears mention but supports little speculation: it is probably best to hope for it as a serendipity."

(5) Tailleur and Bowsher (1979a) stated during a clathrate meeting discussing hydrates in Tunalik No. 1 Test well that: "We have inferred that the gas logs from the upper kilometer of Tunalik Test Well in the northwestern reserve reflect coal gas locked in clathrates to at least 350-m depths. Whereas cutting gas detection correlates strongly with other log indicators of coal, coal did not yield methane to the drilling fluid above about 500 m, a reasonable limit to methane-hydrate stability. We offer this inference for dissection and, given validity, as a potential for specialized clathrate studies and for unmeasured energy resources." During log evaluating of the wells in this study it appears that the log responses have no mud-log gas kicks associated with coal in the upper (permafrost) sections. Below the permafrost zone all wells show a strong coal/mudlog gas kick, a direct indication of the potential for coalbed methane resource development in the area.

(6) Tailleur and Bowsher (1979b) further stated that: "The unmeasured potential of widespread coal deposits in northwestern Alaska has been noted for some time (Tailleur and Brosgé, 1976; Martin and Callahan, 1978) and the resource potential of natural gas in the solid form of clathrate is being considered in the current exploration of the National Petroleum Reserve. The drilling of the Tunalik well, to assess the hydrocarbon prospectiveness of the deep section of rocks in the northwest limit of the Reserve, indicates that the generation of methane from coal and the several-fold volumetric concentration of organic gases on solidifying with water, at near-freezing

temperatures and near-surface rock pressures, creates another resource of unknown potential"; "The pertinent parts of logs from the Tunalik well show methane being released to the drilling fluid in relatively large amounts on penetration of coal layers below the base of permafrost (0° C) in contrast to the release in non-detectable amounts from coal layers in the probably frozen zone above. That the difference reflects the presence of clathrate and not some other factor is inferred with considerable assurance from the absence of a significant difference between amounts of gas evolved on pulverization of the drill cuttings from correlative intervals"; "The known behavior of gas locked up in solid hydrate readily accounts for the measured response from the disturbance by drilling. Methane evolves from the pores of the actually small amounts of rock cut into the elevated conditions of the drilling fluid while remaining locked up in unexposed pore space in the walls of the borehole until energy for the transformation conducts to it. Reduced or absent porosity and permeability on account of the clathrate cement inhibits the flow of any free methane that might have generated in excess of the capacity for hydration. In contrast, methane produced into pore space related to coals at subhydration depths escapes to the borehole on penetration of permeable rock"; "We cannot, of course, speculate on the volumes or viabilities of this probable store of fossil energy. Neither can we recommend assured methods for the requisite determinations. We do think, though, that this is an additional potential resource and, given energy demands that have already made small amounts of coal gas competitive, worth note and consideration."; "The log display also bears importantly on attempts to assess the potential coal resources in north Alaska. The indications of coal on the lithology and resistivity logs resembles the evidence of coal in the Kaolak and Meade test wells. The apparent amounts of coal in those old wells made up about 60 percent of the base for calculating a 100-billion-ton reserve (Barnes, 1967) and projected to the extraordinary figure of nearly 3 trillion tons of hypothetical resource (Tailleur and

Brosgé, 1976)," and "Several-fold greater thicknesses of coal measured by cutting than by the gamma-ray, sonic or density logs of Tunalik well verifies the suspicion that the 10 percent coal in the Kaolak and Meade cuttings exaggerated the amount of coal actually present in the subsurface. The proportion of coal beds in Tunalik aggregates about 4 percent (Gary Stricker, U.S. Geological Survey, Denver, personal com., 1978), the same order of coal concentrations as in the geological analogous Mesaverde Group of the western conterminous states."

(7) Callahan (1979) stated in his article entitled Clathrates associated with coals that: "I have been trying to run down the only reference to hydrates associated with coal that I've heard of, but haven't had much luck. Several years ago, the Bureau of Mines was trying to put together an engineering and economic model for an underground coal mine in northwest Alaska. One of their engineers, Bob Warfield, suggested the possibility of severe gas problems at depths near the base of permafrost, where the reduction of pressure as a result of mining might cause sudden, large inflows of methane released from the hydrate form. He indicated that this had been suspected in one or more underground mines at Svalbard, Norway, as well as in the Soviet Arctic. The Norwegian mines are all within the permafrost zone (above a depth of about 300 meters). Gas generation in the Norwegian mines is about 0.5 cubic meters of gas/24 hr/ton of coal. The Russian Mines reach a depth of 650 meters, well below the base of permafrost. In these mines, gas generation amounts to as much as 17.5 to 20 cubic meters/24 hr/ton of coal. This difference could be the result of gas released from the hydrate state in the sub-permafrost zone. I talked to the MIRL people involved in the permafrost mining study. They did not have any information on hydrates associated with coal, nor could they recall any mention of hydrates in their discussions with the mine operators at Svalbard"; "The question was asked if the natural occurrence of hydrate was limited to the permafrost regions and to ocean sediments. The Antarctic regions are a still unexplored area as far as drilling, and

other regions should not be excluded"; "It was commented that there was something else in the Arctic regions besides temperature which cause hydrates"; "The distinction was made between biogenic and abiogenic carbonaceous material. Biogenic is from a microbic source, abiogenic is not from a microbic source. A further distinction is carbonaceous material formed by the process of maturation, e.g., coalification. The North Slope gas is biogenic, for instance. The biogenic material has as its source both plant and animal matter, chiefly of microscope origin. Hydrates occur in both the Paleozoic and the Devonian. The Russian deposits are Paleozoic"; and "cores should be taken through suspect hydrate zones, particularly through coal zones".

(8) Ahlbrandt (1979) stated: "Sandstone of the Nanushuk Group are thin and discontinuous, and beset with diagenetic problems, ... and are impermeable (5 millidarcys)"; "Overall, the Corwin delta has a low sandstone content and thin, laterally discontinuous sandstone beds (table 1). The single most important deposition unit from a reservoir standpoint is the foreshore sandstones within the basal part of the Nanushuk Group. These sandstones are easily recognized by their prominent, original, nearly horizontal bedding and distinctive vertical burrows. Their predictable occurrences in the Nanushuk indicate the passage of the paleoshoreline. These high-energy environments have the best reservoir potential in the Corwin delta complex because they have (1) the best visible porosity in outcrop and best measured porosity and permeability; (2) greatest maximum thickness (<25 m, commonly 5-10 m); (3) a possible adjacent hydrocarbon source (marine shale); (4) lateral continuity along the paleoshoreline; and (5) a relatively more stable composition due to removal of diagenetically unstable grains under relatively higher energy conditions. The foreshore, offshore-bar, and barrier-island sandstones should have a preferred northwest-southeast orientation in the western area, which is useful for exploration. The Tupikchak Mountain section is the only area studied in which foreshore sandstones rest directly over one another, resulting in an 18-m-thick bed; however,

porosity values are less than 9 percent and permeability values are less than 1 md there"; and "Thus, considering the reservoir quality of the sandstones in the western area, prospects of major oil; accumulations in the Corwin delta complex seem to be poor; porosity values are low to moderate. Thermal-maturation data in both western outcrop and subsurface samples suggest that the Nanushuk is more prone to gas accumulations. However, low permeability and discontinuity of sandstones in the western area may even be a limitation on the size of reservoirs and rate of flow of potential gas production." (Thus, the inference made from these statements is that the coals are the reservoir and source rock for resource development in the Colville Basin, along North Slope).

(9) Fenex and Ehm (*in* Husky Oil NPR, Operations, Inc., 1983), well site geologists at the Kugrua Test Well No. 1, stated: "Methane gas shows associated with the coal beds occurred throughout the Corwin Formation (between depths of surface to 1,420 ft)"; and "Coal is low grade subbituminous and is associated with methane gas" (in describing depths between 115 and 700 feet).

(10) Wermeyer, (Husky Oil NPR, Operations, Inc., 1982), a well site geologist at the Peard Test Well No. 1, noted: "Methane gas occurred in the Nanushuk above 1,000 ft primarily associated with coal beds."

(11) Sable and Stricker (1987) in discussing the NPRA coal -geology and resources and gas hydrate possibility stated: "The potential for natural gas to exist in large volumes as solid phase gas hydrate (clathrate) in regions underlain by permafrost has been discussed in a symposium on natural gas-hydrates (Bowsher, 1979). In this symposium, Tailleur and Bowsher (1979a) suggested that the geophysical well logs of Tunalik Test Well No. 1 in western NPRA indicated the possible presence of clathrate. Clathrate may pose both positive and negative impact; positive, in that clathrate may exist in commercial quantities within or at the base of permafrost, and negative, in that the dissolution of clathrate to the gaseous phase during drilling may

result in abnormally high hole pressure with resultant damage to drilling equipment and danger to personnel"; and "In NPRA areas with abundant coal resources, coal-generated-methane gas may occur in large volumes and may be a potential major component of gas hydrate. Future drilling exploration should consider this factor and monitor the possible presence of clathrate by appropriate drilling techniques and instrumentation outlined in Pratt (1981)".

(12) Claypool and Magoon (1988) stated that: "Gas source rocks are present throughout the NPRA. A high gas content in canned cutting samples was observed in association with low rank coals and disseminated humic organic matter in the Colville and Nanushuk Groups;" "Evaluation of samples from the Tunalik No. 1 well indicates that the Nanushuk Group are unfavorable source rocks for oil but favorable for gas", and "The shallow coal beds are immature and would not be expected to contribute to the presence of gas". These statements are the "traditional view" opinions on coalbed methane resource development that were made prior to the resource development and technology transfer in the Lower 48 States during the late 1980s and early 1990s. It is now a well established fact that migration of thermogenic, secondary biogenic and solution gases to conventional and hydrodynamic traps in coalbed methane reservoirs plays a much larger part in coalbed methane producibility, than was previously recognized.

(13) Kirschner and Rycerski (1988) stated: "Potential reservoirs in sandstones of the Nanushuk Group are present on many of the detached anticlines"; and "The Nanushuk Group reservoirs are generally at depths of less than 4,000 ft (1,200 m), as for example in the Oumalik and Meade No. 1 wells."

(14) Grantz and others (1988) in discussing shallow gas in the NPRA stated: "Shallow free gas has accumulated in several geologic environments beneath the shelf and slope of the western Beaufort and northeastern Chukchi Seas. In some cases this gas may indicate the presence of natural gas deposits in underlying sedimentary strata

(thermogenic origin). In other cases, the gas may originate in surficial sediment as a product of bacterial metabolism of organic constituents (biogenic origin). Wherever it occurs, shallow free gas must be considered a potential engineering hazard to petroleum exploration or development structures founded on the seabed. Such gas can inhibit the normal consolidation of accumulating sediment, leading to abnormally low shear strength. In addition, overpressured gas concentrated in pockets might cause blowouts during drilling".

(15) Grantz and May (1988) also stated: "Exploration in the western NPRA indicates the potential may be greater for gas than oil; and the eastern NPRA "contains a small gas field (Meade) west of the Dease Inlet. It is dominantly non-marine and contains thick coal beds south of Point Lay, and it thins and becomes paralic and then shallow marine to the northeast (Chapman and Sable, 1960; Ahlbrandt, 1979). These conditions should result in improved reservoir quality in that direction. Accordingly, the Nanushuk is expected to be gas-prone and contain less capable reservoirs to the southwest, and to be more likely to contain oil and have more capable reservoirs to the north or northeast. An oil seep from the Nanushuk at Skull Cliff, 50 km southwest of Barrow (McKinnery and others, 1959), may support this contention"; "Offshore seismic data and projection of onshore stratigraphy and thermal maturation data indicate that (in area 1) sandstones from the Permian and Triassic Sadlerochit Group to the lower part of the Albian and Cenomanian(?) Nanushuk Group may be in contact with adequate source rocks and could contain significant pools of oil and, especially, gas"; and "Stratigraphic traps caused by permeability gradients or shale oversteps at one of several unconformities in the section may occur. If present, such traps could be very large because of the uniform but low regional dip."

(16) Collett (1988) in discussing natural gas hydrates from well logs in the Prudhoe Bay stated: "Hydrates can also be found in association with decaying biomatter, such as coal, which would serve as a source for the methane needed for hydrate development

(Pratt, 1981)"; "A possible scenario for the formation of hydrate in the North Slope would begin with free gas migration either from local diagenesis or from depth through relatively permeable sand unit along the base of an impermeable prodelta shale. The overlying shale unit would act as a cap to vertical gas migration. The migrated free gas could be trapped in the up-dip direction by a series of different trapping mechanisms. The two most probable trapping mechanisms would be a self-forming hydrate trap and an impermeable ice-bearing cap". This hydrate discussion is very similar to the Bureau of Economic Geology coalbed methane producibility model statement however, we would call on conventional traps in the form of stratigraphic pinch out of coal beds behind progradational sequences; structural deformation, that is, folding and faulting resulting in permeability barriers for the migration and accumulation of gas; and/or importantly, as stated by Collett (1988): "The impermeable permafrost could also form an up-dip trap to free gas migration. As the free gas migrated updip along the bedding plane, the gas would be trapped at the base of the permafrost and be frozen in place;" and "The recognition of primarily structural - stratigraphic control on the up-dip gas migration model for the hydrate accumulations was a significant contribution."

(17) Collett (1993b) stated: "These analyses suggest that methane is the principal hydrocarbon gas in the near-surface (0 -1,500 m) strata of the North Slope (fig. 41). Stable methane-carbon isotopic analyses of gaseous drill cutting from several gas-hydrate-bearing units yielded carbon isotopic values averaging approximately -49 ‰), suggesting that the methane within the inferred gas- hydrate occurrences is from mixed microbial and thermogenic sources. Gas with stable methane-carbon isotopic compositions -50 ‰ and heavier is considered to be thermally generated; conversely, an isotopic composition of -60 ‰ or lighter indicates that the gas was formed by microbial processes. Vitrinite reflectance (Ro) measurements of about 0.4% show that the gas-hydrate-bearing rocks have never been subjected to

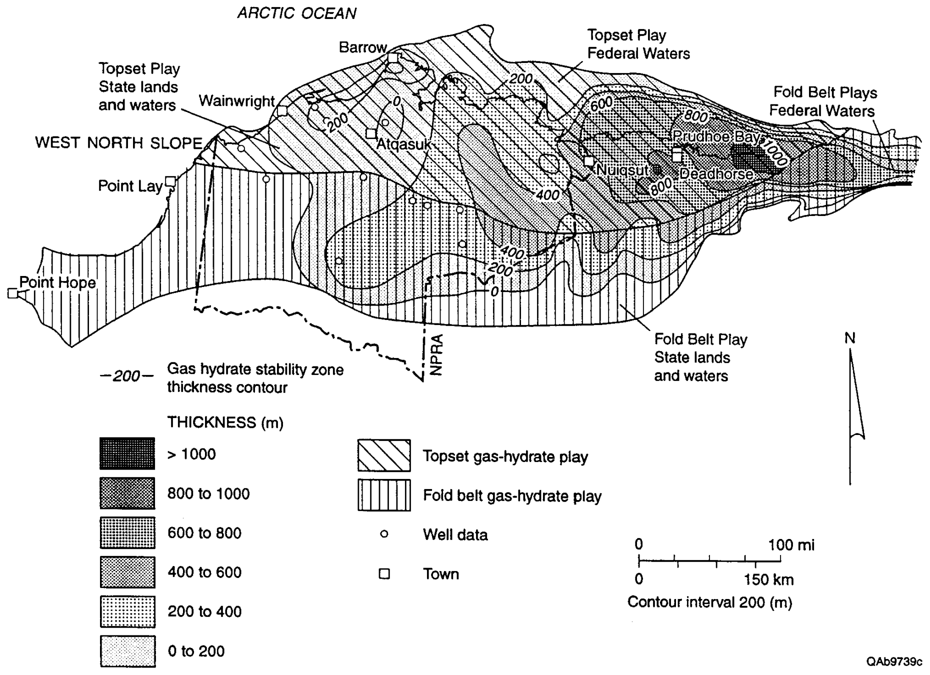


Figure 41. Stability zone and thickness of the Northern Alaska coal province gas-hydrate play (modified from Collett, 1993a). Coalbed methane resource development should be done in conjunction with gas-hydrate development.

temperatures within the thermogenic window (Collett et al., 1990); thus, the thermogenic gas must have migrated from greater depths".

Coalbed Methane Potential

Applying the coalbed methane producibility model to the Colville Basin, it is readily apparent that conventional and hydrodynamic traps for the North Slope are both structural and stratigraphic. Moreover, based on the existing subsurface coal rank data indicating that the coal-bearing rocks at the surface have not reached the threshold of thermogenic gas generation, the North Slope exploration fairway should target thermogenic gases in or below the permafrost zone that have migrated from greater depths in the basin. Stratigraphic traps are related to Nanushuk Group facies changes and up-dip pinch out of the coal beds behind the progradational shoreline sequences in a similar fashion to those conventional and hydrodynamic traps found in the San Juan Basin. Along the North Slope, stratigraphic traps will be found on the southern flanks of the Barrow Arch and on the western flank of the Meade Arch, where the Nanushuk Group thins and/or pinches out behind the progradational shoreline and onto the flanks of the ancestral Meade Arch, respectively. Structural traps within this area will consist of (fault cored) anticlines (Meade and Wainwright Arches) related to the Brooks Range and Barrow Arch orogenesis and permeability barriers/traps formed against smaller-displacement faults. Moreover, the up-dip migration of thermogenic gases within the coal beds and the trapping of the migrated gases beneath permafrost layers must be considered an area for conventional trapping (clathrate/hydrate development) and a highly recommended exploration fairway and development target for the Colville Basin.

It is recommended that a complete drilling and exploration program should focus on defining the exploration target within the fairway defined between the villages of Wainwright and Atqasuk and an area to at least 30 miles south of these villages. The potential for both coalbed methane and hydrate (clathrate) resource development is extremely high. Coalbed methane and gas hydrate resource exploration and development should be done simultaneously, that is, both reservoirs should be part of the future exploration and drilling program. A multidisciplined exploration and drilling project including geology, geohydrology, geophysics, geochemistry, and reservoir engineering should be undertaken within the exploration fairway to establish the physical conditions of the gas contents, in-situ stresses, water geochemistry and geohydrology, and to define the field scale controls on the coalbed methane producibility.

Procedures for drilling should be done using similar practices to that used along the North Slope (Richard Glenn, North Slope Borough, personal. com. 1997) with protection for blowouts, and core should be taken through the hydrate zones and coal beds. Drilling and coring depths must include the base of the permafrost to the total depths of the coal-bearing horizon (at least to 1,000 to 6,000 ft; 305 to 1,829 m). Importantly, this exploration fairway is known as a gas prone area; the Meade No. 1 well is designated as a gas field (Kirschner, 1988). Although the primary target for gas is coalbed methane, gas-charged sandstones could also be evaluated through commingling of production. In the Meade No. 1 well for example, there is evidence that the sandstones may be permeable and gas charged at approximately depths between 1,240 to 1,350 ft (378 to 412 m). Therefore, the potential for the development of a gas resource base within the western Colville Basin appears to be relataively high. Future exploration and advanced reservoir characterization should include coalbed methane, hydrate (clathrate) and tight-gas-sandstone reservoir development within the defined exploration fairway.

Upper Yukon Province: Yukon Basin (Beaver, Birch Creek, Chalkyitsik, Fort Yukon, and Venetie).

The Yukon National Wildlife Refuge, south of the Brooks Range and north of the Alaska Range, consists of several distinct lithostratigraphic units and terranes, which were accreted, amalgamated, and emplaced along two major strike-slip fault systems; the Kaltag-Porcupine Fault Zone and the Tintina Fault Zone (Banet and others, 1987) (figs. 42 and 43). Of these terranes, the Yukon Basin is considered important for oil and gas discovery, based on indirect

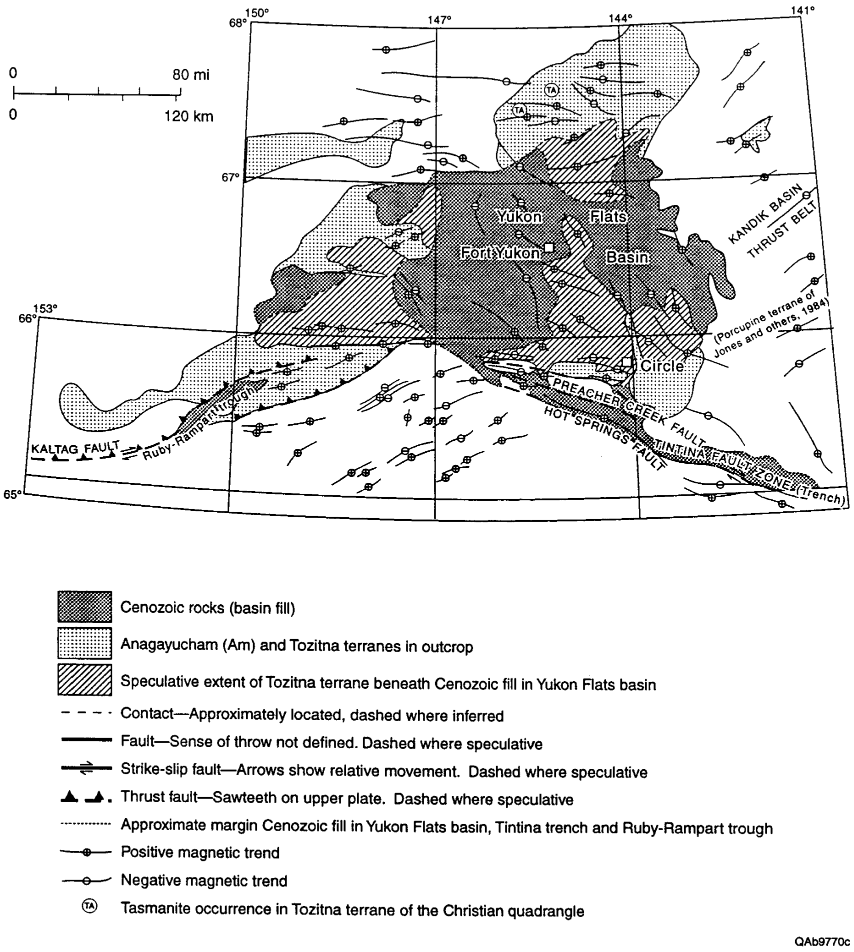


Figure 42. Map showing the location of the Fort Yukon Basin, extent of Cenozoic basin fill, and trends of the magnetic anomalies (modified from Kirschner, 1994). The speculative extent of the Anagayucham and Tozitna terranes in outcrop and beneath Cenozoic fill are shown.

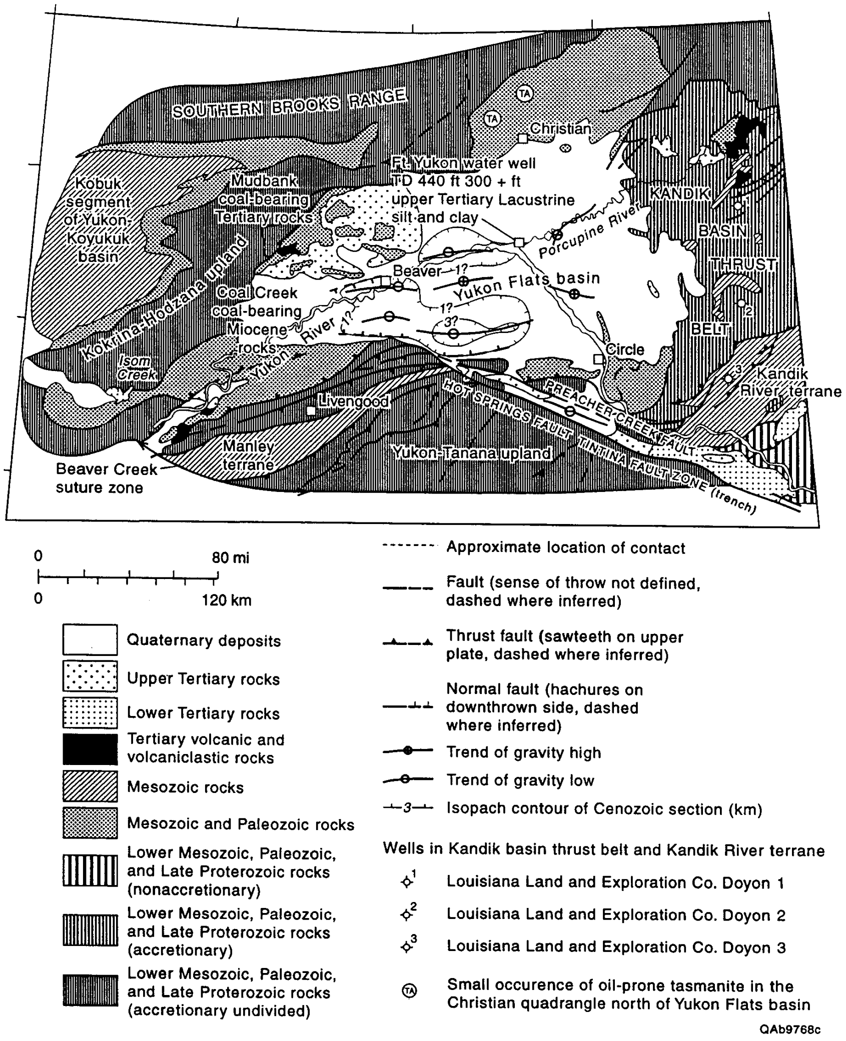


Figure 43. Generalized geologic map of the Yukon Flats Basin and adjacent areas. Modified from Kirschner (1994).

geophysical data in the forms of aeromagnetic and Bouger Gravity surveys and inferred subsurface geology (Banet and others, 1987) (fig. 44). Much of the following text describing the tectonic and depositional settings of the Yukon Basin is taken from Banet and others (1987).

Physiographic and Geologic Setting

The Yukon Basin is the largest interior basin in Alaska covering more than 8,500 mi^2 (22,000 km^2) and is believed to be filled with more than 6,500 ft of Tertiary fill (Smith, 1995) (table 3). The basin is bounded by the Tintina fault system to the south, and the foothills of the Brooks Range to the north (fig. 42). Late Cretaceous and Late Tertiary structural deformation caused the downwarping of the Yukon Basin and stream offsets in the northern part of the Yukon Refuge suggests that at least some Quaternary deformation has occurred (Jones and others, 1981). Bouger gravity anomalies suggest that the thickest Cenozoic fill is located along the Tintina fault zone in the southern part of the basin (Kirschner, 1994) (figs. 43 and 44).

Limited data from oil and gas exploration of the Yukon Refuge shows a complex assemblage of rock types, stratigraphic sequences, and structural styles (Banet and others, 1987). Rocks from all geologic time periods are recognized, including one of the most complete, continuous, and fossiliferous sequences of Proterozoic to Lower Paleozoic carbonates in North America (Banet and others, 1987). Other rock types include intrusive volcanic and mafic igneous rocks (fig. 35), nonmarine clastics, and oceanic, arc trench and continental margin sediments (Banet and others, 1987). Even though well-defined sequences and stratigraphic successions are known, most of the Yukon Basin has poorly known stratigraphic successions, or stratigraphic relationships that cannot easily be explained by facies changes or faulting (Banet and others, 1987). At present, no regional correlations extend across the Yukon Flats due to the lack of subsurface data. In addition, the entire Yukon Flats is covered by Holocene sediments, so the geology of almost half of the refuge can only be inferred (Banet and others, 1987).

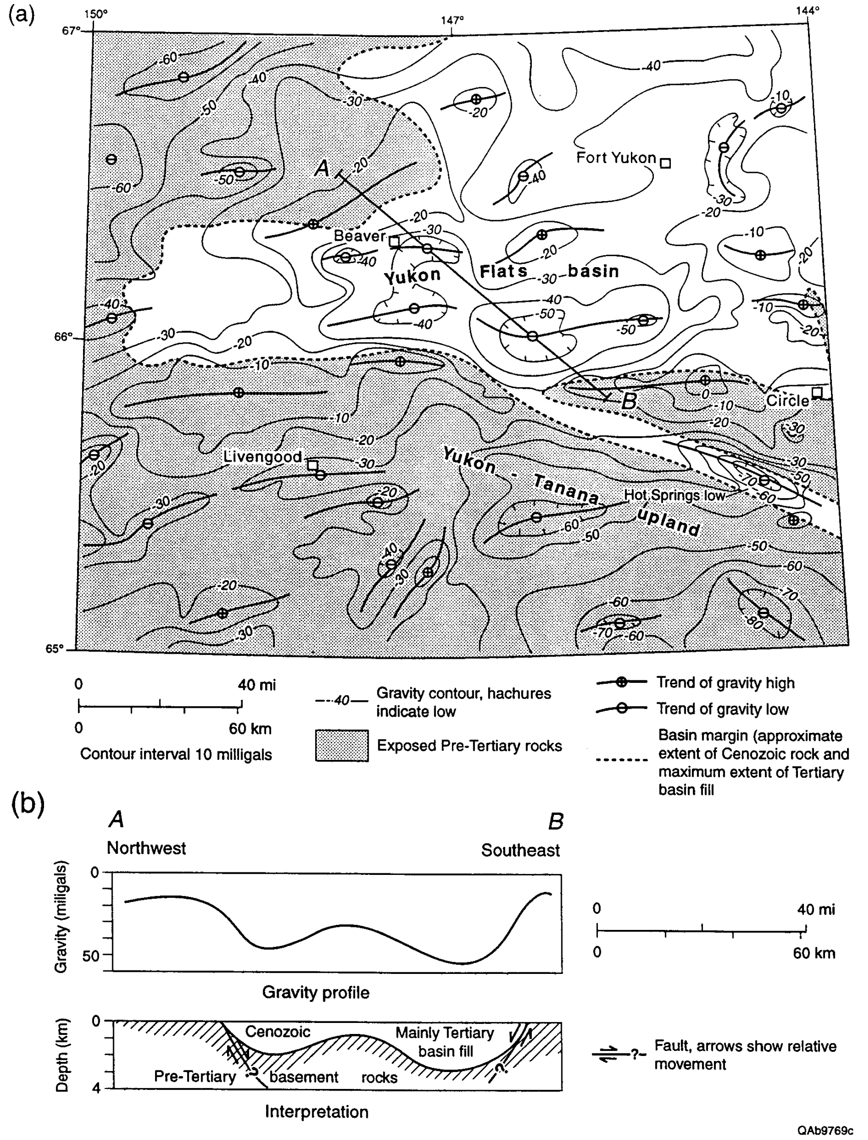


Figure 44. Bouger gravity map of the Yukon Flats Basin and adjacent areas with gravity profile and interpretation of Cenozoic fill in the basin. Modified from Kirschner (1994).

Reconnaissance field work in the vicinity of the prioritized rural villages revealed that the outcrops are extremely rare, occurring in small, highly weathered, and widely scattered exposures along recently eroded stream cutbacks, that, in most instances, were long distances from villages. Along the Yukon River, the surface consists mostly of flat to undulating lowlands dotted with numerous shallow lakes, sloughs, and meandering and braided streams. Local relief, on flood plains, well-developed river terraces, and alluvial fans, generally does not exceed 150 ft (46 m) (Williams, 1962). The Yukon River, the principal drainage, drops only about 200 ft (61 m) in elevation in 180 mi (290 km), as it meanders across the Yukon Flats as a complex, braided stream (Banet and others, 1987). The few coal bed exposures that we visited during our investigation, occur mainly on the extreme flanks of the basin, where basement rocks are mapped as low-to-high grade metamorphic terranes. In most outcrops, forest fires have severdy decomposed and weathered these coal exposures, and accurate descriptions of these coal horizons and cleat attributes were restricted.

Tectonic and Structural Setting

For subsurface coalbed methane evaluation there is significantly little to no subsurface data (table 4). No publicly available stratigraphic or structural correlations and cross sections exist across the Yukon Flats. This results in the coalbed methane geology and hydrology being inferred from limited previous publications based on very regional and possibly speculative interpretations.

The Yukon Flats Basin is located at the intersection of two major fault systems (figs. 41 and 42). The Tintina system, an association of right- lateral strike-slip faults with symmetrical, en echelon second and third order thrust faults, folds, and normal faults (Banet and others, 1987), is estimated to extend from the southwest part of the refuge some 600 mi (966 km) south-southeast to the Rocky Mountain Cordillera with up to 269 mi (433 km) of Lower Paleozoic to Upper Cretaceous episodic displacement (Templeman-Kluit, 1976). The Kaltag Porcupine fault system, another right-lateral system that cuts off the Tintina system, is postulated to be a major plate boundary, extending from the western Bering Sea, through Alaska, into the Canadian Beaufort, and on to northern Greenland (Banet and others, 1987). Initial lateral movement began in the Early Cretaceous, much later than along the Tintina system (Banet and others, 1987). Subsequent offsets during the Late Cretaceous and Late Tertiary caused the downwarp for the Yukon Flats Basin.

Within the basin, the Tertiary coal-bearing section nonconformably overlies the Mesozoic volcanics and mid-Paleozoic metasedimentary rocks, and is interpreted as an extensional half-graben complex. Extensions of the Yukon Basin exist in the form of troughs paralleling the inferred traces of the Kaltag (Rampart Trough), Porcupine, and Tintina faults. Coal occurrences in the Rampart Trough on the extreme flanks of the basin, adjacent to the Kaltag Fault, are generally structurally controlled being folded and tectonically disturbed. While this has resulted in slightly higher rank coals in this area, the beds that are faulted appear to be discontinuous and are steeply dipping to vertical on the flanks of the basin (Banet and others, 1987). Their down-dip lateral extent is unknown.

Depositional Systems and Coal Distribution

Mapping around the Yukon Flats basin has revealed many rock types (Banet and others, 1987). Many of these stratigraphic relationships are not well explained by faulting or facies changes. Both the styles of structural deformation in the area and the wide variations in stratigraphies are more accurately considered as belonging to separate entities called terranes rather than as vaguely related parts of a single geologic domain (Banet and others, 1987). Terranes are lithostratigraphic or tectonostratigraphic units that are fault-bounded geologic entities of regional extent, each characterized by a geologic history that is different from the geologic histories of contiguous terranes (Jones and others, 1981).

The primary coalbed methane targets in the basin are Tertiary, and possibly Upper Cretaceous in age, but the surface and subsurface distribution and characteristics of the coal source rocks in the area are unknown. Sparse outcrop and extremely limited subsurface data severely limit the geologic and hydrologic evaluation of this basin. Fort Yukon coals are believed to have been deposited in a westward progradational, laterally discontinuous fluvial coal system similar to the depositional setting of the Tertiary coals in the Greater Green River and Powder River Basins, Wyoming. It is postulated that if the thickest coals are developed parallel to and adjacent to fluvial axes (Tyler and others, 1995b), then maximum net coal trends would occur parallel to the existing Yukon River. Smith (1995) also suggests that coal-bearing rocks may underlie most of the Yukon Flats Basin. Although potentially thick coals may exist in a fluvial depositional setting closely associated with the current Yukon River basin system, the lateral continuity of these coals may also be limited. Therefore, additional research and subsurface exploration is required to fully evaluate the coal distribution in the basin.

In reconnaissance field work, exposures of Tertiary coal beds were found at the Drew Mine, approximately 40 mi (64 km) upstream from Rampart, near the rivers edge, striking N70° east and dipping at 80° southeast. These coal beds were highly cleated suggesting the possibility of permeability in the subsurface. However, it is uncertain whether the coal sampled is part of the Yukon Flats basin paleotopography or if the coal beds are continuous into the subsurface. The only subsurface control in this large basin is a proprietary oil company (Exxon) seismic survey, shallow core holes, and a 1,200-ft (366 m) core hole drilled in 1994 at Fort Yukon by the U.S. Geological Survey (Smith, 1995). Barker and Goff (1987) report auguring about 20 ft (6 m) of coal with a rank from lignite A to subbituminous B. The U. S. Geological Survey Fort Yukon well encountered a 21 ft (6.4 m) thick Middle Miocene lignitic coal bed at a depth of 1,260 ft (384 m) (Gary Stricker, U. S. Geological Survey, Denver, personal communication with Smith, 1994).

In summary, from limited subsurface and outcrop data we infer that coal-bearing rocks may underlie most of the Yukon Flats Basin, close to the present day fluvial axis of the Yukon River.

However, based on the limited subsurface data, no estimate of the coal bed thickness, depth and coalbed methane resource potential can be made until at least some additional stratigraphic and subsurface data can be obtained from future drill testing and exploration.

Coal Rank

Surface and near-surface coals in the Yukon Basin are between the lignite to subbituminous, having volatile matter (Daf, dry ash-free basis) ranging between 58 to 48%, which corresponds to estimated vitrinite reflectance values between 0.3 to 0.5%. Barker (1981) reported vitrinite reflectance values of 0.3 to 0.5% for isolated patches of Tertiary rocks north of the basin. The U.S. Geological Survey well bore drilled in 1994 encountered a gassy lignite at a depth of 1,260 ft (384 m). An evaluation of the changes in pollen flora near the top of the lignite suggests a rapid loss of broadleaf trees in Alaska which coincides with a global cooling 15 Ma (Ager and Fouch, in press). There are limited chemical analyses on Fort Yukon Basin coals (Collier, 1903; this study) but sulfur content appears to be low and ash content ranges between 4 and 15% (table 7).

Banet and others (1987) report relatively low geothermal gradients (8.5° to 14.0 °F/1,000 ft; 9° to 19°C/km) in wells located west of the Yukon Flats Wildlife Refuge and south of the village of Tanana. If such geothermal gradients exist in the Yukon Flats Basin, then coal rank probably remains relatively low even at great depths. However, the presence of high-volatile B bituminous or higher rank coals at depths less than 6,000 ft (1,829 m) would not be surprising. Significant thermogenic gas generation at depths less than 6,000 ft (1,829 m) is probably not occurring and any gases present in the lignites and coals occurring in shallow sediments are probably secondary biogenic and/or migrated secondary biogenic. These biogenic gases are expected to have gas dryness indices near unity and relatively low amounts of carbon dioxide. However, actual carbon dioxide content may be variable depending on bacterial consortia present in the subsurface.

Hydrodynamics

The Fort Yukon Basin lies within a region of discontinuous permafrost, although permafrost probably underlies much of the area (Ferrians, 1965) (fig. 38) (table 6). Permafrost thickness estimates range from 18 to 390 ft (5 to 119 m) but is generally thinner adjacent to or below recently abandoned meander belts or large lakes. Regional ground-water flow direction is influenced by the Yukon River which flows through the center of the basin. Ground-water flow tends to converge at major river systems, such as the Yukon River, suggesting that migrating biogenic gases could be concentrated along the river to become potential exploration targets. However, stratigraphic and/or structural permeability barriers are necessary to trap these gases. Clay and silty-clay above the lignite in the U. S. Geological Survey water well (Ager and Fouch, in press) may act as a permeability barrier to upward migrating gases, resulting in local wildcat exploration targets. Additionally, permafrost may also act as a permeability barrier and the geometry of the permafrost should also be taken into consideration in effectively delineating areas of higher coalbed methane potential. Importantly, the thickness and lateral continuity of coals and the effectiveness of seals above the coal beds in this area remain unknown.

Subsurface Data and Production: Including Important Statements and Quotations Supporting Coalbed Methane Development in the Upper Yukon Province

Kirschner (1994), stated that "no direct evidence for hydrocarbons have been reported in the Yukon Flats Basin" but "source beds are most probably non-marine Tertiary lacustrine or coal beds;" and "an optimistic evaluation is that gas reserves of economic importance for local consumption could be present" in the Fort Yukon Basin.

Smith (1995), stated that "the U. S. Geological Survey Fort Yukon Well encountered a 21-ft-plus (6.4 m) lignitic coal bed at 1,260 ft. The core sample released a significant amount of gas when brought to the surface (Gary Stricker, person. comm. with Smith, 1994). This resulted in the termination of the drilling (Tom Ager, U. S. Geological Survey, Denver, personal communication with Smith, 1994)."

Coalbed Methane Potential

Sparse outcrop and extremely limited subsurface data severely limit the geologic and hydrologic evaluation of this basin. If wildcat exploration and development of the potentially shallow coalbed methane resources at Fort Yukon is undertaken, the methods used should be similar to those used in the shallow Powder River Basin coalbed methane resource development program. Because the surface and subsurface distribution and character of the coalbed source rocks in the area remain unknown, additional (Exxon, Doyon) seismic and well data for the Fort Yukon area should also be used to assist in locating the wildcat well so that samples can be obtained to estimate the total coal thickness and gas contents within the area. It is hypothesized that shallow, potentially thick coals may exist in a similar fluvial depositional setting closely associated with the present day Yukon River system. These coal beds may be deposited in a similar depositional system to that of the Fort Union Formation in the Powder River and Greater Green River Basins, Wyoming.

From available data, Tertiary coal ranks in the Yukon Basin have apparently not reached the thermal maturity level required to generate significant amounts of thermogenic methane, suggesting that gases in these coal beds are probably secondary biogenic. Coal gases in the Powder River Basin are also secondary biogenic and gas contents in these coal beds are less than 50 scf/ton (1.6 m^3/t) (Tyler and others, 1991). Bacterial activity and subsequent gas generation in the Yukon Basin coal beds may, however, be inhibited by the cold temperatures although paleotemperatures during interglacial periods may have been significantly higher. Assessing the timing of secondary biogenic gas generation will be important for future exploration and development because it will provide valuable information with which to assess the effectiveness of permafrost as an impermeable seal. If secondary biogenic gases were generated during the interglacial periods, permafrost would be less continuous or absent suggesting that the trapping of biogenic gases would be associated with stratigraphic or structural seals rather than from permafrost. The presence of gas escaping from the lignites in the 1994 U.S. Geological Survey test well is encouraging, because it indicates the presence of active biogenic gas generation and/or migration of biogenic gases to this area. Although gas content data were not collected, migration and accumulation of coal gases often results in higher-than-expected gas contents in lower rank coals.

In summary, the coals appear to be relatively thick (>21 ft; >6.4 m) and slightly gassy in this area, but coal thickness, lateral extent, and/or gas content may be insufficient to support adequate coal gas production. In a memorandum from Tom Ager (1993), he acknowledges the "possibility of pockets of shallow organic gas in and below the permafrost" in the first Yukon Basin. As such, a wildcat exploration program for these shallow gas resources, associated with both coal and sandstone, could be undertaken as per discussions in Oldham (1997). Methods for exploration and extracting of these shallow pockets of gas should be similar to those used in the Powder River Basin (see publications by Law, 1976; Oldham, 1997; and Tyler and others, 1994). The exploration target is possibly the migration of thermogenic gases, but, more likely, it is the generation of secondary biogenic gases associated with differential compaction as a mechanism for trap formation and prospect definition. Exploration for shallow gas accumulations must include protection for blowouts and should incorporate both coal and sandstone reservoirs. It is important to remember however, that the lack of data, poor outcrops, inaccessibility, and heavily vegetated terrain, coupled with pervasive permafrost to depths of at least 300 ft (91 m), will pose a major challenge to coalbed methane resource evaluation and development in the Yukon Flats Basin.

Alaska Peninsula Province: Chignik Bay Basin (Chignik, Chignik Lake, and Chignik Lagoon)

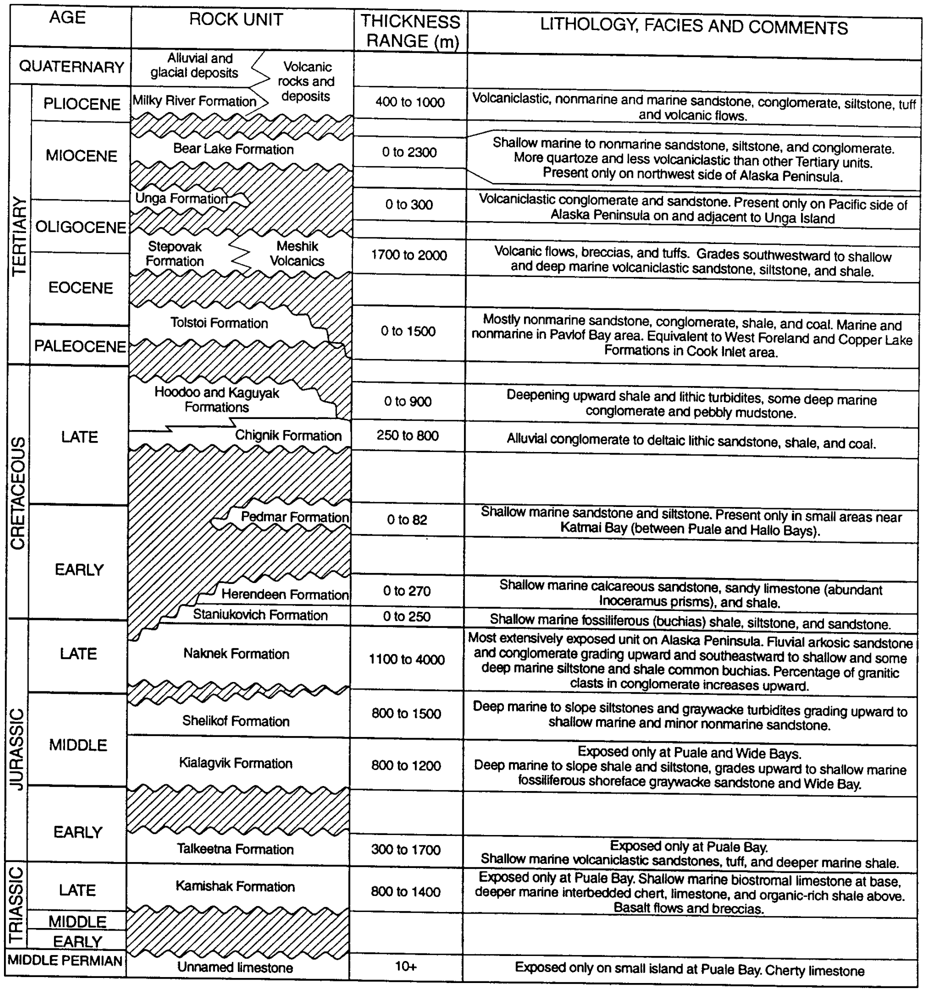
Physiographic and Geologic Setting

Based on the work of Merritt (1986b), Merritt and McGee (1986), and Smith (1995), rocks of the Chignik Formation (Upper Cretaceous) are the prime coalbed methane targets along the Alaskan Peninsula (figs. 45 and 46) (tables 1 through 9). The Chignik Formation is exposed in a long, narrow belt on the Alaska Peninsula between Pavlof Bay and Wide Bay (figs. 46 and 47). The two main coal fields of the region, the Chignik Bay and Herendeen Bay fields are about 100 mi (160 km) apart (Merritt, 1986b) (fig. 46). The Chignik Bay coal field, the prime coalbed methane target, composes an area of about 39 mi^2 (100 km^2) of coal-bearing strata (Merritt, 1986b). It forms a northeast-trending belt about 25 mi (40 km) long and 1 to 3 mi (1.6 to 5 km) wide on the northwest shore of Chignik Bay (Martin, 1925) (fig. 47).

Rock outcrops in the coal fields include clastic, volcanic, and marine to non-marine sediments of Jurassic and Cretaceous age that are intruded by Tertiary and Quaternary dikes and sills and also large, intermediate composition multiphase intrusive bodies (Burk, 1965; McGee, 1979). In general, the Chignik Formation consists of a lower marine shale unit and an upper unit that is also mainly shale but includes some conglomerate and sandstone (fig. 48). The middle unit of the Chignik Formation is the Coal Valley Member which contains many coal beds interlayered with shale-sandstone and conglomerate. The upper unit is generally representative of a marine transgression but also shows evidence of oscillations from marine to continental sedimentation (fig. 48).

Tectonic and Structural Setting

As discussed by Merritt (1986b), the structure of the Chignik Bay coal field has been dominated by convergent plate tectonics and arc-trench development, which have resulted in continuous uplift and erosion of plutonic rocks and subsequent deposition of marine and



AGE		ROCK UNIT	THICKNESS RANGE (m)	LITHOLOGY, FACIES AND COMMENTS
QUATERNARY		Alluvial and glacial deposits Volcanic rocks and deposits		
TERTIARY	PLIOCENE	Milky River Formation	400 to 1000	Volcaniclastic, nonmarine and marine sandstone, conglomerate, siltstone, tuff and volcanic flows.
	MIOCENE	Bear Lake Formation	0 to 2300	Shallow marine to nonmarine sandstone, siltstone, and conglomerate. More quartoze and less volcaniclastic than other Tertiary units. Present only on northwest side of Alaska Peninsula.
	OLIGOCENE	Unga Formation	0 to 300	Volcaniclastic conglomerate and sandstone. Present only on Pacific side of Alaska Peninsula on and adjacent to Unga Island
		Stepovak Formation Meshik Volcanics	1700 to 2000	Volcanic flows, breccias, and tuffs. Grades southwestward to shallow and deep marine volcaniclastic sandstone, siltstone, and shale.
	EOCENE			
	PALEOCENE	Tolstoi Formation	0 to 1500	Mostly nonmarine sandstone, conglomerate, shale, and coal. Marine and nonmarine in Pavlof Bay area. Equivalent to West Foreland and Copper Lake Formations in Cook Inlet area.
CRETACEOUS	LATE	Hoodoo and Kaguyak Formations	0 to 900	Deepening upward shale and lithic turbidites, some deep marine conglomerate and pebbly mudstone.
		Chignik Formation	250 to 800	Alluvial conglomerate to deltaic lithic sandstone, shale, and coal.
	EARLY	Pedmar Formation	0 to 82	Shallow marine sandstone and siltstone. Present only in small areas near Katmai Bay (between Puale and Hallo Bays).
		Herendeen Formation	0 to 270	Shallow marine calcareous sandstone, sandy limestone (abundant Inoceramus prisms), and shale.
		Staniukovich Formation	0 to 250	Shallow marine fossiliferous (buchias) shale, siltstone, and sandstone.
JURASSIC	LATE	Naknek Formation	1100 to 4000	Most extensively exposed unit on Alaska Peninsula. Fluvial arkosic sandstone and conglomerate grading upward and southeastward to shallow and some deep marine siltstone and shale common buchias. Percentage of granitic clasts in conglomerate increases upward.
	MIDDLE	Shelikof Formation	800 to 1500	Deep marine to slope siltstones and graywacke turbidites grading upward to shallow marine and minor nonmarine sandstone.
		Kialagvik Formation	800 to 1200	Exposed only at Puale and Wide Bays. Deep marine to slope shale and siltstone, grades upward to shallow marine fossiliferous shoreface graywacke sandstone and Wide Bay.
	EARLY	Talkeetna Formation	300 to 1700	Exposed only at Puale Bay. Shallow marine volcaniclastic sandstones, tuff, and deeper marine shale.
TRIASSIC	LATE	Kamishak Formation	800 to 1400	Exposed only at Puale Bay. Shallow marine biostromal limestone at base, deeper marine interbedded chert, limestone, and organic-rich shale above. Basalt flows and breccias.
	MIDDLE			
	EARLY			
MIDDLE PERMIAN		Unnamed limestone	10+	Exposed only on small island at Puale Bay. Cherty limestone

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Figure 45. Stratigraphic column of the Late Cretaceous, Chignik, and Hoodoo Formations, Alaskan Peninsula. Modified from Burk (1965).

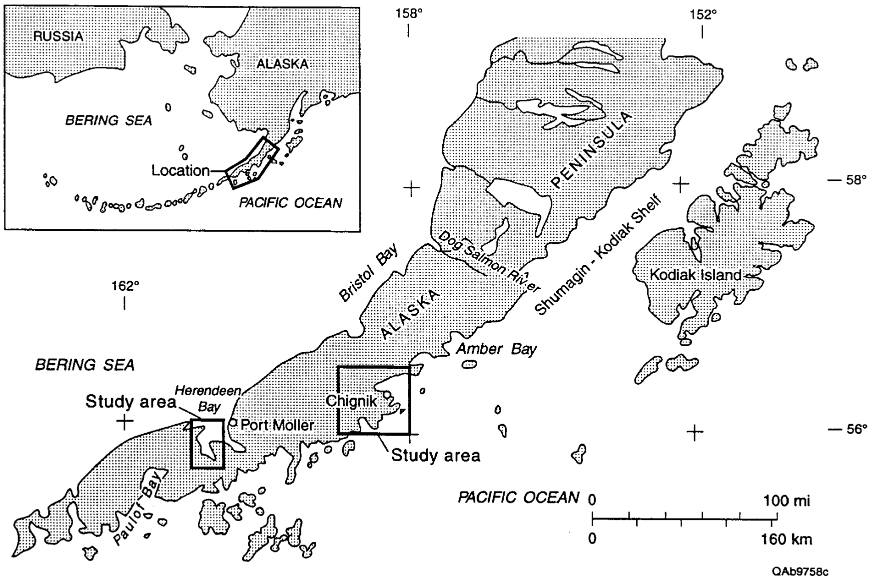

Figure 46. Location of the Chignik Formation study area, Alaskan Peninsula. Modified from Burk (1965).

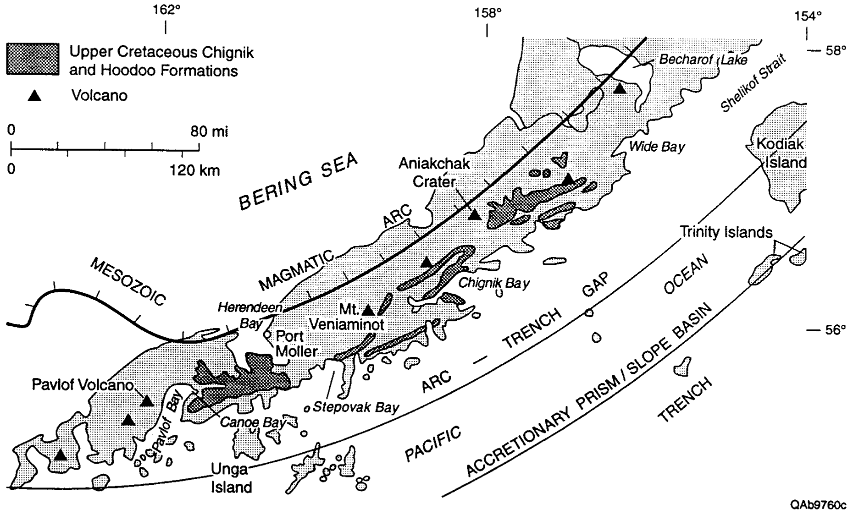

Figure 47. Distribution of Upper Cretaceous Chignik and Hoodoo Formations and the general configuration of the Late Cretaceous tectonic setting including the subduction complex. Modified from Burk (1965).

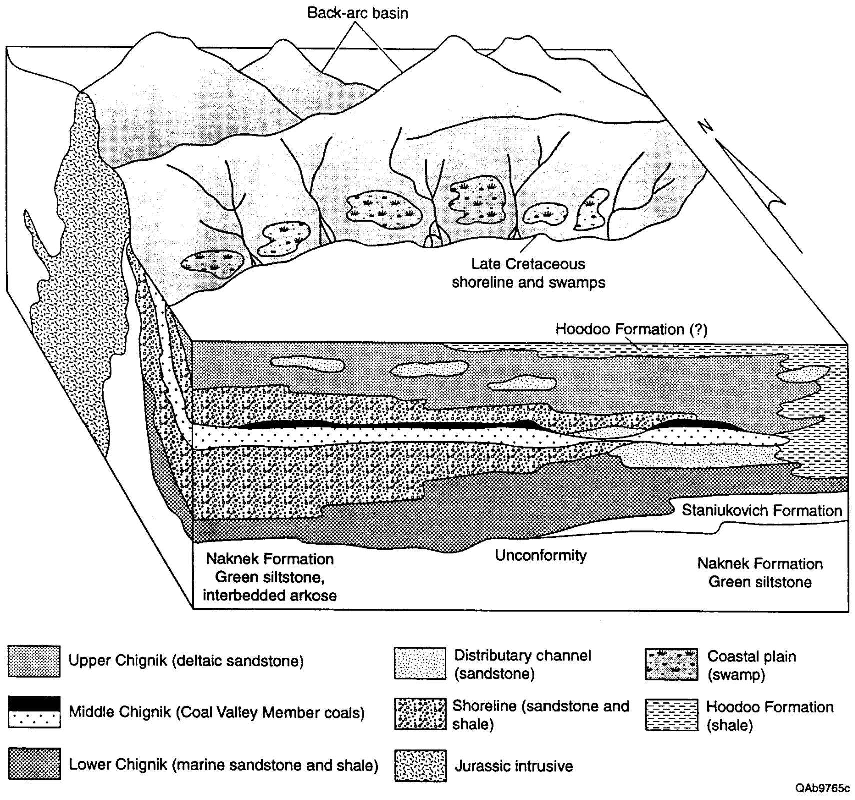

Figure 48. Schematic block diagram of the Late Cretaceous geography in the Chignik area. The subduction zone-trench complex was offshore to the southwest. Modified from Vorobik and others (1981).

nonmarine arkose, claystone, and sandstone. Arc-building was initiated on the Aleutian margin by the emergence of an Early Jurassic magmatic arc along the northern edge of the present Alaska Peninsula (Merritt, 1986b) (fig. 47). Moore and Connelly (1977) identified three periods of magmatic arc and subduction complex activity and infer that plates were mobile from Late Triassic to Late Jurassic, Early to Middle Cretaceous, and Late Cretaceous to Paleocene time. Although Burk (1965) and Moore and Connelly (1977) have slightly differing views on the time of onset of convergence in the Alaska Peninsula region, the result of tectonism from Jurassic time onward is well recorded in the stratigraphic sections in the Chignik Bay and Herendeen Bay areas (Vorobik and others, 1981). The general structure of the Chignik district is that of an intensely shattered rock mass in which the structural constituents consist of relatively small, gently tilted blocks separated by faults or zones of shattering (Merritt, 1986b). The dominant trend of faults and major folds is sub parallel to the long axis of the Alaska Peninsula, that is, generally slightly north of east (Martin, 1925; Resource Associates of Alaska, Inc., 1980) (fig. 47).

The first of three major periods of deformation of Upper Cretaceous Chignik Formation rocks (the prime coalbed methane targets) in the Chignik Bay area involved penecontemporaneous small-scale, low-amplitude folding in the lower but not the upper part of the Chignik Formation (Merritt, 1986b). The second deformational period subjected most of the Jurassic and Cretaceous sediments to intense compressional foreshortening (Merritt, 1986b). The most conspicuous structural feature of this period in the Chignik area is the Chignik anticline and overthrust complex (Merritt, 1986b). Moderately to highly deformed Naknek Formation rocks (fig. 45) have been anticlinally arched and thrust southeastward over Cretaceous Chignik and Hoodoo Formations (Merritt, 1986b). The strike of the Chignik thrust and anticline is subparallel to the dominant structural trend throughout the Chignik area (Merritt, 1986b). The third deformational event involved local, high-angle normal transverse faults (Merritt, 1986b). These faults evidently resulted from late tensional adjustment within the Chignik rocks that postdates the anticlinal arching and is probably a brittle response to a shift in the compressional vector of the convergent plate motion (Vorobik and others, 1981). This structural complexity will significantly impact coalbed methane resource development. High in situ stresses, both paleo- and present-day, will reduce the permeability of the coal beds. For example, experience in the Piceance Basin, Colorado, indicated that high in-situ stresses restricted coalbed methane development even when gas contents were high (Tyler and others, 1996).

Based on reconnaissance field work, there are four major coal outcrop localities in this area: Chignik River, Whaler's Creek, Thompson Valley, and Hook Bay (located northeast of Chignik Bay) (Division of Geological and Geophysical Surveys, 1993). The Chignik River coal occurrence is structurally complex with pinching and swelling of beds and displacement of potential reservoir rocks by high-angle faults (Merritt and others, 1987, unpublished data). Coal beds at this locality strike N2° E and dip 24° E and are highly cleated. However, there is no dominant face cleat orientation, although several overlapping cleat strikes were recorded. Cleat orientations that were measured included 8, 230, 270, and 320 degrees. Spacing of the cleats was also highly variable averaging less than 1/2 inch (1.3 cm) in the most highly cleated coal outcrops. Within some of the structurally deformed coal beds there is also evidence for dip-slip fracturing this is, the coal beds were fractured as if there had been bedding plane slip along the steeply dipping coal beds. The orientation and direction of movement of these fractures could not be recorded as access to the outcrop was limited.

The same coal group that crops out at Chignik River is exposed along the northernmost three main branches of Whalers Creek (Merritt and others, 1987, unpublished data). The beds on Whalers Creek strike N5° E and dip 22° E. The coal beds exposed on the northeast side of Thompson Valley, 3.2 km north of Chignik Bay, strike N60° E and dip 10 to 18° NW (Merritt and others, 1987, unpublished data). These coals are also highly deformed and cleated displaying complicated attributes similar to that documented at Chignik River. Due to the weathered nature of the coalbed, the coal characteristics and the cleat attributes were difficult to evaluate. The coals occur in two horizons separated by a 40-ft (12-m) thick sandstone. It appears that the coal-bearing section of Hook Bay strikes N10° E, dips 35° E, and includes several lenticular seams

(Merritt and others, 1987, unpublished data). This outcrop was not visited on the reconnaissance trip.

Depositional Systems and Coal Distribution

The general depositional environment of the Chignik and coeval Hoodoo Formations (fig. 49) along the Alaska Peninsula is that of a fore-arc basin landward of the trench-slope break (Merritt, 1986b). The Coal Valley Member of the Chignik Formation and the Hoodoo Formation are composed mainly of plutonic rock fragments, feldspar, and quartz, which suggest derivation from the eroding Late Cretaceous arc front (Mancini, 1977). Burk (1965) was the first to suggest that the deposition of nonmarine sands of the Coal Valley Member, nearshore sediments of the Chignik Formation, and the deep-water marine Hoodoo Formation represents a marine transgression (figs. 49 and 50). Mancini (1977) and Merritt (1986b), in turn, interpreted these units as approximately coeval facies deposited in different environments. They cite examples of proximity to source in alluvial-fan, braided-stream, and flood-plain (coastal-plain) depositional environments for the conglomerate, quartz-feldspathic sandstone, and coal of the Coal Valley Member; examples of inner-neritic continental shelf (shoreline) environments for the sandstone and siltstone of the Chignik Formation; and finally outer-neritic continental shelf to bathyal continental slope (offshore) environments for the predominantly fine argillaceous sediments of the Hoodoo Formation (fig. 50). Both Burk (1965) and Mancini and others (1978) interpret the conglomerate and coarse sandstone in the Hoodoo Formation as turbidite deposits. McGee (1979) finds that this general facies model concept is supported in areas where nonmarine beds of the Coal Valley Member locally grade laterally into marine beds very similar to the upper part of the Chignik Formation.

We agree with Burk (1965) and Mancini and others (1978) that the Chignik Formation consists of an alluvial-coastal plain sequence, landward of a southeasterly prograding shoreline (fig. 51). The Chignik Formation sandstones are generally representative of a progradational

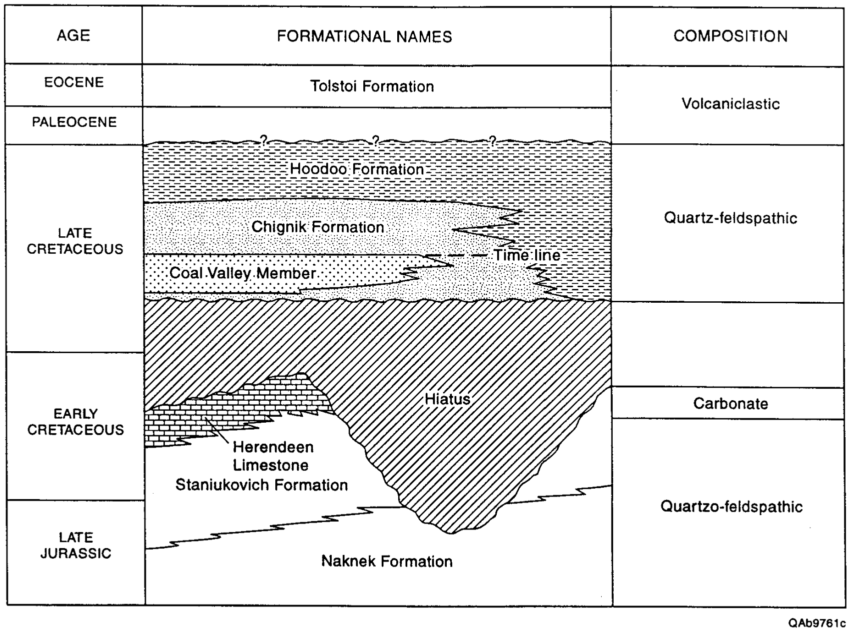

Figure 49. Stratigraphic relations of the Cretaceous sedimentary rocks in the Chignik area, Alaskan Peninsula. Modified from Burk (1965).

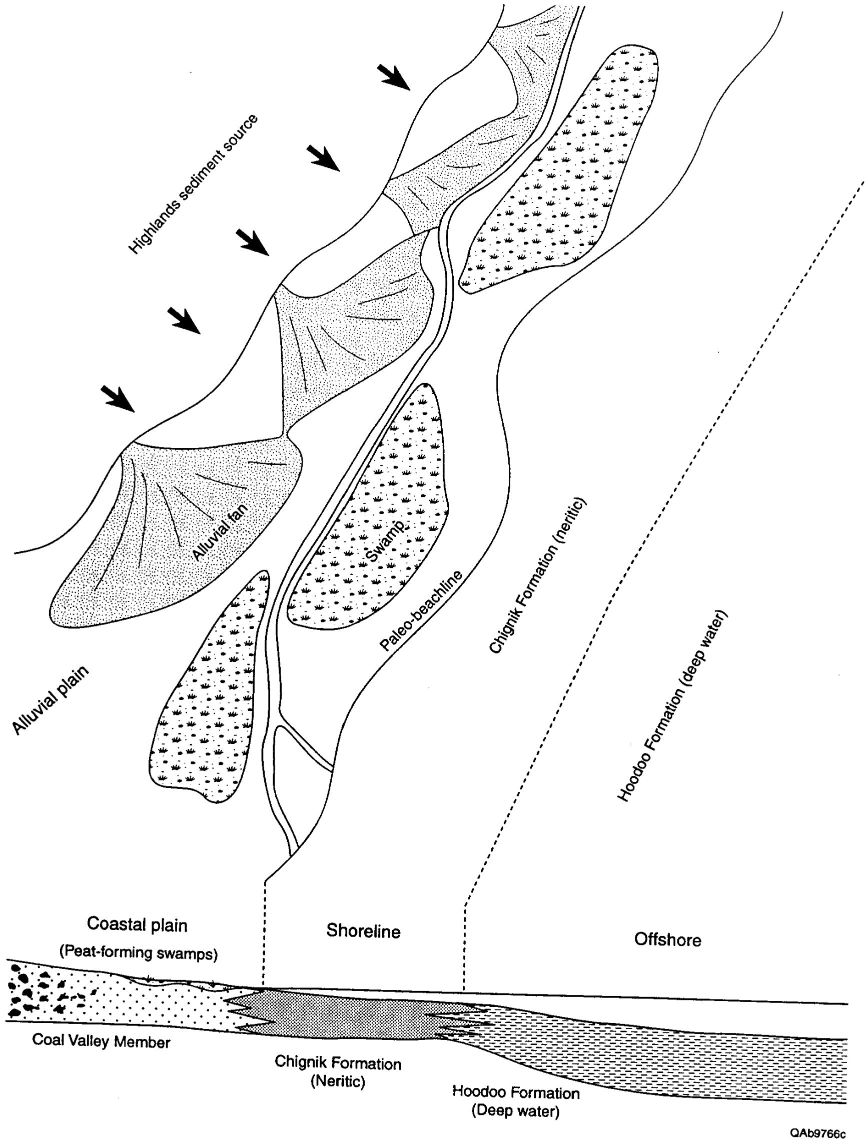

Figure 50. Depositional systems of the non-marine Coal Valley Member, Chignik Formation, and Hoodoo Formation. Modified from Merritt and others (1987).

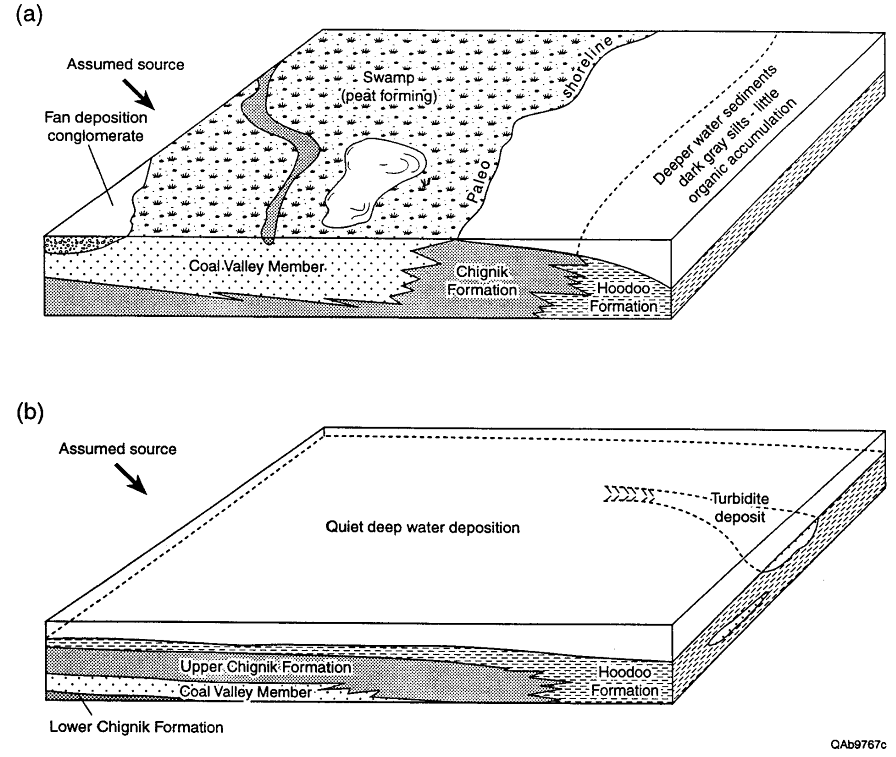

Figure 51. Depositional systems of the Cretaceous Chignik and Hoodoo Formations. (a) Depositional environments of the non-marine Coal Valley Member include a progradational shoreline sequence (Chignik sandstones) backed landward by the coastal-plain, coal-forming depositional environments. (b) Transgressive onlap of the Cretaceous Seaway resulted in the maximum flooding (Hoodoo Formation marine shales) of the coastal-plain, coal-depositional environments. Modified from unpublished data of Merritt and others (1987).

shoreline sequence similar to that found in the Cretaceous coastal plain coals of the Rocky Mountain Foreland and the North Slope Coal Province. Vorobik and others (1981) determined that the Coal Valley Members rests on top of a distinctive basal (progradational) sandstone which acted as a platform for peat accumulation. Coals were deposited in the coastal plain between stream systems on flat and gently sloping areas. Although the coastal plain coal swamps were numerous, their lateral extent may be limited due to the rapidly changing tectonic and structural setting. The large number of thin coal seams suggests that there were many individual areas of peat accumulation and that conditions never stabilized long enough for thick peats to develop (Merritt and McGee, 1986).

Based on the progradational shoreline depositional model developed in the Lower 48 States, the Coal Valley Member net coal trends are probably parallel to the paleoshoreline, where thicker bands of coal deposited between fluvial axes are probably oriented perpendicular to the shoreline. Therefore, the overall coal trends would be oriented to the northeast, whereas areas of thicker net coal deposition within this coal trend may be oriented in a northwest direction parallel to fluvial axes. Importantly, Chignik Formation coals may only be distributed over a limited area of 40 to 50 mi^2 (104 to 130 km^2), whereas Tertiary lignite seams are believed to cover only 10 to 20 mi^2 (26 to 52 km^2) (Smith and Baker, 1924). There is little evidence to suggest that conditions were favorable for coal accumulation during the onlap of upper Chignik Formation sediments (Merritt, 1986b). The presence of rare thin coal beds characteristic of estuarine, delta, or salt marsh environments in the upper Chignik Formation indicates that peat-forming conditions were relatively brief so that thick peats did not accumulate (Merritt, 1986b).

Based on this limited data, exploration and development for coalbed methane should not be undertaken unless an advanced stratigraphic and structural study of the Chignik Bay area is undertaken. Sweet spot identification will be extremely difficult due to the complex geologic nature of Chignik Bay area. Extensive thrusting, faulting, tight folding, generally poor reservoir rock continuity, presence of intrusive/igneous rocks, the extent of recent erosion in the area, limited subsurface data, and unknown extent of the coal-bearing sequences make the Chignik area unfavorable for coalbed methane exploration and development. Further, the potential for high stresses in the subsurface may be a significant restriction to the flow of gas to the well bore. The Aleutian Islands are susceptible to high in-situ stresses and permeability is predicted to be very low.

Coal Rank

Coal rank is variable in the Chignik area, but is generally in the bituminous rank except in localized area of higher heat flow (Division of Geological and Geophysical Surveys, 1993; Smith and Baker, 1924; Merritt and McGee, 1986; Merritt and others, 1987). Vitrinite reflectance values range from 0.58 to 1.76% with nearly all the values less than 1.00% (table 7). Therefore, most of the subsurface coals in the Chignik area have probably reached, or are approaching, the threshold of thermogenic methane generation (0.80% VR). Average reflectance values from coal beds in the Chignik River along the west side of Chignik Lagoon are 0.64% (high-volatile C to B bituminous), whereas coal samples from the east side of Chignik Lagoon (near the village of Chignik Lagoon) are 0.76%, which is borderline between high-volatile B and A bituminous ranks (data from Merritt and McGee, 1986). Vitrinite reflectance values in Thompson Valley average 0.68% which is high-volatile B bituminous rank.

The average maceral composition for subbituminous coal and lignite samples from the Chignik, Herendeen Bay, and Unga Island coal fields in the Alaska Peninsula is vitrinite 92%, inertinite 6%, and liptinite 2% (Merritt, 1986c). The relatively low inertinite content suggests that these coal have a good gas-generating potential and the low exinite content suggests that only relatively minor amounts of heavier hydrocarbons will be generated during coalification. Chignik area coals have as received ash ranging from 4 to 30% (average of 11.6%) and sulfur contents from 0.28 to 4.79% (average of 1.36%) (Alaska Division of Mining and Geological and Geophysical Surveys, 1993).

Hydrodynamics

The Chignik area averages over 125 inches (317 cm) of rain each year (table 6) indicating that significant volumes of ground water could be moving though coal beds in the area. Ground water has been reported in an abandoned coal mine suggesting that at least some coal beds in the area are permeable enough to accept recharge. However, prediction of subsurface ground-water movement is complicated by structural complexity in the area, the local geometry of the coal beds, and the close proximity to the ocean. Additionally, because of the high annual precipitation and proximity to the sea, the dewatering of moderately permeable coal beds may be difficult.

Subsurface Data and Production

Regionally, and away from the priority villages of economic importance to this study, Smith 1995 stated that in the subsurface, "the Chignik Formation has been penetrated by at least four deep oil and gas wells. The Phillips, Big River A-1 penetrated 27 thin coal seams (maximum thickness of 6 feet (1.8 m) over 1,345-ft (410 m) interval at depths greater than 5,800 ft and 4 thin seams at depths between 2,000 and 2,100 ft. The Pan Am, Hoodoo Lake Unit 2 encountered 18 thin coals (maximum thickness of 8 ft (2.4 m) at various depths". The Hoodoo Lake Unit 2 encountered a gassy coal section between 5,800 ft and 6,500 ft (1,768 m and 1,980 m) (Smith, 1995) (fig. 52). Based on the mudlog, this well encountered coal seams up to 20 ft (6m) thick with good mud-log gas shows and trace oil shows (Smith, 1995). The coal is classified as lignite to subbituminous rank and is shaly. The rank of these coals may be higher than described in the mudlog since McClean (1977) reports the vitrinite reflectance values average 1.2% (medium-volatile bituminous) for this interval. Geophysical logs do not verify the thick coals noted on the mudlog. This may be due to the shale interbeds and/or the nature of the shaly coal beds. The Cities, Painter Cr. 1 encountered 9 coal seams with a maximum thickness of only 9 ft (2.7 m) (Smith, 1995), whilst the Pan Am, David River 1-A did not encounter any coal seams in the Chignik Formation (Smith, 1995).

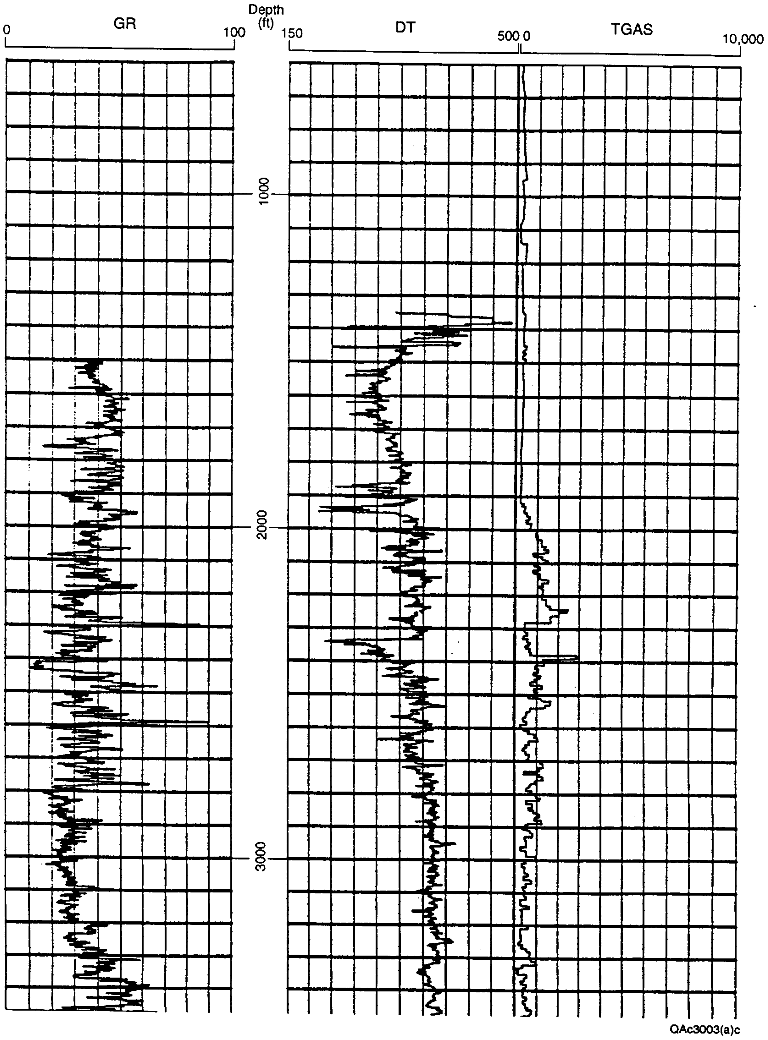

Figure 52. Type log Hoodoo Lake Unit-2, Alaska's Peninsula Coal Province. Note the high gas kicks associated with the mud-logs between 5,800 ft (1,768 m) and 6,500 ft (1,980 m) associated with coal beds.

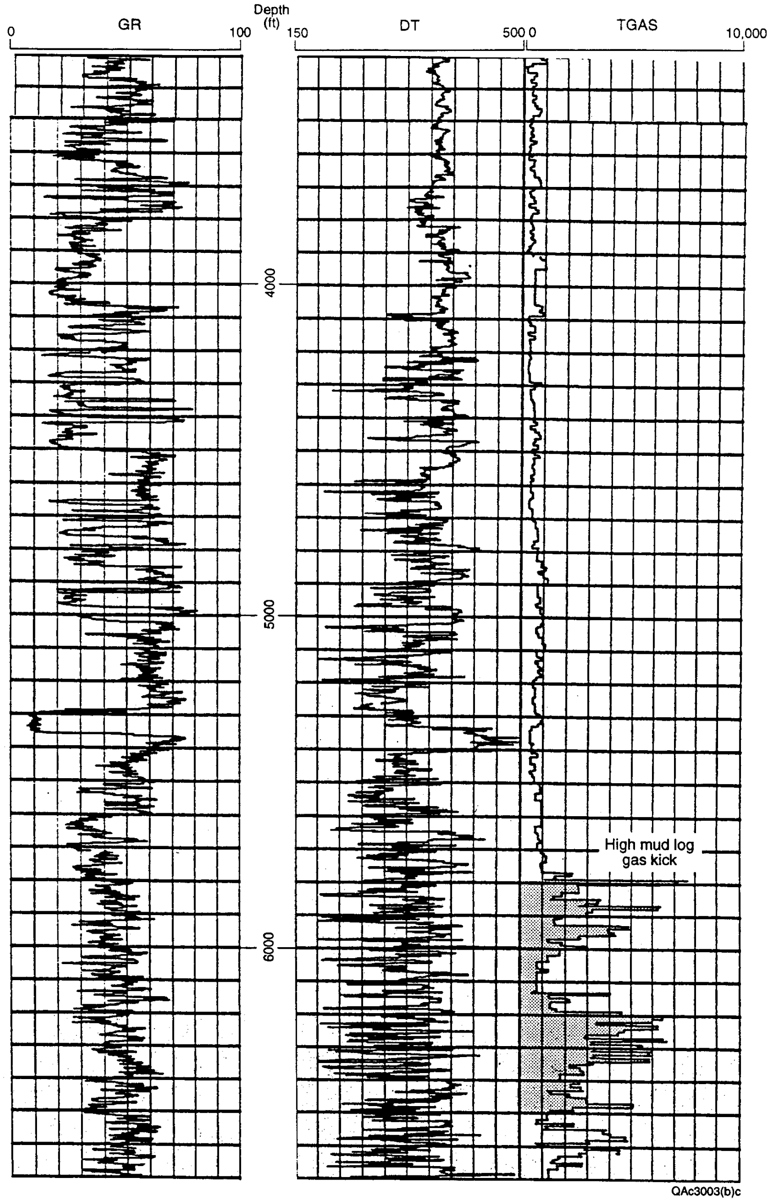

Figure 52 (cont.).

All the wells that encountered coals had excellent mud-log gas shows, but the depth of drilling to the targeted coal beds exceeds 4,000 to 5,000 feet (1,219 to 1,524 m), which is deeper than the exploratory constraints set out in the cooperative agreement. Coal samples from the Hoodoo Lake Unit 2 well at depths greater than 8,000 ft (2,438 m), and the David River 1-A at depths between 8,500 to 10,250 ft (2,590 to 3,124 m) (above the Chignik Formation in the overlying Tolstoi Formation) have a high-volatile to low-volatile bituminous rank. Coals of similar rank are found in outcrops at Chignik and Herendeen Bay, indicating that these areas have undergone considerable uplift since maximum burial. The permeability of the cleat system could be enhanced in the uplifted areas, but high in-situ stresses related to present-day tectonism in this area may result in very low permeabilities.

Minor-to-good gas shows are associated with Tertiary coals as well. For example, the Gulf, Port Heiden Unit -1 shows greatly increased mud-log gas in the coaly section in Bear Lake Formation from depths of 4,000 ft to 5,000 ft (1,219 m to 1,524 m) (Smith, 1995). The mud-log gas levels increased from 20 ppm to over 250 ppm in some of the coal seams. Over this interval, the Port Heiden well encountered approximately 23 coal seams, most of which were less than 5 ft (1.5 m) thick. The David River 1-A well encountered Bear Lake Formation subbituminous coals at similar depths and the Hoodoo Lake Unit 1 penetrated lignitic coals to 5,000 ft (1,524 m) and subbituminous coals to the well's total depth of 8,049 ft (2,453 m) in the Stepovak Formation (McLean, 1977). This trend is consistent to the north, where the General Petroleum, Great Basins 1 encountered immature rocks with an average VR (Vitrinite Reflectance) of 0.3% for the Bear Lake Formation and an average VR of 0.5% for the Stepovak Formation. The David River 1-A well encountered thin, high-volatile to low-volatile bituminous coal seams between the depths of 8,500 ft and 10,400 ft (2,590 m and 3,170 m) (McLean, 1977).

Important Statements and Quotations Supporting Coalbed Methane Development along the Alaskan Peninsula

Smith (1995) noted: "All wells that encountered coals had excellent mudlog gas shows" however, the depth to the coal is at least 4,000 to 6,000 ft (1,219 m to 1,524 m) deep, significantly deeper that the exploration constraints (3,000 ft; 914 m) defined in the cooperative agreement. By restricting the exploration depths, a significant part of the potential for coalbed methane resource development along the Alaskan Peninsula may be forgone.

Coalbed Methane Potential

As stated by Smith (1995), "Cretaceous coal may underlie a significant area of the Alaska Peninsula. However, the coal-bearing rocks in the Chignik Lake area are confined largely to a northeastward-trending belt approximately 25 mi (40 km) long and 1 to 3 mi (1.6 to 4.8 km) wide along the northwest shore of the Chignik Lake. Some development of the coal has occurred, but none of the coal beds have been traced more than short distances" on the surface. No subsurface data exists in the Chignik Lake area. The details of the structure within the area remain unknown, but the beds appear to be moderately to extensively folded and thrusted, being cut by numerous faults and thrusts in some localities. The variability of the coal depositional systems and the structurally discontinuous nature of the thin coal beds make subsurface exploration for coalbed methane difficult, particularly for large-scale operations (Smith, 1995). Of consideration and if economically feasible, wells like the Phillips Big River A-1 or Hoodoo Lake Unit 2 wells with excellent mud-log gas shows and close to the Chignik Lake and Herendeen Bay areas could be recompleted in the coal-bearing zones as a test for local sources of gas. However, depths of greater than 4,000 ft (1,219 m) to the main gas prone coals may make these targets expensive.

In summary, regional exploration for coalbed methane resource should not be undertaken until an advanced stratigraphic and structural model of the Chignik Bay area is developed. Sweet spot identification may be extremely difficult due to the complex geologic nature of the Chignik

Bay area. Extensive thrusting, faulting, high in-situ stresses, generally poor reservoir rock continuity, the presence of intrusive/igneous rocks, and the extent of Recent erosion in the area, make the Chignik area relatively unfavorable for coalbed methane exploration and development. Wildcat coalbed methane exploration on a local scale may be favored because coals in the area are either approaching or have reached the threshold of significant thermogenic gas generation and the mudlogs show gas responses. Moreover, the presence of water in an abandoned coal mine indicates that at least some coal beds are permeable and therefore, secondary biogenic gas generation may have occurred. However, dewatering of highly permeable coal beds may prove to be economically unfeasible because of the high annual precipitation rates and close proximity to the sea.

Nenana Province: Minchumina Basin (Nikolai and McGrath)

Physiographic and Geologic Setting

The Nenana coal province is located north of the Alaska Range and includes fields located in the Minchumina, Middle Tanana, and Nenana Basins. As stated by Smith (1995), these Tertiary coal-bearing basins form a discontinuous belt from the Jarvis Creek Field near Big Delta on the east, through Healy, Lignite Creek, and Suntana Coal Fields in the central portion, to the Farewell-Little Tonzona area (Minchumina Basin) to the southwest. The entire trend extends over 200 mi (320 km) and is over 30 mi (50 km) wide. The coals in these areas are mostly Oligocene to Miocene in age.

The Minchumina Basin, part of the southwestern Nenana coal province and of importance to the rural Alaskan coalbed methane resource development, is located northwest of the Alaska Range and is bounded by the Farewell-Denali and Iditarod-Nixon Fault complexes to the south and north, respectively (figs. 53 and 54). The basin covers about 8,100 mi^2 (21,000 km^2) and is Cenozoic in age (table 3). Bouger gravity maps suggest north and northeast-trends of thicker basin-fill within the Minchumina Basin and are estimated to have between 6,000 and 10,000 ft

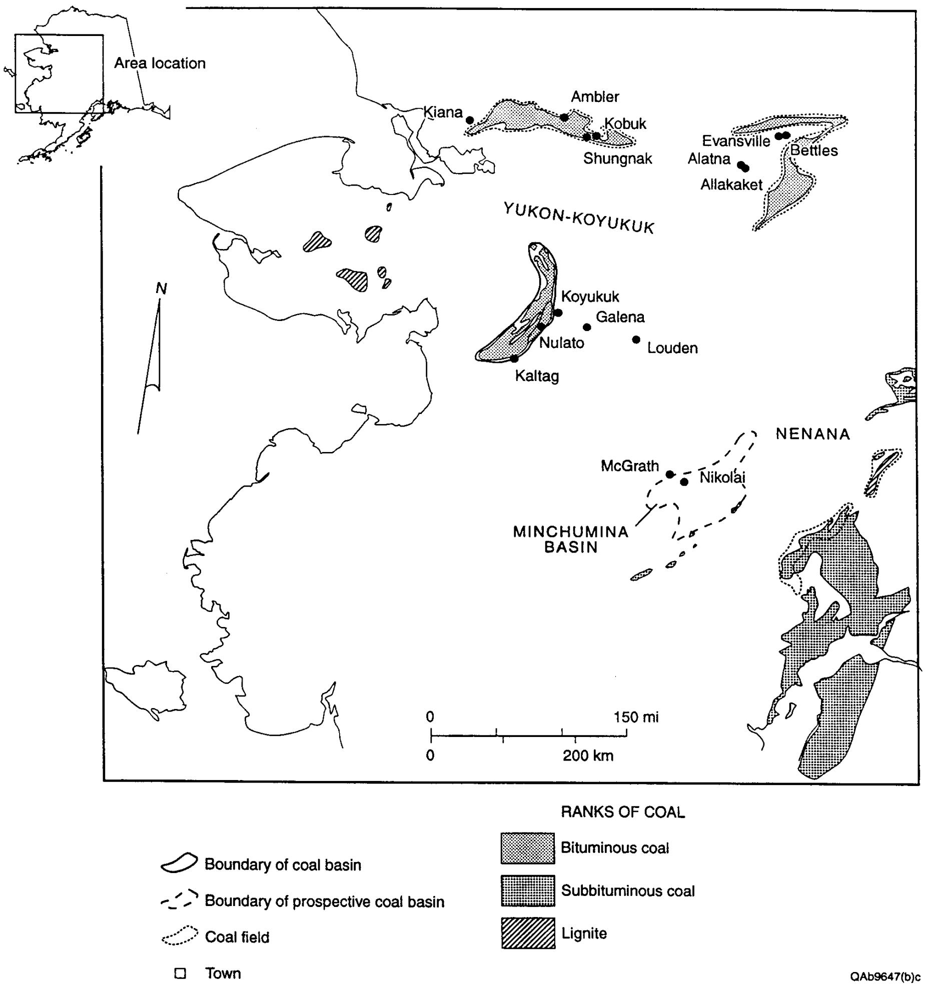

Figure 53. Extent of the Yukon-Koyukuk Coal Province and Minchumina coal basin. Modified from Merritt and Hawley (1986).

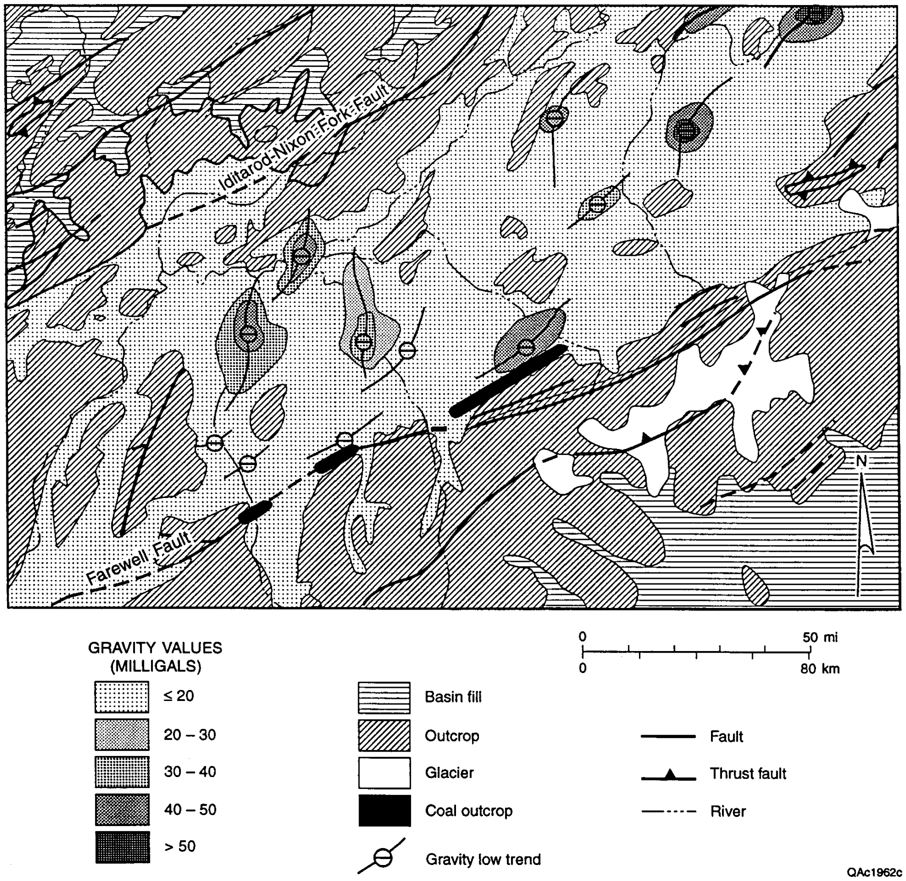

Figure 54. Geologic setting of the Minchumina Basin, showing gravity and regional structural trends. Modified from Kirschner (1994).

(1,800 to 3,000 m) of Middle to Late Tertiary fill (Kirschner, 1994) (fig. 53). Large displacement, high-angle block faulting, and folding in the subsurface, possibly a result of extensional horst-and-graben complex development, are suggested by the steep gravity gradients to be associated with basement highs (Henning and others, 1984).

According to Dickey (1984), the Tertiary coal-bearing section probably developed as a result of the horst-and-graben fault complex. Quartz and argillite clasts from the lowest units were derived from a metamorphic terrane to the northeast while carbonate/shale clasts in the uppermost part of the section were probably derived from the Dillinger Group in the Alaska Range (Bundtzen and Gilbert, 1983).

Tectonic and Structural Setting

The Minchumina Basin is probably a complex of small, extensional basins (Kirschner, 1988) (fig. 53), but no subsurface data is available and, therefore, mapping the structure and lateral extent of coals is problematic. The scattered, Tertiary nonmarine sedimentary rocks that crop out along stream valleys and river bluffs adjacent to the Alaska Range on the southeastern edge of the basin are the only coal data available within the basin. Most outcrops lie on the flanks of the basin, especially along the Farewell Fault Zone (Little Tonzona River Coal Field), which is steeply dipping (Sloan and others, 1981). The steep dips of the section are unquestionably due to the proximity of the beds to the fault zone, and dip slip movement of the Tertiary coal section has been documented (Bundtzen and Kline, 1986). To the west, away from the Farewell Fault, it is conceivable that the dip of the coal section flattens northward into the Minchumina Basin (Bundtzen and Kline, 1986). Moreover, Bundtzen and Kline (1986) hypothesize that the continuity of the coal trend indicates the existence of either a series of fault-bounded depositional basins along the trend of the Farewell fault system, or, one very large coal basin, extending northwest into the Minchumina Basin. If either hypothesis is correct, the coals can be expected to continue at depth for some distance to the northwest of the exposed trend and an incredible amount of coal could be inferred (Bundtzen and Kline, 1986). The depositional systems may be similar to the fluvial coals of the Fort Union Formation, Powder River Basin, Wyoming. Coal cleats within the basin tend to be blocky and the coal is very compact (Bundtzen and Kline, 1986). Late Quaternary stress trajectories are probably to the northwest (Alaska Division of Mining and Geological and Geophysical Surveys, 1986), suggesting that Tertiary face cleats will possibly have a northwest orientation.

Depositional Systems and Coal Distribution

The Little Tonzona coal field, bordering the southeastern edge of the Minchumina Basin, is the only source of coal data for this area. Coal beds range in thickness from 3 to 20 ft (1 to 6 m); multiple coal seams over 3 ft (0.9 m) thick have been mapped (Solie and Dickey, 1982). One subbituminous coal seam of over 100 ft (30 m) thick has been reported from the Farewell-Little Tonzona Field (Player, 1976). In outcrop, the coal-bearing section is best exposed in a steep cutbank on the southwest side of the Little Tonzona River. There, a 277-ft (84-m) stratigraphic section containing a total of 134 ft (81 m) of clean coal in as many as 37 beds may be viewed (Bundtzen and Kline, 1986). Beds are known to locally thicken to 24 ft (7.3 m).

Kirschner (1994) and Dickey and others (1982) describe several depositional systems during the deposition of the Tertiary coal-bearing sequence. According to Dickey and others (1982), the lower coal-bearing section is represented by nonmarine sediments (conglomerate, sandstone and siltstone, and lignite) deposited by southerly flowing braided streams. Quartz and argillite clasts were probably derived from a metamorphic terrane to the northeast (Dickey, 1984). An upper coal-bearing section, consisting mainly of conglomerates, represents alluvial fan deposition from the rising Alaska Range to the southeast.

The absence of subsurface control makes predictions of net coal orientation nearly impossible, although some speculative predictions can be made based on available information. Deposition of the Tertiary coals is believed to be associated with fluvial systems, similar to the

Fort Union Formation coal beds. Dickey (1984) also suggested the presence of northeast-trending fluvial systems and, therefore, peats associated with such a system would have similar net-coal trends. Hamilton (1994) and Tyler and others (1995b) have demonstrated that the location and orientation of fault zones strongly influenced the position of shoreline and fluvial coals in the Greater Green River Basin. By analogy, the extensional horst-and-graben complex development may also have strongly influenced geometry of peat development in the Minchumina Basin. Therefore, the net-coal trends are predicted to be oriented roughly parallel (north-northeast) to gravity anomalies related to basement structures. The location of thick coals along the Farewell Fault between Middle Fork and Windy Fork Rivers corresponds with the orientation of the gravity anomalies described by Kirschner (1994).

Coal Rank

There is limited surface and no subsurface coal rank data in the Minchumina Basin. Surface coals are low rank ranging from subbituminous to high-volatile C bituminous (Solie and Dickey, 1982; Smith, 1995) (table 7). Tertiary coals (Oligocene to Miocene) along the Farewell Fault zone range in sulfur from 0.7 to 1.7% (moderate to high); with low to high ash contents (up to 20%). Solie and Dickey (1982) report sulfur contents in Tertiary lignite of high-volatile C bituminous coals to range from 0.44 to 8.19% (Daf). High-volatile C bituminous coals occurring along Windy Fork have ash (dry basis) ranging between 4.7 to 20.3% and VR values that range from 0.4 to 0.8% (predominately high-volatile C bituminous).

Although there are no subsurface rank data available to evaluate the thermal maturity of coals at depth in the Minchumina basin, the Beaver Lakes State #1-B in northern Susitna Basin (located southeast of the basin) had surface VR values of 0.5%, yet the VR at 8,200 ft (2,500 m) was only 0.7% (high-volatile B bituminous). If the Minchumina Basin had a similar burial history as the Susitna Basin, then the threshold of active coal-gas generation (VR values of 0.8%) probably would not be reached until depths greater than 10,000 ft (3,049 m).

Coal rank in Paleozoic Formations and along major fault systems is high (VR >2.0%). Cretaceous rocks in the southern part of the basin have VR values between 0.6 and 1.3%; rank increases to the southwest of the Minchumina Basin to more than 2.0% (Johnsson and Howell, 1996). Cretaceous rocks on the north side of the Iditarod-Nixon fault system have VR values between 1.6 and 2.0%, whereas Paleozoic rocks on the other south side of the fault have VR values greater than 2.0%.

Hydrodynamics

The Minchumina basin is generally underlain by numerous isolated masses of permafrost (table 6), although moderate-to-thin permafrost occurs in the Kuskokwim Mountains to the north and discontinuous permafrost occurs in the Alaska range (Ferrians, 1965). Permafrost thickness is generally believed to be less than 100 ft (30 m) and may reach a maximum thickness in some areas of 600 ft (183 m). Ground water flows northwestward from the Alaska Range and southeastward from the Kuskokwim Range toward the Kuskokwim River where convergent flow generally occurs (fig. 55). Convergent flow may also be associated with northwest-trending tributaries of the Kuskokwim River. Drinking water in McGrath is derived from private wells that tap into alluvial aquifers under the town and from a public water system that withdraws, treats, and distributes surface water from the Kuskokwim River.

Subsurface Data and Production: Including Important Statements and Quotations Supporting Coalbed Methane Development within the Minchumina Basin

Kirschner (1994) in discussing the petroleum potential of the Minchumina Basin, stated that "although coal-bearing beds could generate gas and fluvial sandstones are likely reservoirs, the size of any accumulation would probably be small: it is concluded the Minchumina Basin potential, at best, is limited to small gas projects."

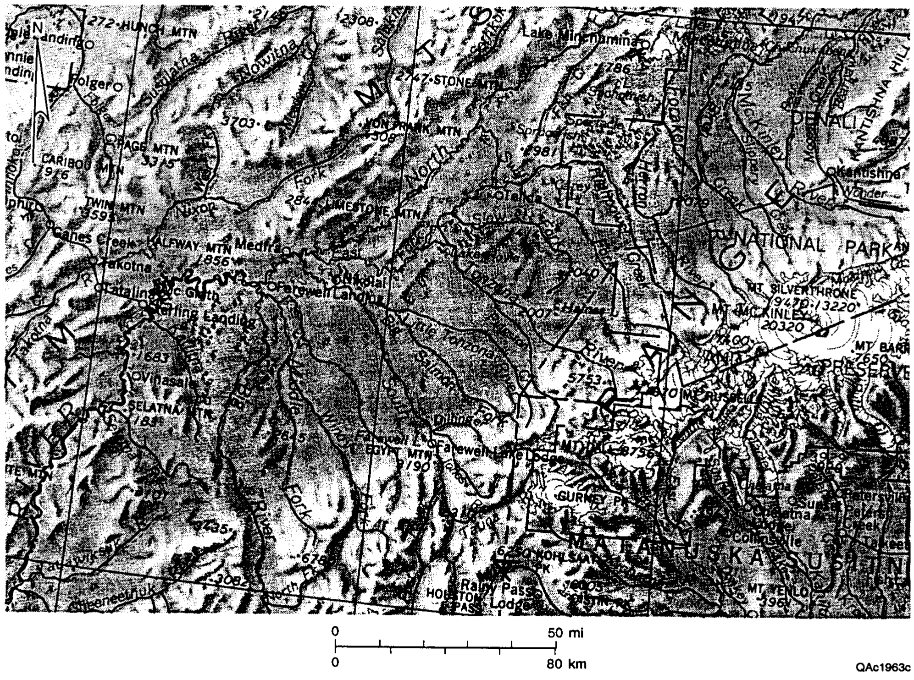

Figure 55. Shaded relief map of the Minchumina Basin showing ground water flow. Ground water flows northwestward from the Alaska Range and southeastward from the Kuskokwim Mountains towards the Kuskokwim where upward flow occurs. From U. S. Geological Survey (1996).

Coalbed Methane Potential

The Minchumina Basin contains coal hypothesized to be of similar depositional systems to that found in the Fort Union Formation of Wyoming. The only known coal occurrences, outcrop along the steeply dipping flanks of the basin and are associated with major faults in the area. No deep subsurface data is available in the Minchumina Basin. Without subsurface control, the extent and depth to these Tertiary coals is unknown and locating viable coalbed methane targets will be difficult (Smith, 1995). Moreover, if the low coal ranks at the surface persist at depth, then the coalbed methane potential will be low, particularly if the coals do not extend to the elevated margins of the basin where recharge may occur. The Town of McGrath, located along the Kuskokwim River, may be an area of convergent and upward-flow potential, suggesting that coal gases may be concentrated in this area. However, the migrated gases will move out of the system if there are inadequate permeability barriers trapping the upward flow. With the apparently low coal rank found near the surface, it is suggested that if gases are discovered, they would be dominantly secondary biogenic in origin. If present, exploration for shallow biogenic gases must be undertaken in a similar fashion to that developed in the shallow fluvial coals of the Powder River Basin, Wyoming.

The town of Nikolai, located approximately 46 mi (74 km) east of McGrath along the South Fork of the Kuskokwim River (fig. 55), may have higher coalbed methane potential because it is in an area of thicker Tertiary fill. If thicker coals are associated with this area of north-trending Tertiary fill, they may have been buried deeper and be of slightly higher coal rank. However, based on the limited data available, the Minchumina Basin is given a lower priority for coalbed methane resource development.

Yukon-Koyukuk Province: Upper Koyukuk, Lower Koyukuk, and Kobuk Basins

Physiographic and Geologic Setting

Based on the work of Smith (1995), the Yukon-Koyukuk Province of western interior Alaska is characterized by a mature, eroded and heavily vegetated terrain with most of the coal found in outcrops along the Yukon, Koyukuk, and Kobuk Rivers. Three poorly-defined coal basins (Upper Koyukuk, Lower Koyukuk, and Kobuk) have been identified in this province by Merritt and Hawley (1986). Within this province, Cretaceous and Tertiary volcanic and sedimentary rocks (Patton and Box, 1989) were deposited in a highly mobile basin complex subject to repeated volcanism and plutonism (Patton, 1973). Up to 25,000 ft (7,620 m) of Cretaceous sedimentary rocks have been documented in this province (Patton, 1973). This assemblage consists of marine volcanic graywacke and mudstone turbidites overlain by a westward-prograding clastic assemblage which includes coal-bearing deltaic deposits at least 10,000 ft (3,048 m) thick (Smith, 1995). Patton (1973) concluded the coal-bearing beds were deposited along a broad, shallow trough extending along the eastern margin of the Yukon-Koyukuk Province. Due to the lack of outcrop, subsurface, and seismic data in the Yukon-Koyukuk Province, the description of the critical criteria for coalbed methane resource development has been combined for the Upper Koyukuk, Lower Koyukuk, and Kobuk basins.

Yukon-Koyukuk Province: Upper Koyukuk Basin (Alatna, Allakaket, Bettles, and Evansville)

Tectonic and Structural Setting, Depositional Systems, and Coal Distribution

The Upper Koyukuk Basin is located south of the Brooks Range and immediately west of the Kokrines-Hodzana Highlands (fig. 53). Barnes (1967) suggested that Upper Koyukuk coal deposits are an eastern extension of coal-bearing rocks in the Kobuk Basin (fig. 53), where Cretaceous marine and non-marine facies trend east-west parallel to the northern basin margin and Endicott Mountains of the Brooks Range. In outcrop, these Cretaceous sediments define a thin (<9 mi wide; <14.5 km), southward transition from fluvial to marine deposition (Dillon and others, unpublished data). Sediments derived from the Brooks Range were transported southward in braided and meandering fluvial systems. According to Smith (1995), the thickest coal seams in the Yukon-Koyukuk Province are found in the Tramway Bar Field in the Upper Koyukuk Basin. The Tramway Bar Field, located 35 mi (56 km) above Bettles on the Middle Fork of Koyukuk River, contains three uncorrelated beds ranging in thickness from less than 1 ft to 17.5 ft (<1 to 5.3 m) and that dip 56° southeast (Rao and Wolff, 1982). Additionally, abundant coal float has been reported on the John River north of Bettles (Barnes, 1967). Coal-bearing upper Cretaceous rock units recognized at Tramway Bar also crop out in a thin (<1 mi; <2 km), east-trending band a few miles north of Bettles and Evansville (Patton and Miller, 1973). These coal-bearing units appear to grade into greywacke and mudstone southward and westward (Patton and Miller, 1973), suggesting that the coal occurrence around Tramway Bar may be laterally discontinuous. The dip of most of the coal-bearing units varies in the Tramway Bar area, but generally is southward in the outcrop belt north of the towns of Bettles and Evansville (Patton and Miller, 1973). The villages of Alatna and Allakaket are located some distance from the known coal outcrops near the convergence of the Koyukuk and Alatna Rivers. In this area, Early Cretaceous rocks cropping out are predominantly volcanic greywacke and mudstones and no coal-bearing rock units have been identified (Patton and Miller, 1973).

From the little coal data that is available, the coal depositional systems exposed in the Upper Koyukuk Basin are interpreted to have formed within a narrow, high-energy nonmarine to marine transition zone. These depositional systems were short-lived or migrated laterally rapidly, resulting in thin coal deposits (Dillon and others, unpublished data). The impure and thin coals associated with these fluvial-marine systems are discontinuous from stratigraphic pinch out and discontinuities arising from fault displacement and erosion (Dillon and others, unpublished data). Net coal-thickness trends are expected to lie predominantly in a north-south direction parallel to fluvial systems except near paleoshorelines where the orientation of the thickest net-coal trends will be more east-west. Because of the lack of well and seismic data, no subsurface information on the extent of the coal beds is available. This severely restricts the coalbed methane resource evaluation and potential of this basin.

Coal Rank

Coals at the Tramway Bar site are reported to be high-volatile B bituminous in rank (Rao and Wolff, 1982), whereas other rock units in the area are reported to be much higher in rank with vitrinite reflectance values ranging between 2.0 and 3.6% (fig. 56). However, more data are required to confirm coal rank in this area, because if the coals are indeed overmature, as suggested by Johnsson and Howell (1996), then the coalbed methane potential may be significantly reduced because the coal have passed through the hydrocarbon generating stage. Rao (1986) reports that a Tramway Bar coal sample contained 35.8% ash (as received) and 0.25% sulfur (Daf).

Hydrodynamics and Coalbed Methane Potential

Permafrost in the Brooks range north of the Upper Koyukuk area is continuous, whereas the Bettles and Evansville area may be underlain by moderate-to-thin permafrost or discontinuous permafrost near rivers (Ferrians, 1965). Ground water flows southward from the Brooks Range towards Bettles and Evansville. The southern margin of the Brooks range is defined by the Malamute Fault which may inhibit subsurface flow of the water. However, there is a thin (<1 mi; <1 km) outcrop of potential coal-bearing rocks exposed immediately south of this fault system (north of Bettles and Evansville) and these rocks are generally dipping to the south (Patton and Miller, 1973), suggesting favorable orientation for recharge (fig. 57). If there are coals present and if they are aquifers, then meteoric recharge may enter the coals north of the two villages, flow southward, and then turn upward at the South Fork Fault located approximately 1 mi (1.6 km) south of Bettles and Evansville. Although this suggests that the towns Bettles and Evansville are in a favorable position for the accumulation of coal gases, the relatively small area

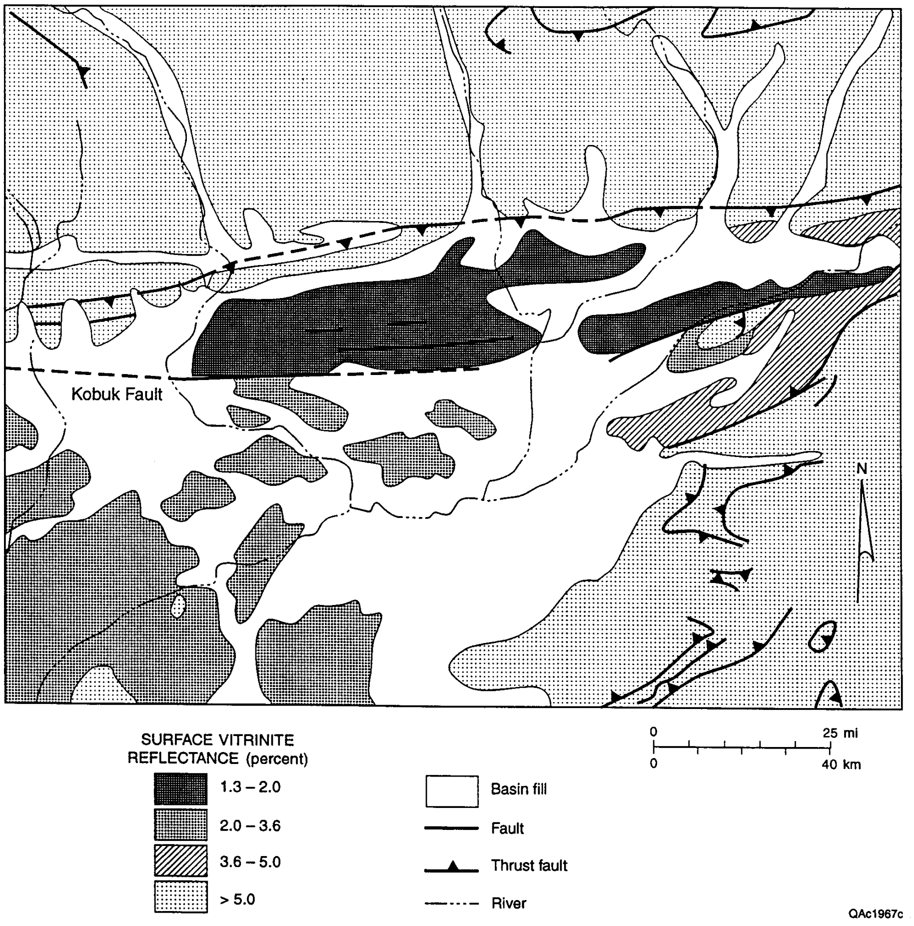

Figure 56. Surface vitrinite reflectance map of the Upper Koyukuk Basin. The high surface vitrinite reflectance values suggest that the coalbed methane potential in this basin may be limited because coals in the subsurface have too high of a thermal maturity level. Modified from Johnsson and Howell (1996).

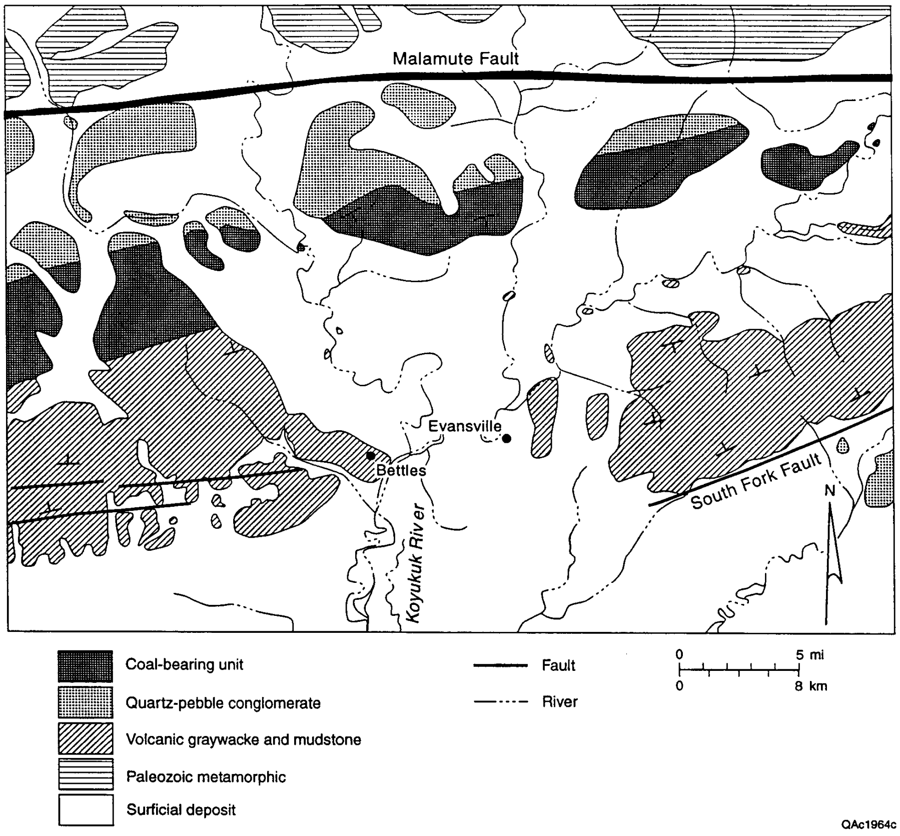

Figure 57. Detailed geologic map of the Upper Koyukuk Basin. Ground water flowing southward from the Brooks Range may turn upward at fault zone south of Bettles and Evansville. Modified from Patton and Miller (1973).

of recharge (fig. 57), discontinuity or absence of coal beds in the area, and high levels of thermal maturity (fig. 56) may limit the coalbed methane potential in this area. The apparent absence of coal-bearing rocks in the Alatna and Allakaket area suggest that coalbed methane is not present in this area. In conclusion, the Upper Koyukuk Basin contains widely scattered outcrops, little surface and subsurface data, lack of continuity of coal seams, and structural complexity making exploration targets very elusive (Smith, 1995) and impossible to define. For this reason, additional data is required before a full evaluation of the coalbed methane potential can be undertaken.

Yukon-Koyukuk Province: Lower Koyukuk Basin (Galena, Kaltag, Koyukuk, Louden, and Nulato)

Tectonic and Structural Setting, Depositional Systems, and Coal Distribution

The Lower Koyukuk coal region consists of upper and lower Cretaceous coal-bearing rocks in the Nulato Hills mountain range. The Lower Koyukuk coal province occurs west of the southward-flowing Yukon River (fig. 53) and coal outcrops consist primarily of scattered coal occurrences between Ruby and Anvik on the Yukon River (Collier, 1903). Although there are numerous reports of coal beds along the Yukon River, these coals are generally thin (less than 6 ft; < 2m), discontinuous, and may have highly variable thickness. The area near Nulato supported several small-scale mines in what is now referred to as the Nulato Field. These coals occur in the Late Cretaceous Kaltag Formation and are generally thin (less than 4 ft thick; Collier, 1903 and Chapman, 1963), although one 11-ft (3.4 m) coal bed has been reported 12 mi (19 km) upriver from Galena (Goff and Barker, 1988). One thick coal bed was also reported near Louden (Goff and Barker, 1988).

In 1960, the Nulato Unit 1 was drilled in the Nulato Hills to 12,000 ft (3,658 m) and is the only deep well to be drilled in this basin. This well was drilled on a northeast-trending surface anticline and penetrated only Cretaceous rocks, yielding little information on the coal-bearing section (Smith, 1995). Sample descriptions indicate that only minor coal was encountered and cores show dips greater than 60° and abundant fracturing and brecciation (Smith, 1995).

Coal Rank

Organic-rich rocks in the Nulato Hills are thermally overmature to supermature having surface VR values between 2.0 and 5.0% (Division of Geological and Geophysical Surveys, unpublished data). The Nulato Unit No. 1 well drilled in this area reported vitrinite reflectance values of 4.5% at 12,000 ft (3,659 m), suggesting that organic-rich sediments at depth have passed out of the hydrocarbon generation window (fig. 58). Lower-rank coal beds with VR values between 0.6 to 1.3% (high-volatile C to medium-volatile bituminous) are located on the west side of the Yukon River between the river and a northeast-trending fault system that corresponds with the southern margin of the Nulato Hills mountains. Lower-rank coals also occur east of Galena near the abandoned town of Louden on the north side of the Yukon River. Therefore, the area of higher coalbed methane potential, based on coal rank between 0.6 to 1.3% VR (high-volatile B and medium-volatile bituminous), is approximately 20 mi (32 km) east of Galena near Louden and west of Galena near the towns of Koyukuk and Nulato.

Sulfur content of coals from the Nulato coal field ranges from 0.6 to 1.4% (moderate to high) and averages 0.7%. Ash content ranges from 2 to 26% and averages 19%. Clough and Roe (1990) report a received ash content of 35% and sulfur content of 0.20% for coals sampled from Hockley Hill.

Hydrodynamics

Permafrost in the Lower Koyukuk region is generally moderate to thin, becoming more discontinuous near rivers (Ferrians, 1965). The depth to permafrost in Galena area is generally less than 3 ft (0.9 m) and permafrost is discontinuous over much of the area (Nakanishi and Dorava, 1994). The maximum thickness of permafrost is probably less than 600 ft (187 m).

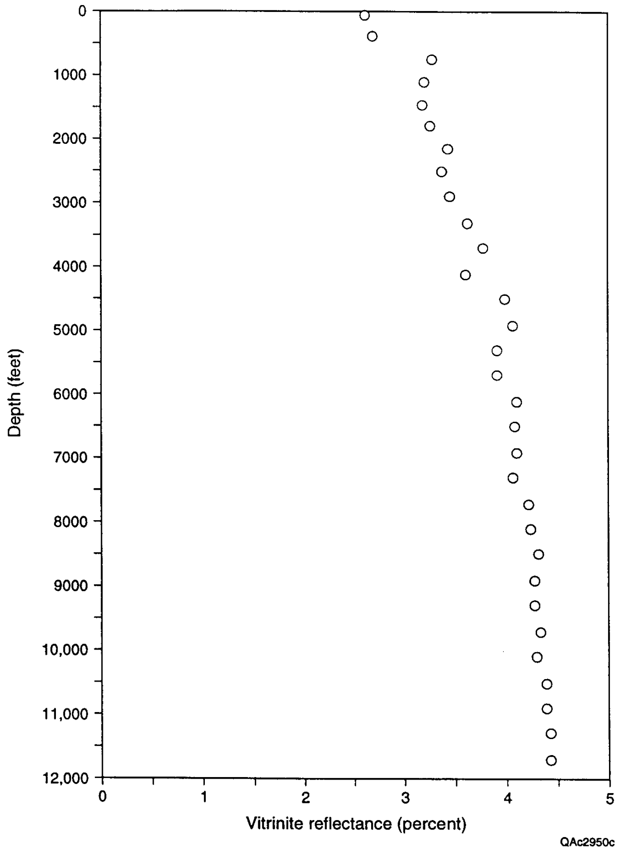

Figure 58. Vitrinite reflectance profile for the Nulato #1 well, Lower Koyukuk. Basin. Vitrinite reflectance values exceed 2.0 percent indicating that coals in this basin are supermature and have little coalbed gas generation potential. Unpublished USGS data.

Overall ground water movement is, to the southwest, parallel to the Yukon River. The proximity of the Yukon River to the Nulato Hills and coals dipping northwest away from Galena suggests that there is probably little or no meteoric recharge from the northwest. Minor ground-water recharge from the Kaiyuh Mountains located to the southeast may occur if coals and/or aquifers crop out in the recharge area. The city of Galena derives drinking water from a shallow aquifer located in the thick alluvium underlying the village (Nakanishi and Dorava, 1994).

Coalbed Methane Potential

The high level of thermal maturity of this area coupled with steeply dipping beds (structural complexity), the presence of only thin and discontinuous coal beds, discontinuous permafrost (general absence of vertical permeability barriers), and limited meteoric recharge basinward towards the Galena Basin probably limits the coalbed methane potential. However, thicker coal beds have been reported near Louden and secondary biogenic and/or migrated thermogenic coal gases may accumulate locally. Therefore, some minor coal gas from bituminous coals along the lower Koyukuk and Yukon Rivers may be present only where migration and trapping of gases has occurred.

Yukon-Koyukuk Province: Kobuk Basin (Ambler, Kiana, Kobuk, and Shungnak)

Tectonic and Structural Setting, Depositional Systems, and Coal Distribution

The Kobuk coal district trends east-west and is located between the Baird Mountains to the north and the smaller Waring Mountains to the south (fig. 53). The Selawik Trough occurs south of the coal district. Target coal beds are Upper Cretaceous in age which apparently underlie most of the coal region. Both upper and lower Cretaceous sediments are exposed in the Waring Mountains and an east-west trending fault zone separates the upper Cretaceous rocks on the north from the lower Cretaceous rocks on the south side of the fault. The north side of the

Waring Mountains corresponds with another fault zone. Coal beds of the Kobuk fields generally are found in broad open folds that are locally steepened by high angle faults (Smith, 1995). This structural complexity suggests the possibility of high in-situ stresses and low permeabilities.

Coal outcrops of Cretaceous or younger age have been identified along the north side of the Kobuk River (fig. 53) and occur in areas where the rock strata are dipping southward into the Kobuk Basin, locally at relatively high angles (Woodward-Clyde Consultants, 1980). Coal float recorded in Shungnak Quadrangle (western Kobuk Basin) and the Ambler River Quadrangle (north-central Kobuk Basin) are assigned a Late Cretaceous age (Patton and Miller, 1968), but coal-bearing strata have not been mapped in detail. Coal-bearing Upper Cretaceous rocks that outcrop near the Kobuk River dip toward the river suggesting that the river is flowing though a small syncline (Patton and Miller, 1968). Some of these coals were sampled by Clough and others (1983) on the west end of the known coal outcrop in the Hockley Hills-Singauruk River (near Kiana) areas. Clough and others (1983) noted some coal seams up to 6 ft (1.8 m) thick with most of the coal thickness less than 2 ft (0.6 m). Additional thin coal beds are reported near the Singauruk River in the southwestern part of the Kobuk coal region. Four distinct coal beds between 4 to 6 ft (1.2 to 1.8 m) in thickness were reported by Dillon and others (unpublished data). Burand (1959) also reported four Cretaceous coal beds from the Selawik Quadrangle that ranged in thickness from 2.0 to 3.5 ft (0.6 to 1 m); these coals are located south of the Waring Mountains. Because of the lack of well and seismic data, no subsurface information on the lateral extent and continuity of coal beds is available for this basin (Smith, 1995). This severely restricts the coal and coalbed methane resource assessment and additional data are required.

Coal Rank

Coal rank in the Kobuk Basin decreases from north to south away from the Baird Mountains. Coal rank in the Baird Mountains to the north of the Kobuk coal district is very high (VR >5.0%; anthracite), whereas rank in the Waring Mountains south of the coal district ranges between medium-volatile bituminous to anthracite (estimated VR values between 1.3 and 2.0%) (Johnsson and Howell, 1996). Cretaceous coals south of the Waring Mountains in the Selawik Basin are much lower in rank. Burand (1959) and Chadwick (1960) reported the coals south of the Waring Mountains to be subbituminous rank, whereas Clough and others (1983) suggested high-volatile C bituminous. Tertiary coal in this area has not been analyzed but may be lignite (VR values less than 0.4%).

The ash content of coals in this area ranges from 8.5 to 48.5% (average 24.2%) and the sulfur content ranges from 0.28 to 0.89% (Smith, 1913; Clough and others, 1983). No analyses of Tertiary coals from the Selawik Quadrangle has been attempted because it has been found primarily as float, but it has been described as lignitic by various authors (Goff and others, 1986).

Hydrodynamics

Permafrost in the Kobuk area is generally moderate to thin in the higher area but becomes discontinuous near the major river systems; maximum permafrost thickness is probably less than 600 ft (183 m) (Ferrians, 1965). Ground water flows southward from the Baird Mountains and northward from the Waring Hills towards the Kobuk River. However, Lower Cretaceous strata are sloping away from the river into the Selawik Basin, indicating that northward recharge through coal beds into the Kobuk Basin probably does not occur. Locally, the Upper Cretaceous coal-bearing formations on both sides of the Kobuk River dip towards the river. The permeability of Cretaceous sedimentary rocks in the area is reported to be generally less than 1 md (Alaska Division of Mining and Geological and Geophysical Surveys, 1986).

Subsurface Data and Production: Including Statements and Quotations Supporting Coalbed Methane Development in the Kobuk-Koyukuk-Kobuk Province

Kirschner (1994), stated that "even the most favorable areas of the Yukon-Koyukuk-Kobuk province could be expected to have, at best, minor gas reserves."

Coalbed Methane Potential

The Kobuk Basin has no subsurface data with which to evaluate the coalbed methane potential and detailed evaluation of the coal resources has not been performed as of yet. Published reports, based on outcrop studies, indicate the presence of only minor coal beds generally less than 3 ft (< 1m) in thickness. Additionally, surface vitrinite reflectance values of Cretaceous coal-bearing rocks north and south of the Kobuk Basin are very high (1.3 to more than 5.0%) indicating that the coals may have already passed through the hydrocarbon-generating window. Cretaceous sedimentary rocks in the area are characterized by very low permeability (Alaska Division of Mining and Geological and Geophysical Surveys, 1993), suggesting that if the coal beds are cleated and permeable, they may be conduits for ground water flow. Moreover, if the coals are laterally continuous, then there may be a potential for secondary biogenic gas generation and accumulation. However, accumulation of coal gas resources will depend on defining the local coal-bed geometry and the presence of permeability barriers and/or seals to trap the coal gases. The Kobuk Basin is therefore assigned a low coalbed methane priority because of high to very high thermal maturities, the apparent presence of thin coal beds (based on available data), and the absence of adequate surface and, particularly, subsurface data required to fully evaluate coal and coalbed methane resources.

RECOMMENDATIONS AND CONCLUSIONS

In targeting exploration fairways in rural Alaskan coal basins, coalbed methane potential has been evaluated for some prioritized villages. Data accumulated and generated from this research and future drilling and recompletion test sites will confirm or negate areas and zones of extraordinary or limited coalbed methane potential. Extraordinary coalbed methane production in rural Alaskan coal basins will require dynamic ground-water flow and migration of thermogenic gases through coals of high thermal maturity (rank) and high gas content toward flow barriers (accompanied by the possible generation of secondary biogenic gas) and conventional trapping of migrated and solution gases along those barriers. The resulting interplay could lead to high gas contents or even fully gas saturated coals for consequent high productivity (as may be the case for the exploration fairway defined in the Colville Basin along the western North Slope).

In the Colville Basin, conventional traps in areas of upward vertical flow potential play an important role in coalbed methane exploration and development. There is, subsequent to basin uplift and cooling, a need for additional sources of gas to be found (because of the low ranks of coals) beyond the gas initially sorbed on the coal surface, in order to achieve high gas contents for production in the Colville Basin. Those additional sources of gas are migrated thermogenic and conventionally trapped gases, and possibly migrated secondary biogenic gases. In other words, the parts of the Colville Basin with the best potential for coalbed methane exploration and development are those where outcrop and subsurface coals are in good hydraulic communication for consequent advective gathering and transport of gas and subsequent resorption and conventional trapping. In the Colville Basin, evidence of migrated thermogenic gases and possibly a dynamic ground-water flow system (both present-day and/or paleohydrologic regimes) is critical to high coalbed methane production when conventional gas traps are targeted as an exploration fairway. In the western Colville Basin, the exploration fairway between the villages of Wainwright and Atqasuk and an area 30 mi (48 km) south of these villages are defined as such an area of conventional trapping, and the traps are postulated to be both structural and stratigraphic (fig. 59). Stratigraphic traps are related to updip pinchout of the coal beds behind the progradational shoreline sequences of the Nanushuk Group. Structural traps may consist of fault-cored anticlines related to the Brooks Range and Barrow Arch orogenesis. The updip migration of thermogenic gases within the coal beds moreover, and the trapping of the

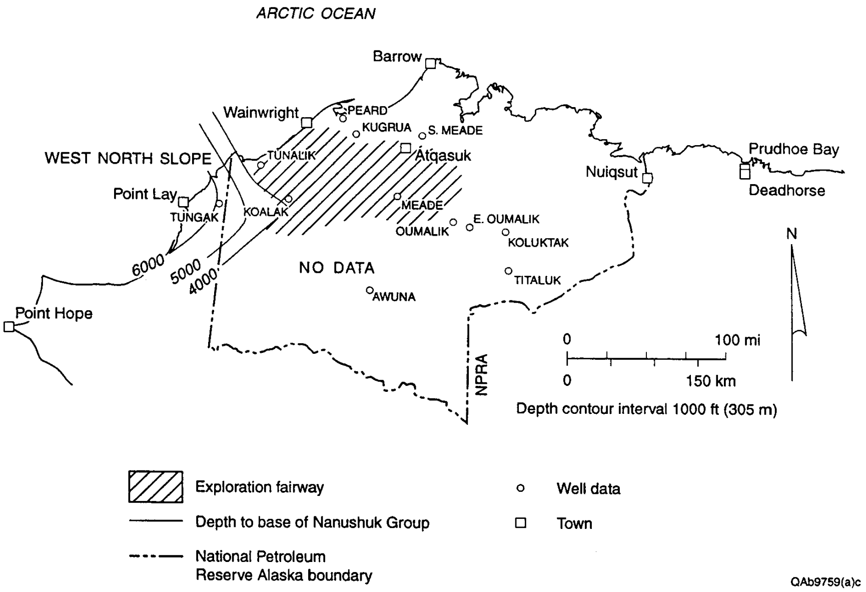

Figure 59. An exploration and development drilling program is recommended within the defined exploration fairway, between the villages of Wainwright and Atqasuk and an area 30 mi (48 km) south of these villages. This is an area where there is potential for upward flow, thick and laterally extensive, higher rank coal bed development, and conventional and hydrodynamic trapping of coalbed gas. Tight gas sands and hydrate (clathrate) development should also be considered potential completion zones in targeting coalbed methane reservoirs.

migrated gases beneath impermeable permafrost layers (clathrate development) should also be considered conventional traps in the course of exploring for coalbed methane resources. Coal ranks are low in outcrop exposures but are reasonably favorable for resource development in the subsurface, with ranks approaching the high-volatile A bituminous, at depths less than 6,000 ft (<1,829 m). The evidence of saline water beneath the permafrost suggests that meteoric recharge from the Brooks Range may be restricted, and, therefore, gases in this basin should be predominantly thermogenic and migrated thermogenic gases. On the basis of the data and results presented, an advanced coalbed methane reservoir characterization and drilling program is recommended for the exploration fairway defined between the prioritized villages of the western Colville Basin. During the development phase of the advanced exploration program, the thick permafrost layers must be taken into consideration for gas-resource development and for protection against blowouts during drilling.

The coalbed methane potential of the Yukon Basin remains unknown because of inadequate data. Structural setting, depositional systems, and coal distribution estimates are tentative. Measured coal rank in the Yukon area is too low for thermogenic gas generation. The presence of gas escaping from the lignites in the U.S. Geological Survey test well, however, may indicate the presence of active biogenic gas generation or migration of biogenic gases. Although the coals appear to be thick and gassy, it is possible that their lateral extent and gas contents are insufficient to support coal gas production. At best, coalbed methane exploration should only be undertaken once access has been given to the U.S. Geological Survey test well and additional subsurface data are obtained. Depending on the economics of setting up the drilling program, this well would be recommended as a wildcat exploration target.

In the Alaskan Peninsula coal basins, coalbed methane producibility will be limited in areas or zones of high in situ stresses, low permeabilities, and structural and stratigraphic complexity. An exploration and development program is recommended only when additional, and detailed, subsurface and surface geologic and hydrologic evaluation is completed in the Chignik Lake area. This evaluation should illuminate areas of high in situ stresses and should define the structural complexity and stratigraphic variability of the area. Importantly, permeability may be reduced even further where high maximum horizontal compressive stresses are perpendicular to face-cleat orientations. Coalbed methane production may also be inhibited in coal reservoirs of exceptionally high permeability associated with meteoric-water and/or sea-water recharge. Coalbed methane wells located near the sea or along major fault systems favorably oriented to accept recharge may therefore have excessive water production. At best, a wildcat exploration program for the Chignik Lake area is proposed that would gain access through a recompletion drilling program to previously drilled wells in the area. The recompletion drilling program should target the high mud-log gas kicks associated with coal beds. The depth to these targets exceeds 4,000 ft (1,219 m), however, deeper than the exploration constraints defined in the cooperative agreement, and the coal-bearing section in some cases is very thin. Coalbed methane wildcat development is moreover, only favored at these depths because coals are either approaching or have reached the threshold of significant thermogenic gas generation. It is concluded that this wildcat exploration would be a high-risk, costly proposition.

The coalbed methane potential of the Minchumina Basin remains low and unknown because of inadequate data. If low coal ranks observed at the surface persist at depth, then the coalbed methane potential may be even lower, particularly if the coals do not crop out along the elevated margins of the basin. The apparently low coal ranks near the surface suggest that gases in this area may be dominantly secondary biogenic.

In the Yukon-Koyukuk Coal Province, the coalbed methane potential of the Upper Koyukuk area remains low and uncertain because of the absence of data. Although there are some favorable hydrogeologic attributes in this basin, the overall coalbed methane potential is questionable because of the absence of thick coal beds. In the Lower Koyukuk Basin, the high level of thermal maturity coupled with structural complexity, the presence of only thin and discontinuous coal beds, discontinuous permafrost, and limited meteoric recharge limits the coalbed methane potential. In the Kobuk Basin, detailed coal and subsurface studies have not been undertaken, making it extremely difficult to fully evaluate the coalbed methane resources.

Published reports indicate the presence of only minor coal beds generally less than 3 ft (<1 m). Additionally, surface vitrinite-reflectance values are very high (1.30 to more than 5.00 percent), indicating that the coals may have already passed through the hydrocarbon-generating window. The Kobuk Basin is therefore assigned a low coalbed methane priority.

It is proposed that the next phase in the development of coalbed methane resources of rural Alaska will be drilling and testing of the defined exploration fairway. This development program must be done in conjunction with detailed basin evaluation, geohydrological sampling analysis, and reservoir engineering assessment. According to data available and application of the producibility model to prioritized basins, drilling and testing of the coalbed methane fairway should be undertaken in the Northern Alaskan Coal Province along the exploration fairway defined between Wainwright and Atqasuk and an area 30 mi (48 km) south of these villages. Consideration to land ownership will be an important issue in siting the test drill-hole location. The North Slope fairway has the highest priority, followed some distance behind by the wildcat prospects of the village of Fort Yukon, Yukon Province, and the Chignik Lake area on the Alaskan Peninsula. Additional data and geologic and hydrologic reservoir characterization are a prerequisite before resource development can take place in the Yukon and Alaskan Peninsula coal provinces. Recompletion of existing well bores may offset some exploration and drilling costs in these areas.

It is our prediction that the first one or two wells drilled in the rural Alaskan exploration program will be the key to the future of coalbed methane resource development in Alaska. As such, fairways should be targeted by choosing the basin that has the most available data (North Slope) and least risk for missing targeted coal beds when drilling begins. Drilling an initial dry hole that has little or no coal and/or low gas contents will severely retard the coalbed methane program in the future. All drilling programs should be accomplished with the cooperation of local operators familiar with drilling in permafrost regions and with local organizations and boroughs that can provide additional data and information for complete evaluation of the coalbed methane potential.

In summary, on the basis of the literature and data available, we think that regional basin evaluation incorporating aspects of the coalbed methane producibility model has been well used to prioritize and focus exploration and development in rural Alaska. Importantly, all rural Alaskan coal basins are thought to have some coalbed methane potential. According to limited data available to date in some rural basins and economic constraints in defining the coalbed methane exploration fairways, however, the Colville, Yukon, and Chignik Basins have data that support the potential for more in-depth analyses of their coalbed methane resources. All three prioritized basins have some subsurface data indicating the presence of gas in coal reservoirs and detailed basin analysis, which includes subsurface drilling and data collection, will confirm or negate the presence of exploration fairways. Above all, the focus remains on delineating interrelated geologic and hydrologic controls that determine the economic feasibility of coalbed methane production in rural Alaska. Importantly, the proposed drilling and testing program and application of the producibility model will provide the State of Alaska with a rationale for future exploration and development strategies. By drilling the potential exploration fairway for coalbed methane in rural Alaska, the recovery of the environmentally friendly coalbed methane resource may be realized.

ACKNOWLEDGMENTS

Funding for this project, provided by the State of Alaska through a cooperative agreement between the Bureau of Economic Geology, The University of Texas at Austin, and the Division of Geological and Geophysical Surveys, Department of Natural Resources, State of Alaska, is gratefully acknowledged. We would also like to thank Neil Strandberg for his assistance in supplying data for and coordinating the field trip. We also acknowledge the support and fruitful discussions with local communities during the research. Word processing and layout done by Susan Lloyd. Figures were prepared by Kerza Prewitt, Pat Alfano, and Jennifer Hughes under the direction of Joel L. Lardon. Jamie H. Coggin designed the cover. Nina Redmond edited the report under the supervision of Susann Doenges.

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Appendix A. 1997 Coalbed methane field survey station locations and face and butt cleat measurements (James G. Clough)

Northern Alaska Province: Colville Basin (North Slope)

97JC1
DATE: 6/21/97
Kukpowruk River
NO COAL

97JC2
DATE: 6/22/97
Kukpowruk River
(locality of 13' seam, also recorded as 20' seam)
FACE CLEAT: 315°
BUTT CLEAT: 215°
SPACING: 0.25 to 3.0 in (face)
0.25 to 3.0 in (butt)

97JC3
N69°32.408' LAT.; W161°33.663'
Kokolik River
Coal
FACE CLEAT: 335°
BUTT CLEAT: 235°
SPACING: 0.25 to 3.0 in (face)

97JC4
N69°42.596' LAT.; W160°49.785' LONG.
BEDDING: nearly horizontal
Coal
FACE CLEAT: NS
BUTT CLEAT: EW

97JC5
DATE: 6/23/97
N70°02.904' LAT.; W161°30.369' LONG.
Omikmak mine site near Wainwright, near Geodetic 1948 Mine Survey, Mine #1
BEDDING: nearly horizontal
FACE CLEAT: 18°
BUTT CLEATS: 304°and 290°

Appendix A (cont.).

Upper Yukon Province: Yukon Basin (Yukon Flats)

97JC6
DATE: 6/26/97
Sand Dune north of Ft. Yukon,with Bonnie Thomas GZ Corp.
NO COAL

97JC7c-1, 97JC7, 7b, 7c
QUADRANGLE: Beaver C-3
DATE: 6/27/97
N66°41.074' LAT.; W148°21.664' LONG.
Hodzana River, "The Mudbank"
Irregular-bedded or possibly "pod" of coal to 3 feet (?)
BEDDING: (poorly defined) 330°; Dip 12°NE
FACE CLEAT: possible face cleat 40°
BUTT CLEAT: possible butt cleat 90°

97JC8
QUADRANGLE: Livengood C-6
DATE: 6/28/97
N65°40.084' LAT.; W149°49.637' LONG.
Drew Mine site upriver from Rampart village
Coal 2.5 ft with shale parting
BEDDING: 20°; 81°SW Dip
FACE CLEAT: 342°(dominant)
BUTT CLEAT: 90°to "face"

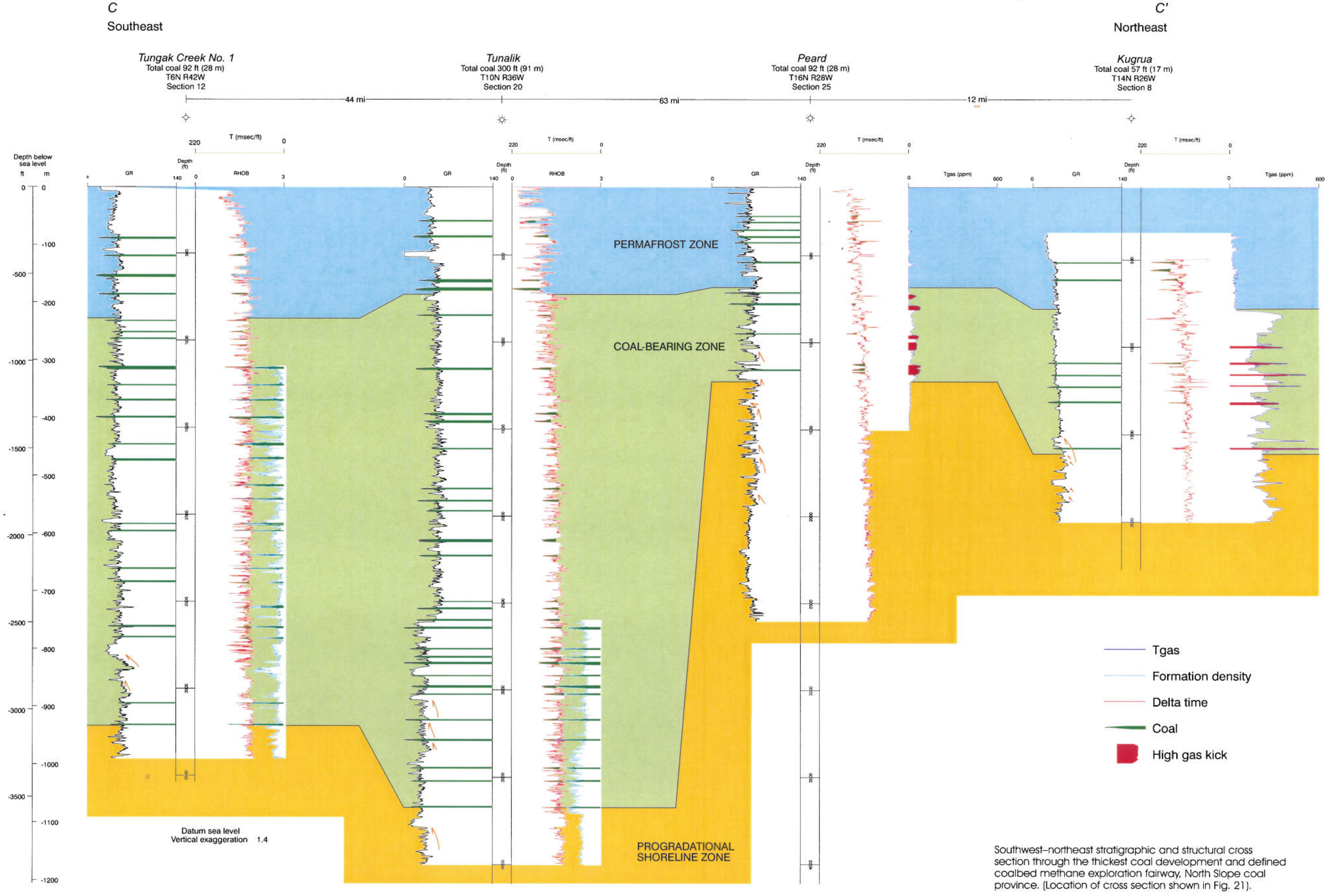
Appendix A (cont.).

Alaska Peninsula Province: Chignik Bay Basin

97JC10
QUADRANGLE: Chignik B-3
DATE:
LAT.; LONG.
Chignik River mine at Fish and Game fish weir
Coal
BEDDING: NS dipping 24°E
FACE CLEAT: 265°
BUTT CLEAT: 320°

97JC11
QUADRANGLE: Chignik B-2
DATE:
LAT.; LONG.
McKinsey Valley
Approx. 4 feet of boney coal (numerous partings)
BEDDING: 30° 22°W
FACE CLEAT: EW 90°
BUTT CLEAT:

97JC13
QUADRANGLE: Chignik B-2
DATE: 7/3/97
N56°19.423' LAT.; W158°30.866' LONG.
Diamond Point at Chignik Lagoon
Approx. 6 feet of coal
BEDDING: 312°12°NE
FACE CLEAT: 322°vertical
BUTT CLEAT:



Southwest–northeast stratigraphic and structural cross section through the thickest coal development and defined coalbed methane exploration fairway, North Slope coal province. (Location of cross section shown in Fig. 21).

FIGURE 27 EXPANDED: SOUTHWEST-NORTHEAST STRATIGRAPHIC AND STRUCTURAL CROSS SECTION THROUGH THE THICKEST COAL DEVELOPMENT AND DEFINED COALBED METHANE EXPLORATION FAIRWAY, NORTH SLOPE COAL PROVINCE