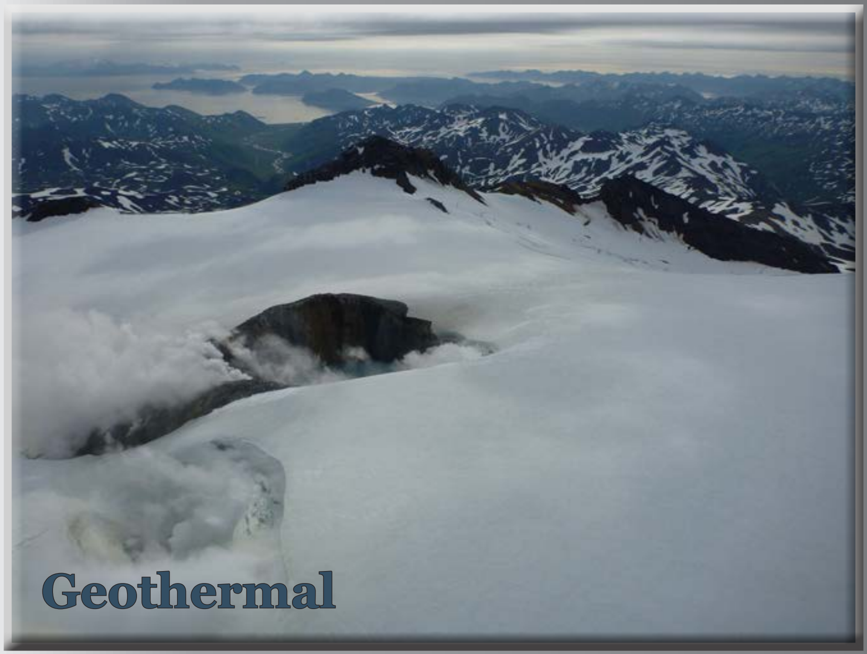

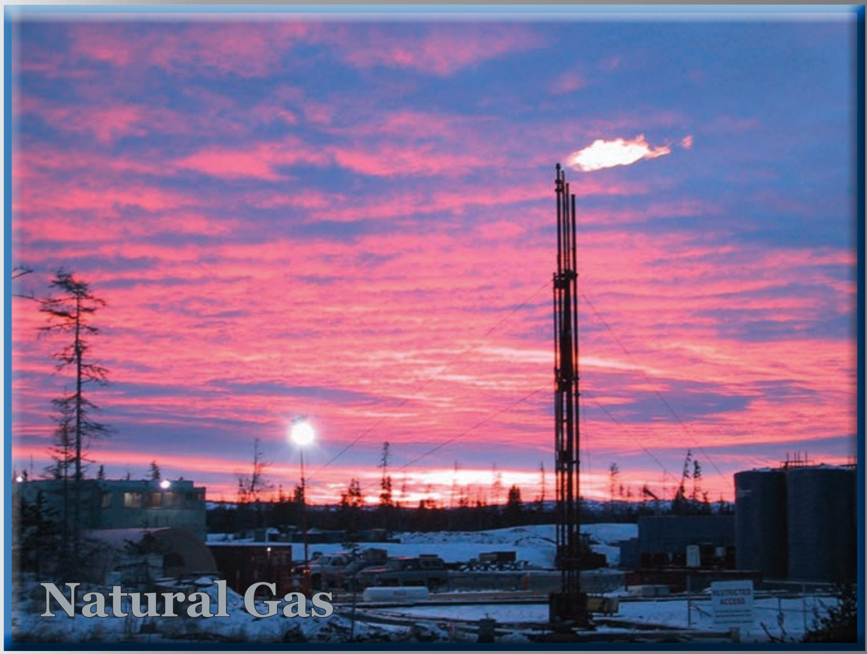

FOSSIL FUEL AND GEOTHERMAL ENERGY SOURCES FOR LOCAL USE IN ALASKA:
Summary of Available Information

edited by
Robert F. Swenson
Marwan A. Wartes
David L. LePain
James G. Clough

Special Report 66

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Summary of Available Information

Edited by: Robert F. Swenson[1], Marwan A. Wartes[1], David L. LePain[1], and James G. Clough[1]

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FRONT COVER PHOTOS:
TOP: *From 1922 to 1962, historic Suntrana Mine operated at this site near Healy, Alaska, using mostly underground mining methods. Usibelli Coal Mine currently mines to the north of Suntrana, using open-pit methods. The prominent black coal bed dipping to the left is near the top of the Suntrana Formation, which contains the thickest seams of subbituminous coal in the Nenana basin. Photo by Jim Clough, September 2008.*

MIDDLE: *View to the east over the persistently steaming summit fumaroles of Makushin Volcano, with Makushin Valley, Unalaska Bay, and Dutch Harbor visible in the distance. Fumaroles are high-temperature steam and gas vents that result from hot or molten igneous rocks releasing gas and boiling off groundwater and melting snow. Makushin Volcano is a viable geothermal prospect near Dutch Harbor. Photo by Janet Schaefer, August 3, 2012.*

BOTTOM: *Natural gas flared from production test of an oil and gas well in Cook Inlet. Photo by Bob Swenson.*

BACK COVER PHOTO:
View from the summit ridge of Mt. Spurr down into the ice cauldron. Bare, warm, steaming rock, part of the turquoise lake, and multiple fumaroles are visible. Photo by Sorokin Maxim.

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DEPARTMENT OF NATURAL RESOURCES
Daniel S. Sullivan, *Commissioner*

DIVISION OF GEOLOGICAL & GEOPHYSICAL SURVEYS
Robert F. Swenson, *State Geologist and Director*

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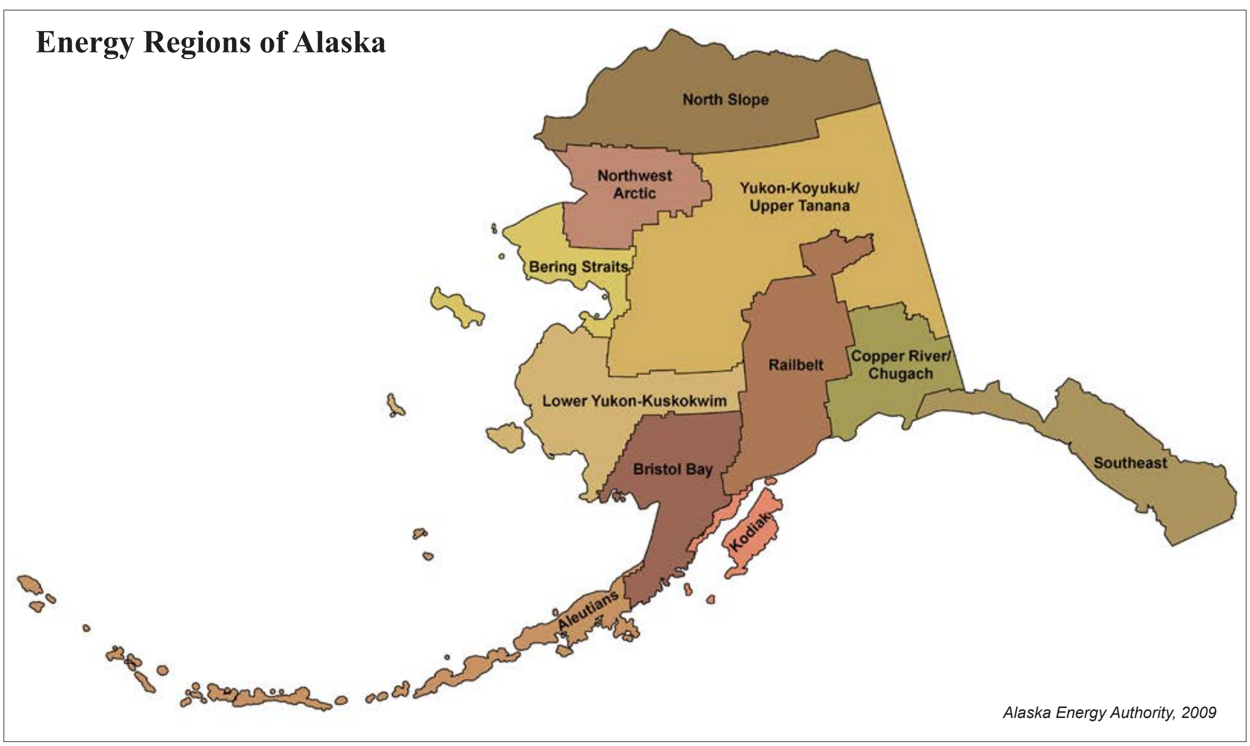
EXECUTIVE SUMMARY

Economic growth and stability in Alaska hinges partially, if not primarily, on the availability of a mix of affordable and sustainable energy sources. The high and volatile prices of diesel fuel and heating oil have created economic hardship in many areas of Alaska, particularly remote rural communities where these imported fuels are the primary source of energy. Developing local energy sources that are not tied to a global market will help diversify the state's energy portfolio and help facilitate economic growth in many regions. Unfortunately, all areas are not created equal in energy accessibility.

The purpose of this report is to summarize existing information concerning locally available, geologically hosted sources of energy across the state. This work considers both geothermal and fossil fuel (oil, natural gas, and coal) resources and is intended to supplement the Alaska Energy Authority's ongoing analysis of non-geologic energy sources such as hydro, wind, and biomass. Collectively, these summaries provide a basis for ensuring that Alaska's entire suite of potential energy sources is considered. Although this review does not represent a comprehensive analysis or resource assessment, the information should assist local, regional, and statewide efforts to reduce the dependence on diesel for heat and electricity.

The potential for locally exploitable natural resources varies widely across the state, and certain regions possess more favorable geologic attributes than others. The chapters of this report are subdivided into the 11 regions recognized by the Alaska Energy Authority (AEA, 2009). For each region, discussion is provided on its potential for geologically hosted energy resources including coal, conventional and unconventional oil and gas, and geothermal resources. Many areas of the state lack sufficient geologic information to reliably evaluate local energy potential; summaries of each region conclude with recommendations regarding what additional data or strategies would be most helpful in developing new energy resources for local or regional use.



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GEOLOGIC REQUIREMENTS FOR EXPLOITABLE FOSSIL FUEL AND GEOTHERMAL ENERGY RESOURCES

by James G. Clough, Paul L. Decker, Ken Helmold, and Christopher J. Nye

INTRODUCTION

Fossil fuel resources come from a variety of geologic sources, including coal, conventional oil and natural gas, and unconventional natural gas. Unlike fossil fuels, geothermal energy comes from heat in the Earth's interior and is considered a renewable resource. In order for any of these energy sources to be present in a region as an exploitable resource, specific geologic features must be present. *If any of the features required for a particular energy category are missing in a region, then that resource is considered to be not present in that region*. The term 'exploitable' as used here means that the resource is present in sufficient quantities that it could be used as an energy source for local communities given currently available technology. This definition does not factor in the economics of developing a resource for local consumption. A resource may be present in an area, but the cost to develop might be too high compared to alternative energy sources. Alternatively, a fossil fuel resource may be present in an area and the economics of its use might be favorable enough to render other potential energy resources less attractive economically.

The purpose of this chapter is to outline the geologic requirements for exploitable fossil fuel and geothermal resources. The economic and environmental costs of each energy category are beyond the scope of this chapter. The chapter concludes with an outline of the geologic requirements for an exploitable geothermal energy resource.

In this report, we divide fossil fuel types into two categories: Conventional fossil fuels and unconventional fossil fuels. Conventional fossil fuel categories covered include coal and conventional oil and gas. Coal must be mined using underground or surface strip-mining techniques. Conventional oil and gas resources are hydrocarbons that will flow to extraction wells without having to make dramatic changes to either the reservoir rock or reservoir fluids.

Unconventional oil and gas resources require either massive stimulation to create permeable conduits (tight gas sands and shale gas), thermal or chemical treatments to reduce oil viscosity (heavy oil and tar sands), or dewatering to promote the relative permeability of gas (coalbed methane). Unconventional fossil fuel categories covered include tight gas sands, shale gas, coalbed methane, and methane hydrates. Tar sands, or heavy oil deposits, share the same geologic requirements as conventional oil, but the viscosity is significantly higher than that of oil. Tar sands are not addressed in this chapter or this review, as there are no known exploitable occurrences of these resources in Alaska.

GEOLOGIC REQUIREMENTS FOR EXPLOITABLE COAL RESOURCES

by James G. Clough

Coal is a brownish-black to black combustible organic sedimentary rock formed by the decomposition of plant material, typically in a swampy or boggy environment (fig. A1). This organic material, called *peat*, is buried, compacted, and hardened over millions of years. This process is called *coalification*. During coalification, peat undergoes several changes as a result of bacterial decay, compaction, heat, and time. Peat deposits are quite varied and contain everything from pristine plant parts (roots, bark, spores, etc.) to decayed plants. The coalification of peat passes progressively through four main phases of coal development: *lignite*, *subbituminous* coal, *bituminous* coal, and *anthracite*. These end products are composed primarily

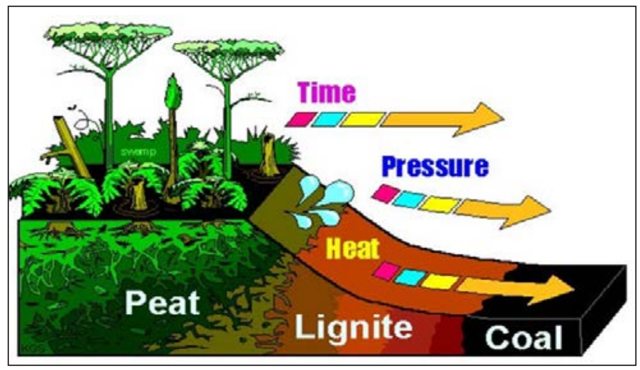

Figure A1. Diagram showing the steps in the formation of coal (Kentucky Geological Survey, 2006).

of carbon, hydrogen, oxygen, and some sulfur along with water moisture and non-combustible ash (table A1). The rank of coal is based on the amount of carbon and volatiles (water and gas) in the coal, as well as the energy content of the coal. The amount of energy in coal is expressed in British thermal units (Btu) per pound. The higher a coal's rank, the greater its heating value (table A1).

Alaska coal formed in widespread deltaic, lacustrine (lake), and alluvial (river flood plains) depositional systems. Coals that formed in delta systems tend to be laterally extensive, whereas coals that formed in river floodplain settings tend not to be as laterally continuous. In Alaska, most of the coals originating in river floodplains tend to be younger than deltaic coals, tend to be of lower rank, and formed in sedimentary basins bounded by complex fault systems that controlled basin formation and influenced peat deposition by differential subsidence (settling or sinking of the land surface over time at different rates in different areas). The main coal areas in Alaska are shown in figure A2 (Merritt and Hawley, 1986) and include the North Slope (subbituminous

Table A1. Table showing important components of coal and heating value by rank. Modified from table in Bowen and Irwin, 2008.

Components and Heating Value of Coal by Rank

% weight	Anthracite	Bituminous	Sub-Bituminous	Lignite
Heat Content (Btu/lb)	13,000-15,000	11,000-15,000	8,500-13,000	4,000-8,300
Moisture	< 15%	2 - 15%	10 - 45%	30 - 60%
Fixed Carbon	85 - 98%	45 - 85%	35 - 45%	25 - 35%
Ash	10 - 20%	3 - 12%	≤ 10%	10 - 50%
Sulfur	0.6 - 0.8%	0.7 – 4.0%	< 2%	0.4 – 1.0%

to bituminous coal), Yukon–Koyukuk (subbituminous coal), Interior–Healy area (mostly subbituminous), south-central Cook Inlet to Matanuska Valley (subbituminous to bituminous coal), Alaska Peninsula (lignite and bituminous coal), and Gulf of Alaska–Bering River area (bituminous coal to anthracite). There are numerous smaller occurrences of coal around Alaska that have small quantities of non-economic coal. With a few exceptions, most Alaska coal is very low in sulfur, in many cases containing less than 0.5 percent, and contains low concentrations of metallic trace elements and nitrogen. These characteristics make Alaska's coals favorable for meeting environmental constraints on combustion in power plants.

Coal resources are defined as naturally occurring concentrations or deposits of coal in the Earth's crust, in such forms and amounts that economic extraction is currently or potentially feasible. What constitutes an *exploitable* coal resource? This is a difficult question to provide a single answer as it is based on the current economics of extracting, transporting, processing, and marketing the coal for the end user. Generally, the question can be stated, "Is the cost of mining the coal and delivering it to the user less than the price of delivered diesel/heating fuel, using the current technology for extracting coal?" The U.S. Geological Survey has published 'standards' for determining 'mineable' coal resources that are based on coal bed thickness related to coal rank and the depth of the *overburden* for both surface mining and underground mining methods. Overburden is non-coal material that lies above the coal and must be stripped away to extract the coal using surface mining methods or to drive a mine shaft through to extract the coal by underground mining methods. Beds of higher rank bituminous and anthracite coal should be 14 inches or greater to be considered a coal resource. Lower rank lignite and bituminous coal should be 2½ feet or thicker to be considered a coal resource. Overburden for surface mining should be 500 feet or less and is generally less than 300 feet in the U.S. Coal that is too impure, too thin, too deep, or for other reasons not considered to be potentially economic, is not classified as a resource but is classified as an *other occurrence* (Wood and others, 1983). Other factors must also be considered when deciding if a coal occurrence is exploitable, including the lateral extent of the coal seam or seams and the position of the coal relative to surface water bodies and groundwater.

Coal mining regulations are very precise and strict for safety and environmental purposes. A description of the

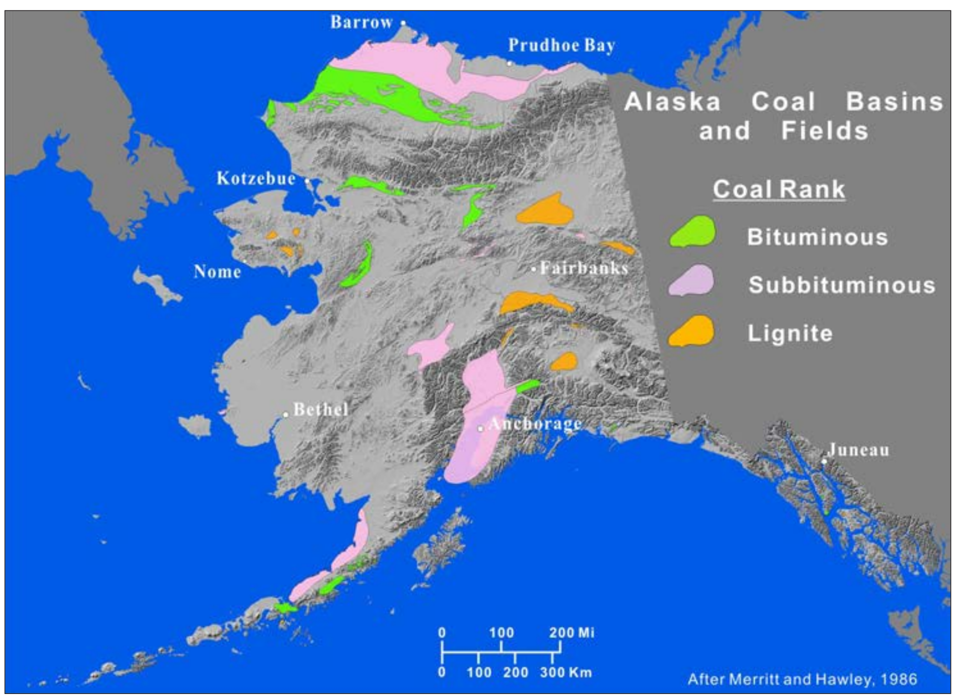

Figure A2. Map of Alaska showing the distribution of coal-bearing sedimentary basins.

State of Alaska Coal Regulatory Program and the specific regulations for coal mining in Alaska can be downloaded from this website: http://dnr.alaska.gov/mlw/mining/coal/index.htm. It seems unlikely that any coals in rural areas of the state would be mined by underground methods for safety issues alone, without even considering the much higher cost of extracting coal from underground mining operations. The most common surface mining method for coal is strip or area mining. Strip mining exposes the coal by removing the overburden in long cuts or strips by excavator or shovel.

GEOLOGIC REQUIREMENTS FOR EXPLOITABLE CONVENTIONAL OIL AND GAS RESOURCES

by Paul L. Decker

For the purposes of this resource inventory, *conventional oil and gas resources* are hydrocarbons that will flow to extraction wells without first having to make dramatic changes to either the reservoir rock or the reservoir fluids. This distinguishes them from various unconventional oil and gas resources, which may require massive reservoir stimulation to create permeable conduits (tight gas sands, shale oil, and shale gas), thermal or chemical treatments to reduce oil viscosity (heavy oil and tar sands), or dewatering to promote the relative permeability of gas (coalbed methane). The formation of conventional hydrocarbon accumulations hinges on a series of crucial geologic processes unfolding in the proper sequence over millions or, in some cases, hundreds of millions of years. When all the necessary components are present, effective, and have had the proper interactions, they are said to make up a conventional petroleum system (Magoon and Dow, 1994).

Alaska is an amalgamation of diverse geologic provinces that have had very different geologic histories. Some settings, such as the North Slope and Cook Inlet, hosted all the processes needed to generate rich fossil-fuel resources. Conditions across much of the rest of Alaska are known to have been less favorable; certain elements of the petroleum system are either missing or they developed in the wrong sequence, ruling out the presence of conventional oil and gas resources. Finally, there are portions of the state where subsurface exploration has not yet determined whether conventional hydrocarbon resources may someday be produced commercially, or could help satisfy rural energy demand. This section describes the four basic elements of conventional petroleum systems—source, reservoir, trap, and seal—and their roles in giving rise to conventional oil and gas accumulations.

Oil source rocks (usually black shales or limestones) contain elevated levels of organic molecules rich in carbon and hydrogen that, when heated slowly to the right temperature (typically greater than about 212 degrees Fahrenheit [212oF; >100 degrees Celsius, 100oC]), react to form the mix of chainlike hydrocarbon molecules we call crude oil. The part of a basin that is buried deeply enough to cause this thermal conversion is called ‘the kitchen.’ With continued burial and increased heating of ‘the kitchen’ (above about 300°F [150°C]), these same rocks generate less oil but expel increasing amounts of the lighter, smaller hydrocarbon molecules (mainly methane) that make up natural gas. Source rocks that start out rich in carbon but leaner in hydrogen (including coals as well as many shales and limestones) can generate natural gas but not the more hydrogen-rich liquid hydrocarbons.

Apart from the thermally driven maturation that accompanies deep burial, natural gas can also be created in low-temperature (175°F [<80°C]) environments by bacterial decay of coal or peat beds. If this biogenic gas forms at or very near the surface, it commonly bubbles away into the atmosphere. However, if it originates at greater depths, the gas may dissolve into the waters surrounding it and remain trapped in the source coal unless subsequent uplift reduces the pressure and allows gas to break out of solution to form a separate vapor phase. Whether of thermogenic or biogenic origin, once oil or gas exists as a liquid or vapor phase separate from the surrounding pore waters, buoyancy quickly drives the hydrocarbons to migrate from the source area, following the path of least resistance through the most permeable strata they encounter.

Conventional reservoir rocks are porous, permeable formations that can store oil and gas in the pore spaces between grains and later allow them to flow out of the rock into wellbores, where they can be recovered. Some of the most efficient petroleum systems have high-quality reservoir formations that closely overlie the source rock unit and serve as conduits for hydrocarbons migrating up and out of the ‘kitchen’ area toward traps closer to the basin edge. Only where these porous, permeable rocks are enclosed in trapping geometries do hydrocarbons stop migrating and accumulate in the reservoir rock to form conventional oil or gas accumulations. The quality of a reservoir depends on several variables, notably its porosity (expressed as a percentage of the total rock volume), permeability, thickness, uniformity, continuity, and hydrocarbon saturation. These factors govern both the recoverable volume of hydrocarbons contained per unit area, and the rate at which oil and gas can be produced.

Effective traps consist of reservoir rock layers overlain and/or laterally bounded by impermeable seal rock, and are of two basic types. *Structural traps* occur where the rock layers are deformed by folding or faulting to form concave-downward shapes capable of containing buoyant fluids such as oil and gas. *Stratigraphic traps* occur where porous, permeable reservoir rocks are encased in impermeable seal rocks as a result of non-uniform deposition of sediments. For example, clean sands on a wave-worked beach may grade laterally into a muddy offshore setting, and with time, the muddy offshore zone may migrate over the older beach sand, setting up a possible future stratigraphic trap. Structural traps are usually much easier to identify and generally host the initial oil and gas discoveries in a given basin. Stratigraphic traps are much harder to target, and their successful prediction normally requires more detailed mapping of the subsurface geology. This might be based on either an abundance of previously drilled wells or advanced processing and interpretation of high-quality three-dimensional seismic data. In any case, for traps to host oil and gas fields, they must be created prior to hydrocarbon generation, expulsion, and migration from 'the kitchen.' Additionally, they must then remain intact, uncompromised by later folding, faulting, or excessive burial.

What determines whether a conventional hydrocarbon accumulation can be exploited depends on numerous geologic and economic factors, including the type of hydrocarbon, producible rate, recoverable volume, development cost, and location. In rural Alaska, either oil or gas resources would be attractive if they could provide energy at a full-cycle cost competitive with currently subsidized deliveries of diesel fuel.

GEOLOGIC REQUIREMENTS FOR UNCONVENTIONAL FOSSIL FUEL RESOURCES

by Ken Helmold and James G. Clough

Coalbed Methane

Coalbed methane is a clean-burning fuel that is comparable in heating value (~1,000 Btu/scf) to conventional natural gas. The production of coalbed methane in the lower 48 states from coal seams accounts for about 10 percent of the gas production in the United States. Coal is one of the most abundant non-renewable energy sources in the world, and Alaska has substantial coal resources in a number of sedimentary basins (refer to the description of exploitable coal in this chapter for more information on the origin of coal). The majority of Alaska's coal is located on the North Slope, followed by the Cook Inlet region, Interior Alaska (mainly Healy), the Alaska Peninsula, Copper River basin, and numerous smaller basins and individual coal localities throughout the state (fig. A2). Within these coal basins there must exist a number of necessary and complex geologic conditions to both generate coalbed methane and to store the gas in an underground reservoir for any possibility of exploiting this potential resource.

Unlike conventional natural gas, in coalbed methane the coal serves as both the source rock and the gas reservoir. Methane (when accompanied by water, nitrogen, and carbon dioxide) is formed when buried plant material is converted into coal over millions of years by heat, pressure, and chemical processes. This coalification process generates methane-rich gas, which often is held in pores and fractures in the coal reservoir and adsorbed to (attached to the surface of) coal particles. As a reservoir, coal is a microporous, carbon-rich mineral capable of holding large quantities of gas that is generated internally. However, gas cannot be extracted from the coal reservoir unless these small micropores are connected through a well-developed fracture system called coal 'cleats' (fig. A3). Fracture permeability is the measurement of how well a fluid or gas moves through a rock when the pores are connected through a cleat or fracture system. Even if there is sufficient coalbed gas, it cannot be produced if there are very few fractures, which results in low permeability.

Importantly, coals must also reach a certain critical threshold of thermal maturity or "coal rank" before very large volumes of thermogenic methane gas is generated (fig. A4). Lower-rank lignite to subbituminous coals contain mostly biogenic gas that results from bacterial action on organic material, in the same manner methane is generated by bacteria in shallow garbage landfills. It is important to note that there is no current production of biogenic gas from lignite coals because they lack a well-developed natural fracture system. Production of biogenic gas from very thick (50 to 200 feet thick) subbituminous coals is occurring in the

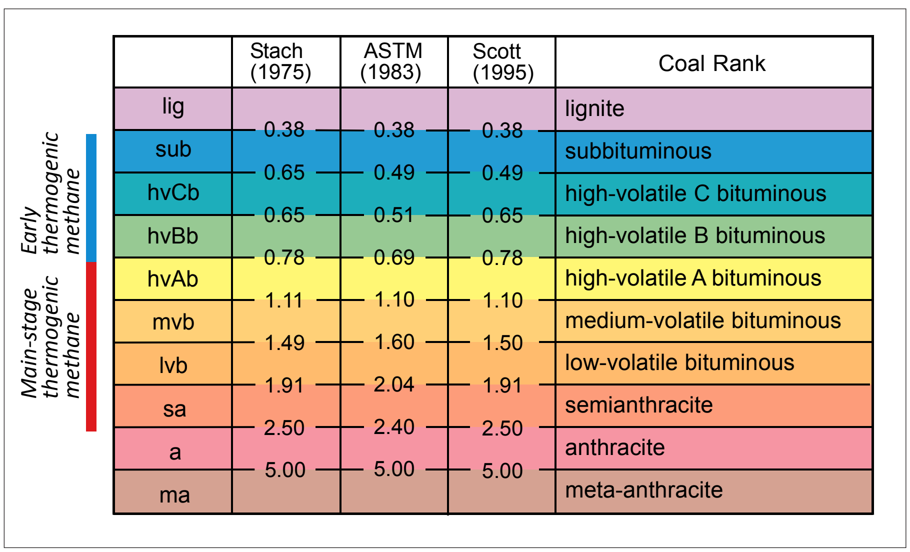

Figure A3. Coal rank. The numbers in the columns refer to rank as determined by vitrinite reflectance. Significant coalbed methane generation does not occur until the high-volatile A bituminous rank is reached. Modified from figure 15 in Scott, 2004.

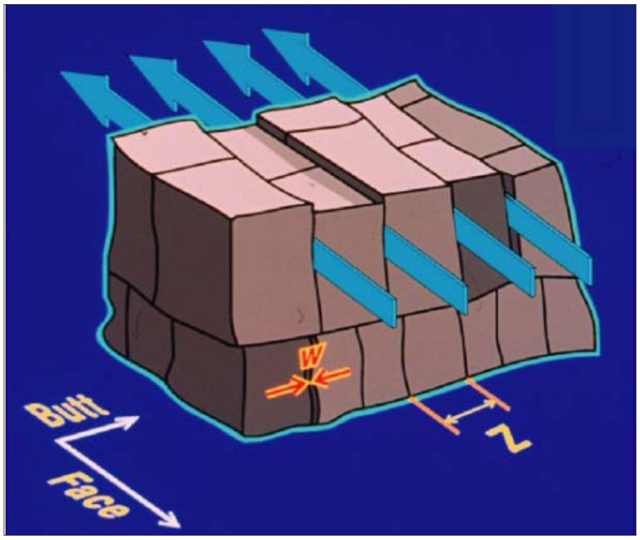

Figure A4. Schematic diagram of an intersecting network of fractures or cleats in a coal seam. While coal has porosity, the pore network is not interconnected, resulting in very low matrix permeability. Cleats provide the permeability required to produce coalbed methane. Modified from figure 4, in Scott, 1999.

Powder River Basin in Wyoming, where gas contents are, on the average, less than 35 cubic feet per ton of coal. However, most commercially-viable coalbed methane production is from coals within the range of high-volatile A bituminous to low-volatile bituminous. Coals of this rank provide both the optimum gas content (as much as 800 cubic feet of gas per ton) and well-developed natural fracture cleat systems to provide a pathway to the well bore.

Finally, coal seams are usually saturated with water, with the hydrostatic pressure keeping the methane within the coal. Sufficient hydrostatic pressure must be present throughout the geologic history of the coal seam for gas to be retained. If pressure is reduced sufficiently by erosion, uplift, or other means, gas can escape from the coal, leaving little or no gas to extract.

The usual method of producing methane from coal is to pump water from a coalbed methane production well, reducing the hydrostatic pressure and causing the methane to desorb (detach from coal particles) and begin to flow from the coal to a pumping well. A key factor in the production of coalbed methane is the fracture permeability of the coal seam. The coal must have well-developed cleats to allow the gas to flow in large quantities from the coal to the producing well. At first, coalbed methane wells produce mostly water, but over time and under proper geologic conditions, the amount of water declines and gas production increases as the bed is dewatered (fig. A5). Water removal may continue for several years. Given that coalbed methane production usually involves significant water production, there must be some way to dispose of the fluid, especially if it does not meet strict EPA water quality standards. Alaska's cold temperatures and permafrost pose significant challenges for disposal of the water by-product. In the Lower 48, produced water is either surface disposed in large evaporation ponds, surface discharged into existing bodies of water, or re-injected into deep disposal wells, depending on the chemistry of the water. Each of these disposal methods presents significant challenges in Alaska arctic and sub-arctic conditions.

A developed coalbed methane well field consists of production wells, gathering lines, separators, compressors, and water disposal facilities. In each development, water and gas from each well site are transported to a single processing site serving water disposal, gas treating, and central compression and distribution pipelines.

Tight Gas Sands

For purposes of this inventory, 'tight gas resources' are defined as hydrocarbons present in low-permeability reservoirs that produce mainly dry gas. Dry gas is natural gas that occurs in the absence of liquid hydrocarbons. A large proportion of these low-permeability reservoirs are sandstone, but limestones and dolomites also have the potential to yield producible quantities of gas. Tight gas resources are distinguished from conventional oil and gas resources in requiring massive reservoir stimulation to create permeable conduits (similar to shale gas) or dewatering to promote the relative permeability of gas (similar to coalbed methane) (Holditch, 2006). They are similar to conventional oil and gas in requiring the presence of an organic-rich, thermally-mature petroleum source rock and a reservoir rock capable of being charged with gas from the source rock (refer to the section on conventional oil and gas for an explanation

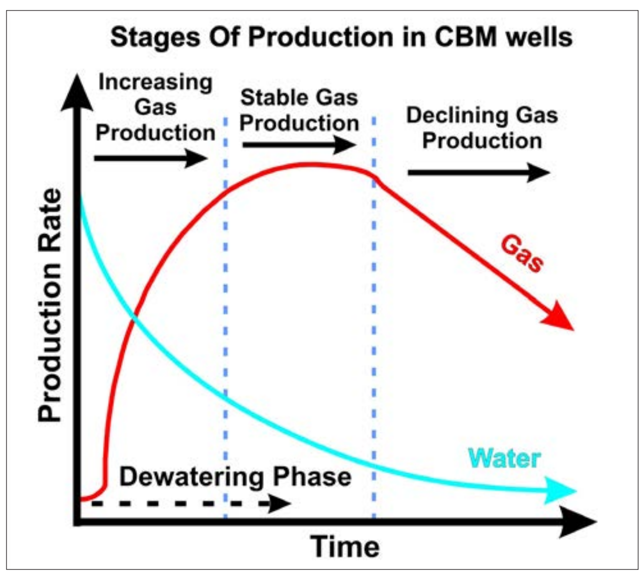

Figure A5. Generalized graph showing the relative proportions of gas and water produced from a coalbed methane well over time. Modified from Schraufnagel (1993).

of source rocks). Stimulation involving a large hydraulic-fracture treatment is usually necessary to create fracture permeability to allow the reservoir to yield commercial gas-flow rates and produce commercial quantities of gas. In fractured reservoirs (naturally fractured or stimulated), the drilling of horizontal wells may dramatically improve producibility over more traditional vertical wellbores, as horizontal wells tend to intersect a greater number of fractures than vertical wells. Tight gas reservoirs produce less gas over a longer period of time compared to conventional reservoirs. Because of this, more vertical wells or long horizontal wells must be drilled in tight reservoirs to produce commercial rates and volumes of gas. Hence, development costs are commonly higher than in conventional gas reservoirs.

Tight gas reservoirs are quite varied in their geological and engineering characteristics and as such there is no typical or ideal example. Characteristics common to all tight reservoirs include: reservoirs that tend to have large areal extents and consist of interlayered, fine-grained sedimentary rocks, commonly sandstones and mudstones, with low permeabilities; have pore networks that are partially or completed filled with gas; have a large percentage of pores that are not interconnected, or have exceedingly small connections that impede, or block, the flow of gas (low permeability); contain gas that was derived from thermally-mature source rocks, as in conventional gas reservoirs; or will not produce gas unless the permeability of the reservoir is increased through massive stimulation efforts that commonly involve the creation of fractures in the reservoir. While some tight gas reservoirs are found at relatively shallow depths, most are located at substantially greater depths of burial, approaching 15,000 to 20,000 feet in many sedimentary basins (Naik, 2007).

Exploration for tight gas sands differs from conventional reservoirs in that they generally extend over much larger areas and consist of interlayered strata of differing physical properties whose pore networks are saturated or partially saturated with gas. Conventional reservoirs have more limited boundaries, including a down-dip water contact, which is absent from continuous reservoirs (Naik, 2007). The down-dip water contact in conventional reservoirs results from the lower density of oil and gas relative to water. The vast majority of continuous reservoirs are charged with gas rather than crude oil.

Exploration for, and production from, tight reservoirs requires thorough knowledge of the local geology. Important parameters that must be known include the stratigraphic distribution of source rocks and tight reservoirs in a basin, the physical and chemical characteristics of the gas source and reservoir rocks, the textural properties and grain composition of the reservoir rocks, and the fracture density in the reservoir rocks. It is also important to have some understanding of the regional geothermal and pressure gradients in the basin containing the tight reservoirs. Because of the low permeability nature of these reservoirs and the depth range at which they tend be located in sedimentary basins, the cost of developing tight gas reservoirs tends to be higher than conventional gas reservoirs (fig. A6).

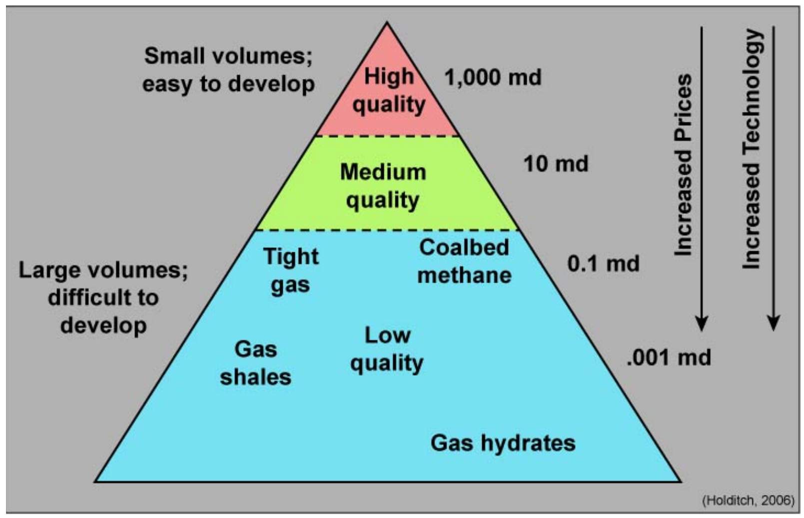

Figure A6. Resource triangle for natural gas (from Holditch, 2006).

Shale Gas

As an unconventional energy resource, shale gas has many similarities to coalbed methane. In fact, it is possible to have both methane-rich shales and coals interbedded in a single reservoir, resulting in production from both lithologies. About 1.0 Tscf (trillion standard cubic feet) of the nation's 2.7 Tscf of unconventional gas production comes from more than 40,000 shale gas wells in five primary basins (Jenkins and Boyer, 2008). Worldwide shale-gas resources are estimated to exceed 16,000 Tscf.

In conventional natural gas reservoirs, the gas has migrated from an organic-rich source rock into pore spaces between sand grains in the reservoir (refer to the section in this chapter on conventional oil and gas for more information). The source rocks are often black, organic-rich shales that have formed in sedimentary deposits given sufficient geologic time (generally millions or more years) and depth of burial. In unconventional shale gas reservoirs, the organic-rich shale is both the source rock and the reservoir. Shale gas can be generated through thermogenic or biogenic processes, and the geologic setting of the basin determines which process is operative. Shale gas source rocks are not as rich in carbon

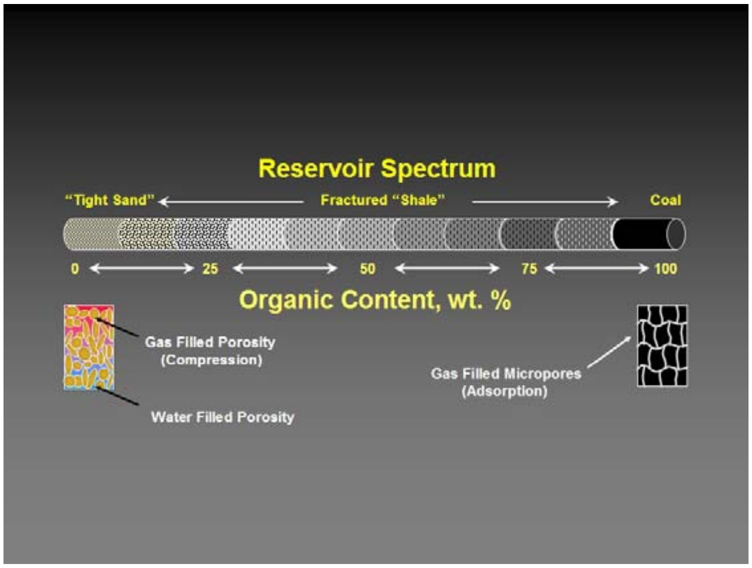

Figure A7. Comparison of organic contents of shales, coals, and tight sands (modified from Hartman, 2008).

as coals, and typically contain less than 50 wt% (weight percent) of organic matter (fig. A7). Once gas is generated in a shale source rock, some of the gas is stored in the rock's pore systems and some becomes attached to the surface of mineral particles comprising the shale in a process referred to as 'adsorption.' The latter gas is said to be adsorbed on the rock matrix. Refer to the sections describing the geologic requirements for exploitable conventional oil and gas, coal, and coalbed methane for more detailed explanations of source rocks, reservoir rocks, adsorption, and the conditions necessary to generate hydrocarbons.

Controls on resource volume and productivity in shale gas systems are similar to those in coalbed methane systems, however, the shale gas reservoirs are typically thicker (30 to 300 feet) and have a much larger volume of free gas in pore space and much lower adsorbed gas content (Jenkins and Boyer, 2008). Whereas coalbed methane reservoirs rely on naturally-occurring orthogonal fracture sets called cleats, shale gas plays have much lower permeabilities than coalbed reservoirs (typically in the nano- to microdarcy range) and rely heavily on induced hydraulic fracturing (stimulation) to connect natural fractures to the wellbore to become gas producers. While both tight gas and shale gas reservoirs may require 'fracking' to maximize production, due to the extremely low natural permeabilities of shales, a special type of fracking suitable for shales is required. A technique called 'slick-water frac' results in maximizing the horizontal length of fractures and minimizes the vertical fracture height, allowing for much greater gas recovery from shales (Harper, 2008).

As in most coalbed reservoirs, some shale-gas reservoirs are water-saturated, and require dewatering to initiate the flow of gas. As this water is produced from the natural and enhanced fracture system, the reservoir pressure declines, gas desorbs from the mineral matrix, and gas production increases. Shale gas production is similar to conventional gas reservoirs, with peak initial rates of production and slow decline thereafter as gas desorption replenishes the fracture system. As with coalbed methane, produced water must be disposed, and in Alaska's high-latitude setting this poses significant challenges.

Because shales ordinarily have insufficient permeability to allow significant fluid flow to a well bore, most shales are not commercial sources of natural gas in their natural state. Because of the low matrix permeability in shales, gas production in commercial quantities requires fractures to increase permeability. Shale gas has been produced for years from shales with natural fractures; the shale gas boom in recent years has resulted from modern technology in hydraulic fracturing to create extensive artificial fractures around well bores.

In summary, shale gas reservoirs are geologically complex and because of their very low permeability (typically <0.1 md) these reservoirs require special techniques for evaluation and extraction. Thus, as in coalbed methane and tight gas reservoirs, detailed understanding of the geology of potential shale gas resource is essential.

Gas Hydrate

According to the U.S. Geological Survey, a gas hydrate is a naturally-occurring, ice-like solid in which water molecules trap gas molecules in a cage-like structure known as a 'clathrate' (fig. A8). A gas hydrate or clathrate is similar to ice, except that the crystalline structure is stabilized by the guest gas molecule in the cage of water molecules. Gas hydrates occur under a very limited range of temperature and pressure conditions, such as in the permafrost environments of the arctic, including northern Alaska. They also occur in deep marine environments at water depths greater than 400 or 500 meters (~1,300 to 1,640 feet), along most continental margins. In these environments (arctic and deep ocean) gas hydrates occur naturally where pressure, temperature, gas saturation, and local chemical conditions combine to make them stable. Before gas hydrates can form, there must be a source for gas molecules. Potential sources include sedimentary rocks that are rich in carbon, such as some black shales, limestones, and coal. Peat is a precursor to coal and can also generate gas under the right conditions. Refer to the summary of the geologic requirements for conventional oil and gas, coal, and coalbed methane for more detailed explanations on the origins of gas.

Gas hydrates are currently considered to be a potentially vast, unconventional energy resource with the possibility

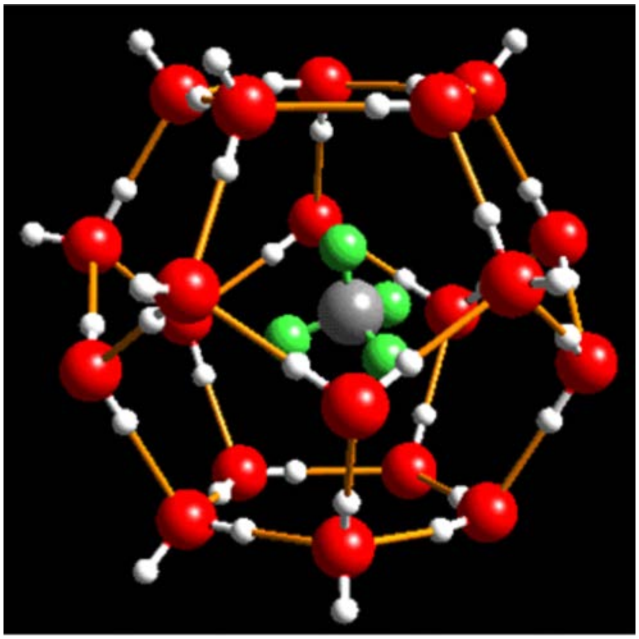

Figure A8. Gas hydrate or clathrate molecule, which consists of a methane molecule (gray and green) surrounded by a cage-like structure of ice (red and white). From Centre for Gas Hydrate Research: http://peggy.uni-mki.gwdg.de/docs/kuhs/clathrate_hydrates.html

for viable production sometime in the future. However, gas hydrates present both scientific and technological challenges in turning them from non-producible accumulations of gas to a useable resource (Collett, 2004). Gas production from hydrates is challenging because the gas is in a solid form, and because hydrates are widely dispersed in hostile Arctic and deep marine environments. Methods proposed for gas recovery from hydrates typically deal with disassociating or "melting" in-situ gas hydrates, by heating the reservoir beyond the temperature of hydrate formation or decreasing the reservoir pressure below hydrate equilibrium. "Depressurization is considered to be the most economically promising method for the production of natural gas from gas hydrates. The Messoyakha gas field in northern Russia is commonly used as an example of a hydrocarbon accumulation from which gas has been produced from hydrates by simple reservoir depressurization. The field was developed for conventional gas, and scientists have long thought that the sustained gas production was because of the contribution of gas from gas hydrate into an underlying free-gas accumulation" (Collett, 2004). Experimental gas production rates reported from recent gas hydrate testing at the Canadian Mallik site compare favorably with the modeled production rates predicted for the gas hydrate occurrences in northern Alaska (Anderson and others, 2008).

In 1995, the USGS conducted an assessment of the gas hydrates in the United States and Alaska (Collett, 1995) and in 2008 they released an assessment of undiscovered, technically recoverable gas hydrate resources beneath the North Slope of Alaska (Collett and others, 2008; Lee and others, 2008). The factors controlling gas hydrate formation, mostly a function of formation temperature and pressure, were assessed to map the spatial distribution of the gas hydrate stability zone in northern Alaska. Only gas hydrates lying below the permafrost interval were assessed, limiting the assessment to the stratigraphic interval below the base of the permafrost and above the base of the gas hydrate stability zone. The USGS estimates that the total undiscovered natural gas resources in gas hydrate range between 25.2 and 157.8 trillion cubic feet (TCF; 95 percent and 5 percent probabilities of greater than these amounts, respectively), with a mean estimate of 85.4 TCF (Collett and others, 2008). Outside of the North Slope region, there are likely no onshore gas hydrates in Alaska.

Underground Coal Gasification

Underground coal gasification (UCG) is a technology that utilizes the *in situ* burning of deep, unmineable coal seams to generate a synthetic gas (syngas) mixture. The combustion of coal seams at depth involves the introduction of water (preferably steam) and oxygen from the surface through an injection well. The syngas is a mixture of hydrogen (H_2), nitrogen (N_2), methane (CH_4), carbon monoxide (CO), and carbon dioxide (CO_2) that is brought to the surface through a production well and used to generate electricity in gas turbines at an electrical power plant (Burton and others, 2007) (fig. A9). The basic reaction to create syngas is $C + H_2O + heat \rightarrow CO + H_2$. The syngas can also be converted into a variety of hydrocarbons, such as diesel fuel, naphtha, and methane using the Fischer-Tropsch process.

The technology to generate syngas from coal has existed for more than a century, and the Yerostigaz plant in Angren, Uzbekistan has been generating 100 megawatts of electricity annually since 1957 using UCG methods. Currently, a number of experimental UCG plants have been constructed and several more are in the planning stages worldwide. The Cook Inlet region of Alaska is being evaluated for UCG potential.

The coal used in the UCG process can be lignite, subbituminous, or bituminous, and coal seams should be at least 10 feet thick. The life of the reaction chamber used for coal combustion increases with coal seam thickness. This reaction chamber cavity should be well below the water table, deeper than 500 feet—depths greater than 1,000 feet are preferred. Additionally, the surrounding rock strata should provide isolation from any aquifers that might be used as domestic water supplies. Strata above and below the coal seam should be structurally competent, and have low permeability.

Underground gasification of coal eliminates the need to mine and transport the coal to a power plant, as well as the costs associated with reclaiming the surface-mined coal areas. Additionally, the ash produced by conventional burning is

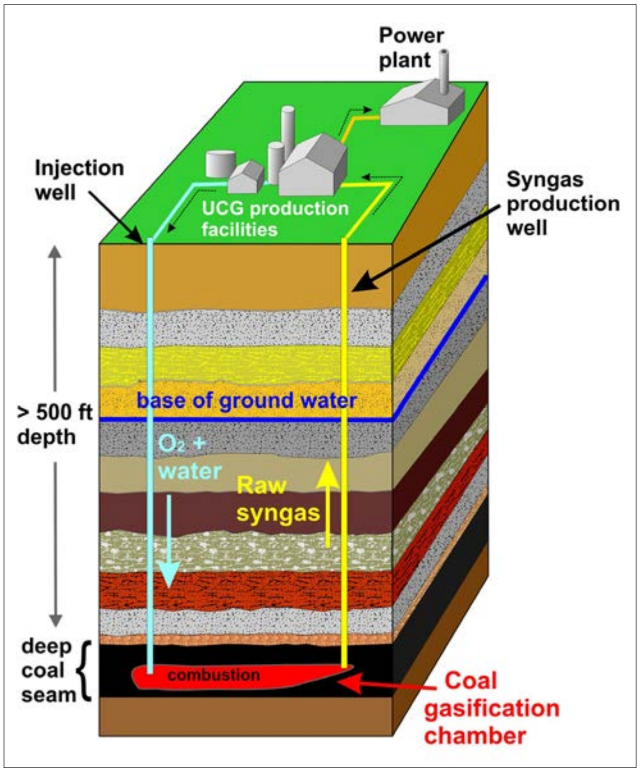

Figure A9. Conceptual model for underground coal gasification of deep, unmineable coal seams. Based on Swan Hills Synfuels in-situ coal gasification diagram, http://swanhills-synfuels.com

left in the ground and most of the heavy metals associated with the ash, such as mercury, arsenic, or lead, also stay in the ground. Many other undesirable reaction products, such as sulfur dioxide (SO_2) and nitrous oxide (NO_x) are greatly reduced as well. The process of UCG can also be coupled with carbon capture and storage technology to reduce CO_2 emissions. The advantages of using deep, unmineable coal seams are that they are less likely to be linked with near-surface potable aquifers, thus avoiding drinkable water contamination and ground subsidence problems.

The underground coal gasification process creates a variety of engineering, data-gathering, monitoring, and environmental challenges. Among the engineering problems, developing effective dispersal of oxygen and combustion within the coal seam, and creating an effective connection between the combustion zone and the production wells can be major challenges. Supplying the right amount of oxygen to maintain optimal combustion and reaction activity, and to keep the reactor chamber at the desired temperature and pressure, can also be problematic. Continuous monitoring of aquifers for the potential for groundwater contamination is also necessary. Additionally, there exists the potential for surface subsidence due to collapse of the subsurface combustion chamber.

GEOLOGIC REQUIREMENTS FOR A GEOTHERMAL ENERGY RESOURCE

by Christopher J. Nye

Geothermal is a general term describing the heat generated and contained within the earth. Although more than 90 percent of the total volume of the earth is warmer than 1,000°F (540°C), only a small amount of this potential energy makes it close enough to the earth's surface to be utilized by conventional technology and considered an energy resource. When it does, the elevated heat manifests itself in a number of uncommon geologic occurrences such as lava flows and volcanic eruptions, steam vents or geysers, hot springs, or merely elevated geothermal gradients creating hot rock. In normal geologic situations the majority of the heat simply slowly dissipates into the atmosphere from forests, prairies, and backyards in an unseen process known as 'conduction.' At the surface of the earth, heat can also be gained from the sun during daylight hours, and especially during the summer months, to depths as great as 100 feet. When ground source heat pumps, which utilize pipes laid out a few feet below the surface, are used installed for heating or cooling buildings, the process can use either solar or geothermal energy. Below a depth of a several tens of feet any heat recovered from the earth will usually be geothermal in origin. Geothermal heat comes from two main sources—the original heat of the earth generated at its formation about 4.5 billion years ago, and more recent decay of the radioactive isotopes of potassium, uranium, and thorium.

Geothermal resources are found on all continents and have been used for a wide variety of purposes. For large-scale (measured in megawatts or millions of watts) electrical power generation, temperatures from about 300°F (150°C) to as high as 650°F (340°C) are typically needed. In Alaska, however, with its cold climate and abundant cold water resources, it is possible to exploit much lower geothermal temperatures for small-scale electrical power generation. In fact, at Chena Hot Springs Resort near Fairbanks, 500 gallons per minute of water with a temperature of 163°F (72.8°C) is currently making around 200 kW (kilowatts) of electricity, which is the amount of electricity used by a village of about 300 residents. The combination of high flow rates of hot water and low surface water temperatures available at Chena allow it to be the lowest-temperature geothermal power plant in the world.

For geothermal energy to be technically and economically feasible a number of conditions must be met. These include: (1) an anomalous thermal gradient or accessible heat in a near-surface region, (2) sufficient porosity and permeability within the section of 'hot rock' so fluids can move freely and transfer heat, and (3) some form of conduit that allows a hot fluid to flow to the surface in sufficient quantities where the energy is converted into a usable form. Clearly, the higher the near-surface temperature, and higher the permeability and flow rates, the more feasible the resource becomes.

Unfortunately, out of the thousands of natural springs in Alaska, only a very few have sufficient temperature and flow rates needed to produce enough electricity to export power from the plant. In some limited cases where high near-surface heat exists, these fluid flow and heat transfer systems can be enhanced by drilling and fracture technology if the geologic conditions are right.

Most of the Earth is not near volcanoes or close to major active faults and therefore lacks open space or fractures that can heat fluids, which are necessary for a shallow geothermal system. In these areas enhanced systems must be created. However, the geothermal industry has long known that developable heat exists within drillable depths in most areas of the globe, yet a technically feasible way to transfer that heat to the surface in economic quantities has been very elusive. If this methodology can be developed, it has the potential to access a tremendous energy resource. One interesting development in this research effort is the use of techniques devised by the oil and gas industry to fracture rocks far below the surface by pumping huge volumes of fluid at very high pressure into the deep strata. The theory contends that once the rocks are broken and permeability established, it is possible to pump cold water down one hole into hot rocks and recover it from a second hole thousands of feet away.

If a sufficient network of interconnected fractures can be created at great depths, and hydraulic connection can be established between distant well bores, the water will ‘mine’ heat from the fracture surfaces between the two holes and become hot enough for direct use and/or electrical power generation. For these types of “enhanced geothermal systems” (EGS) to work, a number of geologic and physical attributes must be present, including brittle stratigraphy and an existing stress regime that is conducive to fracture propagation of sufficient length and orientation.

There has been a wide variance in outcomes from pilot EGS programs, often related to the wide variability of sub-surface geology. Despite many failures, there are some promising experiments underway in France, Germany, and Austria where six small projects are generating between 0.25 and 3.5 megawatts of electrical power from wells between 7,000 and 16,000 feet deep and at temperatures from 206°F (97°C) to 250°F (121°C). A major challenge for any low-temperature application is whether there is enough power generated to run all of the equipment and pumps used in the operation and send the excess offsite. After the power is generated, additional heat is removed from the water for space heating as a part of some of the projects. These European projects have all been expensive, government-supported research projects to date and have taken many years to develop; but with this experience in hand, plans have recently been announced for more than 100 future projects in Germany alone, with outputs as high as 8.5 megawatts for individual projects. In Australia, numerous press releases are touting much higher potential electrical outputs, but no projects are yet on line. Development of enhanced geothermal systems will continue to be a mostly experimental program for the next several years, but bears close scrutiny because there may come a time when it could be used in Alaska where local geologic conditions are favorable.

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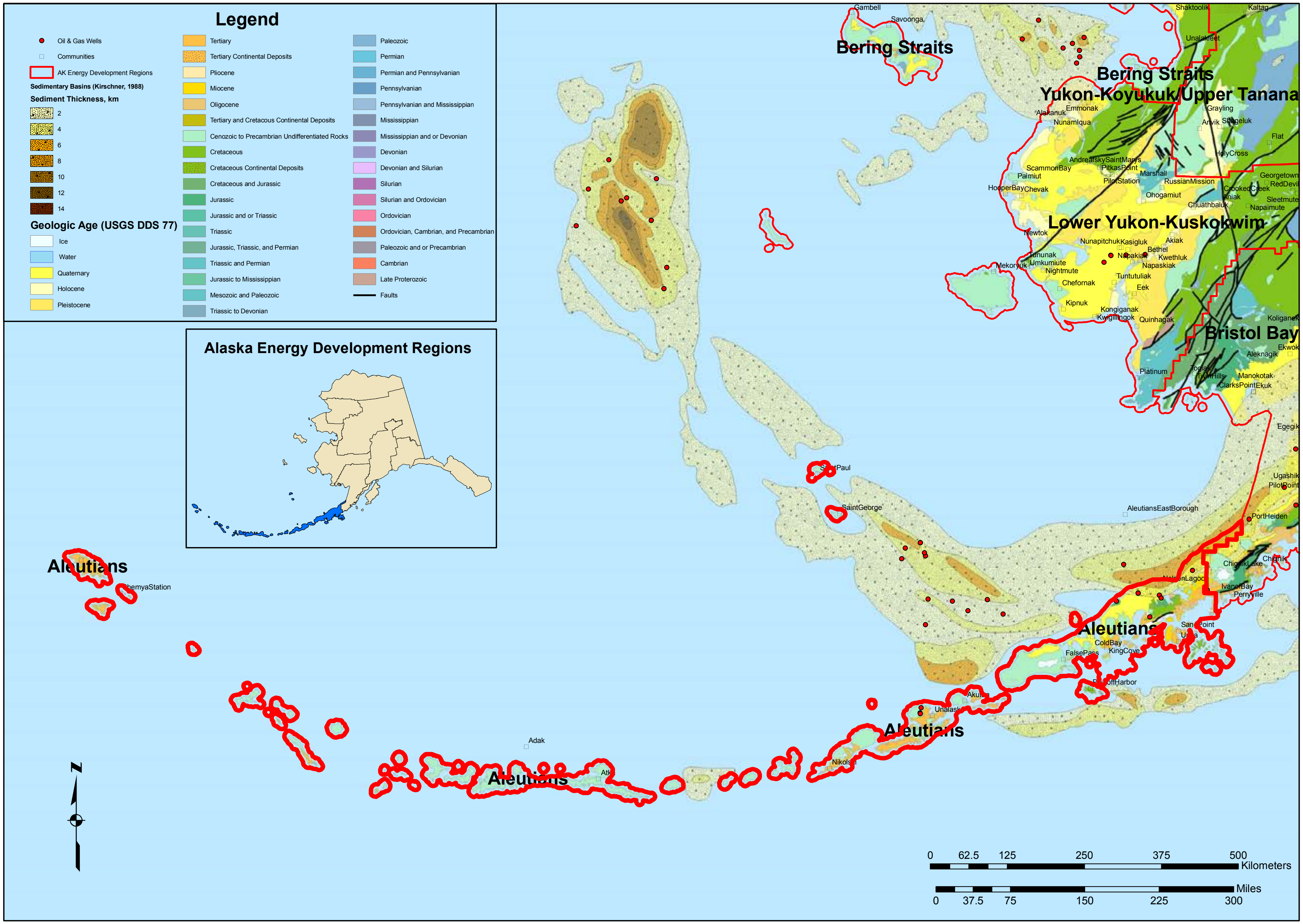
Geology of the Aleutians Energy Region, Alaska



Aleutians

SUMMARY OF FOSSIL FUEL AND GEOTHERMAL RESOURCE POTENTIAL IN THE ALEUTIANS ENERGY REGION

by Paul L. Decker, Robert J. Gillis, Ken Helmold, and Shaun Peterson

INTRODUCTION

Purpose of this report

Economic growth and stability in Alaska's rural and urban areas hinges partially, if not primarily, on the availability of affordable and sustainable energy supplies. Recent price increases in oil and gas commodities have created severe economic hardship in many areas of the state that are dependent on diesel and heating oil as their primary source of energy. All sectors of Alaska's economy rely on affordable energy sources with limited pricing volatility, highlighting the need to diversify the energy portfolio by developing locally available and sustainable resources that are not tied to the global market. Unfortunately, all areas are not created equal in energy accessibility; the resources available for local exploitation vary widely across the state. It is critical that funding decisions for expensive programs to reduce the dependence on diesel for heat and electricity take into account information concerning the entire suite of natural resources that exist in a given area.

This report draws from existing information to provide community and state leaders an objective summary of our current knowledge concerning the potential of locally exploitable fossil fuel and geothermal energy resources in the Aleutians energy region (fig. B1), one of 11 regions recognized by the Alaska Energy Authority in their Energy Plan (AEA, 2009). The potential geologically hosted energy resources considered here include exploitable coal, conventional and unconventional oil and gas, and geothermal resources. This report concludes with recommendations as to what additional data or strategies, if any, would provide the most leveraging in helping to develop new energy resources in the region.

Readers without geological training are encouraged to peruse the geologic summaries of fossil fuel resources and geothermal energy in Chapter A. They provide an overview of the geologic elements that must be present in an area to economically develop coal, conventional oil and gas, unconventional oil and gas, and geothermal resources. These summaries will provide the necessary background to more fully understand the information presented in this chapter.

Geographic and geologic setting

The Aleutians Energy Development Region extends more than 1,350 miles, including all of the Aleutian Island chain and the southwesternmost Alaska Peninsula to approximately Mt. Veniaminof (fig. 1 and sheet 2). A thin strip along the western coast extends farther northeastward to southwest of Port Heiden. Also included are the remote Pribilof Islands to the north, located more than 200 miles from other land areas, near the middle of the Bering Sea. Energy resources in this region, with the exception of geothermal, are limited to the vicinity of the southwestern tip of the Alaska Peninsula and 3 miles northwest of the coast into the adjacent Bristol Bay. Villages in the Aleutian Development Region range in population from more than 4,000 to only 20 persons;

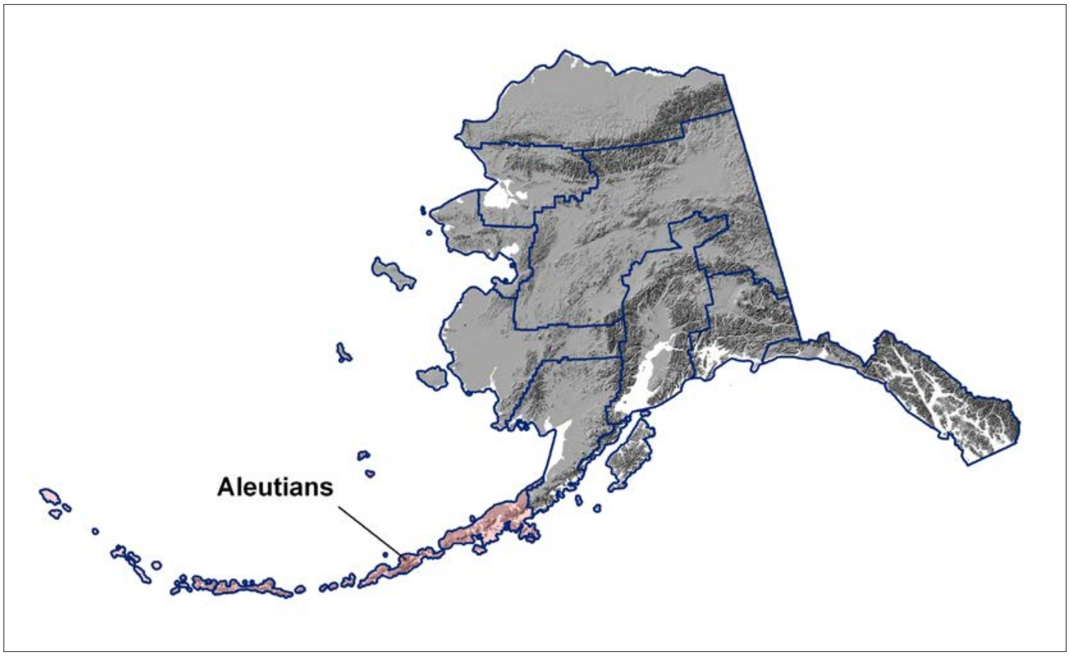


Figure B1. Location map of Aleutians Energy Region.

Aleutians

all reside at tidewater and are only accessible by boat or plane. The largest village is Unalaska with a population of about 4,300. Villages with populations of about 1,000 to 500, in descending order, include Sand Point, King Cove, Akutan, and Saint Paul (in Bristol Bay). Villages with populations of about 300 to 100 include Adak and Saint George (in Bristol Bay). The villages of Atka, Cold Bay, Nelson Lagoon, False Pass, and Nikolski have populations of about 100 or less, with Attu Station near the tip of the Aleutian chain being the smallest at 20 persons.

The geography of the region consists of a diverse mix of volcanic islands, lowland topography, rugged hills, and conical glaciated mountains that rise abruptly from the landscape. Islands of the Aleutian chain are volcanic in origin and extend westward from the southwestern tip of the Alaska Peninsula over 1,000 miles into the North Pacific Ocean. The islands can be elongate, conical, or irregularly shaped and vary in size from 1 mile to tens of miles wide and many more in length. Each island can have any combination of low relief, rugged hills, or peaks up to 9,000 feet or more. The southwestern end of the Alaska Peninsula includes glacially-sculpted lowlands on the northwestern side that support numerous freshwater lakes. The Aleutian Range on the southeastern side of the peninsula is characterized by rolling hills and rugged low mountains composed of commonly tilted Cenozoic age volcanic rocks and folded and faulted Mesozoic age through Cenozoic age sedimentary strata. The boundary between the geographically distinct sides of the peninsula is punctuated by a few tall, conical, volcanic edifices such as Mount Veniaminof and Pavlof Volcano.

Most of the Aleutians Development Region is the product of millions of years of accumulation of volcanic flows and detritus above a subduction zone where the oceanic Pacific plate is currently being thrust toward the northwest beneath the North American plate. Magma generated at this plate boundary has intruded oceanic crust of the overriding North American plate, resulting in an arcuate array of volcanoes referred to as a volcanic island arc. Where these intrusions occur in North American plate continental crust along the Alaskan Peninsula, they form a continental volcanic arc. Major episodes of arc volcanism have occurred at least three times on the Alaska Peninsula over the past 200 million years (Reed and Lanphere, 1969; Wilson, 1985; Amato and others, 2007). The most recent volcanism along the Aleutian chain was initiated about 35 million years ago (Wilson, 1981), and continues to be the dominant geologic process shaping the Aleutians Development Region today. Rocks exposed on the Aleutian Islands consist mostly of igneous and associated sedimentary rocks younger than about 40–45 million years. These rocks formed after major plate tectonic changes in the North Pacific that led to the creation of the present-day Aleutian subduction zone (Worrall, 1991). In contrast, on the Alaska Peninsula and along a belt stretching northwest beneath the Bering Sea toward the Pribilof Islands, bedrock includes much older Mesozoic sedimentary units as well as the younger Cenozoic sedimentary rocks deposited in a collection of basins positioned north of the volcanic arc. The largest and deepest of these are the North Aleutian and Saint George basins in the Bristol Bay area. The Umnak, Amak Plateau, and Sanak basins are shallower or more restricted offshore sedimentary basins in the area east of Unalaska.

Very little is known about the pre-Mesozoic geologic evolution of the Alaska Peninsula area. However, very thick sequences of Mesozoic strata record the development of a major sedimentary basin. These sediments were largely derived from erosion of a nearby igneous arc and include organic-rich rocks that are important components of the petroleum system in the adjacent Bristol Bay and Cook Inlet basins (Detterman and Hartsock, 1966; Decker and others, 2008). Subsequent cycles of tectonic subsidence and uplift since Late Cretaceous time are responsible for the coal-bearing rocks in the northwestern area of the development region (Detterman and others, 1996), as well as many of the petroleum reservoir rocks in the adjacent petroleum basins (Calderwood and Fackler, 1972; Detterman and others, 1996; Helmold and others, 2008). Faulting and folding associated with these tectonic processes during Cenozoic time are responsible for generating most of the hydrocarbon traps for these petroleum systems and conduits for hot fluids in geothermal systems. However, this same deformation adds a component of risk to the area's energy potential by introducing faults and fractures that may breach hydrocarbon traps or partition formerly continuous coal fields.

GEOLOGIC ENERGY RESOURCE POTENTIAL IN THE ALEUTIANS ENERGY REGION

Mineable coal resource potential

Aleutians Development Region. Coal resources and occurrences exist only on the southern Alaska Peninsula portion of the development region, and are not found on the Aleutian Islands. Coal-bearing rocks near tidewater extend from Pavlof Bay northeastward approximately 200 miles to the Dog Salmon River (Conwell and Triplehorn, 1978) in the Bristol Bay Development Region. However, much of the intervening area is covered by younger volcanic rocks and Quaternary glacial deposits that obscure the coal-bearing strata. The two main southern peninsula regions with coal exposures are the Herendeen Bay Field, near Herendeen Bay, and Unga Island Field, on Unga Island (fig. B2). Villages within 100 miles of these coal locations include Port Heiden, Nelson Lagoon, Sand Point, King Cove, Cold Bay, and False Pass.

Herendeen Bay Field. The Herendeen Bay field is near the southwestern tip of the Alaska Peninsula (fig. B2). Coal in the field is derived primarily from the Coal Valley Member of the Upper Cretaceous Chignik Formation, with minor occurrences in the middle to upper Miocene Bear

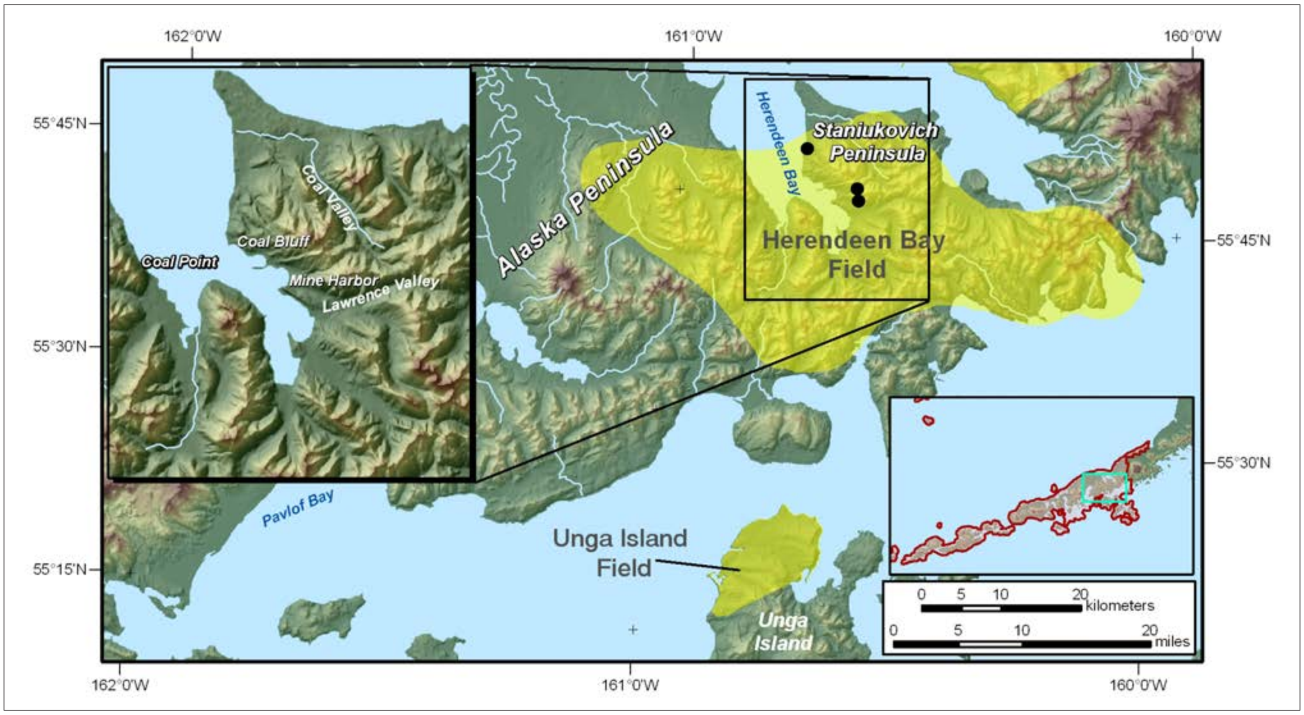


Figure B2. Location map of the eastern Aleutians Energy Region showing selected geographic references noted in the text (note inset detailed map of Staniukovich Peninsula). Black dots indicate reported coal occurrences; yellow-shaded areas inferred to be underlain by coal-bearing rocks.

Lake Formation in the vicinity of Bear Lake. Coal-bearing strata of the Chignik Formation occupy at least 130 square kilometers, with principal exposures at Mine Creek (Mine Harbor area), Coal Bluff, Coal Valley and east of Coal Valley, Lawrence Valley, and Coal Point (Merritt, 1986a; Merritt and McGee, 1986). In the area of Coal Point, coals are discontinuously exposed along the beach for 6.5 kilometers (Merritt and McGee, 1986. The coal has a high-volatile bituminous B rank and high ash content (Merritt, 1986a; Merritt and McGee, 1986). Heating values of about 12,000 Btu/lb can be achieved after washing the coal (Conwell and Triplehorn, 1978). Fifteen coalbeds have been identified in the lower Chignik Formation at these locations with typical thicknesses of 2 feet or less (Atwood, 1911). However, bed thicknesses vary considerably over short lateral distances (Merritt and McGee, 1986) and one report indicated a coal unit up to 10 feet thick (Paige, 1906). Merritt and McGee (1986) estimate total coal resources in the Herendeen Bay field to be about 138 million short tons (125 million metric tons). Chignik Formation strata in the area, primarily on the Staniukovich Peninsula due east of Herendeen Bay, are commonly displaced by faults with several meters to 300 meters of offset (Merritt and McGee, 1986). This is especially true for the area due east of Coal Bluff, where faulting is particularly common (Decker and others, 2008). Such structural complexities disrupt the continuity of coalbeds and can hamper their extraction. Coal studies in this area have consisted of field work in the 1980s that included measured stratigraphic sections and coal quality analyses (Merritt and McGee, 1986). Additional work involving geologic field mapping accompanied by stratigraphic and coal quality studies and exploratory drilling are required to better define the reserves in this area. Merritt (1987) mentions that exploratory drilling for coal has been performed in the Herendeen Bay field and/or Unga Island field in the past, but provides no further details, and no additional information has been uncovered for this report. Although not a particularly large coal reserve as currently understood, the relatively high heating value of its coal and proximity to tidewater may make the Herendeen Bay field, along with the Chignik field in the Bristol Bay development region to the northeast, an attractive target for future study. However, the Herendeen Bay field is part of the Pavlof Unit of the Alaska Peninsula National Wildlife Preserve and surface access for further geologic investigations and potential exploitation of the resource would need to be researched carefully.

Unga Island field. The Unga Island coal field is located on Unga Island, the largest of the Shumagin Islands, about 3.5 miles off the northwestern coast of the Alaska Peninsula near Pavlof Bay and approximately 265 miles southwest of Kodiak Island (fig. B2). Coals in the Unga Island field are derived from the lower to middle Miocene Unga Conglomerate unit. Most are of low rank, yielding relatively low heating values. The coals are typically lignite, but include less abundant beds of subbituminous C coal. Limited analyses reveal that the coal is commonly low in ash and sulfur, with heating values between 8,486 and 12,120 Btu/lb. Bed thicknesses are no greater than 3 feet, and are often less (Merritt, 1986b). Furthermore, the thicker beds often have non-coal partings that detract from their economic value. Merritt (1986b) estimates 90 million short tons of inferred coal in beds more than 1 foot thick, and 70 million short tons in beds more than 1.6 feet thick—values that are consistent with a previous estimate of 150 million short tons of hypothetical reserves (Alaska Division of Energy and Power Development, 1977). In 1977, the Alaska Division of Energy and Power Development listed the Unga Island coal field as not a significant economic energy resource, but rather possibly best suited for local use only. Merritt (1986b) later reported that the Unga Island field coals had a low economic development potential based on his findings of mostly thin coalbeds in the area, their low ranking, and extraction technology at the time.

Conventional oil and gas resource potential

As explained in the discussion of requirements for exploitable oil and gas resources (Chapter A), functioning petroleum systems occur in thick sedimentary basins, and require three basic elements: Effective source rocks, reservoirs, and traps. Each of the elements must be in existence and connected at the time hydrocarbons are generated and migrated. This section provides an overview of the various basins in the Aleutians region and then considers each of the necessary elements of petroleum systems in turn to evaluate the role conventional oil and gas resources may play in supplying rural energy to the region.

Overview of sedimentary basins. Sheet 1 shows the distribution of sedimentary basins (after Kirschner, 1988) that could potentially host petroleum systems in the Aleutians region. The North Aleutian, Amak, Umnak Plateau, St. George, and Sanak basins developed mostly in offshore areas of the northeastern part of the region during Tertiary time. There is very little evidence for thick sedimentary basins on or near the Aleutian volcanic arc west of Unalaska. Hence, the following discussion of petroleum systems elements applies only to the easternmost Aleutian Islands, southwestern Alaska Peninsula, and the Pribilof Islands. The greatest potential for exploration and development of conventional hydrocarbon resources in the region is in the North Aleutian basin on and just offshore from the southwestern Alaska Peninsula (sheet 1).

Source rocks. Outcrop studies have documented oil-prone source rocks in the Upper Triassic Kamishak Formation and the Middle Jurassic Kialagvik Formation, but these units are likely to be present only in certain areas of the Aleutians energy region (McLean, 1977, 1979; Comer and others, 1987; Wang and others, 1988; Sherwood and others, 2006; Decker, 2008). They have generated both oil and gas found in natural seeps near their limited outcrop area, located in federally protected lands near Puale Bay and Wide Bay on the southeastern side of the Alaska Peninsula in the Bristol Bay and Kodiak energy regions (Magoon and Anders, 1992). These oil source rocks, or their age equivalents, are probably present in the subsurface of the easternmost part of the Aleutians energy region on the southwestern Alaska Peninsula. The Cathedral River Unit #1 well drilled northeast of Cold Bay encountered possible oil-prone shales in the Kialagvik Formation, but the presence of oil-based drilling additives in the well raises questions about the reliability of the source rock data from the well (Sherwood and others, 2006). No other wells on the southwestern Alaska Peninsula drilled deep enough to penetrate the Kialagvik and Kamishak Formations or their equivalents, but vitrinite reflectance and burial histories indicate these potential sources long ago reached a thermal maturity level too high for oil production, and are now candidates for gas generation (Molenaar, 1996). Upper Jurassic units were penetrated at the bottom of several wells in the St. George basin, suggesting the likely presence of the Middle Jurassic to Late Triassic source rocks or their equivalents at somewhat greater depth. However, no evidence for Mesozoic-sourced oil or gas has been found in overlying Tertiary strata and effective generation of hydrocarbons from these sources in the St. George basin remains unproven (Sherwood and others, 2006).

Gas-prone sources are more widespread in the sedimentary basins of the Aleutian region, consisting of both shallow marine shales and non-marine coaly strata of Tertiary age (McLean, 1987 Sherwood and others, 2006; Decker, 2008). Both biogenic and thermogenic gas may be present in some parts of the region's sedimentary basins. However, as stated in the discussion of requirements for exploitable resources of conventional oil and gas (see Chapter A), viable accumulations of biogenic gas are unlikely except where recent uplift may have occurred along the southern edge of the North Aleutian basin on the northwest side of the Alaska Peninsula.

The most promising area for thermogenic gas charge appears to be near the southern margin of the North Aleutian basin offshore from Nelson Lagoon and Port Moller. Here, the basin reaches depths consistent with thermogenic hydrocarbon generation (Sherwood and others, 2006; Decker and others, 2005; Decker, 2008). This observation helps explain patterns of nearby oil and gas leasing and the industry's advocacy to allow exploration drilling in adjacent federal waters (Anchorage Daily News, 2005; Shell Exploration and Production, 2008). The deeper parts of the St. George, Amak, and Umnak Plateau basins also have some potential for thermogenic generation from gas-prone Tertiary source rocks (Comer and others, 1987; Sherwood and others, 2006). However, none of the 12 wells that tested the St. George basin encountered any hydrocarbon accumulations (Sherwood and others, 2006). This represents a non-specific failure of the petroleum system that could stem from a variety of causes: Insufficient source rock quantity or quality; problems relating to migration paths; leaky traps or seals; or the timing of trap formation. The Amak, Sanak, and Umnak Plateau basins remain undrilled and are poorly understood. Many of the attributes of these remote basins challenge the viability of possible gas exploration.

Reservoir rocks. Several Tertiary formations likely have adequate thickness of sandstone with sufficient porosity and permeability to serve as reservoirs for either oil or gas. In the North Aleutian basin in particular, much of the Miocene Bear Lake Formation has been widely observed to maintain reservoir quality in outcrop and in wells that encountered it at depth (McLean, 1987; Turner and others, 1988; Sherwood and others, 2006; Decker and others, 2005, 2006). Younger strata also maintain high porosity and permeability, but are too shallow to host effective traps or maintain sufficient reservoir pressure. Alteration of the sandstone after burial has locally degraded the reservoir quality in most formations (Lyle and others, 1979; Turner and others, 1988; Helmold and others, 2008) and should be considered as one component of the overall exploration risk.

Mesozoic formations of the southwestern Alaska Peninsula contain thick sandstones and some limestones that could serve as hydrocarbon reservoirs. Reservoir quality data for these units is limited to select outcrop samples from the Alaska Peninsula that dominantly record porosity values of less than 10 percent and permeabilities typically below 0.10 md (Reifenstuhl and others, 2005; Strauch and others, 2006). Although these data indicate suboptimal reservoir quality in the Mesozoic, the sample set is small, limited to surface samples, and excludes potentially more promising parts of the Jurassic section (Reifenstuhl and others, 2005). In special cases, early entrapment of hydrocarbons can prevent porosity destruction in sandstone reservoirs, and hydrothermal alteration can create secondary porosity in limestone formations. Nevertheless, the presence of clays and other altered grains suggests that encountering reservoir-quality rock in the Mesozoic strata will be a primary challenge to exploration in the region.

Traps. The southwestern Alaska Peninsula and adjacent Tertiary basins have undergone several episodes of deformation related largely to strike-slip processes during Tertiary time (Worrall, 1991; Detterman and others, 1996; Decker and others, 2005). Potential structural traps vary from simple anticlines to structurally complex folds and faults that may create traps for hydrocarbons in the subsurface (Sherwood and others, 2006; Decker and others, 2008). Stratigraphic and unconformity trap configurations are likely to have developed on the flanks of large uplifts such as the Black Hills uplift (Worrall, 1991). Low-permeability silty mudstones capable of sealing hydrocarbons accumulated in traps have recently been documented in several formations on the Alaska Peninsula (Bolger and Reifenstuhl, 2008), but their lateral extent may be limited by restricted nonmarine to marginal marine depositional environments. Although there are likely many trapping geometries developed in the structures of the area, repeated folding and faulting present an exploration risk because trap integrity can sometimes be compromised by leaky faults, fractures, or inadequate seals. An onshore trapped accumulation of hydrocarbons would be most amenable to development for local rural energy markets. However, further evaluation and definition of possible onshore traps would require the collection of significant additional seismic data over large areas where the bedrock of interest is covered by surficial deposits.

Summary of conventional oil and gas resource potential. Sedimentary basins capable of hosting conventional petroleum resources are present only in the eastern part of the Aleutian energy region. Effective source rocks, reservoir rocks, and untested traps are known or likely to be present in different areas of these sedimentary basins. Because these elements of the petroleum system have not yet been proven to coexist and interact to form exploitable accumulations of either oil or gas, the region remains only lightly explored. Based on existing information, the most likely useable conventional hydrocarbon resource is gas derived from coaly Tertiary source rocks, forming accumulations in Tertiary sandstones in structural or stratigraphic traps in offshore or nearshore areas of the southern North Aleutian basin along the northwest side of the Alaska Peninsula.

Unconventional oil and gas resource potential

Coalbed methane. In the Aleutians energy region, coal resources are only present on the southern Alaska Peninsula. The Herendeen Bay coal field, near the southwestern tip of the Alaska Peninsula, is the largest field in the region (fig. B2). The coal has a high-volatile bituminous B rank but is restricted to beds with thicknesses of 2 feet or less (Atwood, 1911). As such, they may be too thin and too discontinuous to produce sufficient coalbed methane to support development. Nevertheless, the geology of the area is complex and has not been extensively explored; reports of rapid lateral changes in coal thickness (Merritt, 1986a) allow for the possibility of thicker coal seams in the subsurface that might house a potential methane resource. Drilling logs of oil and gas exploration wells have noted high gas kicks on subsurface coal seams up to 20 feet thick on the Alaska Peninsula (Tyler and others, 2000). The Herendeen Bay coal occurrences are in the Pavlof Unit of the Alaska Peninsula National Wildlife Preserve, and any future exploration or development may be severely limited or prohibited because of that designation. Additional coals are present in the Unga Island coal field on Unga Island (fig. B2). They are mostly of low rank (lignite and less abundant beds of subbituminous C) with bed thicknesses no greater than 3 feet (Merritt, 1986b). The low thermal maturity of these coals combined with their limited thickness suggests they would be ineffective for coalbed methane development.

Tight gas sands. As noted above, several Tertiary formations have adequate thickness of sandstone with sufficient porosity and permeability to serve as conventional reservoirs for oil and gas. These sands typically have porosities in excess of 20 percent and permeabilities greater than 10 md (Helmold and others, 2008); the result is that reservoir quality is not sufficiently degraded for these sands to be considered tight gas sands.

Many of the Mesozoic sandstones in the Aleutian region, in particular the Staniukovich and Naknek Formations, have been relatively deeply buried and have undergone significant compaction and cementation. Porosities are typically less than 10 percent and permeabilities less than 0.1 md are routinely recorded (Reifenstuhl and others, 2005; Strauch and others, 2006). These older, more lithified sandstones have potential as tight gas sands, particularly those subjected to brittle fracturing in addition to burial diagenesis. Extensive regional fractures have been observed in outcrops of some of the Mesozoic sandstones, particularly the Naknek Formation. These fractures are typical of tight gas sands and may well signal the presence of an unconventional, fractured reservoir. Additionally, these Mesozoic sandstones overlie several candidate hydrocarbon source rocks that could provide the necessary charge to fill a tight reservoir.

Shale gas. One of the primary requirements for shale gas is an organic-rich source rock present in the thermogenic gas window that is sufficiently brittle to host a natural fracture system. As noted above, the most promising area for thermogenic gas charge is in the southern margin of the North Aleutian basin offshore from Nelson Lagoon and Port Moller. Deeper parts of the St. George basin may have some potential for thermogenic generation from gas-prone Tertiary source rocks (Comer and others, 1987; Sherwood and others, 2006), but none of the wells in the basin encountered any hydrocarbon accumulations (Sherwood and others, 2006). Most of the Tertiary source rocks probably lack the well-developed fracture system necessary for efficient shale gas production.

Outcrop and well data indicate the Mesozoic source rocks are mostly oil prone (Decker, 2008). Although associated gas is possible, available information suggests shale gas potential is limited. However, recent advances in drilling technology have resulted in the production of oil directly from this type of oil-prone source rock (termed shale oil). Although this resource type has never been considered in this region, the high quality of the Triassic and Jurassic source rocks indicates this unconventional play may have potential.

Gas hydrates. The primary occurrences of gas hydrates in nature are in modern deep marine sediments, or in the shallow sediments of petroleum-rich basins in arctic regions that maintain a well-developed, continuous permafrost layer. The southerly latitude and maritime climate influence in the Aleutians energy region has resulted in very limited and discontinuous permafrost and is therefore not prospective for onshore hydrate accumulations. Alternatively, the potential for concentrations of deep marine gas hydrates is unknown, but would be limited to deeper parts of the Aleutian Trench and exceedingly expensive to test.

Geothermal resource potential

Geothermal prospectivity in the Aleutians energy region is greater than in any other Alaska Energy Authority (AEA) defined energy region in the State. Twelve occurrences of thermal spring temperatures in excess of 165°F (74°C) have been measured at various locations in the region. By comparison, only five such occurrences have been measured in Alaska outside the Aleutians Energy Region (Motyka and others, 1983).

Makushin Volcano, located on Unalaska, remains one of the state's best understood and most viable geothermal development prospects. Two thermal springs with discharge temperatures in excess of 165°F (74°C), including the state's hottest (305.6°F [152°C]), are located on the flanks of Makushin Valley (Motyka and others, 1983; sheet 2) Three wells (Geothermal D-1, Geothermal E-1, and St. Makushin 1) were drilled in the area in 1982–1983, but ongoing property ownership issues have hampered development of this resource.

Akutan Island contains several chloride-rich thermal springs with surface temperatures ranging from 104°F to 183°F (40°C–84°C). These springs are in Hot Springs Bay Valley, within 3 miles of Akutan Harbor and Akutan village, and represent potentially viable direct-use applications for residential and commercial energy. Measured fumarole temperatures in the area are as high as 210°F (99°C) and reservoir temperature estimates, taken with geothermometers, range from 356°F to 374°F (180°C–190°C) (Motyka and others, 1983). In 2010, two small diamonter temperature gradient core holes were drilled in the floor of Hot Springs Bay Valley to test the geothermal aquifers and the size and extent of the outflow zones (Kolker and others, 2012). Geothermal flow temperatures reached 359°F (182°C) and gas geochemistry data from fumaroles suggests reservoirs could potentially reach 572°F (300°C) (Kolker and others, 2012).

Geyser Bight Valley on Umnak Island hosts the most widespread and hottest chloride-rich thermal spring system in Alaska. The area includes several small geysers, numerous fumaroles, and three thermal springs with temperatures exceeding 165°F (74°C). Isotope geothermometry indicates deep reservoir temperatures may be as high as 491°F (255°C) (Motyka and others, 1983). The village of Nikolski, 25 miles southwest of Geyser Bight, could be a potential benefactor of geothermal development in this region.

Atka Island is host to three thermal springs in excess of 165°F (74°C), located in fumarolic fields near the flanks of Mount Kliuchef and Mount Korovin. Reservoir temperature estimates, based on gas geothermometry, are 338°F–572°F

(170°C–300°C) (Motyka and others, 1983). The proximity of these springs to the village of Atka warrants consideration as a direct-use application of geothermal energy.

Adak Island has numerous saline thermal springs near the base of Mount Adagdak. Reservoir temperature estimates of these spring waters are 320°F–374°F (160°C–190°C), with measured temperature gradients as high as 4.39°F/100 feet (8°C/100 meters) (Motyka and others, 1983) (Motyka and others, 1983). Proximity to the village of Adak could allow direct-use application if this resource is developed.

Considered as a whole, the Aleutian volcanic arc contains a number of widespread geothermal prospects including 26 thermal springs, of which 12 have surface discharge temperatures greater than 165°F (74°C), nine fumarole fields, and various geysers and mud pots (Motyka and others, 1983).

RECOMMENDATIONS

Geothermal resource recommendations

There is clearly a geothermal resource present in the region and numerous possibilities exist for direct use on industrial applications of this energy source in small villages across the Aleutians. The development of a direct-use pilot project would provide insight into the viability of this resource in remote regions. The Makushin geothermal prospect has significant potential, although resolution of land issues and an updated risk assessment and economic analysis would be necessary precursors to development.

Conventional oil and gas resource recommendations

Previous reconnaissance-scale geologic fieldwork has established the framework geology of the Alaska Peninsula (Detterman and others, 1996). However, significant improvements in our understanding of the region's' petroleum potential could be achieved with additional detailed field mapping and stratigraphic studies. This type of work would build on the successful recent topical studies of the Alaska Peninsula by DNR geologists (Reifenstuhl and Decker, 2008).

The petroleum industry has expressed clear interest in exploring federal waters of the southern North Aleutian basin, which is considered prospective for commercial-scale natural gas discoveries (Anchorage Daily News, 2005; Shell Exploration and Production, 2008) that could also potentially make gas available to local markets within the Aleutians energy region. This cannot occur until offshore federal leasing is reinitiated.

Industry has shown only moderate interest in exploring leasable state acreage onshore and beneath state waters, which have been available since 2005 through the Alaska Peninsula areawide lease sale program. Although some limited onshore seismic data exists, there is very limited exposed bedrock geology, and acquisition of high-quality modern seismic data would be required to determine if exploration targets exist under currently accessible lands. An alternative investment strategy would be to encourage industry-led gas exploration of the federal offshore that would provide infrastructure for potential future onshore activity as well.

Coal resource recommendations

Studies of the Herendeen Bay coal in the Aleutians Energy Region are highlighted in the report by Merritt and McGee (1986), which includes measured sections and resource assessment in the Herendeen Bay area. To better define the coal resource in this area, additional detailed work involving geologic field mapping, additional stratigraphic and coal quality studies, and exploratory drilling are required. Estimates of as much as 138 million short tons of coal, along with the relatively high heating value of the coal, make it an attractive target for future study. It is recommended the State consider detailed geologic mapping in the area to determine any future energy potential. The fact that this field is located in the Pavlof Unit of the Alaska Peninsula National Wildlife Preserve should be considered in any future recommendations.

Earlier studies concluded the Unga Island coal field is not a significant economic energy resource (Alaska Division of Energy and Power Development, 1977; Merritt, 1986b) and that it has a low economic development potential due to mostly thin coalbeds in the area and their low rank. No further work evaluating the Unga coal field is recommended at this time.

Unconventional oil and gas resource recommendations

Coalbed methane. Further geologic field investigations and/or exploratory drilling could improve the understanding of coalbed methane resource potential in the Herendeen Bay area. However, based on available data, the limited stratigraphic and areal extent of coals in the region suggests commercial quantities of methane are unlikely. Investment into further investigations in this area would need to be weighed against the economics of other energy alternatives.

Tight gas sands. The possibility exists for encountering fractured tight gas sands in portions of the Mesozoic section in the region, although the probability of recovering commercial quantities of gas is low. In terms of unconventional resources, tight gas sands have the most likelihood of providing producible quantities of hydrocarbons for local use. Nevertheless, it would be difficult to entice companies to conduct commercial exploration for tight gas sands in the area. It is recommended that if the State funds tight gas sand projects, it should be done on a very local scale.

Shale gas. Based on available data, the region does not appear to host extensively fractured source rocks within the thermogenic window necessary for the generation of gas. The likelihood of finding commercial quantities of shale gas in the region is low and no further action is recommended at this time. However, unconventional shale oil has not been evaluated in the region and the high quality of oil-prone Mesozoic source rocks warrants further geologic study to determine its potential.

Gas hydrates. Due to the lack of extensive, continuous permafrost in most of southern Alaska, the likelihood of finding onshore gas hydrates in the region are very low, therefore no further action is recommended.

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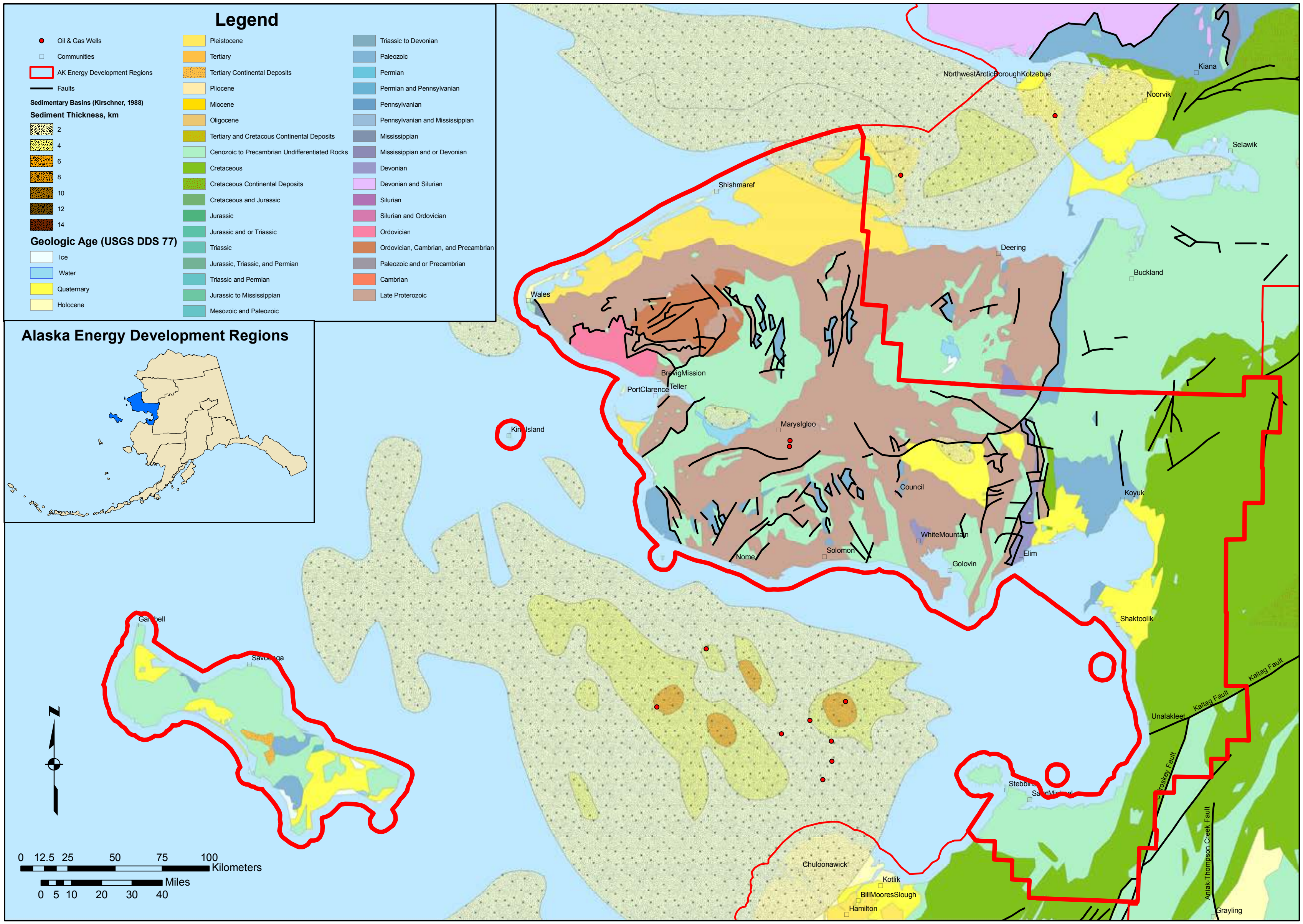
Geology of the Bering Straits Energy Region, Alaska



SUMMARY OF FOSSIL FUEL AND GEOTHERMAL RESOURCE POTENTIAL IN THE BERING STRAITS ENERGY REGION

by Simone Montayne, Marwan Wartes, and James Clough

INTRODUCTION

Purpose of this report

Economic growth and stability in Alaska's rural and urban areas hinges partially, if not primarily, on the availability of affordable and sustainable energy supplies. Recent price increases in oil and gas commodities have created severe economic hardship in many areas of the state that are dependent on diesel and heating oil as their primary source of energy. All sectors of Alaska's economy rely on affordable energy sources with limited price volatility, highlighting the need to diversify the energy portfolio by developing locally available and sustainable resources that are not tied to the global market. Unfortunately, all areas are not created equal in energy accessibility; the resources available for local exploitation vary widely across the state. It is critical that funding decisions for expensive programs to reduce the dependence on diesel for heat and electricity take into account information concerning the entire suite of natural resources that exist in a given area.

This report draws from existing information to provide community and state leaders an objective summary of our current knowledge concerning the potential of locally exploitable fossil fuel and geothermal energy resources in the Bering Straits Energy Region (fig. C1), one of 11 regions recognized by the Alaska Energy Authority in their Energy Plan (AEA, 2009). The potential geologically hosted energy resources considered here include exploitable coal, conventional and unconventional oil and gas, and geothermal resources. This report concludes with recommendations as to what additional data or strategies, if any, would provide the most leveraging in helping to develop new energy resources in the region.

Readers without geological training are encouraged to peruse the geologic summaries of fossil fuel resources and geothermal energy in chapter A. They provide an overview of the geologic elements that must be present in an area to economically develop coal, conventional oil and gas, unconventional oil and gas, and geothermal resources. These summaries will provide the necessary background to more fully understand the information presented in this chapter.

Geographic and geologic setting

The Bering Straits Energy Region is located along the western coast of Alaska (sheet 1). It encompasses the northwest and southern portions of the Seward Peninsula, extends south along the Norton Sound coast to a few miles north of Point Romanof and spans south and eastward 10 to 60 miles from the coast. The region also includes Saint Lawrence Island, King Island, and various other nearshore islands. The region's largest community is Nome, with a current population of nearly 3,500 residents. Other sizable communities include Unalakleet, Savoonga, Gambell, Shishmaref, and Stebbins, with populations ranging from nearly 800 to less than 600 residents. Smaller populations occupy 11 other permanent villages.

Much of the Bering Straits Energy Region's landscape consists of rolling highlands with gentle slopes. Exceptions include several rugged mountain ranges on the Seward

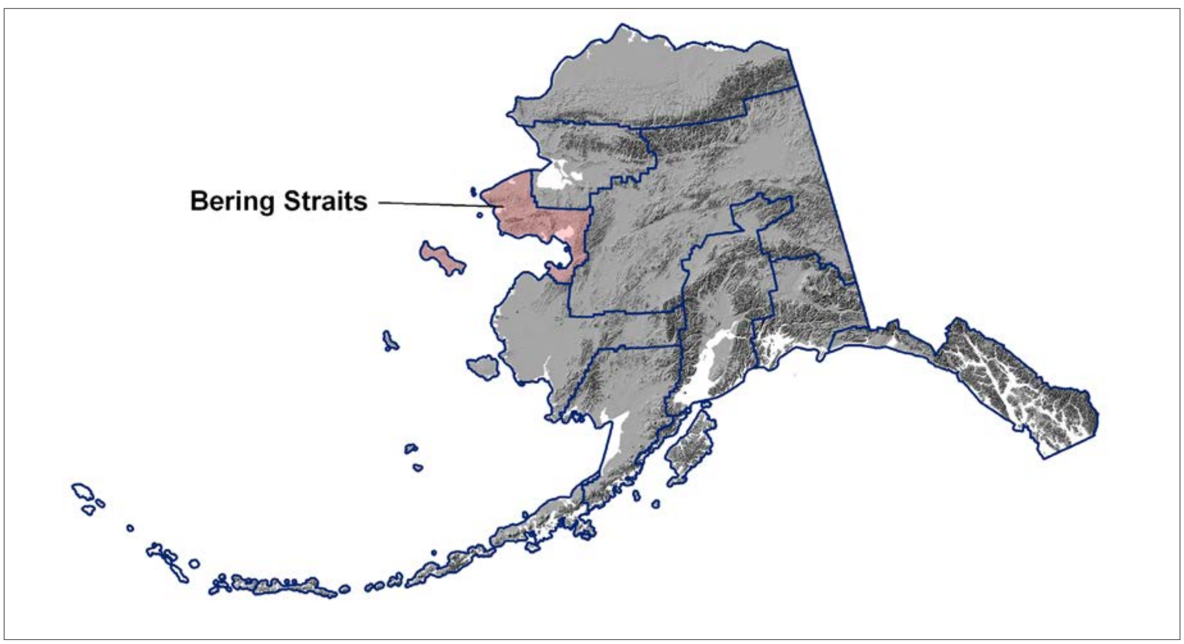


Figure C1. Location map of Bering Straits Energy Region.

Peninsula, including the York Mountains, Kigluaik Mountains, Darby Mountains, Bendeleben Mountains, and the Midnight Mountain area. Plains and lowlands containing numerous small lakes occur along the coastline, along the valleys of the larger rivers and in isolated basins north and south of the Bendeleben and Darby mountains. There are volcanic remnants in the Devil Mountain area of the Seward Peninsula and on Saint Lawrence Island, south of Savoonga (Wahrhaftig, 1965).

The geologic history of the Bering Straits Energy Region is complicated, and in many areas the details are poorly understood. Till and others (2011) compiled available geologic data for the region and present a useful, up-to-date summary of the geologic evolution of the Seward Peninsula. Rock types include sedimentary, igneous, and metamorphic varieties and range in age from Paleozoic through Cenozoic. However, major stratigraphic, lithologic, and structural discontinuities indicate that the geologic history of the region involves large-scale tectonic displacements interspersed with periods of erosion, deposition, and volcanism (Patton and others, 1994). The exposed bedrock of most of the region comprises intensely deformed and/or metamorphosed Precambrian, Paleozoic, and Mesozoic sedimentary and volcanic rocks (Till and Dumoulin, 1994). Numerous stocks and plutons of granitic rocks of Cretaceous and possibly Tertiary age intrude these older units and basalts of Pliocene and Quaternary age cover substantial parts of the region. Significant fault zones include the Kugruk fault zone, which parallels the eastern extent of the Seward Peninsula, and the Kaltag fault, which transects the Bering Straits Energy Region south of Unalakleet. In various places throughout the region, localized structural or topographic basins contain deposits of Cretaceous and Tertiary age coal, shale, sandstone, and conglomerate (sheet 2).

GEOLOGIC ENERGY RESOURCE POTENTIAL IN THE BERING STRAITS ENERGY REGION

Mineable coal resource potential

Coal quality and extent depend on geologic age, depositional setting, and tectonic history. The formation of thick, widespread coal packages requires long time periods of vegetation growth and accumulation in boggy, terrestrial basins sheltered from significant influxes of clastic sediments and accompanied by steady basin subsidence resulting in burial (see Chapter A). Available geophysical evidence, subsurface data, and geologic mapping suggest that most of the Bering Straits Energy Region is underlain by Mesozoic and older igneous, metamorphic, and volcaniclastic sedimentary rocks (Till and others, 2011). Surface exposures of younger, nonmarine siltstone and sandstone lithologies are deposited in fluvial to lacustrine environments that have associated coal deposits. More often these younger, Tertiary-age rocks are eroded or are present in subsiding graben-like structures and covered by Quaternary sediments. Along a number of riverbanks the eroded remnants of the coal deposits are found as small to large fragments of coal 'float' in the river gravels. However, localized coal deposits do exist and drilling has identified some subsurface coals in the region. During the 1980s, several northwest Alaska coal exploration field programs were conducted to ascertain the lateral and/or subsurface extent of known coal exposures throughout the region. Localities selected for detailed investigation within the region were: the Kutzitrin River, McCarthy's Marsh, Death Valley, and Boulder Creek coal districts (fig. C2) and the Sinuk River and Koyuk coal occurrences on the Seward Peninsula; the Unalakleet coal occurrence (fig. C3); and the Niyrakpak Lagoon coal occurrence on St. Lawrence Island (fig. C4).

In the early 1900s, lignite was mined from a bed of coal up to 12 feet thick exposed in a pingo near Turner Creek in the Kuzitrin basin (fig. C2; Hopkins, 1963). In 1982, DGGS visited this locality and collected a sample for coal quality analyses and looked at other outcrops of the Tertiary-age Noxapaga Formation for additional coal seams (Clough and others, 1995). The apparent rank of the coal here is lignite (Clough and others, 1995) and no other substantial coal seams were located. Dames & Moore (1980) suggest that the coal-bearing sediments may extend to the northeast beneath Tertiary-age basalt flows, based on a gravity anomaly associated with the Kuzitrin basin shown in a gravity map by Barnes and Hudson (1977).

Unnamed coal-bearing strata occur at the southernmost edge of the Kiwalik River basin in the Candle Quadrangle (fig. C2). These locations of Tertiary-age coal were first reported by Harrington (1919) and later located by precious-metal exploration in the area and summarized in Dames & Moore (1980). Clough and others (1995) report that extensive areas of the Kiwalik and adjacent Buckland and Koyuk basins are covered by extensive basalt flows that hide the suspected coal-bearing rocks below. The linear shape of the Kiwalik and Buckland basins suggests that they are fault controlled (Dames & Moore, 1980), suggesting they may be similar to other fault-bounded Tertiary basins on the Seward Peninsula. Resource Associates of Alaska examined a 20- to 30-foot-long slumped outcrop of clay and coal on Wilson Creek (fig. C2), a tributary to the Kiwalik River and located a visible 3-foot-thick bed of coal (Fankhauser and others, 1978). Samples of coal float collected from the Wilson Creek area by DGGS in 1982 are lignite in apparent rank based on coal quality analyses (Clough and others, 1995).

The Death Valley basin and its southern extension, Boulder Creek basin (fig. C2), that lie east of the Darby Mountains in the southeastern Bendeleben Quadrangle, contain the thickest documented Tertiary-age coal seams on the Seward Peninsula. Eocene-age coals here are up to 175 feet thick, their discovery in the subsurface the result of exploration drilling for uranium in 1980 (Dickinson and

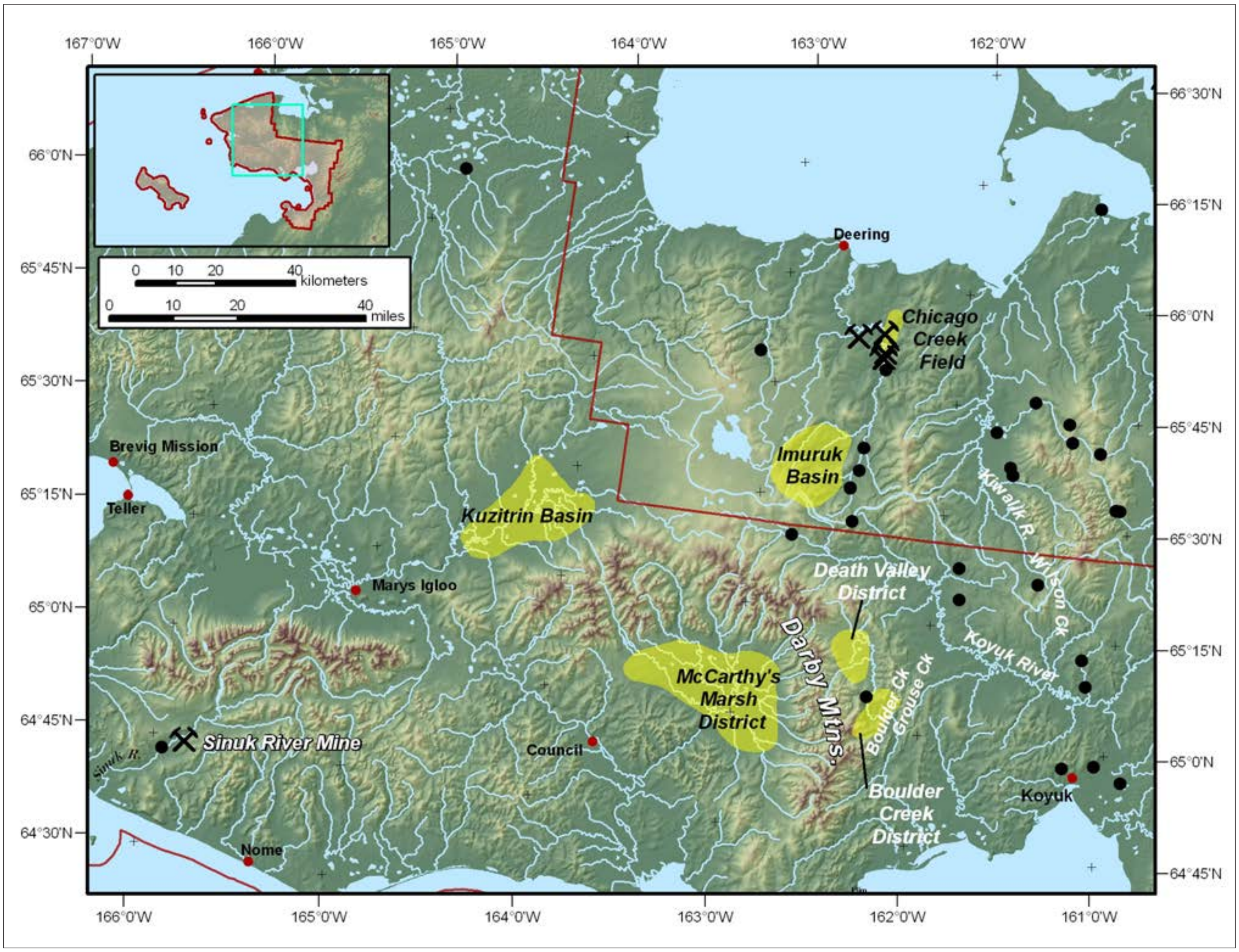


Figure C2. Location map of the central Bering Straits Energy Region, showing selected geographic references noted in the text. Red line shows border of Bering Straits Energy Region; black dots indicate reported coal occurrences; yellow shaded areas are inferred to be underlain by coal-bearing rocks.

others, 1987). These coals are overlain by thick Tertiary basalt flows and were deposited in a graben that formed in the north–south-oriented Kugruk fault zone described by Till and others (1986). A 35-foot-thick outcrop of coal on Grouse Creek, on the east side of Boulder Creek, was first described by West (1953). Coal from this locality is lignite in rank and this outcrop is believed to be a surface expression of the coals encountered in the deep mineral exploration holes (Clough and others, 1995). The Boulder Creek subsurface coal deposit has a very high uranium content (Stricker and Affolter, 1988) and questionable lateral continuity due to extensive faulting evident in the lithology logs from exploration drilling (Clough, 2007). However, the thickness of the coals encountered in the Boulder Creek exploration drilling and at Chicago Creek immediately to the north, and described in the Northwest Arctic Energy Region, suggests that the other Tertiary basins on the Seward Peninsula may have thick coal seams at depth.

A small outcrop of low rank coal at the Sinuk River bridge crossing, about 32 miles west of Nome on the Nome–Teller Highway (fig. C2). Natives from the village at the mouth of the Sinuk River brought this coal occurrence to the attention of gold prospectors in 1902, and efforts to mine this coal were attempted that year (Collier and others, 1908). Although there are small-gauge rails leading from a collapsed adit, rail carts, a boiler, remains of a small cabin and other mining materials present at the site, there is no record of actual production. In the fall of 1982, DGGS drilled 16 exploratory drill holes to depths of up to 77 feet. The actual coal was shown to be very thin, less than 1 inch in thickness, and interbedded with carbonaceous shale and decomposed schist pebbles and clay (Clough and others, 1995). Herreid (1970) considered this coal to be Tertiary in age based on the results of their field examination and drilling; Clough and others (1995) concurred.

Residents of the village of Koyuk have picked up coal along the Norton Bay beach for many years and sometime before 1909 coal was prospected on a creek informally called "Coal Creek" by the local residents (fig. C2). Harrington (1919) indicated that second-hand reports suggested the presence of a 2- to 4-foot-thick coalbed exposed near the mouth of the Koyuk River and that a coal mining permit was issued in 1919 for somewhere on the Koyuk River. During 1982–1983, the State of Alaska explored for coal in the area around Koyuk with subcontractors. This program drilled a number of exploratory rotary drill holes and conducted surface mapping and geophysics on approximately 230 acres near the mouth of the Koyuk River (see Manning and Stevens, 1982; Ramsey and others, 1986; Clough and others, 1995). Results from this program indicate that the coals are in irregularly-shaped lenses rather than laterally continuous coal seams and most of the subbituminous coals are less than 1.5 feet thick (Ramsey and others, 1986; Clough and others, 1995).

At least 300 short tons of coal were mined from a shallow adit on the beach near Unalakleet in 1918 for steamship use (fig. C3; Cathcart, 1920). In 1982 DGGS conducted field studies in the Unalakleet region and in 1983 a subcontractor for the State of Alaska drilled 12 rotary drill holes along the coast at the top of the bluff (Ramsey and others, 1986; Clough and others, 1995). Thin lenses of lignite were intercepted in seven of the drill holes, with the thickest lignite, 2 feet, encountered in a single drill hole (Ramsey and others, 1986; Clough and others, 1995). The thickest exposure of coal is at the mouth of Coal Mine Creek, where a 6-foot-wide pod of clayey lignite pinches out laterally within approximately 20 feet. This pod of coal is probably the bed mined in 1918; it now contains very limited reserves (Clough and others, 1995). The 1983 drilling results indicate that the subsurface coals encountered in the bluffs dip at a steep angle of 40° to 45° east (Ramsey and others, 1986) and would therefore be at deep, unmineable depths within a short distance onshore (Clough and others, 1995). Additionally, the minimum

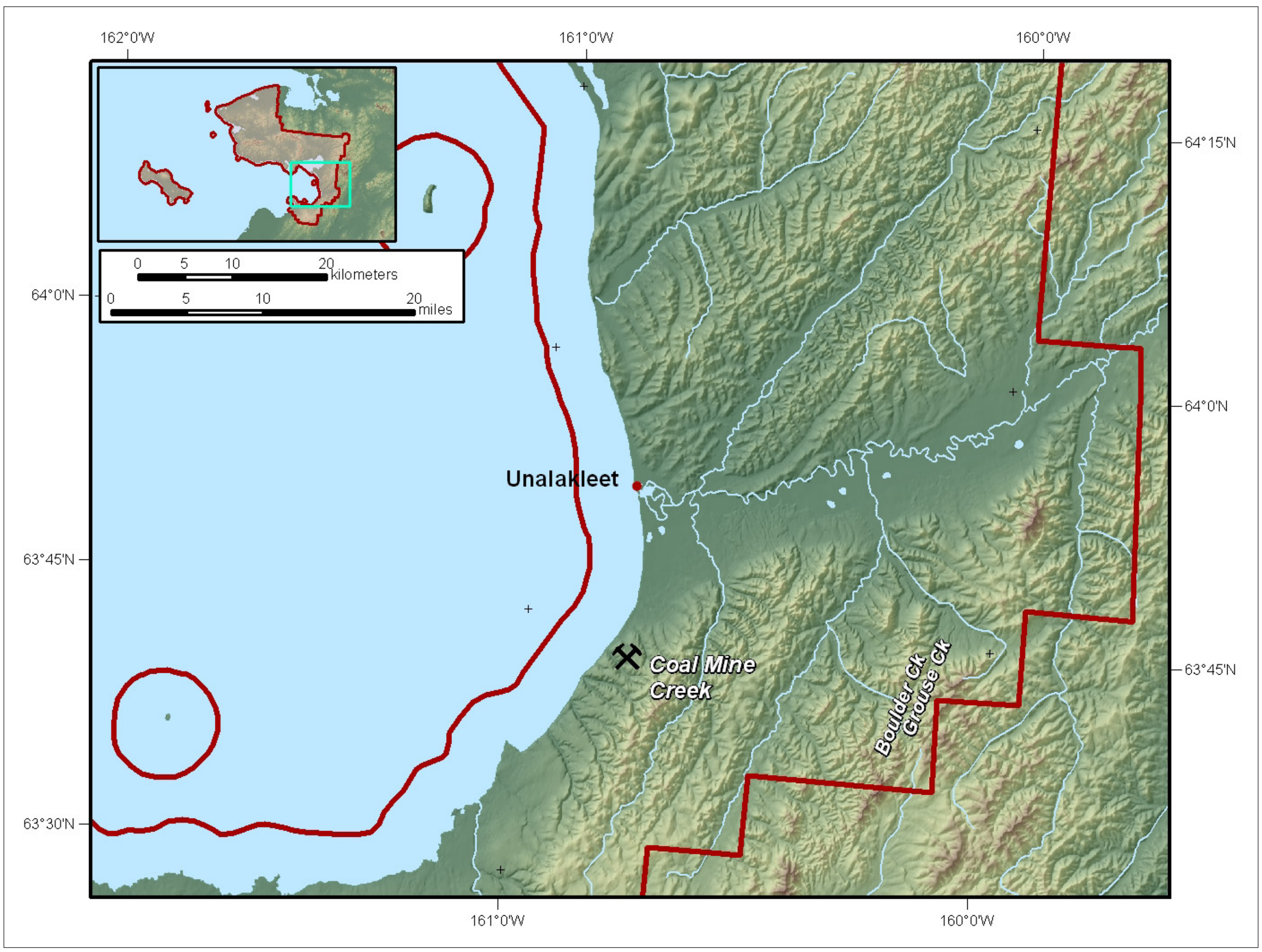


Figure C3. Map of the Unalakleet area, showing the location of a historic coal mine (pick-axe symbol) discussed in the text.

thickness of lignite that is considered to be economically mineable is 30 inches.

On St. Lawrence Island, coal was occasionally used by the local Natives to burn with driftwood in campfires and communal homes (fig. C4). In 1981, the State of Alaska and consultant Dan Renshaw explored the western part of the island for coal occurrences, and a promising site at the western shore of Niyrakpak Lagoon east of Gambell was chosen to conduct a small-scale limited drilling program in 1982 (Renshaw, 1981, 1982; Clough and others, 1995). Here, Tertiary-age lignitic coal up to 18 inches thick is exposed in the shore bluff. Results from 12 auger holes drilled during the summer of 1982 demonstrated that the coal exposed in the lagoon's bluff did not extend very far inland (Renshaw, 1982; Clough and others, 1995). There are a few smaller exposures around the island with thin lenses of coal, up to 6 inches thick, associated with volcanic-derived sediments, and likely formed in small basins that developed between episodes of volcanic eruptions (Renshaw, 1982).

Conventional oil and gas resource potential

As explained in the discussion of requirements for exploitable oil and gas resources (Chapter A), functioning petroleum systems occur in thick sedimentary basins, and require three basic elements: Effective source rocks, reservoirs, and traps. Each of the elements must be in existence and connected at the time hydrocarbons are generated and migrated. This section provides an overview of the various basins in the Bering Straits region then considers each of the necessary elements of petroleum systems in turn to evaluate the role conventional oil and gas resources may play in supplying rural energy to the region.

Overview of sedimentary basins. Most of the Bering Straits Energy Region is underlain by crystalline rocks (igneous and metamorphic) that are inconsistent with the presence of functioning hydrocarbon systems (Ehm, 1983; Patton and others, 1994; Till and Dumoulin, 1994; Troutman and Stanley, 2003). Two small east–west-trending sedimentary basins, the Imuruk and Bendeleben basins (sheet 2), developed on this crystalline basement. No subsurface data are available for these basins, but they are probably filled with Tertiary-age nonmarine sedimentary rocks. Gravity data suggest the deepest parts of both basins may include up to 10,000 feet of sedimentary rocks, but the areal extent of these thick deposits is small (Barnes and Hudson, 1977).

The offshore Norton basin is south of Nome (sheet 2), in the Bering Sea and represents the only basin in the region known to be capable of generating significant hydrocarbons. The Norton basin is a large extensional basin filled with well over 20,000 feet of Tertiary marine and nonmarine sedimentary rocks (Fisher and others, 1981). The tectonic driver for basin subsidence is enigmatic, but inferred to be related to strike-slip movement on the Kaltag fault (Fisher and others, 1982). Seismic mapping indicates the presence of two subbasins separated by a large fault block (Turner and others, 1986. Knowledge of the geology of this offshore

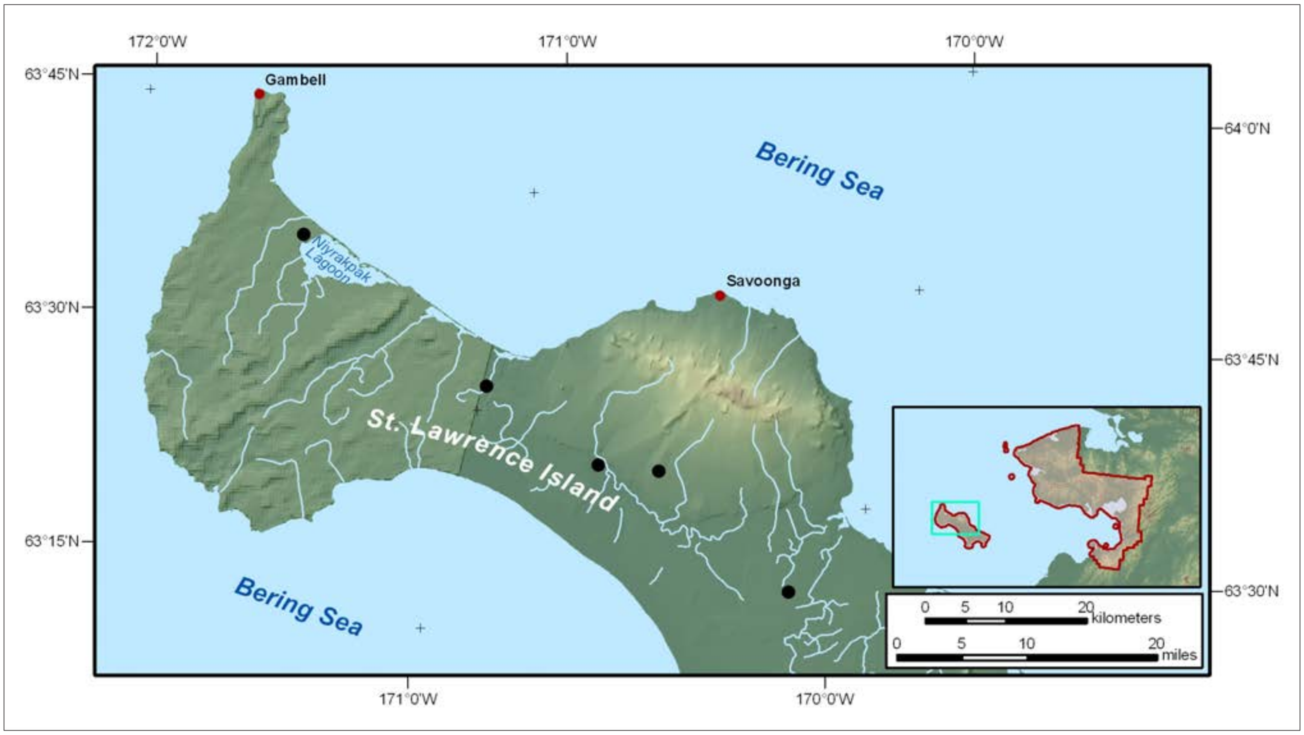


Figure C4. Map of the St. Lawrence Island area, showing reported coal occurrences (black dots) discussed in the text.

region largely comes from publicly available reports on data from two wells drilled in the early 1980s (Norton COST No. 1 and No. 2; Turner and others, 1983a; 1983b). Biostratigraphic data (microfossils and pollen) indicate the basin-filling succession is probably no older than Paleocene at its base.

The Kotzebue basin lies mostly outside of the Bering Straits Energy Region, north of the Seward Peninsula. Similar to the Norton Basin, the Kotzebue basin is an extensional basin filled with a thick succession of Tertiary-age sedimentary rocks. The thinner part of the basin is penetrated by two onshore wells, which indicated volcanic-rich sediments in the lower part of the section and a dominantly nonmarine depositional environment for basin fill (Decker and others, 1987; Fisher, 1988). Further discussion of this basin can be found in the chapter for the Northwest Arctic Energy Region.

Source rocks. Eight deep exploration wells were drilled in the offshore Norton basin south of Nome between 1980 and 1985, all of which were abandoned as dry holes. Although none of the wells discovered commercial hydrocarbons, all encountered moderate to strong shows of gas, often associated with coal-rich sediments, and three encountered weak oil shows. None of the shows were deemed promising enough to warrant a drill stem test (see summary and references in Troutman and Stanley, 2003). These well data demonstrate that the basin locally contains source rocks at depth that have generated some hydrocarbons. Extensive geochemical data collected from the two COST wells show that the deeper parts of the basin (mostly Eocene age) are sufficiently mature to generate thermogenic hydrocarbons (Turner and others, 1986). Most of the sediments are low in total organic carbon and the type of organic matter is prone to generating gas. The gas-generating potential of the Norton basin is also supported by the discovery of a large submarine gas seep originating approximately 30 miles south of Nome (Cline and Holmes, 1977). Although 98 percent of the gas was CO_2 (non-hydrocarbon), analyses indicated the presence of small amounts of light hydrocarbons of probable thermogenic origin (Kvenvolden and Claypool, 1980).

Reservoir rocks. Potential reservoir sandstones in the Norton basin are rich in metamorphic and volcanic rock fragments that are susceptible to compaction and reduced reservoir quality with increased burial depth (Turner and others, 1986). This effect is observed in conventional and sidewall core data from the COST wells. For example, in the COST No. 1 well, permeabilities are generally less than 1 millidarcy below 6,000 feet (Turner and others, 1983a). These low permeabilities limit the potential for conventional oil reservoir below this depth, although gas reservoirs may remain viable. There are notable exceptions to the trend of decreasing reservoir quality with depth, particularly in the Oligocene-age section in the COST No. 2 well where high-energy fluvial to shallow-marine deposits have a higher quartz content and have preserved adequate reservoir quality despite deep burial (Turner and others, 1986).

Traps. The extension that created the Norton basin resulted in a variety of potential trapping mechanisms, including structural, depositional, and erosional processes. Elements of these trapping styles have been tested in the eight unsuccessful exploration wells, although available seismic mapping suggests many untested traps remain, particularly those associated with normal faults creating complex horst and graben structures (Minerals Management Service [MMS], 2006).

Summary of conventional oil and gas resource potential. Sedimentary basins known to be capable of generating hydrocarbons are limited to the offshore portion of the Norton basin. Based on regional geology and the results from eight unsuccessful exploration wells, the U.S. Department of the Interior does not project undiscovered crude oil resources in the basin, although small amounts of liquid condensate are inferred to be present (MMS, 2006). Their mean estimate of natural gas in the basin is 3.06 TCF. Although this estimate indicates significant potential for undiscovered natural gas, the actual amount of this hypothetical resource that could be produced would be significantly smaller because many of the potential discoveries would not prove economically viable due to the high costs of offshore development.

The potential for conventional oil and gas in the small Imuruk and Bendeleben basins is unknown, but likely to be very low. If hydrocarbons are present in these small nonmarine basins, it is most likely to be uneconomic amounts of biogenic gas.

Unconventional Gas Potential

Coalbed methane. Coal resources in the Bering Straits region are relatively poorly known. Most coal occurrences are relatively thin and low grade, which led authors of previous analyses of statewide coalbed methane potential to discount the Bering Straits region as a viable target for this type of rural energy (Tyler and others, 2000). The Boulder Creek basin area does contain locally developed thick coals of appropriate rank, particularly in the subsurface where uranium exploratory drilling has identified a 175-foot-thick coalbed (Dickinson and others, 1987). However, the anomalous rank results from localized thermal alteration by overlying lava flows and is not a basinwide trend (Stricker and Affolter, 1988). Further, the small size of the basin, its structural complexity, and its lateral variability suggest the potential for viable coalbed methane resources is very low.

Tight gas sands. The potential for tight gas sands in the Imuruk and Bendeleben basins is unknown, but considered unlikely due to insufficient burial depth for the generation of thermogenic gas. Well data from the Norton basin suggest that tight gas sands could be present in the basin, particularly at depths greater than 6,000 feet where compaction reduces porosity and permeability (Turner and others, 1986). Data from the two COST wells indicate that the deeper parts of the section are sufficiently mature to generate gas, although most of the sediments are low in total organic carbon (Turner and others, 1983a; 1983b). Tight gas plays typically require closely-spaced wells and artificial stimulation to be effectively produced; this type of unconventional resource would likely be challenging to develop economically in an offshore setting.

Shale gas. Two of the primary requirements for gas to be producible from an organic-rich source rock (shale) are previous heating via burial into the thermogenic gas window and being sufficiently brittle to host a natural fracture system (see Chapter A). Thermally mature organic-rich shales do not appear to be present in the Imuruk and Bendeleben basins and are considered unlikely given the depth of the basin inferred from gravity data (Barnes and Hudson, 1977). Thermally mature gas-prone source rocks are present in the offshore Norton basin, as demonstrated by shows in several wells (Troutman and Stanley, 2003). Most organic matter in this basin consists of woody and coaly matter, which is gas prone (Turner and others, 1986). The presence of this material in brittle rocks capable of hosting a fracture system has not been studied. Similar to tight sands, the infrastructure footprint for this type of unconventional play suggests it would be not be economic to develop in an offshore setting.

Gas hydrates. The main occurrences of gas hydrates in nature are in modern marine sediments and in arctic regions with well-developed, continuous permafrost. Permafrost is not well developed in the Bering Straits Energy Region and, where locally present, is discontinuous. Consequently, the potential for economic concentrations of gas hydrates in the region is low.

Geothermal

The central and eastern Seward Peninsula area lies within a broadly defined belt of west-central Alaska that may be favorable for the discovery of shallow thermal waters (Motyka and others, 1983). The presence of young volcanic rocks and evidence for recent extensional faulting (Till and others, 2011) are consistent with an elevated regional thermal gradient. However, only a few examples of shallow thermal waters have been documented in the region, all apparently associated with fractured plutonic bodies (Miller and others, 1973; Sainsbury and others, 1970; Economides and others, 1982; Kolker and others, 2007). With limited available subsurface drilling data, evaluation of the region's potential is based largely on information from known hot springs localities.

Hot Springs with surface temperatures greater than 122°F (50°C) (the temperature typically cited as a minimum for direct heat applications) in the Bering Straits Energy Region are Lava Creek, Clear Creek, Serpentine Hot Springs, and Pilgrim Hot Springs (fig. C1). Serpentine Hot Springs, Lava Creek, and Clear Creek have reported temperatures of 167°F, 127°F, and 149°F (75°C, 53°C, and 65°C), respectively, but are distant from communities and ground transportation (Miller and others, 1973; Motyka and others, 1983). Pilgrim Hot Springs is approximately 60 road miles north of Nome and has reported surface temperatures ranging from 145°F to 160°F (63°C–71°C) (Miller and others, 1973; Motyka and others, 1983). Due to the proximity to a large community, this potential resource has witnessed a long history of investigative work, including drilling, geologic and geophysical mapping, and preliminary feasibility studies (see Dilley, 2007, for detailed references). The Alaska Center for Energy and Power (ACEP) at the University of Alaska Fairbanks is currently conducting a resource assessment project at Pilgrim Hot Springs that will further evaluate the geothermal potential via remote sensing techniques and by drilling additional exploration wells. The data from this type of study will be critical in determining the viability of geothermal power generation for local or regional use. In addition to the springs noted above, development of Granite Mountain Hot Springs has also recently been considered as a possibility for further geothermal exploration. Although the surface temperature data indicate a sub-optimal resource (120°F [49°C]), geochemical evidence suggests higher temperatures may exist in the near subsurface (Kolker, 2009). ACEP is also evaluating this locality further to assess whether development of this geothermal resource for rural energy is possible and/or economically feasible.

RECOMMENDATIONS

Conventional oil and gas recommendations

The geology of the Bering Straits Energy Region suggests that no functioning petroleum systems are present in the onshore part of the region. However, the geology of the Norton basin, located a short distance offshore in the shallow waters of the northeastern Bering Sea and Norton Sound, suggests significant natural gas potential (MMS, 2006). The lack of correlative strata exposed onshore limit the relevance of additional field stratigraphic studies. However, data from the Seward Peninsula suggest significant Tertiary extensional faulting (Till and others, 2011). Additional detailed mapping of older, pre-Cenozoic bedrock exposures could improve tectonic models for the origin and evolution of the adjacent Norton basin. In addition, further analytical studies could be conducted on material from the COST wells, particularly using newly developed laboratory techniques that were not available in the 1980s. Ultimately, significant new constraints on the natural gas potential of the Norton basin will require additional exploratory drilling. The large capital costs associated with offshore exploration suggests this type of future work will be conducted by industry as part of a search for commercially viable accumulations.

The discovery of an economic gas field could result in the availability of natural gas for local energy needs. Exploration risk could be reduced with the acquisition of modern three-dimensional (3-D) seismic data that can potentially directly image hydrocarbon accumulations.

Geothermal resource recommendations

The Seward Peninsula hosts a number of surface expressions of elevated shallow heat flow; however, the precise geologic origin and extent of these geothermal phenomenon remain poorly understood. Many of the potential geothermal resources are isolated from population centers and not economically feasible to develop; assessing the potential in these areas would require significant and expensive subsurface data. Promising data from the Pilgrim Hot Springs and Granite Mountain areas will require additional investigation to determine their ultimate energy potential and economic viability. Future work to characterize and delineate these prospects includes geochemical and geophysical studies as well as exploration drilling (Dilley, 2007; Kolker, 2009). The University of Alaska Center for Energy & Power has recently acquired new geophysical information and has initiated a temperature probe and drilling program in the Pilgrim area. These new data will help delineate the potential resource and potentially lead to development.

Coal resource recommendations

Available information indicates that, aside from the deposits in the Boulder Creek basin, none of the currently available data on coal occurrences in the region suggest sufficient quantity and rank to meet the U.S. Geological Survey minimum standards for mineable coal resources (see discussion of requirements for exploitable resources for additional explanation). In the Boulder Creek basin, near the lower Tubutulik River area, there exists low to moderate potential for mineable coal to serve as a local energy source for nearby potential uranium mining operations, however, the coal is high in uranium content, making this deposit likely uneconomic (Stricker and Affolter, 1988; Clough, 2007). Investigations in the Koyuk area suggest that, at its thickest, the deposit does not meet the minimum U.S. Geological Survey standards for depth, thickness, and rank for mining. Additionally, drilling results indicate that the deposit is of limited lateral extent (Manning and Stevens, 1986; Ramsey and others, 1986). If new evidence is found for thicker, laterally-continuous coal seams in the Koyuk Basin and near Unalakleet, then these areas might be considered for a second look at coal as a potential local energy source. At present, given the paucity of surface exposures of coal in these areas, without expensive exploratory drilling based on sound science, the potential for coal in these areas is low.

Unconventional oil and gas resources

The geology of the Bering Straits Energy Region strongly suggests that onshore unconventional oil and gas resources are not present. However, the geology of the Norton basin, located a short distance offshore in the shallow waters of the northeastern Bering Sea and Norton Sound, suggests tight gas sands could be present in the basin. Nevertheless, development of unconventional oil and gas resources require significant amounts of expensive technology to test and produce. A full economic analysis should be performed before attempting exploration and development of this type of resource in such a remote and high-risk setting.

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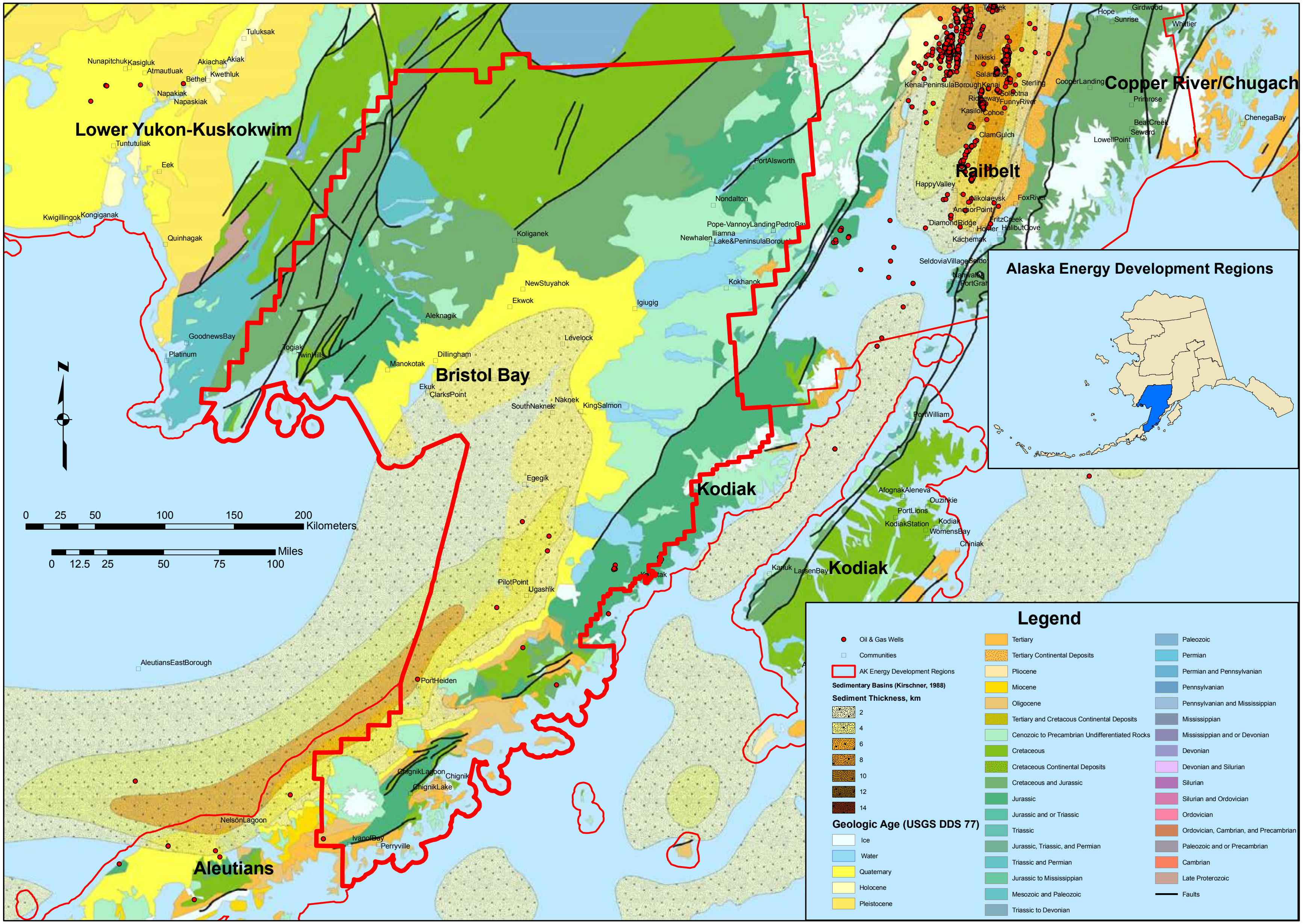
Geology of the Bristol Bay Energy Region, Alaska



Bristol Bay

SUMMARY OF FOSSIL FUEL AND GEOTHERMAL RESOURCE POTENTIAL IN THE BRISTOL BAY ENERGY REGION

by Paul L. Decker, Robert J. Gillis, Ken Helmold, and Shaun Peterson

INTRODUCTION

Purpose of this report

Economic growth and stability in Alaska's rural and urban areas hinges partially, if not primarily on the availability of affordable and sustainable energy supplies. Recent price increases in oil and gas commodities have created severe economic hardship in many areas of the state that are dependent on diesel and heating oil as their primary source of energy. All sectors of Alaska's economy rely on affordable energy sources with limited price volatility, highlighting the need to diversify the energy portfolio by developing locally available and sustainable resources that are not tied to the global market. Unfortunately, all areas are not created equal in energy accessibility; the resources available for local exploitation vary widely across the state. It is critical that funding decisions for expensive programs to reduce the dependence on diesel for heat and electricity take into account information concerning the entire suite of natural resources that exist in a given area.

This report draws from existing information to provide community and state leaders an objective summary of our current knowledge concerning the potential of locally exploitable fossil fuel and geothermal energy resources in the Bristol Bay energy region (fig. D1), one of 11 regions recognized by the Alaska Energy Authority in their Energy Plan (AEA, 2009). The potential geologically hosted energy resources considered here include exploitable coal, conventional and unconventional oil and gas, and geothermal resources. This report concludes with recommendations as to what additional data or strategies, if any, would provide the most leveraging in helping to develop new energy resources in the region.

Readers without geological training are encouraged to peruse the geologic summaries of fossil fuel resources and geothermal energy in Chapter A. They provide an overview of the geologic elements that must be present in an area to economically develop coal, conventional oil and gas, unconventional oil and gas, and geothermal resources. These summaries will provide the necessary background to more fully understand the information presented in this chapter.

Geographic and geologic setting

The Bristol Bay Energy Region of southwestern Alaska encompasses an irregular area measuring approximately 365 miles from north to south and up to nearly 250 miles from east to west that rims the northeast end of Bristol Bay and reaches south to include much of the Alaska Peninsula (sheet 1). Physiographic provinces represented include the Nushagak–Bristol Bay Lowlands, the Nushagak–Big River Hills, and parts of the Aleutian Range, southern Alaska Range, and Ahklun Mountains (Wahrhaftig, 1960). The region's largest community is Dillingham, with a current population of approximately 2,400 residents. Other sizable communities

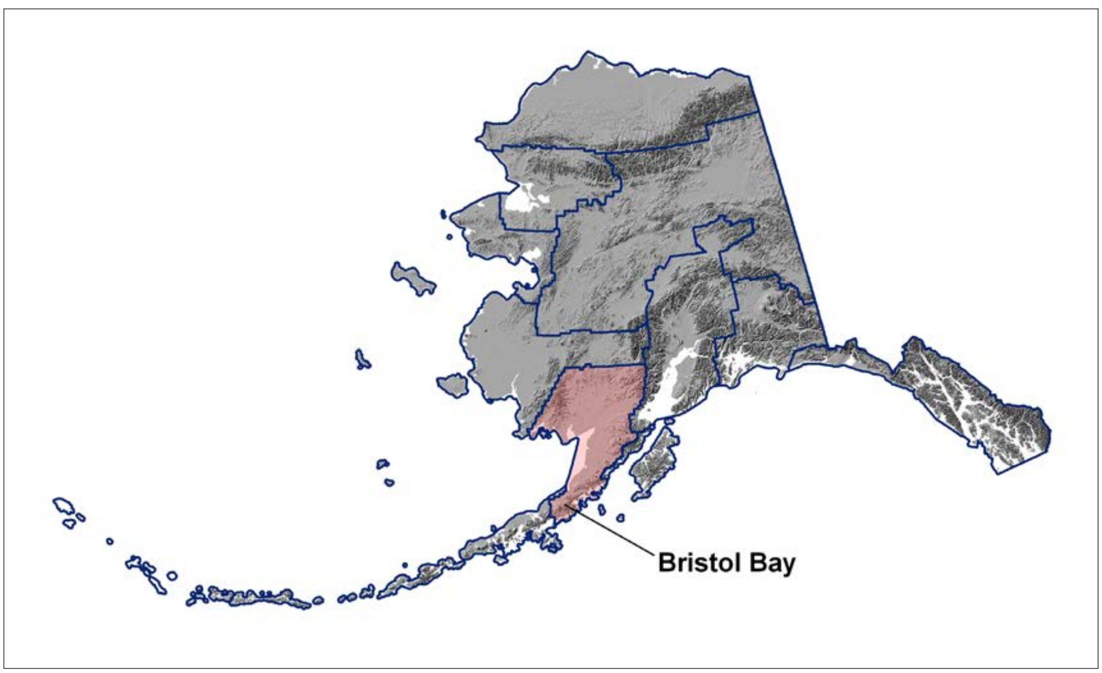


Figure D1. Location map of Bristol Bay Energy Region.

Bristol Bay

include Togiak, Naknek, New Stuyahok, Manokotak, and King Salmon, with populations ranging from nearly 800 to approximately 400 residents. Smaller populations occupy 24 smaller permanent villages. All of these communities are isolated from the major population centers along the Railbelt, and are only accessible by air, boat, or snowmachine.

Topography in the Bristol Bay region varies widely from high, rugged mountains of the southern Alaska Range, to the low-relief Nushagak hills, isolated volcanic peaks on the eastern Alaska Peninsula, and lowlands of the Nushagak and Mulchatna river basins and the western Alaska Peninsula. Geologically, southern Alaska is composed of a series of far-traveled crustal fragments that have been accreting to continental North America since early Cretaceous time (over the last 240 million years). Most bedrock within the Bristol Bay Energy Region represents a complex geologic history of mountain building and sedimentary basin development since early to middle Jurassic time (Detterman and others, 1996). The rock comprising the mountainous regions on the eastern Alaska Peninsula and in the Chigmit Mountains (Peninsular Terrane) are primarily the product of Jurassic-age subduction processes such as arc volcanism and intrusion of igneous rocks into the overriding continental crust, and their subsequent erosion and deposition into neighboring basins. These erosional products and underlying basement rocks are the hydrocarbon sources for the Bristol Bay and Cook Inlet basins (Decker and others, 2008; Detterman and Hartsock, 1966). This area has undergone subsequent episodic uplift and basin development since late Cretaceous time (Detterman and Hartsock, 1966) that has resulted in deposition of some of the coal-bearing rocks on the Alaska Peninsula and the principal hydrocarbon reservoir rocks in the Bristol Bay and Cook Inlet basins (Calderwood and Fackler, 1972; Helmold and others, 2008). These plate boundary processes, including arc volcanism and locally elevated geothermal gradients, were similar to what is presently occurring along the southcentral coast of Alaska.

Like many parts of Alaska, the region spans several fault-bounded geologic blocks or terranes that were assembled by strike-slip and collisional tectonic processes during Mesozoic to early Tertiary time (Silberling and others, 1992). From southeast to northwest, the major faults in the region that mark the suturing of these provinces are the Bruin Bay, Castle Mountain, and Mulchatna faults and the Togiak–Tikchik strands of the larger Denali–Farewell fault system. Except where overlapped by younger Tertiary sedimentary strata on the edges of the North Aleutian (or Bristol Bay) basin (sheet 2), or by Tertiary and younger volcanic cover, bedrock in the Bristol Bay Energy Region consists of a wide variety of older, Mesozoic rock types. In the northern part of the region, outcrops include mostly metamorphic and igneous basement and complexly to pervasively deformed sedimentary to low-grade metamorphic rocks. Southeast of the Bruin Bay fault system, along the southeast side of the Alaska Peninsula, most bedrock comprises moderately folded and faulted Mesozoic sedimentary formations that were never buried to great depths and have maintained relatively lower thermal maturity. Two of the older formations in this succession include excellent oil and gas source rocks, and the youngest unit contains potential coal resources. The youngest bedrock units in the Bristol Bay region are the volcanic and associated sedimentary rocks formed by eruptions of the Aleutian arc volcanoes within the last 10 million years (summarized from Kirschner, 1988; Beikman, 1980).

GEOLOGIC ENERGY RESOURCE POTENTIAL IN THE BRISTOL BAY ENERGY REGION

Mineable coal resource potential

Significant coal resources occur only in the Alaska Peninsula region of the development area. The main coal-bearing area is the Chignik Field, near Chignik Bay (fig. D2). Nearby villages include Ivanof Bay, Chignik, Chignik Lake, Chignik Lagoon, Perryville, Port Heiden, Ugashik, Pilot Point, and Egegik.

Chignik Field. Coal in the Chignik Bay area occurs primarily in the Coal Valley Member of the Late Cretaceous-age Chignik Formation, with less abundant coal occurrences in the Paleocene–Early Eocene Tolstoi Formation. The Chignik Field extends for approximately 25 miles along the northwest shore of Chignik Bay, amounting to about 50 square miles of coal-bearing rocks (fig. D2; Merritt and McGee, 1986). Principal coal deposits in the Chignik Formation occur in a 1- to 3-mile-wide swath best exposed along the Chignik River, Whalers Creek, Thompson Valley, and Hook Bay, and in the areas of the Anchorage, Amber, and Nakalilok bays (Merritt and McGee, 1986; Detterman and others, 1984). The Alaska coal mined land inventory lists four mines in the Chignik area that were active to some degree in the late 1800s to early 1900s (Plangraphics, 1983). The Chignik River mine opened in 1893 and operated for at least 12 years to supply coal to a nearby cannery (Plangraphics, 1983). Activity on the Hook Bay mine was begun in 1908 (Plangraphics, 1983), however there is no data on actual coal production from these mines. Coals in these areas are ranked as high-volatile B bituminous with high ash content (~20 percent), low sulfur content, and raw heating values that range widely from approximately 5,500 to 12,500 Btu. After washing, this value may increase on average to more than 12,000 Btu with an ash content of less than 12 percent.

Peninsula-wide, it is estimated that there are 14 beds in the Chignik Formation that are greater than 14 inches thick. Individual coalbeds in the Chignik Field range in thickness from approximately six inches to 4.5 feet (Conwell and Triplehorn, 1978). Conwell and Triplehorn (1978) allude to possibly 8 square miles of recoverable coal from the Chignik Formation in the Chignik River area, amounting to about 60 million tons. Detterman and others (1984) conducted a

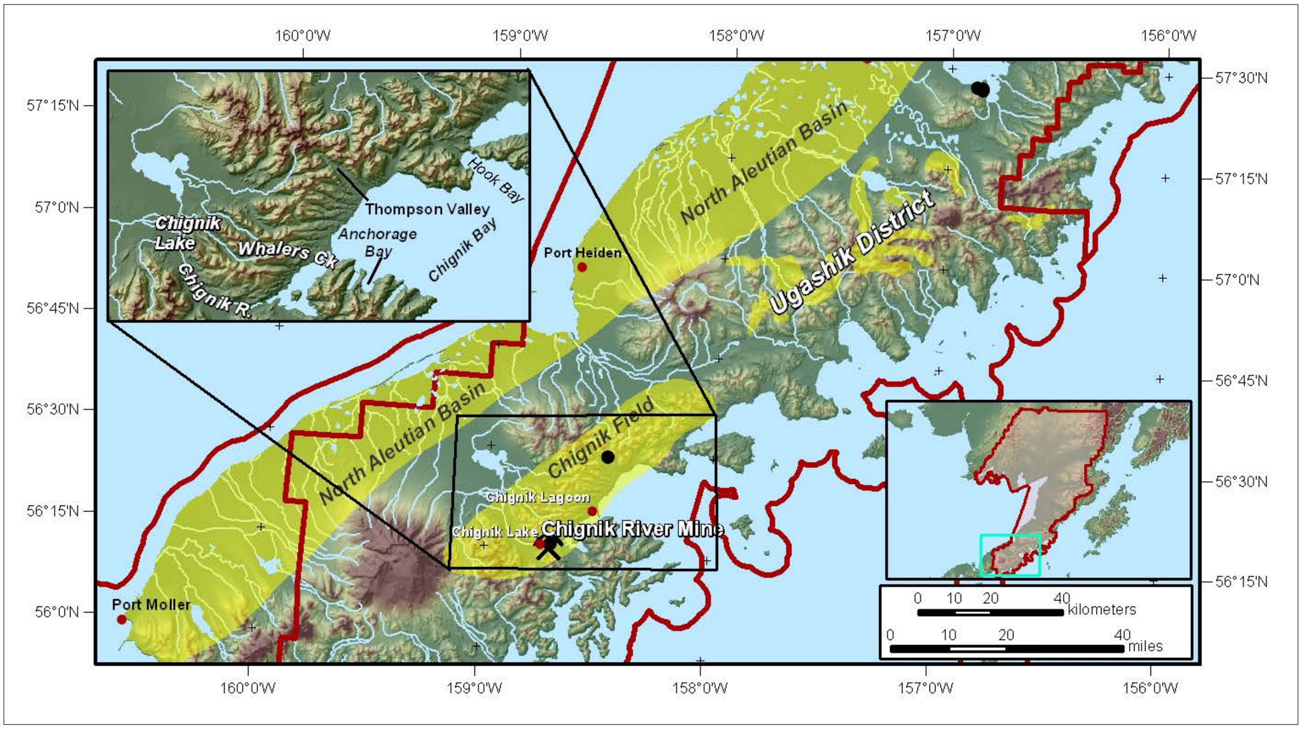


Figure D2. Location map of the southwestern Bristol Bay Energy Region, showing selected geographic references noted in the text (note inset detailed map of the Chignik Bay area). Black dots indicate reported coal occurrences; pick-axe symbol indicates location of a historic coal mine; yellow shaded areas are inferred to be underlain by coal-bearing rocks.

reconnaissance study in the Chignik area and estimated 242 million tons of inferred coal resources. Of the total resources, 56.4 million tons are estimated for the Chignik River area, 62.6 million for the Anchorage Bay area, 49.9 million for the Thompson Valley–Hook Bay areas, and 73.1 million for the Nakalilok Bay area (fig. D2). There are an estimated 430 million short tons of identified coal, and over 3 billion short tons of hypothetical coal Peninsula-wide, including the Herendeen Field in the Aleutian Energy Development Region to the south (Merritt and Hawley, 1986).

Coal quality and thickness vary greatly, both laterally and from bed to bed (Conwell and Triplehorn, 1978). Rocks of the Chignik Formation have also undergone multiple episodes of folding and faulting and, as a consequence, coalbeds along the Chignik River pinch and swell steeply-dipping faults (Merritt and McGee, 1986). Coalbeds in the Thompson Valley area have been alternately reported as mildly deformed (Merritt and McGee, 1986) to intensely deformed (Tyler and others, 2000). The lateral equivalent of coalbeds found along Chignik Bay also occur several miles inland, but are thinner and steeply dipping at the ground surface. These factors will complicate extraction of the coal, since single beds may not be traceable over long distances and may require underground mining in areas that may be prone to saltwater invasion. However, the field's close proximity to tidewater may also be an advantage for transportation of coal to market. Geologic field mapping of the Chignik Field with measurement of stratigraphic sections, and a well-conceived reconnaissance exploratory drilling program are required to better estimate the coal reserves in the area.

Other occurrences. Thin coalbeds have also been observed in the headwaters of the Kanektok River approximately 60 miles north of the village of Togiak on the north shore of Bristol Bay (fig. D3; Roehm, 1937), but they are low-grade lignite and not likely to be a significant source of energy. Isolated coal occurrences of unknown extent are reported near Puale Bay and Cape Douglas (lignite), and Amalik Bay (bituminous) by Merritt and Hawley (1986). Merritt and Hawley (1986) also depict a Ugashik coal district southeast of Ugashik Lakes (fig. D4) in what are Chignik and Tolstoi Formation strata, although mention of the district does not appear in prior or subsequent reports. Nonetheless, a local resident in the Ugashik Lakes area reported a 6- to 8-foot-thick coalbed near Old Creek (Roland Briggs, 2009, written commun.); although the rank and quality of this occurrence have not been evaluated, it may suggest a more significant coal resource in the region.

Conventional oil and gas resource potential

As explained in the discussion of requirements for exploitable oil and gas resources (Chapter A), functioning petroleum systems occur in thick sedimentary basins, and consist of three basic elements: Effective source rocks, reservoirs, and traps. Each of the elements must be in

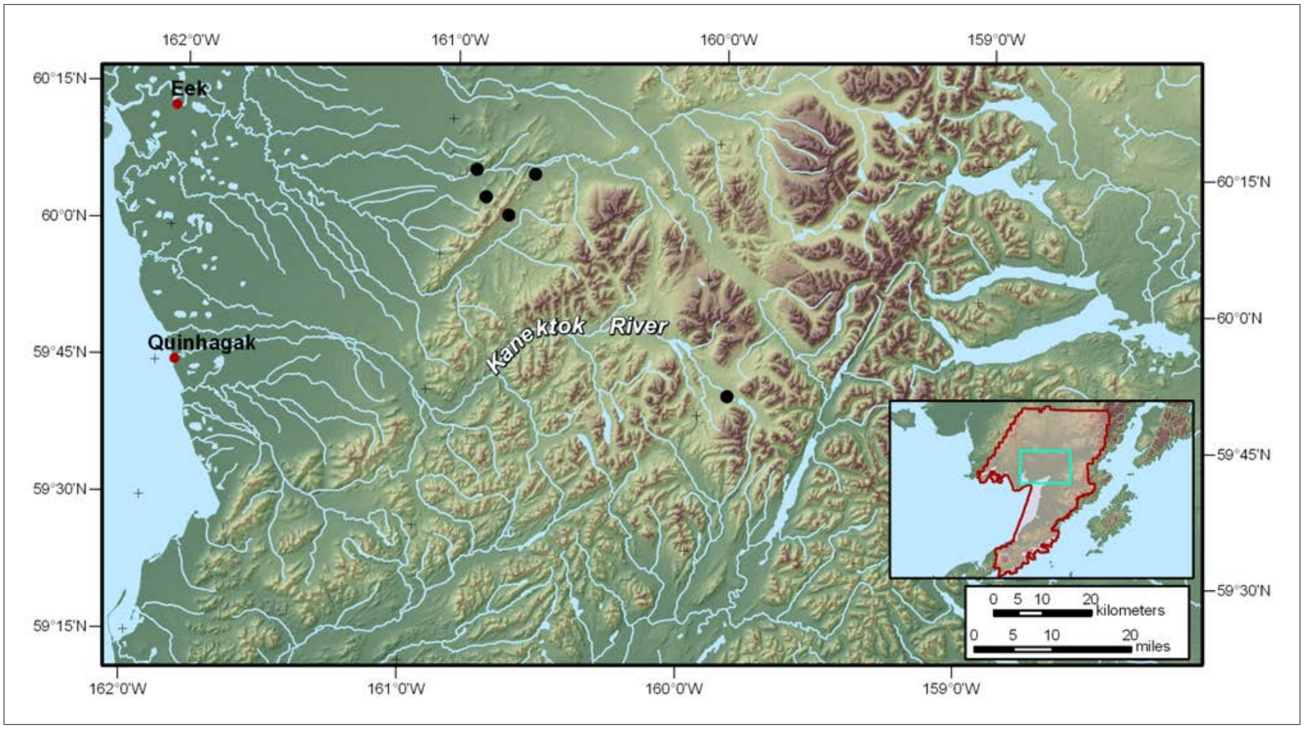


Figure D3. Location map of the central Bristol Bay Energy Region, showing reported coal occurrences (black dots) discussed in the text.

existence and connected by migration pathways at the time hydrocarbons are generated. This section considers each of these necessary elements of petroleum systems in turn to evaluate whether conventional oil and gas resources may play a role in supplying rural energy in the Bristol Bay Energy Region.

Distribution of sedimentary basins. Sheet 2 illustrates the distribution of Tertiary sedimentary basins (after Kirschner, 1988) that could potentially host petroleum systems in and near the Bristol Bay region. Other areas are underlain by igneous, metamorphic, or thermally overmature sedimentary rocks that are incapable of supporting a petroleum system. Geophysical data and limited exploration drilling demonstrate that the North Aleutian basin is the largest, thickest, and most likely to contain effective source rocks, reservoir rocks, and hydrocarbon traps, particularly along its southern margin near Nelson Lagoon and Port Moller. The northern part of the basin that extends into the Nushagak–Bristol Bay Lowlands near Naknek and Dillingham is much thinner and is unlikely to contain exploitable oil or gas accumulations because of low thermal maturity and limited source rock potential. Entirely offshore to the southeast of the Alaska Peninsula are the Shumagin, Tugidak, and Shelikof basins, all of which are smaller, relatively shallow, and have attracted limited exploration interest.

Source rocks. Outcrop studies have documented oil-prone source rocks in the Mesozoic Kamishak and Kialagvik Formations (Wang and others, 1988; Decker, 2008). These units are known to exist only in the belt of sedimentary rocks with low thermal maturity southeast of the Bruin Bay fault system near the southeast border of the Bristol Bay Energy Region. These source rocks are not known to be present beneath the main part of the North Aleutian basin, and available data indicate they are also absent from the remainder of the Bristol Bay energy region (Sherwood and others, 2006; McLean, 1977, 1979; Decker, 2008). Geochemical data indicate Mesozoic sources generated the oil and gas that occurs in a cluster of natural seeps near Puale Bay and Wide Bay on the southeast side of the Alaska Peninsula (Magoon and Anders, 1992; Blodgett and Clautice, 2005). Migrated oil or gas derived from these Mesozoic sources have not been documented in the younger Tertiary formations of the North Aleutian basin.

Farther northwest in the lower Nushagak River drainage, occurrences of iridescent sheen on standing water in boggy environments have been mistaken for oil seeps. Field studies and laboratory analyses have shown that the sheen observed in many of those locations is due to natural bacterial iron oxide films common in swampy settings and surficial peats, rather than oil seepage from the subsurface (Decker and others, 2005; Miller and others, 1959). In another case, a thin sheen of oil on the Nushagak River itself was attributed to human pollution (Miller and others, 1959). These findings are consistent with regional geologic information that suggests a lack of oil-prone source rocks in the northern and western parts of the Bristol Bay Energy Region.

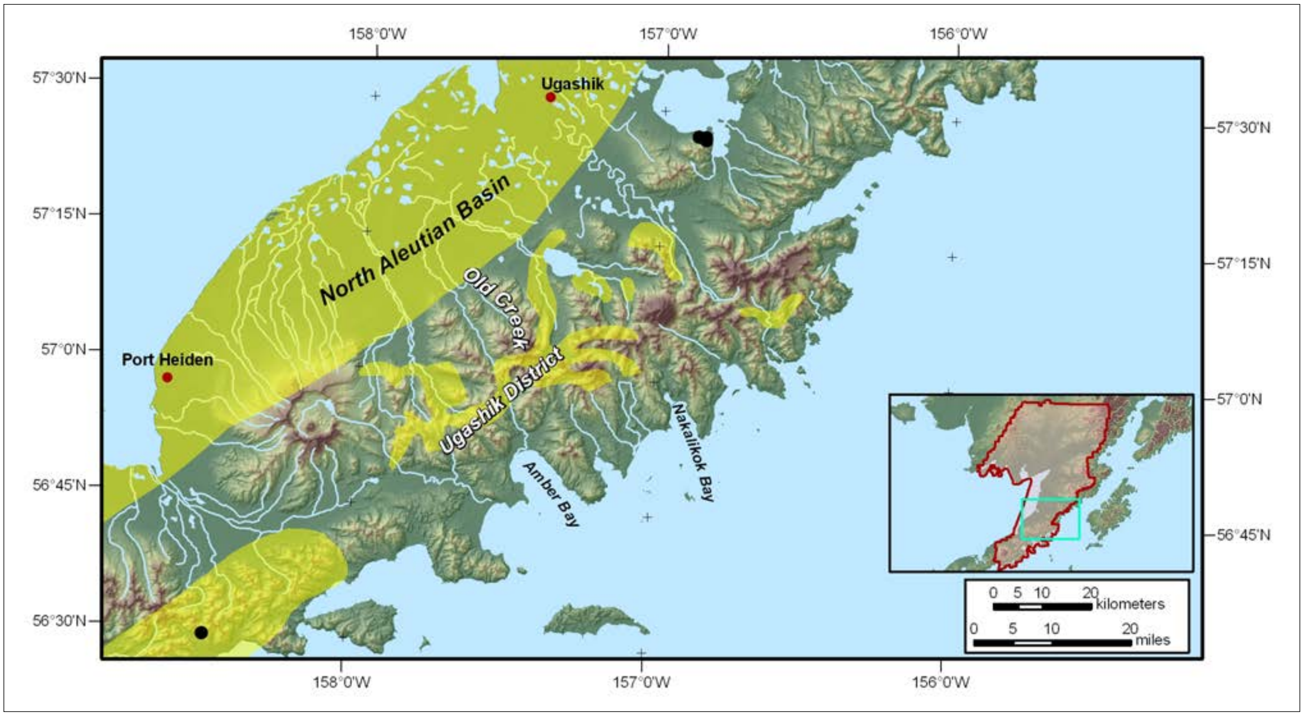


Figure D4. Location map of the south-central Bristol Bay Energy Region, showing selected geographic references noted in the text. Black dots indicate reported coal occurrences; yellow shaded areas are inferred to be underlain by coal-bearing rocks.

Outcrop and well control indicate that gas-prone source rocks are more widespread than oil-prone sources in the region, consisting of both shallow marine shales and nonmarine coaly strata of Tertiary age, notably in the Tolstoi, Stepovak, and Bear Lake Formations (McLean, 1987; Sherwood and others, 2006; Decker, 2008). Both biogenic and thermogenic gas may be present in some parts of the region's sedimentary basins. Exploitable accumulations of biogenic gas require recent uplift to migrate the gas into conventional reservoirs (Chapter A). This type of uplift may have occurred along the southern edge of the North Aleutian basin on the northwest side of the Alaska Peninsula but additional seismic and exploration drilling is required to substantiate..

The most promising area for thermogenic gas charge in the Bristol Bay Energy Region is beneath the Bristol Bay Lowlands near the southeastern margin of the North Aleutian basin (sheet 2). Between Egegik and Ugashik, as well as southwest of Port Heiden, much of the lower part of the Tertiary basin-fill succession appears to be mature for hydrocarbon generation (Sherwood and others, 2006). The area between Ugashik and Port Heiden was a massive volcanic complex during early to mid Tertiary time (Sherwood and others, 2006; Decker and others, 2008), and is likely devoid of coals or other strata with hydrocarbon source potential.

Reservoir rocks. Several Tertiary formations in the North Aleutian basin have adequate thickness of sandstone with sufficient porosity and permeability to serve as reservoirs for either oil or gas. In particular, the Bear Lake Formation and parts of the Stepovak Formation have been widely observed to have good reservoir quality in outcrop and in wells that encountered it at depth (McLean, 1987; Turner and others, 1988; Sherwood and others, 2006; Decker and others, 2005, 2006). The younger Milky River Formation also maintains high porosity and permeability, although this unit may be too shallow to host effective traps or maintain sufficient reservoir pressure. Available data indicate many formations are affected by alteration of the sandstone after burial, potentially creating a challenge to preserving reservoir quality (Lyle and others, 1979; Turner and others, 1988; Helmold and others, 2008). For example, well tests of gas-bearing sandstones in these units in the Becharof #1 well documented low flow rates and weak flowing pressures, consistent with compromised permeability.

Mesozoic formations of the Alaska Peninsula south and east of the Bruin Bay fault contain thick sandstones and some limestones that, where favorably altered, could serve as hydrocarbon reservoirs. Existing analyses of the porosity and permeability remaining in these units is typically below thresholds necessary for conventional oil and gas production. However, these data represent a relatively modest set of subsurface (well) and outcrop samples. In special cases, early entrapment of hydrocarbons can prevent porosity destruction in sandstone reservoirs, and hydrothermal alteration can create secondary porosity in limestone formations.

However, available data do not suggest that these processes have been effective over significant parts of the Alaska Peninsula, indicating that identifying adequate reservoir quality in Mesozoic units may be a challenge. Further, if hydrocarbons are sequestered in reservoirs with low porosity and permeability, then significant stimulation techniques may be required to induce production.

Traps. The Alaska Peninsula and adjacent parts of the North Aleutian basin have undergone several episodes of deformation related largely to strike-slip processes during Tertiary time (Worrall, 1991; Detterman and others, 1996; Decker and others, 2005). Potential structural traps vary from simple anticlines to structurally complex folds and faults that may create traps for gas in the subsurface (Sherwood and others, 2006; Decker and others, 2008). These types of structures are best imaged in the offshore region, which has more dense seismic data coverage. The structural framework in onshore areas is generally insufficiently understood at present to define specific trapping geometries. Stratigraphic and unconformity trap configurations may exist along the southeast margin of the basin beneath the Bristol Bay Lowlands. Low-permeability silty mudstones capable of sealing hydrocarbons accumulated in traps have recently been documented in several formations on the Alaska Peninsula (Bolger and Reifenstuhl, 2008), although their lateral extent is not well constrained.

Summary of conventional oil and gas resource potential. The North Aleutian sedimentary basin has the highest potential to host exploitable conventional petroleum resources in the Bristol Bay energy region. Although limited exploration hasn't resulted in a discovery, the basin is known to contain effective source rocks, reservoir rocks, and untested traps, especially in the federally managed Outer Continental Shelf acreage beneath Bristol Bay. Based on existing information, the most likely conventional hydrocarbon resource for local energy use would be gas derived from coaly Tertiary source rocks. This gas may form exploitable accumulations in Tertiary sandstones in structural or stratigraphic traps in offshore or nearshore areas of the eastern North Aleutian basin, particularly along the northwest side of the Alaska Peninsula, southwest of Port Heiden or between Ugashik and Egegik. Other parts of the North Aleutian basin are probably too shallow or dominated by volcanic rocks.

Unconventional oil and gas resource potential

Coalbed methane. In the Bristol Bay region, coal primarily occurs in the Coal Valley Member of the Chignik Formation, with minor occurrences in the Tolstoi Formation. The Chignik field includes the most extensive coal-bearing exposures in the region, covering approximately 39 square miles (Merritt, 1986). Individual coalbeds in outcrop are relatively thin, ranging from 6 inches to 4.5 feet, and occasionally up to 8 feet thick (Merritt and McGee, 1986). Most analyses indicate a bituminous rank, except where altered by localized areas of high heat flow (Merritt and others, 1987). The Chignik area was evaluated for its coalbed methane potential by Smith (1995) and Tyler and others (2000). Both studies concluded the area was relatively unfavorable for exploration and development at the time, largely due to geologic complexity. Nevertheless, limited subsurface data from the area are promising, most notably significant gas shows in oil exploration wells where coal seams were encountered (Smith, 1995).

Scattered thin coals are also present in the Ugashik district although less is known about the thickness and aerial distribution of these occurrences. Based on available data these coals are probably insufficient in thickness and extent to support coalbed methane development.

Tight gas sands. A majority of Neogene sandstones in the North Aleutian basin have not been buried deep enough to reduce reservoir quality into the range considered typical for tight gas sands. Measured porosities are often in excess of 20 percent and permeabilities greater than 10 millidarcys (mD) have been measured in samples from both outcrop and subsurface core from the Milky River, Bear Lake, and Unga Formations (Helmold and others, 2008). Some of the Paleogene sands (Stepovak and Tolstoi Formations) have undergone sufficient compaction and cementation to significantly degrade reservoir quality. Porosities of 10 percent are common in these sandstones with permeabilities in the range of 0.1 to 10 mD. These rocks are more lithified than the Neogene sandstones and could represent tight reservoirs along the southern margin of the North Aleutian basin.

Many of the Mesozoic sandstones in the Bristol Bay region, in particular the Herendeen, Staniukovich, and Naknek Formations, have been relatively deeply buried and have undergone significant compaction and cementation. Porosities are typically less than 10 percent and permeabilities less than 0.1 mD are routinely recorded. These older, more lithified sandstones have potential as tight gas sands, particularly those that may have been naturally fractured and underwent burial diagenesis. Extensive regional fractures have been observed in outcrops of some of the Mesozoic sandstones, especially the Naknek Formation. These fractures are typical of tight gas sands and may well signal the presence of an unconventional, fractured reservoir. Furthermore, these Mesozoic sandstones overlie several candidate hydrocarbon source rocks that could provide the necessary charge to fill an adjacent tight reservoir.

Shale gas. One of the primary requirements for shale gas is an organic-rich source rock present in the thermogenic gas window that is brittle enough to host a natural fracture system. As noted above, the most promising area for thermogenic gas charge in the Bristol Bay energy region is beneath the Bristol Bay Lowlands. Burial depth estimates for the lower part of the Tertiary stratigraphy suggest it should be in the gas window, but insufficient data are available to assess the presence of a well-developed fracture system necessary for efficient shale gas production.

Mesozoic source rocks appear to be restricted to the southeastern coastal areas of the region and outcrop and well data indicate they are most likely oil prone (Decker, 2008). Although associated gas is possible, available information suggests shale gas potential is limited. However, recent advances in drilling technology have resulted in the production of oil directly from this type of oil-prone source rock (termed shale oil). Although this resource type has never been considered in this region, the high quality of the Triassic and Jurassic source rocks indicates that hydrocarbons may be reservoired directly in their source rock.

Gas hydrates. The main occurrences of gas hydrates in nature are in modern marine sediments and in arctic regions with a well-developed, continuous permafrost. Permafrost is not well developed in the Bristol Bay Energy Region and is discontinuous where locally present. Consequently the potential for economic concentrations of gas hydrates is low.

Geothermal resource potential

Geothermal prospectivity in the Bristol Bay Energy Region is limited to the southern and eastern parts of the area, between Katmai National Park and Stepovak Bay. Two thermal springs with surface discharge temperatures of 73°F (23°C) and 151°F (66°C) are present in the region. The most promising geothermal feature in the region is the Mother Goose hot spring system, located at the northwest base of Mount Chiginagak. The largest Mother Goose spring discharges 151°F (66°C) water at a rate of >106 gallons per minute into a small stream that feeds into Volcano Creek (Motyka and others, 1994). Stream flow and temperature measurements indicate thermal water is discharged from the entire Mother Goose hot spring system at a rate of >1,321 gallons per minute (Motyka and others, 1994). The springs are near the contact of the Mount Chiginagak volcanic rocks and the underlying fossiliferous, feldspathic sandstone of the Cretaceous-age Staniukovich Formation (Motyka and others, 1994). The closest community is Ugashik, located 27 miles northwest of Mother Goose hot spring.

The Aniakchak thermal spring has a discharge temperature of 73°F (23°C) and emanates from near an old volcanic vent and flows into Surprise Lake, in the northeast part of Aniakchak caldera (Motyka and others, 1994).There are also numerous fumarole fields in Katmai National Park surrounding the site of the Valley of 10,000 Smokes, where Novarupta volcano deposited up to 700 feet of ash during a massive eruption in June 1912. Today there are at least seven fumarole fields actively steaming in the area, at temperatures of up to 212°F (100°C) (Motyka and others, 1983). Geothermal gradients established by temperatures taken in deep oil and gas exploratory wells show a normal heat flow in most of the region, except in local areas near volcanic centers.

RECOMMENDATIONS

Conventional oil and gas resource recommendations

Previous reconnaissance-scale geologic fieldwork has established the framework geology of the Alaska Peninsula (Detterman and others, 1996). However, significant improvements in our understanding of the region's petroleum potential could be achieved with additional detailed field mapping and stratigraphic studies. This type of work would build on the successful recent topical studies of the Alaska Peninsula by DNR geologists (Reifenstuhl and Decker, 2008).

The petroleum industry has expressed clear interest in exploring federal waters of the southern North Aleutian basin, which is considered prospective for commercial-scale natural gas accumulations (Anchorage Daily News, 2005; Shell Exploration and Production, 2008). A significant discovery could potentially make gas available to markets in the Bristol Bay energy region, although this cannot occur until offshore federal leasing is reinitiated. Industry has shown only moderate interest in exploring leasable state acreage onshore and beneath state waters. These lands have been available for leasing since 2005 through the Alaska Peninsula areawide lease sale. Acquisition of high-quality modern seismic data would be required to determine whether there are exploration prospects on currently accessible lands that would be worth evaluating by drilling. New industry-led exploration would improve knowledge of the prospectivity of state lands and any commercial discovery may have the potential to supply affordable energy resources to nearby communities.

Unconventional oil and gas resource recommendations

Coalbed methane. The Chignik area does possess coal of sufficient rank to host coalbed methane. The presence of gas in these coal seams was confirmed by significant mud log gas shows encountered during oil exploration drilling. However, compilations of available data conclude that stratigraphic and structural complexity poses a significant challenge to coalbed methane exploration or development (Smith, 1995; Tyler and others, 2000). Prior to any exploration drilling, it is recommended that substantial geologic fieldwork be conducted in the area, including detailed geologic mapping, structural studies, and analysis of lateral changes in sedimentary units.

Tight gas sands. The possibility exists for encountering fractured tight gas sands in portions of the Mesozoic section in the region, although available data suggest the probability of recovering commercial quantities of gas is low. In terms of unconventional resources, tight gas sands have the highest likelihood of providing producible quantities of hydrocarbons for local use. Nevertheless, this type of resource has not been extensively evaluated in the region and it would be difficult to entice commercial exploration for tight gas sands in this remote region. Although local exploration may succeed in identifying a resource, developing this type of unconventional play typically involves significant drilling and stimulation costs that could challenge its economic viability as a local source of energy.

Shale gas. Prior geologic investigations have not documented extensively fractured source rocks that are in the thermogenic gas window. The likelihood of finding commercial quantities of shale gas in the region is low and no further action is recommended at this time. However, unconventional shale oil has never been evaluated in the region and the high quality of oil-prone Mesozoic source rocks may warrant further geologic study to determine their potential.

Gas hydrates. Due to the lack of extensive, continuous permafrost in most of southern Alaska, the likelihood of finding gas hydrates in the region are very low, therefore no further action is recommended.

Coal resource recommendations

Coals from the Chignik Field offer the greatest potential to produce an economic resource. Prior work has established the presence of an extensive resource with appropriate coal quality. However, available information suggests the stratigraphic and structural complexity of the area would pose a challenge to any effort to exploit this resource for local energy use. A robust assessment of the coal potential of the Chignik region would require significant geologic mapping and topical stratigraphic studies of the coal-bearing section. Although these investigations should be a necessary precursor to any exploratory program, ultimately subsurface drilling data would likely be required to delineate the resource and accurately appraise the economic viability of potential resource development. Available information suggests coals from other areas in the region are unlikely to represent an exploitable resource. However, prior work has been largely reconnaissance in nature, and additional field studies of the local geology could improve our knowledge of the potential for mineable coal in regions like the Ugashik Lakes area.

Geothermal resource recommendations

Evidence for elevated subsurface heat flows in the Bristol Bay Region is closely associated with the Aleutian volcanic arc. Of the two thermal springs in the region, only Mother Goose has a discharge temperature >100°F (38°C). Steaming ground fumaroles and boiling-lake fumaroles are also abundant in the Mount Katmai region. However, these indications of active hydrothermal systems are currently located on protected federal lands and not available for development. In addition, the distance between population centers and known occurrences of elevated subsurface temperatures will be a limiting economic factor for geothermal exploration or development of any potential resource for local energy use.

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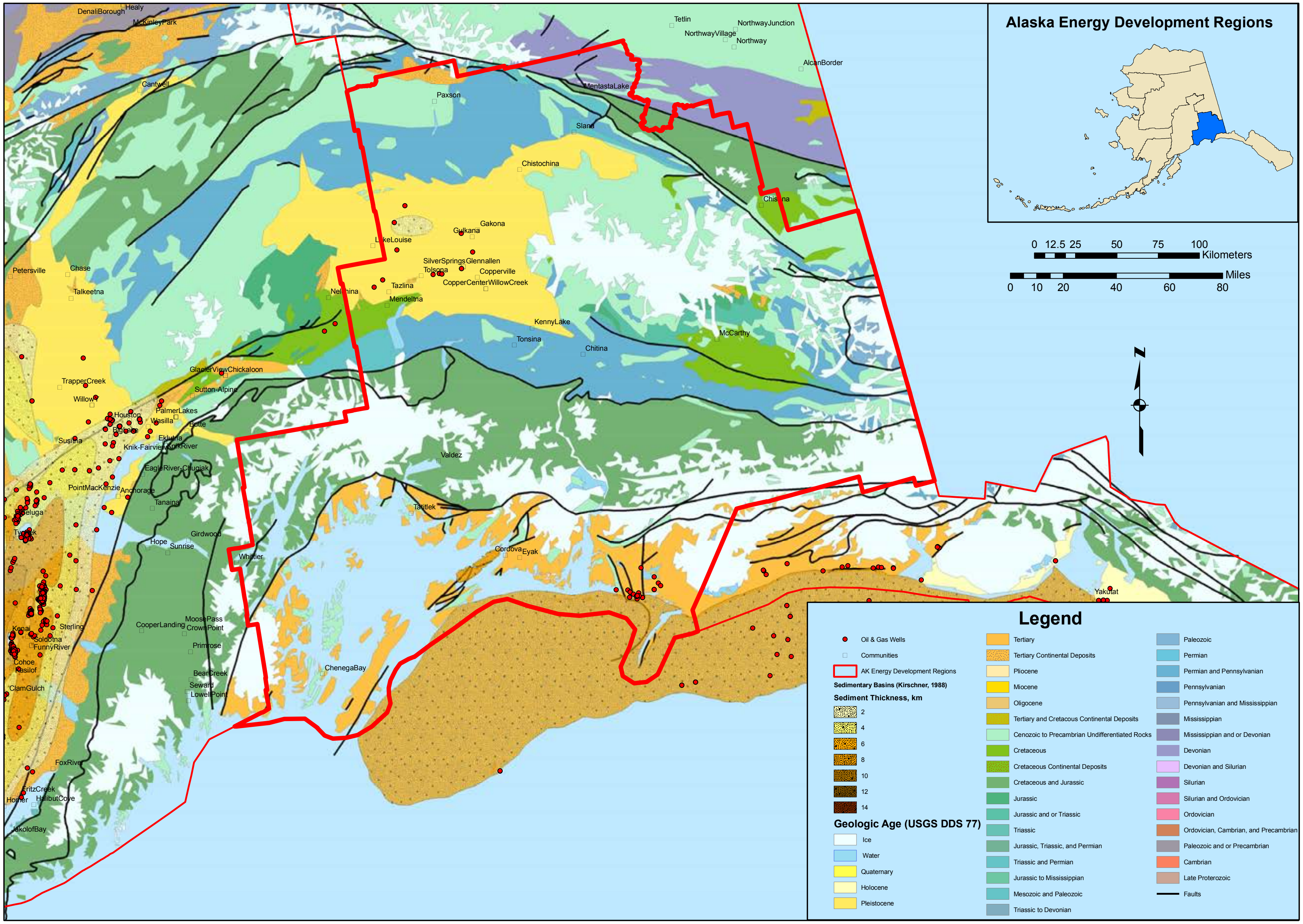
Bristol Bay

Geology of the Copper River/Chugach Energy Region, Alaska



SUMMARY OF FOSSIL FUEL AND GEOTHERMAL RESOURCE POTENTIAL IN THE COPPER RIVER–CHUGACH ENERGY REGION

by Paul L. Decker, Robert J. Gillis, Ken Helmold, and Shaun Peterson

INTRODUCTION

Purpose of this report

Economic growth and stability in Alaska's rural and urban areas hinges partially, if not primarily, on the availability of affordable and sustainable energy supplies. Recent price increases in oil and gas commodities have created severe economic hardship in many areas of the state that are dependent on diesel and heating oil as their primary source of energy. All sectors of Alaska's economy rely on affordable energy sources with limited price volatility, highlighting the need to diversify the energy portfolio by developing locally available and sustainable resources that are not tied to the global market. Unfortunately, all areas are not created equal in energy accessibility; the resources available for local exploitation vary widely across the state. It is critical that funding decisions for expensive programs to reduce the dependence on diesel for heat and electricity take into account information concerning the entire suite of natural resources that exist in a given area.

This report draws from existing information to provide community and state leaders an objective summary of our current knowledge concerning the potential of locally exploitable fossil fuel and geothermal energy resources in the Copper River–Chugach Energy Region (fig. E1), one of 11 regions recognized by the Alaska Energy Authority in their Energy Plan (AEA, 2009). The potential geologically hosted energy resources considered here include exploitable coal, conventional and unconventional oil and gas, and geothermal resources. This report concludes with recommendations as to what additional data or strategies, if any, would provide the most leveraging in helping to develop new energy resources in the region.

Readers without geological training are encouraged to peruse the geologic summaries of fossil fuel resources and geothermal energy in chapter A. They provide an overview of the geologic elements that must be present in an area to economically develop coal, conventional oil and gas, unconventional oil and gas, and geothermal resources. These summaries will provide the necessary background to more fully understand the information presented in this chapter.

Geographic and geologic setting

The Copper River–Chugach Energy Region of southeastern central Alaska extends roughly 160 miles north–south between the town of Paxson and the north Pacific coastline and approximately 180 miles east–west between the Canada border and the town of Tazlina (sheet 1). Included in this region are the Wrangell, Saint Elias, and Chugach mountains and Prince William Sound. The region's largest communities are the fishing towns of Valdez, with a current population of more than 4,300 residents and Cordova with nearly 2,200 residents. Glennallen and Kenny Lake are the

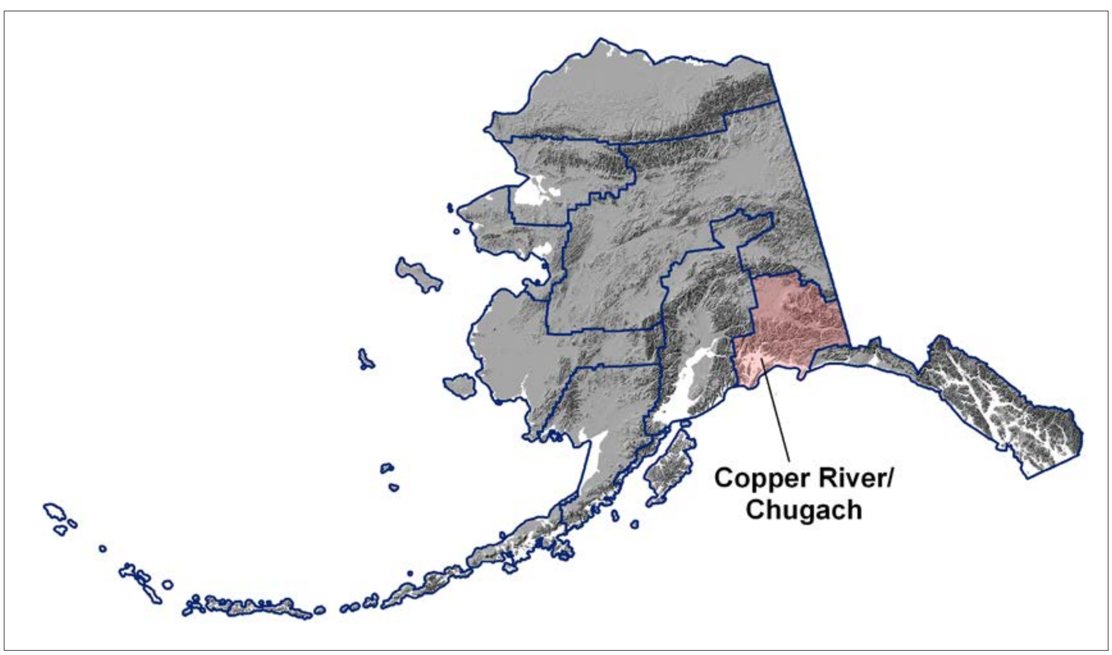


Figure E1. Location map, Copper River–Chugach Energy Region.

largest of 15 communities with populations of 100–500 residents. Smaller populations occupy at least nine smaller permanent villages.

Geography of the Copper River–Chugach Energy Region is dominated by the Wrangell, Saint Elias, and Chugach mountain ranges in the southern and western portions of the region and the Copper River and northwestern Gulf of Alaska basins in the central and southern portions of the region. The mainland along the northern Gulf of Alaska consists of alluvium- and glacier-covered coastal lowlands 0–25 miles wide, backed by a belt up to 25 miles wide of rugged foothills rising to 6,600 feet (Plafker and others, 1994). These foothills are bordered to the north by the exceedingly rugged Chugach and Saint Elias mountains (Plafker and others, 1994). The geology of the region is dominated by three major crustal blocks commonly referred to by geologists as terranes. A terrane is a fault-bounded crustal block with geologic characteristics that are distinctly different from neighboring terranes. These terranes include the Yakutat, Wrangellia composite, and Southern Margin composite terranes which, through plate tectonic processes since Cretaceous time, were accreted to inboard terranes comprising the interior of Alaska. The Yakutat terrane is a thick sequence of Cenozoic clastic marine and nonmarine sedimentary rocks underlain partly by an offset fragment of the Chugach terrane and partly by Paleogene oceanic crust (Plafker and others, 1994). The Wrangellia composite terrane, composed of several smaller terranes, including the Peninsular, Alexander, and Wrangellia terranes, consists dominantly of Paleozoic- and Mesozoic-age arc-related magmatic and sedimentary rocks (Plafker and others, 1994). The Southern Margin composite terrane is composed of deep-marine rocks south of the Border Ranges fault and consists of the Chugach and Prince William terranes, the Ghost Rocks Formation and late Cenozoic accreted rocks (Plafker and others, 1994). Cenozoic-aged strata, which are most prospective for conventional and unconventional resources in this region, occur primarily in two sedimentary basins in the region (sheet 2). The northern Gulf of Alaska basin is largely offshore, but also includes sedimentary rocks exposed onshore near the coast. This basin includes a Cenozoic-age sedimentary succession between 9,800 and 16,400 feet thick; outcrops are scattered throughout the region, including Prince William Sound, Cordova, and east of the Copper River delta along the northern Pacific coast east of the sound (Kirschner, 1988). This basin developed on older rocks of the Yakutat and Southern Margin composite terranes. The Copper River basin, where there has been recent interest in oil and gas exploration, contains Cenozoic sediments between 0 and 9,800 feet thick (Kirschner, 1988). This basin is underlain by Paleozoic- and Mesozoic-age rocks of the Wrangellia composite terrane.

GEOLOGIC ENERGY RESOURCE POTENTIAL IN THE COPPER RIVER–CHUGACH ENERGY REGION

Mineable coal resource potential

Coal resources in the Copper River–Chugach Energy Region occur mostly in the Bering coal field (fig. E2), where coal has a relatively high rank and bed thicknesses can reach tens of feet. The Bering River coal field is located along the tributaries to the Bering River approximately 12 to 25 miles inland of Controller Bay, and approximately 35 miles to the east of the mouth of the Copper River. The field encompasses about 70–80 square miles with an estimated 160 million short tons of identified resources, and 3.5 billion short tons of hypothetical resources (Merritt, 1988). Coal resources in the Bering River field are concentrated at Carbon Creek, Trout Creek/Clear Creek/Cunningham Ridge, and Carbon Mountain (fig. E2). Coal-bearing strata occur in Middle–Late Eocene- to Early Oligocene-age Kushtaka Formation strata (Martin, 1908; Wolfe, 1977), subsequently mapped as Kulthieth Formation by Winkler and Plafker (1993). Coals in these rocks range in rank from subbituminous in the western part of the field to anthracite in the eastern region, and thus on average have relatively high heating values, averaging around 14,000 Btu, with medium ash and sulfur contents. Coal in the Bering River field may be best represented in the Carbon Creek area, where beds commonly occur in thicknesses of 5 to 10 feet, with some seams 30 to 60 feet thick (Merritt, 1988). Some coal beds are laterally discontinuous and sheared due to local folding and faulting. Although this structural complexity would inhibit successful mining, other areas in the field exhibit continuous coal beds for two or more miles (Martin, 1908).

Other known coal deposits in the Copper River–Chugach Energy Region are principally small, scattered occurrences of probable Eocene- to Miocene-age lignite exposed on the flanks of the Nutzotin and Wrangell mountains and southern foothills of the Alaska Range. Lignite exposures of limited aerial extent are reported to occur in tributaries to Beaver and Rocker creeks on the northeast flank of the Nutzotin Mountains, near the international border with Canada (Capps, 1915), an area that is also near the boundary with the Yukon–Koyukuk–Upper Tanana development region. Lignite also occurs on the southern flank of the Wrangell Mountains northeast of McCarthy near the head of the Chitistone River (Moffit and Knopf, 1910), and perhaps the head of Chisana Glacier (Merritt and Hawley, 1986) in the Wrangell–St. Elias Wilderness area, and to the southwest of Kennicott Glacier (Henning and Dobey, 1973; Merritt and Hawley, 1986). Henning and Dobey (1973) considered this entire area to be of low coal potential, although little is known about the coal resources in each of these areas.

The potential for mineable coal resources along the southern foothills of the eastern Alaska Range is poorly known. Coals in this area are from the Eocene-age Gakona

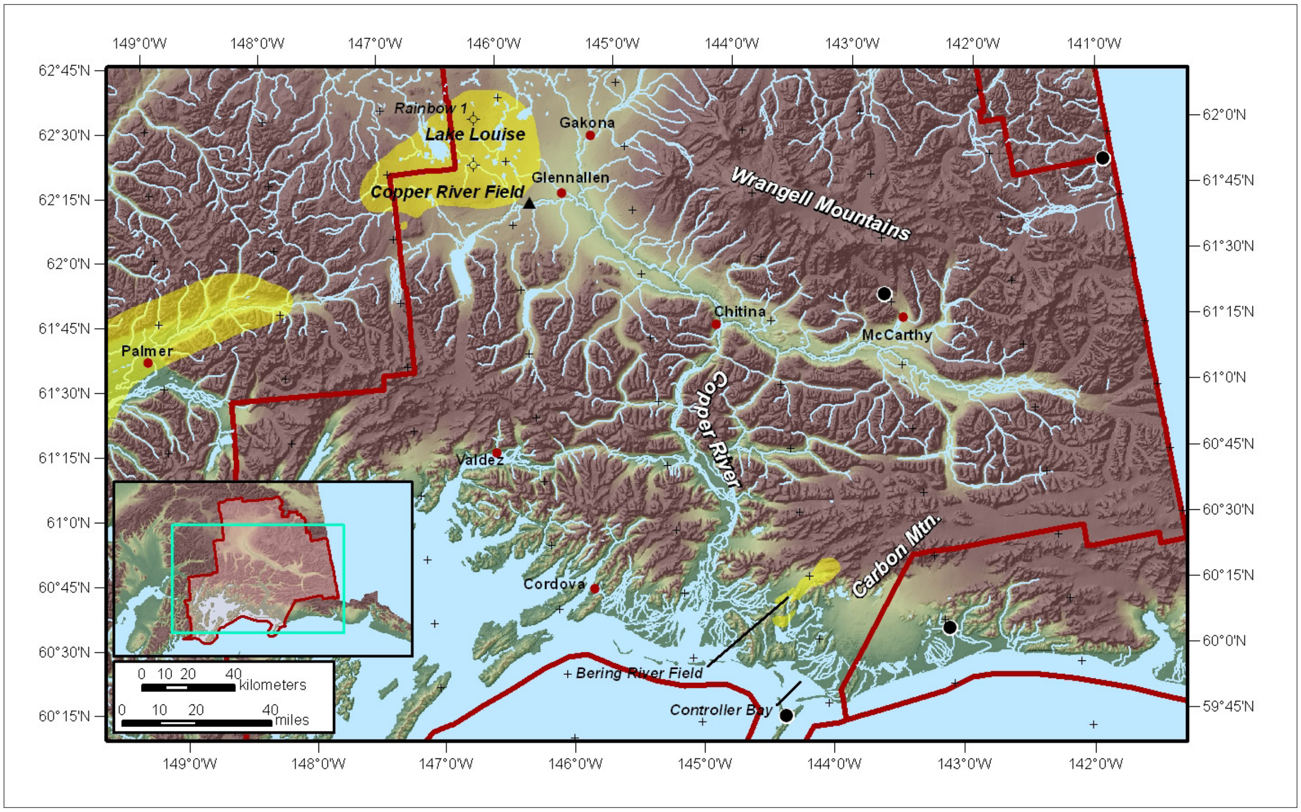


Figure E2. Location map of the Copper River–Chugach Energy Region, showing selected geographic references noted in the text. The black triangle indicates the location of the methane-emitting Tolsona group of mud volcanoes; black dots indicate reported coal occurrences; yellow-shaded areas are inferred to be underlain by coal-bearing rocks.

Formation (Mendenhall, 1905), and are also lignite in rank. Beds are reportedly up to 30 inches thick, but are likely of limited lateral extent (Moffit, 1954). Principal exposures occur near the range front along the Delta, Gulkana, Gakona, and Chisana river drainages (Moffit, 1954), although lignite beds presumably continue into the subsurface for some distance southward into the Copper River basin (sheet 2; fig. E2). A number of oil and gas exploration wells drilled in the Copper River basin have encountered lignite seams. Shallow Tertiary sedimentary rocks in the Salmonberry No. 1 and Rainbow No. 1 wells contain low-rank coal in individual seams up to 30 feet thick, and at depths of between 700 and 2,000 feet (Crick and Lian, 1970). Near Lake Louise, the lignite is near the surface and has been encountered at shallow depths in water wells drilled in the area (J. Clough, oral commun., 2012). In the middle of the Copper River basin, Merritt and Hawley (1986) depict a poorly constrained, but sizable lignite field in Miocene-age sediments in the Lake Louise area (fig. E2).

Conventional oil and gas resource potential

As explained in the discussion of requirements for exploitable oil and gas resources (see Chapter A), functioning petroleum systems occur in thick sedimentary basins, and consist of three basic elements: effective source rocks, reservoirs, and traps. Each of the elements must be in existence and connected at the time hydrocarbons are generated. This section considers each of these necessary elements of petroleum systems in turn to evaluate whether conventional oil and gas resources may play a role in supplying rural energy in the Copper River–Chugach Energy Region.

Overview of sedimentary basins. Sedimentary basins that may be capable of sustaining effective petroleum systems in the Copper River–Chugach region include the Copper River basin and the northwestern part of the Gulf of Alaska basin (sheet 2; fig. E2). Neither basin currently supports commercial oil or gas production, but recent gas exploration has been undertaken in the Copper River basin, and the Katalla oil field in the northern Gulf of Alaska basin was the site of shallow, small-scale commercial oil production from 1902 to 1932. These two sedimentary basins are entirely separate from each other and were formed at different times in response to the plate tectonic processes that assembled numerous different crustal blocks or terranes to form the complex geologic mosaic of southern Alaska. Other parts of the Copper River–Chugach Energy Region are underlain by igneous, metamorphic, or thermally overmature sedimentary rocks that are incapable of hosting exploitable accumulations of oil and gas.

The Copper River basin includes Cenozoic strata less than about 65 million years old that reach thicknesses of up to approximately 1 kilometer (sheet 2; Kirschner, 1988, 1994). These younger strata overlie older Mesozoic formations of the Peninsular terrane that are closely related to Mesozoic rocks of the Alaska Peninsula and Cook Inlet. These older rocks were originally deposited in ancestral basins south of their present location, and were slowly transported long distances northward by plate tectonic processes and ultimately sutured onto the previously assembled blocks of what is now interior Alaska (Silberling and others, 1992; Plafker and others, 1994).

In contrast, the Gulf of Alaska sedimentary basin (sheet 2) consists entirely of Cenozoic formations on Alaska's present-day southern continental margin. The most prospective lands for oil and gas exploration belong to the Yakutat terrane, a crustal block composed of Cenozoic sedimentary units up to 9 kilometers thick deposited on slightly older Cenozoic and Mesozoic basement. Geologic and paleomagnetic evidence indicate that the Yakutat block originated approximately 50 million years ago near the present-day coast of British Columbia, 1,100 to 1,800 kilometers south of its current position (Risley and others, 1992). Since then, plate tectonic processes have transported the Yakutat block north along the western edge of North America, resulting in collisional deformation and mountain building in southern Alaska that continues into modern times.

Source rocks. The hydrocarbon potential in the Copper River basin is likely gas. Of the 13 exploration holes drilled in the basin to date, a few of the easternmost wells have encountered mudlog shows of methane gas, but none reported significant indications of oil. Gases seeping from the Tolsona group of mud volcanoes and saline springs in the western part of the basin (fig. E2) contain methane in varying amounts ranging from <1 percent to more than 72 percent, in addition to noncombustible gases such as carbon dioxide and nitrogen (Motyka and others, 1986). Carbon isotopic signatures of nearly all the methane from these seeps suggest it is sourced from thermogenic and biogenic alteration of coal and lignite beds in late Mesozoic to early Cenozoic nonmarine units in the basin (Reitsema, 1979).

The Tuxedni Formation, the Mesozoic source rock for most of the oil in Cook Inlet reservoirs, is also present in the Copper River basin, but it is sandy and apparently not as oil-prone (Magoon and Valin, 1996). Several wells have encountered overpressured Mesozoic formations at depth that contain saline formation waters charged with methane. These subsurface units are believed to be hydraulically connected with some of the mud volcanoes and saline springs at the surface (Motyka and others, 1986). The two most recent wells drilled in the basin were on private Ahtna Native Corporation lands, so complete information is not publicly available, but reports of high-pressure gas-bearing zones suggest that follow-up work may be warranted (Petroleum News, 2007). Limited thermal maturity information for the Copper River basin indicates a relatively low geothermal gradient (Motyka and others, 1986), and with the exception of the Wrangell Mountains volcanic field on the basin's eastern edge, the petroleum generation window likely lies at depths below 8,000 feet (Magoon and Valin, 1996). Therefore, given the basin's limited thickness, most of the basin is immature to only marginally mature for oil and gas generation (Utah International, Inc., 1987; DGSI, 1995; unknown, 1995b, 1995c). This interpretation is further evidenced by the scarcity of significant shows encountered during drilling, and it remains unclear whether the Copper River basin has generated appreciable quantities of either biogenic or thermogenic hydrocarbons.

As noted above, the western segment of the Gulf of Alaska basin is the other area of oil and gas interest in the Copper River–Chugach Energy Region. The greatest petroleum potential is within the onshore portion of the Yakuta terrane; the crustal blocks of the Chugach Range and Prince William Sound to the north and west are devoid of source rocks and, for the most part, are thermally overmature. In the Katalla area, on the northwestern edge of the Yakutat block, natural oil and gas seeps and historic oil production from a shallow, fractured shale reservoir point to a petroleum system with moderate potential. Source rocks for onshore oil and gas seeps in the northern Gulf of Alaska region include shales of the Poul Creek Formation and coals of the Kulthieth Formation (Risley and others, 1992; Magoon 1994; Larson and Martin, 1998; Van Kooten and others, 2002). In the Katalla area, these source rocks range from early mature to overmature for hydrocarbon generation (Mull and Nelson, 1986).

Reservoir rocks. There is relatively little data available from the Copper River basin to estimate the subsurface extent of formations with sufficient porosity and permeability to serve as conventional oil or gas reservoirs. Published resource assessments invoke upper Mesozoic to lower Cenozoic sandstones as the most likely reservoirs (Magoon and Valin, 1996). These formations are near the top of the basin's stratigraphic succession, where it is thought they may have retained more porosity and permeability than older units buried to greater depths. The slightly older and overpressured Nelchina Formation has been targeted as a gas reservoir by recent drilling (Petroleum News, 2007), and further drill stem tests and other reservoir evaluation techniques will be required to determine whether this unit will be capable of sustained hydrocarbon production.

In the Gulf of Alaska basin, potential conventional reservoir rocks are restricted to the Yakutat block; other terranes are made up of highly altered formations with insufficient porosity and permeability. Reservoir candidates in the Yakutat terrane include wave-reworked sandstones of the upper Cenozoic Yakataga Formation, local sandstones in the upper part of the mid-Cenozoic Poul Creek Formation, and nonmarine to deltaic sandstones of the lower Cenozoic Kulthieth and Tokun Formations (Risley and others, 1992; Larson and Martin, 1998). In the part of the Gulf of Alaska basin in the Copper River–Chugach Energy Region, the reservoir quality of these formations is variable. The Yakataga Formation consists of poorly sorted glaciomarine beds with unstable mineralogy, but is known to maintain local zones of good porosity and permeability at depths below 11,000 feet in offshore wells (Larson and Martin, 1998). The Kulthieth Formation contains abundant sandstone with poor to moderate reservoir properties farther east in the Southeast Energy Region, but in the Copper River–Chugach Energy Region, it consists almost exclusively of fine-grained, non-reservoir rocks (or perhaps unconventional reservoirs). Finally, only locally does the Poul Creek Formation contain potential reservoir sandstones; it consists in large part of highly deformed silty to shaly rocks like those hosting the oil seeps and shallow fractured reservoir at Katalla. On the favorable side, the Kulthieth and Poul Creek Formations have the advantage that they also contain source rocks, increasing the likelihood that any potential reservoir sandstones may have received hydrocarbon charge.

Traps. Both the Copper River basin and the northern Gulf of Alaska basin have been strongly affected by faulting and folding accompanying compressional and strike-slip tectonics, creating numerous fold and fault structures that have the potential to trap hydrocarbons. Additional traps may be stratigraphic in nature, established by lateral variations in thickness, grain size, permeability, and other sedimentary characteristics inherent in these geologically complex settings. However, repetitive deformation commonly forms complicated structures that can create exploration and development challenges and limit accumulation sizes. Although several structures in the Gulf of Alaska were unsuccessfully tested by exploration wells, many promising and large structures remain undrilled (Risley and others, 1992).

Summary of conventional oil and gas resource potential. Only a limited number of exploration wells have been drilled in the Copper River basin, yet none have resulted in commercial discoveries. Although oil potential appears to be low (Magoon and others, 1996), natural gas seeps and significant gas shows during exploration drilling suggest the area has some potential to host a functional petroleum system. Available subsurface data are sparse and more information is required to reliably assess the basins potential (Thomas and others, 2004).

Major seeps of both oil and gas are present on the northern margin of the Yakutat terrane, indicating that the northern Gulf of Alaska basin does contain a viable petroleum system. Despite the lack of any commercial discoveries to date, potential remains for future production of conventional hydrocarbons. Many large structural and stratigraphic traps likely remain undrilled and the province is underexplored relative to comparable oil-bearing basins in North America. The most recent available estimates of technically recoverable resources from the Gulf of Alaska region report a mean value of 630 million barrels of oil and 4.65 trillion cubic feet of natural gas (MMS, 2006a, 2006b). These numbers reflect undiscovered, hypothetical resources that have not been confirmed by drilling, and the actual amount that could be discovered and produced may be significantly smaller when filtered against the high costs of offshore development. Nevertheless, the large estimates reflect the overall promising nature of the region for future hydrocarbon exploration.

Unconventional oil and gas resource potential

Coalbed methane. The most significant known coal resources in the Copper River–Chugach Energy Region primarily occurs in the Bering River coal field, where coal-bearing strata are common in the Paleogene Kushtaka Formation (Kulthieth Formation). In the Carbon Creek area of the field, coal seams are commonly 5 to 10 feet thick, with seams locally ranging up to 30 to 60 feet thick. Coal rank ranges from subbituminous to anthracite and is of sufficient grade to produce coalbed methane. However, many of the coal-bearing strata are part of a regional fold and thrust belt and coals are locally laterally discontinuous due to stratigraphic pinch-out or structural truncation. The structural complexity of high-rank coals in the Bering River field would present a challenge to effective production of significant coalbed methane resources. Other known coal deposits in the region consist of small, scattered exposures of lignite along the foothills of the Alaska Range and in the Copper River Basin. The reported low maturity of these coals indicate they are unlikely to have natural fractures (cleats) that are necessary for successful coalbed methane production.

Tight gas sands. Published data suggest upper Mesozoic and lower Cenozoic sandstones are likely to form conventional reservoirs capable of producing some hydrocarbons in the Copper River–Chugach Energy Region. Many of the Mesozoic sandstones in the Copper River region, in particular the Nelchina, Staniukovich, and Naknek Formations, have been relatively deeply buried and have undergone significant compaction and cementation. If these units were sufficiently charged from nearby source rocks, they may serve as potential tight gas reservoirs. Extensive regional fractures have been observed in outcrops of some of the Mesozoic sandstones, particularly the Naknek Formation. These fractures are typical of tight gas sands and may well signal the presence of an unconventional, fractured reservoir.

In the Gulf of Alaska region, the Eocene Kulthieth Formation may locally have potential as a tight gas sand. It consists of relatively thick nonmarine to deltaic sandstones with variable reservoir quality. While much of the unit has fair to good porosity, zeolite cements (particularly laumontite) have locally degraded reservoir quality to the extent that sands have permeabilities less than 0.01 millidarcy. Potential source rocks in the lower part of the Kulthieth Formation consist of gas-prone shallow marine deltaic to basinal marine sediments (Plafker and others, 1994) that could act as an intra-formational source. Local fractures have been observed in thin sections of the Kulthieth Formation (ARCO White Lake #1) and may signal the existence of a more regionally extensive fracture system necessary for an effective unconventional, fractured reservoir. The ARCO OCS Y-0211 (Yakutat No. 1) well encountered significant oil and gas shows in the Kulthieth sandstones.

Shale gas. One of the primary requirements for shale gas is an organic-rich source rock present in the thermogenic gas window that is sufficiently brittle to host a natural fracture system (see Chapter A). Data from the Copper River basin are sparse, but the scarcity of significant hydrocarbon shows in exploration wells suggest that significant quantities of thermogenic hydrocarbons may never have been generated. However, important aspects of the subsurface of this basin remain unknown. In the Katalla area of the Gulf of Alaska, basin shales of the Poul Creek and Kulthieth Formations are potential source rocks for both oil and gas. Furthermore, most of the observed seeps in the region are believed to be intraformational, indicating that naturally fractured source rocks were capable of generating and storing hydrocarbons.

Gas hydrates. The main occurrences of gas hydrates in nature are in modern marine sediments and in arctic regions with well developed, continuous permafrost. Permafrost is not well developed in the Copper River–Chugach Energy Region, and where locally present is discontinuous. Consequently, the potential is low for economic concentrations of gas hydrates.

Geothermal resource potential

Geothermal prospectivity in the Copper River–Chugach Energy Region is limited to the immediate vicinity of Glennallen and western portions of the Wrangell Mountains. Three occurrences of thermal spring temperatures above 60°F (16°C) have been measured in the region. By comparison, 12 occurrences of thermal springs with temperatures above 165°F (74°C) have been measured in the Aleutian region and three occurrences above 165°F (74°C) have been measured in the Southeast region (Motyka and others, 1983).

Two groups of mud volcanoes are located near Glennallen. The Klawasi group, east of Glennallen, has slightly warmer waters and considerably more carbon dioxide gas than the Tolsona group west of Glennallen (Motyka and others, 1983). Both groups discharge highly saline waters thought to originate from a zone of overpressured Cretaceous-age marine sedimentary rocks underlying the Copper River basin (Motyka and others, 1983; Motyka and others, 1986). The proximity of the Klawasi group to the Quaternary volcanoes in the western Wrangell Mountains has led to speculation that a geothermal resource underlies the mud volcanoes and acts as the source of the measured carbon dioxide gas (Motyka and others, 1983). The source of the methane measured in the Tolsona group, and to a lesser extent in the Klawasi group, is likely coal beds in the Cretaceous formations underlying the basin; however, the particularly heavy isotopic signatures for the methane gas at the Klawasi mud volcanoes infers a mantle component, suggesting a potential geothermal source (Motyka and others, 1986). Geothermometers applied to the Klawasi spring waters are inconclusive, with some suggesting a cold-water source and others indicating temperatures higher than 302°F (150°C) (Motyka and others, 1983). The Copper River–Chugach region contains one fumarolic field near the north summit crater of Mount Wrangell with measured temperatures as high as 187°F (86°C) (Motyka and others, 1983).

When considered as a whole, the Copper River–Chugach Energy Region contains only a limited number of geothermal manifestations, all of which are inside the Wrangell–Saint Elias National Park and Preserve boundary. Of the three thermal springs in the region, none are at surface temperatures >100°F (38°C).

RECOMMENDATIONS

Unconventional oil and gas resource recommendations

Coalbed methane. Due to the limited areal extent and structural complexity of the Bering River coal field, the volume of accessible coal does not appear sufficient to produce commercial quantities of coalbed methane. Available data from the Copper River basin area suggest most coals are thin and insufficiently mature to serve as viable coalbed methane reservoirs. However, these coals are poorly understood and may warrant additional reconnaissance geologic investigation prior to discounting their potential completely.

Tight gas sands. Available data suggest that Mesozoic sandstones in the Copper River region may possess either matrix or fractured reservoir quality sufficient to host a tight gas accumulations. Similarly, Eocene-age sandstones in the Gulf of Alaska region may have local potential as an unconventional reservoir. This type of resource play has not been targeted in this frontier region, and more geologic data would be required to reduce exploration risk. Development of tight gas sandstones in this setting typically requires a high density of wells and artificial stimulation, both of which add significantly to exploration and development costs, challenging economic viability.

Shale gas. Insufficient data are available to reliably assess the potential for shale gas in the deeper parts of the Copper River basin. However, available information suggests that few, if any, source rocks have reached the thermogenic gas window. Subsurface data on source rock quality and maturity would be required to further evaluate the basin's potential for shale gas. Shales of the Poul Creek and Kulthieth Formations in the Gulf of Alaska region have some potential as a resource play, particularly in the fold and thrust belt where a significant natural fracture system may be present. Additional geologic information could improve assessments of this play, including data on the distribution of source rock quality and thermal maturity. However, the economic feasibility of this type of development in a frontier region would be challenging; unconventional resource plays typically produce relatively small amounts of hydrocarbons from each well and profitability depends on inexpensive drilling costs.

Gas hydrates. Due to the lack of extensive, continuous permafrost in most of the Copper River basin, the likelihood of finding gas hydrates in the region are very low, therefore no further action is recommended.

Conventional oil and gas resource recommendations

The locations of rural communities in the Copper River–Chugach Energy Area are largely on the road system, and patterns of land ownership are important considerations in weighing the state's options for oil and gas energy development for local use in the Copper River–Chugach Energy Region. The sparse drilling record in the Copper River basin has not discovered any commercial hydrocarbons, but did locally record shows of natural gas. The ultimate potential of the basin remains poorly known. A more robust understanding of the hydrocarbon potential could be developed via additional geologic field studies along the basin margins. However, evaluation of the prospective subsurface part of the basin would require new, modern seismic data, followed by targeted exploration drilling.

Major seeps of both oil and gas are present on the northern Gulf of Alaska east of the Copper River delta. Despite the lack of any commercial discoveries to date, many large structural and stratigraphic traps remain undrilled, and there is still potential for future production and potential remains for future production of conventional hydrocarbons. The available data suggest the region warrants additional investigation, including onshore geologic mapping and the collection of modern seismic data. Although this region may ultimately yield commercial hydrocarbon discoveries, there are no communities in close enough proximity to this prospective resource to be able to directly utilize it for local energy.

Coal resource recommendations

The generally limited thickness and low thermal maturity of coals surrounding the Copper River basin do not appear to warrant additional consideration as a viable local energy source. However, many of the reported occurrences have not been studied in detail, and further geological evaluation could improve knowledge of the distribution and character of any potential coal resources. The Bering River field includes high-quality coal, but may be complicated by local structure—a characteristic that led Alaska Division of Energy & Power Development (1977) to rank the field low on a list of future developable coal fields. Nevertheless, the region has witnessed very few detailed geologic studies, and a reliable assessment of the potential coal resources would require further mapping and focused stratigraphic and structural studies.

Geothermal resource recommendations

There are only limited possibilities for developable geothermal resources in the Copper River–Chugach Energy Region. The most promising geothermal features are in the Wrangell–Saint Elias National Park and Preserve boundary and are thus currently unavailable for geothermal development. The Tolsona mud volcanoes, while located outside the National Park and Preserve boundary, produce cool surface discharge temperatures (50°F [10°C]) and isotopic analysis performed on Tolsona mud volcano gases suggests a coal and lignite source rather than a magmatic source. For these reasons, Tolsona shows little potential for a viable geothermal application. Because of limited geothermal manifestations and land ownership issues, no further investigation is warranted at this time.

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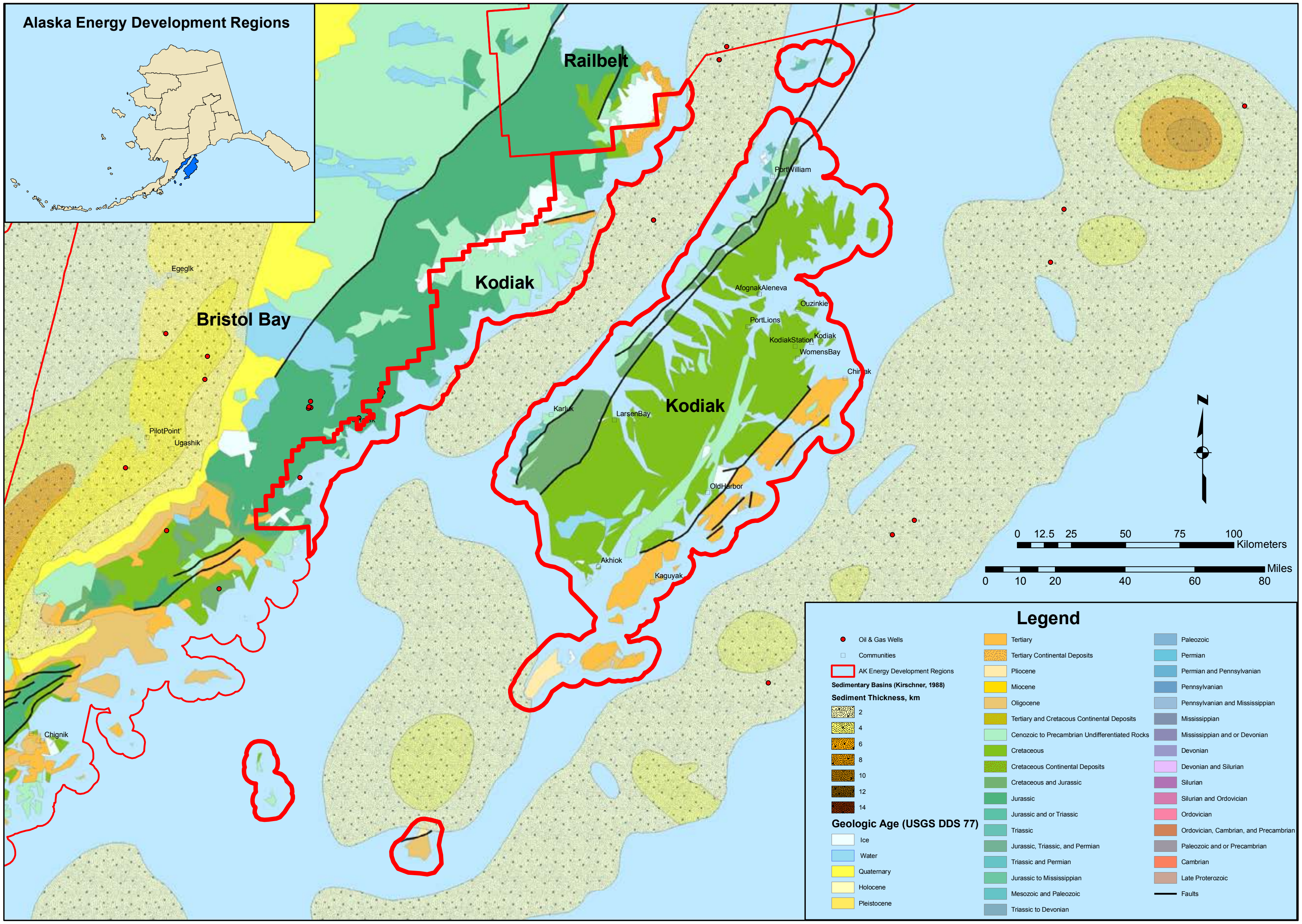
Geology of the Kodiak Energy Region, Alaska



SUMMARY OF FOSSIL FUEL AND GEOTHERMAL RESOURCE POTENTIAL IN THE KODIAK ENERGY REGION

by Paul L. Decker, Robert J. Gillis, Ken Helmold, and Shaun Peterson

INTRODUCTION

Purpose of this report

Economic growth and stability in Alaska's rural and urban areas hinges partially, if not primarily, on the availability of affordable and sustainable energy supplies. Recent price increases in oil and gas commodities have created severe economic hardship in many areas of the state that are dependent on diesel and heating oil as their primary source of energy. All sectors of Alaska's economy rely on affordable energy sources with limited price volatility, highlighting the need to diversify the energy portfolio by developing locally available and sustainable resources that are not tied to the global market. Unfortunately, all areas are not created equal in energy accessibility; the resources available for local exploitation vary widely across the state. It is critical that funding decisions for expensive programs to reduce the dependence on diesel for heat and electricity take into account information concerning the entire suite of natural resources that exist in a given area.

This report draws from existing information to provide community and state leaders an objective summary of our current knowledge concerning the potential of locally exploitable fossil fuel and geothermal energy resources in the Kodiak energy region (fig. F1), one of 11 regions recognized by the Alaska Energy Authority in their Energy Plan (AEA, 2009). The potential geologically hosted energy resources considered here include exploitable coal, conventional and unconventional oil and gas, and geothermal resources. This report concludes with recommendations as to what additional data or strategies, if any, would provide the most leveraging in helping to develop new energy resources in the region.

Readers without geological training are encouraged to peruse the geologic summaries of fossil fuel resources and geothermal energy in Chapter A. They provide an overview of the geologic elements that must be present in an area to economically develop coal, conventional oil and gas, unconventional oil and gas, and geothermal resources. These summaries will provide the necessary background to more fully understand the information presented in this chapter.

Geographic and geologic setting

The Kodiak Development Region encompasses a series of islands across Shelikof Bay from the southeast coast of the upper Alaska Peninsula (sheet 1; fig. F1). Included from northeast to southwest are the Barren Islands, Shuyak, Afognak, Kodiak, and, Sitkalidak islands, the Trinity Islands, and Chirikof Island. Also included in the development region are coastal lands on the upper Alaska Peninsula facing the greater Kodiak Island area separated by the Shelikof Strait. This strip of land extends from Point Douglas southwestward to Mount Kialagvik, at the head of Wide Bay. The largest community in the development region is Kodiak, with a current population of 5,691, followed by Kodiak Station and Women's Bay, with current populations of 1,817 and 830, respectively. Several other, much smaller communities are widely scattered across the region.

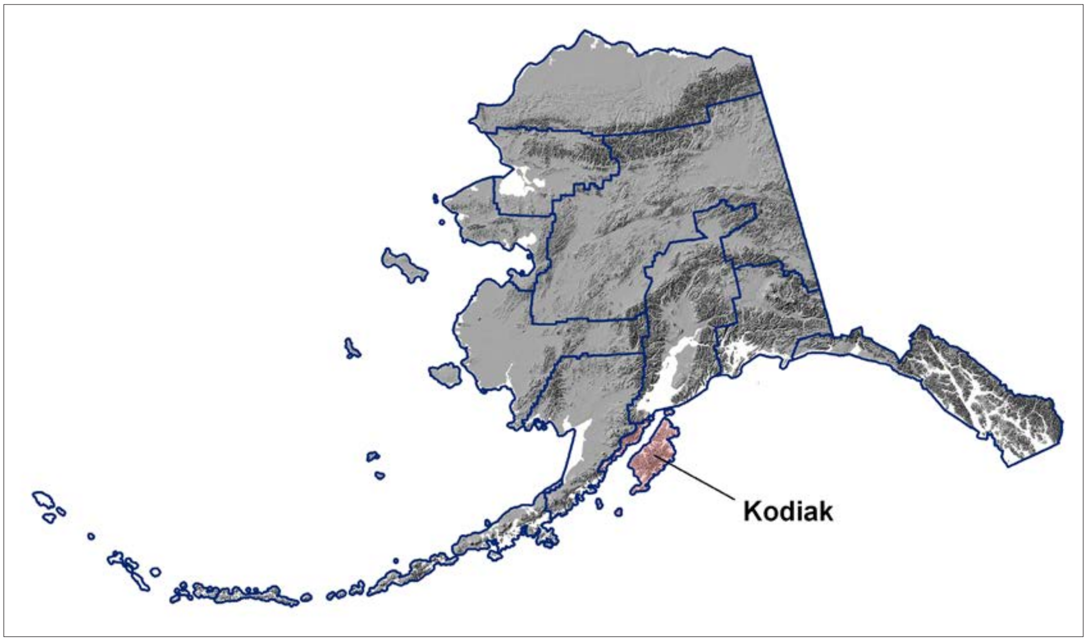


Figure F1. Location map of Kodiak Energy Region.

Most of the land area in the Kodiak Development Region is represented by Kodiak, Afognak, and smaller nearby islands that essentially are the subaerial expression of a northwest-trending mountain belt emerging from the Gulf of Alaska waters, and are an extension of the Kenai Mountains to the northeast. The largest of these islands, Kodiak, hosts rugged mountains with peaks reaching nearly 4,500 feet. Glacially-sculpted, generally northwest-trending fjords are best developed on the northwest side of the island, producing a highly irregular coastline. Inland topography is defined by orthogonal linear ridges and broad glacial valleys. Lowlands, especially on the southwestern end of the island, support numerous small lakes and marshes. Afognak Island shares similar traits, but with more subdued, less rugged topography. The smaller islands to the northeast and southwest are of low to moderate relief. The northwestern boundary of the Kodiak Development Region on the Alaska Peninsula essentially traces the spine of the Aleutian Range from near Point Douglas southwestward to Mount Kialagvik. The rugged topography of the range often extends to the coast, which is scalloped by numerous bays.

Most of the Alaska Peninsula and Aleutian Islands are the product of millions of years of accumulation of volcanic flows and detritus above a subduction zone that has been active for about 200 million years (Trop and Ridgway, 2007; Amato and others, 2007). This process continues today with the oceanic Pacific plate being thrust toward the northwest beneath the North American plate. Magma generated at the plate boundary has intruded the overriding North American plate, resulting in an arcuate array of volcanoes referred to as a volcanic island arc. Major episodes of arc volcanism have occurred at least three times on the Alaska Peninsula over the past approximately 200 million years (Reed and Lanphere, 1969; Wilson, 1985; Amato and others, 2007). Volcanism along the Aleutian chain was underway by about 35 million years ago (Wilson, 1981). Today, arc volcanism is the dominant geologic process shaping the Aleutian Islands and Alaska Peninsula. Paleozoic and early Mesozoic metamorphic and sedimentary rocks that comprised a major crustal block collided with continental North America in early to middle Triassic time and became the catchment for thick accumulations of sediments that were shed from the earliest continental arc on the Alaska Peninsula. The rocks forming the catchment and some of the early sediments filling the basin are believed to be petroleum source rocks for the adjacent Bristol Bay and Cook Inlet petroleum basins (Detterman and Hartsock, 1966; Decker and others, 2008). Subsequent cycles of tectonic subsidence and uplift since Late Cretaceous time are responsible for the coal-bearing rocks in the northwestern area of the development region (Detterman and others, 1996), as well as many of the petroleum reservoir rocks in the adjacent petroleum basins (Calderwood and Fackler, 1972; Detterman and others, 1996; Helmold and others, 2008). Cenozoic-age faulting and folding near the plate margin result from compression and transpression associated with the subduction zone and form most of the potential hydrocarbon traps for these petroleum systems and conduits for hydrothermal fluids in geothermal systems. The Kodiak Island chain is a direct expression of the same subduction processes that formed the Chugach Mountains of the Kenai Peninsula. Erosional remnants of a continental volcanic arc preserved on the northwestern sides of Kodiak and Afognak islands are the same age as the earliest volcanic arc rocks found on the Alaska Peninsula and as far north as the Talkeetna Mountains (Hill and Morris, 1977). These arc rocks are in fault contact with high-grade metamorphic rocks to the southeast that represent remnants of an extinct subduction zone that was active prior to about 190 million years ago (Carden and others, 1977). Between about 190 and 120 million years ago, subduction moved southeastward more than 100 miles to near its present-day position in the Gulf of Alaska. Since that time, sediments shed oceanward from the continental margin have been scraped off of the subducting oceanic plate and piled against the continental edge to form the rugged mountains on the eastern side of Kodiak and Afognak islands (Connelly, 1978; Bradley and others, 2009). Approximately 59 million years ago, this pile of highly-deformed strata was intruded by magma that formed the Kodiak batholith (Farris and others, 2006). None of these pre-Cenozoic rocks have value in terms of energy resources, owing to their igneous origins, high metamorphic grade, lack of organic composition, or high degree of deformation. However, a sedimentary basin developed along the southeastern coast of the islands and offshore to the southeast on the Kodiak Shelf during Eocene time (sheet 2) and includes marine and terrestrial strata that possess modest fossil fuel potential (Nilsen and Moore, 1979).

GEOLOGIC ENERGY RESOURCE POTENTIAL IN THE KODIAK ENERGY REGION

Mineable coal resource potential

Coal is not known to occur in large quantities in the Kodiak Energy Region. The few reported occurrences are concentrated in middle or late Oligocene strata of the Sitkinak Island Formation (Nilsen and Moore, 1979). Exposures of these strata are relatively small, discontinuous, and located near the southern end of the central tidal flat on Sitkinak Island, Tanginak Anchorage on the northeastern coast of Sikalidak Island, and Boulder Bay on the eastern coast of Kodiak Island (fig. F2; Nilsen and Moore, 1979). References to coal in the Kodiak Energy Region are rare, probably owing to its meager occurrences in the area. Most of what is known about coal on Kodiak Island is found in a 1972 report by D.L. McGee, which is a compilation of earlier, and often reconnaissance-level, studies. McGee (1972) reports coal beds on Kodiak Island to be thin and likely not an economic resource. However, no bed thicknesses or

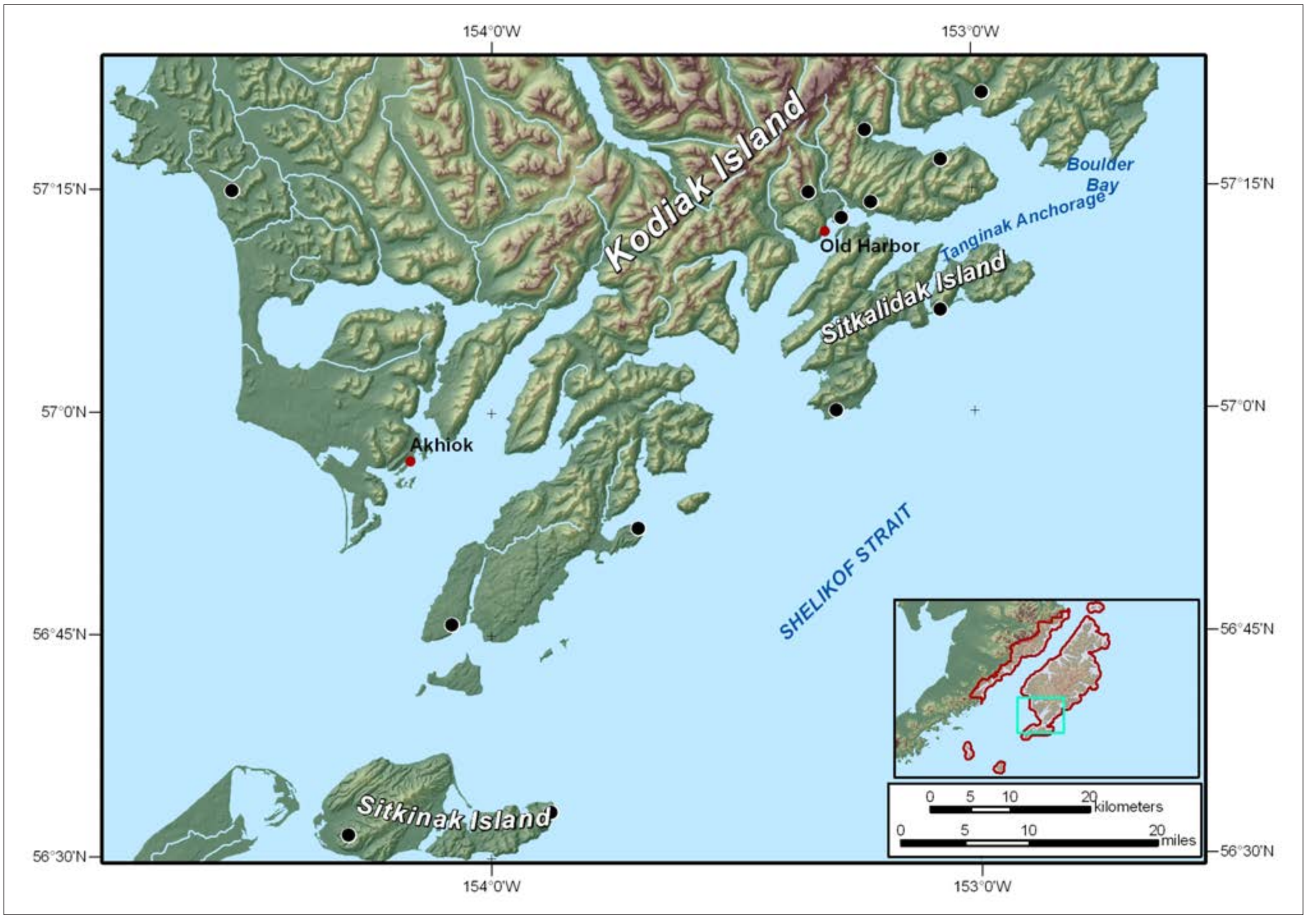


Figure F2. Location map of the southwestern Kodiak Energy Region, showing selected geographic references noted in the text. Black dots mark reported coal occurrences.

abundances are offered, nor is any information given on coal quality. Related coals on Sitkinak Island are documented in higher detail in four reports and several correspondences (Jasper and Robinson, 1959; Warfield, 1962; Anderson, 1969; Nilsen and Moore, 1979), although the earliest report significantly conflicts with the later reports in terms of coal thicknesses in the area. Jasper and Robinson (1959, and included correspondence) discuss two steeply-dipping coal beds 25 and 90 feet thick that were not observed by later workers despite efforts to locate the beds. Subsequent reports agree that coal beds on Sitkinak Island are typically thin, often impure, and laterally discontinuous (Warfield, 1962; Anderson, 1969; Nilsen and Moore, 1979). The coal that is present, however, is subbituminous A with as-received heating values of about 11,500 Btu. Other isolated coal occurrences of unknown extent in the Kodiak Energy Region are found on the upper Alaska Peninsula to the northeast (figs. F3 and F4), across the Shelikof Strait near Puale Bay and Cape Douglas (lignite), and Amalik Bay (bituminous) (Stone, 1905; Merritt and Hawley, 1986).

Conventional oil and gas resource potential

As explained in the discussion of requirements for exploitable oil and gas resources (Chapter A), functioning petroleum systems occur in thick, sedimentary basins, and require three basic elements: Effective source rocks, reservoirs, and traps. Each of the elements must be in existence and connected at the time hydrocarbons are generated. This section provides an overview of the various basins in the Kodiak region, then considers each of the necessary elements of petroleum systems in turn to evaluate the role conventional oil and gas resources may play in supplying rural energy to the region.

Overview of sedimentary basins. Onshore areas of the Kodiak archipelago are underlain primarily by Mesozoic to early Cenozoic (Paleogene) rocks, including large areas of pervasively deformed and metamorphosed deep marine deposits, strongly deformed shallow marine deposits, and more restricted granitic intrusive bodies (Lyle and others, 1978; Fischer and others, 1984; Fischer, 1988; Kirschner, 1988; Beikman, 1980). These Eocene and older rocks are thermally overmature for hydrocarbon generation, have minimal porosity and permeability, and constitute basement,

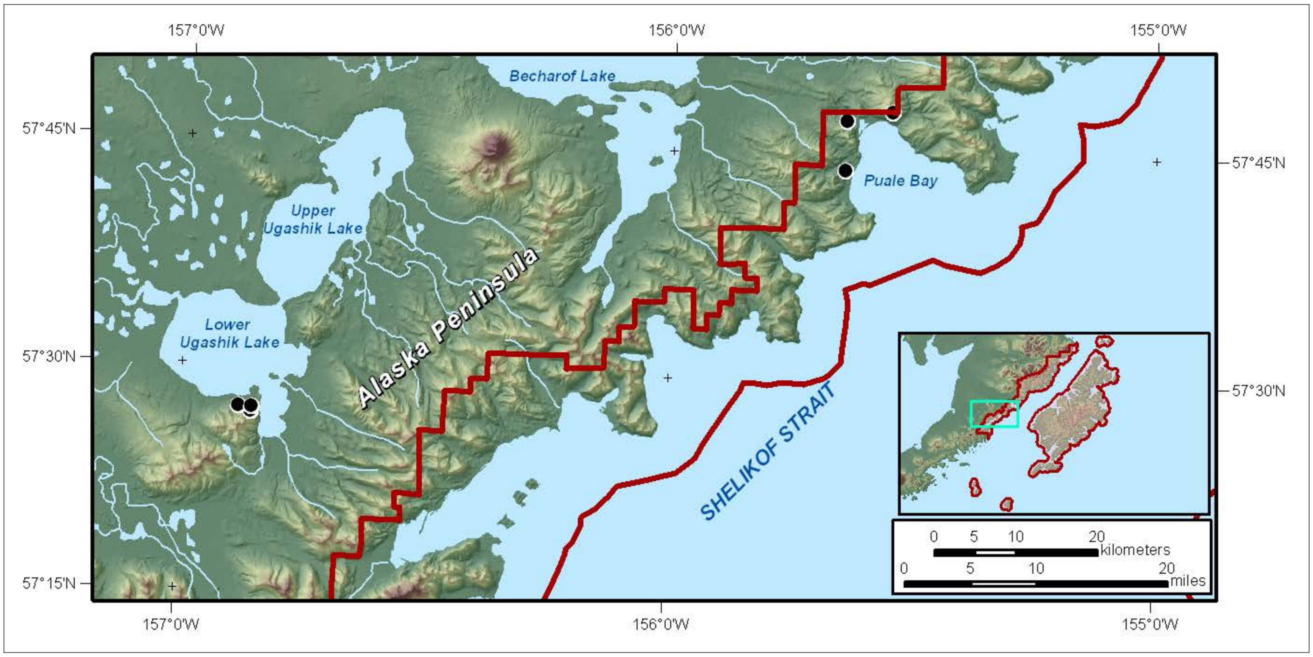


Figure F3. Location map of the western, mainland portion of the Kodiak Energy Region (Alaska Peninsula). Black dots in the Puale Bay and Lower Ugashik Lake areas indicate reported coal occurrences.

incapable of sustaining functioning petroleum systems. Less deformed late Cenozoic (Neogene) sandstone and siltstone are exposed very locally on the southeastern shore of Kodiak Island and on islands at the south end of the archipelago (Lyle and others, 1978; Marincovich, 1990). This Neogene sedimentary sequence thickens appreciably offshore into the Tugidak, Trinity, Albatross, and Stevenson basins of the Kodiak shelf (sheet 2). These shelf basins are tens to hundreds of kilometers offshore and contain 3–7 km of relatively undeformed Miocene and younger sedimentary fill (Fisher and others, 1984; Kirschner, 1988). Seismic basement beneath these Neogene basins is believed to be mainly Eocene and older rocks similar to non-prospective rocks of similar age onshore (Von Huene and others, 1980; Fisher, 1988). Six continental offshore stratigraphic test (COST) wells were drilled on the Kodiak shelf in 1976 and 1977 to acquire data in preparation for a possible lease sale that never occurred (Turner and others, 1987).

Northwest of the Kodiak archipelago, Shelikof Strait is a relatively shallow southern extension of Cook Inlet basin (sheet 2). Containing up to approximately 2 kilometers of Cenozoic strata (Magoon and others, 1979; Kirschner, 1988), this narrow basin lacks the thicker depocenters found outboard of the islands on the Kodiak shelf. However, seismic data indicate that Cenozoic strata of Shelikof Strait unconformably overlie the Mesozoic formations that host oil and gas seeps on the southeastern end of the Alaska Peninsula and source the oil in Cenozoic reservoirs in upper Cook Inlet (Magoon and others, 1979; Magoon, 1986).

Source rocks. The Neogene sequence that fills the offshore Kodiak shelf basins contains organically lean shales and other non-source rock types; few intervals are known to exceed 0.5 percent total organic carbon (Fisher and others, 1984; Fisher, 1988). There is a greater chance of sourcing hydrocarbons from the underlying Eocene strata, but even these are only marginally carbon rich(<0.6 percent total organic carbon), contain only gas-prone terrestrial kerogen, and are thermally immature to marginally mature where they have been penetrated by wells (Horowitz and others, 1998). This potential source interval may be more thermally mature if it exists beneath thick Neogene depocenters. Gas shows were described from one of the six COST wells, but there is no indication that these shows represented a producible gas accumulation.

It is probable that source rocks of the Middle Jurassic Tuxedni Group (source of oil in Cook Inlet) or the partially equivalent Kialagvik Formation exist and are thermally mature beneath much of Shelikof Strait (Magoon and others, 1979; Bruns, 1982). If so, hydrocarbons generated in these units would likely migrate up to and across the unconformity at the base of Cenozoic strata, where they may or may not have encountered shallowly-buried reservoirs. The only well drilled offshore in Shelikof Strait (OCS Y-0248-1/1A) encountered minor shows of dry, possibly biogenic, gas associated with coals in the Cenozoic section, and trace amounts of probable thermogenic hydrocarbons in Mesozoic rocks.

Kodiak

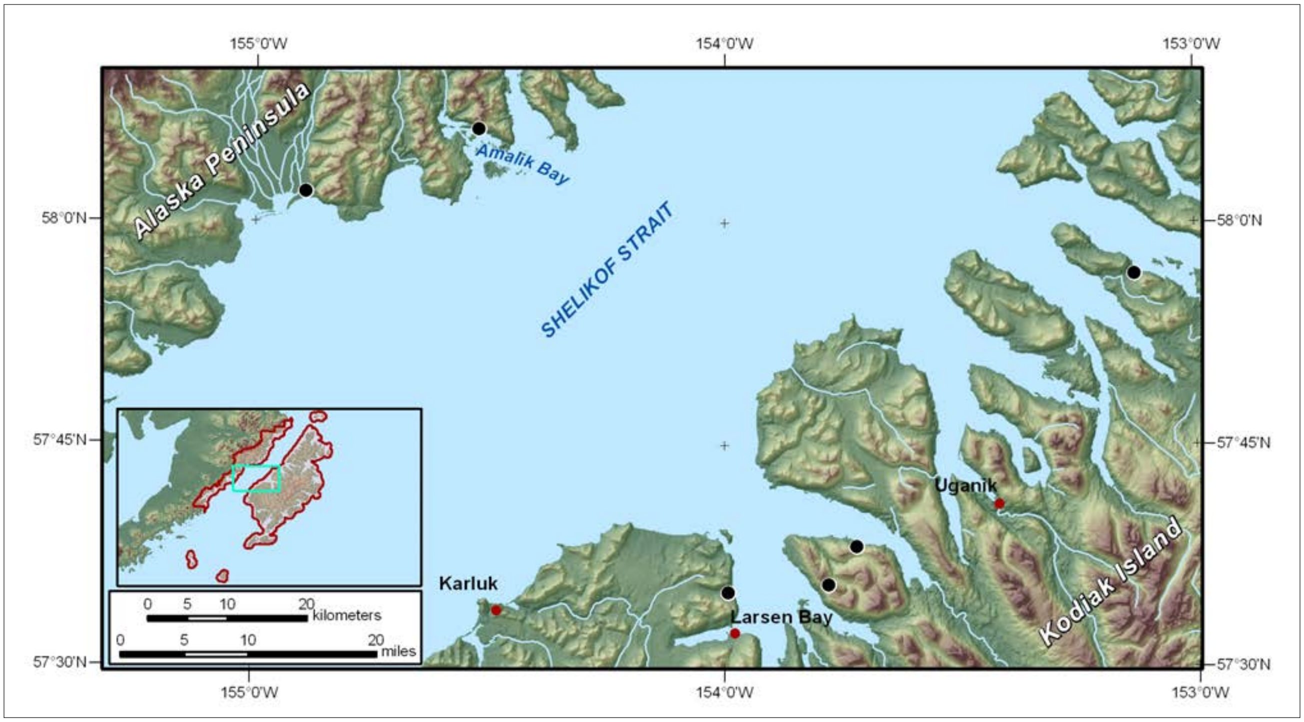


Figure F4. Location map of the Shelikof Strait area of the Kodiak Energy Region (Alaska Peninsula). Black dots mark reported coal occurrences.

Reservoir rocks. Potential reservoir units in the offshore Neogene basins of the Kodiak shelf consist of marine shelf turbidite sandstones. These sandstones are mostly Middle Miocene age, more quartz-rich than older Cenozoic sandstones, and have low to moderate reservoir quality (Horowitz and others, 1998; MMS, 2006a,b). Cenozoic sandstones in Shelikof Strait are similar in many respects to age-equivalent reservoir formations of the lower and upper Cook Inlet. However, their shallow depth in much of Shelikof Strait is a practical concern (Bruns, 1982) as it could imply ineffective seals and low reservoir pressures. The OCS Y-0248-1/1A well encountered the base of the sandy Cenozoic section at a depth of only 2,619 feet below sea level in Shelikof Strait, underlain by dominantly fine-grained Mesozoic rocks. Although the reservoir potential of the Mesozoic section is unknown, it likely includes thick Jurassic sandstone and some limestone that, where favorably altered, could serve as hydrocarbon reservoirs. Limited outcrop data from correlative units in lower Cook Inlet and the Alaska Peninsula have not identified significant porosity or permeability in Jurassic rocks (Helmold and others, 2008, 2011).

Traps. Numerous structural traps are mappable from seismic data offshore on the Kodiak shelf and in Shelikof Strait (Hoose and Whitney, 1980; Fisher and others, 1984; Fisher, 1993). The most prospective of these structures are anticlines related to thrust faults and normal faults (Horowitz and others, 1998) that coexist in this high-relief continental shelf prism adjacent to the Aleutian trench subduction zone.

Summary of conventional oil and gas resource potential. Currently available data suggest the chance is low that recoverable oil resources are accessible either onshore or offshore in the Kodiak Energy Region. However, the data are very limited and the identification of significant Jurassic or even Triassic oil-prone source rocks would significantly improve the prospects for this area. There is an estimated 40 percent chance (Horowitz and others, 1998) that technically recoverable gas exists beneath the federally managed waters of the Kodiak shelf offshore of the Kodiak Energy Region. The most recent federal assessment (MMS, 2006a,b) estimates the mean undiscovered, technically recoverable resource at 1.8 trillion cubic feet (TCF), likely distributed as small accumulations among many different late Cenozoic reservoirs in anticlinal traps tens to hundreds of kilometers offshore.

Unconventional oil and gas resource potential

Coalbed methane. As noted above, coal resources in the Kodiak region are areally limited, discontinuous, and of uncertain thickness (Nilsen and Moore, 1979). There is very little in the public record documenting the nature of coals on Kodiak and surrounding islands. Available data on the thickness of these coals, combined with uncertain areal footprint, suggests they would be ineffective as potential sources of coalbed methane.

Tight gas sands. The bulk of the sandstones in the Neogene basins of the Kodiak shelf are too young and too shallowly buried to be effective tight gas reservoirs. Despite the low to moderate reservoir quality of these sandstones, they do not exhibit a well-developed regional fracture system conducive to the genesis of tight gas sands. Given this fact, combined with available data suggesting only lean source rocks in the region, the likelihood of tight gas sands in the Cenozoic section is low. The thickness and character of Jurassic units beneath the Shelikof Straight are poorly known. If the stratigraphy is comparable to lower Cook Inlet and parts of the Alaska Peninsula, then well-lithified units may potentially have reservoir quality consistent with a tight gas play.

Shale gas. The bulk of potential Neogene source rocks in the Kodiak shelf basins are lean in organic matter and probably not capable of producing sufficient quantities of gas to support a shale gas resource play.

Gas hydrates. The main occurrences of gas hydrates in nature are in modern marine sediments and in arctic regions with well-developed, continuous permafrost. Permafrost is not well developed in the Kodiak Energy Region and, where locally present, is discontinuous. Consequently, the potential for economic concentrations of gas hydrates is low.

Geothermal resource potential

There are no known occurrences of thermal springs, fumaroles, warm lakes, or mud pots in the Kodiak Energy Region and the overall geothermal prospectivity in the area is low. The current understanding of the regional geology suggests that discovery of a developable geothermal system is unlikely, with the exception of the westernmost part of the region, which borders several fumaroles in the Katmai area (see Bristol Bay Energy Region, Chapter D).

RECOMMENDATIONS

Coal resource recommendations

Given the restricted distribution and thinness of coal beds that have been observed by most researchers, further investigation of coal resources in the Kodiak Island area are unwarranted. Additionally, Sitkinak and Sikalidak islands are part of the Alaska Maritime Wildlife Refuge, which would complicate any plans to develop a resource at those locations. Reconnaissance-level mapping of reported coal occurrences on the Alaska Peninsula may help determine if further investigation into coal resources is warranted. However, these sites are with the Katmai National Park and Preserve and Becharof National Wildlife Refuge, and thus may not be accessible for coal-resource development.

Conventional oil and gas resource recommendations

The oil potential in the Shelikof Strait is poorly constrained, but generally assumed to be limited. Technically recoverable gas resources may be present offshore on the Kodiak shelf or in Shelikof Strait. However, these areas have seen limited drilling, and there has been no petroleum industry interest in the region for 25 years. The onshore areas host no active petroleum system. Although industry may eventually pursue offshore exploration, conventional hydrocarbons are unlikely to fulfill local energy needs in the near future.

Unconventional oil and gas resource recommendations

Coalbed methane. Due to the limited stratigraphic and areal extent of coals in the region, the volume of available coal is not sufficient to produce commercial quantities of coalbed methane, and no further action is recommended.

Tight gas sands. The possibility of encountering fractured tight gas sands in the Kodiak Energy Region is low due to the young age and shallow burial of Cenozoic reservoirs. Little is known regarding possible Mesozoic tight gas reservoirs. Characterizing potential Mesozoic reservoirs would require expensive drilling in the Shelikof Strait area and such an investment is not recommended.

Shale gas. Due to the lack of extensively fractured source rocks in the thermogenic gas window, the likelihood of finding commercial quantities of shale gas in the region is low; therefore no further action is recommended.

Gas hydrates. Due to the lack of extensive, continuous permafrost on Kodiak and surrounding islands, the likelihood of finding gas hydrates in the region are very low; therefore no further action is recommended.

Geothermal resource recommendations

Due to the lack of documented geothermal manifestations, the potential for developable geothermal energy in the region is low and no further action is recommended.

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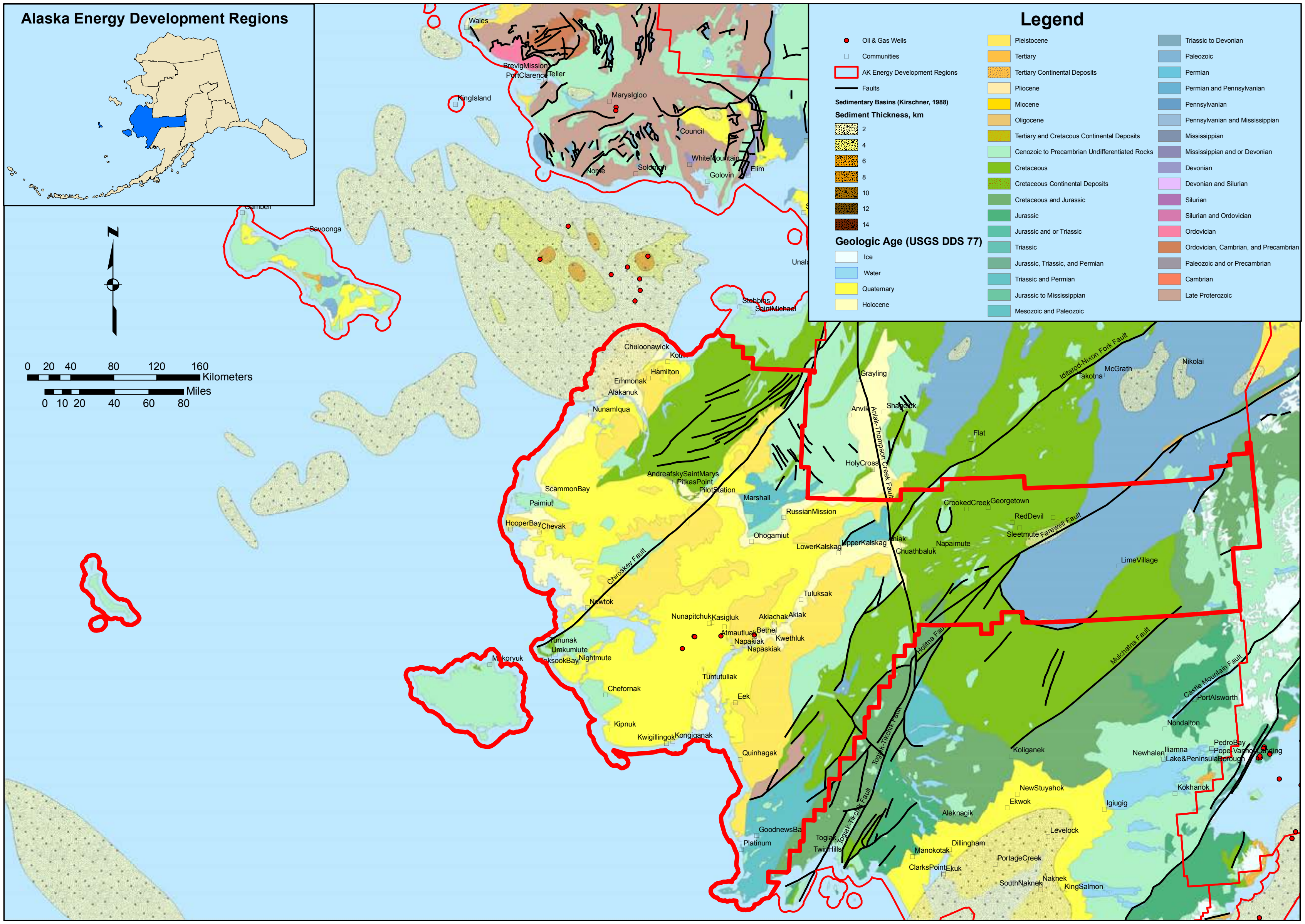
Geology of the Lower Yukon-Kuskokwim Energy Region, Alaska



SUMMARY OF FOSSIL FUEL AND GEOTHERMAL RESOURCE POTENTIAL IN THE LOWER YUKON–KUSKOKWIM ENERGY REGION

by David L. LePain

INTRODUCTION

Purpose of this report

Economic growth and stability in Alaska's rural and urban areas hinges partially, if not primarily, on the availability of affordable and sustainable energy supplies. Recent price increases in oil and gas commodities have created severe economic hardship in many areas of the state that are dependent on diesel and heating oil as their primary source of energy. All sectors of Alaska's economy rely on affordable energy sources with limited price volatility, highlighting the need to diversify the energy portfolio by developing locally available and sustainable resources that are not tied to the global market. Unfortunately, all areas are not created equal in energy accessibility; the resources available for local exploitation vary widely across the state. It is critical that funding decisions for expensive programs to reduce the dependence on diesel for heat and electricity take into account information concerning the entire suite of natural resources that exist in a given area.

This report draws from existing information to provide community and state leaders an objective summary of our current knowledge concerning the potential of locally exploitable fossil fuel and geothermal energy resources in the Lower Yukon–Kuskokwim energy region (fig. G1), one of 11 regions recognized by the Alaska Energy Authority in their Energy Plan (AEA, 2009). The potential geologically hosted energy resources considered here include exploitable coal, conventional and unconventional oil and gas, and geothermal resources. This report concludes with recommendations as to what additional data or strategies, if any, would provide the most leveraging in helping to develop new energy resources in the region.

Readers without geological training are encouraged to peruse the geologic summaries of fossil fuel resources and geothermal energy in Chapter A. They provide an overview of the geologic elements that must be present in an area to economically develop coal, conventional oil and gas, unconventional oil and gas, and geothermal resources. These summaries will provide the necessary background to more fully understand the information presented in this chapter.

Geographic and geologic setting

The Lower Yukon–Kuskokwim Energy Region covers approximately 65,206 square miles in Southwest Alaska and extends from the east side of the Lime Hills Quadrangle, south of McGrath, to the Yukon–Kuskokwim delta at the western edge of the state (sheet 1). There is no road corridor from the Railbelt area and access to the region is limited to air and boat. The region's largest community is Bethel, located along the Kuskokwim River, with a current population of nearly 5,700. Other sizable communities include Hooper Bay, Mountain Village, and Aniak, with populations ranging from nearly 1,150 to slightly more than 500 residents. Many smaller villages are scattered widely throughout the region, and most of these are located in the vast Yukon–Kuskokwim

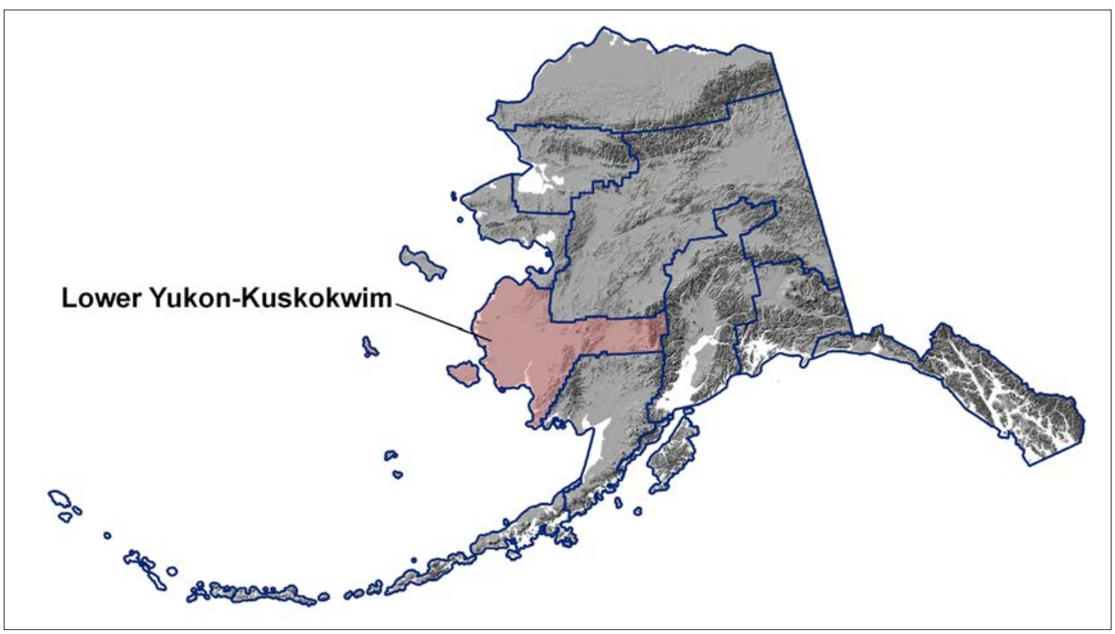


Figure G1. Location map of Lower Yukon–Kuskokwim Energy Region.

coastal lowland. The region includes the Pribilof Islands, St. Matthew Island, and Nunivak Island—all located in the Bering Sea west of the Yukon–Kuskokwim lowland.

The region includes diverse topography, ranging from the steep, mountainous terrain of the southwestern Alaska Range at the far eastern end of the region, to rolling, hilly terrain represented by the Nushagak–Big River and Nulato Hills and the Ahklun and Kuskokwim mountains, to low-relief lowland areas including the Holitna and Innoko lowlands and the broad flats of the Yukon–Kuskokwim coastal lowland (Wahrhaftig, 1965).

The high topography of the Alaska Range, which makes up the eastern end of the region, consists of intensely deformed (folded and faulted) Paleozoic- through Mesozoic-age sedimentary rocks that represent uplifted pieces of former marine sedimentary basins (Nokleberg and others, 1994). West of these rocks the geology of the region consists of fault-bounded packages of Precambrian through Mesozoic sedimentary and volcanic rocks (Decker and others, 1994). The old Precambrian-age rocks represent a small crustal sliver of the crystalline foundation of North America that was probably transported to its present location in Southwest Alaska along crustal-scale strike-slip faults (Decker and others, 1994). The rest of the region consists of fragments of Paleozoic through early Mesozoic sedimentary basins and oceanic volcanic arcs that were deformed and accreted to North America over many tens of millions of years—a process that was largely completed by late Mesozoic time (approximately 90 million years ago; Patton and Box, 1989; Decker and others, 1994). A diverse collection of sedimentary and volcanic rocks characterize these basin fragments and include limestones, dolomites, sandstones, shales, bedded cherts, and volcanic-arc-related igneous rocks. Late Mesozoic-age (middle to Late Cretaceous age) sandstones and shales deposited in deep marine through coastal sedimentary environments accumulated in the Yukon–Koyukuk and Kuskokwim basins after accretion of the older sedimentary basins to North America (Patton and Box, 1989; Box and Elder, 1992).

Several major crustal-scale high-angle fault zones, including the Denali–Farewell, Iditarod–Nixon Fork, and Chiroskey faults, trend northeasterly across the region (sheet 2), and are largely responsible for the present-day distribution of these basin and volcanic arc fragments. The northeast-trending Tertiary-age Holitna basin (sheet 2) resulted from extension-related subsidence along the Denali–Farewell fault zone in the Sleetmute Quadrangle (Kirschner, 1994). Deformed Paleozoic and possibly Mesozoic rocks underlie this basin. The fill of this basin is poorly known, but is thought to include Cenozoic-age nonmarine sedimentary rocks similar to those exposed in the McGrath Quadrangle near Farewell (Kirschner, 1994; LePain and others, 2003). The shallow Bethel basin (sheet 2) is filled with up to 2,000 feet of Cenozoic-age nonmarine(?) sedimentary rocks that were deposited on deformed late Mesozoic-age sedimentary rocks similar to those recognized in the Yukon–Koyukuk and Kuskokwim basins (Kirschner, 1994; Mull and others, 1995). Numerous Cenozoic-age basaltic cinder cones and lava flows are present at the surface in the western part of the region (Kirschner, 1994).

The Norton basin, located in the northeastern Bering Sea (sheet 2), a short distance north of the modern Yukon delta and just beyond the northwestern boundary of the Lower Yukon–Kuskokwim region, formed because of strike-slip motion along the Kaltag fault zone and possibly east–west crustal extension (Fisher and others, 1981). Metamorphosed Precambrian-, Paleozoic-, and Mesozoic-age rocks underlie the basin, which is filled with more than 20,000 feet of Tertiary marine and nonmarine sedimentary rocks (Turner and others, 1983). A prominent fault-bounded high comprising Mesozoic or older rocks trends north–south through the basin, splitting it into two sub-basins. The thick Tertiary successions in each sub-basin thin dramatically over this basement high (Fisher and others, 1981).

GEOLOGIC ENERGY RESOURCE POTENTIAL IN THE LOWER YUKON–KUSKOKWIM ENERGY REGION

Mineable coal resource potential

Noteworthy occurrences of coal are known from only two areas—the Cheeneetnuk River and Nelson Island (figs G2 and G3). Both occurrences are relatively poorly understood, and available information is summarized below. Minor occurrences of coal are known elsewhere in the region, where they occur in nonmarine(?) deposits of the Kuskokwim Group. One such occurrence is along the North Fork of the Eek River and consists of several thin (few inches) coals and carbonaceous shales (Clough and others, in press). These occurrences are too thin to serve as viable energy resources for rural communities. At best, they might provide a heat source for a few remote cabins located nearby.

Cheeneetnuk River. Cenozoic-age coal-bearing sedimentary rocks are discontinuously exposed in a narrow belt that extends along the Alaska Range mountain front from at least the Little Tonzona River northeast of Farewell to the Cheeneetnuk River, southwest of White Mountain (fig. G2; Sloan and others, 1979; Bundtzen and Kline, 1986; LePain and others, 2003). W.H. Condon reported discontinuous exposures of coal-bearing rocks along a several-mile-long stretch of the Cheeneetnuk River, including one exposure with a 6-foot-thick seam of bright, brittle coal that appeared to be of bituminous rank, and suggested they occupied a downthrown fault block underlain by Paleozoic limestone (cited in Barnes, 1967, p. B21). Gilbert (1981) mapped these exposures in the McGrath A-5 and Lime Hills D-7 quadrangles (his map unit uTs) and noted that friable coal beds 1.6 to 16.5 feet thick occur in three places. Solie and Dickey (1982) present coal quality data for samples collected

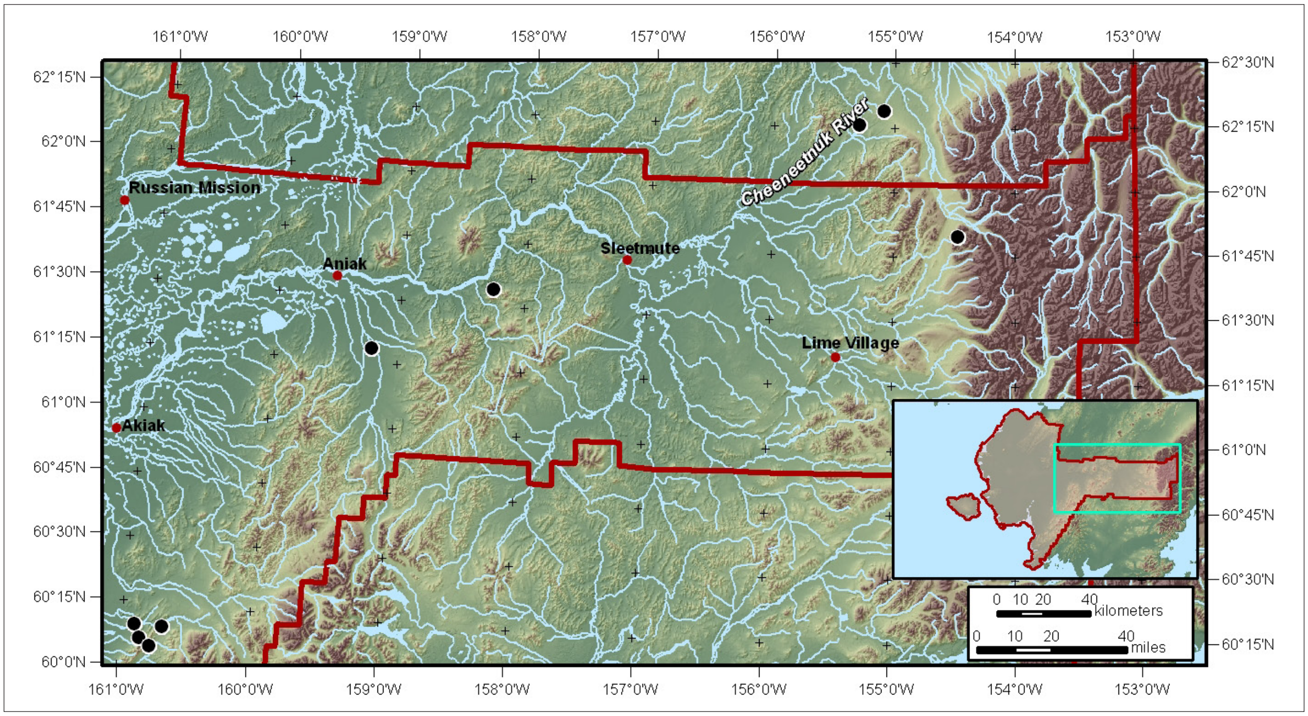


Figure G2. Location map of the eastern Lower Yukon–Kuskokwim Energy Region, showing selected geographic references noted in the text. Black dots indicate reported coal occurrences, particularly along the Cheeneetnuk River area.

by Gilbert from two of these locations (see their figure 5), including a 13- to 20-inch-thick bed and a 4- to 6-meter-thick bed. They reported bed dips of up to 75 degrees, and that coal rank ranged from subbituminous B to high-volatile C bituminous. Ash content is low to moderate, and sulfur content ranges from high to very high (1.95 to 8.19 total sulfur on a moisture- and ash-free basis). The higher sulfur values suggest incorporation of interbedded ferruginous mudstone in the coal sample. LePain and others (2003) visited this area in 2000 and found low, overgrown exposures of mudstone along the north bank of the river, including coal float (small fragments), but were unable to locate exposures of coal. The presence of coal in this area is well established, but the number of seams, seam thickness, and lateral extent are unknown. Available information suggests that coal seams are of limited lateral extent and thickness, and thus likely do not represent a significant resource. Additional detailed geologic mapping and targeted shallow exploration (trenching and/or shallow drilling) would provide more detailed information that could alter this conclusion, but the absence of nearby communities makes additional work hard to justify (Sleetmute is more than 50 miles to the southwest and McGrath more than 60 miles to the north).

Nelson Island. Coal-bearing Cretaceous-age rocks crop out in coastal exposures on the west side of Nelson Island (fig. G3; Coonrad, 1957). Spurr (1900) reported coal from Nunivak Island (fig. G3) across Etolin Strait; no information is available for that coal occurrence, however, it appears to be a continuation of the nonmarine succession exposed on Nelson Island. The coal-bearing section on Nelson Island is part of a late-Mesozoic-age succession similar to that described by Patton and others (1994) in the Yukon–Koyukuk basin to the north. Clough and others (1994) measured and described a total of approximately 365 feet of nonmarine sedimentary rocks on this island and noted that coal accounted for less than 1.5 percent of this total. The thickest seam encountered was 19 inches, located east of the village of Toksook Bay. A coal sample from this section was submitted for laboratory analysis, which established its rank as medium-volatile bituminous, with ash content of 14.6 percent, and 0.5 percent sulfur (Clough and others, 1994). A 29-inch-thick bed of bituminous coal was reported on the north shore of the island at Hazen Bay, east of the village of Tununak (Spurr, 1900; Weber, 1944); however, this coal was covered by a thick snowbank and could not be evaluated in 1992 (Clough and others, 1994). Reportedly, a few tons of coal were mined from this locality but the years when this coal was mined are not known (Weber, 1944). Available data suggest coal from these seams represents a resource suitable for use by individuals to heat cabins. The lack of thick coal seams and uncertainty of the subsurface volume and extent of any coal suggests that coal has little potential for providing an energy source for local communities.

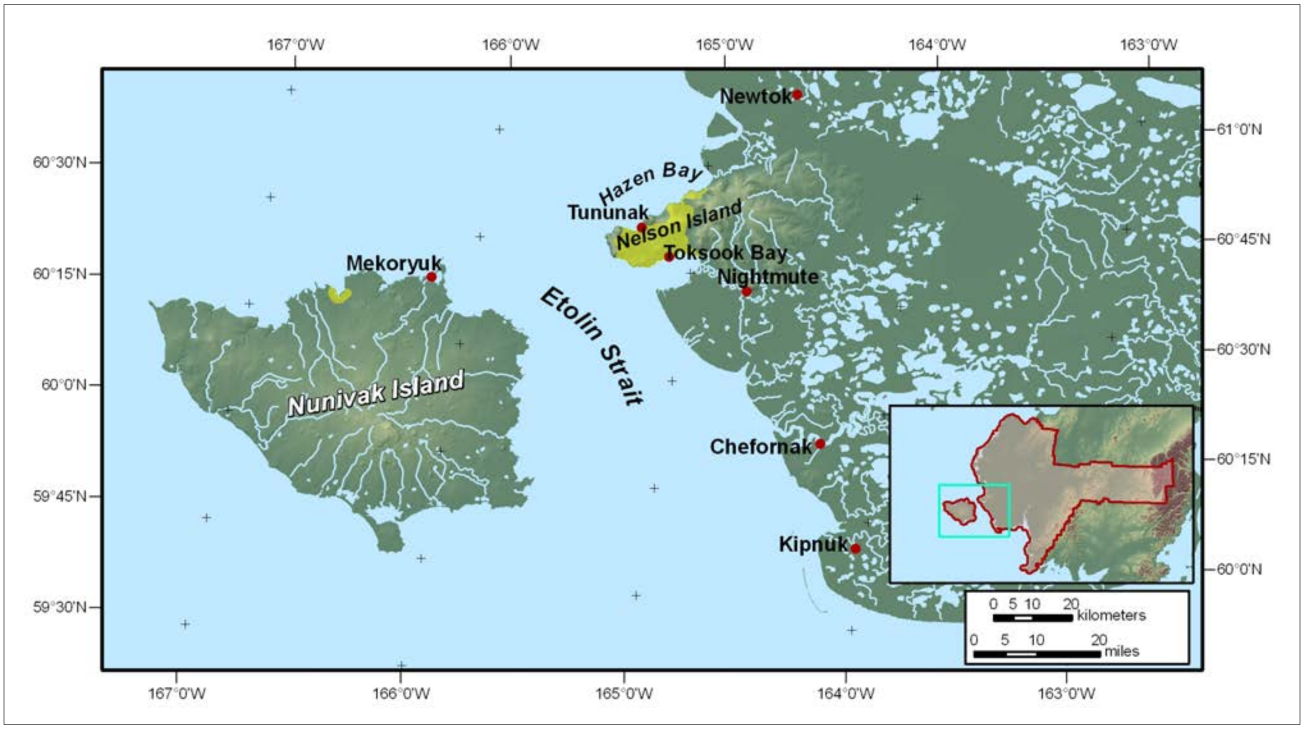


Figure G3. Location map of the western Lower Yukon–Kuskokwim Energy Region, showing reported coal occurrences (black dots) in the Nelson and Nunivak Island areas.

Conventional oil and gas resource potential

As explained in the discussion of requirements for exploitable oil and gas resources (see Chapter A), functioning petroleum systems occur in thick, sedimentary basins filled with thick successions of sedimentary rocks, and consist of three basic elements: Effective source rocks, reservoirs, and traps. Each of the elements must be in existence and connected at the time hydrocarbons are generated; if any one element is missing, a petroleum system is not present. This section considers each of the necessary elements of petroleum systems to evaluate whether conventional oil and gas resources may exist as an exploitable resource in the Lower Yukon–Kuskokwim Energy Region. The vast majority of the region is underlain by crystalline rocks and has no petroleum potential due to a geologic history of intense deformation, heating, and recrystallization under igneous and/or metamorphic conditions.

Overview of sedimentary basins. The distribution of sedimentary basins that could potentially host petroleum systems in the Lower Yukon–Kuskokwim region are shown on sheet 2. These include the Paleozoic-age Holitna basin, the Cretaceous-age Yukon–Koyukuk and Kuskokwim basins, and the Cenozoic-age Holitna and Bethel basins. The Paleozoic-age Holitna basin, to the northeast of the Kulukbuk fault, differs from the Cenozoic-age Holitna basin in age, size, and in the types of sedimentary rocks present. The Paleozoic Holitna basin is a fragment of a much larger sedimentary basin and is filled with deep marine through nearshore marine sedimentary rocks, including limestones, dolomites, sandstones, and shales. The Yukon–Koyukuk and Kuskokwim basins cover a large portion of the region, developed in Mesozoic time, and are filled with deep marine through nonmarine(?) strata (Nilsen, 1989). Late-Mesozoic-age sandstones and shales, similar to those known from both the Yukon–Koyukuk and Kuskokwim basins, underlie a thin cover of Cenozoic-age strata throughout the Bethel basin (Kirschner, 1994; Mull and others, 1995), and most likely extend beneath a large part of the lower Yukon–Kuskokwim area, including the Yukon delta. The Cenozoic-age Holitna basin is a teardrop-shaped basin along the Denali–Farewell fault zone and gravity data suggest it is filled with nearly 15,000 feet of younger sedimentary rocks (sheet 2; Kirschner, 1994). Based on regional geology, the basin fill is assumed to be exclusively nonmarine, although the actual rock types in the subsurface are unknown owing to the absence of well data or rock outcrops in the footprint of the basin (LePain and others, 2000; 2003). The Cenozoic Bethel basin (sheet 2) is relatively thin, as indicated by the single exploration well that penetrated one of the deepest parts of the basin identified in gravity data (Mull and others, 1995).

The Yukon River has accreted a large delta where it has discharged into the Bering Sea over the last 12,000 to 15,000 years. Prior to this time, during the height of the last glacial episode, the delta was several hundred kilometers southwest of its present position, at the edge of the Bering Sea shelf. Hoare and Condon (1962) mapped surface sediments in the onshore portion of the modern delta and noted that unconsolidated deposits include silt, sand, gravel, and layers of brown peat up to several feet thick. They noted these deposits are many hundreds of feet thick. No deep wells have been drilled in the delta and details of the stratigraphy are known only from industry seismic lines. These data suggest a slightly thickened Tertiary succession underlies surficial deltaic sediment. The ancestral Yukon delta may have deposited sediment in the offshore Norton basin, located a short distance north of the modern delta, in the Federal outer continental shelf (OCS) area of the northeastern Bering Sea and Norton Sound. The Norton basin is an extensional basin filled with more than 20,000 feet of Tertiary-age marine and nonmarine sedimentary rocks (Fisher and others, 1981; Turner and others, 1983). Although outside of the Lower Yukon–Kuskokwim Energy Region, the Norton basin is included in the summary that follows.

Source rocks. Outcrop studies have documented that sedimentary rocks in the Paleozoic-age Holitna basin generally contain organic carbon in amounts less than what is generally regarded as a good petroleum source rock (LePain and others, 2000). Likewise, outcrop studies have documented that Cretaceous-age sedimentary rocks in the Yukon–Koyukuk and Kuskokwim basins generally contain organic carbon in amounts less than what is normally considered a good petroleum source rock, and the organic material that is present is typically gas-prone (Lyle and others, 1982). The Nulato Unit No. 1 well, in the western part of the Yukon–Koyukuk basin and outside of this region, penetrated 12,000 feet of deformed and tightly cemented Cretaceous-age sandstone, siltstone, and shale. No information is available on the organic content of shales encountered in this well, but the drilling reports (available from the Alaska Oil & Gas Conservation Commission) suggest the siltstones and shales have poor petroleum source potential. The Napatuk Creek No. 1 well, approximately 50 miles southwest of Bethel, penetrated approximately 2,000 feet of Cenozoic-age rock and nearly 13,000 feet of interbedded sandstone, siltstone, and shale of Cretaceous age. The entire section penetrated by this well contains little organic material, and the material encountered was gas-prone (Mull and others, 1995).

The stratigraphy of the Cenozoic-age Holitna basin is not known and that of the Bethel basin is known only from a single exploration well (Napatuk Creek No. 1). Outcrop studies of Cenozoic-age sedimentary rocks along the Denali–Farewell fault zone in the McGrath Quadrangle by Sloan and others (1979), Dickey (1982), and LePain and others (2003) demonstrate the presence of coal and carbonaceous mudstone. These rocks are thought to be similar to the stratigraphy of the Cenozoic Holitna basin (LePain and others, 2003). Laboratory analysis of samples collected from the coal-bearing section in the McGrath Quadrangle (LePain and others, 2003) and of samples of similar-age rocks exposed in the Middle Tanana basin near Healy (Stanley and others, 1990) demonstrate their potential as source rocks for gas and also show some potential to generate liquid hydrocarbons (condensate) if buried deep enough. Gravity data suggests that the Holitna basin may locally contain nearly 15,000 feet of sediment in its deepest part (Kirschner, 1994). If the basin has a normal geothermal gradient, then any organic-rich sediment from the deeper parts of the basin could generate thermogenic hydrocarbons. Biogenic gas, generated by microbial processes, is often considered an unconventional resource due to its method of production in coalbed methane systems (see Chapter A). However, in some basins, such as the prolific Cook Inlet in southern Alaska, biogenic methane has been known to occur in conventional reservoirs. If thick coals are present in the Holitna Basin, it is reasonable to assume biogenic gas has been generated due to the microbial breakdown of buried organic matter. However, in order for biogenic gas to migrate into a conventional reservoir, an unusual set of geologic conditions are required involving the formation of early traps, rapid burial, and finally rapid uplift (Rice, 1993).

Details of the subsurface stratigraphy of the Yukon delta are poorly known. Hoare and Condon (1962) mapped the surface sediments in the delta, noted the presence of brown peat layers up to several feet thick, and stated the deltaic sediments are many hundreds of feet thick. Regional seismic data in the area suggest that a slightly thickened Tertiary-age succession may be present beneath the delta, but no information is available on the organic carbon content of these rocks and they are likely insufficiently thick to host a mature source rock (Mull and others, 1995).

Eight deep wells were drilled in the Norton basin in the early 1980s. Data from the COST No. 1 well are summarized in Turner and others (1983). Cuttings are typically organically lean (low percentage of organic carbon), except where contaminated by coaly material. Organic carbon is dominantly land-derived woody and herbaceous material. This type of carbon, when present in sufficient quantities at sufficient burial depths, typically generates gas. Geochemical data demonstrate sufficient temperatures and quantities of organic carbon beneath approximately 9,500 feet to generate conventional hydrocarbons. Of the eight deep wells drilled in the basin, all had moderate to strong gas shows and three had weak oil shows, demonstrating that rocks capable of generating hydrocarbons are present in the basin and have generated some petroleum. Thermally mature, organically lean strata of Eocene to middle Oligocene age are the most likely source rocks (Minerals Management Service [MMS], 1998).

Reservoir rocks. Partly dolomitized limestones in the Paleozoic Holitna basin commonly include visible porosity (LePain and others, 2000) and laboratory measurements demonstrate porosities greater than 10 percent in some samples of this lithology (Smith and others, 1985). It is reasonable to suggest that this rock type may also include sufficient permeability to function as a potential reservoir for petroleum. Most Cretaceous sandstones in the area are tightly cemented and have porosity and permeability below thresholds necessary for conventional oil and gas production (Lyle and others, 1982; Mull and others, 1995). Cenozoic sandstones exposed in the McGrath Quadrangle near Farewell appear tightly cemented, however, laboratory porosity and permeability measurements are not available. Similar age rocks exposed near White Mountain to the west appear loosely cemented and probably include significant porosity and permeability. Again, the stratigraphy of the Cenozoic Holitna basin is unknown. Consequently, it is unknown whether or not these tightly cemented and/or loosely cemented sandstones are present in the basin. Sandstone is abundant in the offshore Norton basin and samples collected from the Norton Basin COST No. 1 well have average porosities well in excess of 10 percent. However, samples with porosities less than 24 percent tend to have low permeabilities (1 millidarcy or less; Turner and others, 1983), decreasing their potential as conventional hydrocarbon reservoirs.

Traps. The Paleozoic Holitna, Mesozoic Yukon–Koyukuk and Kuskokwim, and Cenozoic Holitna basins have all been subjected to one or more episodes of deformation (Decker and others, 1994; Patton and others, 1994; LePain and others, 2003). Complex folds and faults recognized in sedimentary rocks of the Paleozoic Holitna, Mesozoic Yukon–Koyukuk, and Mesozoic Kuskokwim basins suggest that potential structural traps for oil and gas are present in the subsurface of these basins. Complex folding and faulting of the Cenozoic section in the McGrath Quadrangle suggests similar deformation in the fill of the Cenozoic Holitna basin, providing potential for structural traps in that basin as well. Stratigraphic traps associated with pinch-outs of coarse-grained sandstones within shaley and silty horizons are also most likely present in the Mesozoic and Cenozoic basins. Trapping geometries formed by erosional truncation of sandstones beneath major erosion surfaces (unconformities) can also be expected. Low-permeability shales and siltstones are common in Cretaceous and Tertiary successions in the region and are probably capable of sealing hydrocarbons accumulated in traps. Seismic sections across the offshore Norton basin show ample evidence for potential structural and stratigraphic traps, including faulted anticlines and stratigraphic onlap above older basement rocks.

Summary of conventional oil and gas resource potential. After reviewing available data, LePain and others (2000) concluded the petroleum potential of the Paleozoic Holitna basin was very low due to the lack of suitable petroleum source rocks. Their conclusion is in general agreement with that of Smith and others (1985) from a study conducted in the early 1980s. Likewise, Mull and others (1995) concluded the petroleum potential of the Bethel basin was low for similar reasons and this conclusion can safely be extrapolated to the portion of the Yukon–Koyukuk and Kuskokwim basins underlying the western part of the region. LePain and others (2003) evaluated the shallow gas potential (coalbed methane—unconventional gas) of the Cenozoic Holitna basin and concluded it was low due to the likely structural complexity of the basin fill. If coal-bearing rocks are present in the Cenozoic Holitna basin at depths below approximately 5,000 feet, the basin could have some conventional gas potential and possibly some liquid hydrocarbon potential (condensate). The area comprising the deepest part of the basin is small and unlikely to support sizable petroleum accumulations. The next logical step in pursuing conventional hydrocarbons in the Cenozoic Holitna basin is to consider acquiring seismic data to image the subsurface structure and stratigraphy. Ultimately, one or more exploration wells will be required to test the conventional oil and gas potential of this basin.

The offshore Norton basin includes many of the elements necessary to have a functioning petroleum system. Geochemical samples collected from wells as deep as 9,500 feet in the Norton Sound COST No. 1 are rich enough in organic carbon and have been buried deeply enough to produce hydrocarbons and, in fact, gas shows were present in all eight deep wells drilled in the basin. An economic analysis by the U.S. Minerals Management Service (Reitmeier, 2005), which included numerous assumptions, concluded that an accumulation of at least 40 billion cubic feet of gas, if found within 40 miles of Nome, would be marginally capable of competing with diesel fuel at 2004 prices. Diesel prices are now higher and such a gas discovery would likely be more competitive. This analysis pertains to Nome only, where a sizable population is present and is relatively close to the basin. The many small communities scattered around the Lower Yukon–Kuskokwim Energy Region constitute a small and widely dispersed market that would likely render gas from a source in this basin non-economic for these communities. While Bethel and Aniak are sizable communities, they are most likely too far from the basin to justify exploration there to meet their energy needs alone.

Unconventional oil and gas resource potential

Coalbed methane. As explained in the discussion of requirements for coalbed methane, shalebed gas, and gas hydrates (see the appropriate summary reports for the requirements for these resource categories), several factors must be considered when evaluating whether a basin has unconventional oil and gas potential. Most importantly, suitable thicknesses of coal of the appropriate rank, or source rocks capable of generating gas must be present in a sedimentary basin. These rocks must then have a suitable geologic history in order to generate petroleum.

LePain and others (2003) evaluated the shallow gas potential (coalbed methane—unconventional gas) of the Cenozoic Holitna basin and concluded the potential was low due to the likely structural complexity of the basin fill. As stated above regarding conventional oil and gas in the Cenozoic Holitna basin, no subsurface data are available from this basin and the next logical step in evaluating its conventional and unconventional petroleum potential is to acquire shallow seismic data and, pending results from these data, drill an exploration well (or wells).

Similarly, the subsurface stratigraphy beneath the modern Yukon delta is unknown. Seismic data suggest a slightly thickened Tertiary-age sedimentary succession, which could include unconventional gas accumulations. It is also possible that minor accumulations of biogenic gas are present in the shallow delta stratigraphy (Quaternary-age deposits). The sizes of these accumulations are likely to be very small, rendering their utility as energy sources marginal for even the smallest communities in the region. Assessing the coalbed methane potential of the deeper Tertiary stratigraphy will require one or more exploration wells, which require significant investment, with a relatively low chance of success.

Tight gas sands. As noted above, Cretaceous formations in the region typically lack sufficient porosity and permeability to function as conventional reservoirs for oil and gas and are correctly considered tight sandstone formations. However, the absence of suitable source rocks suggests these sandstones are not likely to have gas in their pore and fracture networks. Tight sandstones interbedded with coals and carbonaceous mudstones may be present in the subsurface of the Tertiary Holitna basin. Interbedded sandstones, coals, and carbonaceous mudstones are known from outcrops to the northeast in the McGrath Quadrangle (Dickey, 1982; LePain and others, 2003) and it is reasonable to infer their presence in the Holitna basin. Although the area of the Holitna basin is small, biogenic gas could have been locally generated from coals and migrated during uplift into tight reservoirs.

Available well data from the Norton basin suggest that tight gas sands could be present in the basin, particularly at depths greater than 6,000 feet, where compaction reduces porosity and permeability (Turner and others, 1986). Data from the two COST wells indicate that the deeper parts of the section are sufficiently mature to generate gas, although most of the sediments are low in total organic carbon (Turner and others, 1983a,b). Tight gas plays typically require closely spaced wells and artificial stimulation to be effectively produced; this type of unconventional resource would likely be challenging to economically develop in an offshore setting.

Shale gas. One of the primary requirements for shale gas is the presence of an organic-rich source rock present in the thermogenic gas window that is sufficiently brittle to host a natural fracture system (see Chapter A). For the same reasons outlined in the previous sections, the shale gas potential of Paleozoic- and Cretaceous-age rocks in the region is very low due to the likely absence of suitable source rocks. For the same reasons cited in the discussion of coalbed methane potential, carbonaceous mudstones, if present in the Tertiary Holitna basin, are likely to be in structurally complex fault blocks, significantly reducing their potential as a shale gas resource.

Gas hydrates. The main occurrences of gas hydrates in nature are in modern marine sediments and in arctic regions with well-developed, continuous permafrost. Permafrost is not well developed in the Lower Yukon–Kuskokwim region and, where locally present, is discontinuous. Consequently, the potential for economic concentrations of gas hydrates in low.

Geothermal resource potential

Three hot springs are known in the Lower Yukon–Kuskokwim region (sheet 2). These include Ophir, Chuilnuk, and an unnamed hot spring near the Tuluksak River (~5 miles west of Ophir hot springs; Motyka and others, 1983). All three are known to be spatially associated with granitic plutons (Gassaway and Abramson, 1978). Measured water temperature at Ophir Hot springs is 142°F (61°C) and the flow rate is estimated at 71 gallons/minute. Measured water temperature at Chuilnuk is 124°F (51°C) and flow rate is estimated at 145 gallons/minute. Temperature and flow data are not available for the unnamed hot springs. Ophir and the unnamed hot springs are both approximately 15 miles north of Nyac and 25 miles southeast of Kalskag, and Chuilnuk Hot Springs is approximately 40 miles southwest of Sleetmute. Given these distances, these hot springs are unlikely to represent resources capable of providing energy to nearby communities. The low-grade nature of these hotsprings, combined with their remote locations, significantly reduces their potential as viable geothermal energy resources.

RECOMMENDATIONS

Conventional oil and gas resource recommendations

The petroleum industry has expressed interest in the Lower Yukon–Kuskokwim region several times since the 1960s, when the Napatuk Creek 1 well was drilled in the Bethel basin. Since completion of that dry hole, a loose grid of two-dimensional (2-D) seismic data was collected from the Yukon delta area and several industry field parties conducted surface geologic investigations in and around the Holitna Lowland. These activities added to the geologic knowledge base of the region, but did not lead to additional exploratory drilling. Available geologic data suggest that Cretaceous-age sedimentary rocks in the region have low potential for conventional oil and gas due a lack of recognizable source rocks and sandstone characteristics that suggest poor reservoir potential. Sedimentary rocks in the Tertiary Holitna basin could include coal and carbonaceous mudstone capable of generating biogenic gas or even thermogenic gas and condensates in the deepest part of the basin. The area comprising the deepest part of the basin is small and unlikely to support sizable petroleum accumulations. Nonetheless, the State should encourage private-sector exploration of the Tertiary Holitna basin, as it is possible that a small, but locally significant, gas accumulation could be present.

Of the areas covered in this summary, the Norton basin, located a short distance north of the Yukon delta in the Bering Sea and just beyond the boundary of the Lower Yukon–Kuskokwim region, is the most prospective for conventional gas. The large capital costs associated with offshore exploration and the low chance of achieving the desired outcome, suggest this type of future work will be conducted by industry as part of a search for commercially viable accumulations. The discovery of an economic gas field could result in the availability of natural gas for local energy needs. Exploration risk could be reduced with the acquisition of modern three-dimensional (3-D) seismic data that can potentially directly image hydrocarbon accumulations.

Geothermal resource recommendations

The remote location of the Ophir and Chuilnuk hot springs limit their utility as potential sources of geothermal energy. However, the presence of shallow heat flow at these springs is a positive indication of a locally elevated geothermal gradient, allowing for the possibility of additional hidden geothermal resources elsewhere in the region. Exploring directly for these potential resources would be difficult and expensive. One option to assist in the identification of areas of higher potential would be to include evaluation of local and regional geothermal gradients during mineral resource exploration activities, such as airborne geophysical surveys and core drilling.

Unconventional oil and gas resource recommendations

Coalbed methane. Due to the limited stratigraphic and areal extent of coals along the Cheeneetnuk River and on Nelson Island, the volume of coal likely present in these areas is insufficient to generate commercial quantities of coalbed methane. Coal and carbonaceous mudstone may be present in the subsurface Tertiary Holitna basin, but no subsurface data are available that test this possibility. Nearby outcrops of coal-bearing strata along the Denali–Farewell fault zone in the McGrath Quadrangle are highly deformed. If a similarly deformed coal-bearing section is present in the subsurface Holitna basin, its coalbed methane potential could be limited by steeply-dipping beds and extreme compartmentalization into many small, fault-bounded blocks.

Tight gas sands. Due to the lack of potential gas source rocks, the tight gas sand potential of Cretaceous strata in the region is low. For reasons mentioned above, the tight gas sand potential of the Tertiary Bethel and Holitna basins is low. Any projects to evaluate tight gas sands in the region should only be undertaken in combination with a more comprehensive analysis of the biogenic and thermogenic gas potential in any of the area's sedimentary basins.

Shale gas. Due to the lack of extensively fractured source rocks present within the thermogenic gas window, the likelihood of finding commercial quantities of shale gas in the region is low, therefore no further action is recommended.

Gas hydrates. Due to the lack of extensive permafrost and absence of identified source rocks, the likelihood of finding gas hydrates in the region is very low and therefore no further action is recommended.

Coal resource recommendations

Available information suggests that coals in seams of mineable thickness are limited to a small area along the Cheeneetnuk River in the southwestern and northwestern McGrath and Lime Hills quadrangles, respectively. Available data also suggest that the lateral extent of seams in this area is limited. Additional geologic mapping combined with excavation of shallow test pits could alter this conclusion and represent the next logical step in exploring the possibility that mineable coal deposits are present in this area. This area's location far from rural communities does not currently justify this work. However, if mineral development were to occur nearer to these coals, then the resource may warrant additional evaluation as a local source of energy for a mine.

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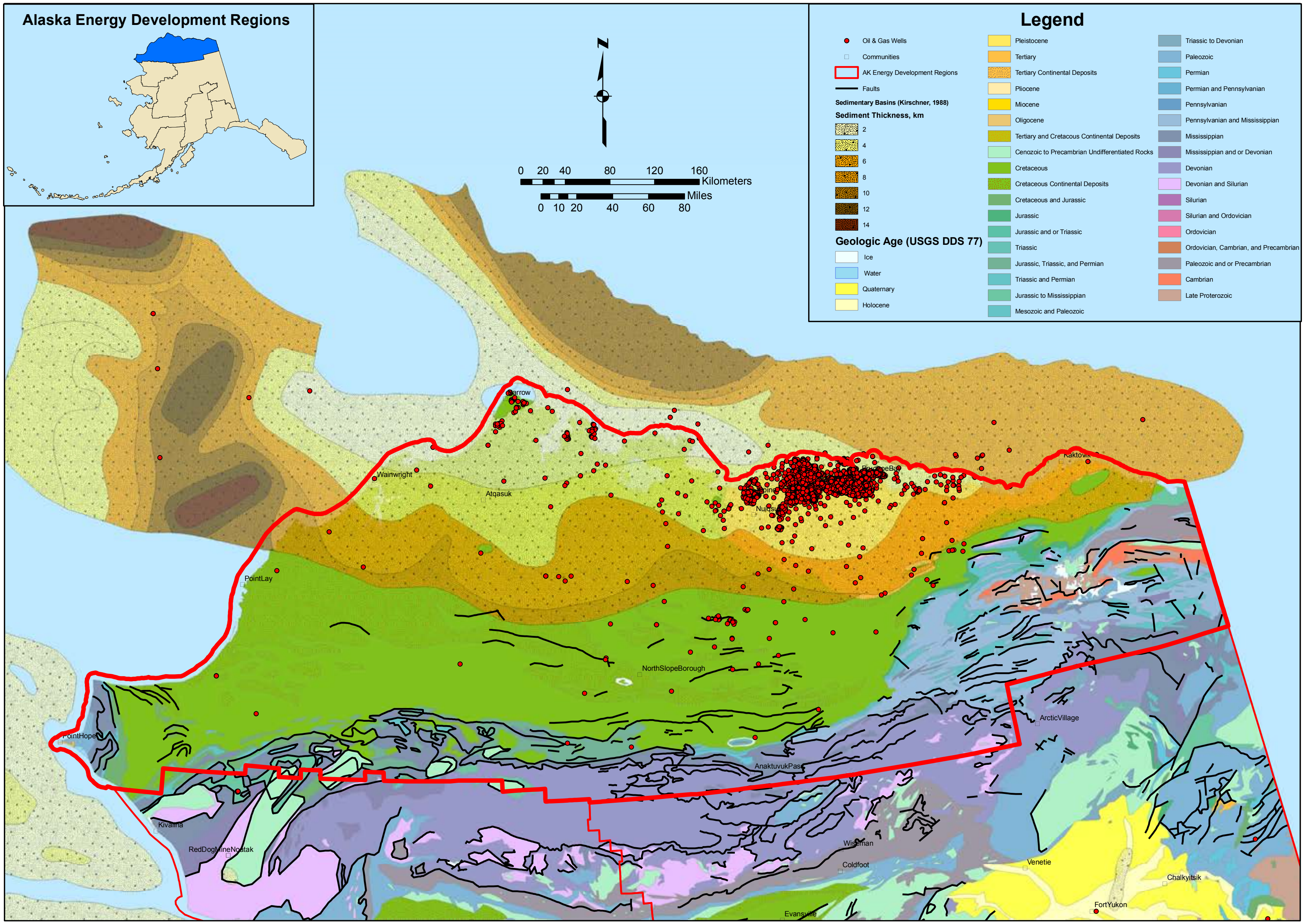
Geology of the North Slope Energy Region, Alaska



North Slope

SUMMARY OF FOSSIL FUEL AND GEOTHERMAL RESOURCE POTENTIAL IN THE NORTH SLOPE ENERGY REGION

by Marwan A. Wartes

INTRODUCTION

Purpose of this report

Economic growth and stability in Alaska's rural and urban areas hinges partially, if not primarily, on the availability of affordable and sustainable energy supplies. Recent price increases in oil and gas commodities have created severe economic hardship in many areas of the state that are dependent on diesel and heating oil as their primary source of energy. All sectors of Alaska's economy rely on affordable energy sources with limited price volatility, highlighting the need to diversify the energy portfolio by developing locally available and sustainable resources that are not tied to the global market. Unfortunately, all areas are not created equal in energy accessibility; the resources available for local exploitation vary widely across the state. It is critical that funding decisions for expensive programs to reduce the dependence on diesel for heat and electricity take into account information concerning the entire suite of natural resources that exist in a given area.

This report draws from existing information to provide community and state leaders an objective summary of our current knowledge concerning the potential of locally exploitable fossil fuel and geothermal energy resources in the North Slope energy region (fig. H1), one of 11 regions recognized by the Alaska Energy Authority in their Energy Plan (AEA, 2009). The potential geologically hosted energy resources considered here include exploitable coal, conventional and unconventional oil and gas, and geothermal resources. This report concludes with recommendations as to what additional data or strategies, if any, would provide the most leveraging in helping to develop new energy resources in the region.

Readers without geological training are encouraged to peruse the geologic summaries of fossil fuel resources and geothermal energy in chapter A. They provide an overview of the geologic elements that must be present in an area to economically develop coal, conventional oil and gas, unconventional oil and gas, and geothermal resources. These summaries will provide the necessary background to more fully understand the information presented in this chapter.

Geographic and geologic setting

The North Slope Energy Region includes the largest borough in the state and is extremely remote, even by Alaska standards. Eight villages are located in the region (sheet 1); in descending order of population these include Barrow, Point Hope, Wainwright, Nuiqsut, Kaktovik, Anaktuvuk Pass, Point Lay, and Atqasuk. Barrow is notably larger than other communities with a population of more than 4,000 (all others have between 220 and 700 residents). The region can be subdivided into three main physiographic provinces—the Brooks Range in the south, which transitions northward into rolling foothills and finally into the low-relief coastal plain.

The geologic evolution of northern Alaska is recorded by the development of two main stratigraphic packages (megasequences) that include sediments derived from

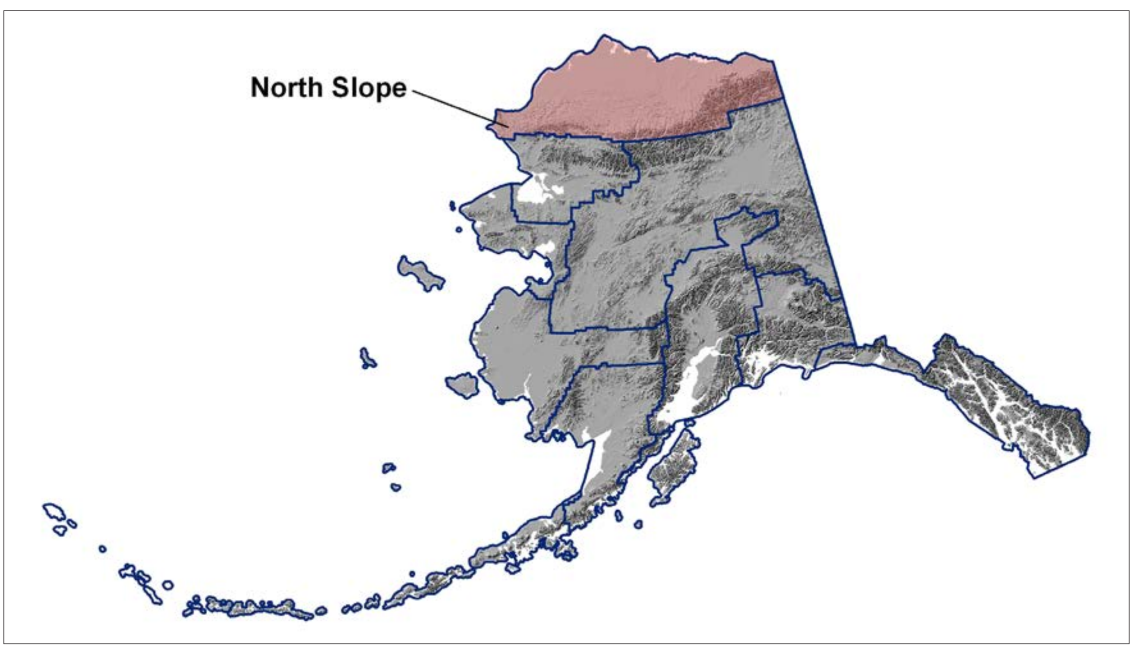


Figure H1. Location map of North Slope Energy Region.

North Slope

distinctly different source areas (Moore and others, 1994). The older units include a wide variety of rock types that were generally derived from the north between about 360 and 120 million years ago and record marine deposition in progressively deeper water to the south (toward the present-day Brooks Range). The younger unit (~120 Ma to present) is dominated by sandstone and shale derived from the Brooks Range that progressively filled the large Colville basin from the southwest to the northeast. This change in sedimentation patterns, and the subsiding basin itself (a foreland basin developed in front of the growing mountain belt), formed in response to the tectonic collision that gave rise to the ancestral Brooks Range mountain belt.

The long geologic history of northern Alaska has endowed the region with an unusually rich collection of natural resources including coal, oil, and gas. To date, the North Slope has produced about 15 billion barrels of oil and represents one of the most prolific petroleum provinces in North America. Recent estimates by federal agencies suggest the region includes vast undiscovered resources (Houseknecht and Bird, 2006) and will likely continue to be the site of significant domestic exploration and production.

GEOLOGIC ENERGY RESOURCE POTENTIAL IN THE NORTH SLOPE ENERGY REGION

Mineable coal resource potential

As explained in the discussion of requirements for mineable coal (see Chapter A), several factors must be considered when evaluating whether a coal deposit is exploitable. The most important factors include the maturity of the coal (rank), seam thickness, amount of impurities (ash and sulfur content), amount of overburden, and the degree of structural complications (steeply dipping seam, folds, faults, etc.). The higher the coal rank, the higher its energy content by weight. Coal rank also influences the minimum seam thickness worth exploiting. Low ash and sulfur contents are highly desirable, as ash reduces the amount of combustible material in a seam and sulfur combines on combustion to form environmentally damaging compounds.

The Colville basin includes a staggering volume of coal in both Cretaceous and Cenozoic rocks, perhaps one-third of the known coal resource in all of the United States. Although estimates of the total reserves vary depending on the vintage of the assessment and the methodology used, studies have concluded the North Slope may contain as much as 3.2 trillion short tons of coal in the Cretaceous alone (Sable and Stricker, 1987) that is bituminous to subbituminous in rank (fig. H2). The Cretaceous coals of the western North Slope are most relevant to discussions of rural energy due to their superior quality, rank, and proximity to villages (fig. H2). Despite this vast resource, the history of coal mining in the region is limited to local use at select Eskimo villages and their hunting and fishing camps (Sanford and Pierce, 1946), seasonal mining along the Chukchi Sea coast to fuel whaling ships around the turn of the century, and brief mining ventures in the 1940s to support local needs (Flores and others, 2004).

The village of Wainwright overlies thick, coal-bearing strata of the Cretaceous Nanushuk Formation (Martin and Callahan, 1978), and near-surface coals are known from a number of nearby localities bordering Peard Bay and along the Kugrua and Kuk rivers (fig. H3; Sanford and Pierce, 1946). Several coal beds from 5 to 10 feet thick are recognized; Kaiser Engineers, Inc. (1977) deemed these coals to have high potential for surface mining based on characteristics such as rank (high-volatile subbituminous B and C), high coal quality (low ash and low sulfur), limited overburden, and shallow dip. The proximity of this resource to Wainwright (7–20 miles) suggests coal would be a viable alternative source of energy in this rural community.

Atqasuk similarly overlies coal-rich rock of the Cretaceous Nanushuk Formation, and surface exposures have been recognized in a number of locations along the Meade River (fig. H3). A modest mining effort was undertaken beginning in the mid 1940s to alleviate acute shortages in the community of Barrow approximately 60 miles to the north (Sanford and Pierce, 1946). The characteristics of these coals are very similar to the Wainwright occurrences noted above (5–6 feet thick, subbituminous, moderately low ash), suggesting extraction of this resource could be a reasonable source of local energy in Atqasuk.

Point Lay lies adjacent to a moderately well studied, high-quality coal province and has long been considered for possible commercial development. A number of private, government, and Native organizations have undertaken geological and exploratory drilling programs aimed at delineating this resource (Kaiser Engineers, Inc., 1977; Clough and others, 1995). The Corwin Mine, south of the community of Point Lay near Corwin Bluffs (fig. H4), was a producer of bituminous coal for steamships from 1880 to 1923 with about 2,600 short tons of coal reportedly mined (Plangraphics, 1983). Smith and Mertie (1930) indicate there were four mines on the bluff and two mines up the nearby creek. Most recently, the Arctic Slope Regional Corporation was working closely with BHP Billiton on a coal exploration program in the region to the east of Corwin Bluffs, although recent reports indicate they will not proceed further (R. Kirkham, Alaska Division of Mining, Land and Water, written commun.). This long-standing interest stems from the outstanding resource base in the region. The abundant coals are found in the Cretaceous Nanushuk Formation, similar to the above examples, although deeper burial to the south has given rise to higher maturity (high-volatile bituminous) and excellent heating values up to 13,000 Btu/lb (Clough and others, 1995). The exposures of coal nearest the village of Point Lay appear to be along the Kukpowruk and Kokolik rivers (fig. H4), where Eskimos historically mined small amounts for local use (Plangraphics, Inc., 1983). Coal has

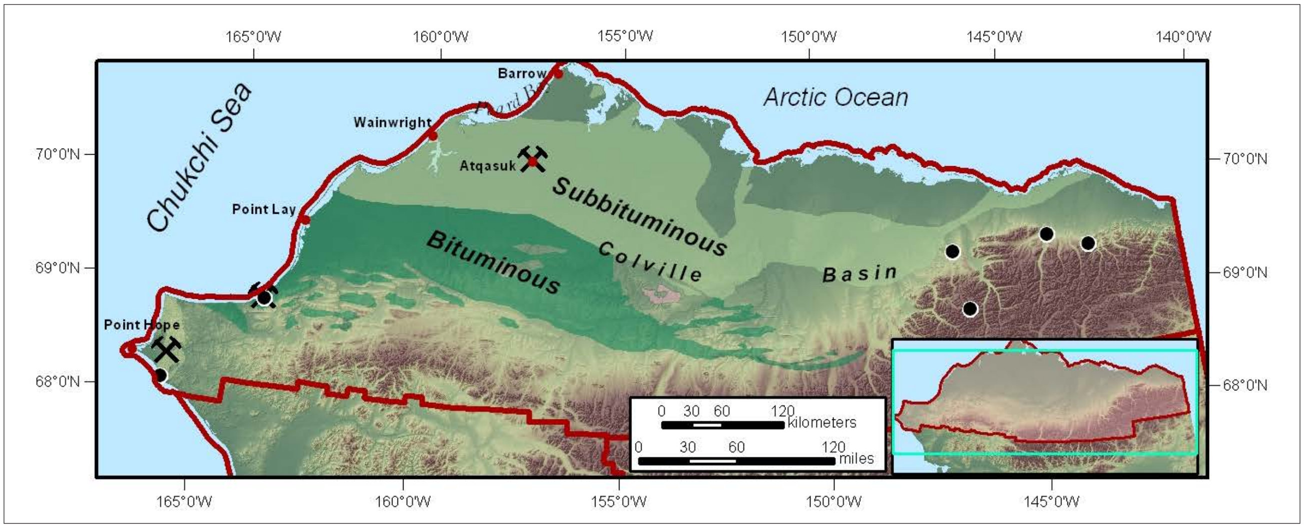


Figure H2. Location map of the North Slope Energy Region, showing extensive distribution of rocks bearing bituminous and subbituminous coal. Black dots indicate additional, more isolated reported coal occurrences.

been noted on the Kukpowruk River as close as 5 miles from the mouth, although the best candidate for development appears to be about 40 miles farther upstream, where a 15-foot-thick coal seam dips gently at river level (Toenges and Jolley, 1947). Less data exist for the Kukpuk River locality, although local Natives reported a 10-foot-thick seam approximately 15 miles east of the village (Toenges and Jolley, 1947). The quality and abundance of coal in the vicinity of Point Lay suggest it could reasonably supply energy for local use.

Point Hope is near some of the oldest coal beds known in Alaska, found in the early Mississippian age Kapaloak Formation (Tailleur, 1966). These coals crop out intermittently along the western side of the Lisburne Hills from Cape Thompson to Cape Dyer and along the Kukpuk River and various other drainages in the area (fig. H4) (Clough and others, 1995). Although Eskimos had reportedly long collected coal along the beaches for local use, explorers in the region first observed these coals 1831; the convenient location along the sea cliffs led to extensive use by passing whaling ships and revenue cutters in the late 1800s and early 1900s (Collier, 1906). These coals are reportedly low-sulfur, low-volatile bituminous to semi-anthracite and possess very high heating quality (11,457–14,731 Btu/lb) (Conwell and Triplehorn, 1976; Clough and others, 1995). Unlike the Cretaceous coals to the north, the rocks in the Lisburne Hills were significantly affected by the development of the Brooks Range and are complexly folded and faulted (Clough and others, 1995). This deformation complicates subsurface prediction and estimation of reserves, resulting in higher exploration and mining risk. Nevertheless, the proximity of this resource to Point Hope and the high heating quality of the coal suggest it could potentially be utilized to satisfy local energy needs.

Conventional oil and gas resource potential

As explained in the discussion of requirements for exploitable oil and gas resources (see Chapter A), functioning petroleum systems occur in thick sedimentary basins, and consist of three basic elements: Effective source rocks, reservoirs, and traps. Each of the elements must be in existence and connected at the time hydrocarbons are generated. This section considers each of these necessary elements of petroleum systems in turn to evaluate whether conventional oil and gas resources may exist as an exploitable resource near any of the communities in the North Slope Energy Region.

Overview of sedimentary basins. Sheet 2 illustrates the broad distribution of Cretaceous and Tertiary sediments of the Colville basin (after Kirschner, 1988), which spans the North Slope region and represents the largest onshore sedimentary basin in Alaska. Beneath these Brooks-Range-derived sediments is a thick package of Mississippian through Cretaceous rocks derived from an enigmatic source to the north (Moore and others, 1994). The most intensive exploratory drilling (sheet 2) highlights the most prospective portion of the basin along the Barrow arch, a relative subsurface high along the north flank of the basin where source and reservoir rocks were not buried too deeply and subtle uplift generated favorable trapping relationships (Houseknecht and Bird, 2006).

Source rocks. Alaska's North Slope is endowed with several excellent oil and gas source rocks in the Triassic, Jurassic, and Cretaceous (Magoon and Claypool, 1985) and this parameter is generally not a limiting factor in most exploration targets. The total depth of burial is often a more important issue, particularly when considering regions south of the Barrow arch, such as near the community of Point Lay, where many of the source rocks are very deeply

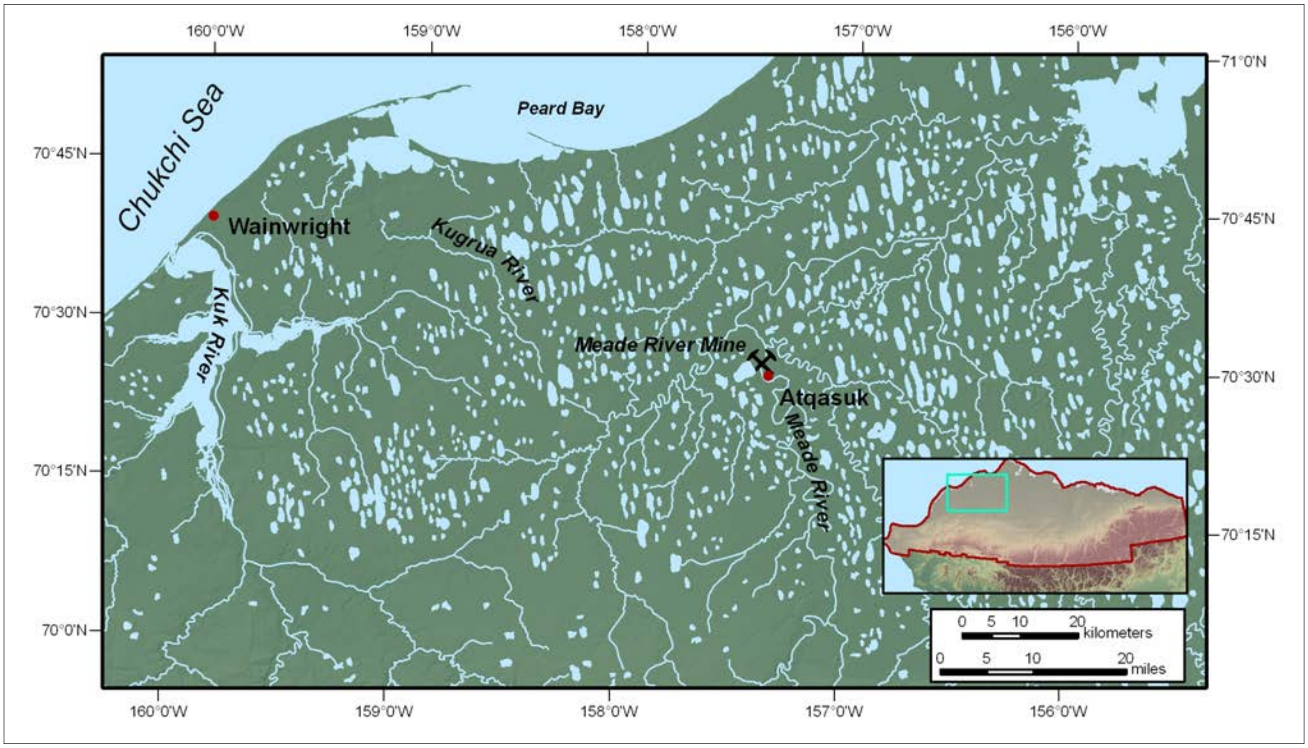


Figure H3. Map marking coal localities near Wainright, and the Meade River Mine near the village of Atqasuk. The pick-axe symbol marks the location of the historic coal mine.

buried beneath sediments shed from erosion of the Brooks Range and are likely no longer oil prone. Gas shows in a number of exploration wells support the contention that the central and western North Slope contains a number of gas-prone source rock horizons, although their quality decreases west of the Meade arch, a subtle subsurface high (Magoon and Bird, 1988). This north–south-trending arch runs east of Atqasuk and two wells indicate the region possesses an unusually high geothermal gradient (Claypool and Magoon, 1988). The Meade No. 1 well (MAP) is recognized as a noncommercial gas discovery with poorly constrained reserves of approximately 20 bcf (Kumar and others, 2002). Although this well is considerably south of Atqasuk, it demonstrates the viability of a gas charge in the general region. More salient and encouraging data come from several methane gas seeps observed in small lakes near the community; government and academic researchers are currently evaluating the source of this gas, which emits nearly 140 m^3/day (Ruppel and others, 2009). Less data are available for the Kaktovik area due to restrictions on exploration within the Arctic National Wildlife Refuge and the proprietary nature of the one well drilled near the community. Nevertheless, the presence of nearby oil seeps and regional assessments suggest the settlement likely overlies excellent Cretaceous oil and gas source rocks noted in the producing fields to the west (Bird, 1999). The communities of Point Hope and Anaktuvuk Pass are part of the Brooks Range Mountain belt where source rocks are generally mature to overmature or have already been uplifted and eroded away (Johnsson and others, 1996).

Reservoir rocks. The most prospective reservoir unit of interest for Point Lay, Wainwright, and Atqasuk is the Cretaceous Nanushuk Formation. Regional porosity and permeability data (Bartsch-Winkler and Huffman, 1988) indicate reservoir quality in this unit is more favorable in the coastal plain than in the foothills, although reported values are locally adequate for gas even near Point Lay. Results from a recent shallow coalbed methane well drilled at Wainwright indicate that thick sandstones deposited in ancient river channels possess good reservoir quality with measured porosity locally exceeding 25 percent (K. Helmold, written commun.). In the Kaktovik area, the most prospective reservoir rocks are likely within Cenozoic strata of the Canning and Sagavanirktok Formations, both of which are locally oil-stained at the surface or tested significant hydrocarbons in regional drilling (Bird, 1999). Conventional reservoirs beneath Point Hope and Anaktuvuk Pass are likely very limited, due to deep burial, thorough cementation, and complex deformation during creation of the Brooks Range.

Traps. A number of stratigraphic traps might occur in the Nanushuk Formation where isolated sandstone bodies are encased in impermeable mudstone (Houseknecht, 2003). However, in the vicinity of Wainwright, Atqasuk, and Point Lay, these settings are likely very difficult to predict or document without the benefit of high-resolution three-

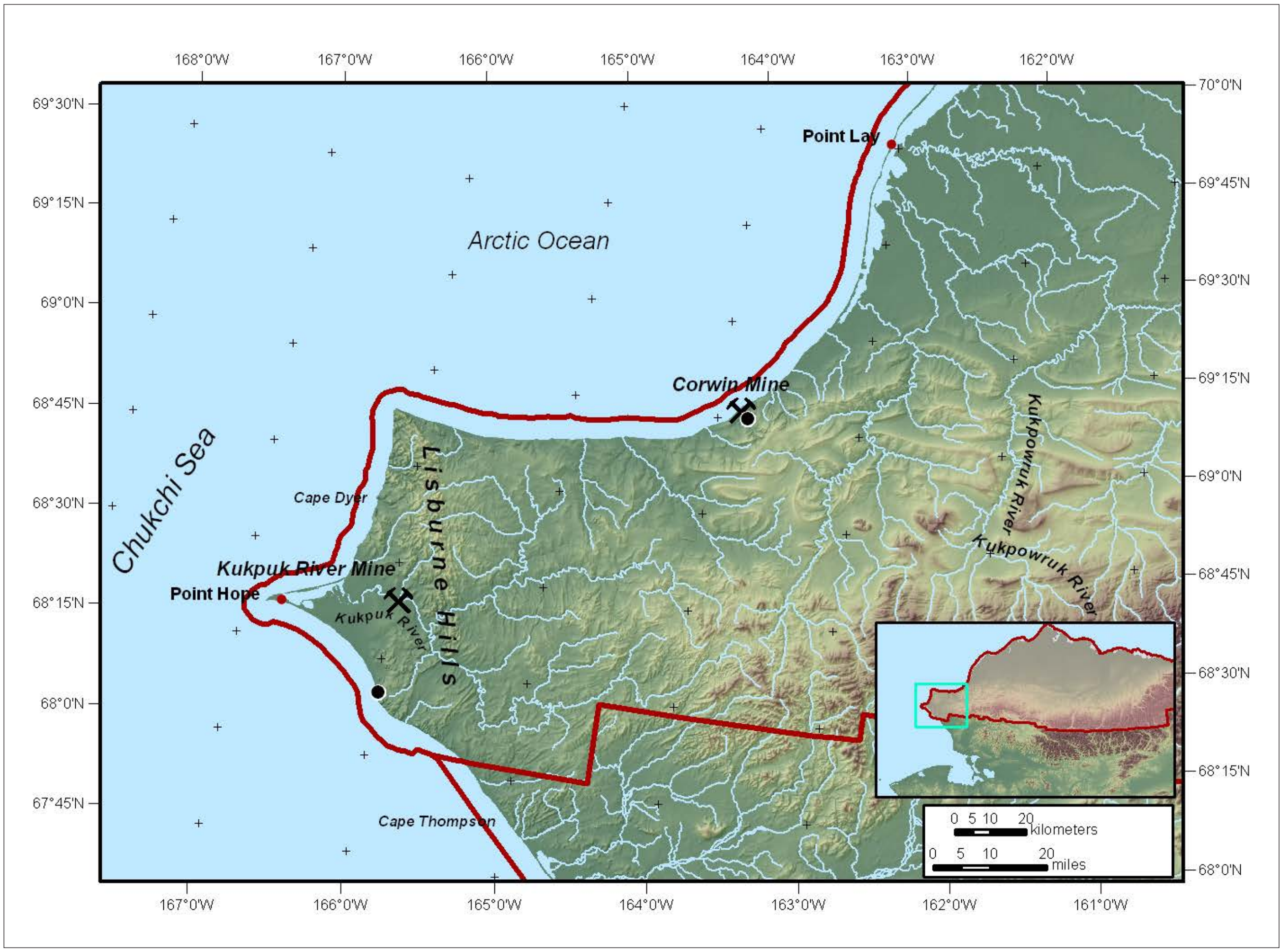


Figure H4. Map of the westernmost Brooks Range and Point Hope and Point Lay areas, showing select geographic references noted in the text. The pick-axe symbol indicates the location of the historic Kukpuk River and Corwin coal mine; black dots mark additional reported coal occurrences.

dimensional (3-D) seismic data. Anticlinal structural traps are also possible in the Point Lay area, although significant risk exists regarding the timing of folding relative to hydrocarbon generation (Potter and Moore, 2003). Assessment of Native lands near Kaktovik suggests a number of possible trapping configurations including stratigraphic traps involving marine and nonmarine Cenozoic sediments (Houseknecht and Schenk, 1998), and structural traps associated with both contractional and extensional folds and faults (Perry and others, 1998). The intense and complex structural deformation associated with the Brooks Range presents a significant challenge to exploration in the Point Hope and Anaktuvuk areas and any structural traps are likely to be small gas accumulations.

Summary of conventional oil and gas resource potential. Much of the North Slope Energy Region north of the Brooks Range is underlain by several rich source rocks that have contributed hydrocarbons to several functioning petroleum systems. These source rocks tend to be more deeply buried in the west-central and southwestern North Slope and, consequently, are likely gas-prone. Communities near or close to the Barrow arch in the north-central and western North Slope may be favorably situated for discovery of nearby conventional gas accumulations similar to accumulations near Barrow. Less data are available for the Kaktovik area, given restrictions on exploration in the Arctic National Wildlife Refuge. The presence of nearby oil seeps and likely excellent oil and gas source rocks at depth suggests this area may be located near oil and gas accumulations that could be utilized by Kaktovik residents.

Unconventional oil and gas resource potential

Coalbed methane. The Cretaceous Nanushuk Formation of the North Slope Energy Region possesses abundant bituminous and subbituminous coal (fig. H2), which is the default required ingredient for this resource. Recent assessments suggest these coals in the central and western North Slope contain an estimated mean of 15 tcf of undiscovered coalbed gas (Roberts and others, 2008). This extremely large number reflects the broad, laterally continuous distribution of thick coal beds of the appropriate rank and burial depth as well as documented gas shows associated with coals penetrated in regional exploration wells (Roberts, 2008). Wainwright, Atqasuk, and Point Lay all lie within this prospective "fairway" for coalbed methane accumulations (Tyler and others, 2000; Roberts, 2008). In fact, the village of Wainwright was selected as a test site for coalbed methane shallow coring in the Arctic, resulting in the successful drilling to a depth of 1,613 feet and documentation of more than 20 total feet of methane-bearing coals beneath the permafrost (Clark and others, 2007; Clark and others, 2010). Preliminary data indicate that the coals are fully saturated with gas (average of 140 asf gas/ton coal) and conservative estimates indicate this resource could serve village energy needs for 10 to 100 years, depending on the number of seams that are tapped and the total area of extraction (Petroleum News, 2007). Testing is continuing from additional monitoring and delineation wells, although a number of economic and engineering hurdles remain. Ongoing studies of the gas seeps near Atqasuk may help establish whether or not the methane is derived from shallow coalbed methane sources. Regardless, the village has good potential for this resource. Similarly, the abundant coal beneath Point Lay has modest coalbed methane potential, possibly assisted by fold-related traps (Roberts, 2008). Although high-quality, mature coals are recognized in the vicinity of Point Hope, the degree of structural disruption suggests coalbed methane accumulations are unlikely (Smith, 1995).

Tight gas sands. The Colville basin contains the two most important features for tight gas accumulations: Abundant gas-prone source rocks and thick, low-permeability reservoir units. The potential for this resource is best developed in the Brooks Range foothills, where geologically rapid and deep burial has matured probable Jurassic and Cretaceous source rocks beneath and adjacent to deep-water sandstones of the Torok Formation. Evidence suggesting tight gas resources may be present largely comes from exploration wells, many of which indicate gas charge, overpressure, and undercompaction within potential tight gas sandstone units (Nelson and others, 2006). Point Lay, Atqasuk, and Wainwright each have some potential for tight gas, although Point Lay is the best situated of the three due to its location above the thicker, deeper parts of the Colville basin.

Shale gas. The presence of organic-rich, gas-prone shales within the Brooks Range and Colville basin suggest there is significant potential for shale gas in northern Alaska. The only exploration for this resource to date is in the western Brooks Range (Northwest Arctic region), where organic-rich Mississippian-age mudstones are recognized to contain gas trapped within a self-sourcing system. Although preliminary results from shale gas exploration around Red Dog have been promising, it is unclear how extensive this resource might be. Similar rocks are known in the Lisburne Hills east of Point Hope, but complex folding and faulting indicate exploration would be a very high risk. As part of the Colville basin, Point Lay, Wainwright, Atqasuk, and Kaktovik all overlie several possible shale gas targets, although too little is known to reliably assess their potential.

Gas hydrates. Gas hydrates are found in a narrow range of modern environments and only occur within specific temperature and pressure conditions. Presently, the North Slope appears to be the only onshore region in Alaska with sufficient permafrost to preserve significant methane hydrate. Recent evaluations point to a vast amount of gas hydrate in the region; the mean estimate of more than 85 tcf exceeds that of all other sources of conventional and unconventional gas (Collet and others, 2008). Recovering this gas presents a number engineering and development challenges, although ongoing research in northern Alaska and Canada suggests that gas can be produced with existing technology (Collet, 2009). Wainwright and Kaktovik are in the critical gas hydrate stability zone (Atqasuk may also be, although the elevated geothermal gradient associated with the Meade arch limits the thickness of critical permafrost). As our understanding of this resource improves, this gas may eventually prove to be viable source of local energy.

Geothermal resource potential

There are only two recognized thermal springs in the North Slope region, both in the northeastern Brooks Range (sheet 2). The temperatures reported for these springs are relatively low (84°F and 120°F [29°C and 49°C]) and flow rates have not been measured (Motyka and others, 1983). Neither of these is close enough to Kaktovik to be an exploitable energy resource.

RECOMMENDATIONS

Conventional oil and gas resource recommendations

Alaska's North Slope remains the most prospective onshore conventional hydrocarbon province remaining in North America. Despite this recognized potential, large parts of the region remain underexplored due to the remoteness and hostile climate that results in unusually high exploration and development costs. In this context, the economics surrounding pursuing conventional oil and gas for rural energy alone are extremely challenging. Rural energy success stories such as Barrow and Nuiqsut depended originally upon third-party investment in commercial-led exploration. Any future exploration (or pipelines) in the vicinity of other villages in the region should similarly attempt to secure agreements for local distribution. The vigorous gas seeps near Atqasuk deserve further research to determine the source and nature of the methane (biogenic vs. thermogenic). It remains possible these seeps are leaking from an exploitable conventional accumulation that could be harnessed for local use. If so, engineering and economic studies would also be critical in assessing whether this potential resource is competitive with present energy sources.

Coal resource recommendations

The western part of the North Slope Energy Region contains abundant subbituminous and bituminous coal reserves that might benefit the following communities: Point Hope, Point Lay, Wainwright, and Atqasuk (fig H2). Of these communities, our understanding of the high-quality coal resources near Point Lay is the most mature due to recent exploration efforts. Local energy needs could be supplied by these coals, particularly if a local use agreement is planned into future commercial-scale development. If commercial development proceeded, there is a sufficient resource base to support a power plant feeding other communities along the western Arctic coast. The modest historic mining near Point Hope, Wainwright, and Atqasuk demonstrates the feasibility of further exploitation. In these three communities, a logical next step would be improved geologic characterization, particularly shallow drilling near Wainwright and Atqasuk, where surface exposures are limited in the coastal plain. Exploration risk associated with mining the coals in the Point Hope area could be reduced through the execution of detailed geologic mapping and stratigraphic work to characterize the local and regional structural relationships. Remaining villages in the region are either not in need of additional local energy sources (Barrow and Nuiqsut), or are not situated near any mineable coals (Kaktovik and Anaktuvuk Pass). It should be noted that the development of any of these coal resources would need to overcome nontrivial difficulties associated with the extreme climate, including plans for reclamation in sensitive permafrost environments. Additionally, the National Petroleum Reserve Alaska is closed to mineral development, which includes coal mining. Any coal mining in the NPRA would require a change in the regulations for mineral development near the affected villages.

Unconventional oil and gas resource recommendations

Coalbed methane. The abundance of subbituminous to bituminous coal and gas-prone source rocks near the communities of Wainwright, Atqasuk, and Point Lay suggest the overall potential for coalbed methane is fair to good. However, coalbed methane production techniques are unproven in rural Arctic Alaska and it remains unclear if any of these could be developed in a cost-effective manner. The results of coalbed methane test drilling at Wainwright are encouraging, although a number of engineering challenges remain, including effective water disposal and production in permafrost settings. Nevertheless, depending on the results of ongoing studies and sustained investment in the project, this unconventional resource may ultimately provide Wainwright with local energy and serve as a critical benchmark for future exploration elsewhere in rural Alaska. The nature and source of gas seeps in the Atqasuk area remain poorly known and deserve further study. The results of ongoing studies by academic and government researchers should provide preliminary constraints and assist in evaluations of whether or not this gas might represent a viable source of energy for the community.

Tight gas sands and shale gas. The ultimate potential of tight gas sands and shale gas in rural Alaska remains unknown; given the abundance of gas-prone source rocks across the North Slope, future assessment of these resources is warranted, perhaps including detailed analysis of existing well data and new sample analyses.

Gas hydrates. Although the estimated volume of gas hydrate resource on the North Slope is enormous, long-term production is unproven and its application in rural settings must await further government- and industry-led research.

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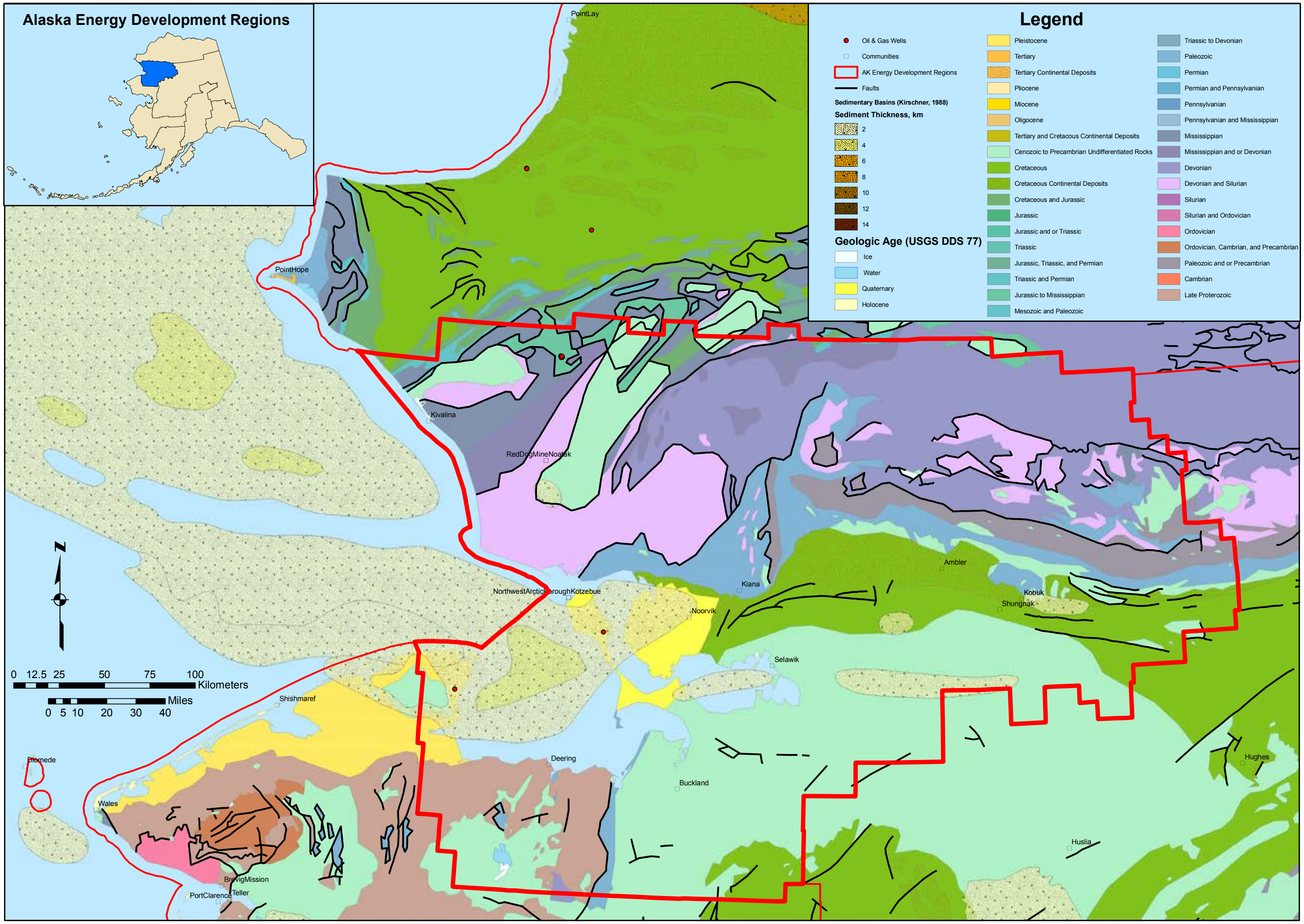
Geology of the Northwest Arctic Energy Region, Alaska



SUMMARY OF FOSSIL FUEL AND GEOTHERMAL RESOURCE POTENTIAL IN THE NORTHWEST ARCTIC ENERGY REGION

by Marwan A. Wartes

INTRODUCTION

Purpose of this report

Economic growth and stability in Alaska's rural areas hinges partially, if not primarily, on the availability of affordable and sustainable energy supplies. Recent price increases in oil and gas commodities have created severe economic hardship in many areas of the state that are dependent on diesel and heating oil as their primary source of energy. All sectors of Alaska's economy rely on affordable energy sources with limited price volatility, highlighting the need to diversify the energy portfolio by developing locally available and sustainable resources that are not tied to the global market. Unfortunately, all areas are not created equal in energy accessibility; the resources available for local exploitation vary widely across the state. It is critical that funding decisions for expensive programs to reduce the dependence on diesel for heat and electricity take into account information concerning the entire suite of natural resources that exist in a given area.

This report draws from existing information to provide community and state leaders an objective summary of our current knowledge concerning the potential of locally exploitable fossil fuel and geothermal energy resources in the Northwest Arctic Energy Region (fig. I1), one of 11 regions recognized by the Alaska Energy Authority (AEA) in their Energy Plan (AEA, 2009). The potential geologically hosted energy resources considered here include exploitable coal, conventional and unconventional oil and gas, and geothermal resources. This report concludes with recommendations as to what additional data or strategies, if any, would provide the most leverage in helping to develop new energy resources in the region.

Readers without geological training are encouraged to peruse the geologic summaries of fossil fuel resources and geothermal energy in Chapter A. They provide an overview of the geologic elements that must be present in an area to economically develop coal, conventional oil and gas, unconventional oil and gas, and geothermal resources. These summaries will provide the necessary background to more fully understand the information presented in this chapter.

Geographic and geologic setting

The Northwest Arctic Energy Region is approximately 39,000 square miles and includes the second largest borough in Alaska (sheet 1). There are 11 permanent villages in the region, and like much of remote western Alaska, transportation infrastructure is limited. The largest community in the region is Kotzebue, a regional hub with more than 3,000 residents. Other sizable communities include Selawik (population ~800) and Noorvik (population ~600). The remaining eight villages in the region each have fewer than 500 residents. The Red Dog mine, operated by Teck Cominco Alaska, is located in the northern part of the region and is an important regional employer.

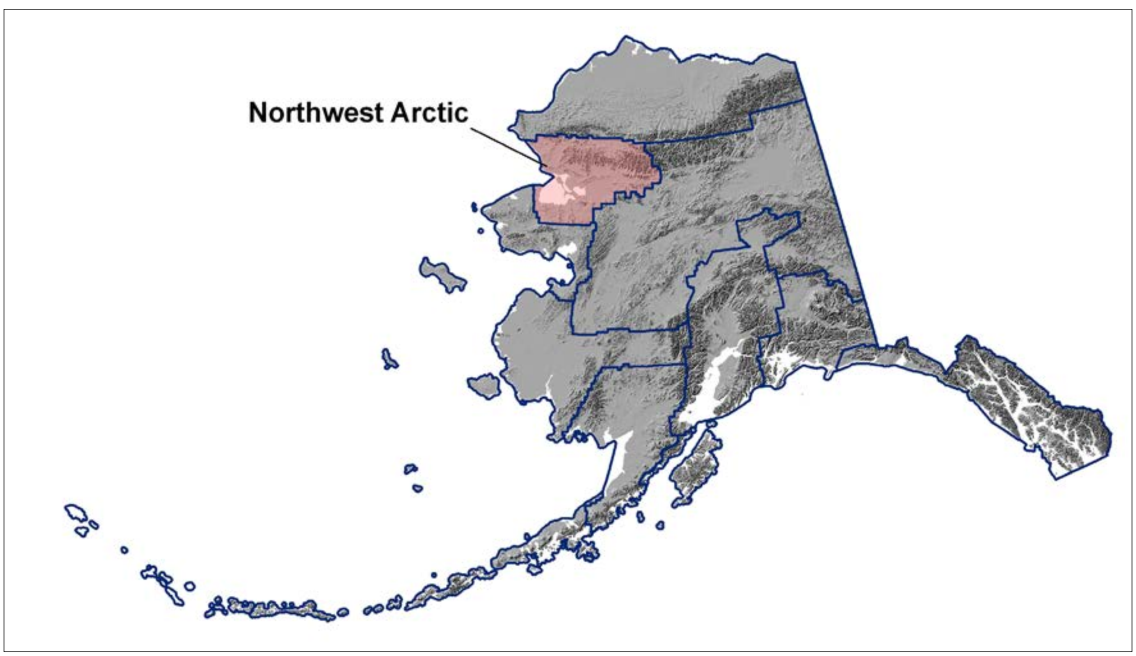


Figure I1. Location map of Northwest Arctic Energy Region.

The northern part of the Northwest Arctic Energy Region is bounded by the western Brooks Range. This compressional mountain belt includes the DeLong Mountains, which are a complexly folded and faulted series of Paleozoic and Mesozoic sedimentary rocks. The Baird Mountains upland lies further south and is composed of rock types similar to those of the northern Brooks Range, although they've been subjected to more intense pressure and temperature, resulting in metamorphism. These two upland areas are separated by the glacially sculpted Noatak lowland. The central part of the region lies south of the Brooks Range and is dominated by the Kobuk Selawik Lowlands, an expanse of low relief that is broken by modest topography in the Waring Mountains and Selawik Hills. The Kobuk River occupies the northern part of this lowland and drains westward into Kotzebue Sound. The landscape throughout this part of the region partly reflects the underlying geology, specifically the development of Cenozoic-age extensional sedimentary basins bounded by local uplifts (sheet 2). This series of basins may be a continuation of the distant offshore Hope Basin that generally thins eastward toward the Kotzebue Basin and eventually the smaller onshore Selawik trough, Kobuk Basin, and perhaps even the Noatak Valley. The southwest part of the region encompasses a portion of the Seward Peninsula that includes a southern onshore segment of the Kotzebue Basin. The Seward Peninsula also includes a number of Cretaceous- and Cenozoic-age plutonic and volcanic rocks, but is otherwise composed of metamorphic rocks similar to those of the southern Brooks Range. Beneath the eastern part of the Cenozoic-age sedimentary basins lies an older series of Jurassic and Cretaceous sedimentary, volcanic, and plutonic rocks. This complex belt of deformed rocks, termed the Koyukuk terrane, records the collision of an ancient volcanic chain that led to the formation of the ancestral Brooks Range.

GEOLOGIC ENERGY RESOURCE POTENTIAL IN THE NORTHWEST ARCTIC ENERGY REGION

Mineable coal resource potential

As explained in the discussion of requirements for mineable coal (see Chapter A), several factors must be considered when evaluating whether a coal deposit is exploitable. The most important factors include the maturity of the coal (rank), seam thickness, amount of impurities (ash and sulfur content), amount of overburden, and the degree of structural complications (steeply dipping seam, folds, faults, etc.). The higher the coal rank, the higher its energy content by weight. Coal rank also influences the minimum seam thickness worth exploiting. Low ash and sulfur contents are highly desirable, as ash represents the amount of non-combustible material in a seam and sulfur combines on combustion to form environmentally damaging compounds.

The Northwest Arctic Energy Region has a long history of using coal as an energy source, ranging from very local use by Inupiaq Eskimos to more substantial extraction efforts in support of gold mining, steamship, and related activities in the region. Significant development of this resource diminished in the early part of the twentieth century and commercial extraction efforts appear to have largely ceased by the 1930s. The following discussion summarizes information on coal occurrences in the Northwest Arctic Energy Region and briefly evaluates whether or not these resources might be reasonably exploited as a local energy source. The region's coal resources can generally be considered in two parts, based on their stratigraphic age (Cretaceous or Cenozoic).

Cretaceous Coal Occurrences. Cretaceous-age sedimentary rocks of the Koyukuk–Kobuk basin are present in the east-central part of the region, although they have not been studied in detail and are not well understood. Regionally, this package of rocks may be up to 8,000 meters thick, although reconnaissance geologic mapping in the Waring Mountains indicates that only a small part of these sediments were deposited in nonmarine environments conducive to coal development (Patton and Miller, 1968). No subsurface drilling data are available for these rocks and surface outcrops are generally described as poor and limited to local stream cuts. Nevertheless, a number of thin coal seams have been reported, particularly in the Waring Mountains and along the Kobuk River and its tributaries (fig. I2). Several of the more notable occurrences are described in the following paragraphs.

The Kallarichuk River area (fig. I2) has several isolated exposures of moderate to steeply dipping Late-Cretaceous-age coal-bearing rocks (Dames and Moore, 1980; Clough and others, 1982b; Goff and others, 1986). Several of these sites were actively mined as far back as the 1880s and the Haralan Mine probably yielded more than 150 tons of coal up through the early 1930s (Reed, 1931; Plangraphics, 1983). The Kobuk River "mine" was mined during the early days of the Squirrel River gold rush, and about 100 tons of coal may have been mined (Reed, 1931; Plangraphics, 1983). Subsequent attempts to revisit these mines and other exposures have met with limited success due to mine cave-ins, high river levels and generally poor exposure quality. However, the consensus is that a few of the coal beds are 1–2 feet thick, and most are considerably thinner. Coal quality analyses available are limited and indicate the coals are high-volatile bituminous, although the ash content is relatively high (Clough and others 1995).

Farther east on the Kobuk drainage a number of occurrences of coal have been reported over the years from the Hunt, Ambler, and Kogoluktuk rivers (fig. I3; see summaries in Dames and Moore, 1980; Goff and others, 1986). Based on their geologic position, they are most likely bituminous and related to coal-bearing strata found elsewhere along the Kobuk River. To date, all of these appear to be float, indicating that although coal is present in the vicinity, its thickness and quality remain unknown.

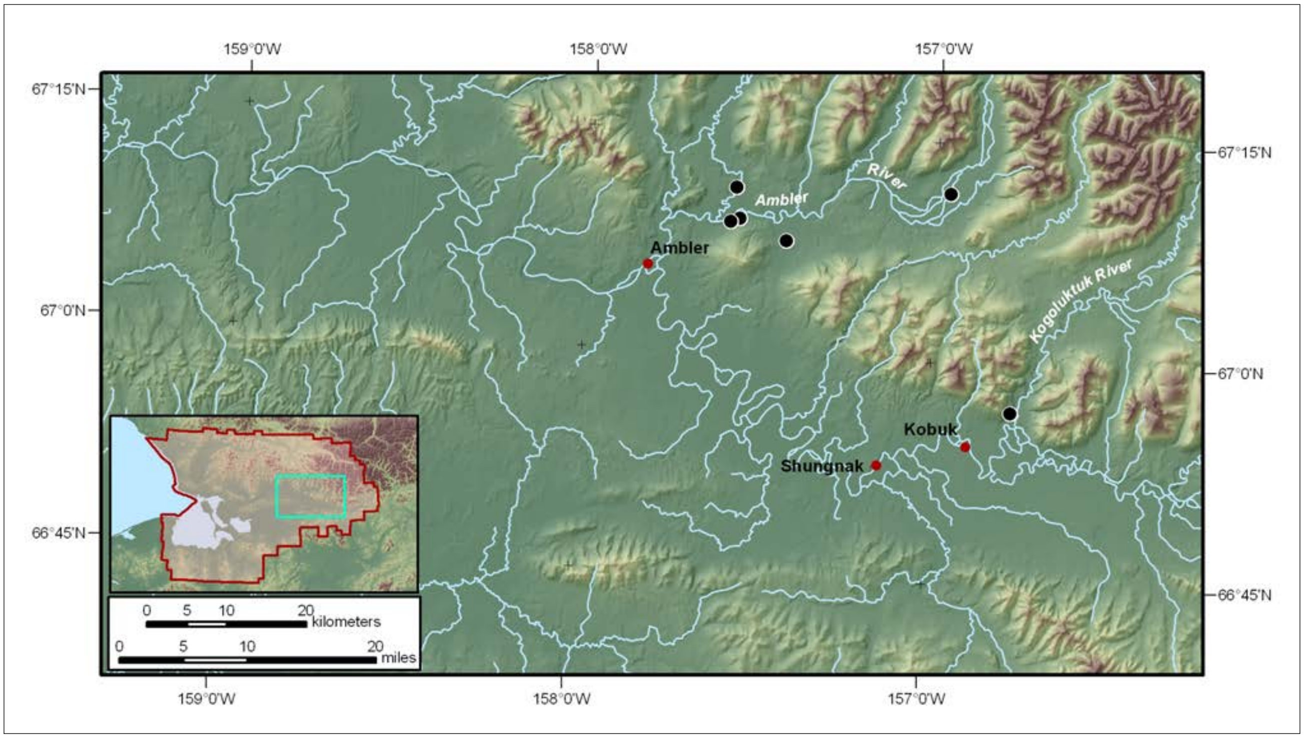


Figure I2. Location map of the west-central Northwest Arctic Energy Region, showing selected geographic references noted in the text. Black dots indicate reported coal occurrences; pick-axe symbols indicate historic coal mines in the Kobuk River area.

Several coal occurrences have been reported from the Hockley Hills, in the southwestern Waring Mountains. Exposures on the north side of the hills are poor and include only very thin streaks, but considerably thicker, more promising outcrops occur on the south side along the Singauruk River (fig. I2). The main exposure is about 300 feet up the river bluff and includes four main coal seams ranging from 3 to 6 feet thick (Clough and others, 1982a). Many thin shale partings occur with these seams and depending on the analytical technique employed, these coals range from subbituminous to bituminous; the latter assessment is likely more accurate considering the relatively high ash content (Clough and others 1995). This coal has properties similar to samples analyzed from the Kobuk River area and may be broadly correlative.

Cenozoic Coal Occurrences. Cenozoic sediments are interpreted to fill several separate but related sedimentary basins in the Northwest Arctic Energy Region based on scattered outcrops, two exploration wells, and widely spaced two-dimensional (2-D) seismic lines (sheet 2; Kirschner, 1994). These extensional basins are known to contain lignitic coals that are locally very thick, especially at the Chicago Creek mine (fig. I4), where extensive shallow drilling and geophysical work in the early 1980s constrained the local distribution and extent of the resource. The following discussion briefly summarizes known examples of Cenozoic coal at the surface.

The most important known occurrence of Cenozoic coals are from the Kugruk River and Kiwalik River areas (fig. I4) in the southwestern part of the region. Although surface exposures are lacking, several smaller tributaries (Chicago, French, Goose, Independence, Mina, Hunter, and Wilson creeks) (see summary in Dames and Moore, 1980) contain coal float, suggesting a potential coal resource likely underlies much of the area. Four small mines (Chicago Creek, Wallin, Superior, and Kugruk) were active in the early 19th century, all probably exploiting the same very thick coal seam (Plangraphics, Inc., 1983; Clough and others, 1995). In the early to mid 1980s, the State of Alaska sponsored a significant investigation of the most promising of these mines at Chicago Creek, acquiring subsurface information on the resource. Of particular note were 14 shallow drill holes totaling 2,800 feet that offer vital constraints on the lateral continuity and thickness variability of the resource. Summaries of this work indicate that the main coal seam has been traced over 8,000 feet laterally in the subsurface and reaches thicknesses of up to 100 feet (Ramsey and others, 1986). Correlations between drill holes indicate significant complications due to folding and faulting and the coal is highly deformed locally. Coal quality data indicate a low rank of lignite with significant moisture content typical of low-maturity coals (Clough and others, 1995). Based on this subsurface delineation, the Chicago Creek mine area is estimated to contain at least 3.4 million tons of demonstrated coal resource (Ramsey

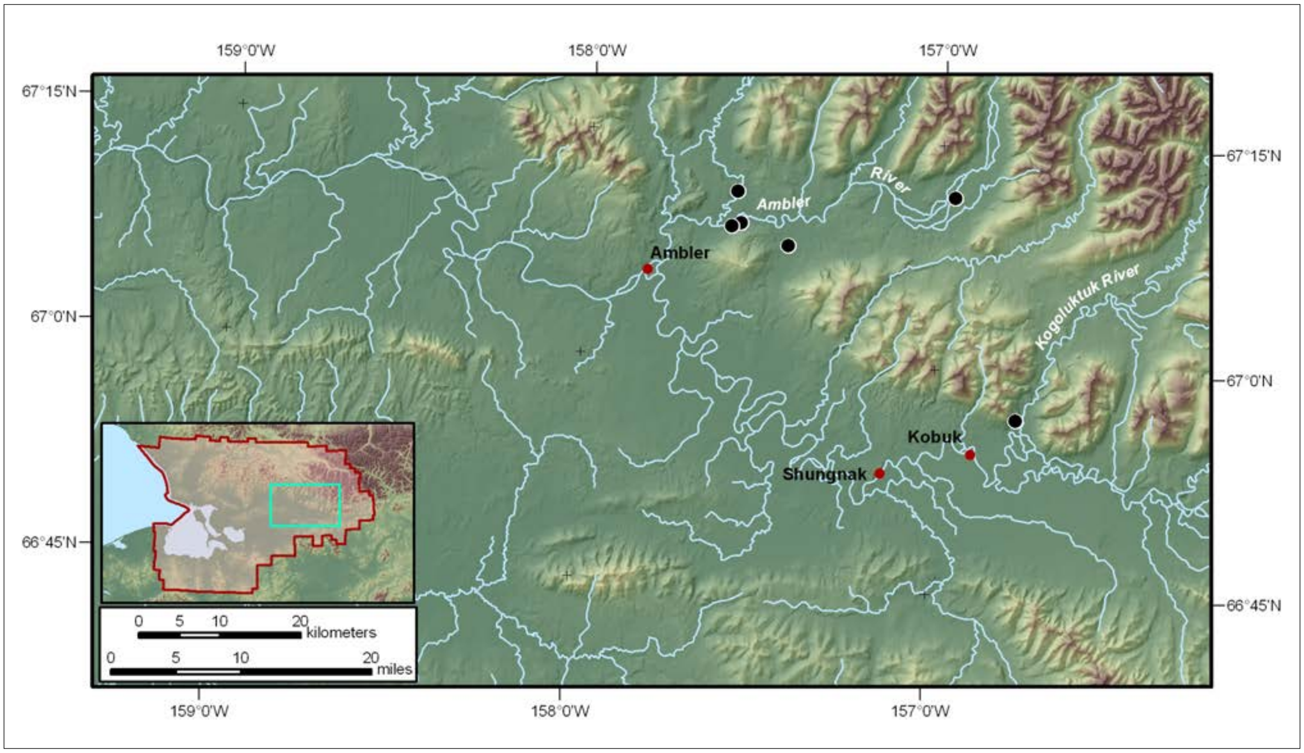


Figure I3. Location map of the east-central Northwest Arctic Energy Region, showing selected geographic references noted in the text. Black dots indicate reported coal occurrences.

and others, 1986). A significant result from this work was a preliminary mine plan and feasibility study in the mid-1980s that suggested this resource could provide a 30-year power supply for Kotzebue if an average of 50,000 short tons of lignite were mined per year (Retherford and others, 1986).

Another often-cited coal occurrence is near Elephant Point in Eschscholtz Bay (fig. I4; Patton and Miller, 1968; Patton, 1973). When first noted in 1909, the coal was reported to be 2 feet thick, although subsequent investigations have only noted a 4-inch-thick bed exposed at low tide (Dames and Moore, 1980). Although no analyses have been performed on this coal, it is most likely lignite. Farther east, additional coal float has also been reported from a small tributary of the Mangoak River (fig. I4; Patton and Miller, 1968; Patton, 1973). This is also most likely Cenozoic lignite that accumulated near the southern margin of the Selawik trough (sheet 2), or a subsidiary smaller, fault-bounded basin.

Conventional oil and gas resource potential

As explained in the discussion of requirements for exploitable oil and gas resources (see Chapter A), functioning petroleum systems occur in thick sedimentary basins, and consist of three basic elements: Effective source rocks, reservoirs, and traps. Each of the elements must be in existence and connected at the time hydrocarbons are generated. This section considers each of these necessary elements of petroleum systems in turn to evaluate whether conventional oil and gas resources may exist as an exploitable resource in the Northwest Arctic Energy Region.

Overview of sedimentary basins. Sheet 2 shows the distribution of sedimentary basins (after Kirschner, 1988) that could potentially host petroleum systems in the Northwest Arctic Energy Region. The main sedimentary basins are a family of relatively thin, Cenozoic-age, fault-bounded lows created by crustal extension. The largest of these, the Kotzebue basin, is dominantly offshore and separated from the larger Hope basin in the Chukchi Sea by the Kotzebue arch. East of Kotzebue Sound, the Selawik basin (also called trough) occupies the lowlands between the Waring Mountains and the Selawik Hills. Based principally on gravity data, several smaller basins have been identified, including the Noatak basin and subsidiary basins north and northeast of the main Selawik basin (Troutman and Stanley, 2003). Older Cretaceous sedimentary strata are very thick along the southern Brooks Range, indicating a significant sedimentary basin once existed here, although intense folding and faulting has uplifted and dissected these rocks.

Source rocks. Oil-prone source rocks are not recognized beneath or associated with the Cenozoic basins. The basement rocks for much of the area are metamorphic and thus not potential sources of oil or gas. This unfavorable basement rock type can be inferred from regional geology in the southern Brooks Range and Seward Peninsula, but was further confirmed at the bottom of the two exploration

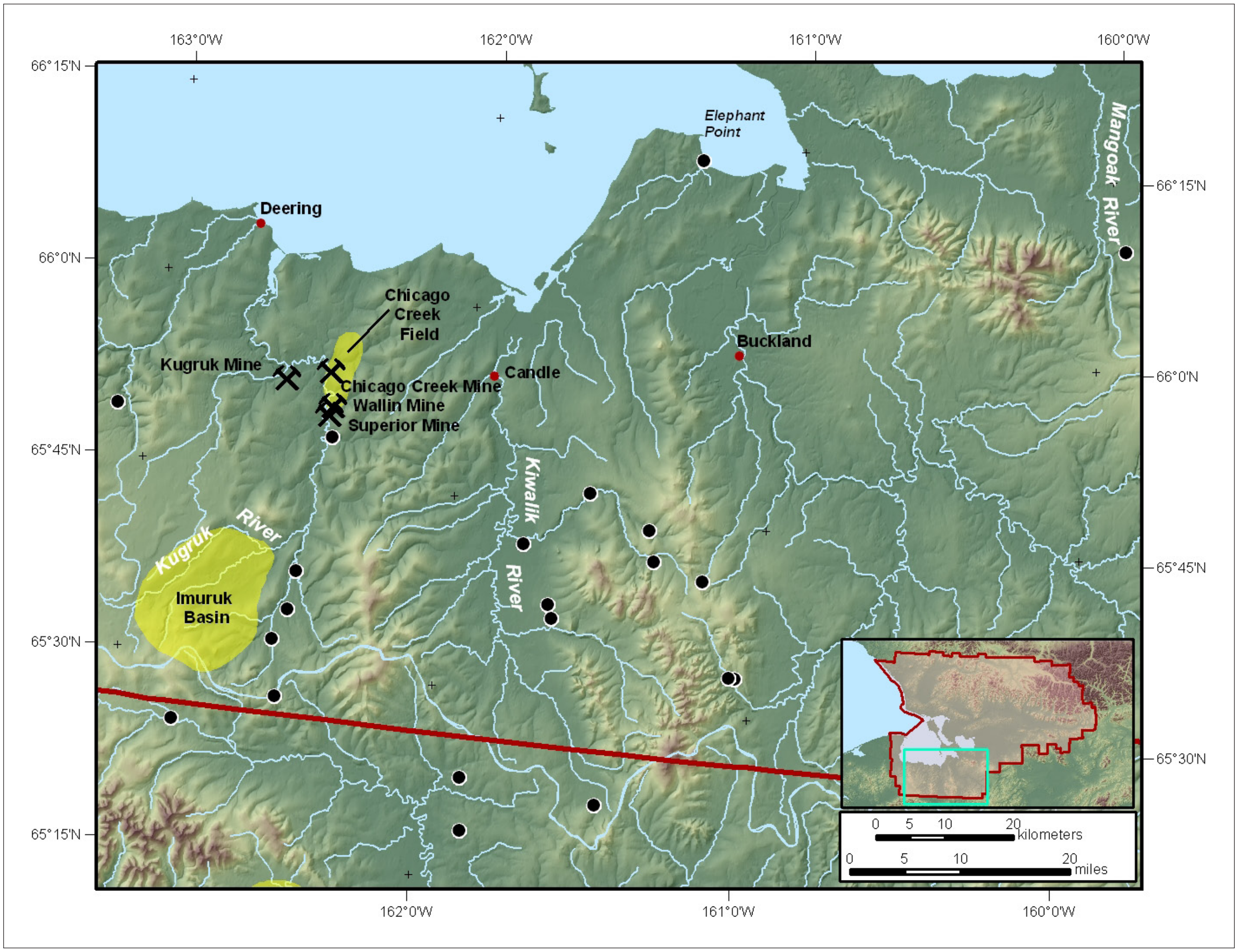


Figure I4. Location map of the southern Northwest Arctic Energy Region, showing selected geographic references noted in the text. Black dots indicate reported coal occurrences; pick-axe symbols indicate historic coal mines in the Kugruk River area.

wells in the Kotzebue basin (sheet 2; Nimiuk Point and Cape Espenberg; Fisher, 1988). In addition, shallow drill holes at Chicago Creek documented metamorphic rocks directly underlying the Cenozoic lignite section (Ramsey and others, 1986). The Selawik basin, which is farther inland, may partly be underlain by the thick Cretaceous sediments recognized in the Waring Mountains. However, selected outcrop samples indicate these rocks are overmature and have very low amounts of organic carbon and do not represent viable source rocks for oil or gas (Decker and others, 1987).

Source rock data from the two exploration wells also were not encouraging. The samples from the wells indicate that low amounts of organic carbon are present and the composition of the organic matter is dominantly cellulosic, meaning it would be gas-prone, if sufficiently matured (Decker and others, 1987). Thermal maturity values indicate the section has not been sufficiently buried or heated to generate thermogenic gas. These observations are consistent with data from the scattered outcrops of coal-bearing Cenozoic strata in the region, indicating the coals are all still lignite and thus have not been deeply buried.

Biogenic gas, generated by microbial processes, is often considered an unconventional resource due to its method of production in coalbed methane systems (see Chapter A). However, in some basins, such as the prolific Cook Inlet in southern Alaska, biogenic methane has been known to occur in conventional reservoirs. Due to the unusually thick Cenozoic coals recognized at Chicago Creek, it is reasonable to assume biogenic gas has been generated due to the microbial breakdown of buried organic matter. The presence of biogenic gas is supported by trace amounts of methane associated with coal-bearing strata in both exploration wells in the region (Troutman and Stanley, 2003). However, in order for biogenic gas to migrate into a conventional reservoir, an unusual set of geologic conditions are required involving the formation of early traps, rapid burial, and finally rapid uplift (Rice, 1993).

Small amounts of gas have been encountered in shallow drilling around Kotzebue Sound (seismic shot holes and a water well). These occurrences are all considered to be biogenic (Troutman and Stanley, 2003) based on their chemistry. The shallow positions of the encountered gas may suggest that it is produced by small amounts of decaying organic matter (Miller and others, 1959) with the resulting methane byproduct likely trapped beneath impermeable permafrost. This type of ephemeral accumulation is not likely to yield sustained production.

Reservoir rocks. Sparse data indicate the reservoir quality in the region is variable, but generally low. The abundance of chemically unstable volcanic debris in sandstone commonly produces poor reservoirs. Based on 39 samples of Cretaceous sandstone, the average porosity was 4.7 percent, significantly lower than required for conventional petroleum reservoirs (Decker and others, 1987). The low reservoir quality suggested by these results is consistent with regional studies of these rocks across western Alaska, which indicates minerals such as laumontite have precipitated in the pore space (Hoare and others, 1964).

The younger Cenozoic section is likely to have better reservoir quality due to less burial. Porosity values extrapolated from geophysical logs in the two exploration wells suggest values as high as 40 percent in the shallow section, decreasing to 5 percent near the base (Fisher, 1982). The elevated porosity is probably a function of limited compaction and cementation in the near-surface sediments. The consistent decrease in reservoir quality with depth is not encouraging, and deeper targets in the Kotzebue and Selawik basins would presumably follow a similar trend.

Traps. Existing geologic maps indicate variable intensities of folding and faulting have impacted the region. The Cretaceous rocks in the Waring Mountains and Kobuk River area are complexly deformed, likely by multiple phases of tectonics. This history suggests the development and preservation of structural traps is very unlikely and that exploration for such targets would be challenged to find accumulations.

The extension that created Cenozoic basins in the region is conducive to the development of a variety of hydrocarbon traps. The juxtaposition of uplifted blocks and down-dropped lows, combined with local and regional tilting, can be effective elements of a trap. Although seismic data are limited, the available lines indicate that reasonable trapping geometries may be present in the Kotzebue and Selawik basins. Due to the very limited exploratory drilling, many untested large structures are likely to be present. If shallow biogenic accumulations are targeted, the integrity of seal rocks may present a risk factor due to insufficient compaction.

Summary of conventional oil and gas resource potential. The regional potential for oil accumulations is considered low due to the lack of identified oil-prone source rocks. In the northern and eastern parts of the region, the potential is further hampered by poor reservoir quality and structural complexity. In the Cenozoic basins, data suggest most rocks are immature, having been subjected to insufficient burial to convert the organic matter to liquid hydrocarbons. Conventional gas prospects are considered fair due to the abundance of terrestrial organic matter. It is possible that sufficient maturity has been reached in the deepest parts of the Kotzebue–Selawik basins for the generation of thermogenic gas. In addition, it remains possible that biogenic gas could have accumulated in conventional reservoirs, similar to the process inferred for Cook Inlet. However, this unusual phenomenon requires an abrupt decrease in the hydrostatic pressure (usually by uplift) in order for the gas to migrate. At present, the timing and magnitude of any uplift events involving Cenozoic strata in the Kotzebue and Selawik basins are insufficiently known to reliably evaluate this potential. Although the likelihood of this mechanism operating in this region is low, additional field studies (geologic mapping, structural studies, thermochronology, etc) would help to test the viability of this resource type for exploration.

Unconventional oil and gas resource potential

Coalbed methane. The region possesses abundant evidence for coal (see above), which is the required ingredient for this resource. However, most thick Cenozoic coals are lignite and thus do not have well-developed cleating. These natural fractures create the permeability that is required to effectively produce methane hosted in the coal (see Chapter A). The onshore Selawik basin may have as much as 10,000 feet of basin fill (Patton, 1973), allowing for the possibility that deeper parts of the basin may have witnessed sufficient burial maturity to develop cleating. The older Cretaceous coal-bearing section around the Kobuk River area likely has better maturity (bituminous) and includes adequate cleating. However, the surface exposures of these coals indicate they are considerably thinner and more structurally complex than the Cenozoic examples. Available surface mapping indicates coal beds are often steeply dipping and affected by extensive folding and faulting—all of which adds a significant component of risk to exploration success. Presently the geometry and distribution of these coals in the subsurface are very poorly known.

Tight gas sands. The Cretaceous sediments in the Kobuk River region could be categorized as tight gas sands based on their low permeability. However, the absence of source rocks and structural complexity suggests the potential for gas accumulation is very low. The Cenozoic sediments associated with the Kotzebue, Selawik, and other basins have similarly provided little evidence for source rocks, and available data indicate insufficient maturity has been reached to generate thermogenic gas (Decker and others, 1987). There is evidence for mature source rocks in the western Brooks Range and it is conceivable some gas is trapped in low-porosity sandstone or limestone. However, the repeated episodes of folding and faulting that have affected this area diminish the probability of a trap maintaining its integrity.

Shale gas. Similar to tight gas, noted above, most of the region lacks the identified source rocks necessary for a successful shale gas petroleum system. The exception is within the western Brooks Range (northwestern part of the region), where organic-rich, Mississippian-age mudstones are recognized to contain gas trapped in a self-sourcing system. The large Red Dog Mine received State approval for a multi-well exploration program to explore for this resource, hoping to replace or defray the escalating cost of diesel fuel (Alaska Division of Oil & Gas, 2006). The targeted shales have good to excellent total organic carbon contents (up to 15 percent) and measured gas contents ranging from ~16 to 65 scf/ton, comparable to many successful shale-gas fields in the Lower 48. As noted in the description of this resource type (see Chapter A), successful production of this gas will require the rock to be manually fractured to induce permeability and flow. In addition, substantial volumes of water would be produced and appropriate disposal of this water must be considered in evaluating exploration costs. Although the preliminary results from the shale gas exploration around Red Dog have been promising, it is unclear how extensive this resource might be. Similar rocks are known across the western Brooks Range, although the only villages situated nearby are Noatak and possibly Kivalina.

Gas hydrates. Gas hydrates are found in a narrow range of modern environments and only occur within specific temperature and pressure conditions. Presently, Alaska's North Slope appears to be the only onshore region with sufficient permafrost to preserve methane hydrate.

Geothermal resource potential

There are limited data regarding the geothermal prospectivity of the region, but regional geologic considerations indicate several conditions are present that commonly lead to elevated near-surface temperatures. These include evidence for recent crustal extension, geologically young volcanic activity, and possibly elevated geothermal gradient of about 104°F (40°C) (Fisher, 1988). However, these characteristics by themselves do not result in an exploitable resource. Only three recognized thermal springs lie within the region (sheet 2): The Reed River, Upper Division, and Lower Division springs (Motyka and others, 1983). The Reed River occurrence (Pessel, 1975) is in the easternmost part of the region, but its protected land status (Gates of the Arctic National Park) precludes future development. The Division hot springs are located in the southeastern part of the region in the Purcell Mountains, approximately 40 miles south of the villages of Kobuk and Shungnak. This family of springs issues at very high rates (up to 547 gallons per minute) from an unusually radioactive pluton (Miller and Johnson, 1978). Although this flow rate is promising, measured temperatures of less than 158°F (70°C) are below the threshold required for modern small power generation units (Kolker, 2009).

The Seward Peninsula area of the adjacent Bering Energy Region has several prospective geothermal resources that may benefit the Northwest Arctic Energy Region. Of particular note is the Granite Mountain hot spring approximately 40 miles south of Buckland. The characteristics of this occurrence are similar to the Division hot springs in terms of possessing excellent flow rates, but sub-optimal temperatures.

RECOMMENDATIONS

Coal resource recommendations

The Northwest Arctic Energy Region contains widely spaced Cretaceous and Cenozoic coal occurrences that should be considered as a potentially viable source of energy for local use. Not all occurrences are located near villages (figs. I2–I4), and it is recommended that any future work focus on those coals that might most economically serve regional needs. Many of the coals in the area have not been adequately evaluated; the following discussion offers some general comments on the potential for locally developing coal as an energy source and highlights additional work that might mitigate risk and improve the knowledge of this resource.

Significantly more geologic information is needed to reliably assess the Cretaceous coal prospects. Although the bituminous rank is promising, the lateral continuity of coal beds and correlations between outcrops remain unknown. Additional surface fieldwork, such as detailed geologic mapping and stratigraphic studies, might offer some first-order constraints on the geologic context of these coals, although ultimately drilling would likely be required to delineate this resource. The generalized map pattern shown for the Cretaceous coal-bearing strata (Patton and Miller, 1968) is perhaps misleading with respect to the structural complexity of the area. As noted by the authors in text discussions, the Waring Mountains and Kobuk River area has been significantly deformed as evidenced by numerous tight folds and high-angle faults, many of which could not be depicted at the reconnaissance scale of that mapping. These complications are relevant as they add significant risk to development mining where the orientation of the target seam is difficult to predict or is abruptly offset by faulting. Despite these caveats, it is possible there are sufficient Cretaceous coal deposits for local energy use, particularly those villages that might be served by shipments along the Kobuk and Singauruk rivers. It is noteworthy that some of the coal occurrences in the Kobuk region are within designated National Park lands and likely unavailable for mine development.

The Tertiary coals in the Chicago Creek area are exceptionally thick and warrant additional consideration as a potential long-term source of energy. The existing subsurface data for this area has sufficiently documented the resource and a robust cost estimate and engineering plan for development of a modern mine could be calculated. Nevertheless, the existing geologic information indicates there would still be uncertainty associated with efforts to exploit this resource. Perhaps most importantly, a detailed understanding of the distribution of faults and folds in the area would greatly reduce the risk associated with predicting coal distribution. Additional drilling or geophysical techniques, such as detailed magnetometer surveys (Ramsey and others, 1986), might supply the necessary constraints on the structural geology. It is also important to note that the low grade of this coal will require more lignite to be mined than would be required for a bituminous coal that has a much higher energy density. Further, the high moisture content may increase processing costs. Depending on the scale of a proposed mine in this area and the preferred method of power transmission, this resource could potentially support several communities bordering Kotzebue Sound.

Unconventional oil and gas resource recommendations

Coalbed methane. The abundance of terrestrial organic matter in the form of coal gives rise to possible coalbed methane prospects in the region, particularly in the deeper parts of the Selawik trough. The better studied and thickest seams in the region are undermature, whereas those with adequate maturity are poorly known and likely to be structurally disrupted. Seismic data would be helpful in evaluating the lateral continuity of coal bearing-sections and the total thickness of basin fill in the Selawik trough. This type of data would also be useful for inferring burial history and maturity—key parameters in identifying viable targets for coalbed methane exploration.

Tight gas sands. The complex geological history of the Northwest Arctic Energy Region suggests that the tight gas sand resource potential is low.

Shale gas. Early reports from shale gas exploration near the Red Dog mine appear promising and may ultimately yield sufficient gas for local and even regional use. If a sufficient resource can be documented and the considerable development challenges overcome, this may entice a larger exploration effort to document the extent of shale gas. It should be noted that exploration in the immediate Red Dog area leverages decades of detailed geologic study and dense mineral prospect drilling. An expanded search for this type of resource would require a substantial geologic field program to better map the regional geology of the western Brooks Range.

Gas hydrates. Due to the lack of extensive, continuous permafrost in the Northwest Arctic, the likelihood of finding gas hydrates in the region is very low therefore no further action is recommended.

Conventional oil and gas resource recommendations

The regional potential for oil accumulations is considered low due to the lack of identified oil-prone source rocks. Conventional gas prospects are considered fair due to the abundance of terrestrial organic matter. Due to the limited outcrops, the acquisition of expensive subsurface data (seismic and wells) would be most useful in evaluating the region's potential. The region's Native corporation (NANA) recently reached an agreement with Trio Petroleum to drill as many as four exploration wells in the Kotzebue Sound area (Petroleum News, 2009); the results of this program will provide much-needed new constraints on the ultimate potential of this area to host conventional oil and gas resources.

Geothermal resource recommendations

The southernmost part of the region is likely to be the most prospective, based on regional, though isolated, surface indications of elevated geothermal activity across central and western Alaska. Unfortunately, identified resources are all at least 40 miles from the nearest settlement, meaning power transmission costs would likely be prohibitive. However, further geologic studies of known sites such as Granite Mountain and Division, may extend the subsurface footprint of the resource and shorten the ultimate distance between power generation and consumption. In particular, soil surveys and possibly remote geophysical techniques may assist in improved delineation of the geothermal anomalies (Kolker, 2009).

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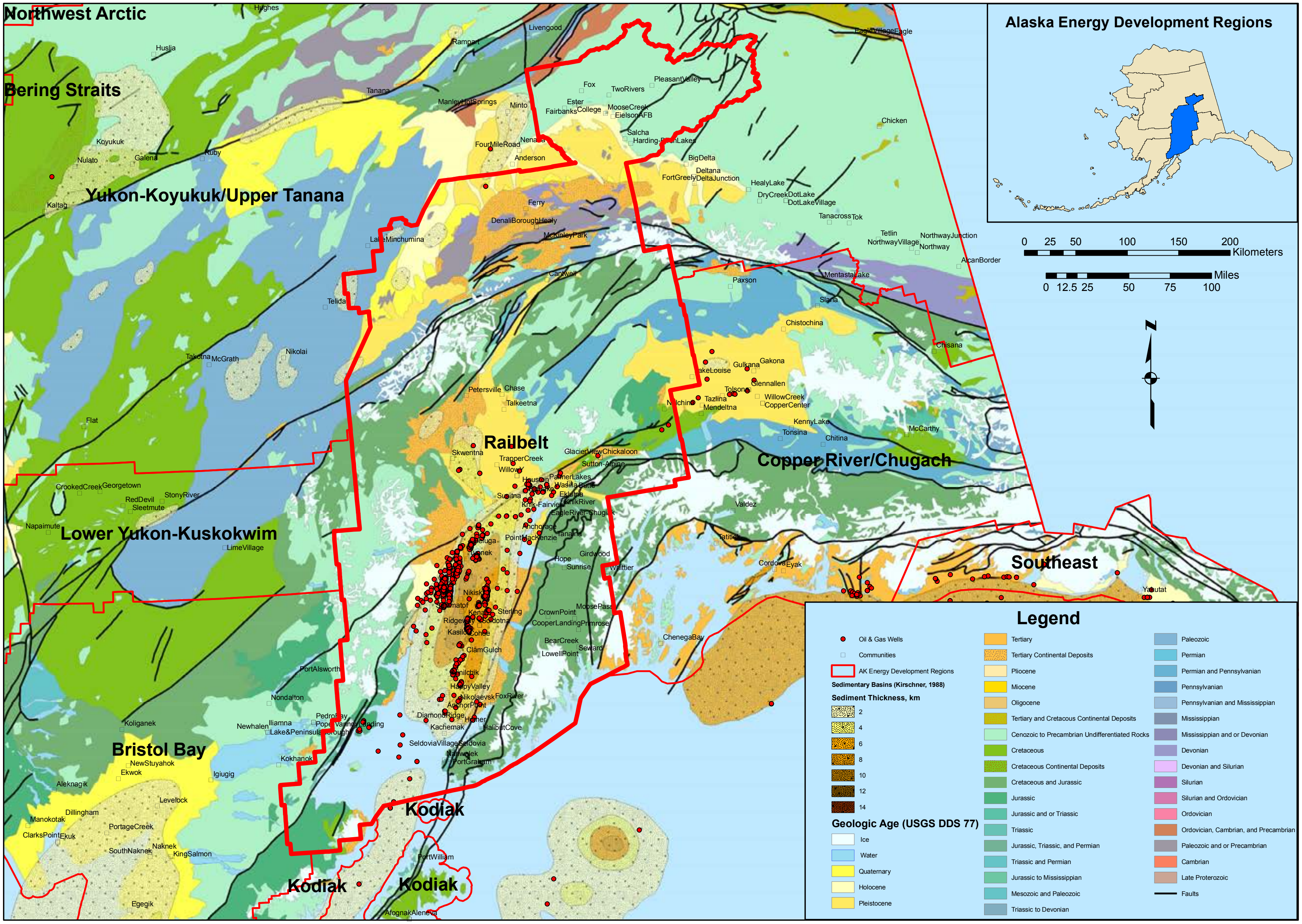
Geology of the Railbelt Energy Region, Alaska



SUMMARY OF FOSSIL FUEL AND GEOTHERMAL RESOURCE POTENTIAL IN THE RAILBELT ENERGY REGION

by Paul L. Decker, Robert J. Gillis, Ken Helmold, and Shaun Peterson

INTRODUCTION

Purpose of this report

Economic growth and stability in Alaska's rural areas hinges partially, if not primarily, on the availability of affordable and sustainable energy supplies. Recent price increases in oil and gas commodities have created severe economic hardship in many areas of the state that are dependent on diesel and heating oil as their primary source of energy. All sectors of Alaska's economy rely on affordable energy sources with limited price volatility, highlighting the need to diversify the energy portfolio by developing locally available and sustainable resources that are not tied to the global market. Unfortunately, all areas are not created equal in energy accessibility; the resources available for local exploitation vary widely across the state. It is critical that funding decisions for expensive programs to reduce the dependence on diesel for heat and electricity take into account information concerning the entire suite of natural resources that exist in a given area.

This report draws from existing information to provide community and state leaders an objective summary of our current knowledge concerning the potential of locally exploitable fossil fuel and geothermal energy resources in the Railbelt Energy Region (fig. J1), one of 11 regions recognized by the Alaska Energy Authority (AEA) in their Energy Plan (AEA, 2009). The potential geologically hosted energy resources considered here include exploitable coal, conventional and unconventional oil and gas, and geothermal resources. This report concludes with recommendations as to what additional data or strategies, if any, would provide the most leverage in helping to develop new energy resources in the region.

Readers without geological training are encouraged to peruse the geologic summaries of fossil fuel resources and geothermal energy in Chapter A. They provide an overview of the geologic elements that must be present in an area to economically develop coal, conventional oil and gas, unconventional oil and gas, and geothermal resources. These summaries will provide the necessary background to more fully understand the information presented in this chapter.

Geographic and geologic setting

The Railbelt Energy Region covers approximately 72,526 square miles of south-central and central interior Alaska, encompassing most of the major Alaska population centers, and a significant portion of the main Alaska transportation corridors including rail, road, and maritime routes (sheet 1). The development region extends from the upper Alaska Peninsula just south of Kamishak Bay and the southernmost Kenai Peninsula, on its southern end, to the White Mountains north of Fairbanks on its northern end. The development region is bounded to the west by the spine of the southern Alaska Range, the western boundary of Denali National Park, and the eastern margin of Minto Flats. To the east, it extends to just west of Prince William Sound, and is bounded by

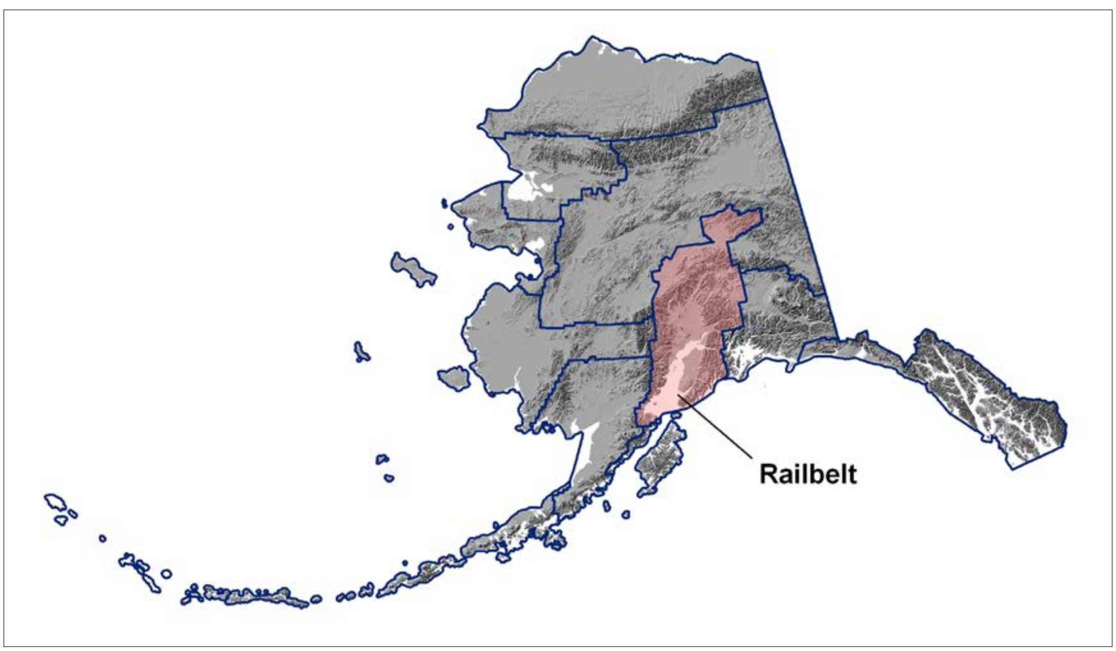


Figure J1. Location map of Railbelt Energy Region.

approximately the western boundaries of the Copper River basin, Fort Greely, and the Yukon–Charley Rivers National Preserve. The largest population center in the Railbelt Energy Region is the municipality of Anchorage, which also includes the community of Eagle River, for a total of approximately 284,000 residents. The majority of the remaining population is found in three large boroughs: the Fairbanks North Star Borough (~97,000), the Matanuska–Susitna Borough (~80,000), and the Kenai Peninsula Borough (~52,000). The Fairbanks North Star Borough is anchored by the city of Fairbanks and other communities with between 2,000 and 12,000 people, such as College, Eielson Air Force Base, Ester, and North Pole. The Matanuska–Susitna Borough includes a large number of small communities of fewer than 10,000 people, including Wasilla, Palmer, and Houston. The Kenai Peninsula Borough is similarly composed of a large number of smaller communities, including Kenai, Homer, Nikiski, Soldotna, and Seward. Towns along the Parks Highway near Denali National Park include Cantwell, McKinley Park, Healy, Ferry, and Anderson with a combined population of about 2,000. The development region also includes many smaller, outlying villages with fewer than 200 people.

The Railbelt Energy Region encompasses a diverse assortment of physiographic and geologic settings ranging from rugged, glaciated mountain ranges, to solitary volcanoes, rolling hills, and coastal and interior lowlands. Major mountainous areas in the region include the Alaska Range and Kenai, Chugach, and Talkeetna mountains. These elevated regions are flanked by Tertiary sedimentary basins such as the Cook Inlet, Susitna, and Nenana basins, each of which contains significant known coal resources and energy potential. The petroleum potential of these basins is variable with the Cook Inlet area having produced significant volumes of hydrocarbons, whereas the more interior basins remain only lightly explored. The region also includes limited areas prospective for geothermal development, such as the Mount Spurr and Chena Hot Springs areas. Each of these physiographic features and potential energy resources are an expression and direct consequence of ancient and ongoing tectonic, erosional, and biologic processes that have been shaping the landscape for about the last 200 million years. Some of the most prominent topographic features of the Railbelt: the Kenai–Chugach Mountains, Cook Inlet basin, the southern Alaska Range, and volcanic centers such as mounts Iliamna, Redoubt, and Spurr, are the result of a long-lived, and currently active, tectonic plate boundary off the southern coast of Alaska.

An oceanic plate (currently the Pacific Plate), has been subducting northwestward beneath the continental crust of Alaska since early Jurassic time (~200 million years) (Trop and Ridgway, 2007; Amato and others, 2007). Voluminous magma was intruded into the overriding continental crust and partially expelled to the surface during several cycles of volcanic events lasting millions of years (Reed and Lanphere, 1969; Wilson, 1985; Amato and others, 2007). A phase of arc magmatism is occurring today, resulting in the numerous volcanoes along the northwest side of Cook Inlet. This volcanic activity provides the heat source for potential geothermal fields, such as near Mount Spurr.

Compressive forces at the plate boundary have uplifted and exhumed much of this ancient intrusive arc system, exposing the granitic roots of the arc in what are now the southern Alaska Range and Talkeetna Mountains on the northwestern and northern margins of the Cook Inlet. To the southeast, massive amounts of sediment eroded off of the continental margin and deposited on the subducting oceanic plate have been scraped off and piled up since about 190 to 120 million years ago to form what are now the Kenai–Chugach Mountains (Connelly, 1978; Bradley and others, 2009). The strata composing the Kenai–Chugach Mountains were deposited at a location farther to the southeast than they occur today, and were transported northwestward along the now inactive Border Ranges fault to their current position by latest Cretaceous to early Paleocene time (Plafker and others, 1994).

The Cook Inlet forearc basin (sheet 2) resides between the topographic highs of the southern Alaska Range and Kenai–Chugach Mountains and maintains the highest energy resource potential in the region. The thick sedimentary rock package is bounded on the north and northwest by major fault systems that have been active at various times through the basin's history. The inactive Border Ranges fault separates the Cook Inlet basin to the northwest from the Kenai and Chugach mountains to the southeast. A system of faults defining the northwest boundary of the basin includes the Bruin Bay, Lake Clark, and Castle Mountain faults. Segments of each of these faults are believed to have been active within the last ~500 years to 1.8 million years. Beginning in Paleocene time, approximately 21,000 feet of sediment accumulated in the basin, sourced from erosion of the adjacent Alaska Range and Kenai–Chugach Mountains (Plafker and others, 1992, Conwell and others, 1982; Swenson, 2003; Haeussler and others, 2000). Nearly all of the hydrocarbons produced from the Cook Inlet were reservoired in these Tertiary rocks. An extension of the Cook Inlet basin exists northwest of the Castle Mountain – Lake Clark fault system in the Capps Glacier–Tyonek area (east of Mount Spurr). This fault-bounded depression, termed the Beluga basin (Hackett, 1977), is expressed as a gravity low and is filled by Eocene and younger nonmarine conglomerate, sandstone, mudstone, coal, tuff, and volcaniclastic deposits (Barnes, 1966; Magoon and others, 1976; Gillis and others, 2009; Finzel and others, 2009).

The adjacent Susitna lowland is a mostly fault-bounded, relatively shallow (Conwell and others, 1982) basin located at the northwestern end of the Cook Inlet basin and bordered by the Alaska Range to the west and north, and the Talkeetna Mountains to the east (sheet 2). The Susitna basin shares the younger stratigraphy of the Cook Inlet basin, including coal-bearing upper Tertiary strata. However, it appears to lack many of the same older stratigraphic units that provided the organic material to source the oil found in Cook Inlet. The timing of basin formation is uncertain, but has to be at least about 30 million years old, based on the oldest sediments (the Tyonek Formation) captured within the confines of the basin (Barnes, 1966). However, the mechanisms under which it was formed are uncertain.

The most prominent topographic feature in the Railbelt development region is the central Alaska Range, with its tallest peak reaching over 20,000 feet in elevation, making it the highest mountain range in North America. The central Alaska Range is bounded to the north by the active right-lateral strike-slip Denali Fault, and situated where the fault bends to the southwest. As the crust to the south of the fault moves around the bend against the backstopping crust to the north of the fault, it runs out of space and must shorten and thicken, thus creating topographic relief that is incised by erosion into rugged peaks. The initial phases of this uplift may have started as early 52 to 39 million years ago (Plafker and others, 1992), but significant uplift did not occur until as recently as 6 million years ago (Fitzgerald and others, 1995), making the central Alaska Range one of the youngest mountain ranges in Alaska. The uplift of the Alaska Range may represent far-field effects of the collision of the Yakutat microplate into, and continued underplating beneath continental Alaska at the subduction zone near Prince William Sound.

Tertiary age sediments deposited in the Nenana basin (sheet 2) record some of the history of Alaska Range uplift. Initial deposition into the basin was from source areas in the Yukon–Tanana highlands to the north (Wahrhaftig, 1969; Ridgway and others, 2007), in part from the northernmost Railbelt development area. As the Alaska Range became a more imposing topographic feature, detritus eroded from its flanks was carried by northward-flowing rivers into the Nenana basin (Wahrhaftig, 1969; Ridgway and others, 2007), and presumably southward-flowing rivers into the Cook Inlet and Susitna basins (Plafker and others, 1992). Currently, the Nenana basin is host to the only major coal mining operations in Alaska, and is considered a major underdeveloped coal province. Natural gas may also be important in the basin (see the following sections on Railbelt coal and petroleum resources, respectively).

GEOLOGIC ENERGY RESOURCE POTENTIAL IN THE RAILBELT ENERGY REGION

Mineable coal resource potential

The Railbelt development region contains the two of the largest coal provinces in Alaska (the Cook Inlet–Susitna and Nenana coal provinces; fig J2). Unlike other coal-rich regions, such as Alaska's remote western North Slope, the Cook Inlet and Nenana coal provinces are located in close proximity to rail and major road transportation systems and within 75 miles of the two largest metropolitan areas in Alaska: Anchorage and Fairbanks (sheet 1). Commercial coal extraction has either occurred in the past, or is currently underway, for both provinces. Due to this mining activity, the geology of both regions is moderately well understood. The Cook Inlet – Susitna coal province comprises the Cook Inlet and Susitna lowland areas and is the largest of the Railbelt development region coal provinces. The Nenana coal province lies along the northern foothills of the central Alaska Range, mostly between the Parks and Richardson highways. The coals in these provinces are broadly similar in age and both formed in low energy environments. The following discussion proceeds from the largest geographic category (coal province), followed by summaries of individual coal fields and their constituent districts (fig. J3).

Cook Inlet – Susitna Coal Province. Coal-bearing rocks in the Cook Inlet–Susitna coal province are late Oligocene to early Pliocene in age and make up the Tyonek, Beluga, and Sterling formations of the Cook Inlet and Susitna basins. These strata are generally flat-lying or gently tilted except in the proximity of faults, where coal-bearing rocks are commonly tightly folded, steeply tilted, heavily sheared, and/or abruptly truncated. Most bedrock located onshore within this coal province has been buried by more recent glacial and stream deposits, severely hampering the estimation of coal reserves. Coal-bearing rocks are generally exposed only along the faulted basin margins and associated folds, and it is only at these discontinuous exposures that surface geologic mapping can aid coal resource assessment. The remaining vast majority of the basin must be evaluated using more expensive subsurface methods such as exploratory drilling. The lenticular shape of individual coal beds limits their lateral continuity and further complicates extrapolating coal reserves over broad regions (Merritt, 1990).

Coal throughout the Cook Inlet – Susitna coal province is commonly low- to medium-grade subbituminous in rank, but ranges from high grade anthracite in areas of the Matanuska Valley to low grade lignite in the outlying Broad Pass coal field area (fig. J3; Apell, 1944; Merritt, 1985a). Total coal resources in the Cook Inlet – Susitna coal province are estimated at 1.5 trillion short tons of hypothetical coal, with identified resources estimated at 11 billion short tons (Merritt, 1990). A coal-potential map published by Merritt (1990) shows much of the uppermost Cook Inlet and areas rimming the Susitna lowland as having low to moderate coal potential. High potential areas include the Beluga region on the west side of upper Cook Inlet and the Matanuska Valley. Identified coal resources in the Beluga–Yentna region are estimated at 10 billion tons with total resources estimated at around 30 billion tons (McGee and O'Connor, 1975; Sanders, 1981). Individual coal fields within the Cook Inlet – Susitna province are ranked in decreasing size below, based on

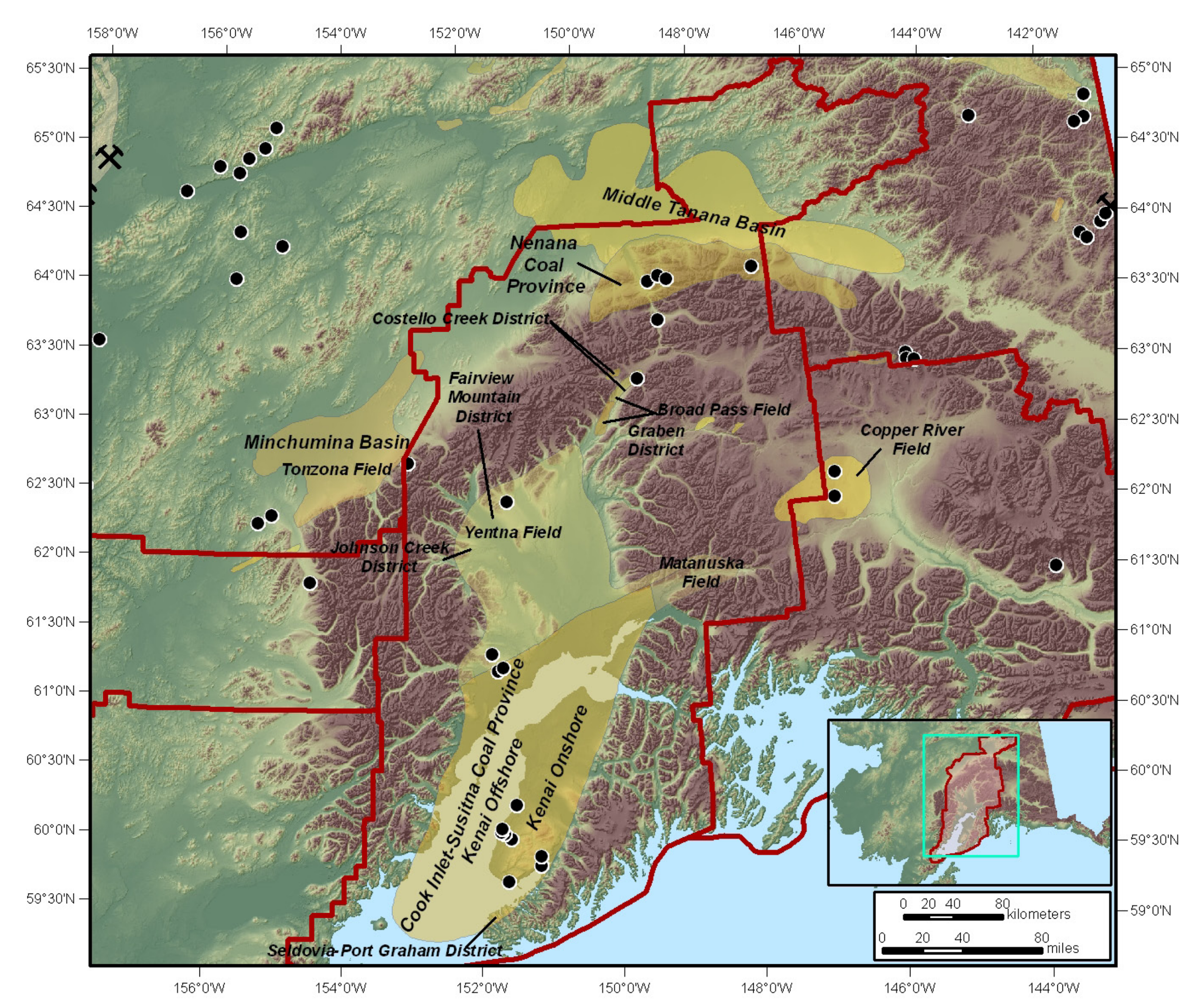


Figure J2. Location map of the Railbelt Energy Region, showing the Cook Inlet–Susitna and Nenana coal provinces (tan shaded areas). Black dots indicate selected reported coal occurrences.

estimates of indicated coal reserves. A short discussion of the coal potential of each field is also included.

Yentna Field. The Yentna field is located north of the Beluga and Susitna fields along the remote northwestern and northern side of the Susitna basin (fig. J3; sheet 2). Most of the Yentna field is separated from transportation infrastructure by the Kahiltna and Yentna rivers as well as 25 to 50 miles of low relief wetlands. The field is divided into the Canyon Creek, Johnson Creek, and Fairview Mountain districts (Merritt and Hawley, 1986). Coals from these districts are primarily derived from the Tyonek Formation, similar to the adjacent Beluga field. Few coal quality analyses have been published for the Yentna field, although measurements from coal throughout the Susitna lowland range from lignite to subbituminous B, and are commonly subbituminous C in grade (Barnes, 1996). Mean heating value of coal in the Susitna lowland is around 8,000 Btu/lb as-received, and nearly 12,000 Btu/lb after drying and removal of ash (Merritt, 1990).

Coals in the Canyon Creek district generally range in thickness from 2 to 23 feet, most of which are exposed along Canyon Creek. Coal bed thicknesses may be over 55 feet-thick in some locations with few or no partings (Barnes, 1966). The district covers an area of less than20 mi^2, and is surrounded by igneous and non coal-bearing Mesozoic rocks. Nevertheless, indicated coal reserves for the area are estimate at 100 million tons (Barnes, 1966). Intermittent coal exposures in the Johnson Creek District range in thickness from 3 to 24 feet, and indicated coal reserves in the Johnson Creek area are estimated at about 20 million tons based on reconnaissance field investigations by Barnes (1966). The thickest coals in the Yentna field are found in the Fairview

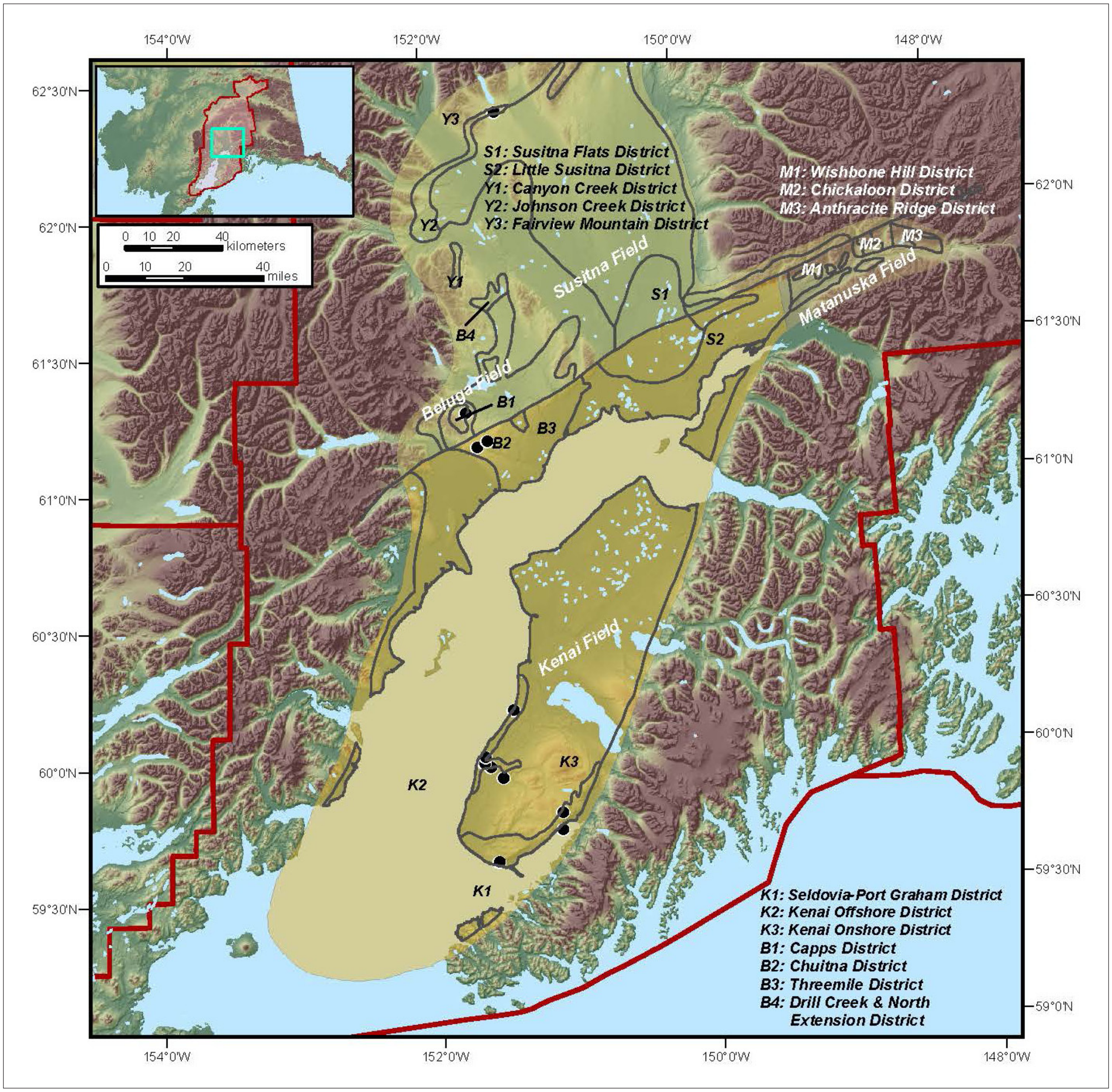


Figure J3. Map of the central Railbelt region, highlighting the coal fields and districts in the Susitna basin area. Black dots mark significant surface coal occurrences.

Mountain district near the northwestern margin of the Susitna basin, where coal beds are commonly 3 to 7 feet thick, with one bed reported to be 55 feet thick (Barnes, 1966). Indicated reserves in the Fairview Mountain district are based on reconnaissance field investigations and are estimated at 40 million tons (Barnes, 1966). Additional isolated exposures are found along the northern margin of the Susitna basin in the Peters Hills area where several low-grade coal beds are exposed along creek cuts. Cache Creek, northwest of Peters Hills has several beds of coal up to 2.5 feet thick (Barnes 1966). Twelve shallow boreholes were drilled to depths of less than 400 ft in the Peters Creek area near the Parks Highway by Portland General Electric in 1976—; none of which penetrated more than two coal beds thicker than 1.5 to 4 feet (Merritt, 1990). Indicated coal reserves estimated by Barnes (1966) in the Peters Hills area are 4.5 million tons.

Overall, coal-bearing exposures in the Susitna lowland are limited to small isolated outcrops along the margins of the basin. Although the main part of the basin is masked by widespread glacial and alluvial deposits, the known rock types and age are very similar to the more extensive exposures in the Beluga–Chuitna areas (see below), suggesting much of the covered Susitna lowland could be underlain by coal-bearing strata. Due to extensive cover and limited subsurface data, the Susitna lowland remains the least well understood region in the entire Cook Inlet coal provinces. Substantial subsurface exploration would be required to determine the volume and extent of potential coal resources.

Beluga Field. The Beluga field is perhaps the most studied field in the Cook Inlet coal province, and is the largest in terms of identified resources. It is located approximately 45 miles west of Anchorage on the western margin of the Cook Inlet and is divided into four main districts: the Capps district , the Chuitna district, the Threemile district, and Drill Creek and North Extension district (fig. J3; Merritt and Hawley, 1986). Although the Beluga field is not connected to commercial rail or highway infrastructure, it lies within 6 to 25 miles of port sites on Cook Inlet. The Beluga area has undergone considerable geologic and coal resource investigation since the mid-1950s including regional gravity surveys, stratigraphic studies, and reconnaissance geologic mapping to constrain sedimentary basin geometry, stratigraphic architecture, and rock distribution (e.g. Grantz and others, 1963; Barnes, 1966; Adkison and others, 1975; Hackett, 1976, Flores and others, 1994; Flores and others, 1997). More focused studies include delineation of the resource and geotechnical characterization through publicly- and privately-funded exploratory drilling projects (e.g. Warfield, 1959; Chleborad and others, 1980, 1982; Odem, 1986; and Odem and others, 1986), and baseline studies of stream water and soil quality (e.g. Scully and others, 1980; Gough and Severson, 1983; Maurer, 1984, 1986 and 1987).

Coal in the Capps, Chuitna, and Drill Creek and North Extension districts are part of the late Oligocene to late Miocene age Tyonek Formation, whereas coal in the Threemile district are from the younger, Miocene age Beluga Formation. Coal in the Beluga field is generally of subbituminous grade with reported heating values ranging from about 7,500 to 8,500 Btu/lb. The measured ash content of these coals are moderately high and may require crushing and washing to increase its heating value (Merritt and Hawley, 1986; PacRim Coal, 2005).). The sulfur content is low; which reduces the risk of producing acid rain and acid mine drainage compared with many coal sources in the contiguous 48 states (Merritt and others 1986).

The Capps deposit south of Capps Glacier contains approximately 11 to 13 square km of mineable coal in two major beds. Dobey and McGee (1976) estimated that the Capps district contains nearly 550 million tons of identified mineable coal, although more conservative estimates from the Beluga Coal Company put the mineable reserves at approximately 200 million tons (Merritt, 1990). Merritt (1990) assigns high coal potential to the entire area south of Capps Glacier northeastward to Coal Creek, and including Drill Creek.

The Chuitna district northeast of the Chuitna River is currently leased to PacRim Coal, who reports measured reserves of 809 million tons and additional indicated reserves of 254 million tons (PacRim Coal 2005). The proposed mine is in the advanced stages of the permitting process for both coal extraction and infrastructure development; if permitted, most of the coal extracted from the Chuitna district will likely be bound for foreign markets, although local in-state use would remain an option if a viable market were developed.

The Drill Creek and North Extension district is located east of Beluga Lake and west of Beluga Mountain. The total reserves for this district are uncertain although Dobey and McGee (1976) speculate that the region may contain more than one billion tons of coal. At Drill Creek, field observations (Barnes, 1966) and exploratory drilling (Warfield, 1959) identified coal beds greater than 10 feet thick totaling an estimated 64 million tons of coal. Coal reserves have not been estimated along the other major drainages, but are likely of minor significance because only 1 to 4 beds (each no greater than 4 feet thick) have been observed and the surrounding bedrock limits the lateral extent of the seams. The Threemile Creek district located along the Beluga River near the Cook Inlet coast is estimated to contain 150 million tons of coal (McGee, 1973). The Beluga Coal Company estimates 69 million tons of this coal is in beds approximately 10 feet-thick at a stripping ratio of 9:1 (Merritt, 1990).

The outlying areas of the Beluga field are less well understood than the defined districts. Dobey and McGee (1976) speculated that a 25 square-mile region between the Chuitna and Chakachatna rivers may contain 25 million tons of hypothetical coal. Part of this same region was deemed to have high coal potential by Merritt (1990). However, because of widespread glacial deposits that cover most of the underlying coal-bearing strata, additional exploratory drilling will be required to further delineate the presence and abundance of mineable coal resources in the outlying areas of the Beluga field.

Kenai Field. The Kenai field occupies nearly the entire lowland region of the Kenai Peninsula on the east side of upper Cook Inlet, including a small area near Seldovia (fig. J2 and sheet 2). The field encompasses, or lies within close proximity to, existing commercial highway and rail infrastructure and tidewater ports (Homer and Seward). The area is divided into three coal districts: Kenai onshore, Kenai offshore, and Port Graham (Merritt and Hawley, 1986). Coal from the Kenai onshore district occurs within the Middle Miocene to Early Pliocene age Beluga and Sterling formations. The coal beds are primarily visible in discontinuous coastal bluffs along the Kenai Lowland, from north of Clam Gulch on the western side of the Kenai Peninsula, to the Fox River, north of Kachemak Bay. Many coal seams are encountered in petroleum wells, indicating that coal-bearing strata underlie the entire Kenai Lowland. The grade of coal in the Kenai onshore district ranges from lignite to subbituminous, which is considered to have low to medium heating potential, with an average heating value of 7,700 Btu/lb. The rank decreases in younger, shallower rocks. The coals have moderately high to high ash contents and may require crushing and washing to increase their heating value. The low measured sulfur content of the coal and overburden indicate a relatively low potential for producing acid rain or acidic contamination from mine waste materials.

The number and thickness of coal beds decreases northward along the Kenai Peninsula. Although Tertiary strata in the Kenai Lowland are typically flat lying or gently dipping, coal beds in the region are lenticular and locally offset by high-angle faults, making it difficult to extrapolate over lateral distances greater than ~0.5 km. The 1,100 square-mile area south of Tustumena Lake and the Kasilof River contains a total of 57.6 million tons of calculated measured, 347.2 million tons identified, and 41,550 million hypothetical tons of coal (Merritt and others 1987). Bedrock north of Tustumena Lake is obscured by thick Quaternary glacial deposits, but several thousand feet of coal-bearing deposits have been penetrated by wells in the Swanson River field as well as other exploration wells in the region. The main challenge to extraction of coal in the Kenai onshore district is the presence of glacial overburden that can be up to several hundred feet thick, particularly farther north along the peninsula. Because of the thick glacial deposits that cover the underlying coal-bearing bedrock, additional drilling will be required to further delineate the resource potential for much of the Kenai Peninsula. For further information, refer to Barnes and Cobb (1959) and Barnes (1967).

The Port Graham district, south of Kachemak Bay includes the site of the earliest coal mine in Alaska. The mine was operated by the Russians between 1855 and 1867, but was closed due to unprofitability (Stone, 1906). Estimates of the volume of coal in the Port Graham district have not been made, but recent field work in the area by the Alaska Department of Natural Resources suggests that coal is present only in thin (less than 20 cm thick), laterally discontinuous lignite seams.

An estimated 532 million short tons of coal from the Beluga and Tyonek formations of the Kenai Group are estimated to underlie much of Cook Inlet in the Kenai offshore district in beds more than 20-feet thick (McGee and O’Connor, 1975). Estimates were based on electric log interpretation from 47 exploratory and development wells on the west side of Cook Inlet. However at present, the coal is beyond extraction with current technology.

Matanuska Field. The Matanuska field encompasses approximately 195 square miles in the Matanuska Valley, located approximately 50 miles from downtown Anchorage (fig. J3 and sheet 2). The field is located directly adjacent to Alaska Highway 1 (Glenn Highway) at the upper end of the Knik arm of the Cook Inlet. Thus, the Matanuska field is in close proximity to commercial road and rail infrastructure, a tidewater port, and the largest population center in the State of Alaska. The field was mined for coal from 1914 to 1968, with the Premier Mine providing coal for local needs until 1982 (Merritt, 1988).

The field is divided into the Chickaloon, Wishbone hill, and Anthracite Ridge mining districts (Merritt and Hawley, 1986). Coal from each of these districts is derived from the Paleocene age Wishbone Formation. Coal grade in the district decreases southwestward from high grade semi-anthracite to anthracite grade at Anthracite Ridge to medium-grade bituminous coal in the Chickaloon district. Coal extracted from the Matanuska field has heating values that range from approximately 10,400 to 14,400 Btu/lb (Merritt, 1985a, Merritt and Hawley, 1986) and has relatively high ash and low sulfur contents (Merritt, 1986; Merritt and Hawley, 1986).

Coal overburden analyses yield low concentrations of pyritic sulfur, indicating low potential for acid mine drainage (Merritt, 1986). Resources for the entire field are estimated at 48.5 million short tons measured, 165 million short-tons identified, and hypothetical resources estimated up to 551 million short tons as of 1990 (Alaska Division of Geological & Geophysical Surveys, 1990). Most of the mineable coal is concentrated in the Wishbone Hill and Chickaloon districts. Potential challenges to sustained coal extraction noted by Merritt (1986a) include significant faulting, sometimes with large magnitude offsets, coal beds that are laterally discontinuous, steeply-dipping coal beds that make strip mining difficult, and pinching and swelling of coal beds. Other potential complications include local degradation of coal quality from nearby igneous activity, the presence of locally abundant coal-bed methane that can add cost to underground mining operations, and the presence of impurities within the coal that would require crushing and washing to increase the energy value of the coal. Merritt (1988) also notes that the Matanuska field is unlikely to support large-scale mines with annual productions greater than one million tons per year. For a more thorough examination of the Matanuska field, refer to Merritt (1985).

Susitna Field. The Susitna field is bisected by the Castle Mountain fault (sheet 2), a significant structure that generally separates the field into two districts: the Susitna Flats to the north and the Little Susitna to the south (fig. J3). The Susitna Flats district lies within the Susitna basin between Mount Susitna and the Talkeetna Mountains. Coals in this district are part of the lower to middle Kenai Group (likely Tyonek Formation), and are known primarily through data from oil and gas exploration wells in the area (Conwell and others, 1982). The coal grade and resource potential for this area are uncertain. Merritt and Hawley (1986) assume mineable seams of sub-bituminous grade occur throughout much of the Susitna Flats district, although this may be in part due to their inclusion of locally exposed coal beds in the Houston area previously considered part of the Little Susitna district (Barnes and Sokol, 1959). Conversely, Merritt (1990) show a mostly low potential for mineable coal for the Susitna Flats district, highlighting the uncertainty of coal resources in the region.

The Little Susitna district has only been studied at a reconnaissance level through investigation of small, sparsely distributed coal outcrops and limited exploratory drilling (Barnes and Sokol, 1959). Coal in this district is hosted in the Oligocene to Miocene age Tyonek Formation and is sub-bituminous grade. Heating values determined from only a few samples range from about 8,500 to 13,000 Btu/lb. Coal beds are thin, typically less than 4 feet-thick with abundant clayey partings, and are often widely spaced and laterally discontinuous. A poorly defined potential reserve in the Little Susitna district is estimated by May and Warfield (1957) to be 14.7 million tons.

Broad Pass Field. The Broad Pass field is located near Broad Pass, south of Cantwell, and is divided into the Graben and Costello Creek districts (fig. J3; Merritt and Hawley, 1986). The relationship between coal-bearing strata in the Broad Pass area and those in the Cook Inlet–Susitna and Nenana areas is uncertain, but the Broad Pass coal is believed to also be Tertiary, perhaps Pliocene in age (Merritt and Hawley, 1986). Two to 10 feet-thick lignite beds in the Graben district have heating values that range from about 6,600 to 7,400 Btu/lb and high ash contents from about 9 to 32% (Hopkins 1951). The lignite seams contain low sulfur values ranging from 0.2 to 0.4 percent (Merritt and Hawley, 1986). Coal in the Costello Creek district is slightly higher in grade at subbituminous A (Wahrhaftig, 1944).

Estimated coal reserves in the Graben district are based on limited trenching and few exposures, thus the conservative estimate of 13.5 million tons of lignite is poorly constrained (Hopkins, 1951). Indicated coal reserves in the Costello district, including the long-closed Dunkel mine, are 353,000 tons (Wahrhaftig, 1944). Despite easy accessibility of the Broad Pass field by rail and road systems, the low grade of coal in this field probably does not warrant further consideration as an energy alternative for local communities. However, the region is actively being explored for gold and related minerals and if development occurred, these low grade coals may warrant further exploration as a potential energy source.

Nenana Coal Province. Coal-bearing strata in the Nenana coal province occur within the Nenana Basin in a series of discontinuous sub-basins arrayed along the northern foothills of the central Alaska Range (fig J2 and sheet 2). These coal-bearing rocks extend from the Jarvis Creek coal field in the Yukon–Koyukuk/upper Tanana energy region (see chapter L) at their eastern extent, approximately 200 miles southwestward to about the Kantishna Hills in a belt that is up to 30 miles wide (Merritt, 1985b). Southwest of the Kantishna Hills the belt continues discontinuously to at least the Cheeneetnuk River area, southwest of Farewell, in the Lower Yukon–Kuskokwim energy region. Coal-bearing strata are found within five geologic formations of late Oligocene to late Miocene-age; from oldest to youngest, these include the Healy Creek, Sanctuary, Suntrana, Lignite Creek, and Grubstake formations (Wahrhaftig and others, 1969; Wolfe and Toshimasa, 1980). Of the five formations, the Suntrana, Healy Creek, and Lignite formations contain significant coal reserves. The coal is typically subbituminous B and C in rank, with heating values ranging from 8,000 to 9,500 Btu. They have medium ash contents and very low sulfur contents. Thicknesses of individual coal beds range from 10 to 60 feet (Merritt, 1985). Identified coal resources of the Nenana coal province are estimated at 7 billion short tons, and inferred coal resources throughout the province are estimated at about 10 billion short tons, for a total of 17 billion potential tons (Sanders, 1981). The geology and coal resources of the two largest fields (Lignite Creek and Healy Creek) are well characterized, however comparably little has been published about the remaining smaller fields.

Ten coal fields are recognized within the Nenana Coal Province, although only seven occur within the Railbelt Development Region. The Jarvis Creek, West Delta, and East Delta fields are considered part of the Nenana coal province, but are located to the east in the Yukon–Koyokuk/upper Tanana development region (chapter L). The seven individual fields within the Railbelt region are discussed below in order of decreasing size based on estimated reserves within 500 feet of the surface and coal bed thicknesses of at least 29 inches or greater (Merritt, 1985b).

Lignite Creek field. Coal in the Lignite Creek field is discontinuously exposed in outcrop over an area of approximately 100 square miles, extending from the Nenana River and Parks Highway near Healy in the west, to the headwaters of Tatlanika Creek in the east. Coal beds in this field can achieve 60 feet in thickness, and some seams are laterally continuous for up to ten miles. Mineable reserves at a stripping ratio of 4.25:1 were estimated at 150 million tons in the mid 1970's for the Lignite Creek field (Renshaw, 1977). Merritt (1985b) estimates that 936 million short tons of potentially mineable coal with bed thicknesses of at least 29 inches exists in the field within 500 feet of the surface. The Lignite Creek field has produced 50 million tons of coal to date and the Usibelli Coal Mine currently produces an average of 1.5 million tons of coal per year from this field (Usibelli Coal Mine, Inc., 2009).

Healy Creek field. The Healy Creek field is located directly south of the Lignite Creek field and encompasses less than 25 square miles from the Nenana River and Parks Highway in the west to the middle of the Healy Creek drainage to the east. The field includes a similar stratigraphic succession as recognized elsewhere in outcrop along the southern margin of the Nenana Basin. The Usibelli Coal

Company (and others before them) mined coal from the Healy Creek field over a thirty-year period from 1944 to 1972. The field now is largely depleted of easily accessible deposits, but may still have as much as 250 million mineable short tons of coal using more expensive mining methods (Merritt, 1985).

Western Nenana field. The Western Nenana field spans the Parks Highway between the Nenana and Sanctuary Rivers, and lies in part in Denali National Park. Estimated coal resources in this area are 250 million tons (Wahrhaftig and others, 1951) from the lower Nenana Basin coal-bearing stratigraphy, with an estimated volume of potentially mineable coals within 500 feet of the surface of 80 million short tons (Merritt, 1985).

Tatlanika field. Coal-bearing strata of the Tatlanika field are exposed over an area of approximately a 120 square miles, and is located about 12 miles east of Liberty Bell Mine and 25 miles east of the Parks Highway, extending from Buzzard Creek in the west to Grubstake, Roosevelt, and Hearst creeks on the east. Merritt (1985) estimates that 77 million short tons of potentially mineable coal with bed thicknesses of at least 29 inches exist in the field within 500 feet of the surface from the Healy Creek through Grubstake formations.

Wood River field. Coals of the Wood River field occur in an area of less than 40 square miles located on the northwest flank of Mystic Mountain about 40 miles east of the Parks Highway. At least 16 significantly thick coals occur within the field and span the entire stratigraphic range of coal-bearing units within the Nenana Province. The field has an estimated 80 million short tons of potentially mineable coal within 500 feet of the surface (Merritt, 1985).

Rex Creek field. Coal-bearing strata of the Rex Creek field occupy 25 square miles located about 15 miles east of the Parks Highway in an area crossed by Rex Creek located east of Rex Dome and west of Iron Creek. At least 15 million short tons of potentially mineable coal occur in the Healy Creek, Sanctuary, and Suntrana formations (Merritt, 1985).

Mystic Creek field. The Mystic Creek field is located east of the Wood River between Keevy Peak to the southwest and Mystic Peak to the northeast, about 35 miles east of the Parks Highway. At least 10 coal beds up to 15 feet thick are present in outcrop over a 20 square mile area. The field has an estimated 20 million short tons of potentially mineable coal from the Healy Creek Formation and other undifferentiated strata (Merritt, 1985).

Conventional oil and gas resource potential

As explained in the discussion of requirements for exploitable oil and gas resources (Chapter A), functioning petroleum systems occur in thick sedimentary basins, and require three basic elements: effective source rocks, reservoirs, and traps. Each of the elements must be in existence and connected at the time hydrocarbons are generated. This section provides an overview of the various basins in the Railbelt region then considers each of the necessary elements of petroleum systems in turn to evaluate the role conventional oil and gas resources may play in supplying rural energy to Alaska's Railbelt energy region.

Overview of sedimentary basins. The Railbelt region encompasses several main Tertiary age sedimentary basins, including the Cook Inlet, Susitna, the eastern part of the greater Nenana basin, and the northeast part of the Minchumina basin (sheet 2; Kirschner, 1988). The Nenana basin is also known as the Tanana basin (e.g. Trop and Ridgway, 2007) or Middle Tanana basin (Ehm, 1983; Stanley and others, 1990).

The Cook Inlet basin contrasts with the other Railbelt basins in many respects, including areal extent, thickness, tectonic setting, and petroleum productivity. Situated above southern Alaska's subduction zone, the Cook Inlet is a forearc basin filled by sediment eroded from the Aleutian Range and southern Alaska Range magmatic arc to the west, the central Alaska Range and Talkeetna Mountains to the north, and the Chugach–Kenai Mountains accretionary prism to the southeast. Most exploration in the Cook Inlet basin has occurred on state-managed land, whereas extensive private and federally protected areas are either lightly explored or closed to exploration. The vast majority of hydrocarbons produced from basin thus far were found in Tertiary nonmarine strata deposited in alluvial fans, river channels, floodplains, lakes, and coal swamps. These units overlie older Mesozoic formations of mixed marine and nonmarine origin. Proven petroleum systems in the Cook Inlet basin have supplied local and export markets more than 1.3 billion barrels of oil and nearly 7.75 trillion cubic feet of gas since the late 1950s (Alaska Division of Oil and Gas, 2007; Hartz and others, 2009). Most of this success has resulted from targeted exploration of large anticlinal structures that are readily apparent on seismic data. Although many of these structures have been drilled and tested, these folds continue to attract exploration and active industry leases suggest the potential for future discoveries. Significant additional hydrocarbons are likely also housed in stratigraphic traps, although this type of accumulation is subtle and has only been lightly explored.

The Cook Inlet basin has witnessed declining production from existing fields drawing attention to its role in meeting south-central Alaska's future energy needs. Recent studies undertaken by the Alaska Division of Oil and Gas (Hartz and others, 2009) suggest there may be significant volumes of recoverable gas in parts of Cook Inlet's complex fluvial reservoirs that are not tapped effectively by existing wells. It may be feasible to recover some of this nonproducing gas through more complete field development projects in the near term. Furthermore, the State of Alaska is attempting to incentivize new exploration activity via major tax credits.

Exploitable petroleum systems may exist in the Susitna, Nenana, and Minchumina basins, although limited exploration has not yielded oil or gas production. Both the

Railbelt

Susitna and Nenana basins are candidates for exploration under active State-issued exploration licenses.

The Susitna basin is regarded as a northern extension of the Cook Inlet basin, separated by the Castle Mountain – Lake Clark fault, one of several arcuate strike-slip fault systems that traverse south-central Alaska. Nonmarine Cenozoic sedimentary strata reach a thickness of at least 3.7 km in the axis of the Susitna basin, indicating the region witnessed much less subsidence than the Cook Inlet basin. The origin and tectonic history of the Susitna basin is poorly known; subsidence may reflect activity on steep basin-bounding faults (Ehm, 1983; Kirschner, 1988), or deeper processes associated with a colliding crustal fragment to the southeast (Finzel and others, 2011). Miocene and younger basin-filling units are recognized in Susitna lowland outcrops (Reed and Nelson, 1980; Dickinson, 1995), and Paleocene to Eocene age strata are believed to be penetrated in the deeper exploration wells (R. Stanley, USGS, written communication). Two wells were drilled in the Susitna basin west of the Susitna River, in 1964 and 1980. Some 3,470 km^2 of the basin, including its deepest parts, are eligible for new drilling within the two adjacent exploration licenses issued on State lands in 2003.

The Nenana and Minchumina interior basins lie at the north end of the Railbelt region, along the northern flank of the Alaska Range. The Nenana basin is bound to the north by the Yukon–Tanana uplands and the Minchumina basin occupies the lowlands between two range-bounding fault systems, the Farewell fault zone to the south and Iditarod fault zone to the north. Only the shallow southern and eastern part of the Nenana basin and the northeastern part of the Minchumina basin fall within the Railbelt energy region; the remainders of both basins are located in the Yukon–Koyukuk/Upper Tanana energy region.

The Nenana basin contains Eocene and younger nonmarine deposits overlying metamorphic basement. The coal-bearing Usibelli Group and Nenana Gravel are exposed in the northern foothills of the Alaska Range (in an area sometimes referred to as the Healy basin). However, broad, low-lying areas of the greater basin are covered by Quaternary surficial deposits, limiting direct examination of the stratigraphy. The source of these sediments is interpreted to change over time; the older Usibelli Group was deposited by streams that flowed southward from the ancient Yukon–Tanana uplands, whereas the Nenana Gravel was deposited by streams flowing north out of the Alaska Range following major uplift in late Cenozoic time (e.g., Stevens, 1971; Buffler and Triplehorn, 1976; Wahrhaftig, 1987; Stanley and others, 1992; Trop and Ridgway, 2007).

The age of sediments deposited in the Minchumina basin is poorly constrained. Upper Cenozoic (Neogene) gravels are locally exposed at its eastern periphery, and their equivalents probably extend beneath surficial cover throughout most of the basin. Lower Cenozoic (Paleogene) nonmarine sedimentary strata are inferred to be present in the subsurface near the Farewell fault zone (Kirschner, 1988), but they do not appear in outcrop (Wilson and others, 1998).

Constraints on the thickness of the Nenana and Minchumina basins come from integrating regional gravity and local seismic data with the observed depth to basement in the two wells with publicly available data: the Union Nenana 1 (located in the adjoining Yukon–Koyukuk/Upper Tanana energy region) and the ARCO Totek Hills 1 (located just inside the boundary of the Railbelt energy region). Both wells were drilled at the edge of the main fault-bounded Nenana basin, and penetrated basement at depths less than 1.1 km. A third well was drilled in the basin in 2009 (Nunivak 1) and although most of the data remain confidential, it is known to have targeted a prospect at approximately 3.2 to 3.3 km depth, located between even deeper fault bounded depressions containing up to 4–6 km of sedimentary strata (Petroleum News, 2009; Petrotechnical Resources and Doyon, Ltd., undated; Frost, 2003; Grether and Morgan, 1988). This sector of the Nenana basin is sufficiently deep to host an effective conventional petroleum system based on thermogenic-sourced hydrocarbons. This part of the basin is mostly encompassed by the exploration license issued in 2002, and is located outside the Railbelt energy region.

No oil or gas wells have been drilled in the Minchumina basin. Gravity data indicate basement lies at shallow depths (a kilometer or less) across much of the basin, although deeper fault-bounded depressions appear to be present in localized areas and are presumably filled with nonmarine Tertiary strata. (Meyer and Krouskop, 1986; Kirschner, 1988; Meyer, 2008). Most of the Minchumina basin that falls within the Railbelt energy region is encompassed by Denali National Park and Preserve, and is unavailable for energy resource development.

Source rocks. Natural seeps of oil and gas in the Iniskin Bay–Chinitna Bay area on the northwest side of Cook Inlet are associated with outcrops of the Middle and Upper Jurassic formations, and were reportedly known in Russian colonial times (Martin, 1905; Martin, 1921; Detterman and Hartsock, 1966). Modern geochemical analysis suggest that nearly all the oil (and associated gas) produced from upper Cook Inlet oil fields, is sourced from thermogenic maturation of thick, widespread organic rich marine siltstone and shale of the Middle Jurassic Tuxedni Formation (Magoon and Anders, 1992). In contrast, most of the natural gas fields in Cook Inlet have a different source. This gas is biogenic in origin, sourced by low-temperature bacterial decay of the abundant coals present in Cenozoic formations (Claypool and others, 1980). A critical factor in developing conventionally exploitable biogenic gas accumulations is late-stage uplift, which lowers the subsurface pore pressure, allowing the dissolved gas to desorb from the coal so it can coalesce as a free gas phase and migrate into reservoir pore space. Most of the Cook Inlet gas fields probably owe their existence to significant uplift and erosion during the last few million years of late Cenozoic time (Haeussler and others, 2000; Swenson, 2003).

The trend of the Jurassic forearc basin suggests the Susitna Basin is unlikely to be underlain by the same Jurassic oil-prone source rocks that are present beneath the Cook Inlet Basin. The thickness of Cenozoic sediments in most of the Susitna basin appears to be insufficient to have generated significant thermogenic hydrocarbons. However, the abundance of coal in the basin suggests favorable conditions for biogenic gas generation. Little is known of the uplift history of the basin, but similar to Cook Inlet, it may have undergone late-stage uplift freeing biogenic gas.

Available data indicate the Nenana and Minchumina basins are exclusively filled by nonmarine strata and are likely to contain mostly gas-prone coaly source rocks. However, limited publicly available information from the Totek Hills #1 well and outcrops near Healy suggests there may be intervals with potential to generate petroleum liquids (Grether and Morgan, 1988; Stanley and others, 1990). The Nenana basin's deepest portions might be mature for thermogenic hydrocarbon generation, and abundant coals allow for the possibility that biogenic gas could occur in shallower portions of the Nenana and northeastern Minchumina basins.

Reservoir rocks. Cenozoic sandstones in Cook Inlet exhibit variable reservoir quality depending on their grain size, composition and total depth of burial (Hickey and others, 2007). The younger strata within the basin (Miocene and Pliocene) are often only lightly cemented and yield very high porosity and permeability values (Helmold and others, 2011). Reservoir quality data for the Susitna, Nenana and Minchumina basins is very limited or absent. However, nonmarine sandstones in these basins may have derived from broadly similar source terrains as Cook Inlet and thus potentially share similarly favorable reservoir quality. Sandstone reservoirs in these nonmarine basins often exhibit significant lateral and vertical variability reflecting the positions of ancient river channel deposits. The ultimate complexity of this type of reservoir will determine the size of any possible hydrocarbon accumulations.

Traps. The active tectonic setting of southern and central Alaska ensures the presence of numerous structural and stratigraphic trapping configurations. All major producing oil and gas accumulations in the Cook Inlet basin occur in anticlinal closures, many of which contain stacked successions of reservoir sandstones and sealing mudstones. This reliable trapping mechanism is likely in the other Railbelt basins, although insufficient subsurface mapping is available to evaluate the style folding. The elements necessary for fault-bounded traps and stratigraphic traps are probably also present in the energy region, and may be effectively sealed. Stratigraphic traps are likely to be subtle features and represent a challenging target for future exploration.

Summary of conventional oil and gas resource potential. The Cook Inlet Basin has a long history as the hub of oil and gas exploration and production within the Railbelt region. Although many producing assets in Cook Inlet are mature, significant potential remains in under-developed reservoirs in producing fields and undrilled prospects. The most recent USGS assessment of the region estimated a mean value of 599 million barrels of oil and 13.7 trillion cubic feet of natural remain to be discovered in Cook Inlet (Stanley and others, 2011). The Susitna and Nenana basins have no proven economic oil and gas resources. However, these basins have only been lightly explored and the limited available geologic information suggest there is some gas resource potential. Additional data and exploratory drilling will be needed before it will be possible to predict how much, if any, of the Railbelt's long-term energy demand these basins can be supply. The northeast part of the Minchumina basin that falls within the Railbelt energy region has very minor gas resource potential; encompassed by Denali National Park, it is not a candidate for energy development.

Unconventional oil and gas resource potential

Coalbed methane. The Railbelt energy region includes two large coal provinces with potential for significant volumes of coalbed methane: the Cook Inlet province and Nenana province. The overall coalbed methane potential for the Cook Inlet coal province is high as evidenced by a recent USGS assessment estimating a mean value of more than 4.5 trillion cubic feet of coalbed gas remains undiscovered in the greater Cook Inlet area (Stanley and others, 2011). Although this number evaluates technically recoverable resources, it includes offshore regions that are unlikely to be economically developed. Nevertheless, the abundance of Cenozoic coal beds in the Cook Inlet Basin and available geologic data are consistent with a very large gas resource present within shallow subsurface coal seams in the region. The resource potential is greatest in regions with higher rank coals, such as the Matanuska coalfield that contains bituminous and semi-anthracite coals. The Kenai, Broad Pass, and Beluga coalfields possess lower rank coals, some of which may not have sufficiently developed natural fractures (cleats) to permit gas flow. Desorption analyses of cores and cuttings indicate an average gas content of 230 scf/ton (standard cubic feet per ton) for bituminous coals and 80 scf/ton for subbituminous coals. Isotherms constructed for samples of both coal ranks suggest that bituminous coals are saturated with respect to methane, whereas subbituminous coals are locally unsaturated (Flores and others, 2004). Coals range in thickness from 2 to 50 ft (0.6 to 15 m) and in gas content from 50 to 250 scf/ton. They occur in the Miocene–Oligocene fluvial deposits of the Kenai Group (Montgomery and others, 2003) and are the probable source of more than 7 trillion cubic feet of biogenic gas that has been produced from conventional sandstone reservoirs in the basin. Many of the coal beds in the Tyonek Formation in the upper Cook Inlet Basin contain coalbed methane (Smith, 1995). Gas content ranges from 63 ft^3 per short ton at standard temperature and pressure (STP) for coal beds at a shallow depth of 500 ft to 245 ft^3 per short ton at standard temperature and pressure for coal beds at a depth of 1,200 ft (Flores and others, 2004).

Coal beds of the upper Tyonek and lower Beluga Formations contain the best coalbed methane potential on the Kenai Peninsula, especially in reservoirs less than 6,000 ft deep. They occur at shallow depths along the western coast of the southern Kenai Peninsula and are readily accessible. Coals in the Tyonek and Beluga Formations contain as much as 2.5 percent by volume of coalbed methane (Flores and others, 2004). Based on borehole data, coals in the upper part of the Tyonek Formation contain by far the most coalbed methane resources. Coals in the lower part of the Beluga Formation contain moderate amounts of coalbed methane resources and coals of the Sterling Formation contain very low coalbed methane concentrations. The difference in the coalbed methane content between the Beluga and Sterling coals may be related to the variation in their rank, beds in the Sterling Formation being mainly lignite and those in the Tyonek and Beluga Formations being mainly subbituminous (Barnes and Cobb, 1959).

Attempts to develop Tyonek coal beds by energy companies (Union and Ocean Energy) in the Wasilla area were adversely affected by the co-production of water. Large amounts of groundwater were encountered, which posed production problems in separating methane from produced water, as well as water-disposal problems by re-injection. Other targets for coalbed methane development in the Upper Cook Inlet are in the Tyonek area where the coal beds in the Tyonek Formation are as much as 50 ft thick occur at shallow depths of less than 2,000 ft (Flores and others, 2004). The existing infrastructure of petroleum development in the area, including pipelines, would be an additional aid to the development of coalbed methane. Based on gas contents of the Tyonek coals in the upper Cook Inlet which range from 63–245 scf/t at STP, the in-place methane resources in that part of the basin may be significant.

The coalbed methane potential in the Nenana coal province is lower than for the Cook Inlet coal province. The coal beds in this coal province are mainly subbituminous, range from 50 to 66 ft (15 to 20 m) in thickness, and occur to depths of 3,000 ft (910 m). Exploration targets for coalbed methane are along the axes of large synclinal basins such as the Healy Creek and Lignite Creek Basins. Most of the coals in the Healy Creek and Suntrana Formations are thick (up to 65 ft) and are at shallow depths of 1,000-to 3,000-ft (Wahrhaftig and others, 1994). Coals in the Healy Creek, Suntrana, and Lignite Creek fields are mainly of subbituminous rank, with lesser lignite, and generally increase in grade to the south–southeast, toward the Alaska Range. Outcrop and surface-projected vitrinite values of the coal-bearing Usibelli Group in the Central Alaska–Nenana coal province range from 0.21 to 0.48 percent, which corresponds to lignite to subbituminous C coal ranks (Flores and others, 2004).

Tight gas sands. In the Railbelt energy region, the Cook Inlet basin has the most potential for extensive tight gas resources. Potential exists in both Tertiary and Mesozoic age strata, although the greater age and depth of burial of the Mesozoic section suggests increased potential for tight gas sands. The vast majority of Sterling, Beluga and Tyonek sandstones in upper Cook Inlet are conventional oil and gas reservoirs with typical porosities greater than 20% and permeabilities greater than 10 md (Helmold and others, 2011). West Foreland sandstones have undergone more compaction and cementation than the younger Tertiary reservoirs and, where sufficiently buried, may act as tight gas sands.

Many of the Mesozoic sandstones in the Cook Inlet region, in particular the Naknek Formation and Tuxedni Group have been relatively deeply buried and have undergone significant compaction and cementation (Helmold and others, 2011). Porosities are typically less than 10% and permeabilities less than 0.1 md are routinely recorded. These older, more lithified sandstones have potential as tight gas sands particularly those subjected to cataclastic deformation in addition to burial diagenesis. Extensive regional fractures have been observed in outcrops of some of the Mesozoic sandstones, particularly the Naknek formation in the lower Cook Inlet basin. Preliminary measurements of these fractures suggest they may have formed prior to Cenozoic folding and hydrocarbon migration, a scenario that improves the probability of a fracture-based unconventional petroleum system in Cook Inlet (Gillis and Wartes, 2011).

Shale gas. One of the primary requirements for shale gas is an organic-rich source rock present in the thermogenic gas window that is sufficiently brittle to host a natural fracture system (see chapter A). In Cook Inlet the most promising area for thermogenic gas charge is the widespread marine siltstone and shale of the Middle Jurassic Tuxedni Formation. Although the Mesozoic source rocks appear mostly oil prone there is some potential for thermogenic gas generation, as evidenced by the recent USGS assessment estimates a mean value of 637 billion cubic feet of shale gas remain to be discovered in the basin (Stanley and others, 2011). The general lack of thermogenic gas recognized in nonmarine Tertiary rocks suggests shale gas potential is low. This likely reflects a combination of factors, including insufficient maturity in parts of the basin and a lack of laterally continuous gas-prone mudstone intervals.

As noted above, the Susitna and Beluga basins probably have no underlying Mesozoic oil or gas source rocks and therefore have little potential for shale gas. In addition, these basins are not deep enough to have reached the thermal maturity necessary for generating appreciable thermogenic gas.

Nonmarine strata filling the Nenana and Minchumina basins are likely to contain mostly gas-prone coaly source rocks and may have limited potential for shale gas. It is uncertain whether these basins are hot and deep enough to generate significant quantities of thermogenic gas to sustain an economic shale-gas reservoir. Gravity data for both basins suggests that only small areas are deep enough for thermogenic gas, which significantly reduces the aerial extent of potential shale gas source rocks.

Gas hydrates. The main occurrences of gas hydrates in nature are in modern marine sediments and in arctic regions with well developed, continuous permafrost. Permafrost is not well developed in the Railbelt Energy Region and, where locally present, is discontinuous. Consequently the potential for economic concentrations of gas hydrates in the region is low.

Geothermal resource potential

The Railbelt Energy Region has only one recognized thermal spring and several fumarole fields (sheet 2; Motyka and others, 1983). However, the proximity of these potential resources to population centers and infrastructure has led to more exploration and development activity than other regions in the state, including three geothermal lease sales in the Mount Spurr area and a successful geothermal development project at Chena Hot Springs Resort. Geothermal production of electricity at Chena hot springs has attracted attention because of the slightly lower temperature of the resource than most other binary power plants. Historically, ten Chena thermal springs, resulting from circulation of meteoric waters along fractures and faults in intrusive and metamorphic rock units, produced a combined flow rate of 225 gal/min at a maximum discharge temperature of 145°F (63°C) (Motyka and others, 1983). Geothermometry estimated a reservoir temperature between 266°F–293°F (130°C–145°C) (Motyka and others, 1983). More recently, nearly 20 wells have been drilled at Chena Hot Springs to depths of 100–1000 ft to facilitate geothermal energy production and to measure temperatures (hottest being 176.5°F [80.3°C]) and pressures of the shallow geothermal system (Chena Hot Springs Resort, 2009b).

There are at least six mapped fumarole fields situated in close proximity to the chain of volcanoes running down the west side of Cook Inlet from Mount Spurr to southwest of Mount Douglas (Motyka and others, 1983). Mount Spurr's potential for geothermal development has received the most interest over the past 26 years (Wescott and others, 1985) and as a result there have been three State lease sales conducted in 1983, 1986, and 2008. The first two leases attracted bids on three tracts, all of which have expired or been terminated. During the most recent sale, Ormat Technologies, Inc. successfully acquired 15 leases on the south flank of the volcano. With matching State funds, Ormat has recently conducted an exploration program, including airborne geophysics and drilling. In 2011, well difficulties prevented drilling to the planned depth; preliminary data indicate a viable geothermal resource was not identified, although water chemistry and alteration suggest the well may have been peripheral to a hydrothermal system (B. Martini, Ormat, oral comm., 2011). If future drilling is attempted and proves successful, the project would require approximately 40 miles of transmission line to tie into the Beluga power plant. In addition to geologic and economic hurdles, any successful development project would need to address the risk associated with infrastructure on the flanks of an active volcano.

The active Augustine volcano in central Cook Inlet has been proposed for state geothermal leasing as recently as 2008. Despite its proximity to population centers on the Kenai Peninsula, leasing has not moved forward, principally due to the lack of any identified hydrothermal resource and concerns over natural hazard risks associated with any infrastructure on the volcanic island.

Four wells drilled in the lower Susitna basin in the Willow–Big Lake area registered geothermal gradients of 2.25°F–6.75°F/100 feet (4.1°C–12.3°C/100 meters) in thick Tertiary successions overlying granitic basement rocks (Motyka and others, 1983). One interpretation for this unexpectedly high thermal gradient is a shallow, discontinuous, low-grade geothermal reservoir up to 40 square miles (104 square kilometers) in area (Turner and Wescott, 1982). However, recent re-evaluation of key well data by geologists at DGGS concluded the anomalous bottom hole temperature is most likely a drilling artifact or otherwise erroneous (C. Nye, DGGS, written commun., 2011).

RECOMMENDATIONS

Conventional oil and gas resource recommendations

The Cook Inlet basin has been producing oil and gas for more than 50 years, but there is reason to believe that with continuing investment in second- and third-cycle development projects, several of its largest gas fields may be able to meet regional demand for the immediate and mid-term future. Renewed exploration of undeveloped prospects with known or inferred bypassed gas shows, and focused exploration for stratigraphically trapped gas may yield discoveries that will contribute to meeting long-term demand. This next generation of exploration will require an improved understanding of the stratigraphic architecture and distribution of reservoir quality within the Cook Inlet basin. Continued efforts by geologists at the Department of Natural Resources to publish results of detailed field and subsurface investigations could significantly improve the understanding of the petroleum system. The net effect of better publicly available data and more resolved geologic models is a reduction in risk, possibly enticing additional new exploration investment.

The Susitna and Nenana basins have some potential for hosting undiscovered gas resources, and both are candidates for exploration under the terms of State-issued exploration licenses. Both remain underexplored, and insufficient data are available to predict the role these frontier basins may play in supplying energy to the Railbelt region. New geologic mapping and associated field studies along the margins of these basins would provide much needed constraints on the framework geology and hydrocarbon prospectivity. Furthermore, the collection of high resolution gravity and aeromagnetic surveys in key areas might yield important and relatively cost-effective insights into the structure, fill, and gas resource potential of the Susitna and Nenana basins. In order to stimulate future exploration by industry, the State could consider exercising its right to publicly release currently confidential seismic data to the public if and when exploration licenses terminate.

Coal resource recommendations

Many of the most prospective coal fields in the Railbelt development region—namely the Beluga, Matanuska, Lignite Creek and Healy Creek fields have a substantial history of coal exploration, and in some cases, coal extraction. The geology of these fields is reasonably well-defined, and further studies are unlikely to change the available assessments of their resource potential. Other fields, such as the Kenai, Susitna, and Broad Pass fields are either covered by thick deposits of glacial detritus or are of such low rank as to make further study unwarranted. There may be merit for additional reconnaissance-level studies of the perimeter of the Yentna field in the Susitna Basin, and the smaller Western Nenana, Tatlanika Creek, Wood River, Rex Creek, and Mystic Creek fields in the Nenana coal province. Such investigations may involve more detailed geologic mapping and stratigraphic studies to further assess the potential resources in those locations. These may be followed up by a thoughtful reconnaissance drilling program if results of surface investigations look promising.

Unconventional oil and gas resource recommendations

Coalbed methane. The abundance of biogenically produced gas in the greater Cook Inlet area indicates the potential for coalbed methane is high. However, additional exploration is required to confirm that the resource, if present, can be economically produced. Methods for separating methane from produced water and disposal of produced water in the region's cold climate must be addressed before this resource can be pursued to meet local energy needs.

Coal rank in the Nenana province is generally too low to suggest a significant methane resource is present and producable. However, additional surface and subsurface data is required to better understand the distribution, rank, and gas content of coal beds over large portions of the province. Exploration for coalbed methane in the Healy Creek and Suntrana coal beds should consider areas removed from coal mining operations where depressurization from dewatering could hamper potential methane extraction.

Tight gas sands. The possibility exists for encountering fractured tight gas sands the lower part of the Tertiary section and in portions of the Mesozoic stratigraphic section in Cook Inlet. While producible hydrocarbons may be present in tight sands in these sections, exploring for this resource will require significant exploration investment and the use of emerging fracture inducing technology.. Recent State incentives encourage new exploration drilling to penetrate the Mesozoic section; these wells could provide much needed data on the tight gas resource potential in the deeper parts of the Cook Inlet basin. The presence of low porosity and permeability sandstone in the Nenana and Susitna basins is poorly constrained and the overall potential for tight gas reservoirs is largely unknown.

Shale gas. The potential for shale gas in the region is poorly known. The dearth of thermogenic gas recognized in conventional Tertiary reservoirs in Cook Inlet suggests the potential for shale gas in Tertiary units is low. Relatively few wells penetrate the middle Jurassic organic-rich rocks in the deeper part of the basin, although available data suggest modest potential for unconventional shale gas plays. State incentives for exploratory wells to drill into the Mesozoic may offer new insight into the potential for Jurassic shales to produce gas.

The nonmarine nature of the Susitna and Nenana basins are generally not conducive to regional shale gas plays. However too little is known, particularly from the deeper parts of the Nenana basin, to rule out the possibility of this resource type.

Gas hydrates. Due to the lack of extensive, continuous permafrost in most of the Railbelt region, the likelihood of finding gas hydrates are very low and doesn't warrant further consideration at this time.

Geothermal resource recommendations

The proximity of geothermal resources to population centers in the railbelt region has attracted significant attention, most recently manifest by the successful lease sale at Mt. Spurr. Recent State subsidized exploration activity by Ormat has improved our geologic understanding, but has thus far not demonstrated the existence of a geothermal resource. Detailed examination of the data collected during their 2011 exploration should guide any decisions on whether or not to invest in further drilling.

To determine whether anomalous thermal gradients in the Willow–Big Lake area are the result of a geothermal resource at depth, it is recommended that the State encourage additional exploration work in the area and if results warrant, conduct a geothermal lease sale. It is also recommended that the State continue to encourage exploration for geothermal resources in the Railbelt energy region by conducting additional geothermal lease sales within identified areas of interest.

The possible elevated geothermal gradient inferred from wells in the Willow–Big Lake area has long generated interest in a possible geothermal resource. However, this anomaly may be a drilling artifact; any further investment should await more definitive data.

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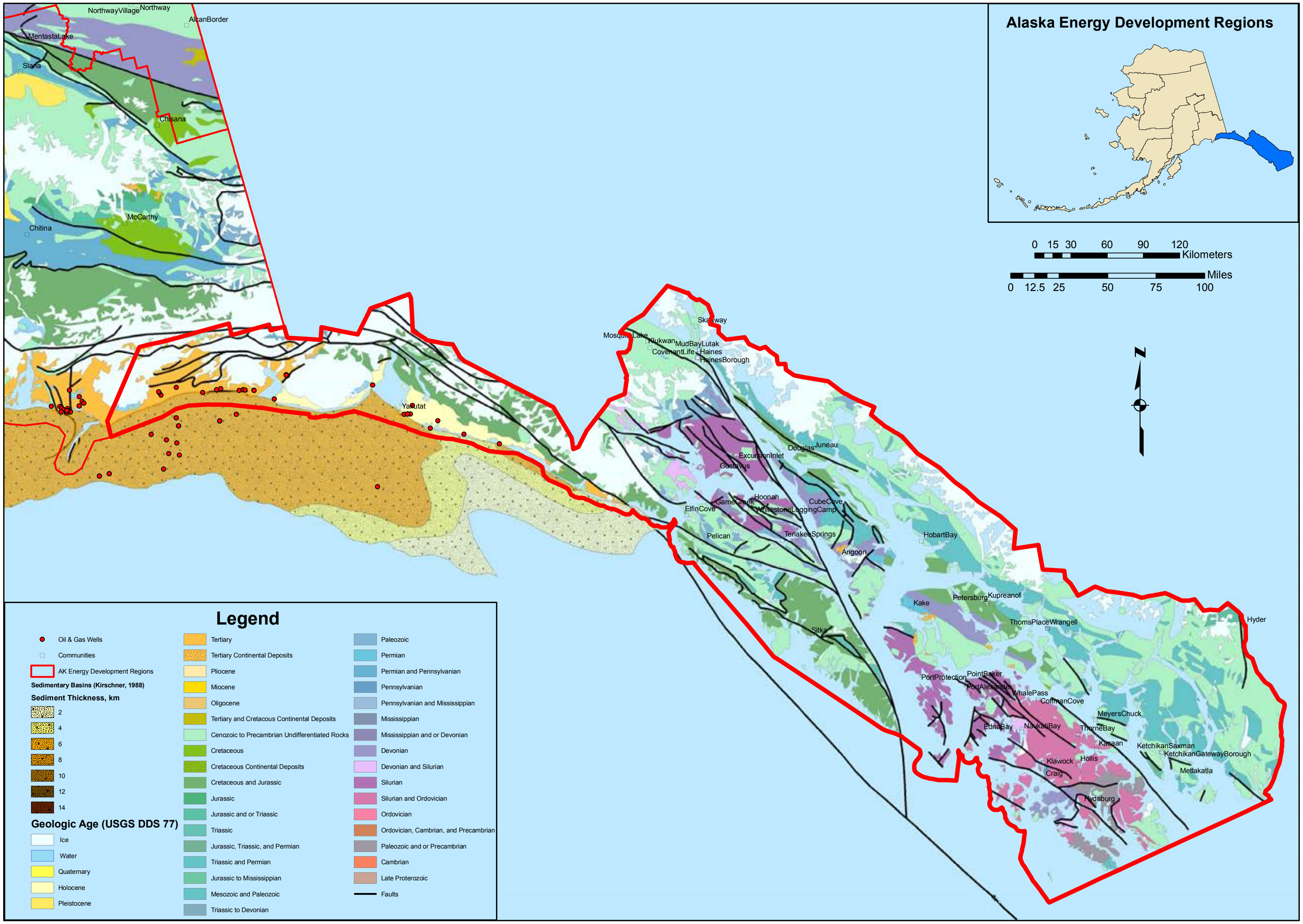
Geology of the Southeast Energy Region, Alaska



Southeast

SUMMARY OF FOSSIL FUEL AND GEOTHERMAL RESOURCE POTENTIAL IN THE SOUTHEAST ENERGY REGION

by Paul L. Decker, Robert J. Gillis, Ken Helmold, and Shaun Peterson

INTRODUCTION

Purpose of this report

Economic growth and stability in Alaska's rural areas hinges partially, if not primarily, on the availability of affordable and sustainable energy supplies. Recent price increases in oil and gas commodities have created severe economic hardship in many areas of the state that are dependent diesel and heating oil as their primary source of energy. All sectors of Alaska's economy rely on affordable energy sources with limited price volatility, highlighting the need to diversify the energy portfolio by developing locally available and sustainable resources that are not tied to the global market. Unfortunately, all areas are not created equal in energy accessibility; the resources available for local exploitation vary widely across the state. It is critical that funding decisions for expensive programs to reduce the dependence on diesel for heat and electricity take into account information concerning the entire suite of natural resources that exist in a given area.

This report draws from existing information to provide community and state leaders an objective summary of our current knowledge concerning the potential of locally exploitable fossil fuel and geothermal energy resources in the Southeast Energy Region (fig. K1), one of 11 regions recognized by the Alaska Energy Authority (AEA) in their Energy Plan (AEA, 2009). The potential geologically hosted energy resources considered here include exploitable coal, conventional and unconventional oil and gas, and geothermal resources. This report concludes with recommendations as to what additional data or strategies, if any, would provide the most leverage in helping to develop new energy resources in the region.

Readers without geological training are encouraged to peruse the geologic summaries of fossil fuel resources and geothermal energy in Chapter A. They provide an overview of the geologic elements that must be present in an area to economically develop coal, conventional oil and gas, unconventional oil and gas, and geothermal resources. These summaries will provide the necessary background to more fully understand the information presented in this chapter.

Geographic and geologic setting

The Southeast Energy Region of Alaska extends more than 500 miles along Southeast Alaska's north Pacific coast from south of Metlakatla to north of Yakutat with an average width of approximately 100 miles (sheet 1). The region is dominated by the southeast archipelago, but also includes the Fairweather and Boundary ranges as well as the southern portion of the Saint Elias Mountains. The region's largest cities are Juneau, with a current population of more than 30,000 residents, and Sitka, with a current population of more than 8,600 residents. Other sizable communities include Ketchikan, Douglas, Petersburg, Wrangell, and Haines, with

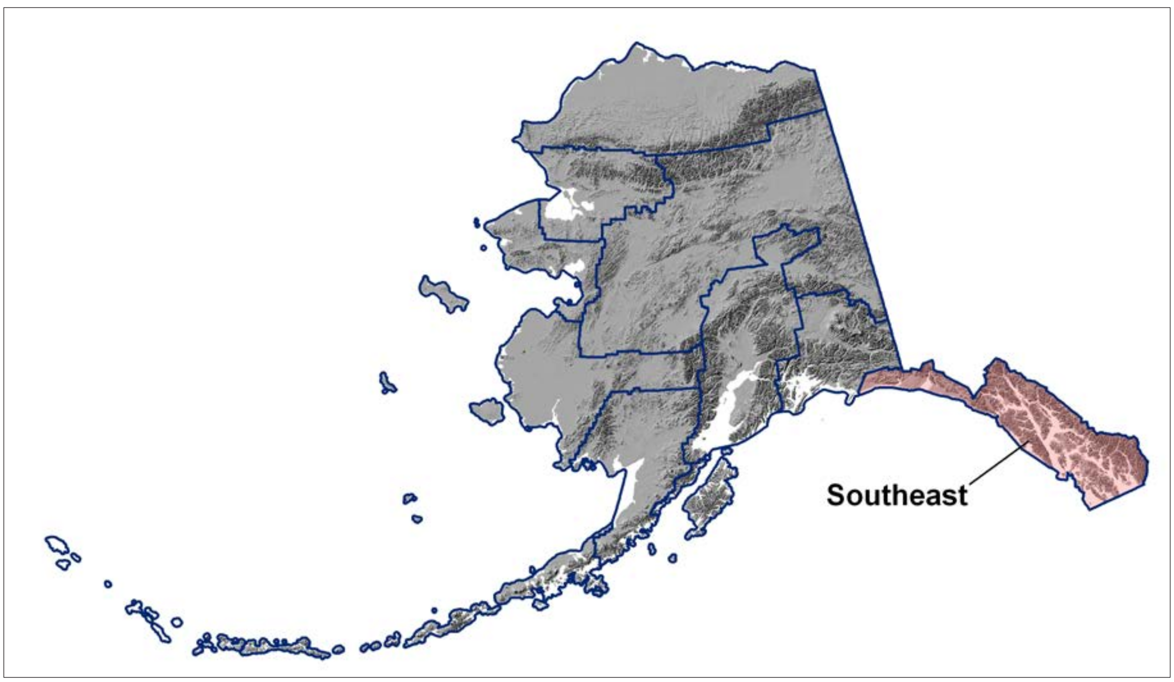


Figure K1. Location map of Southeast Energy Region.

populations ranging from nearly 8,000 to fewer than 1,500 residents. Smaller populations occupy at least 21 additional permanent villages.

Southeast Alaska lies within the circum-Pacific seismic belt that rims the northern Pacific Basin and has been tectonically active since at least early Paleozoic time (Lemke, 1975). Southeast Alaska can be divided into at least five separate geologic terranes based on distinct geologic records; these include the Alexander, Chugach, Stikinia, Taku, and Wrangellia terranes (Gehrels and Berg, 1994). The Alexander terrane comprises many units, the most widespread of which are the volcaniclastic turbidites, shallow-marine carbonate rocks, and Silurian-aged conglomerates (Gehrels and Berg, 1994). The Chugach terrane consists of coherent but strongly deformed graywacke, argillite, and slate in addition to a deformed and disrupted mélange composed of volcanic rock, chert, ultramafic rock, and limestone in a matrix of tuffaceous argillite (Gehrels and Berg, 1994). The most significant portion of the Stikinia terrane in southeastern Alaska is composed of Devonian carbonates, Carboniferous volcanic and sedimentary rocks, Permian basinal strata and platform limestone, and Jurassic–Triassic arc-type volcanic, plutonic, and clastic sedimentary rocks (Gehrels and Berg, 1994). The Taku terrane consists of deformed and metamorphosed strata of pre-Permian to Late Triassic age. Rocks of Triassic age include basalt, pillow basalt, basaltic breccias, carbonaceous limestone, slate, and phyllite (Gehrels and Berg, 1994). The Wrangellia terrane is characterized by a coherent sequence of unfossiliferous strata on Chichagof and Baranof islands distinguished by thick subaerial basalt flows, shallow- to deep-marine carbonates, and pelitic sedimentary rocks, with Jurassic tonalitic plutons being the youngest component of the terrane (Gehrels and Berg, 1994).

Tertiary- and Quaternary-age strata, which are most prospective for conventional and unconventional resources, occur at Mount Edgecumbe, in the Coast Mountains east of Ketchikan and Petersburg, in the Prince of Wales Island region, on islands in Cross Sound, and in many other areas of southeastern Alaska (Gehrels and Berg, 1994).

GEOLOGIC ENERGY RESOURCE POTENTIAL IN THE SOUTHEAST ENERGY REGION

Mineable coal resource potential

Coal resources and occurrences in southeastern Alaska are somewhat limited and discontinuous in areal extent and range in rank from lignite to bituminous. They occur only in erosional remnants of late Eocene or early Oligocene through Miocene-age (~37 to 5 million years ago) Kootznahoo Formation strata that were deposited on eroded Mesozoic and Paleozoic marine basement rocks that were uplifted in early Tertiary time. They are generally restricted to relatively small exposures on Admiralty, Kupreanof, Kuiu, Zarembo, and Prince of Wales islands (figs. K2–K4; Buddington and Chapin, 1929; Loney, 1964; Lathram and others, 1965; Muffler, 1967; White and Mitchell, 2004). It is likely that rocks assigned to the “Kootznahoo Formation” on Kupreanof and Kuiu islands that are considerably older (Paleocene) will be assigned to an older, separate stratigraphic unit with future stratigraphic studies (especially those exposed on Hamilton Bay, Kupreanof Island) (Blodgett, 2008, verbal commun.; Clough and others, in press). Coals in the Kootznahoo Formation rarely exceed 2 feet of thickness, and more typically are less than 16 inches thick and of lignite grade. An approximately 8-square-mile area on the south side of Kanalku Bay in the Kootznahoo Inlet on the southern end of Admiralty Island (fig. K2) contains the most abundant potential coal resources of these locations. The most recent discussions of the coal in the Kootznahoo Formation are those of White and Mitchell (2004) and Wahrhaftig and others (1994).

The Stepphagen Mine, located on Kootznahoo Inlet (fig. K3), produced the first coal mined in southeastern Alaska in 1862, and some of the first mined in Alaska (Merritt, 1988), and approximately 51 tons were mined in 1868 and 1869 for the steamship *U.S.S. Saginaw* (DeArmond, 1997). The Harkrader Mine (fig. K3), also on Kootznahoo Inlet, opened in 1928 on an inclined shaft several hundred feet deep and extracted coal throughout 1929 and then closed (Merritt, 1988). There is no record of production after 1929, but the residents of Angoon remember local use of the coal in their school in the 1950s (Gabrial John, Angoon, verbal commun., July 2003). The total past production from the Kootznahoo Formation east of Angoon was less than 1,000 tons (Merritt, 1988). Coal from the spoils pile at the Harkrader mine petrographically analyzed by White and Mitchell (2004) indicates a sample rank of subbituminous A to high-volatile C bituminous. Bituminous coal less than 5 feet thick reportedly occurs in Murder Cove east of Point Gardner (Roehm, 1943). However, all of these occurrences are relatively small and are in the Admiralty Island National Monument wilderness area.

Other coal occurrences in the region include the south side of Kadake Bay on Kuiu Island (fig. K2), where chunks of lignite coal as thick as 2 feet have been observed lying on the beach, but have not been observed in outcrop due to thick vegetation on the slopes above (Roehm, 1945). A 2.5-foot-thick lignite bed has also been reported at Port Camden on Kuiu Island opposite Keku Strait (fig. K2; Roehm, 1943). At the head, and on the west side of Kupreanof Island along the south shore of Hamilton Bay (fig. K2), coal-bearing strata occur in the shallow subsurface and in outcrop (Roehm, 1945). The coal-bearing beds are only exposed during low tide and are reported to contain lignite beds generally less than 8 inches thick, but have been observed at 16 inches thick (Roehm, 1945). Merritt and Hawley (1986) describe local occurrences of lignite and, rarely, subbituminous coal southeast of Sitka on Baranof Island, Snow Dome northeast of Glacier Bay, and near Lituya Bay on the Gulf of Alaska coast

Southeast

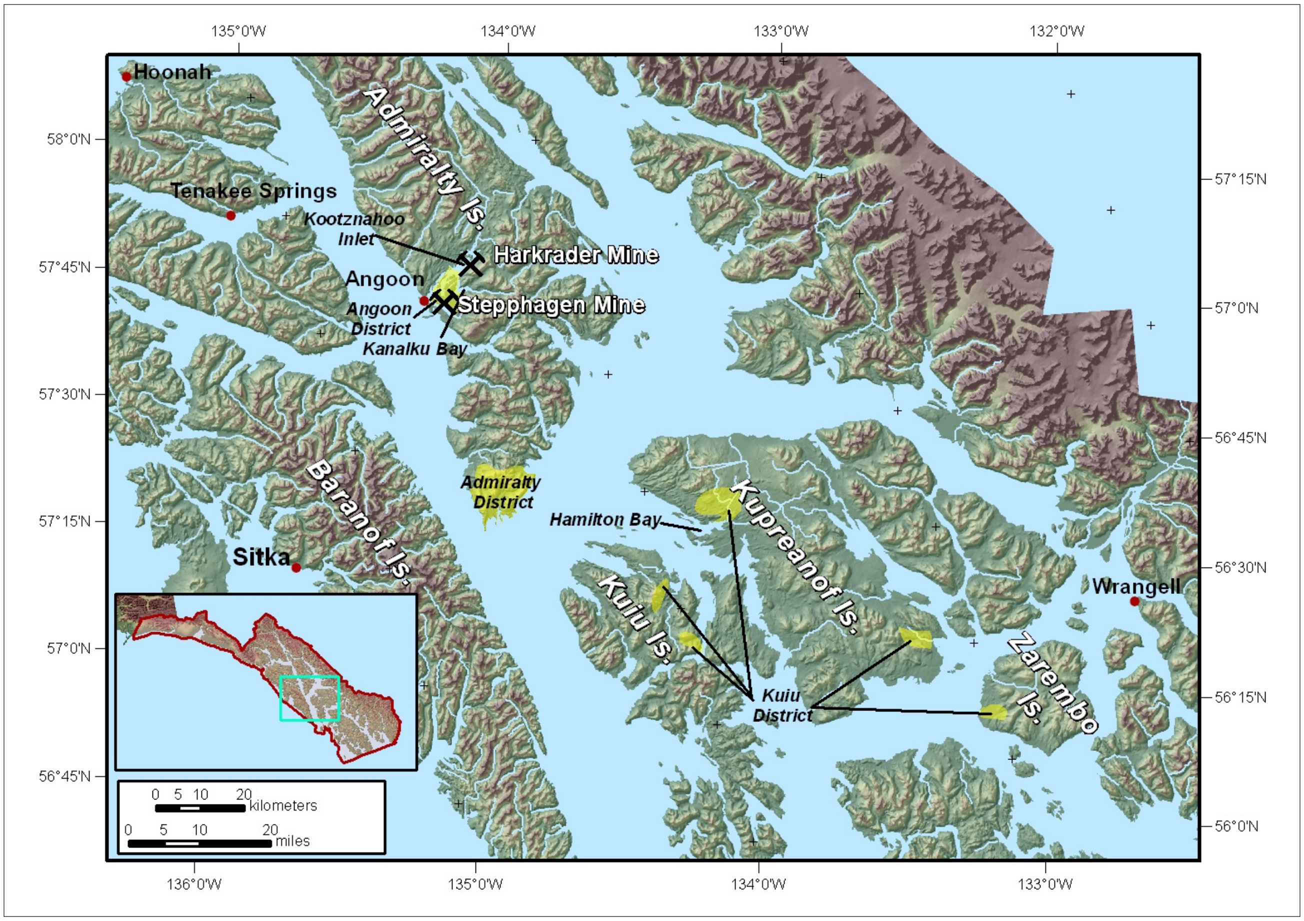


Figure K2. Location map of the central part of the Southeast Energy Region, showing selected geographic references noted in the text. Yellow shaded areas are inferred to be underlain by coal-bearing rocks; pick-axe symbols indicate locations of historic coal mines.

between Yakutat Bay and Cross Sound (figs. K2 and K5). These exposures are in the South Baranof Wilderness area and Glacier National Park and Preserve, respectively, and little is known about them. Yet other local occurrences of lignite and bituminous coal are reported by Merritt and Hawley (1986) near Yakutat Bay, north of Malaspina Glacier, and southeast of Bering Glacier. The latter includes a coal deposit from strata that are laterally equivalent to coal-bearing rocks of the Bering River field in the Copper River/Chugach Energy Region (Merritt, 1986). Individual coal beds in this region encompassing the Robinson Mountains are reportedly up to 6 feet thick, but otherwise there is little information about the potential resource.

Conventional oil and gas resource potential

As explained in the discussion of requirements for exploitable oil and gas resources (Chapter A), functioning petroleum systems occur in thick, sedimentary basins, and require three basic elements: Effective source rocks, reservoirs, and traps. Each of the elements must be in existence and connected at the time hydrocarbons are generated. This section considers each of these necessary elements of petroleum systems in turn to evaluate whether conventional oil and gas resources may play a role in supplying rural energy in Alaska's Southeast Energy Region.

Overview of sedimentary basins. The northwestern part of the Southeast Energy Region contains most of the onshore and nearshore portions of the Gulf of Alaska sedimentary basin (sheet 2). This basin continues westward into the Copper River/Chugach Energy Region and the adjacent federal offshore outer continental shelf (OCS). Exploitable petroleum systems could exist offshore and along a belt of the coastal plain and adjacent mountains that extends inboard up to 50 kilometers. Cenozoic sedimentary fill in the Gulf of Alaska basin ranges from zero to more than 9 km in thickness. These basin-filling strata belong to the Yakutat terrane, a crustal block consisting of sedimentary units deposited on slightly older Cenozoic and Mesozoic basement. Geologic and paleomagnetic evidence indicate that the Yakutat terrane originated approximately 50 million years ago near

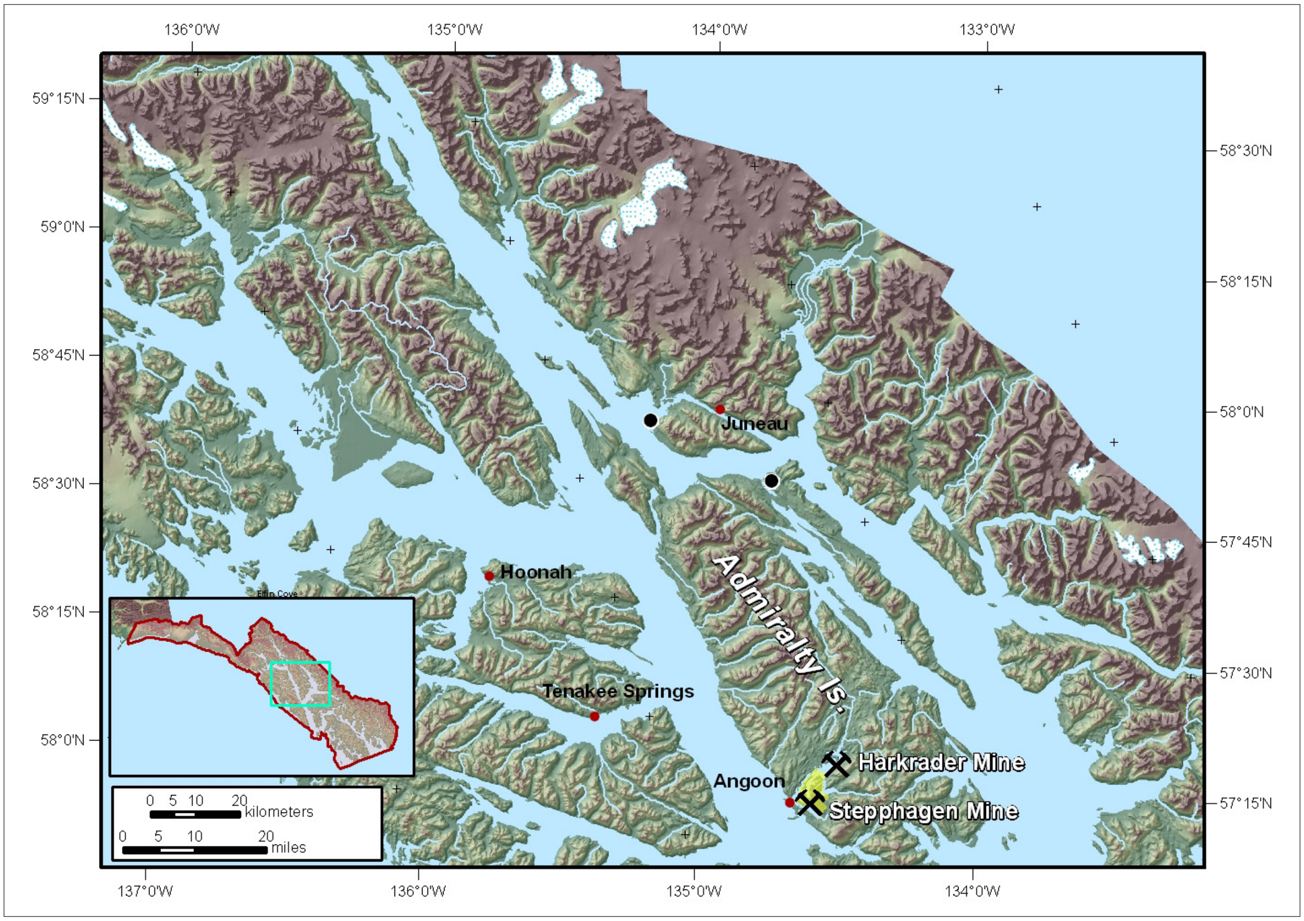


Figure K3. Location map of the central part of the Southeast Energy Region, showing selected geographic references noted in the text. Yellow shaded areas are inferred to be underlain by coal-bearing rocks; pick-axe symbols indicate locations of historic coal mines; black dots show locations of additional reported coal occurrences.

the present-day coast of British Columbia, 1,100 to 1,800 kilometers south of its current position (Risley and others, 1992). Since then, plate tectonic processes have transported the Yakutat terrane north along the western edge of North America, resulting in collisional deformation and mountain building in southern Alaska that continues into modern times.

The narrow coastal plain of the Southeast Energy Region has been tested by 23 onshore oil and gas exploration wells drilled between 1927 and 1963. The onshore belt explored by drilling stretches from the Kaliakh River in the Yakataga district on the northwest to the mouth of the Alsek River southeast of Yakutat. Thirteen more wells were drilled in nearby OCS waters between 1975 and 1983. The basin does not currently support commercial oil or gas production, but the Katalla oil field (in the adjacent Copper River/Chugach Energy Region) was the site of shallow, small-scale commercial oil production from 1902 to 1932.

Source rocks. Natural oil and gas seeps are prevalent in Cenozoic outcrops along the northern margin of the Yakutat terrane, constituting conclusive proof of effective source rocks on the onshore edge of the Gulf of Alaska basin. Literally dozens of seepages have been reported in strata now assigned to the Poul Creek Formation, spanning distances of approximately 25 miles in the Katalla district and some 18 miles along the length of the Sullivan anticline in the Yakataga district (Martin, 1921; Miller, 1951a, 1951b, 1957, 1975; Risley and others, 1992). Many more seeps have been mapped in the slightly older Kulthieth Formation in the Samovar Hills adjacent to the Malaspina Glacier. Shales of the Poul Creek Formation and some coals of the Kulthieth Formation have been shown to be source rocks for both oil and gas (Risley and others, 1992; Magoon 1994; Larson and Martin, 1998; Van Kooten and others, 2002), and most of the seeps are interpreted to have been sourced directly from the formations in which they occur. Thermal maturity increases toward the northwest in the Yakutat terrane and these source rocks are interpreted to be marginally mature to mature for generation of oil and gas in much of the onshore part of the basin (Barnes, 1967; Bruns, 1982, 1983; Mull and Nelson, 1986; Bujak Davies Group, 1989a, 1989b, 1989c, 1989d; Magoon, 1994). The southeastern portion of the basin near Yakutat is devoid of seeps. The Poul Creek Formation appears

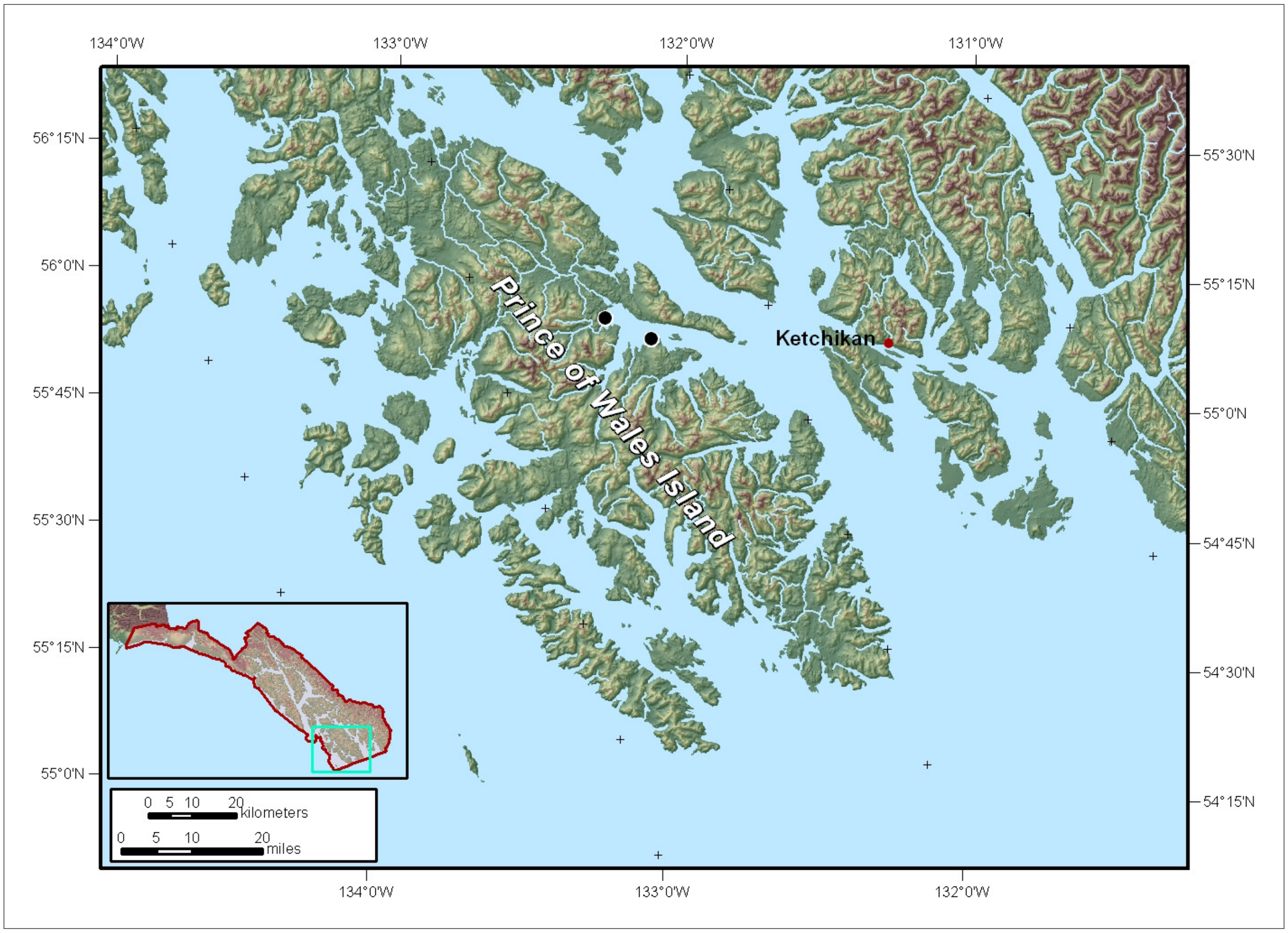


Figure K4. Location map of the southern part of the Southeast Energy Region, showing locations of reported coal occurrences (black dots) on Prince of Wales Island.

to be present offshore, but absent from most onshore wells in this area due to non-deposition, but probable source rocks are known in the Kulthieth Formation in this sector, which extends onshore (Risley and others, 1992). Thermal maturity levels in the Kulthieth Formation in the Yakutat area range from immature to overmature for oil and gas generation (Pawlewicz, 1990a, 1990b; Risley and others, 1992), but oil and gas shows were poor to moderate, and no zones were found to contain producible hydrocarbons.

Reservoir rocks. Potential conventional reservoir rocks in the Gulf of Alaska basin are restricted to the Yakutat terrane; other terranes in the region are made up of highly altered or metamorphosed formations with negligible porosity and permeability. Reservoir candidates in the Yakutat terrane include wave-reworked sandstones of the upper Cenozoic Yakataga Formation, local sandstones in the upper part of the mid-Cenozoic Poul Creek Formation, and nonmarine to deltaic sandstones of the lower Cenozoic Kulthieth and Tokun Formations (Risley and others, 1992; Larson and Martin, 1998). Reservoir quality in each of these formations varies considerably. The Yakataga Formation consists mainly of poorly sorted glaciomarine beds with unstable mineralogy, but is known to maintain local zones of good porosity and permeability at depths exceeding 11,000 feet in offshore wells (Larson and Martin, 1998). The Kulthieth Formation in the Southeast Energy Region contains abundant sandstone beds with adequate thickness and fair to good porosity. However, permeability is limited due to compaction and alteration of the sands upon burial. Kulthieth Formation reservoir properties generally improve northeastward and toward the top of the unit (Risley and others, 1992). The Poul Creek Formation is dominantly composed of fine-grained rock types, but does contain locally significant thicknesses of glauconitic sandstone. The formation was not considered in Risley and others' (1992) analysis of potential reservoir units, despite the fact that the Katalla oil seeps originate from shallow, fractured mudstone of the Poul Creek Formation. Both the Kulthieth and Poul Creek Formations contain organic-rich source rocks, increasing the likelihood that any potential reservoir sandstones are in direct contact with and may have received hydrocarbon charge.

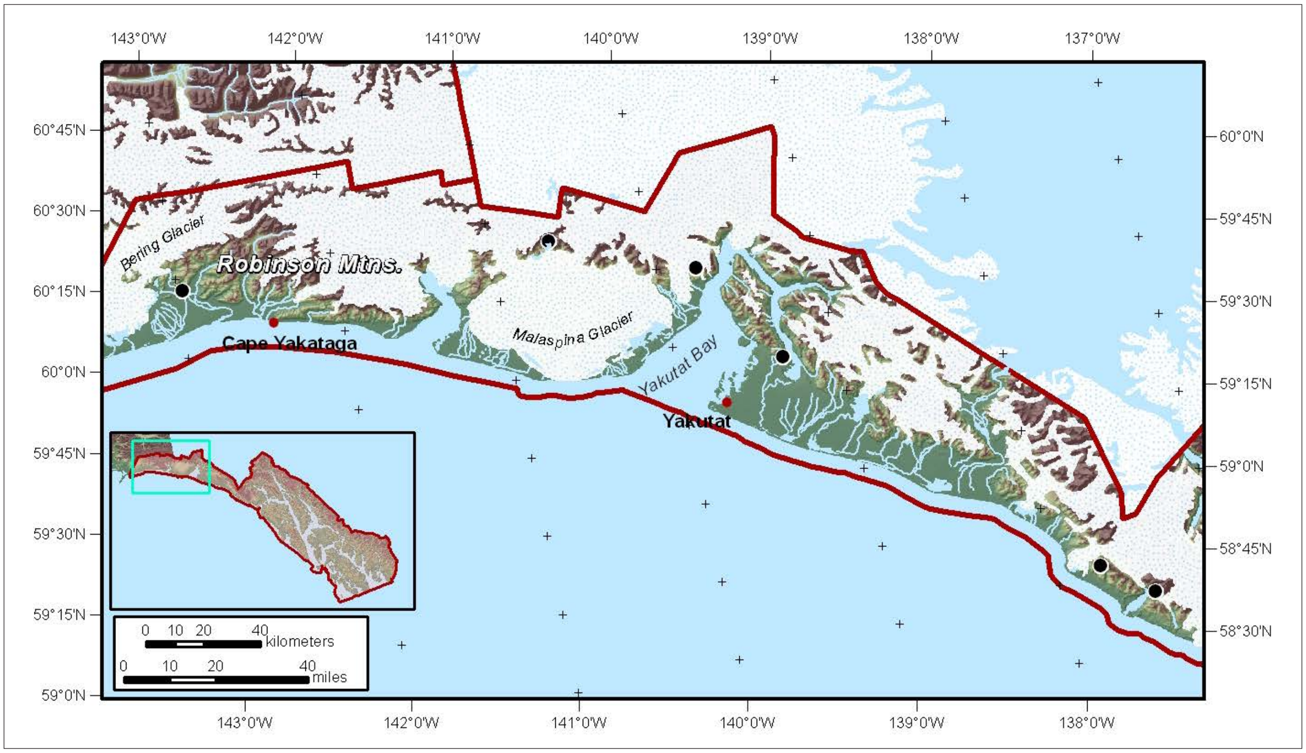


Figure K5. Location map of the northwestern part of the Southeast Energy Region, showing locations of reported coal occurrences (black dots).

Southeast

Traps. The northern Gulf of Alaska basin has been affected by faulting and folding accompanying compressional and strike-slip tectonics, creating numerous fold and fault structures that have the potential to trap hydrocarbons. Although several of these structures were unsuccessfully tested by exploration wells, many promising and large structures remain undrilled (Risley and others, 1992). Additional traps may be stratigraphic in nature, established by lateral variations in thickness, grain size, permeability, and other sedimentary characteristics inherent in geologically complex settings.

Summary of conventional oil and gas resource potential. Major seeps of both oil and gas are present on the northern margin of the Yakutat terrane, indicating that the northern Gulf of Alaska basin does contain a viable petroleum system. Despite the lack of any commercial discoveries to date, potential remains for future production of conventional hydrocarbons. Many large structural and stratigraphic traps have not been drilled and the province is underexplored relative to comparable basins in North America. The most recent available estimates of technically recoverable resources from the Gulf of Alaska region report a mean resource of 630 million barrels of oil and 4.65 trillion cubic feet of natural gas (Minerals Management Service [MMS], 2006). These numbers reflect undiscovered, hypothetical resources that have not been identified by drilling, and the actual amount that could be discovered and produced may be significantly smaller when filtered against the high costs of offshore development. Nevertheless, the large estimates reflect the overall promising nature of the region for future hydrocarbon exploration.

Unconventional oil and gas resource potential

Coalbed methane. As noted above, coal resources in southeastern Alaska are areally limited, discontinuous, and typically of low grade (Roehm, 1943). Coals in the Kootznahoo Formation rarely exceed 2 feet in thickness, and typically are less than 16 inches thick and of lignite grade. Other coals in the area are also of lignite grade and typically less than 2 feet in thickness. The low quality of these coals combined with their limited thickness and limited areal footprint renders them ineffective as potential sources of coalbed methane.

Tight gas sands. The Eocene Kulthieth Formation in southeastern Alaska may locally have potential as a tight gas sand. It consists of relatively thick nonmarine to deltaic sandstones with variable reservoir quality. While much of the unit has fair to good porosity, zeolite cements (particularly laumontite), have locally degraded reservoir quality to the extent that sands have permeabilities less than 0.01 millidarcy. Potential source rocks in the lower part of the Kulthieth Formation consist of gas-prone shallow marine deltaic to basinal marine sediments (Plafker and others, 1994) that could act as an intra-formational source. Local fractures have been observed in thin sections of the Kulthieth Formation (ARCO White Lake #1) and may signal the existence of a more regionally extensive fracture system necessary for an effective unconventional, fractured reservoir. The ARCO OCS Y-0211 (Yakutat No. 1) well encountered significant oil and gas shows in the Kulthieth sandstones.

Shale gas. One of the primary requirements for shale gas is an organic-rich source rock present in the thermogenic gas window that is sufficiently brittle to host a natural fracture system (see Chapter A). Shales of the Poul Creek and Kulthieth Formations are potential source rocks for both oil and gas, with most of the observed seeps in the region believed to be inter-formational. The highest stages of thermal maturity for these source rocks approach marginally mature to mature for generation of oil and gas. Thermal maturity levels in the Kulthieth Formation in southeastern Alaska area range from immature to overmature for oil and gas generation. It is therefore unlikely that a significant volume of brittle source rocks are present within the thermogenic gas window.

Gas hydrates. The main occurrences of gas hydrates in nature are in modern marine sediments and in arctic regions with well developed, continuous permafrost. Permafrost is not well developed in the Southeast Energy Region and, where locally present, is discontinuous. Consequently the potential for economic concentrations of gas hydrates in the region is low.

Geothermal resource potential

Geothermal prospectivity in the Southeast Energy Region is second only to geothermal prospectivity in the Aleutians Energy Region. Three occurrences of thermal spring temperatures in excess of 165°F (74°C) have been measured at various locations in the Southeast Energy Region (sheet 2). By comparison, only two such occurrences have been measured in Alaska outside the Aleutians and Southeast energy regions (Motyka and others, 1983).

Bell Island has thermal springs situated 1,300 feet inland and 16 feet above high tide line with surface discharge temperatures ranging from 153°F to 165°F (67°C–74°C) (Motyka and Moorman, 1987). A direct-use application has previously been employed by utilizing five concrete basins to collect thermal water discharge at a rate of 22 gallons per minute to heat the main lodge and several cabins at the Bell Island fishing resort (Motyka and Moorman, 1987). Geothermometers predict an estimated reservoir temperature of 275°F (135°C), suggesting wells could be drilled to access higher temperature fluids to provide broader direct-use applications to the community of Bell Island (Motyka and others, 1983).

The Bailey Bay hot springs site, located 50 miles north of Ketchikan near Behm Canal, has the highest measured surface discharge temperature, at 196°F (91°C), in the Southeast Energy Region. The estimated reservoir temperature underlying these springs is 302°F (150°C) (Motyka and others, 1983). Ten principal springs and numerous seeps account for a combined total discharge of 66 gallons per minute issuing from granitic bedrock on a steep northwest-facing slope of Spring Creek valley and draining into Lake Shelokum (Motyka and Moorman, 1987). High spring discharge rates and close proximity to the fishing community of Bell Island could make a direct-use application at Bailey Bay hot springs a viable project.

Tenakee Inlet thermal spring, located north of Tenakee Village on Chichagof Island, has a measured surface temperature of 176°F (80°C). Tenakee Village has 18 springs situated along its shoreline with temperatures ranging from 86°F to 106°F (30°C–41°C). Geothermometry at Tenakee Village yields reservoir temperature estimates of 149°F–212°F (65°C–100°C). The springs appear to originate as meteoric waters that circulate along deep fractures associated with nearby fault zones (Motyka and others, 1983; Motyka and Moorman, 1987). To investigate direct-use applications, six shallow test wells were drilled at Tenakee to depths ranging from 23 to 177 feet. The deepest well produced 98°F (37°C) water at a rate of nearly 1.5 gallon per minute (Motyka and others, 1983). Water temperature and flow rate were deemed insufficient for district heating following the study; however, based on geothermometry, it remains likely that deeper wells would yield higher fluid temperature, making direct-use applications in Tenakee Village potentially viable.

When considered as a whole, the southeast archipelago contains a widespread number of geothermal springs (sheet 2), including three thermal springs with discharge temperatures greater than 165°F (74°C), ten thermal springs with discharge temperatures in the range of 100°F–165°F (38°C–74°C), and two thermal springs with surface discharge temperatures greater than 69°F (21°C). In addition, six shallow wells drilled in the Tenakee region yielded an average surface discharge temperature of 99°F (37°C) (Motyka and others, 1983).

RECOMMENDATIONS

Geothermal resource recommendations

There are numerous possibilities for direct-use applications in small villages across the southeast archipelago. There may also be sufficient geothermal resources for a low-temperature Organic Rankin Cycle (ORC) geothermal power plant similar to the one utilized to generate electrical power at Chena Hot Springs in the interior. Because success or failure at this level of development will provide needed insight on the viability of larger-scale projects, funding a direct-use pilot project or ORC project is recommended. It is recommended that the State facilitate a revised assessment aimed at expanding previously proven direct-use applications at Bell Island by drilling test wells into the geothermal reservoir. It is likewise recommended that the State consider supporting a deeper test well at Tenakee Village to reassess the viability of direct-use applications that were previously deemed not feasible.

Conventional oil and gas recommendations

Patterns of land ownership and the location of rural communities are important considerations in weighing the state's options for oil and gas energy development in the Southeast Energy Region. State-controlled lands in the Gulf of Alaska basin are limited to the Yakataga area between Cape Suckling and Icy Bay, and much of that is designated as game refuge. Most of the rest of the onshore Gulf of Alaska basin is federal national forest, national park, BLM, Native corporation, and private land. The only permanent community in the Southeast Energy Region in the Gulf of Alaska basin is Yakutat; all other communities are located at least 200–600 kilometers away in the archipelago region where petroleum systems cannot exist. Of the wells drilled near Yakutat, none appear to be capable of sustaining production, but there remains potential that future exploration in the vicinity might yield a different result, perhaps one or more discoveries capable of delivering local-use gas or oil supply. The Yakataga district, with its numerous seeps and subsurface oil and gas shows, probably has the region's best potential for conventional hydrocarbon production. However, the lack of a permanent local population there means that a viable transportation system, built to withstand a variety of potentially severe geologic hazards (Combellick, 1994), would be required to deliver producible hydrocarbon resources to consumers.

To summarize, the complex geology, prior exploration history, land status, and population distribution of the Southeast Energy Region suggest that undiscovered hydrocarbon resources are most likely to occur hundreds of kilometers remote from the communities in need of energy. Future exploration for these resources in this frontier province would mostly likely be undertaken by industry and aimed at major commercial discoveries, rather than local markets. Reliable estimates of the ultimate conventional oil and gas resource potential in the Gulf of Alaska are hampered by limited published geologic data. Exploration risk could be reduced through the acquisition of significant new geologic mapping and associated field data.

Coal resources

Due to the limited stratigraphic and areal extent of coals, previous statewide assessments classified Southeast Alaska as a region of low coal potential (Merritt, 1987). However, significant coal occurrences have been noted in Kootznahoo Inlet and Murder Cove. Although these may be suitable for local energy use, they are presently inaccessible for extraction due to their location in the Admiralty Island National Monument wilderness area. The coal beds reported from the Robinson Mountains are likely broadly equivalent to the Bering River coal field about 50 miles to the west. However, little data is available to assess the viability of these coals for local use. Further reconnaissance field work may be warranted to evaluate the local geology in this area and determine whether utilization of this potential resource should be considered further.

Unconventional oil and gas resource recommendations

Coalbed methane. Due to the limited stratigraphic and areal extent of coals in the region, the volume of available coal does not appear sufficient to produce commercial quantities of coalbed methane.

Tight gas sands. The possibility exists for encountering fractured tight gas sands in portions of the Cenozoic section in the region, although available data suggest the probability of recovering commercial quantities of gas is low. Exploration for this type of resource in a frontier province would most likely be led by industry, although the geologic uncertainties indicate significant risk would be present.

Shale gas. Shales of the Poul Creek and Kulthieth Formations have some potential as a resource play, particularly within the fold and thrust belt, where a significant natural fracture system may be present. This was confirmed by the limited production of oil from fractured Poul Creek strata in the Katalla area. Additional geologic information is needed to ultimately evaluate this play type, particularly data on the distribution of source rock quality and thermal maturity. However, development of unconventional resource plays typically requires closely spaced wells and artificial stimulation, both of which add significantly to exploration and development costs. Given the geologic uncertainties and the costs of exploring in this remote area, shale gas is unlikely to be a primary target for industry and will thus not contribute to local energy supplies in the near future.

Gas hydrates. Due to the lack of extensive, continuous permafrost in most of southeastern Alaska, the likelihood of finding gas hydrates in the region are very low; therefore no further action is recommended.

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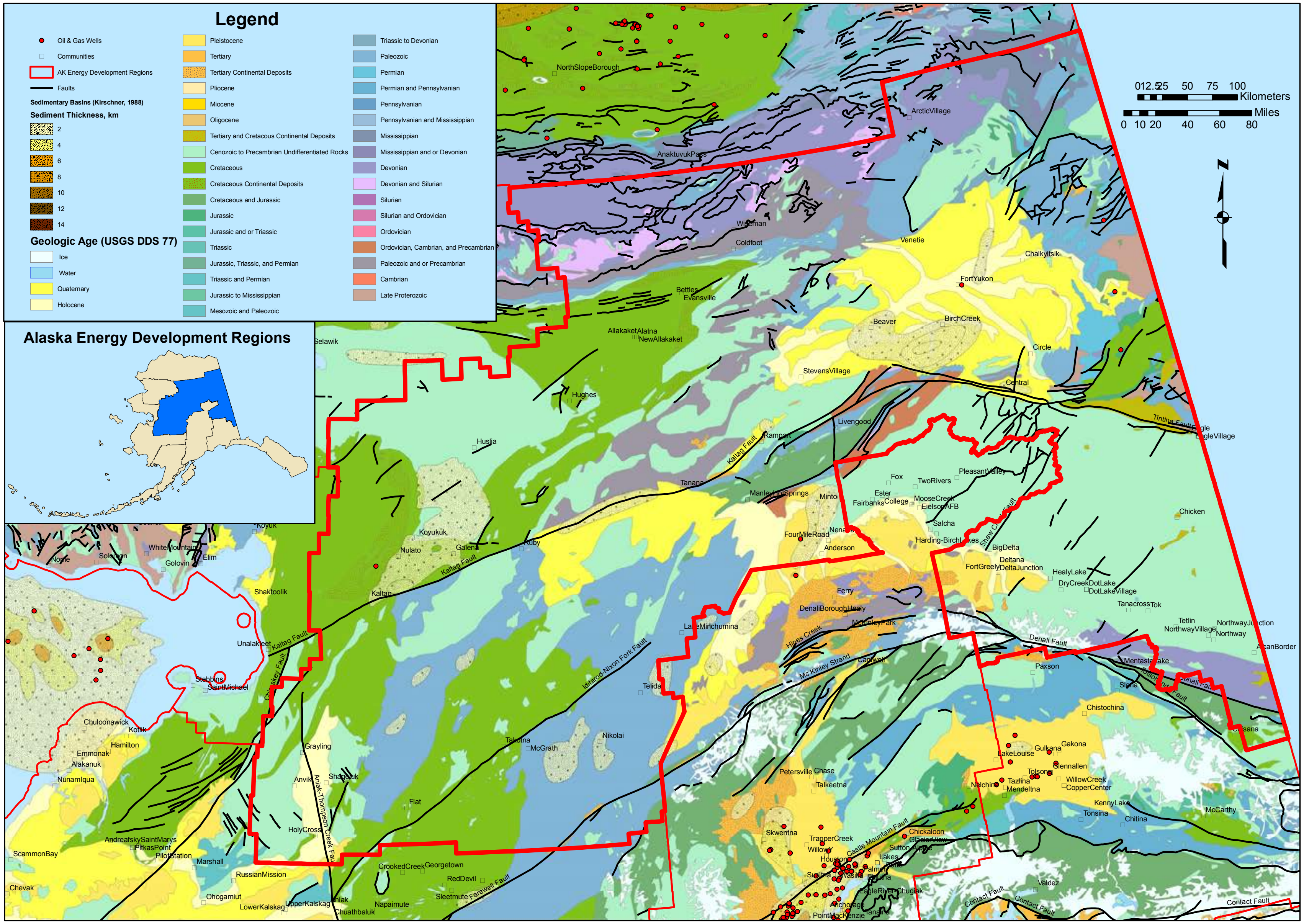
Geology of the Yukon-Koyukuk/Upper Tanana Energy Region, Alaska



Yukon–Koyukuk/Upper Tanana

SUMMARY OF FOSSIL FUEL AND GEOTHERMAL RESOURCE POTENTIAL IN THE YUKON–KOYUKUK/UPPER TANANA ENERGY REGION

by David L. LePain and Marwan A. Wartes

INTRODUCTION

Purpose of this report

Economic growth and stability in Alaska's rural areas hinges partially, if not primarily, on the availability of affordable and sustainable energy supplies. Recent price increases in oil and gas commodities have created severe economic hardship in many areas of the state that are dependent on diesel and heating oil as their primary source of energy. All sectors of Alaska's economy rely on affordable energy sources with limited price volatility, highlighting the need to diversify the energy portfolio by developing locally available and sustainable resources that are not tied to the global market. Unfortunately, all areas are not created equal in energy accessibility; the resources available for local exploitation vary widely across the state. It is critical that funding decisions for expensive programs to reduce the dependence on diesel for heat and electricity take into account information concerning the entire suite of natural resources that exist in a given area.

This report draws from existing information to provide community and state leaders an objective summary of our current knowledge concerning the potential of locally exploitable fossil fuel and geothermal energy resources in the Yukon–Koyukuk/Upper Tanana Energy Region (fig. L1), one of 11 regions recognized by the Alaska Energy Authority (AEA) in their Energy Plan (AEA, 2009). The potential geologically hosted energy resources considered here include exploitable coal, conventional and unconventional oil and gas, and geothermal resources. This report concludes with recommendations as to what additional data or strategies, if any, would provide the most leverage in helping to develop new energy resources in the region.

Readers without geological training are encouraged to peruse the geologic summaries of fossil fuel resources and geothermal energy in Chapter A. They provide an overview of the geologic elements that must be present in an area to economically develop coal, conventional oil and gas, unconventional oil and gas, and geothermal resources. These summaries will provide the necessary background to more fully understand the information presented in this chapter.

Geographic and geologic setting

The Yukon–Koyukuk/Upper Tanana region in interior Alaska encompasses approximately 170,000 square miles and extends roughly east–west from the Canada border in the east to the Nulato Hills in the west, between the Brooks and Alaska ranges to the north and south, respectively (fig. L1 and sheet 1). Road access is limited to a central corridor that connects the communities of Wiseman, Coldfoot, Livengood, Manley, Circle, Central, and Eagle to communities in the Railbelt to the south. The region's largest community is Tok, located on the road system, with a current population of 1,353. Other sizable communities situated on the road system

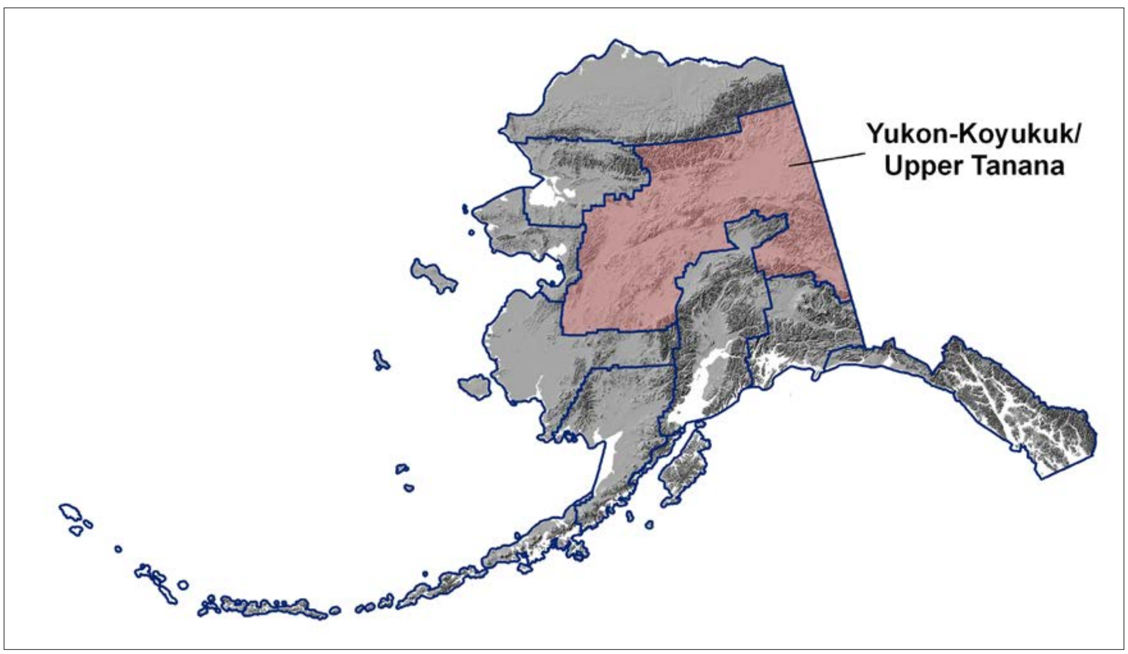


Figure L1. Location map of Yukon–Koyukuk/Upper Tanana Energy Region.

Yukon–Koyukuk/Upper Tanana

include Delta Junction and Big Delta, with populations of 975 and 790, respectively. The largest community off the road system is Galena, with a current population of 610. Other sizable communities that are off the road system include Fort Yukon, McGrath, Nulato, Tanana, Huslia, and Holy Cross, with populations ranging from nearly 600 to 200. The region is characterized by upland areas underlain by igneous and metamorphic rocks, including the Hogatza plutonic belt, Kaiyuh Mountains, Kokrines–Hodzana Highlands, south flank of the Brooks Range, and the Yukon–Tanana Upland (Kirschner, 1988; Dover, 1994; Foster and others, 1994; Patton and others, 1994). Intervening areas mostly encompass broad flats, plateaus, and rolling, hilly terrain underlain by Mesozoic and younger Cenozoic sedimentary rocks deposited in a series of sedimentary basins. Mesozoic basins include the Yukon–Koyukuk and Kuskokwim, which are both filled with many thousands of feet of texturally and mineralogically immature sedimentary rocks deposited in deep marine through coastal plain settings (Kirschner, 1994; Patton and others, 1994). Sediment supplied to these basins was derived from ancient subduction zones and related volcanic arcs. The original shape and distribution of these basins was subsequently modified by strike-slip motion along a series of crustal-scale breaks, including the Tintina, Kaltag, Iditarod, and Denali–Farewell fault zones (sheet 2), and the basin-fills are highly deformed (folded and faulted).

Younger Cenozoic sedimentary basins formed along these fault zones in response to strike-slip fault motion, and include a few thousand to many thousands of feet of nonmarine sedimentary rocks (sheet 2). The largest and deepest of these include the Yukon Flats and Middle Tanana (also referred to as the Nenana basin) basins, which both include at least 10,000 feet of sedimentary rocks in their deepest parts, including lignitic and bituminous coal (note that only the northwestern and eastern parts of the Middle Tanana basin are within this AEA region). The Innoko and Minchumina basins are shallower and probably only include 3,000 to 4,000 feet of nonmarine sedimentary rocks in their deepest parts (Kirschner, 1994). The Tintina trench and Ruby–Rampart trough extend as arms outward from the Yukon Flats basin along the Tintina and Kaltag fault zones, respectively, and are each filled with several thousand feet of Cenozoic nonmarine sedimentary rocks.

The Kandik area north of the Tintina fault zone in east-central Alaska includes a highly deformed (folded and faulted) succession of Mesozoic-age deep-water strata similar to those filling the Yukon–Koyukuk and Kuskokwim basins to the west, and deformed older Mesozoic- and Paleozoic-age rocks similar to rocks in the Brooks Range and North Slope (Dover, 1994; Van Kooten and others, 1997? no 1996 in references). The latter rocks include the Glenn Shale, which is similar in age and composition to the Shublik Formation, a prolific oil and gas source rock on the North Slope. Mesozoic deep-water strata in this area were subjected to compressional deformation and include fold and fault structures analogous to a rumpled carpet that was torn along breaks parallel to the folds. In the deformation process, the older Mesozoic and Paleozoic rocks, including the Glenn Shale, were transported along low-angle compressional faults (thrust faults) over the younger Mesozoic deep-water sedimentary rocks. Younger strike-slip motion along the Tintina fault zone offset a segment of this fold and thrust belt to the Livengood area, north of Fairbanks (Dover, 1994).

Young Cenozoic and Holocene(?) volcanic rocks cover a small percentage of the region. These rocks are generally flat-lying, undeformed, and overlie older Cenozoic, Mesozoic, and Paleozoic rocks. Cretaceous- and early Cenozoic-age plutons are widespread throughout the region and occur in older Paleozoic-age metamorphic rocks in the upland areas and in Cretaceous sedimentary rocks of the Yukon–Koyukuk and Kuskokwim basins (Miller, 1994). These plutons were significant sources of heat in the past and some continue to supply heat to low-grade geothermal systems in the region.

The patchwork of metamorphic and igneous uplands, Paleozoic and early Mesozoic basin fragments, and Cretaceous and Cenozoic sedimentary basins described here are the result of a long history of colliding oceanic and continental fragments with an ever growing Alaska continental mass, and subsequent structural modification by crustal-scale strike-slip faults. This process continues to the present day with the ongoing collision between a fragment of crust in the Yakutat area and mainland Alaska.

GEOLOGIC ENERGY RESOURCE POTENTIAL IN THE YUKON–KOYUKUK/ UPPER TANANA ENERGY REGION

Mineable coal resource potential

As explained in the discussion of requirements for mineable coal (see Chapter A), several factors must be considered when evaluating whether a coal deposit is exploitable. The most important factors include coal rank, seam thickness, ash and sulfur content, thickness of overburden, and structural attitude of the coal (bedding dip angle). The higher the coal rank, the higher its energy content (Btus per pound) and the greater its ability to provide heat. Coal rank also influences the minimum seam thickness worth exploiting. For bituminous and anthracite coal, seam thickness should be at least 14 inches, whereas lignite seams should be at least 2.5 feet thick. These thickness minimums were developed for commercial-scale mining; thinner seams could be exploited for limited local use. For open-pit surface mining to be feasible, overburden should be less than 300 feet. Low ash and sulfur contents are highly desirable, as ash reduces the amount of combustible material in a seam and sulfur can form environmentally damaging compounds when burned. Depth to groundwater and proximity to surface water bodies must also be considered when evaluating the potential of a coal deposit.

This section summarizes information on coal occurrences to evaluate coal resources in the Yukon–Koyukuk/Upper Tanana Energy Region and whether these resources are potentially exploitable. The summary is organized from best known to least known coal occurrence.

Little Tonzona Field. Thick seams of Cenozoic-age coal are exposed on the west bank of the Little Tonzona River, near the northwestern corner of the Talkeetna C-3 Quadrangle (fig. L2). Considerable baseline data are available for these seams: Detailed descriptions are provided by Player (1976, unpublished consulting report), Sloan and others (1979), and LePain and others (2003), and laboratory data on coal quality are presented by Rao and others (1991). This exposure is located in the Railbelt Energy Region, less than 1 mile from its boundary with the Yukon–Koyukuk/Upper Tanana Energy Region, and field studies demonstrate that the coal-bearing section extends at least 2 miles into the latter energy region. The coal-bearing section is on Doyon Ltd. land holdings that cover the inferred limits of the Little Tonzona coal field (Rao and others, 1991). This coal field is part of a belt of Tertiary-age sedimentary rocks that are locally coal-bearing and extend at least from the Little Tonzona River southwest to the Cheeneetnuk River, southwest of White Mountain (Lime Hills Quadrangle; Sloan and others, 1979; Bundtzen and Kline, 1986; LePain and others, 2003). This belt is correlative with coal-bearing strata to the northeast near Suntrana and Jarvis creeks, close to the Parks and Richardson highways, respectively.

The Little Tonzona River exposure includes a coal-bearing section at least 279 feet thick, containing seven seams totaling 113 feet of clean coal, with a maximum seam thickness of 29 feet (Sloan and others, 1979). Coal seams dip steeply (47 and 63 degrees) toward the northwest and an unpublished report states that dip decreases northward into the Minchumina basin. Steep dips are the result of deformation associated with the Farewell fault zone, which is less than 0.25 mile south of the exposure. A mining company conducted a two-season exploration program in 1980 and 1981 under an agreement with Doyon Ltd. Drill-hole data combined with isolated outcrops of coal and clinker demonstrate that the coal-bearing section extends at least 3 miles along strike to the southwest of the Little Tonzona

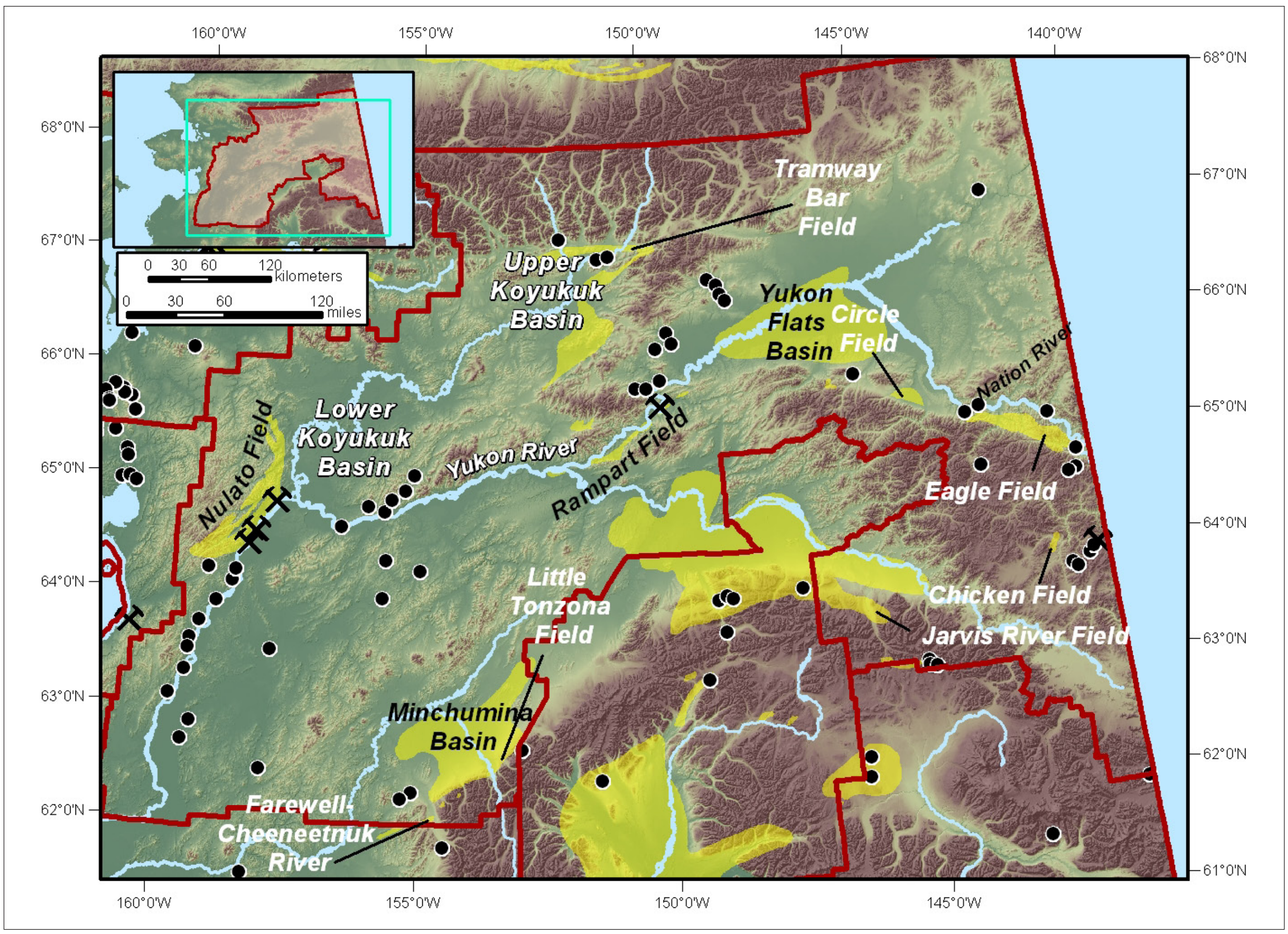


Figure L2. Regional location map of the Yukon–Koyukuk/Upper Tanana Energy Region. Black dots indicate reported coal occurrences; yellow shaded areas are inferred to be underlain by coal-bearing rocks.

River, to the headwaters of Deepbank and Knee Deep creeks in the McGrath Quadrangle (Player, 1976; Sloan and others, 1979; LePain and others, 2003; Rao and others, 1991).

Laboratory analysis of subsurface coal samples by Rao and others (1991) show that rank ranges from subbituminous-C to lignite. The ash content is low and the sulfur content is several times higher than other Alaska Tertiary coals, averaging 1.04 percent on an equilibrium moisture basis. Coal near Deepbank Creek is lower in sulfur (average sulfur content of 0.7 percent on an ash- and moisture-free basis) than coal at the Little Tonzona River (Sloan and others, 1979).

The Little Tonzona field includes an identified resource of 1.5 billion short tons of coal (Merritt, 1986). The steep dips observed in outcrop, low coal rank, and high sulfur content pose challenges to any plans for exploiting coal in this area and it is unknown how much coal could be extracted using surface mining methods. Despite the fact that the coal-bearing section extends at least 3 miles along strike to the southwest, the ultimate strike extent is unknown. Similarly, the northern extent of the coal-bearing section into the Minchumina basin is unknown. If the structural dip of beds decreases northward away from the Farewell fault zone, and if this dip decrease occurs over a short distance northward from the outcrop belt, an enormous volume of coal could be present at mineable depths. The only way to answer these questions is through additional drilling. The communities of Sleetmute and McGrath are located more than 140 miles to the southwest and more than 75 miles to the northwest, respectively, from the Little Tonzona location; Donlin Creek gold prospect is more than 120 miles west of the Little Tonzona exposure. Given the cost of transportation, the Little Tonzona deposit is unlikely to economically provide energy to rural communities in the region at this time.

Eastern Nenana Basin–Jarvis Creek Field. The extensive Cenozoic coal fields in the Healy area (see Chapter J) are known to extend eastward along the northern Alaska Range (Wahrhaftig and Hickcox, 1955). Three coal fields are recognized in this part of the basin: East Delta, West Delta, and Jarvis Creek, all of which are thought to correlate with the prolific Healy Creek Formation to the west (Merritt and Hawley, 1986). The Jarvis Creek Field (fig. L2) is the most promising occurrence due in part to its convenient location adjacent to the Richardson Highway. This area was an operating open pit mine during the 1960s and retains moderate to high potential for further development with measured reserves of more than 17 million short tons and hypothetical reserves of up to 500 million short tons (Clough, 1995). Additionally, considerable baseline geologic data exists for this occurrence (Belowich, 1988). At least 30 coal beds are recognized ranging from 1 to 10 feet thick with a variety of subbituminous ranks and relatively low total ash content (Belowich, 1986). The proximity of this documented resource to some of the larger populations in the region (Delta, Delta Junction, and Fort Greely) suggest further consideration of these coals as a source of local energy is warranted. Exploratory drilling would be a logical next step in evaluating and constraining existing resource estimates.

Farewell–Cheeneetnuk River. Cenozoic-age coal-bearing sedimentary rocks are discontinuously exposed between the Windy Fork and Middle Fork of the Kuskokwim River, southwest of Farewell (Sloan and others, 1979; Gilbert and others, 1982; Solie and Dickey, 1982; Bundtzen and others, 1997), and along the Cheeneetnuk River, southwest of White Mountain (fig. L2; Barnes, 1967; Gilbert, 1981). This area is at the southwest end of an outcrop belt of Cenozoic-age sedimentary rocks that are locally coal-bearing that includes the Little Tonzona River deposit already described. Detailed geologic mapping of coal-bearing rocks between the Windy and Middle Forks and along the Cheeneetnuk River are provided by Dickey (1982) and Gilbert (1981), respectively.

More than 5,000 feet of Tertiary-age sedimentary rocks are discontinuously exposed in high-angle fault-bounded slivers along the Farewell fault zone, between the Windy and Middle Forks of the Kuskokwim River (Dickey, 1982). Sedimentary rocks in these slivers typically include thick conglomerate and sandstone bodies (20–65 feet thick) that are separated by thicker, poorly exposed mudstone deposits (LePain and others, 2003). These mudstones are locally highly carbonaceous (carrying abundant coaly plant fragments) and include minor coal. Coals range from thin stringers tenths of an inch thick to thin seams a few inches thick. Some fault slivers include several hundred feet of clay shale, abundant siltstone, carbonaceous mudstone, and thin coal seams between sandstone and conglomerate bodies (LePain and others, 2003). Coals in these sections range from thin stringers to seams more than 1.5 feet thick, range from subbituminous-A to high-volatile C bituminous in rank, have low sulfur contents, and most have high ash contents (Solie and Dickey, 1982). The similarity between the exposures on Windy and Middle Forks suggests they are the same stratigraphic succession, but the succession exposed on the Khuchaynik River between these two drainages is quite different and does not include appreciable coal. Numerous high-angle faults mapped by Dickey (1982) between these drainages suggest the coal-bearing section has been cut out by motion along the Farewell fault zone. Bundtzen and Kline (1986) estimate 4.4 million U.S. short tons of coal are present in this area, but this volume is unproven. Given the paucity of thick, low-ash coal seams and the structural complexity, estimating the volume of coal accessible through surface mining methods is difficult. More detailed surface geologic mapping combined with stratigraphic studies of the coal-bearing section are needed and, ultimately, a program of drilling will be required to properly estimate mineable volumes with a reasonable level of confidence and to evaluate the feasibility of applying surface mining methods. The absence of nearby communities may make this work difficult to justify (Sleetmute is more than 80 miles to the southwest and McGrath is over 55 miles to the northwest).

Discontinuous exposures of coal-bearing rocks have been reported along a several-mile-long stretch of the Cheeneetnuk River, including one exposure with a 6-foot-thick seam of bright, brittle coal that appeared to be of bituminous rank (Barnes, 1967, p. B21). Gilbert (1981) mapped these exposures (McGrath A-5 and Lime Hills D-7 quadrangles), and noted that friable coal beds 1.6 feet to 16.5 feet thick occur in three places. Solie and Dickey (1982) present coal-quality data for samples collected by Gilbert from two of these locations (see their figure 5), including a 13- to 20-inch-thick bed and a bed of unknown thickness. They reported bed dips of up to 75 degrees, that coal rank ranged from subbituminous-B to high-volatile C bituminous, ash content is low to moderate, and sulfur content is high to very high (1.95 to 8.19 total sulfur on a moisture and ash free basis). The high sulfur content might reflect incorporation of interbedded iron-rich mudstone in the coal samples. LePain and others (2003) visited this area in 2000 and found low, overgrown exposures of mudstone along the north bank of the river, including coal float (small fragments), but were unable to locate exposures of coal. Available information suggests that coal seams in this area are of limited lateral extent and thickness. Additional detailed geologic mapping and targeted shallow exploration (trenching and/or shallow drilling) would provide more detailed information, but the absence of nearby communities makes additional work hard to justify (Sleetmute is over 50 miles to the southwest and McGrath more than 60 miles to the north).

Rampart Field. Collier (1903a, 1903b) provided the first relatively detailed description of coal deposits in the Rampart area. Occurrences of Cenozoic-age coal extend from the west bank of the Yukon River (Drew Mine), across from the mouth of Hess Creek, upstream from the village of Rampart, nearly to the village of Tanana, located downstream from Rampart (figs. L2 and L3). None of these occurrences included coal of sufficient thickness and quality at the surface to have warranted development. Coal in this area occupies a narrow, fault-bounded basin along the Kaltag fault zone, southwest of the Yukon Flats basin (sheet 2).

Coal at the Drew Mine location warrants further discussion. Drew Mine is on the west bank of the Yukon River, several miles upstream from the village of Rampart, and is bounded by water on three sides in a prominent river bend (fig. L3). The description that follows is taken from Collier (1903a, 1903b) and Barnes (1967). The mine was opened in a 19-foot-thick coaly section that included a total of only 3 feet of coal distributed in two benches. Approximately 1,000 tons of coal was mined prior to 1902 for use in river steamers. Coal at this location is bituminous and ash content is relatively high (18 percent; Barnes, 1967). The section in this area is reported to include six other coal beds that all dip steeply toward the southeast. The two benches exploited by the mine are thought to comprise the sixth seam up from the bottom of a coal-bearing section less than 1,000 feet thick. A test pit dug below the mined seam encountered the next seam down-section and exposed 4 to 7 feet of crushed coal. The strike extent of these seams is probably limited to a 4-square-mile area bounded by the bend in the Yukon River. The information presented here suggests that coal deposits

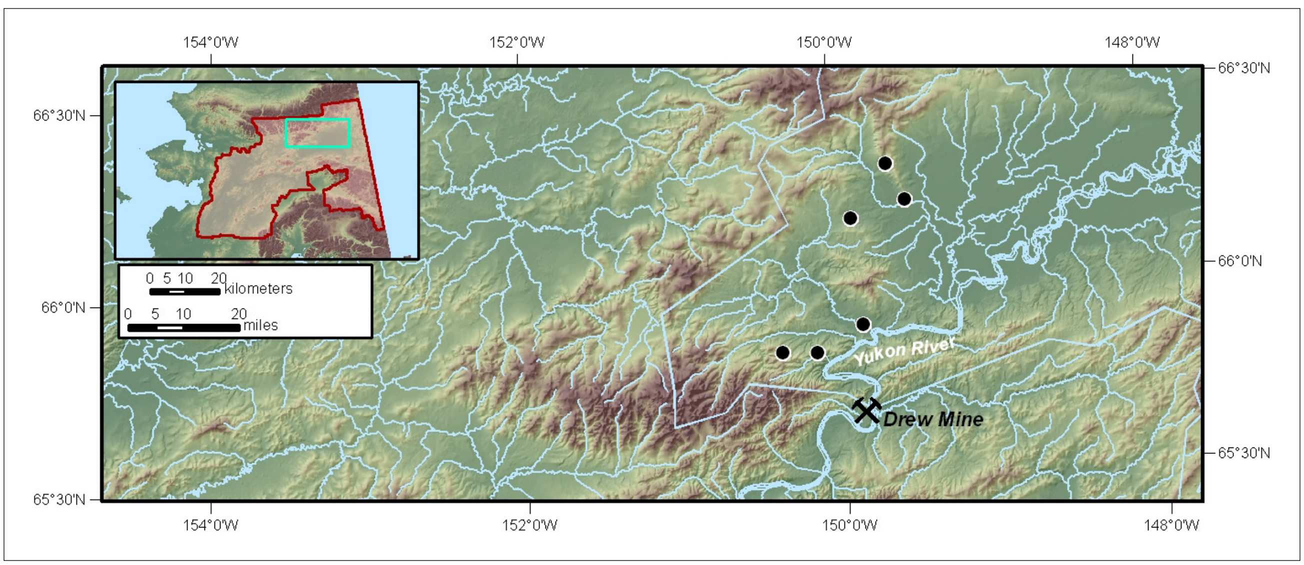


Figure L3. Map of the north-central part of the Yukon–Koyukuk/Upper Tanana Energy Region, showing reported coal occurrences (black dots) and the location of historic coal mining (pick-axe symbol).

at Drew Mine are marginal in volume and quality. However, detailed geologic mapping in the vicinity of the old mine might be warranted. Based on the outcome of this mapping, a decision could be made on whether or not to pursue drilling to further delineate the coal deposits in the area.

Scattered occurrences of coal are known along the south bank of the Yukon River, extending a mile or two above and below the village of Rampart (Collier, 1903a). Coal at these locations is thin and of poor quality. An occurrence of lignite at a location known as the Palisades, downstream from the village of Tanana, appears to be a Pleistocene-age peat based on associated fossil-bearing strata. None of these occurrences warrant additional study owing to poor coal quality and limited seam thickness and lateral extent.

Lower Koyukuk basin: Nulato–Galena–Ruby Region. Collier (1903b), Chapman (1963), and Barnes (1967) describe numerous coal occurrences along the west bank of the Yukon River between Nulato and Ruby (sheet 1; figs. L2 and L4). These coals are Cretaceous in age and part of the sedimentary fill of the Yukon–Koyukuk basin (Patton and others, 1994) that Merritt and Hawley (1986) call the Yukon–Koyukuk coal province. Merritt and Hawley (1986) further subdivide this province into the Lower Koyukuk basin, the Upper Koyukuk basin (fig. L2), and the Tertiary-age Yukon basin. Most coals in the upper and lower Koyukuk basin are bituminous in rank, are steeply dipping, and less than 3 feet thick. Thicker seams have been reported in the region, but are very poorly described and more recent field studies in the 1980s and 1990s have not found any of the earlier reported thick seams of coal.

Coal was mined in limited quantities in the late 19th and early 20th century at a number of localities along the west bank of the Yukon for use at telegraph stations and in river steamers, especially in the Nulato Field. Plangraphics (1983) summarizes several localities near Nulato that served the early steamships (fig. L4). The Blatchford Mine, about 9 miles below Nulato, was worked in the early 1900s and perhaps about 300 tons of coal was mined. The Bush Mine is about 4 miles downriver from Nulato where a 40 foot tunnel was present in 1903 but the degree of mining at that site is unknown (Collier, 1903a or b?). The Pickart Mine, situated about 10 miles upstream from Nulato, is one of the oldest mines in Alaska, originally mined by the Pickart brothers in 1898. The mine has a 600 foot drift tunnel excavated at the river bank. Chapman (1963) could find no evidence of the mine by 1944. None of these locations suggest the existence of coal of sufficient quality and thickness to warrant further development.

Coal-bearing rocks are mapped along the banks of the Yukon River at Hartnet Island, approximately 12 miles east of Galena (Cass, 1959). Here, there are exposed a 1-foot-thick coal bed and a 9-foot-thick coal bed that have an apparent rank of Subbituminous A. Stephenson and others (2002) indicate that the 9 foot coal seam dips steeply about 70° to the southeast, away from the city of Galena. A shallow seismic reflection/refraction reconnaissance investigation at the city of Galena suggests that potential coal-bearing bedrock is at least as deep as 550 feet in the immediate vicinity of town and this bedrock could be deeper than 1,000 feet under alternate interpretations (Stephenson and others, 2002).

Many 1:250,000-scale geologic maps covering various quadrangles north and south of the Yukon River show Cretaceous-age nonmarine strata that include some thin coal beds (Bickel and Patton, 1957; Chapman and others, 1982; Patton and others, 1980; Patton and others, 1966). The geology of the region is complex and details regarding the

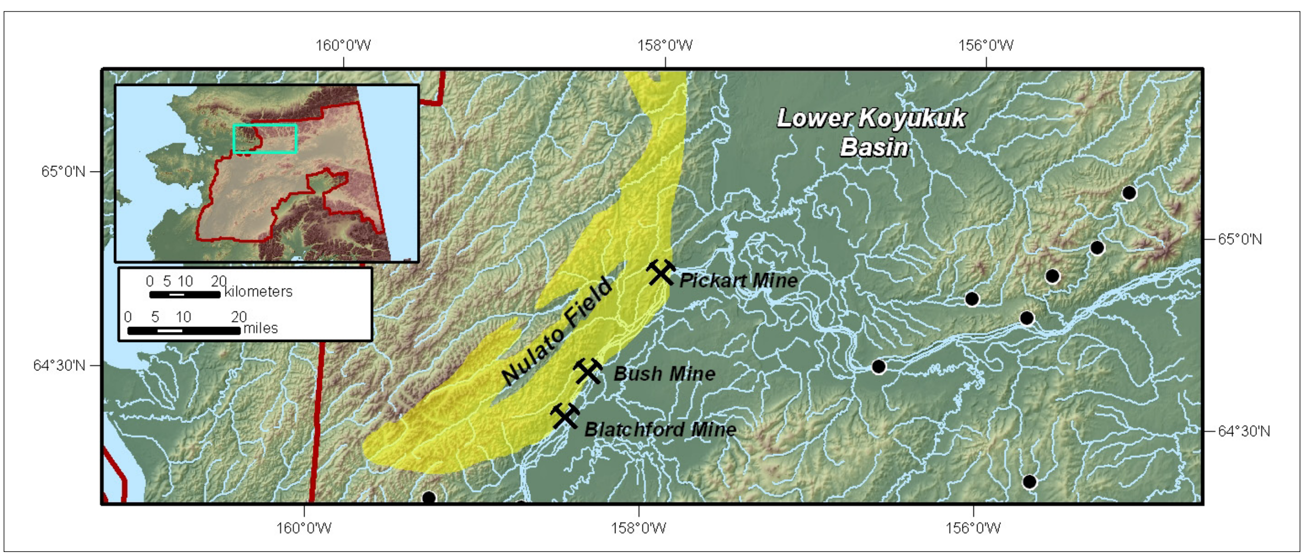


Figure L4. Map of the northwestern part of the Yukon–Koyukuk/Upper Tanana Energy Region (lower Koyukuk basin). Black dots indicate reported coal occurrences; pick-axe symbols show locations of historic coal mines.

stratigraphy of the coal-bearing sedimentary rocks are very poorly known. Before any conclusions regarding exploitation can be made, detailed geologic mapping must be carried out in selected areas where coal has been reported.

Upper Koyukuk basin: Tramway Bar Field. An exposure of steeply dipping Cretaceous-age coal approximately 5 miles upstream of Tramway Bar on the Middle Fork of the Koyukuk River (fig. L2) stands out in sharp contrast to the thin coal occurrences of Cretaceous age in the western part of the Yukon–Koyukuk basin, and represents the easternmost known coal occurrence in the basin. F.C. Schrader found this exposure in 1899 (Schrader, 1904); it was subsequently described in various levels of detail by Collier (1903b), Smith and Mertie (1930), Barnes (1967), Rao and Wolff (1980) – not in references, and Kurtak and others (2002). The information summarized here is taken from Rao and Wolff (1980) and Kurtak and others (2002). The location includes three seams, one 8 inches thick, a second 3 feet thick, and a third seam 17 feet thick. Beds dip 56 degrees toward the southeast. Coal rank is high-volatile B bituminous, ash content is high (35 percent), but sulfur content is very low. The coal was reportedly used by early miners in the district for blacksmithing purposes (Kurtak and others, 2002). Rao and Wolff (1980) noted that silt bands in the coal add to the high ash content and that washing the coal could be effective in its reduction. The lateral extent of the deposit is poorly known, although Kurtak and others (2002) suggest an inferred coal resource of 18,000 short tons. Detailed geologic mapping and subsequent drilling would help establish the lateral extent of this deposit and could yield information on additional coal seams and its true resource potential.

Western Yukon Flats. The Yukon Flats basin (sheet 2) is likely underlain by extensive Late Cretaceous(?) and Cenozoic coal-bearing strata, although confirmation to date is limited to one well near Fort Yukon (Clark and others, 2009) and scattered surface exposures limited to the western basin margin. The most notable occurrences are in the Fort Hamlin Hills area, particularly along the Ray, Hodzana, and Dall River valleys and their tributaries (fig. L3; Mendenhall, 1902). Although most occurrences are rubble or float, one seam along Coal Creek is 18 feet thick and constrained as Eocene based on a K-Ar date (Barker, 1981). Although outcrops are limited, available analyses indicate coals are Cenozoic in age and range from high-grade lignite to subbituminous B and C with heating values between 9,000 and 12,000 Btu (Barker, 1981). Most samples are low sulfur and have modest levels of ash (6–10 percent), although a few samples yielded greater than 20 percent ash (Barker, 2006). Due to poor exposures, the distribution and structural relationship of these various coal seams is not well constrained. Nevertheless, most outcrops are gently dipping and the coal-bearing zones are inferred to be broken up into a series of grabens (Barker, 2006). Aspects of these occurrences appear promising for future exploration, however the lack of nearby villages makes this an unlikely future source of rural energy.

Eagle Field and Tintina Trench. A belt of Cenozoic and Cretaceous(?) coal-bearing sediments occur along the trace of the Tintina fault (sheet 2 and fig. L2). The nature of this sedimentary basin and its full extent and age are not well known, though it is likely controlled by motion along the Tintina Fault. The most notable occurrence is along Washington Creek, where seams up to 5.5 feet thick were mined for steamships on the Yukon River (Collier, 1903a, b). The coals reportedly range from lignite to subbituminous C, possess low sulfur, and have a heat content ranging from 6,100 to 9,100 Btu/lb (Merritt, 1986). Bedding orientations are sparse although 35°–45° dips appear common and indicate mining would likely require significant excavation or underground operations. The location of these coals is far removed from settlements and infrastructure; the village of Eagle is approximately 40 miles away.

Nation River area. An enigmatic coal occurs along the Nation River, just upstream from its confluence with the Yukon River (fig. L2). This coal, first reported by Collier (1903a), was briefly mined for local steamship use and appears to be confined to sheared pods up to 8 feet thick, likely in a fault zone (Merritt, 1988). Although most reports suggest the coal is probably Cretaceous or Cenozoic in age, the high sulfur content (~3 percent), bituminous grade, and high heat content (10,900–11,500 Btu/lb) may suggest the coal is actually Paleozoic. The limited lateral extent, steep dips, and remoteness of this occurrence make it an unlikely candidate for further exploitation.

Chicken Field. An isolated subbituminous coal bed occurs near the community of Chicken (fig. L2; Barnes, 1967). Although little is known about this occurrence, it is anomalously thick—at least 22 feet—and the top and bottom were not observed (Mertie, 1930). The location near a rural population is promising. However, the lack of surface exposures limits speculation on the extent of this resource. The vertical orientation of the bed is problematic and significantly reduces the amount of readily accessible resource.

Conventional oil and gas resource potential

As explained in the discussion of requirements for exploitable oil and gas resources (see Chapter A), functioning petroleum systems occur in thick sedimentary basins, and consist of three basic elements: Effective source rocks, reservoirs, and traps. Each of the elements must be in existence and connected at the time hydrocarbons are generated. This section considers each of these necessary elements of petroleum systems in turn to evaluate whether conventional oil and gas resources may exist as an exploitable resource in the Yukon–Koyukuk/Upper Tanana Energy Region. Large areas in the region are underlain by crystalline rocks that have no (or very little) petroleum potential due to a geologic history of intense deformation, heating, and recrystallization under igneous and/or metamorphic conditions. These areas include the Hogatza plutonic belt, Kaiyuh Mountains, Kokrines–Hodzana Highlands, south flank of the Brooks Range, and the Yukon–Tanana Upland.

Distribution of sedimentary basins. The distribution of sedimentary basins that could potentially host petroleum systems in the Yukon–Koyukuk/Upper Tanana Energy Region are shown in sheet 2. The Yukon–Koyukuk and Kuskokwim basins cover a large portion of the region, developed in Mesozoic time, and are filled with deep marine through nonmarine strata. The Kandik area includes part of a Mesozoic-age basin filled with deep marine strata similar to the Yukon–Koyukuk and Kuskokwim basins, and part of an older Paleozoic–early Mesozoic basin that was possibly once continuous with rocks now exposed in the foothills north of the Brooks Range. The Yukon Flats, Middle Tanana, Innoko, and Minchumina basins formed during Cenozoic time and are filled with nonmarine sedimentary rocks. The Rampart and Tintina troughs are narrow basins filled with Cenozoic-age nonmarine sedimentary rocks that developed along the Kaltag and Tintina fault zones, respectively. The greatest potential for exploration and development of conventional hydrocarbon resources in the region is in the Yukon Flats and Middle Tanana basins in the south-central and eastern parts of the region.

Source rocks. The Kandik basin possesses the best source rock in the region, namely the Triassic–Jurassic Glenn Shale that locally exceeds 10 percent total organic carbon (Howell, 1996). Additional organic-rich black shales are recognized in older units of the Kandik region, suggesting that the hydrocarbon potential of this region is not limited by source rock. This notion is further supported by numerous occurrences of remnant biodegraded oil in the form of solid hydrocarbon (Van Kooten and others, 1997). The extents of these potential source rocks are not well constrained due to limited seismic data and only three well penetrations. However, based on regional magnetic and gravity data, it appears these rocks do not underlie the Yukon Flats basin. Additionally, the potential source rocks are locally overmature (too deeply buried), further limiting the extent of viable source rocks (Underwood and others, 1989). Along the periphery of the Yukon Flats, occurrences of tasmanite have been reported in association with the Tozitna terrane (Tailleur and others, 1967). Although this unusual rock type is extremely organic rich, its distribution appears to be limited in outcrop. Nevertheless, regional gravity and magnetic data support the hypothesis that rocks of the Tozitna terrane underlie parts of the Yukon Flats basin (Saltus and others, 2007).

Outcrop studies have documented that Cretaceous-age sedimentary rocks in the Yukon–Koyukuk and Kuskokwim basins generally contain organic carbon in amounts less than what is normally considered a good petroleum source rock, and the organic material that is present is typically gas-prone (Lyle and others, 1982). The Nulato Unit No. 1 well, in the western part of the Yukon–Koyukuk basin (fig. L1), penetrated 12,000 feet of deformed and tightly cemented Cretaceous-age sandstone, siltstone, and shale. No information is available on the organic content of shales encountered in this well, but the drilling reports (available from the Alaska Oil & Gas Conservation Commission) suggest the siltstones and shales have poor petroleum source potential. The Napatuk Creek No. 1 well, approximately 30 miles west of Bethel and outside of this region, penetrated at most a few thousand feet of Cenozoic-age rock and nearly 13,000 feet of interbedded sandstone, siltstone, and shale of Cretaceous age. The entire section penetrated by this well contains little organic material, and what little organic material that was encountered is gas-prone (Mull and others, 1995).

Outcrop studies combined with limited subsurface data from exploration wells and shallow coreholes suggest that coal and carbonaceous mudstones are common in Cenozoic-age rocks of the Yukon Flats, Middle Tanana, and Minchumina basins. Laboratory analysis of these lithologies from outcrop samples collected near Healy (Middle Tanana basin) and south of McGrath demonstrate their potential as source rocks for gas and also show some potential to generate liquid hydrocarbons (condensate; Stanley, 1988; Stanley and others, 1990; LePain and others, 2003). Of these basins, only the Middle Tanana and Yukon Flats are deep enough to have the potential to generate petroleum through thermal alteration of organic material (Stanley and others, 1990). The Minchumina basin is large, but probably too shallow to generate conventional petroleum from organic material that might be present in the basin fill (Kirschner, 1994). The stratigraphy of the Cenozoic-age Galena and Innoko basins is unknown, but they are probably too shallow to generate petroleum through thermal alteration of organic material; gravity data suggest deeper parts of these basins exist, but they underlie very small areas and are probably not capable of generating appreciable volumes of petroleum.

Reservoir rocks. Most Cretaceous sandstones in the area are tightly cemented and have porosity and permeability below thresholds necessary for conventional oil and gas production (Lyle and others, 1982; Mull and others, 1995). Some Cretaceous sandstones are so altered that porosity and permeability are likely entirely absent (Hoare and others, 1964). Cenozoic-age rocks include sandstones of sufficient thickness to serve as potential reservoirs (Stanley and others, 1992; LePain and others, 2003). In outcrop these sandstones range from poorly cemented (likely to have high porosity and permeability) to tightly cemented (likely to have low porosity and permeability). Laboratory measurements have been obtained for a limited suite of outcrop and drill core samples from the perimeter of Yukon Flats basin that show rocks in that area have poor to fair porosity and permeability

(Reifenstuhl, 2006). These measurements were obtained from sandstones that have been subjected to deformation along major fault zones and it is unclear whether they are representative of porosity and permeability values in the subsurface. Similar-appearing tightly cemented sandstones are present in outcrop in fault slivers along the Farewell fault zone south of McGrath, yet a short distance farther southwest near White Mountain, along the same fault zone, sandstones are poorly cemented and appear to have significant porosity and permeability. These variations in degree of cementation suggest porous and permeable sandstones are probably present in the subsurface of the Yukon Flats and Middle Tanana basins. Little is known about the reservoir quality of Paleozoic carbonates in the Kandik region, although the occurrence of bitumen in some outcrops and reports of vug and fracture porosity in Canadian equivalents to the east (Hannigan and others, 2000) suggest further analysis may be warranted. The reservoir quality of Mesozoic-age sandstones in the region are poorly known, but they are probably comparable to similar age sandstones in the Yukon–Koyukuk basin, where they are typically tightly cemented and characterized by low porosities and permeabilities.

Traps. The Yukon–Koyukuk/Upper Tanana Energy Region has undergone several episodes of deformation related to various collisional processes (Dover, 1994; Foster and others, 1994; Patton and others, 1994). Complex folds and faults recognized in sedimentary rocks of the Yukon–Koyukuk, Kuskokwim, and younger Cenozoic basins suggest that structural traps for oil and gas are present in the subsurface of these basins. Stratigraphic traps associated with pinchouts of coarse-grained sandstones within shaley and silty horizons are also most likely present. Traps formed by erosional truncation of sandstones beneath major erosion surfaces (unconformities) can also be expected. Low permeability shales and siltstones are common in Cretaceous and Tertiary successions in the region and are probably capable of sealing hydrocarbons accumulated in traps. The complex structural history of these basins decreases the likelihood of large, unbreached traps. Similarly, in the Kandik Basin (northeastern part of the region), the compound structural evolution involving contraction, extension, and strike-slip faulting (Van Kooten and others, 1997) decreases the probability of large, unbreached traps.

Summary of conventional oil and gas potential. Patton (1970) concluded the Cretaceous-age section filling the Yukon–Koyukuk basin in the western and central parts of the region was low. A review of similar rock to the south by Mull and others (1995) reached a similar conclusion based on the tightly cemented potential reservoirs, complex deformation, and poor source-rock characteristics.

In contrast, of all the Cenozoic sedimentary basins in the region, the Yukon Flats and Middle Tanana basins have the best potential to host conventional hydrocarbons. These basins are filled with thick sections of sedimentary rocks, including coal and carbonaceous mudstone that, under the right geologic conditions, can be very good source rocks for gas. Stanley and others (1990) suggest that these lithologies may also have potential to generate liquid hydrocarbons in the Middle Nenana basin. The U.S. Geological Survey recently evaluated the petroleum potential of the Yukon Flats basin and concluded, based on a thorough review of available data, that the basin probably has technically recoverable oil and gas resources (Stanley and others, 2004). The Middle Tanana basin includes geologic elements similar to those of the Yukon Flats basin, suggesting that it, too, may include technically recoverable oil and gas resources. The remaining Tertiary-age sedimentary basins in the region (Galena and Innoko) are probably too shallow to support functioning conventional petroleum systems. Although the Kandik region remains only lightly explored, its excellent source-rock characteristics suggest further potential exists for oil and gas prospects.

Unconventional oil and gas resource potential

Coalbed methane. As explained in the discussion of requirements for coalbed methane, shalebed gas, and gas hydrates (see Chapter A), several factors must be considered when evaluating whether a basin has unconventional oil and gas potential. Most importantly, suitable thicknesses of coal of the appropriate rank or source rocks capable of generating gas must be present in a sedimentary basin. These rocks must then have experienced a suitable geologic history in order to generate petroleum. For the same reasons outlined in the previous section, the unconventional oil and gas potential of Cretaceous-age rocks in the Yukon–Koyukuk and Kuskokwim basins is very low. The presence of a thick, coal-bearing section between the Little Tonzona River and Deepbank Creek in the western Talkeetna and eastern McGrath quadrangles suggests that the southern part of the Minchumina basin may have some coalbed methane potential. The rank of coal in this area may be too low (some subbituminous coal, but mostly lignitic) and it is unclear if suitable cleats (fractures) have developed in the coal seams. Exploring for these resources will be very expensive and involve significant risk of failure. The likely presence of thick coal- and carbonaceous-mudstone-bearing sections in the Yukon Flats and Middle Tanana basins indicates that these basins possess some potential for coalbed methane. Tyler and others (2000) arrived at a similar conclusion after examining the coalbed methane potential of coal-bearing strata throughout the state.

In the Yukon Flats basin, a multi-agency study of the coalbed methane potential included a local seismic survey (Miller and others, 2002) and a single shallow test well near the village of Fort Yukon (Clark and others, 2009). The well successfully documented the presence of Cenozoic coals as well as methane, although the gas saturation level was low. In addition, the lignite-grade host rock would not have well-developed natural cleating, giving rise to a need for substantial mechanical stimulation and dense well spacing to recover this gas for local needs. The Yukon Flats basin is believed to be up to 8 kilometers thick (Phillips and Saltus, 2005); it remains possible that a deeper well may encounter more thermally mature methane-bearing coals. Most of the thick coals in the Middle Tanana basin are subbituminous, leading to moderate coalbed methane potential, especially in the deeper parts of the basin. The long history of coal mining and intermittent outcrops along the southern margin of the basin provide modest constraints on the geology of the region (Wahrhaftig and others, 1994). Although the results are not yet available, a recent exploration well, only the third in the basin, should shed light on the subsurface stratigraphy and provide new insight on the potential of this basin for unconvential coalbed methane production. The thick mantle of poorly consolidated Nenana Gravel deposits would complicate drilling efforts and is at least partly responsible for the lack of exploration to date (Peapples, 2004). If an adequate resource is documented in the Middle Tanana basin, it may prove a viable source of energy to several population centers in the eastern part of the basin such as Big Delta, Delta Junction, and Fort Greely. The relative proximity to transportation infrastructure (rail and highways) may also benefit future exploration and/or development.

Tight gas sands. Tightly cemented Cretaceous-age sandstones in the Yukon–Koyukuk basin could serve as reservoirs for gas under the right geologic conditions (see Chapter A). The apparent absence of potential source rocks throughout the region suggests that the potential for tight gas sands is very low. Organic-rich source rocks in the Kandik basin could have provided gas to tight sand reservoirs, although available data on reservoir quality are limited. The tight gas sand potential of the Middle Tanana and Yukon Flats basins are unknown.

Shale gas. The shalebed gas potential for most of the region is unknown, but is regarded here as very low. One possible exception is the Kandik basin in the northeastern part of the region where organic-rich, thermally mature source rocks have been recognized (Howell, 1996).

Gas hydrates. The main occurrences of gas hydrates in nature are in modern marine sediments and in arctic regions with well-developed, continuous permafrost. Permafrost is not well developed in the Yukon–Koyukuk/Upper Tanana Energy Region and, where locally present, is discontinuous. Consequently, the potential for economic concentrations of gas hydrates in the region is low.

Geothermal resource potential

Numerous hot springs are known throughout the region (sheet 2; Gassaway and Abramson, 1977; Motyka and others, 1983) and most are at least spatially associated with granitic plutons (Miller and others, 1973). Most hot springs in the region either lack surface evidence of sufficient fluid movement and/or do not have sufficiently hot enough water to warrant further consideration as a potential energy resource (see Chapter A). Several notable exceptions include the following sites: South hot springs (water temperature 153°F [67°C] and flow rate 357 gallons per minute), Upper Division hot springs (water temperature 154°F [68°C] and flow rate 217 gallons per minute), Lower Division hot springs (water temperature 133°F [56°C] and flow rate 547 gallons per minute), Kilo hot springs (water temperature 126°F [52°C] and flow rate 264 gallons per minute), and Manley Hot Springs (water temperature 138°F [59°C] and flow rate 375 gallons per minute). With the exception of Manley, all of these hot springs are located significant distances from rural communities. The community of Manley is essentially located at Manley Hot Springs, which includes a high enough flow rate of high-temperature water to warrant further consideration of the resource for local energy.

RECOMMENDATIONS

Coal resources recommendations

Many coal occurrences are known throughout the Yukon–Koyukuk/Upper Tanana Energy Region, but only the accumulations near the Little Tonzona River and in the eastern Nenana–Jarvis Creek areas stand out as clearly including substantial volumes of coal. Drilling in the Little Tonzona field in the 1980s failed to establish the strike extent (parallel to the Alaska Range mountain front) and dip extent (northward into the Minchumina basin) of the coal-bearing section. Exploratory drilling in the eastern Nenana–Jarvis Creek area may be warranted, particularly in the Jarvis Creek field. The proximity of this field to communities along the Richardson Highway suggests these resources are a potentially viable source for local energy.

Conventional oil and gas recommendations

The best potential for conventional oil and gas in the Yukon–Koyuk/Upper Tanana energy region lies in the Middle Tanana, Yukon Flats, and Kandik basins. Thick, coal-bearing sections similar to those seen in outcrop around the perimeter of the first two basins are thought to be present in the subsurface of the Middle Tanana and Yukon Flats basins, and mature oil-prone source rocks are known to be present in the Kandik basin. The petroleum industry has expressed only moderate interest in exploring these basins. The Nenana basin (adjacent to Middle Tanana basin) is currently being explored under State-issued exploration license, although the results of recent exploratory drilling west of Nenana are not publicly available. Collectively, these basins remain underexplored, and insufficient data are available to predict the role these frontier basins may play in supplying energy to the region. New geologic mapping and associated field studies along the margins of these basins would provide much-needed constraints on the framework geology and hydrocarbon prospectivity. Additionally, the collection of high-resolution gravity and aeromagnetic surveys in key areas might yield important and relatively cost-effective insights into the structure, fill, and gas resource potential of the Yukon Flats and Middle Tanana basins. The collection of high-quality seismic data, although expensive, would significant improve our knowledge of these basins. To be able to stimulate future exploration by industry, the State could consider exercising its right to publicly release currently confidential seismic data to the public if and when the exploration license for the Nenana area terminates.

Unconventional oil and gas recommendations

Coalbed methane. Thick, coal-bearing sections are known in the Middle Tanana basin and are suspected in the subsurface of the Yukon Flats basin. A recent shallow test well near Fort Yukon documented the presence of coal and methane, but gas saturation levels were too low due to the low rank of the coal. It is possible that higher rank coals could be present deeper in the basin, and may include higher gas saturation levels. A deeper coalbed methane test well might be justified in this basin, but the cost of drilling and testing such a well versus the risk of failure/benefits from success must be weighed.

The coalbed methane potential of the Middle Tanana basin is poorly known, but the presence of thick coals along the Alaska Range mountain front combined with the basin's proximity to transportation infrastructure make the basin an attractive target for future coalbed methane exploration and development. One or more coalbed methane test wells could be drilled, targeting the most attractive parts of the Middle Tanana basin.

Despite the attractive characteristics of both basins, it is important to bear in mind that regardless of how much effort and investment are expended, all exploration programs carry inherent risk of failure.

Tight gas sands. The tight gas sand potential in the region is probably low. The presence of tightly cemented Cretaceous-age sandstones is well documented, but the apparent absence of suitable source rocks throughout most of the region suggest tight gas sands are not present. The Kandik basin is an exception, as organic-rich source rocks and tightly cemented sandstones are known in this basin.

Shale gas. With the exception of the Kandik basin, the shale gas potential in the region is considered low. Organic-rich mature source rocks are known in the Kandik basin and, given available information, shale gas potential cannot be ruled out. Additional work to characterize the petrophysical and organic geochemical properties of these rocks might be warranted.

Methane hydrates. Due to the lack of extensive, continuous permafrost in most of central Alaska, the likelihood of finding gas hydrates in the region are very low, therefore no further action is recommended.

Geothermal resource recommendation

Surface indications of geothermal activity are known at several locations throughout the region. Most hot springs include only low-grade thermal springs that are too far from communities to warrant further action. Manley Hot Springs is a notable exception, being co-located with the community of Manley and including characteristics that suggest it could provide energy for local use. Additional characterization is warranted.

The presence of shallow heat flow at hot springs across the region is a positive indication of a locally elevated geothermal gradient, allowing for the possibility of additional hidden geothermal resources elsewhere in the region. Exploring directly for these potential resources would be difficult and expensive. One option to assist in the identification of areas of higher potential would be to include evaluation of local and regional geothermal gradients during mineral resource exploration activities, such as airborne geophysical surveys and core drilling.

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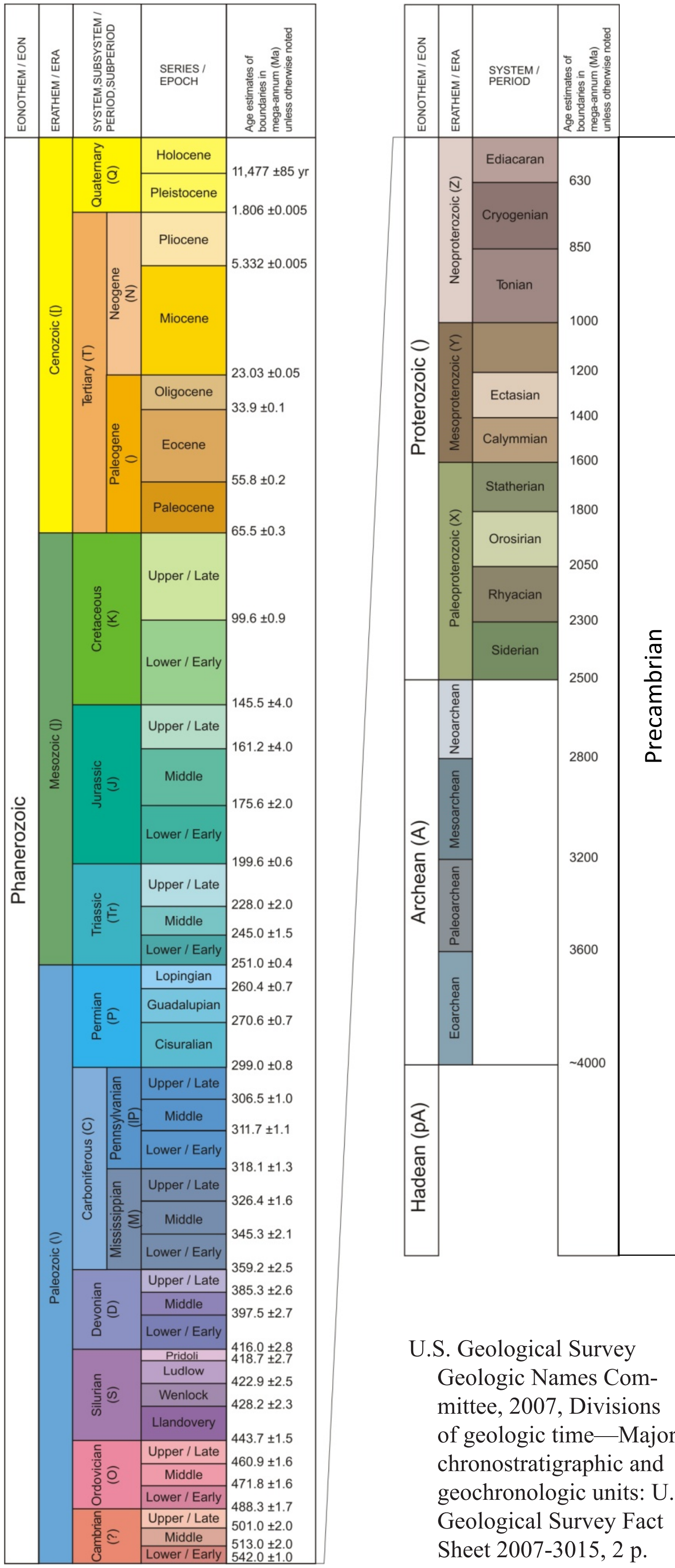
Appendix I



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Glossary

This glossary is intended to provide brief, non-technical definitions of terms or concepts used in this report. Except where noted, definitions are from the American Geological Institute's Dictionary of Geological Terms, 5th Edition (2005).

Terms in Red Small Caps *refer to geologic time; Appendix 1 contains a simplified graphic representation of the geologic time scale. A note regarding geologic time references in literature: With the possible exception of hydrothermal resources, all of the geologic resources that we use for energy were formed by Earth processes that occurred thousands to millions of years ago. Defining when an event occurred is a significant component of geologic research, particularly in areas of limited data, because geologic events follow known patterns of progression. Dating materials found in surface exposures and rock cores allows geologists to understand the sequence of events that led to the development of a particular resource, and then make educated inferences and predictions about its thickness and lateral extent.*

accretionary prism—A generally wedge-shaped mass of tectonically deformed sediment at a convergent plate boundary formed when sediment and volcanic material are scraped off the downgoing plate during the process of subduction.

alteration—Any change in the mineralogic composition of a rock brought about by physical or chemical means, especially by the interaction of minerals with fluids passing through the rock. Excessive diagenetic alteration can compromise reservoir quality by filling the critical pore space into which hydrocarbons need to migrate.

anticline—A fold, generally convex upward, whose core contains the stratigraphically older rocks.

arc—See 'volcanic arc'

basalt—A general term for a dark-colored, fine-grained igneous rock composed of iron- and magnesium-rich silicate minerals. Basalts commonly represent cooled (solidified) lava flows.

biogenic gas—Coal or shale gas that is generated by the action of bacteria on the organic-rich rock. Biogenic gas is formed at shallow depths and low temperatures by anaerobic bacterial decomposition of sedimentary organic matter.

Btu—The term used to describe the heating value (energy content) of fuels, including natural gas and coal, defined as the amount of energy needed to heat 1 pound (454 grams; 0.1198 U.S. gallons; 454 milliliters) of water from 39°F to 40°F (3.8°C to 4.4°C).

Cambrian—The oldest period of the **Paleozoic** era of the geologic time scale, spanning between 542 million and 488.3 million years ago.

carbonate—A sediment formed by the biotic or abiotic precipitation from aqueous solution of carbonates of calcium, magnesium, or iron; for example, limestone and dolomite.

Carboniferous—A period of the Paleozoic era of the geologic time scale, spanning between 318 million and 299 million years ago.

cataclastic—Structures produced in a rock as a result of severe mechanical stress; characteristic features include the bending, breaking, and granulation of the minerals.

Cenozoic—The youngest of ten eras into which geologic time is subdivided. It extends from 65 million years ago to the present and occurs after the **Mesozoic** era. The **Cenozoic** era is subdivided into the **Quaternary** and **Tertiary** periods. The **Quaternary** period is subdivided into the **Holocene** and the **Pleistocene** epochs. The **Tertiary** period is divided into the **Neogene** and **Paleogene** subperiods, which are further subdivided into the **Pliocene**, **Miocene**, **Oligocene**, **Eocene**, and **Paleocene** epochs. The **Cenozoic** era is also known as the 'Age of Mammals', because the extinction of dinosaurs that marks the transition from the **Mesozoic** to the **Cenozoic** era allowed mammals to greatly diversify. The study of **Cenozoic** geology is an important part of energy resource development because many of Alaska's modern mountain ranges were built during **Cenozoic** time and the resultant sedimentary rocks are locally sources for coal and hosts to oil and gas reserves.

charge (gas charge or oil charge)—The process of a reservoir filling up with hydrocarbons (oil or gas).

cinder cone—A conical-shaped hill centered around a volcanic vent formed by volcanic rock fragments ejected from a volcanic vent. Many cinder cones have a bowl-shaped summit crater.

cleats—Fractures in most coal seams that form under tectonic stress during the coalification process. There are two types: *butt cleats* and *face cleats*, which occur at nearly right angles to each other and provide both permeability and gas pathways within coalbed methane reservoirs.

clinker—As used in this publication, clinker refers to sandstone, siltstone, and shale beds that have been heated, baked and melted by nearby burned coal seams. Clinker is commonly red-orange in color, hard, and brittle. The term "clink" is derived from the sound made when the burned rocks are struck by a rock hammer or walked on. This definition differs from that provided by the American Geological Institute, which defines clinker as coal that has been baked by igneous intrusion and as the vitreous slaggy mass of coal ash.

coalbed methane—A clean-burning fuel that forms within the matrix of coal seams, which serve as both the source of the methane and the reservoir for the gas. In coalbed methane reservoirs, the gas molecules adhere to the surface of the coal within pores and as free gas within fractures. The heating value of coalbed methane (commonly referred to as CBM) is comparable to conventional natural gas (~1,000 Btu/scf).

coal gasification—The process of converting solid coal into a synthetic natural gas or a gaseous mixture by reacting the coal at a high temperature with a controlled amount of oxygen and water. The resulting mixture is called syngas, which can be burned directly as a fuel or converted into synthetic liquid fuels. The coal gasification process can be conducted at the surface with already mined coal or in the subsurface utilizing deep, unmineable coal seams (known as underground coal gasification [UCG] or *In-situ* coal gasification [ISCG]).

coal rank—A measure of the degree of alteration as a coal matures; from lowest to highest, lignite, subbituminous, bituminous, and anthracite. The heating value of each progressively higher rank of coal increases due to higher carbon content.

coal resource estimates (from Wood and others, 1983)**:**

measured coal—Tonnage estimates for measured coal resources are determined by projection of thicknesses of coal and overburden, rank, and quality data for a radius of 0.25 mile (0.4 kilometer) from a drill hole or outcrop point of measurement. Measured coal resources include anthracite and bituminous coal 14 or more inches (35 or more centimeters) thick and lignite and subbituminous coal 30 or more inches (75 or more centimeters) thick, to a depth of 6,000 feet (1,800 meters).

indicated coal—Tonnage estimates for indicated coal resources are determined by projection of thicknesses of coal and overburden, rank, and quality data for a radius of 0.25 mile (0.4 km) to 0.75 mile (1.2 kilometers) from a drill hole or outcrop point of measurement. Indicated coal resources include anthracite and bituminous coal 14 or more inches (35 or more centimeters) thick and lignite and subbituminous coal 30 or more inches (75 or more centimeters) thick, to a depth of 6,000 feet (1,800 meters).

demonstrated coal—Demonstrated coal resources are the sum of the estimates for measured and indicated coal resources. Demonstrated coal resources include anthracite and bituminous coal 14 or more inches (35 or more centimeters) thick and lignite and subbituminous coal 30 or more inches (75 or more centimeters) thick, to a depth of 6,000 feet (1,800 meters).

inferred coal—Tonnage estimates for inferred coal resources are determined by projection of thicknesses of coal and overburden, rank, and quality data for a radius of 0.75 mile (1.2 kilometers) to 3 miles (4.8 kilometers) from a drill hole or outcrop point of measurement. Inferred coal resources include anthracite and bituminous coal 14 or more inches (35 or more centimeters) thick and lignite and subbituminous coal 30 or more inches (75 or more centimeters) or more thick, to a depth of 6,000 feet (1,800 meters).

identified coal—Identified coal resources are the sum of **demonstrated** (measured + indicated) and **inferred** coal resources. Identified coal resources include anthracite and bituminous coal 14 or more inches (35 or more centimeters) thick and lignite and subbituminous coal 30 or more inches (75 or more centimeters) thick, to a depth of 6,000 feet (1,800 meters).

hypothetical coal—Hypothetical coal resources represent undiscovered coal in beds beyond a radius of 3 miles (4.8 kilometers) that may reasonably be expected to exist based on known geologic conditions including thickness and lateral continuity of coal seams, environment of coal deposition, and general coal quality and rank of the sedimentary basin. In general, tonnages of hypothetical coal resources are estimated based on evidence from distant outcrops and drill holes. Hypothetical coal resources include anthracite and bituminous coal 14 or more inches (35 or more centimeters) thick and lignite and subbituminous coal 30 or more inches (75 or more centimeters) thick to a depth of 6,000 feet (1,800 meters).

conventional oil and gas resources—Hydrocarbons that will flow to production wells without first having to make dramatic changes to either the reservoir rock or the reservoir fluids (in contrast, see 'unconventional oil and gas resources'). These methods include flow though its own physical pressure, physical lift, water flooding and pressure from water or natural gas.

Cretaceous—The youngest period of the **Mesozoic** era of the geologic time scale, spanning the time between 145.5 million and 65 million years ago.

crust—The outermost layer of the Earth. The thickness of the crust depends on whether it underlies ocean basins (oceanic crust) or continents (continental crust). The average thickness of oceanic crust is 3 miles and continental crust is 21 miles.

deltaic—Pertaining to or characterized by a river delta; for instance, "deltaic sedimentation" or "deltaic deposit." A delta is a triangular-shaped landform that may form at the mouth of a river, where the river flows into an ocean, sea, estuary, or lake. As the river flow enters the standing water, it is no longer confined to its channel and expands in width, flow velocity is reduced, and sediment drops out of the flow-forming deposits. The name "delta" is derived from the landform's similarity to the shape of the Greek letter Δ (delta). Deltas may be either river-, wave-, or tide-dominated, and these controls influence the resulting shape of deltaic deposits.

Devonian—A period of the **Paleozoic** era of the geologic time scale, spanning between 416 million and 359 million years ago.

diagenesis—A general term that encompasses changes to a sediment after initial deposition as the material is gradually buried beneath successively younger sediments. These changes result in progressive alterations to the sediment's original mineralogy and texture with increasing depth and time of burial. Burial diagenesis is the process through which plant and animal matter are transformed into hydrocarbons.

Eocene— An epoch of the **Tertiary** period of the geologic time scale. It is set within the **Paleogene** subperiod, covering the time period between 53 million and 34 million years ago.

fault scarp—A topographic high resulting from the vertical displacement of the land surface by movement along faults.

fault zone—A fracture zone along which there has been displacement on the sides relative to each other parallel to the zone.

fluvial—Of or pertaining to a river or stream and its associated landforms including terraces, floodplains, and lakes. Sediments deposited by fluvial processes may show evidence of transportation of coarser grains by currents along the river or stream bottom, or as suspended fine sediments. Meandering rivers and streams often create "oxbow lakes"—U-shaped lakes that are abandoned river channels that may develop into swamps that accumulate peat and subsequently form coal deposits.

fold—A bend in bedding or some other planar feature in a rock. Folding is usually, but not always, caused by deformation. Folds that are convex upward are referred to as anticlines and folds that are convex downward are referred to as synclines.

forearc basin—A sedimentary basin, usually elongate, lying between the volcanic arc and the accretionary prism in a convergent plate boundary zone.

foreland basin—A type of sedimentary basin caused by a downward flexing of the crust due to unusually thick crust in an adjacent compressional mountain belt.

fossil fuel—A general term for any hydrocarbon or carbonaceous rock that may be used for fuel: primarily petroleum, natural gas, and coal.

fracking—See 'hydraulic fracturing'

fumarole—A vent, usually volcanic, from which gases and vapors are emitted; it is characteristic of a late stage of volcanic activity. Fumaroles may occur along a fissure or in apparently chaotic clusters or fields.

gas hydrate—A naturally-occurring, ice-like solid in which water molecules trap gas molecules in a cage-like structure known as a 'clathrate.' Gas hydrates occur under a very limited range of temperature and pressure conditions, such as in the permafrost environments of the arctic (Collett, 2004).

geothermometer—A mineral or other feature in a rock that forms within a known temperature, pressure, and composition range. The mineral can be used to infer conditions of formation, such as temperature.

geothermal gradient—The rate of increase in temperature with increasing depth below the Earth's surface. The geothermal gradient differs from place to place due to differences in the thermal conductivity of different rock types.

geyser—A type of hot spring that intermittently erupts jets of hot water and steam, the result of groundwater coming into contact with hot rock at considerable depth, usually more than 6,600 feet (2,000 m). The combination of boiling water at depth results in pressurized steam that streams to the surface and sprays out of the geyser's surface vent in a hydrothermal explosion. Geysers are fairly rare and generally occur only active volcanic areas.

graben—An elongate trough or basin, bounded on both sides by nearly parallel high-angle normal faults that dip toward one another. A graben forms as the result of a block of land being downthrown, producing a valley with a distinct fault scarp on each side. Graben often occur side-by-side with horst structures (see horst). Such horst and graben structures indicate tensional forces in action due to crustal stretching.

granite—Broadly defined as any quartz-bearing, crystalline plutonic rock.

Holocene—The **Holocene** is a geologic epoch, which began at the end of the **Pleistocene** (about 11,500 years ago) and continues to the present.

horst—A horst is an uplifted, elongate block formed by parallel normal faults; they are often associated with complementary downthrown blocks called graben (see graben). Horst blocks in the subsurface may create traps for preserving hydrocarbons and are often the targets of oil and gas exploration.

hydraulic fracturing—The process of pumping fluids under high pressure into a well to create artificial fractures, typically in low permeability rocks. This process, known as Induced Hydraulic Fracturing, often utilizes propping agents such as grains of sand, ceramic, or other particulates to prevent the newly created fractures from closing once injection is stopped. The new fractures create pathways that allow hydrocarbons to flow from the reservoir into the wellbore.

igneous rock—A mineral or rock that formed by crystallizing from molten material (magma). One of the three main classes of rock.

Jurassic— The middle period of the **Mesozoic** era of the geologic time scale, spanning between 200 million and 145.5 million years ago.

kerogen—The organic component of sedimentary rocks that are insoluble to alkaline and common organic solvents.

lacustrine—Pertaining to sediments formed in a lake or lakes; for example, "lacustrine sands" deposited on the bottom of a lake or shoreline. In contrast to seas and oceans, lakes are smaller, nearly closed systems with finer-grained sediment (silt and clay); they are most often fresh water.

lava flow—Outpouring of molten lava from a vent or fissure onto the Earth's surface.

maturation—The process of a source rock becoming capable of generating oil or gas when exposed to appropriate pressures and temperatures. The maturity of a source rock reflects the ambient pressure and temperature as well as the duration of conditions favorable for hydrocarbon generation (Schlumberger, 2012).

Mesozoic—The second youngest of ten eras into which geologic time is subdivided. It extends from 251 million years ago, the end of the **Paleozoic** era, to 65 million years ago. The **Mesozoic** is subdivided into the **Cretaceous**, **Jurassic**, and **Triassic** periods. It is often called the 'Age of Dinosaurs' because dinosaurs were the dominant vertebrates of the time. **Mesozoic** rocks occur throughout Alaska but are particularly dominant on the North Slope and in Southwest Alaska. Much of Alaska's oil and gas is generated by **Mesozoic** sedimentary rocks and Cretaceous rocks on the North Slope host globally significant volumes of coal.

metamorphic rock—Rocks derived from preexisting rocks through physical and chemical changes that take place in the solid state. Metamorphic rocks form in response to changes in temperature, pressure, stress, and chemical conditions at depth beneath earth's surface. One of the three main classes of rock.

migration—The movement of hydrocarbons from their source into reservoir rocks. Migration typically occurs from a structurally low area to a higher area because of the relative buoyancy of hydrocarbons in comparison to the surrounding rock. Migration can be local or can occur along distances of hundreds of kilometers in large sedimentary basins, and is critical to the formation of a viable petroleum system (Schlumberger, 2012).

Miocene—An epoch of the **Tertiary** period of the geologic time scale. It is set within the **Neogene** subperiod, between 5.3 million and 23 million years ago.

Mississippian—The older subperiod of the **Carboniferous** period of the geologic time scale, spanning between 359 million and 318 million years ago.

mudlog—Graphical representation of the drilling rate, rock type (lithology), hydrocarbon shows, and other drilling parameters prepared by a mudlogger. The rock type is determined by the mudlogger through examination of rock cuttings generated by a drill bit and transported to the earth's surface by circulating drilling mud.

mud pot—A type of hot spring containing boiling mud, usually sulfurous and often multicolored; commonly associated with geysers and other hot springs in volcanic areas.

Neogene— The younger subperiod of the **Tertiary** period of the geologic time scale, spanning between 23 million and 2.6 million years ago.

normal fault—A type of fault typically associated with extension, or the pulling apart of the crust.

Oligocene—An epoch of the **Tertiary** period of the geologic time scale. It is set within the **Paleogene** subperiod, spanning between 34 million and 23 million years ago.

onlap—Progressive overlap of successively younger sedimentary deposits in which each younger bed extends some distance beyond, commonly landward, the underlying bed.

Ordovician—A period of the **Paleozoic** era of the geologic time scale, spanning between 488.3 million and 433.7 million years ago.

Paleocene—The oldest epoch of the **Tertiary** period of the geologic time scale. It occurs within the **Paleogene** subperiod, between 65 million and 53 million years ago.

Paleogene—The older subperiod in the **Tertiary** period of the geologic time scale, spanning between 65 million and 23 million years ago.

Paleozoic—The third youngest of ten eras into which geologic time is subdivided. It extends from 542 million years ago to 251 million years ago, the beginning of the **Mesozoic** era. The **Paleozoic** era is subdivided into six periods: **Permian**, **Carboniferous**, **Devonian**, **Silurian**, **Ordovician**, and **Cambrian**. The **Carboniferous** period is further subdivided into the **Pennsylvanian** and **Mississippian** subperiods. The opening of the **Paleozoic** era corresponds to a major profusion of multicellular life forms. From a resource perspective, the most important Paleozoic sedimentary rocks in Alaska occur in east-central Alaska, across the Brooks Range, and in the North Slope subsurface.

Pennsylvanian—The younger subperiod of the **Carboniferous** period of the geologic time scale, spanning the period between 318 million and 299 million years ago.

Permian—The youngest period of the **Paleozoic** era of the geologic time scale, spanning between 299 million and 251 million years ago.

petroleum system—The components that are necessary for a hydrocarbon accumulation, including an organic-rich source rock, thermal maturation, migration pathway, reservoir rock, trap, and seal. These elements and processes must all be present and occur with appropriate relative timing for oil and gas to be generated and stored.

plate—A rigid, relatively thin segment of the Earth's outermost shell. This shell is divided into seven major segments, or plates, that move relative to each other. Each plate is bounded by a seismic (active faulting and earthquakes) zone.

Pleistocene—The older epoch of the **Quaternary** period, spanning between 2.6 million and 11,500 years ago.

Pliocene—The most recent epoch of the **Tertiary** period of the geologic time scale. It is set within the **Neogene** subperiod, between 5.3 million and 2.6 million years ago.

pluton—A large, irregularly-shaped body of crystalline igneous rock that cooled slowly from a molten state after intruding preexisting rocks.

PRECAMBRIAN—Describes the large span of time in Earth's history before the **CAMBRIAN** period of the geologic time scale. It is a generalized term used to encompass the time between 4.5 billion years ago and 542 million years ago. The majority of **PRECAMBRIAN** rocks in Alaska have been been metamorphosed during very deep burial and thus no long have potential to host oil and gas resources.

QUATERNARY—The youngest period of the **CENOZOIC** era of the geologic time scale, spanning between 2.6 million years ago and the present. The **QUATERNARY** period is often remembered as both the 'the age of man' and 'the ice age.' The climate was one of periodic glaciations with continental glaciers covering much of North America. Alaska's modern landscape was significantly shaped by **QUATERNARY** glacial activity.

reservoir—A subsurface body of rock having sufficient porosity and permeability to store and transmit fluids. Sedimentary rocks are the most common reservoir rocks because they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system (Schlumberger, 2012).

reverse fault—A type of fault, typically dipping greater than 45 degrees, associated with compression in the crust.

seal—A relatively impermeable rock, commonly shale, anhydrite, or salt, that forms a barrier or cap above and around reservoir rock such that fluids cannot migrate beyond the reservoir. A seal is a critical component of a complete petroleum system (Schlumberger, 2012).

sedimentary rock—A layered rock formed through the consolidation of sediment or from the consolidation of material precipitated from surface water bodies. Examples of the former include sandstone and claystone. Examples of the latter include salt and other types of evaporate deposits. One of the three main classes of rock.

sedimentary basin—A low area on the surface of Earth's crust in which sediment accumulates over long timespans.

shale gas—Natural gas that is trapped within a very-fine-grained, organic-rich rock. In contrast with conventional reservoirs, shale gas is typically produced from rocks with very low permeability and porosity, which require artificial well stimulation (see 'hydraulic fracturing') to promote higher flow rates.

SILURIAN—A period of the **PALEOZOIC** era of the geologic time scale, spanning between 433.7 million and 416 million years ago.

source rock—A rock rich in organic matter which, if heated sufficiently, will generate oil or gas. Typical source rocks, usually shales or limestones, contain about 1 percent organic matter and at least 0.5 percent total organic carbon (TOC), although a rich source rock might have as much as 10 percent organic matter. Rocks of marine origin tend to be oil-prone, whereas terrestrial source rocks (such as coal) tend to be gas-prone. Preservation of organic matter without degradation is critical to creating a good source rock, and necessary for a complete petroleum system. Under the right conditions, source rocks may also be reservoir rocks, as in the case of shale gas reservoirs (Schlumberger, 2012).

stratigraphic—Pertaining to stratigraphy, which is the subdiscipline in geology concerned with the characteristics and attributes of stratified (layered) rock. Stratigraphers are geologists that specialize in studying the geographic distribution and sequence of strata in a region.

stripping ratio—The amount of waste (non-economic) rock that must be removed to produce a unit of coal.

stock—An igneous intrusion, usually discordant with surrounding rock, that is less than 40 square miles in surface exposure.

strike-slip—The component of slip that is parallel to the strike of a fault.

structural thinning—Thinning of a rock body because of deformation, commonly associated with the removal of material due to faulting.

subduction zone—A long, narrow, curvilinear zone in which one plate slides beneath an adjacent plate. Volcanic arcs typically develop on the upper (overriding) plate in response to melting of the downgoing (subducting) plate at depth. The resulting magma is buoyant and rises to the earth's surface, where it erupts and forms volcanoes. The present-day south-central and southwestern margin of Alaska is bounded offshore by the Aleutian subduction zone. Modern volcanoes in south-central and southwestern Alaska formed as result of subduction of the Pacific plate beneath the North American plate.

subsidence—The settling or sinking of the land surface over long time periods; continued deposition of sediments in areas of subsidence eventually creates a sedimentary basin.

syncline—A fold, the core of which contains the stratigraphically younger rocks; it is generally concave upward.

tectonics—A branch of geology dealing with the major structural or deformation features in the outer layer of the earth, and their origin, spatial relations, and evolution through time.

TERTIARY—The older period of the **CENOZOIC** era of the geologic time scale, covering the time span between 65 million and 2.6 million years ago. Mammals, birds, grasses, and flowering plants thrived during **TERTIARY** time. The early **TERTIARY** global climate was primarily tropical or sub-tropical but gradually cooled as time progressed.

Appendix II

Many of Alaska's largest coal fields developed during the **Tertiary** period. The **Tertiary** period is subdivided into the **Neogene** and **Paleogene** subperiods, which are further subdivided into the **Pliocene**, **Miocene**, **Oligocene**, **Eocene**, and **Paloecene** epochs.

terrane—A fault-bounded crustal block with geologic characteristics that are distinctly different from neighboring terranes. Alaska has been subdivided into a number of terranes, reflecting the region's complex geologic history.

thermal maturity—The degree of heating of a source rock in the process of transforming kerogen into hydrocarbon.

thermochronology—The study of the thermal evolution of a region using various radiometric dating methods.

thermogenic gas—The thermal cracking of sedimentary organic matter into hydrocarbon gas. The formation of thermogenic gas requires relatively deep depths and sufficient geologic time to generate hydrocarbon gas and liquids (in contrast see 'biogenic gas').

thrust fault—A type of fault with a dip of less than 45 degrees that is associated with compression in the crust.

tight gas resources—Hydrocarbons present in low-permeability reservoirs (tight gas sands) that produce mainly dry gas (natural gas that occurs in the absence of liquid hydrocarbons). Tight gas resources require massive reservoir stimulation to create permeable conduits or dewatering to promote the relative permeability of gas.

trap—A configuration of rocks suitable for containing hydrocarbons and sealed by a relatively impermeable formation through which hydrocarbons will not migrate. Traps are described as structural traps (in deformed strata such as folds and faults) or stratigraphic traps (in areas where rock types change, such as unconformities, pinch-outs and reefs). A trap is an essential component of a petroleum system.

Triassic—The oldest period of the **Mesozoic** era of the geologic time scale, covering the time span between 251 million and 200 million years ago.

unconformity—A break or gap in the geologic record. Expressed locally as a break in the normal sedimentary succession.

unconventional oil and gas resources—Hydrocarbons that may require massive reservoir stimulation to create permeable conduits (tight gas sands, shale oil, and shale gas), thermal or chemical treatments to reduce oil viscosity (heavy oil and tar sands), or dewatering to promote the relative permeability of gas (coalbed methane). The volume of unconventional oil and gas resources considerably exceeds the amount of conventional oil and gas reserves, but are much more difficult and expensive to develop.

volcanic arc—The curvilinear chain of volcanoes that form in the overriding tectonoic plate above subduction zones. The present-day Aleutian Islands and the onshore continuation along the Alaska Peninsula and the west side of Cook Inlet are an example of a volcanic arc.

volcanic rocks—Igneous rocks erupted from a volcano that have reached or nearly reached the Earth's surface before solidifying.

volcaniclastic—Clastic rocks consisting of volcanic material, regardless of origin, in which the rock particles were derived from pre-existing volcanic rocks.

weight percent—A measurement of the quantity of organic carbon (or Total Organic Carbon, TOC) present in a rock, reported in weight percent (wt.%) carbon. For example, 1.0 wt.% carbon means that in 100 grams of rock sample there is 1 gram of organic carbon. Source: Pennsylvania Department of Conservation and Natural Resources website, http://www.dcnr.state.pa.us/topogeo/econresource/oilandgas/marcellus/sourcerock_index/sourcerock_quanity/index.htm

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Appendix II

STATE OF ALASKA

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Daniel S. Sullivan, *Commissioner, Department of Natural Resources*
Robert F. Swenson, *State Geologist and Director*