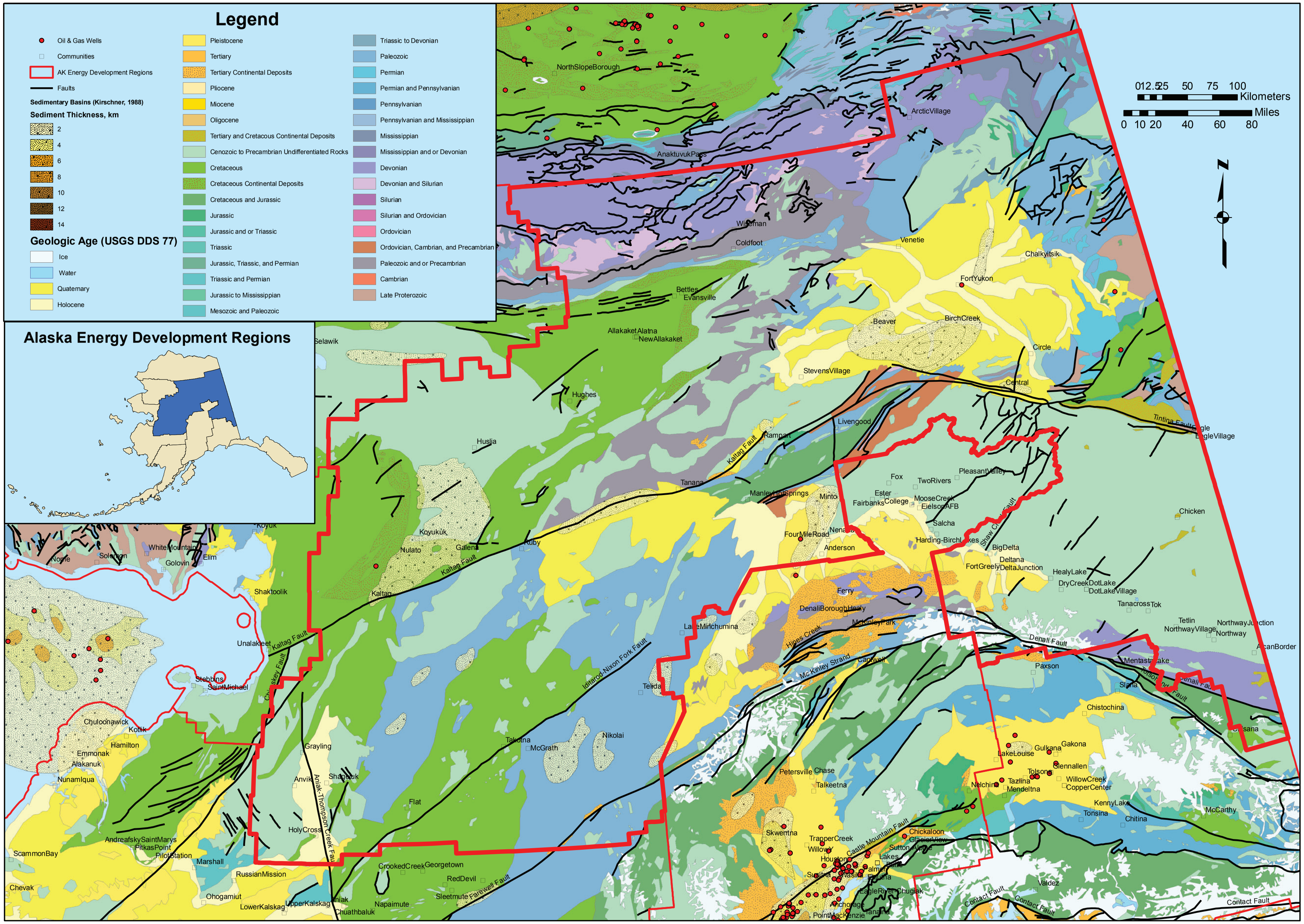
Geology of the Yukon-Koyukuk/Upper Tanana Energy Region, Alaska



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

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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

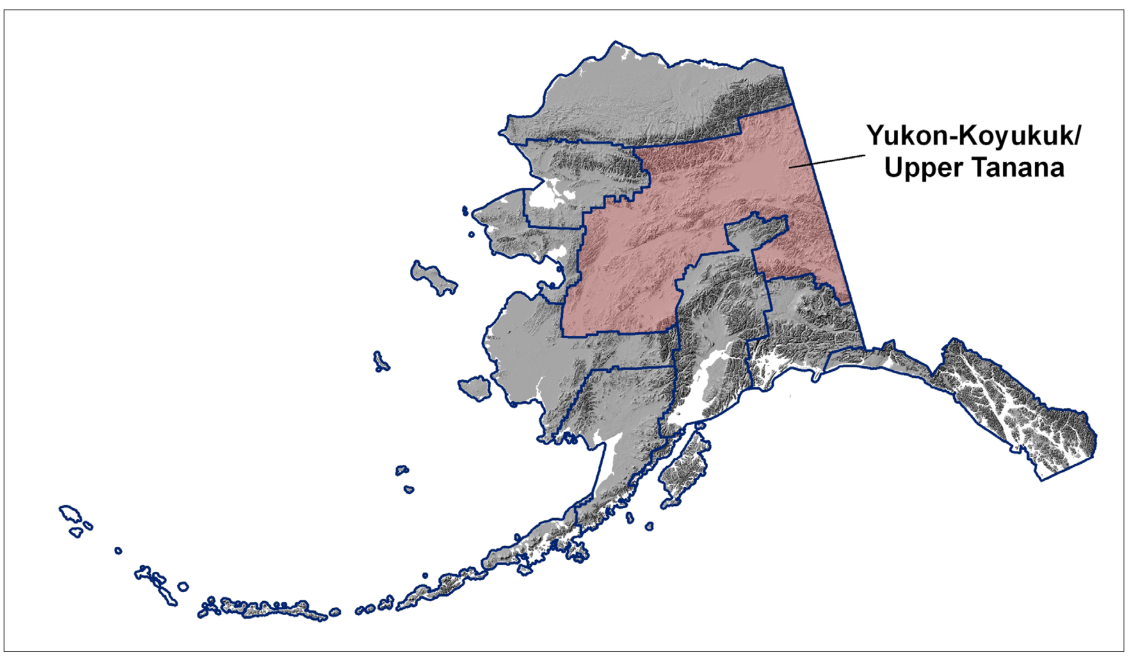

Figure L1. Location map of Yukon–Koyukuk/Upper Tanana Energy Region.

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

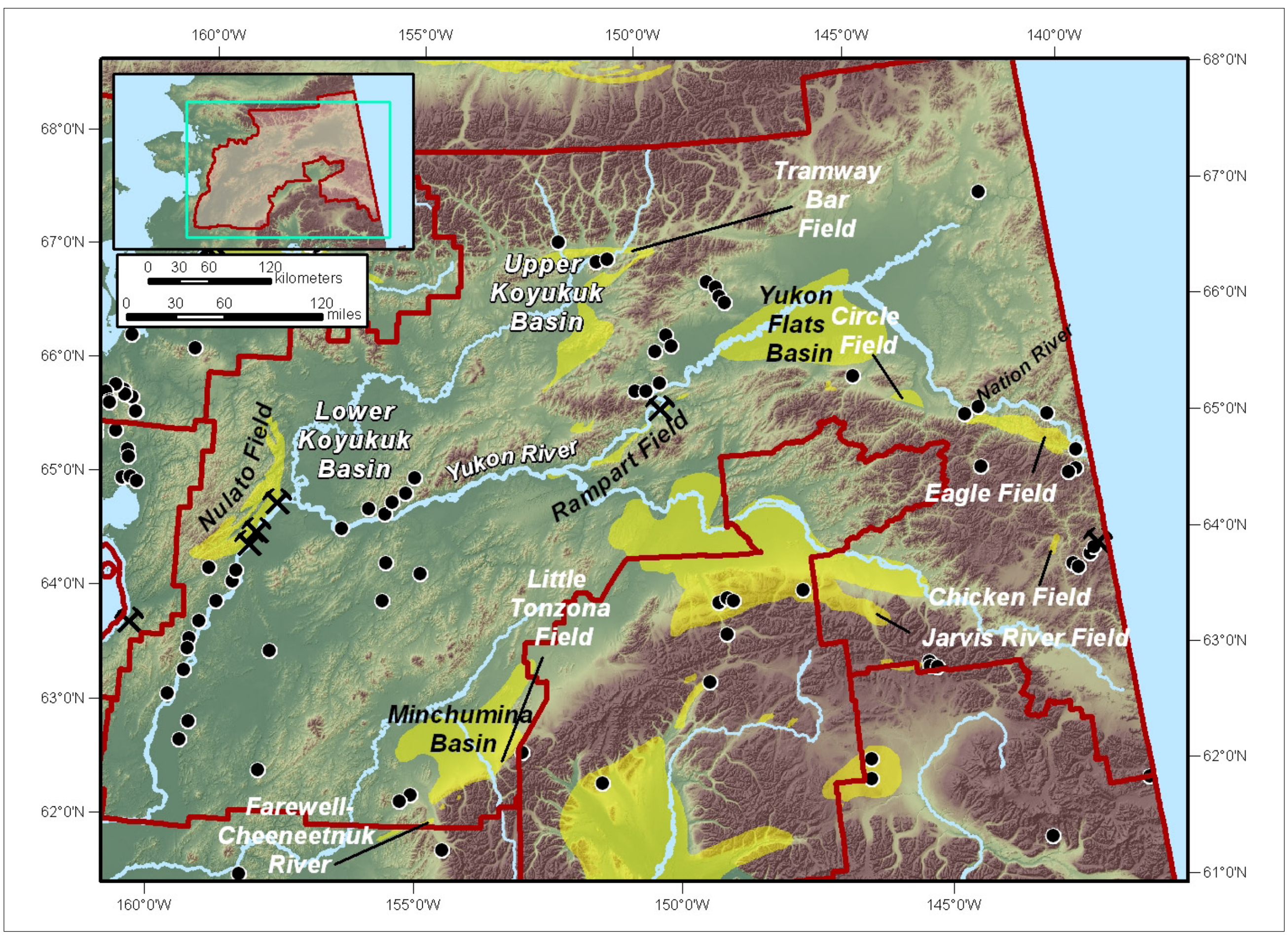

Figure L2. Regional location map of the Yukon–Koyukuk/Upper Tanana Energy Region. Black dots indicate reported coal occurrences; yellow shaded areas are inferred to be underlain by coal-bearing rocks.

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

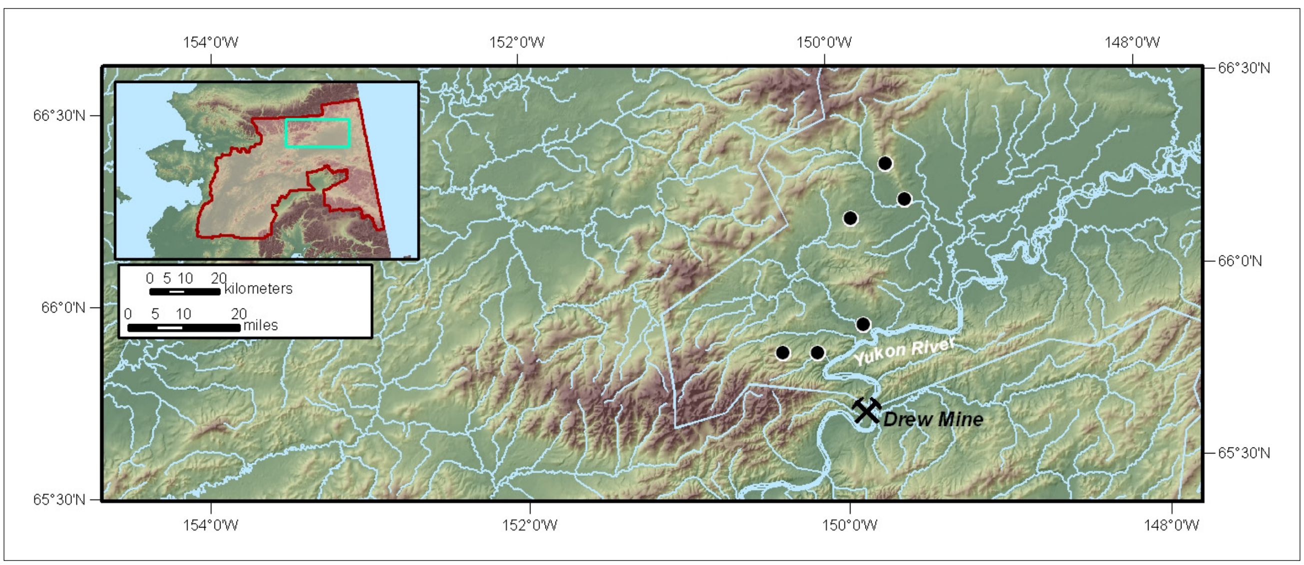

Figure L3. Map of the north-central part of the Yukon–Koyukuk/Upper Tanana Energy Region, showing reported coal occurrences (black dots) and the location of historic coal mining (pick-axe symbol).

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

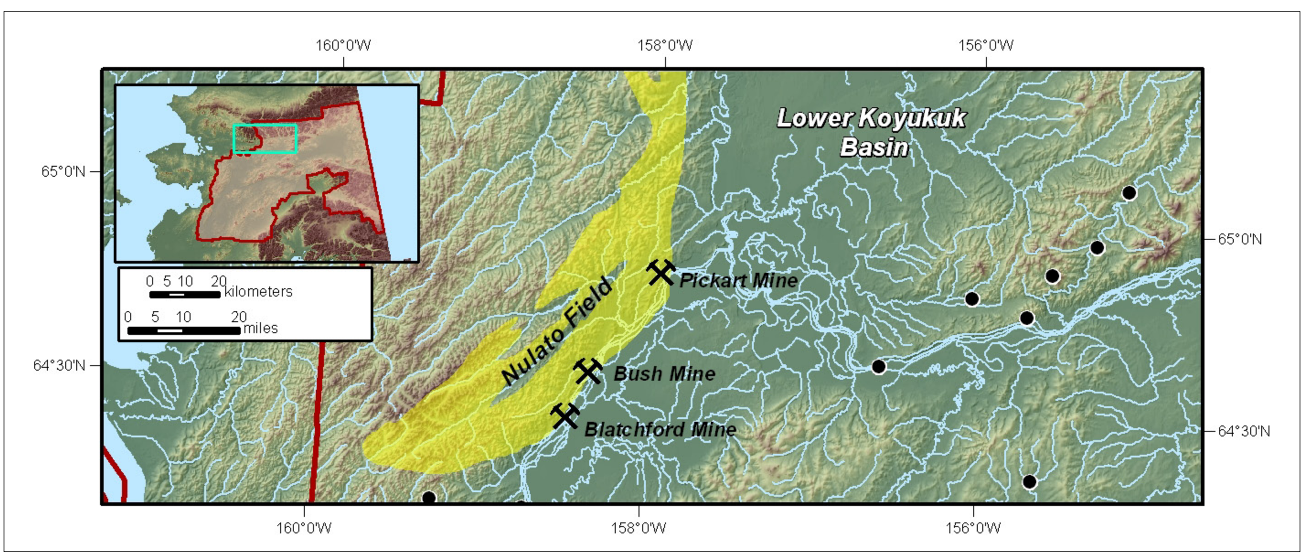

Figure L4. Map of the northwestern part of the Yukon–Koyukuk/Upper Tanana Energy Region (lower Koyukuk basin). Black dots indicate reported coal occurrences; pick-axe symbols show locations of historic coal mines.

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.

REFERENCES CITED AND SELECTED BIBLIOGRAPHY

Alaska Energy Authority (AEA), 2009, Alaska energy—A first step toward energy independence: Alaska Energy Authority, 245 pages. Available online at http://www.akenergyauthority.org/pdf files/AK Energy Final.pdf (accessed November 12, 2009).

Barker, J.C., 1981, Coal and uranium investigation of the Yukon Flats Cenozoic basin: U.S. Bureau of Mines Open File Report 140-81, 63 p.

———2006, Evidence for geothermal tungsten and germanium mineralization in Eocene coal and associated sediments, Fort Hamlin Hills, area, Interior Alaska: Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report 2006-1, 24 p.

Barnes, F.F., 1967, Coal resources of Alaska: U.S. Geological Survey Bulletin 1242-B, p. B1–B36, 1 sheet, scale 1:2,500,000.

Belowich, M.A., 1986, Basinal trends in coal, petrographic, and elemental composition with applications toward seam correlation, Jarvis Creek coal field, Alaska, *in* Rao, P.D., ed., Focus on Alaska's Coal '86: University of Alaska Fairbanks Mineral Industry Research Laboratory Report No. 72, p. 300–335.

———1988, Stratigraphy, petrology, and depositional environments of the Jarvis Creek coal field, east-central Alaska: Fairbanks, Alaska, University of Alaska Fairbanks, Master of Science thesis, 135 p., 2 sheets.

Bickel, R.S., and Patton, W.W., Jr., 1957, Preliminary geologic map of the Nulato and Kateel Rivers area, Alaska: U.S. Geological Survey Miscellaneous Investigations 249, 1 sheet, scale 1:125,000.

Bundtzen, T.K., and Kline, J.T., 1986, Coal, peat, and geothermal potential of the Kuskokwim Area Plan: Alaska

Division of Geological & Geophysical Surveys Public Data File 86-88, 16 pages.

Bundtzen, T.K., Harris, E.E., and Gilbert, W.G., 1997, Geologic map of the eastern half of the McGrath Quadrangle, Alaska: Alaska Division of Geological & Geophysical Surveys Report of Investigation 97-14A, 34 p., 1 sheet, scale 1:125,000.

Cass, J.T., 1959, Reconnaissance geologic map of the Nulato Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigation Map I-291, 1 sheet, scale 1:250,000.

Chapman, R.M., 1963, Coal deposits along the Yukon River between Ruby and Anvik, Alaska, *in* U.S. Geological Survey Staff, Contributions to economic geology of Alaska: U.S. Geological Survey Bulletin 1155, p. 18–29.

Chapman, R.M., Yeend, Warren, Brosgé, W.P., and Reiser, H.N., 1982, Reconnaissance geologic map of the Tanana Quadrangle, Alaska: U.S. Geological Survey Open-File Report 82-734, 18 p., 1 sheet, scale 1:250,000.

Clark, A., Barker, C.E., and Weeks, E.P., 2009, Drilling and testing the DOI-04-1A coalbed methane well, Fort Yukon, Alaska: U.S. Geological Survey Open-File Report 2009–1064, 69 p.

Clough, J.G., 1995, Summary of coal resource potential of the Jarvis Creek coal field: Alaska Division of Geological & Geophysical Surveys Public Data File 95-22, 23 p.

Collier, A.J., 1903a, Coal resources of the Yukon basin, Alaska, *in* Emmons, S.F., and Hayes, C.W., eds., Contributions to economic geology, 1902: U.S. Geological Survey Bulletin 213, p. 276–283.

———1903b, The coal resources of the Yukon, Alaska: U.S. Geological Survey Bulletin 218, 71 p., 1 sheet.

Dickey, D.B., 1982, Tertiary sedimentary rocks and tectonic implication of the Farewell fault zone, McGrath Quadrangle, Alaska: Fairbanks, University of Alaska Fairbanks, Master's Thesis, 54 p.

Dover, J.H., 1994, Geology of part of east-central Alaska, *in* Plafker, George, and Berg, H.C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-1, p. 153–204.

Foster, H.L., Keith, T.E.C., and Menzie, W.D., 1994, Geology of the Yukon–Tanana area of east-central Alaska, *in* Plafker, George, and Berg, H.C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-1, p. 205–240.

Gassaway, J.S., and Abramson, B.S., 1977, Map and table showing distribution of known thermal springs and selected igneous rocks in central Alaska: U.S. Geological Survey Open-File Report 77-168-H, 1 sheet, scale 1:1,000,000.

Gilbert, W.G., 1981, Preliminary geologic map and geochemical data, Cheeneetnuk River area, Alaska: Alaska Division of Geological & Geophysical Surveys Alaska Open-File Report 153, 10 p., 2 sheets, scale 1:63,360.

Gilbert, W.G., Solie, D.N., and Dickey, D.B., 1982, Preliminary bedrock geology of the McGrath B-3 Quadrangle: Alaska Division of Geological & Geophysical Surveys Alaska Open-File Report 148, 1 sheet, scale 1:40,000.

Hannigan, P.K., Osadetz, K.G., Dixon, J., and Bird, T., 2000, Petroleum resource assessment of the Kandik Basin, Yukon Territory, Canada: Geological Survey of Canada, for Yukon Department of Economic Development, 74 p. http://www.emr.gov.yk.ca/oilandgas/pdf/ra_kandikbasin.pdf

Hite, D.M., and Nakayama, E.N., 1980, Present and potential petroleum basins of Alaska, *in* Landwehr, M.L., ed., Exploration and economics of the petroleum industry—New ideas, new methods, new developments: Dallas, Texas, Institute on Petroleum Exploration and Economics, p. 511–554.

Hoare, J.M., Condon, W.H., and Patton, W.W., Jr., 1964, Occurrence and origin of laumontite in Cretaceous sedimentary rocks in western Alaska, *in* U.S. Geological Survey Staff, Geological Survey research 1964, Chapter C: U.S. Geological Survey Professional Paper 501-C, p. C74–C78.

Howell, D.G., 1996, Kandik Basin, *in* Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995 National Assessment of United States Oil and Gas Resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series-30, Release 2, CD-ROM.

Kirschner, C.E., 1988, Map showing sedimentary basins of onshore and continental shelf areas, Alaska: U.S. Geological Survey Miscellaneous Investigations Series Map 1873, 1 sheet, scale 1:2,500,000.

———1994, Interior basins of Alaska, *in* Plafker, George, and Berg, H.C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-1, p. 469–493.

Kurtak, J.M., Klieforth, R.F., Clark, J.M., and Maclean, E.A., 2002, Mineral investigations in the Koyukuk mining district, northern Alaska: U.S. Bureau of Land Management, BLM–Alaska Technical Report 50, 450 p.

LePain, D.L., Blodgett, R.B., and Clough, J.G., 2003, Sedimentology and hydrocarbon source rock potential of Miocene–Oligocene strata, McGrath Quadrangle—An outcrop analog for the Holitna Basin: Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report 2002-5, 75 p.

Lyle, W.M., Palmer, I.F., Jr., Bolm, J.G., and Flett, T.O., 1982, Hydrocarbon reservoir and source-rock characteristics from selected areas of southwestern Alaska: Alaska Division of Geological & Geophysical Surveys Professional Report 77, 15 p., 7 sheets, scale 1 inch = 25 feet.

Mendenhall, W.C., 1902, Reconnaissance from Fort Hamlin to Kotzebue Sound, Alaska, by way of Dall, Kanuti, Allen, and Kowak rivers: U.S. Geological Survey Professional Paper 10, 68 p., 2 sheets.

Mendenhall, W.C., 1905, Geology of the central Copper River region, Alaska: U.S. Geological Survey Professional Paper 41, 133 p., 4 sheets, scale 1:250,000.

Merritt, R.D., 1986, Alaska coal fields and seams: Alaska Division of Geological & Geophysical Surveys Public Data File 86-67, 41 p.

———1988, Alaska bituminous coal and anthracite: Alaska Division of Geological & Geophysical Surveys Public Data File 88-15, 116 p.

Merritt, R.D., and Hawley, C.C., 1986, Map of Alaska's coal resources: Alaska Division of Geological & Geophysical Surveys Special Report 37, 1 sheet, scale 1:2,500,000.

Miller, T.P., 1994, Geothermal resources of Alaska, in Plafker, G., and Berg, H.C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-1, p. 979–987.

Miller, T.P., Barnes, Ivan, and Patton, W.W., Jr., 1973, Geologic setting and chemical characteristics of hot springs in central and western Alaska: U.S. Geological Survey Open-File Report 73-188, 19 p., 2 sheets.

Miller, R.D., Davis, J.C., Olea, Ricardo, Tapie, Christian, Laflen, D.R., and Fiedler, Mitchell, 2002, Delineation of coalbed methane prospects using high-resolution seismic reflections at Fort Yukon, Alaska: Lawrence, Kansas, Kansas Geological Survey, Open-File Report 2002-16, 47 p.

Motyka, R.J., Moorman, M.A., and Liss, S.A., 1983, Geothermal resources of Alaska: Alaska Division of Geological & Geophysical Surveys Miscellaneous Publication 8, 1 sheet, scale 1:2,500,000.

Mull, C.G., Bundtzen, T.K., and Reifenstuhl, R.R., 1995, Hydrocarbon potential of the Lower Kuskokwim River area, Yukon–Kuskokwim Delta, southwest Alaska: Alaska Division of Geological & Geophysical Surveys Public Data File 95-28, 34 p.

Patton, W.W., Jr., 1970, Petroleum possibilities of the Yukon-Koyukuk province, Alaska: U.S. Geological Survey Open-File Report 70-257, 13 p., 1 sheet.

Patton, W.W., Jr., and Miller, T.P., 1966, Regional geologic map of the Hughes Quadrangle, Alaska: U.S. Geological Survey Miscellaneous Investigations 459, 1 sheet.

Patton, W.W., Jr., Box, S.E., Moll-Stalcup, E.J., and Miller, T.P., 1994, Geology of west-central Alaska, *in* Plafker, George, and Berg, H.C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North America, vol. G-1, p. 241–269.

Patton, W.W., Jr., Moll, E.J., Dutro, J.T., Jr., Silberman, M.L., and Chapman, R.M., 1980, Preliminary geologic map of Medfra Quadrangle, Alaska: U.S. Geological Survey Open-File Report 80-811-A, 1 sheet, scale 1:250,000.

Peapples, P.R., 2004, Summary of coalbed methane studies, Delta Junction area, Alaska: Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report 2004-4B, 11 p.

Phillips, J.D., and Saltus, R.W., 2005, Thickness of sedimentary rocks in the Yukon Flats basin, east-central Alaska, as estimated using constrained iterative gravity inversion [abs.]: Geological Society of America Abstracts with Programs v. 37, no. 4, p. 94.

Plangraphics, Inc., 1983, Alaska coal mined land inventory, *in* Report for the Alaska Abandoned Mined Land Reclamation Program: Prepared for the Alaska Department of Natural Resources, Division of Minerals and Energy Management, 247 p., 2 sheets, scale 1:2,500,000.

Player, Gary, 1976, The Little Tonzona coal bed near Farewell, Alaska—An important extension of the coal fields north of the Alaska Range: Report by Consulting geologist Gary Player, 17 p.

Rao, P.D. and Wolff, E.N., 1980, Characterization and evaluation of washability of Alaskan coals: University of Alaska Mineral Industry Research Laboratory Report No. 42, 47 p .

Rao, P.D. and Wolff, E.N., 1982, Characterization and evaluation of washability of Alaskan coals—Phase III, Selected seams from the northern Alaska, Nulato, Eagle, Nenana, Broad Pass, Kenai, Beluga, and Chignik coal fields: University of Alaska Mineral Industry Research Laboratory Report No. 62, 63 p.

———1982, Characterization and evaluation of washability of Alaskan Coals—Phase IV, Selected seams from the northern Alaska, Chicago Creek, Unalakleet, Nenana, Matanuska, Beluga, Yentna, and Herendeen Bay coal fields: University of Alaska Mineral Industry Research Laboratory Report No. 63, 60 p.

Rao, P.D., Walsh, D.E., Phillips, N., Jr., and Charlie, K.G., 1991, Characterization and washability studies of raw coal from the Little Tonzona Field, Alaska: University of Alaska Mineral Industry Research Laboratory Report No. 88, 120 p.

Reifenstuhl, R.R., 2006, Yukon Flats Basin, Alaska: Reservoir characterization study: Alaska Division of Geological & Geophysical Surveys Report of Investigation 2006-1, 25 p.

Saltus, R.W., Phillips, J.D., Stanley, R.G., Till, Alison, and Morin, R.L, 2007, Geophysical characterization of pre-Cenozoic basement for hydrocarbon assessment, Yukon Flats, Alaska: U.S. Geological Survey Open File Report 2007-1208, 1 plate.

Schrader, F.C., 1904, A reconnaissance in northern Alaska across the Rocky Mountains, along Koyukuk, John, Anaktuvuk, and Colville rivers and the Arctic Coast to Cape Lisburne, in 1901: U.S. Geological Survey Professional Paper 20, 139 p., 2 sheets, scale 1:1,250,000.

Sloan, E.G., Shearer, G.B., Eason, J.E., and Almquist, C.L., 1979, Reconnaissance survey for coal near Farewell, Alaska: U.S. Geological Survey Open-File Report 79-410, 18 p., 4 sheets, scale 1:250,000.

Smith, P.S. and Mertie, J.B., Jr., 1930, Geology and mineral resources of northwestern Alaska: U.S. Geological Survey Bulletin 815, 351 p., 4 sheets, scale 1:500,000.

Solie, D.N., and Dickey, D.B., 1982, Coal occurrences and analyses, Farewell–White Mountain area: Alaska Division of Geological & Geophysical Surveys Alaska Open-File Report 160, 20 p., 1 sheet, 1 inch = 20 meters.

Stanley, R.G., 1988, Hydrocarbon source potential and thermal maturity of the Sanctuary Formation (middle Miocene), northern foothills of the Alaska Range, *in* Galloway, J.P., and Hamilton, T.D., eds., Geologic Studies in Alaska by the U.S. Geological Survey during 1987: U.S. Geological Survey Circular 1016, p. 117–120.

Stanley, R.G., Ahlbrandt, T.S., Charpentier, R.R. Cook, T.A., Crews, J.M., Klett, T.R., Lillis, P.G., Morin, R.L., Phillips, J.D., Pollastro, R.M., Rowan, E.L., Saltus, R.W., Schenk, C.J., Simpson, M.K., Till, A.B., and Troutman, S.M., 2004, Oil and gas assessment of Yukon Flats, east-central Alaska, 2004: U.S. Geological Survey Fact Sheet 2004-3121, 2 p.

Stanley, R.G., Flores, R.M., and Wiley, T.J., 1992, Fluvial facies architecture in the Tertiary Usibelli Group of Suntrana, central Alaska, *in* Bradley, D.C., and Ford, A.B., eds., Geologic studies in Alaska by the U.S. Geological Survey, 1990: U.S. Geological Survey Bulletin 1999, p. 204–211.

Stanley, R.G., McLean, Hugh, and Pawlewicz, M.J., 1990, Petroleum source potential and thermal maturity of the Tertiary Usibelli Group of Suntrana, Alaska, *in* Dover, J.H., and Galloway, J.P., eds., Geologic studies in Alaska by the U.S. Geological Survey, 1989: U.S. Geological Survey Bulletin 1946, p. 65–76.

Stephenson, W.J., Williams, Robert, Odum, Jack, Worley, David, Barker, Charles, Clark, Arthur, and Clough, James, 2002, Reconnaissance shallow seismic investigation of depth-to-bedrock and possible methane-bearing coalbeds, Galena, Alaska: U.S. Geological Survey Open-File Report 02-450, 34 p., http://pubs.usgs.gov/of/2002/ofr-02-450/

Tailleur, I.L., Brosge, W.P., and Reiser, H.N., 1967, Oil shale in the Christian region of northeastern Alaska: U.S. Geological Survey Professional Paper 575, Chapter A, p. A12.

Tyler, Roger, Scott, A.R., and Clough, J.G., 2000, Coalbed methane potential and exploration targets for rural Alaska communities: Alaska Division of Geological & Geophysical Surveys Preliminary Interpretive Report 2000-2, 169 p.

Underwood, M.B., Laughland, M.M., Wiley, T.J., and Howell, D.G., 1989, Thermal maturity and organic geochemistry of the Kandik Basin region, east-central Alaska: U.S. Geological Survey Open-File Report 89-353, 41 p.

Van Kooten, G.K., Watts, A.B., Coogan, James, Mount, V.S., Swenson, R.F., Daggett, P.H., Clough, J.G., Roberts, C.T., and Bergman, S.C., 1997, Geologic investigations of the Kandik area, Alaska, and adjacent Yukon Territory, Canada: Alaska Division of Geological & Geophysical Surveys Report of Investigation 96-6A, 3 sheets, scale 1:200,000.

Wahrhaftig, Clyde, Bartsch-Winkler, S., and Stricker, G.D., 1994, Coal in Alaska, *in* Plafker, George, and Berg, H.C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North America, vol. G-1, p. 937–978.

Wahrhaftig, Clyde, and Hickcox, C.A., 1955, Geology and coal deposits, Jarvis Creek coal field, Alaska: U.S. Geological Survey Bulletin 989-G, p. 353-367, 3 sheets.