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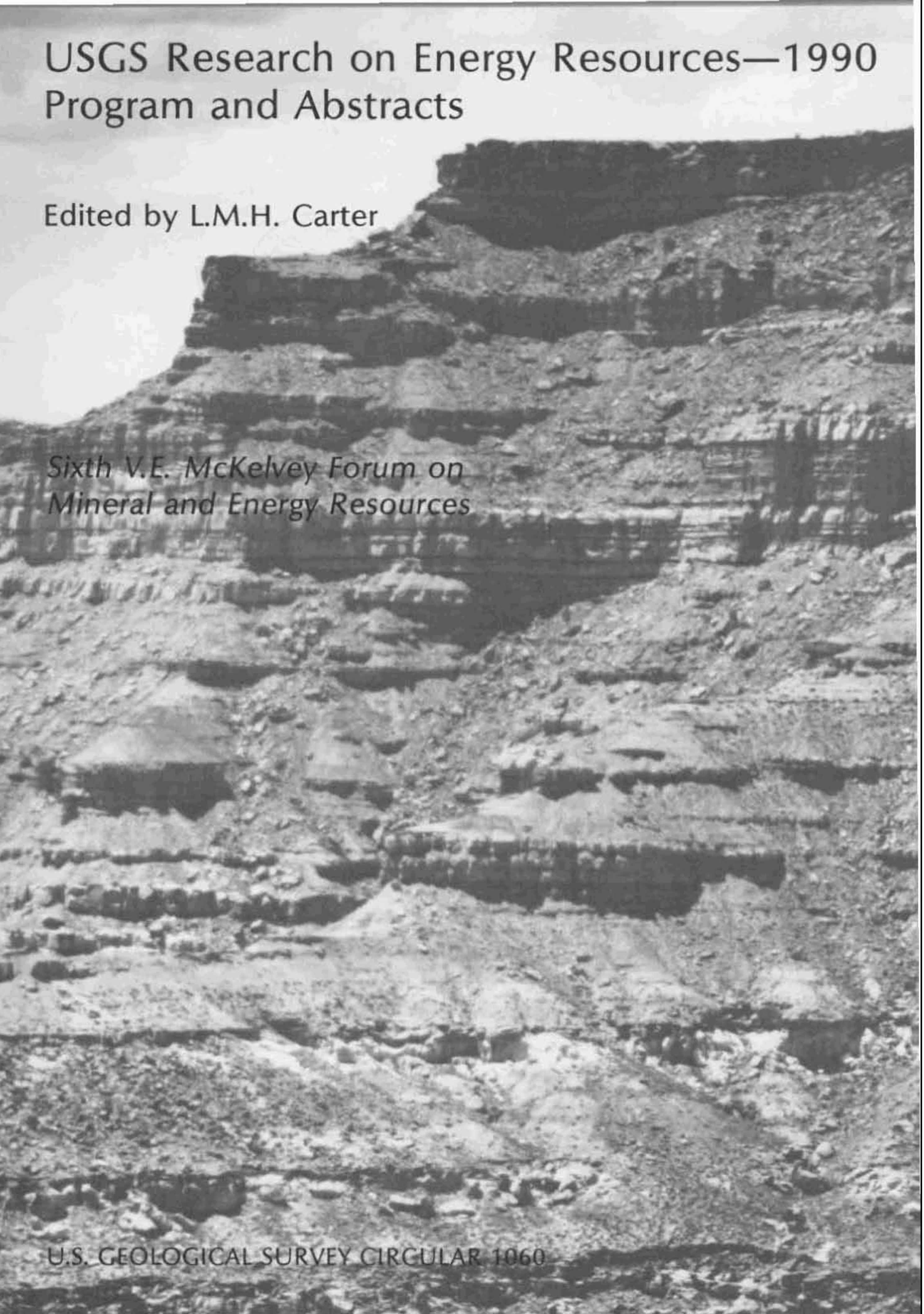

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GLORIA Images from the Gulf of Alaska and British Columbia—Subduction Zones, Transforms, and Channels

T.R. Bruns, P.R. Carlson, A.J. Stevenson, M.A. Fisher, H.F. Ryan, D.M. Mann, Maxwell Dobson, Quentin Huggett, Lindsay Parson, and N.G.T. Fannin

GLORIA data obtained during 1986, 1988, and 1989 in the Gulf of Alaska show the sea-floor morphology from Unimak Pass to Dixon Entrance, from the shelf break seaward to about 400 km. An additional 70-km-wide swath was imaged along the British Columbia margin to follow the trace of the Queen Charlotte fault south of Dixon Entrance. Major features seen include the following continental-margin deformational structures and submarine-channel systems: (1) The Aleutian convergent margin is characterized by canyons and numerous slumps along the upper and middle slope. Unimak Ridge is a prominent midslope feature from Sanak Island to Unimak Pass. Along the lower trench slope, the structure ranges from highly discontinuous folds to long continuous folds. (2) Southeast of the Aleutian Trench, ocean plate structural and bathymetric features are either parallel to magnetic anomalies, or are parallel to the trench and caused by normal faults as the plate bends into the Aleutian Trench subduction zone. (3) The margin between Middleton Island and Cross Sound is commonly either extensively cut by dendritic drainages or covered by glacially derived sediment. Large actively growing structures are present beneath the slope between Middleton Island and Pamplona Spur, but they are notably absent from Pamplona Spur to Cross Sound. (4) From Cross Sound to south of the Queen Charlotte Islands, the active trace of the Queen Charlotte fault is strikingly imaged as a narrow linear feature composed of ridges and troughs that have vertical offset. Horizontal offset is visible on a canyon wall and on offset channels. Numerous large anticlines are present seaward or, and trend parallel to, the fault. The active fault trace steps westward at the Tuzo Wilson Knolls, which structurally may be part of a small spreading ridge segment or pull-apart basin. (5) On the abyssal plain, turbidite channels form three separate drainage systems. The Surveyor channel system is comprised of tributary channels that arise along the margin between Pamplona Spur and Alsek Canyon, and that coalesce on the abyssal plain into a single channel (Surveyor channel) which ends at the Aleutian Trench southeast of Kodiak Island. The Chirikof channel system (new name) similarly arises from the margin between Fairweather Ground and Cross Sound, eventually forming a single channel that terminates in turbidite fans south of the Kodiak-Bowie Seamount chain. The Mukluk-Horizon channel system starts along southeast Alaska, with drainages from submarine fans joining to form Mukluk and Horizon channels. Both channels end more than 1,000 km away on the Tufts abyssal plain.

Natural Gas Hydrates in the Prudhoe Bay–Kuparuk River Area of Northern Alaska

Timothy S. Collett

Gas hydrates are crystalline substances composed of water and gas in which the solid-water lattice accommodates the gas molecules in a cage-like structure, or clathrate. Significant quantities of naturally occurring gas hydrates have been detected in many regions of the Arctic including Siberia, the Mackenzie River delta, and the North Slope of Alaska. Gas hydrates are generally regarded as a potential (unconventional) source of natural gas. Soviet researchers, however, have demonstrated that hydrates are an immediate, producible source of natural gas; their Messoyakh gas field in the West Siberian Basin has reportedly produced about 100 billion cubic feet of gas from hydrates over an eight-year period (1971–1978).

The primary purpose of the U.S. Geological Survey Gas Hydrate Project is to identify gas hydrates and to evaluate the geologic properties controlling their distribution on the North Slope of Alaska. Our North Slope studies suggest that the methane-hydrate stability zone is areally extensive beneath most of the coastal plain province and has thicknesses greater than 3,000 feet in the Prudhoe Bay area. Thermal conditions, however, preclude the occurrence of gas hydrates in the north-central part of the National Petroleum Reserve in Alaska and in the foothills east of Umiat.

Gas hydrates have been identified in 34 exploratory and production wells by using well-log responses calibrated to the response of an interval in one well where gas hydrates were recovered in a core by ARCO Alaska and Exxon. Most gas hydrates that we have identified occur in six laterally continuous Upper Cretaceous and lower Tertiary sandstone and conglomerate units; all these hydrates are geographically restricted to the area overlying the eastern part of the Kuparuk River oil field and the western part of the Prudhoe Bay oil field. Many wells have multiple gas-hydrate-bearing units, with individual occurrences ranging in thickness from 5 to 60 feet. Most of the gas hydrates occur below the base of ice-bearing permafrost; however, high gas readings on mud logs from some wells in the Kuparuk River oil field suggest that several of the gas-hydrate-bearing units extend up-dip into the ice-bearing permafrost sequence. Recent drilling and geologic/geochemical sampling have revealed the presence of a gas-hydrate/free-gas contact at the predicted base of the methane-hydrate stability zone in the west end of the Prudhoe Bay oil field. Our calculations suggest that the volume of gas within the delineated gas hydrates of northern Alaska is approximately 8 to 10 TCF (trillion cubic feet) (2.4×10^{11} to 2.9×10^{11} m^3), or about one-third the volume of conventional gas in the Prudhoe Bay field. Because of the low drilling density outside the Prudhoe Bay–Kuparuk River area, many more gas hydrate occurrences may exist.

Stable carbon isotope geochemical analysis of well cuttings in the Kuparuk River area indicates that rocks within and below the zone of hydrate stability contain a mixture of microbial and thermogenic gas. We suggest

Cretaceous and Tertiary Sagavanirktok Formation in the Prudhoe Bay–Kuparuk River Area, Northern Alaska

Timothy S. Collett and Kenneth J. Bird

Detailed well correlation sections and ongoing USGS studies of gas hydrates and basin evolution have provided new insights on the stratigraphic framework of the Cretaceous and Tertiary Sagavanirktok Formation in the Prudhoe Bay–Kuparuk River area of the North Slope. The Sagavanirktok Formation is the youngest part of the Brookian sequence, a sequence composed of siliciclastic rocks whose provenance is the Brooks Range, to the south. The study area overlies the axis of the Barrow arch and marks the boundary between a foreland basin to the south (Colville basin) and a passive margin (Beaufort margin) to the north. The principal oil accumulations of the Brookian sequence in the Prudhoe Bay–Kuparuk River area are in the informally named West Sak and Ugnu sands of the Sagavanirktok Formation. ARCO Alaska estimates that the combined oil in-place in these two reservoirs could be as large as 40 billion barrels. Our studies of gas hydrates, crystalline substances composed of water and gas, within the Sagavanirktok Formation suggest that the volume of methane gas within the hydrates of this area is about 8 to 10 trillion cubic feet at standard temperature and pressure.

The Sagavanirktok Formation consists of Upper Cretaceous and Tertiary shallow-marine shelf and delta plain deposits composed of sandstone, shale, conglomerate, and coal. The areal distribution of the Sagavanirktok Formation is limited to the coastal plain of the eastern half of the North Slope and the adjacent continental shelf. The regional structure of the Sagavanirktok Formation in this area is a gentle (1°–2°) northeasterly-dipping monocline. The present regional northeast tilt is the combined result of sediment loading and continued thermal subsidence of the Beaufort margin. In the study area the Sagavanirktok Formation thickens from southwest (≈1,000 m) to northeast (≈2,000 m), and conformably overlies marine shale of the Canning Formation. Depositional strike migrated from a nearly north-south trend in Late Cretaceous time to its present west-northwest trend in about Eocene time.

Detailed well-correlation sections show the Sagavanirktok Formation in this area consists of complexly interbedded marine and nonmarine deposits that include at least one regional unconformity. The lowermost sandstone sequence within the Sagavanirktok Formation includes the West Sak and Ugnu sands. The Late Cretaceous West Sak interval represents transitional inner-shelf and delta-front deposits. The primary West Sak reservoirs are within the upper part of the sequence, which consists of two distinct and laterally extensive sandstone units. The West Sak interval is separated from the overlying Ugnu interval by a regionally extensive marine (30–45-m-thick) mudstone. The Late Cretaceous–early Tertiary Ugnu interval (80 to 100 m thick) consists of a series of interbedded sandstone and mudstone units. Overlying the Ugnu interval is a 250–300-m-thick nonmarine interval composed of numerous fining-upward channel and overbank siltstone and sandstone units. This nonmarine sequence is overlain by a 200–300-m-thick interbedded sandstone and mudstone marine sequence that was deposited during a basin-wide marine transgression in Eocene time. This sequence thins southwesterly and laterally coarsens to a sandstone in the eastern part of the Kuparuk River field. The upper boundary of this marine sequence is an erosional unconformity. East of Prudhoe Bay field, near the delta of the Sagavanirktok River, this unconformity has eroded part of the underlying marine sequence; however, to the southwest into the Kuparuk River area, the unconformity apparently disappears and the sequence becomes conformable. The rocks overlying the unconformity are generally of uniform composition both laterally and vertically in the section, and appear to have been deposited in a delta-plain environment. Individual sandstone units in this interval thicken to the northeast, which may represent the direction of the northeast-prograding deltaic depocenter. Other unconformities may occur within the Sagavanirktok Formation; however, with our present well-log data base we are unable to identify any additional hiatuses.

In the Kuparuk River area the Sagavanirktok Formation is cut by northwesterly-trending high-angle normal faults, generally downthrown to the east. A similar set of northwesterly-trending faults cut the older rocks in this area, suggesting a genetic linkage with the faults within the Sagavanirktok Formation. These faults are important in that they may serve as conduits for oil and gas migration from the underlying Prudhoe Bay field. Geochemical similarities suggest that oils, and presumably the associated gas, within the Sagavanirktok Formation were "spilled" from the underlying Prudhoe Bay Sadlerochit Group reservoir as a consequence of regional tilting during middle to late Tertiary time. We also note that the shallow heavy-oil and gas hydrates occur either up-dip from or near one of the major through-going faults, the Eileen fault zone.

New Information on the Nuwok Member of Sagavanirktok Formation; Implications for Petroleum Geology of the North Slope and Beaufort Sea—Evidence from Carter Creek, Arctic National Wildlife Refuge (ANWR), Alaska

T.D. Fouch, E.M. Brouwers, D.H. McNeil, Louie Marincovich, Jr., K.J. Bird, and H. Rieck

Examination of the Nuwok Member of the Sagavanirktok Formation has identified at least 220 m of Nuwok-like strata, a significant addition to the previously described 80 m assigned to the member. The beds are exposed on the north limb of the Marsh Creek anticline along Carter Creek, which is located about 160 km east of Prudhoe Bay and 0.8 km south of the Beaufort Sea (lat 70° N.). Beds are deeply weathered and eroded, but where trenched, yield exposures sufficient for stratigraphic reconstruction, and for sedimentologic, paleomagnetic, and biostratigraphic sampling and analysis.

The Nuwok at Carter Creek represents marine shelf and prodeltaic sedimentation and consists primarily of lithified and unconsolidated pebbly fine sands and silts. Upper parts of the Nuwok contain concretions, and medium- and coarse-grained sandy units. Lower strata of the Nuwok contain laminated to thin flat beds of siltstone, argillaceous claystone, and fine-grained sandstone, associated with ostracode and benthic foraminifers that suggest middle-shelf water depths. Abundant suspended siliceous pebbles (dropstones?) and a high proportion of rafted plant material (fine organic debris, twigs, limbs, and mineralized and woody logs) express considerable terrestrial input. Some units contain pebbles, their long axes randomly aligned, suspended in a poorly sorted, very fine grained structureless matrix; these probably represent submarine debris flows.

The section displays an overall upward-shoaling trend indicated by progressive upward coarsening of the overall sequence and of individual units, increasing thickness of bed sets and scale of crossbeds, concentrations of large log fragments upsection, and the appearance of inner-shelf mollusk and ostracode assemblages. Coarsest strata are best developed between 95–105 m and 155–176 m above the base of the measured exposures; they include units several meters thick composed of prograding unconsolidated medium- and coarse-grained sand units in multiple cycles of offlap-downlap crossbed sets (some greater than 10 cm thick) each mantled by clayey drapes (traction and suspension cycles). This association suggests periodic episodes of near-shore progradational sediment transport across a shallow (inner-shelf?) sea floor.

The precise age of the Nuwok Member at Carter Creek is uncertain. Benthic fossil groups yield widely disparate ages. A prolific calcareous benthic foraminifer assemblage ranges through the entire Nuwok sequence. The ubiquitous occurrence of *Turrilina alsatica*, known from the western North Atlantic, the North Sea, and northwestern Europe, indicates a late Oligocene age; this age is supported by Sr 87/86 ages of 23.8–27.0 Ma from Nuwok foraminifers and mollusks. The foraminifer assemblage is diverse and abundant for a high-latitude site; absolute diversity is greater than 70 species, and specimen abundance is as high as 100 per gram. The fauna is dominated by *Cibicidoides*, *Cribroelphidium*, *Elphidiella*, *Melonis*, *Nuttallides*, *Trifarina*, *Turrilina*, as well as miliodids, nodosarids, polymorphinids, and unilocular genera. A normal marine shelf environment is indicated.

The Nuwok contains two distinct mollusk assemblages with mutually exclusive species: a lower *Chesapecten nuwokensis* zone, ranging from the base of the sequence to a concretionary unit at 95 to 105 m, and an upper *Arctica carteriana* zone, extending from 105 to 300 m from the base. The mollusks are all Atlantic-derived, indicating a pre-Bering Strait age (>3 Ma). Generic level correlations and the evolutionary lineage of *Chesapecten* imply a maximum age of middle Miocene.

Age arguments based on ostracodes are weaker, being based on the presence of extant species, correlation with global climatic trends, and genus-level comparison with lower latitude faunas. Two ostracode assemblages are recognized: the lower assemblage ranges from 60 to 90 m above the base and includes warm-water genera (*Cytheretta*, *Echinocythereis*, *Cytherelloidea*); the upper assemblage, ranging from 90 to 245 m above the base, consists of temperate to warmer subfrigid genera (*Rabilimis*, *Robertsonites*, *Cytheropteron*, *Paracyprideis*). Several taxa range throughout the section, but most species show stepwise disappearance believed related to changes in climate and water depth. Warm-water genera do not occur above 110 m, most dropping out just below a concretionary zone at 95 to 105 m.

Paleomagnetic analysis indicates that the Nuwok strata have normal polarity from the base of the measured section to about 40 m, reversed polarity from the 40 to 180 m level m with several ≈10-m-thick sequences of normal polarity, one of which corresponds to the concretionary zone extending from 95 to 100 m; and normal polarity from 180 to 190 m. Lack of adequate exposures precludes collection of samples from 190 to 300 m. Laboratory analysis indicates some magnetization is carried by secondary minerals. However, the presence of clearly defined polarity zones suggests that the mineralogic changes occurred shortly after deposition.

Strata that are presumably partial age equivalents to the Nuwok (Oligocene and younger—based upon palynomorph interpretations) have been penetrated in drill holes west of Carter Creek near the Canning River, and in the Beaufort Sea north of Camden Bay. Excellent petroleum reservoir sandstone units were penetrated in these tests that may be represented by the thick inner-shelf progradational sand sequences exposed along Carter Creek.

The Search for Subtle Traps Across Onshore Alaska

David G. Howell

For most of this century the U.S. Geological Survey has collaborated with industry and academic scientists exploring and characterizing the petroleum potential of Alaska. Discoveries in Cook Inlet, Point Barrow, and Prudhoe Bay are the obvious successes. These three oil and gas fields lie along north and south margins of continental Alaska; between these two areas Alaska is viewed as a collage of tectonostratigraphic terranes that have agglomerated since approximately Middle Jurassic time. The stratigraphy of these terranes indicates a tectonic mixing of oceanic magmatic arcs and continental slivers. The latter presumably represent truncated portions of the North American margin. Mapping and geophysical experiments indicate that these terranes are either enveloped or underlain by a vast volume of gray-wacke. Although these rocks initially posed as an intriguing potential hydrocarbon source, numerous Rock-Eval and associated thermal studies now suggest that the sedimentary strata are over-mature, rendering a deep-gas scenario only improbable.

The greater part of the accretion tectonism of interior Alaska had ended by the close of the Mesozoic. Latest Cretaceous to Neogene sedimentary overlap sequences reflect three general phases of basin accumulation, all of which are nonmarine. Locally these basin strata are as thick as 5 km, but nowhere is there thought to be anything other than small quantities of dry-gas resources.

In spite of this pessimistic forecast, two areas remain of interest owing to recent preliminary studies that suggest the potential for oil accumulations. The first is the Yukon Flats–Kandik basin area of east-central Alaska. Here, thermally over-mature Mesozoic strata lie structurally(?) above a thick Precambrian to lower Mesozoic sequence that remains thermally within the oil window; furthermore, several horizons within this lower sequence are excellent potential hydrocarbon source rocks. Understanding the tectonic history, the regional structural patterns, and the subsurface extent of thermally cool strata will better enable us to evaluate this region.

The second area is the region along the northern margin of the Brooks Range. Here, tectonic duplexing likely thickened and shortened sequences of organically rich lower and middle Mesozoic strata along with early foreland basin deposits (Upper Jurassic and Lower Cretaceous). These same beds are the source of the oil trapped in the giant Prudhoe Bay field, and migration of the oil probably followed pathways up the south flank of the northerly migrating lithospheric bulge, which formed as a consequence of tectonic loading in the interior zone of the Brooks Range thrust belt. Because this bulge once existed farther south, tracking its movement history may predict other occurrence of trapped oil.

Is There a Future for 4.0 Trillion Tons of Low-Sulfur Alaskan Coal?

Gary D. Stricker

With an ever-increasing interest in acid rain, the demand for and utilization of low-sulfur coal will increase. Alaska's coal resources have a unique position in the United States' overall coal resource picture and can only be described as enormous: 4.0 trillion tons of hypothetical onshore coal. Alaska's coal is also low in sulfur: mean total sulfur content of 0.34 percent (range is 0.06 to 6.6 percent, $n=262$). Mean ash content is 10.9 percent and mean apparent rank is subbituminous B. By contrast, Carboniferous coal of the Appalachian region and Interior Province has a mean total sulfur content of 2.34 percent (range of 0.1 to 19.2 percent, $n=5{,}497$); mean ash content of 11.16 percent; and a mean apparent rank of high-volatile A bituminous. Lower 48 Cretaceous and Tertiary coals have a mean total sulfur content of 0.86 percent (range of 0.02 to 18.9 percent, $n=2{,}754$); mean ash content of 11.97; and a mean apparent rank of subbituminous B. Thus, Alaskan coal's mean sulfur content is 2.5 times less than the mean for western U.S. coal and 6 times less than the mean for Carboniferous U.S. coal.

A 1987 report by Wood and Bour lists 50 major and minor coal fields and occurrences of coal in Alaska.

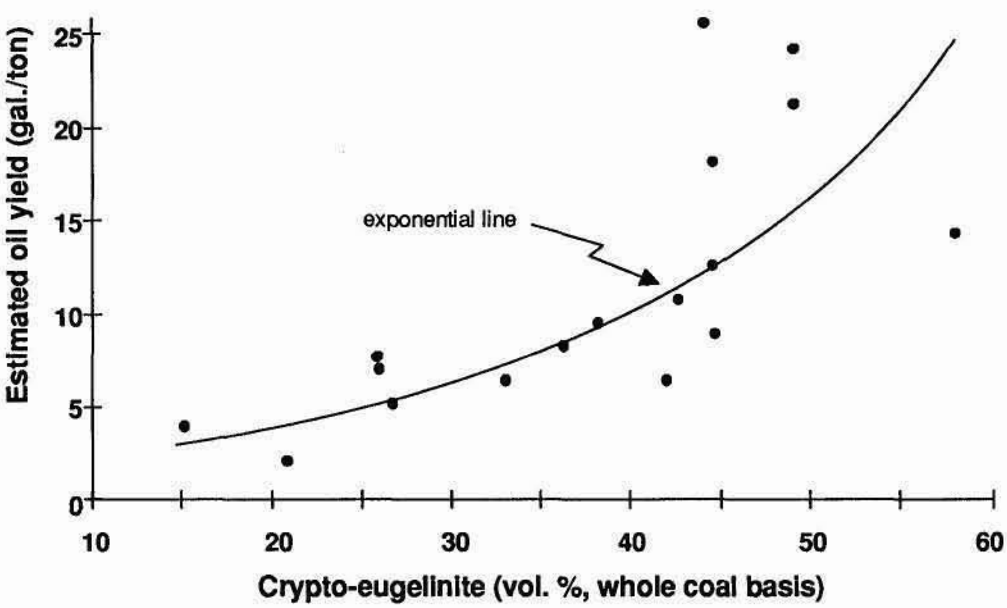

Figure 1 (Stanton). Low-temperature carbonization yields of Wyodak-Anderson coal samples.

The bulk of Alaska's coal resources are in six major coal fields, which are (in order of decreasing economic potential) Nenana, Cook Inlet, Matanuska, Chignik–Herendeen Bay, North Slope, and Bering River. The Tertiary Nenana coal basin, containing the only active coal mine in Alaska, has the most economic potential. Mean total sulfur content in that coal is 0.24 percent (range of 0.1 to 1.5 percent), mean ash content is 9.9 percent, and mean apparent rank is subbituminous C. Resources are estimated to be 1 billion tons of identified coal and 2 billion tons of hypothetical coal.

In the Cook Inlet region, two coal fields are of interest: Beluga and Kenai, in both of which coal is of Tertiary age. In the Kenai field, mean total sulfur content is 0.33 percent (range of 0.06 to 1.1 percent), mean ash percent is 14.3, and apparent rank is subbituminous C. Resources are estimated to be 320 million tons identified and 35 billion tons hypothetical. In the Beluga field, mean total sulfur is 0.18 percent (range of 0.08 to 0.33 percent). Mean ash content is 16.4 percent and apparent rank is subbituminous C. This field contains 10 billion tons identified and 30 billion tons of hypothetical coal.

The Tertiary Matanuska coal field has a mean total sulfur content of 0.45 percent (range of 0.2 to 1.5 percent). Mean ash content is 12.3 percent and mean apparent rank is high-volatile A bituminous. Coal resources are estimated as 150 million tons identified and 500 million tons hypothetical.

Coal in the Chignik–Herendeen Bay fields is Cretaceous in age. Total mean sulfur content for these coal units is 0.82 percent (range 0.3 to 1.3 percent), mean ash content is 13.6 percent, and mean apparent rank is high-volatile B bituminous. Resources are estimated to be 360 million tons identified and 3 billion tons hypothetical.

The Alaskan North Slope has the largest estimated coal resources in Alaska. Coal ranges in age from Cretaceous to Tertiary. For the Cretaceous coal the total mean sulfur is 0.32 percent (range of 0.01 to 2.02 percent), mean ash content is 10.4 percent, and mean apparent rank is subbituminous B. Resource estimates for the Cretaceous coal are 3.2 trillion tons of hypothetical coal. For the Tertiary coal, the total mean sulfur is 0.37 percent (range of 0.08 to 2.02 percent), mean ash content is 10.6 percent, and mean apparent rank is subbituminous C. No resource estimates are available for Tertiary coal.

The Tertiary Bering River coal field has a mean sulfur content of 1.2 percent (range 0.4 to 5.22 percent). Mean ash content is 13.6 percent and apparent rank is semianthracite. Resources for this tectonically deformed coal field are 110 million tons of identified and 3.5 billion tons of hypothetical coal.

Even though Alaska has 4.0 trillion tons of hypothetical low-sulfur coal, this resource has not been developed. Factors limiting coal development are: (1) increased shipping cost because of large distances to potential markets; (2) inhospitable climate during long and cold winters, which adds to the cost of mining; and (3) little infrastructure in areas where many coal fields are located. Unless the United States and world energy picture changes, this abundant resource will not be utilized in the near future.