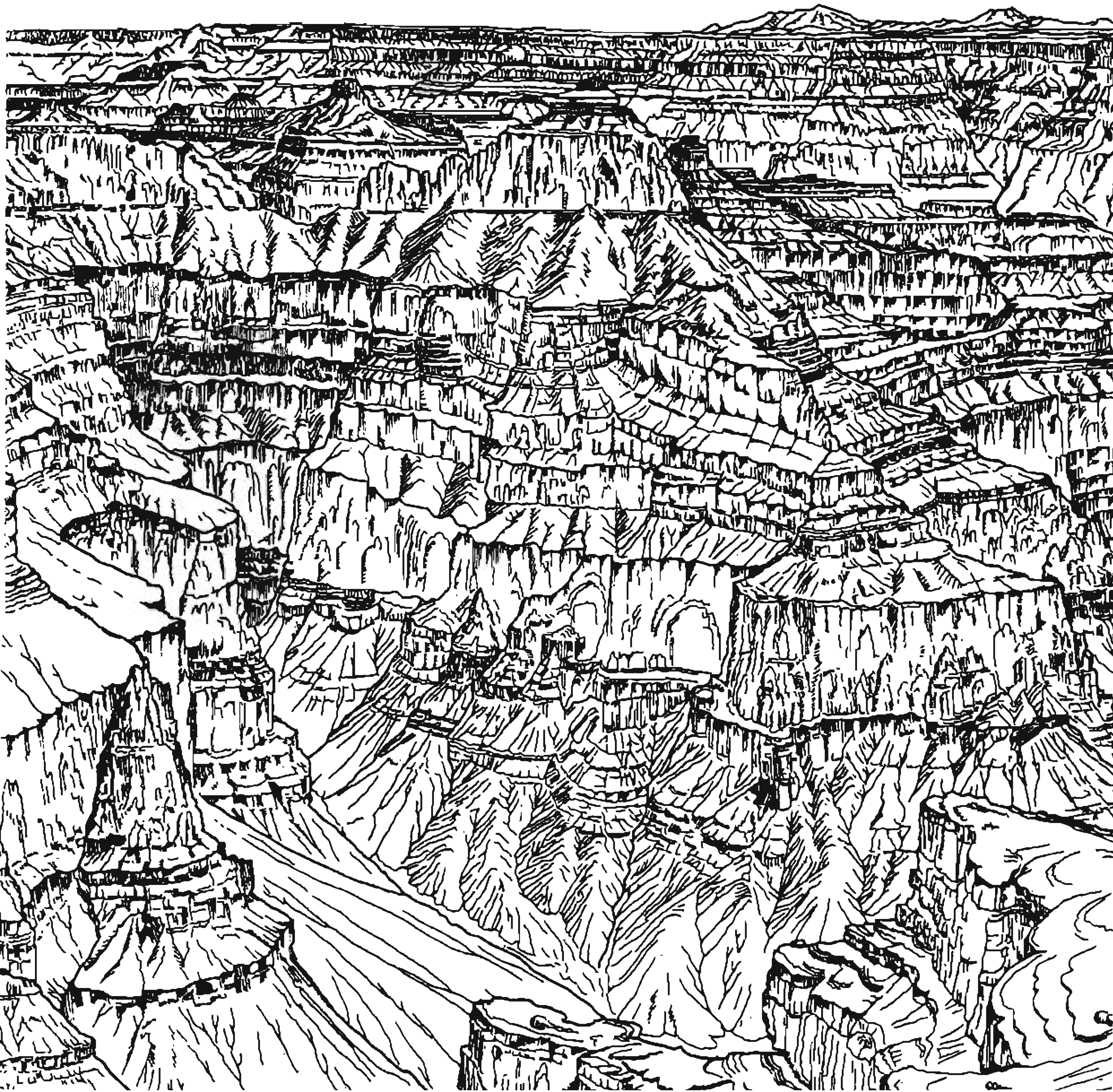
USGS RESEARCH ON ENERGY RESOURCES, 1992

PROGRAM AND ABSTRACTS

EIGHTH V.E. McKELVEY FORUM ON MINERAL AND ENERGY RESOURCES

U.S. GEOLOGICAL SURVEY CIRCULAR 1074



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Edited by L.M.H. CARTER

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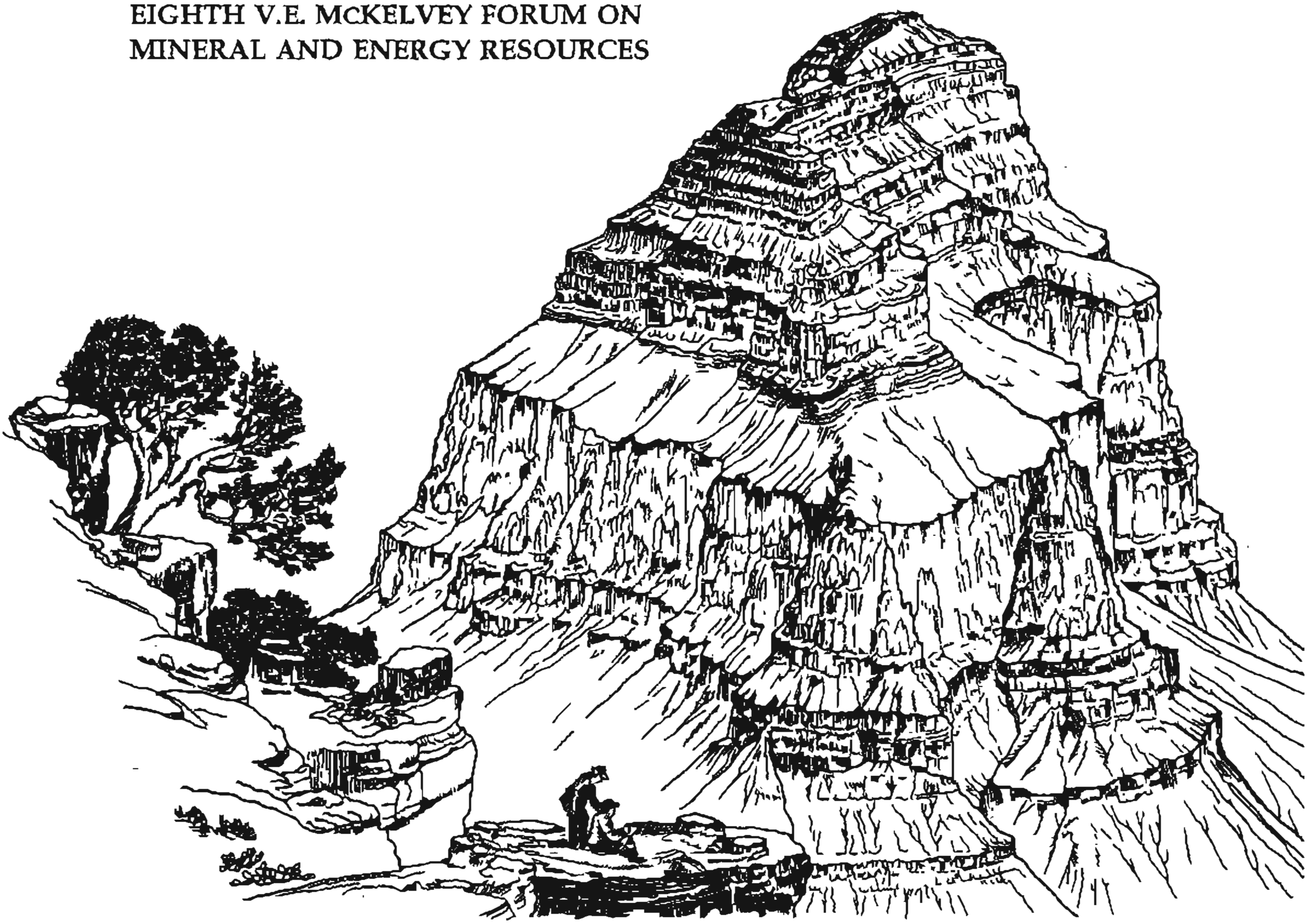


U.S. GEOLOGICAL SURVEY CIRCULAR 1074

Sagavanirktok Formation— A New Look with Seismic Data in the Prudhoe Bay–Kuparuk River Region, Alaskan North Slope

Kenneth J. Bird and Timothy S. Collett

The Upper Cretaceous and Tertiary deltaic Sagavanirktok Formation constitutes the latest stage of filling of the Alaskan North Slope's Colville basin and a treasure trove of energy resources. These resources include an estimated 40–60 billion barrels (in place) of low-gravity oil, 37–44 trillion cubic feet of natural gas in hydrate form, and more than 600 billion metric tons of low-rank coal. Most oil and gas deposits in the Sagavanirktok occur at shallow depths (<1,000 m) in a relatively restricted area overlying the giant oil and gas fields, Prudhoe Bay and Kuparuk River. The first commercial oil production from the Sagavanirktok Formation was initiated in the Milne Point field in 1990 by the Continental Oil Company; however, at this time most Sagavanirktok oil and gas deposits are classified as unconventional resources.

Access to approximately 200 km of multichannel seismic data in the Prudhoe Bay–Kuparuk River region, courtesy of the Exxon Company, provides new insight into the structural and stratigraphic framework of this area. These are the first modern seismic data available to us in this region; they represent a significant addition to our study of gas hydrates in the Sagavanirktok Formation, a project partially funded by the U.S. Department of Energy. Preliminary analysis of the seismic data confirms the northeast-trending regional dip and northward-expanding thickness of the Sagavanirktok Formation. The clinoform style of progradation, well demonstrated to the west in the National Petroleum Reserve in Alaska, continues through the Prudhoe Bay–Kuparuk River region: the Sagavanirktok representing the topset and the coeval Canning Formation representing the foreset and bottomset parts of the clinoform sequence. Bundles of strong reflections in the topset strata delineate the main coal-bearing intervals. Local high-amplitude reflectors in the bottomset strata may indicate turbidite sand accumulations within prodelta mudstone of the Canning Formation. In the region of the Prudhoe Bay oil field, prominent flat-lying reflections, which occur discontinuously at about 0.7 s (two-way travel time), cut across northeasterly dipping reflectors that mark the regional dip of the Sagavanirktok Formation. Preliminary analysis reveals that these flat-lying reflections occur at a depth of about 950 m, approximately coincident with the calculated base of the hydrate stability zone in this area. In the marine environment, prominent reflections coincident with the base of the hydrate stability zone are well known (bottom simulating reflectors, BSR's) and are postulated to be the result of free gas trapped below a hydrate seal. The reflectors observed on the seismic section over the Prudhoe Bay oil field appear to be the onshore equivalent of a BSR.

As production from the Prudhoe Bay and other North Slope oil fields declines, the enormous hydrocarbon resources of the Sagavanirktok Formation will become increasingly important. Exploration for new hydrocarbon resources will require appreciation of subtle structural-stratigraphic traps and other traps unique to the Arctic region, such as gas hydrates. Production of these hydrocarbon resources presents a major challenge and will require innovative approaches and new thinking.

Alaskan North Slope Geothermics, Geodynamics, and Hydrology—Implications for Oil and Gas

Kenneth J. Bird, David G. Howell,
Mark J. Johnsson, and Leslie B. Magoon

Alaskan North Slope petroleum studies by the U.S. Geological Survey (USGS) are focused on the practically unexplored fold-and-thrust belt of the Brooks Range, a region estimated to have considerable resource potential. Questions being addressed include the quality, quantity, and distribution of reservoir- and source-rocks and the timing of trap formation relative to generation and migration of oil and gas. The answers to these questions will have an important bearing on this region's petroleum potential and, therefore, on resource assessment and exploration strategies.

The North Slope is one of the most prolific petroleum provinces in the United States. It currently supplies one-quarter of our daily domestic oil production (≈2 million barrels/day), has productive and nonproductive conventional oil accumulations and nonproductive heavy oil accumulations that originally contained nearly 70 billion barrels of oil (BBO) in place, and has large in-place volumes of principally associated natural gas (≈40 trillion cubic feet of gas, TCFG) that are presently uneconomic. In the 1987 national assessment of undiscovered recoverable conventional oil and gas resources, the USGS estimated that, at the mean, nearly one-quarter of our Nation's remaining undiscovered conventional oil resources (≈13 BBO) and one-seventh of its undiscovered natural gas resources (≈54 TCFG) lie beneath the North Slope and adjacent State offshore waters.

A peculiar feature of discovered North Slope oil and gas accumulations is their geographic concentration in a relatively small area on the foreland—more than 95 percent are located within 60 km of Prudhoe Bay. Yet the considerable volume of undiscovered oil and gas is estimated to be much more widely distributed—about 60 percent in the fold-and-thrust belt region and 40 percent in the foreland region. The fold-and-thrust belt region is estimated to contain undiscovered resources amounting to ≈6 BBO (mean; range 1–18 BBO) and ≈32 TCFG (mean; range, 7–86 TCFG). The basis for these estimates is the existence of hundreds of undrilled structures, the presence of clastic and carbonate reservoir rocks, abundant source rocks, seemingly favorable maturity patterns, oil and gas indications in wells and outcrop, and seven small to medium-sized oil and gas fields (six gas, one oil).

Our current studies are analyzing regional patterns of thermal maturity (based on vitrinite reflectance and conodont color indices) and integrating surface and subsurface geology along a series of five planned transects oriented perpendicular to the fold-and-thrust belt and spaced, on the average, at 200-km intervals. We have completed thermal maturity mapping of the surface and subsurface of the North Slope and two seasons of field work on our first transect, located along the Dalton Highway.

Our findings to late 1991 show that nearly 12 km of uplift has occurred in the central Brooks Range, where reflectance isograds are cut by major thrust faults, indicating that maximum burial postdated at least early phases of thrusting. In the foothills, warping of reflectance isograds indicates that some folding (and faulting?) continued subsequent to thermal imprinting, an observation which suggests that oil and gas exploration in the fold-and-thrust belt may be a matter of looking for re-migrated hydrocarbons. Regional patterns on the surface show that thermal maturity decreases northward from the Brooks Range to the coastline; minimal maturity values are found east of Prudhoe Bay. In the central North Slope (between about long 149° and 158° W.), thermally immature rocks extend nearly to the front of the Brooks Range, whereas to the east and west thermally mature rocks are exposed. We interpret this to indicate regional differential uplift along the strike of the Brooks Range orogen, with greater uplift in the west and east than in the center. This central area should be prospective for oil for longer distances to the south than to adjacent areas west and east.

A related USGS study in the National Petroleum Reserve in Alaska has found that geothermal gradients and heat flow are higher on the north (foreland) side of the basin and lower in the foothills (fold and thrust) belt of the Brooks Range. This thermal pattern is consistent with forced convection by a topography-driven groundwater flow system that would effectively cool the topographically higher fold-and-thrust belt and warm the topographically lower foreland region. Similarities between present-day thermal gradients and vitrinite reflectance profiles suggest that the postulated groundwater flow system probably has been a feature of the fold-and-thrust belt throughout its 150-m.y. history and may have provided a driving mechanism for petroleum migration.

High-Resolution Paleoclimate Reconstruction From Alaskan Ice-Core Records

J.J. Fitzpatrick, T.K. Hinkley, G.P. Landis, R.O. Rye, and G. Holdsworth

Deep ice cores from the large continental ice sheets of Greenland and Antarctica provide long-term climate records. From Alaska, however, where the ice contains a record of a climate influenced by Northern Pacific Ocean weather patterns, little information is available.

We selected as our study site the 4,420-m col between Mts. Churchill and Bona in the St. Elias Range of southeastern Alaska. The ice core we plan to recover will contain a high-resolution paleoclimate record dating back to as long as 1,200 years B.P. The site is a broad, relatively flat expanse of snow and ice, about 1.0 × 1.3 km, sloping gently to the east.

In late spring 1991 we conducted an initial, reconnaissance field season. This emphasized observation, sampling of snow strata from dug pits, and sampling of gases in the snow and firn using shallow and deep probes.

The site is located in the dry facies zone and is part of the ultimate source of the Klutlan Glacier, well above the equilibrium line. No significant melting horizons were observed in snowpits. Net annual accumulation of snow is 1.9–2.0 m per year (approximately 70 cm water equivalent), judging by the minimally compacted most recent year's strata. Snow densities of the topmost year range from a minimum, near the spring surface, of about 0.18 g cm^{-3} to a maximum of about 0.43 g cm^{-3} at a depth of 2 m.

Preliminary analytical results show the following:

The light stable isotopic composition of snow within 1 year's accumulation exhibits a large seasonal range (δD = −157 to −292), indicating at least two sources of moisture and a correspondingly large range in temperature. Concentration of biologically produced oceanic methanesulfonic acid (MSA) in snow strata closely parallels the isotopic extremes, with a small time lag. MSA maxima appear with the most negative isotopic values (cold times). This may suggest that different latitudinal sources of moisture exist for different seasons, and that the more arctic regions produce more biogenic sulfur. Alternatively, these variations in stable isotopic composition, and biogenic sulfur, may be related to the tropospheric stratification proposed to dominate in these altitudes and latitudes. (See a 1991 study by Holdsworth and others.)

Gases adsorbed from the atmosphere on accumulating snow crystals are present in different proportions than in the atmosphere. Upon recrystallization of snow grains, with aging and burial of the strata, excess adsorbed gases are released, and residual adsorbed gases approach atmospheric proportions, exchanging in an open system with the atmospheric gases that circulate through the permeable snowpack. At least a decade may be required in this locality for desorption and redistribution of gases from the snow and equilibration of firn gases with the atmosphere. Strata isolated by impermeable layers may retain the fractionated and anomalous proportions of adsorbed atmospheric gases.

We anticipate that concentrations of rock-forming, sea-salt, and volcanic-exhalation metals in seasonal snow strata will give additional information about changing air mass sources.

Fracturing and Reservoir Development in the Katakturuk Dolomite, Arctic National Wildlife Refuge, Alaska

John S. Kelley, Chester T. Wrucke, and
Augustus K. Armstrong

The Katakturuk Dolomite of Proterozoic age, a possible petroleum reservoir under the Arctic coastal plain of the Arctic National Wildlife Refuge (ANWR), is about 2,500 m thick in the Sadlerochit and Shublik Mountains. The Katakturuk in this area has a structural setting similar to that north and east of the Sadlerochit Mountains under the coastal plain of ANWR, where pre-Mississippian rocks are involved in Brooks Range thrusting.

Reservoir properties of the Katakturuk Dolomite owing to depositional fabric and diagenesis are poor but likely are enhanced by fracturing. Reservoir properties were examined in thin section and measured from outcrop samples in the Sadlerochit Mountains and core from the Canning River Unit A–1 well west of the Sadlerochit Mountains, but their values are too low to explain the flow rate from a drill-stem test in the Katakturuk. In the Canning River Unit A–1 well, the Katakturuk yielded 134 barrels of fresh water with a calculated flow rate of 4,800 barrels per day (data from the 1987 study of Bird and others). The drill-stem test from which the flow rate was calculated included the interval cored and sampled for porosity and permeability measurements. Enhancement of permeability through fracturing could explain the flow rate. Fractures are pervasive in the Katakturuk in the Sadlerochit Mountains and likely are related to folding and thrust faulting.

Early dolomitization and cementation in the Katakturuk Dolomite largely obliterate porosity and permeability. Dolomite rhombs 2–6 μm across replace framework clasts originally composed of peloids, microbial fragments, microbial-laminated clasts, ooids, pisolites, oncolites, mud pellets, coated grains, and fragments of microbial mats, early cements, and micrite. Dolomite cement, chalcedony, and spar calcite infill voids consisting of internal molds in oolites and pisolites and fenestral cavities in microbial mats and stromatolites. Much of the formation is massive dolostone composed of xenotropic dolomite rhombs 100–500 μm across. The intercrystal pore space of the massive dolostone is mostly filled with dolospar, calcite, and silica cements.

Forty-three samples of the Katakturuk Dolomite from the Sadlerochit Mountains and 9 samples from core in the Canning River Unit A–1 well have low measured porosity and permeability (according to a 1987 study by K.J. Bird and others). Mean porosity for outcrop samples is 2.3 percent. Although a single outcrop sample had a porosity of 10 percent, all other samples had porosities of 0.8 to 6.2 percent. Measured permeabilities from outcrop samples range from less than 0.1 to 1.6 mD (millidarcies); nearly half the samples have permeabilities less than 0.1 mD. Samples from the Canning River Unit A–1 well have a mean porosity of 0.7 percent and a range from 0.3 to 1.1 percent. Permeabilities for all well samples are 0.1 mD or less.

The Katakturuk Dolomite in the Sadlerochit Mountains crops out in the south limb of an east-trending, doubly plunging regional anticline. The Katakturuk dips 10°–30° more steeply to the south than unconformably overlying Mississippian and younger strata. The steeper dips in the Katakturuk largely result from the angular unconformity beneath Mississippian limestone. The south-dipping Weller thrust at the base of the Katakturuk extends the length of the anticline and emplaces the Katakturuk over steeply dipping strata of Paleocene age in the western Sadlerochit Mountains. Displacement on the thrust diminishes to the east and becomes negligible where the thrust separates the Katakturuk from underlying Precambrian argillite and sandstone in the eastern Sadlerochit Mountains. Two sets of high-angle faults in the Katakturuk subtend the direction of tectonic transport in the Sadlerochit Mountains. One set trends about N. 30° E. and the other set about N. 45° W. The northeast-trending faults have left-lateral separations that typically are greatest near the thrust and diminish upward and away from the thrust. Systematic offset is not recognized in northwest-trending faults. Fracturing in the Sadlerochit Mountains is most intense within the Katakturuk that crops out between the folded angular unconformity at the base of concentrically folded Mississippian strata and the Weller thrust.

The fractures and faults in the Katakturuk Dolomite are thought to have resulted as the dolomite accommodated to concentric folding that developed during Tertiary time in Brooks Range thrusting. As concentric folds became dominant in the Mississippian limestone and younger strata, the angular relation between the Katakturuk and Mississippian and younger strata severely limited bedding-plane slip as an accommodation to concentric folding within the Katakturuk. Pervasive fracturing and movement by distributed shear within the Katakturuk became the principal mechanism of deformation of the brittle carbonate strata of the Katakturuk as the dolomite became incorporated into the core of the fold during folding and thrusting. The sets of high-angle faults above the Weller thrust and mostly within the Katakturuk are likely conjugate faults that provided a mechanism of mass transport and contributed maximum contraction north-northwest, parallel to the direction of tectonic transport during folding and thrusting.

Development of the Ellesmerian Continental Margin and the Brookian Orogeny, Alaska—A DNAG Perspective

Thomas E. Moore, Wesley K. Wallace,
Kenneth J. Bird, Susan M. Karl, and C. Gil Mull

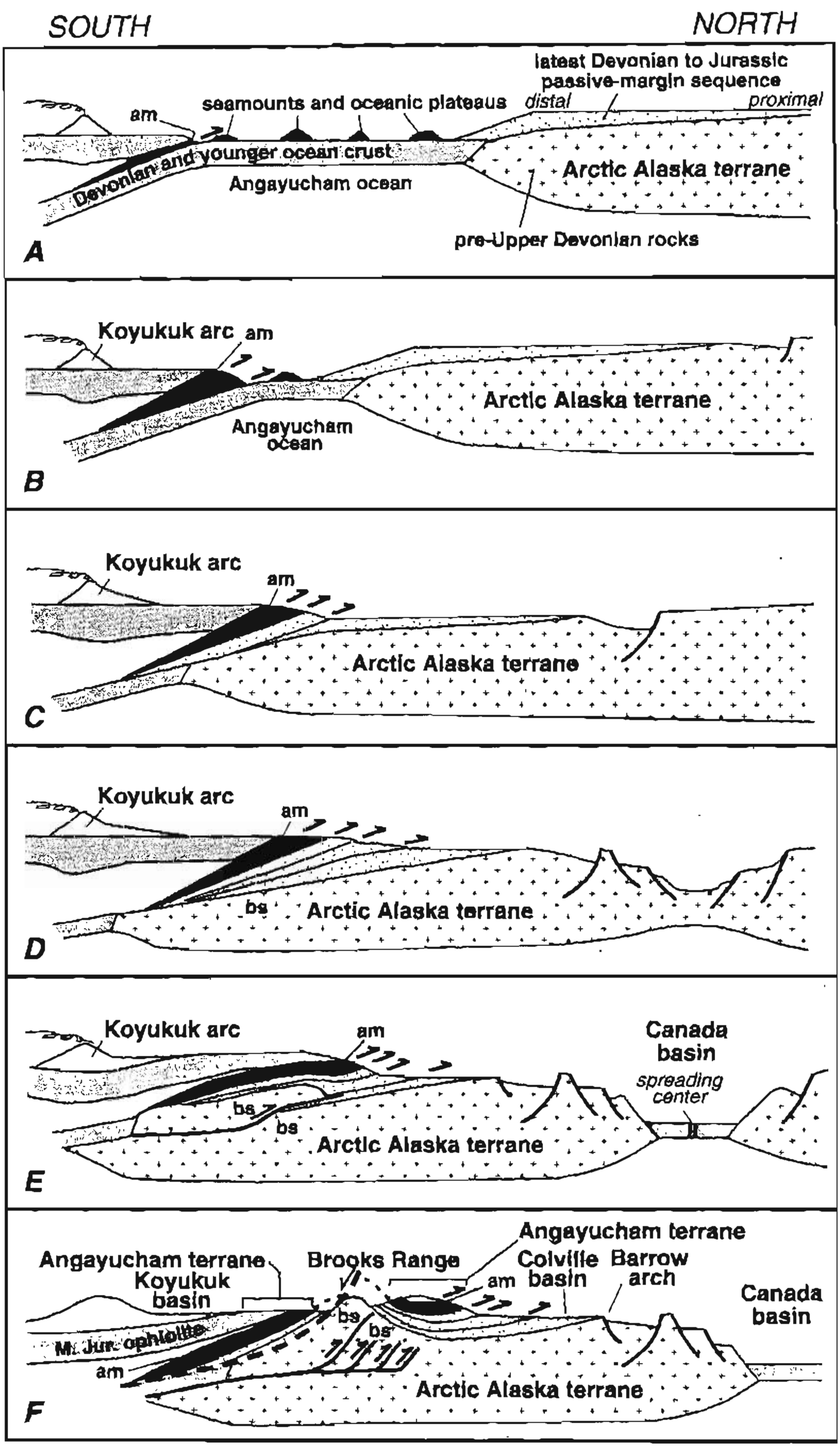
A synthesis of the geologic history of northern Alaska developed for the Decade of North American Geology (DNAG) project divides the stratigraphy of the region into the continental Arctic Alaska terrane and oceanic Angayucham terrane. The Arctic Alaska terrane, one of the largest terranes in Alaska, underlies the North Slope and most of the Brooks Range. Rocks of the Arctic Alaska terrane are divided, from bottom to top, into (1) structurally and stratigraphically complex Proterozoic to Middle Devonian rocks of diverse affinity; (2) a laterally extensive succession of uppermost Devonian and Lower Mississippian to Lower Cretaceous nonmarine to marine passive continental margin deposits (equivalent to the Ellesmerian sequence); and (3) upper Mesozoic and Cenozoic siliciclastic foredeep deposits (Brookian sequence). The pre-uppermost Devonian rocks apparently record early to middle Paleozoic convergent deformation and plutonism along the edge of North America, which was followed by rifting in Devonian time. The Devonian rifting event culminated in formation of an ocean basin and paleogeographically complex south-facing Ellesmerian passive margin by Late Devonian time. Subsidence along the passive margin resulted in (1) progressive northward onlap of nonmarine and carbonate platform deposits in Late Devonian and Mississippian time and (2) deposition of neritic to bathyal sediments in Mississippian to earliest Cretaceous

time. The neritic to bathyal deposits are characterized by a southward increase in abundance of condensed basinal deposits. A second rifting event culminated in opening of the Canada basin in Early Cretaceous time and produced the Barrow arch and the modern northern continental margin of Alaska.

The Angayucham terrane, exposed in isolated klippen in the Brooks Range and beneath Jurassic to Lower Cretaceous volcanic-arc rocks of the Koyukuk basin to the south, structurally overlies the Arctic Alaska terrane. The Angayucham terrane consists of two subparallel, allochthonous lithotectonic assemblages, both of oceanic affinity. The structurally lower assemblage consists of imbricated Devonian to Jurassic ocean-island basalts and pelagic sedimentary rocks, whereas the structurally higher assemblage consists of ultramafic and gabbroic rocks of a Middle Jurassic ophiolite. Rocks of the lower unit were metamorphosed to amphibolite facies along the base of the ophiolitic assemblage in Middle Jurassic time. The Angayucham terrane is interpreted to represent an accreted subduction complex and overlying ophiolite that formed the forearc region of a Middle Jurassic volcanic arc in the ocean basin adjacent to the Ellesmerian continental margin.

The Brookian orogeny began in the Middle and Late Jurassic with southward subduction and closure of the part of the Angayucham ocean basin that lay outboard of the south-facing passive margin of the Arctic Alaska terrane (fig. 1*A*). Fragments of the upper Paleozoic and lower Mesozoic oceanic upper crustal rocks were underplated by subduction beneath an intraoceanic arc and ophiolite and locally metamorphosed amphibolite, thus forming the Angayucham terrane and overlying Koyukuk arc terrane (fig. 1*B*). In Late Jurassic and Early Cretaceous time, the outer (distal) south-facing passive continental margin succession of the Arctic Alaska terrane was partially subducted and underplated beneath the Angayucham terrane (fig. 1*C*). Northward thrust imbrication sequentially placed more distal parts of the continental margin over its more proximal parts (fig. 1*D*). The axis of associated Brookian foredeep sedimentation migrated northward with the thrust front such that older foredeep deposits were involved in later thrusting. The continental substructure of the continental margin of the Arctic Alaska terrane was subducted to deeper levels, resulting in tectonic thickening (fig. 1*E*) and high-pressure–low-temperature metamorphism (blueschist-facies metamorphic rocks). By Albian time, the rate of underthrusting diminished, and the orogenic belt was rapidly uplifted and unroofed, resulting in setting of isotopic cooling ages and deposition of huge volumes of Brookian clastic detritus southward into the hinterland (Koyukuk basin) and northward into the foredeep (Colville basin) (fig. 1*F*). Latest Early Cretaceous down-to-the-south, low-angle normal faulting in the southern Brooks Range contributed significantly to this unroofing and uplift and overlapped in time with the formation of the extensional northern Alaska continental margin. Subsequent Late Cretaceous and early Tertiary Brookian orogenesis resulted in deformation of the southern Colville basin. Deformation has continued to the present in the eastern Brooks Range, where thrusting and foredeep deposition have migrated northward into the offshore region.

Figure 1 (Moore and others) (facing page). Development of the Brookian orogeny; am, amphibolite; bs, blueschist-facies metamorphic rocks. Heavy line, fault; dashed where inferred; barb shows direction of relative movement. *A*, Middle Jurassic; *B*, Late Jurassic; *C*, early Early Cretaceous (Berriasian); *D*, middle Early Cretaceous (Hauterivian); *E*, late Early Cretaceous (Aptian); *F*, latest Early Cretaceous (Albian).


SOUTH
NORTH
latest Devonian to Jurassic passive-margin sequence
seamounts and oceanic plateaus
distal
proximal
am
Devonian and younger ocean crust
Arctic Alaska terrane
Angayucham ocean
pre-Upper Devonian rocks
A
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Arctic Alaska terrane
D
Koyukuk arc
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Canada basin
spreading center
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Arctic Alaska terrane
E
Angayucham terrane
Angayucham terrane
Brooks Range
Colville basin
Barrow arch
Koyukuk basin
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Canada basin
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Arctic Alaska terrane
F

Reservoir Heterogeneities in the Morrison Formation in Southern Utah—A Prudhoe Bay Analog

John W. Robinson and Peter J. McCabe

Examination of the Salt Wash Member of the Morrison Formation (Jurassic) in the southern Henry Mountains region of southern Utah allows a better understanding of heterogeneities in fluvial reservoirs with high net-to-gross sandstone ratios. The Salt Wash Member is interpreted as the deposits of braided rivers that flowed towards the northeast into a playa lake in central Utah from a source area in north-central Arizona. Cliffs and canyons provide exceptional exposures that allow a three-dimensional study of vertical and lateral facies relationships of the member over an area of 1,000 km^2. Interpretation of photomosaic panoramas of cliffs up to 350 m high and 3.2 km long allows for description of the facies architecture and measurement of potential large-scale reservoir heterogeneities. More detailed photomosaics of smaller areas allow an assessment of smaller scale heterogeneities. This work is being supplemented by measurement of detailed stratigraphic sections, minipermeameter analysis of outcrops and freshly cut cores, correlation of subsurface well logs, and petrographic studies.

The Salt Wash Member is 150 m thick, and is composed predominantly of sandstones with <10 percent interbedded siltstones and mudstones. These sandstones have an overall coarsening-upward trend through the unit, with very fine grained quartz-rich beds at the base and chert granule and pebble conglomeratic sandstones toward the top. The sandstones form fining-upward units, from 1 to 5 m thick, that are dominated by trough cross-stratification; the size of individual cross-beds increases higher in the section. The section also contains a few horizontal and ripple-laminated beds. Individual fining-upward units are laterally extensive over tens of meters and are separated by discontinuous, 0.01- to 1-m-thick mudstone drapes and (or) mudstone intraclast pebble lags. Fining-upward units amalgamate to form sandstone sheets that are up to 20 m thick and laterally extensive for 100 m to more than 2 km. These sandstone sheets have flat bases and tops and are separated by rooted and burrowed, red and green mudrock units generally less than 3 m thick. Minipermeameter data from outcrop and core average 600 mD in trough-crossbedded and massive sandstones, 200 mD in horizontal laminated sandstones, and <50 mD in fine-grained deposits.

We believe that conclusions from our study could be used to better model flow unit continuity in large fluvial reservoirs to aid in better reservoir development. Mudrock beds and intraclast conglomerates of varying thickness and continuity would divide a reservoir into flow unit compartments on various scales, influencing fluid migration and drainage. Data from these outcrops provide a guideline to predict the scale of reservoir heterogeneities from field-spaced core and log data. In particular, the Salt Wash Member appears similar to the Ivishak Formation of the Sadlerochit Group (Permian and Triassic) of the Prudhoe Bay field, Alaska. Similarities include (1) an overall coarsening-upward character to the strata; (2) presence of amalgamated sandstone sheets, deposited by braided fluvial streams, separated by discontinuous floodplain mudstones; (3) a vertical evolution of cross-stratification types; and (4) a high net sandstone composition dominated by a lithic chert component. The scale of our study (1,000 km^2 area $\times$150 m thickness) allows a realistic three-dimensional comparison with a major reservoir such as the Ivishak (770 km^2 area $\times$130 m thickness).