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Petroleum Geology of the Central North Slope, Alaska: Opportunities for Independents

Four of the top ten producing oil fields in the United States are located on Alaska's North Slope, where total production currently accounts for at least 15% of domestic production in the United States. The bulk of that oil comes from the super giant Prudhoe Bay field and the giant Kuparuk River field (Figure 1). Large integrated oil companies have dominated the North Slope since the wave of exploration began in the early 1960s that ultimately lead to the Prudhoe Bay discovery in 1967. As the North Slope province matures, the largest integrated major oil companies increasingly focus their exploration resources on opportunities overseas. Recent advances in 3-D seismic and drilling technology have led to a ten-fold increase in exploration success in the region. These facts coupled with Alaska's predictable area-wide leasing program provide real opportunities for independents.

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The petroleum geology of Arctic Alaska is controlled by a complex post-middle Devonian geologic history that includes three tectono-stratigraphic megasequences deposited in response to three distinct plate tectonic settings involving the Arctic Alaska terrane (Figure 2) (Hubbard and others, 1987). From Late Devonian to Late Triassic time Arctic Alaska was part of a south-facing (present-day coordinates) passive continental margin that was connected to a northern source terrane. The sedimentary record of this tectonic regime is assigned to the Ellesmerian sequence, a 6,000-foot-thick (1,800 meters) succession of ramp and basinal carbonates, including porous dolomitic tidal and peritidal facies, quartzose sandstones derived from northern sources, and organic-rich shales. Ellesmerian strata are time-transgressive toward the north, where they progressively onlapped the northern source terrane.

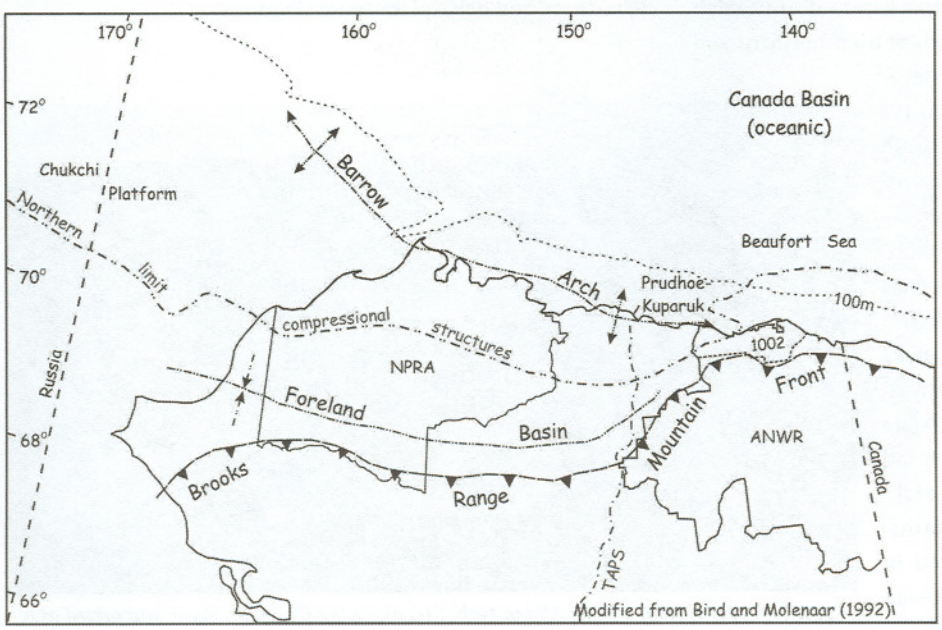

Figure 1 – Location map showing major tectonic elements recognized on the North Slope. Modified from Bird and Molenaar (1992).

Basin polarity gradually changed over a 100–Ma period from Early Jurassic to Late Neocomian time. During this period Arctic Alaska experienced active crustal extension that culminated in Valanginian—Hauterivian time in uplift of a rift shoulder, the Barrow arch, opening of the oceanic Canada Basin, and formation of the present day coastline of Arctic Alaska. The sedimentary record of this period is assigned to the Beaufortian sequence ➢

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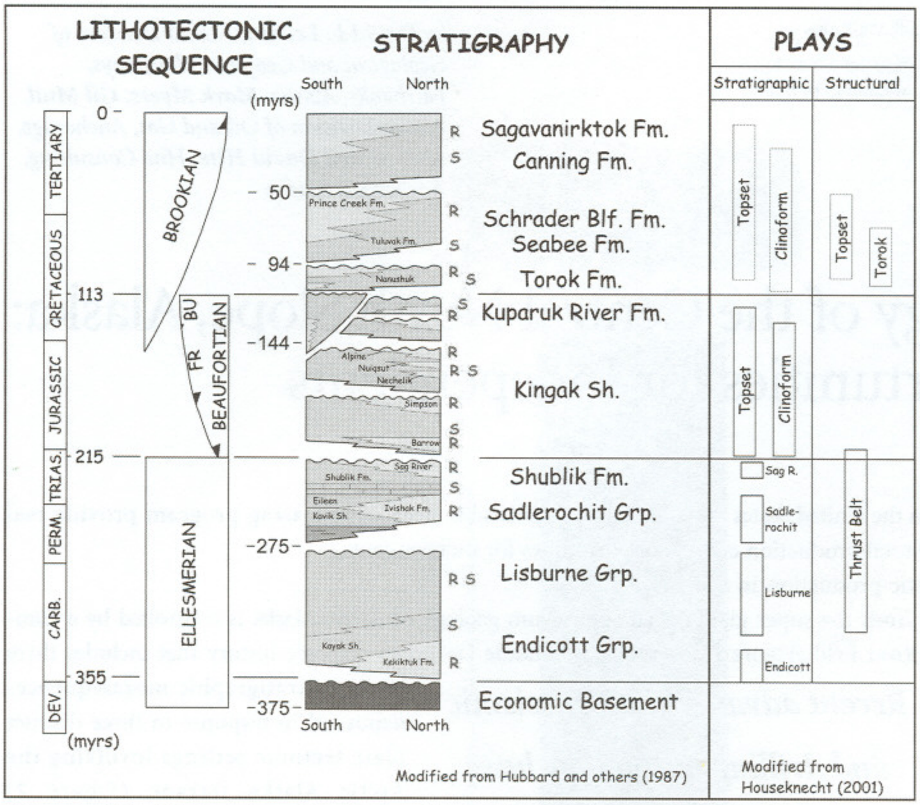

Figure 2 – Simplified stratigraphic column of the North Slope showing major lithotectonic sequences and petroleum play groups. Lithotectonic sequences modified from Hubbard and others (1987) and play groups modified from U.S. Geological Survey Fact Sheet 045-02.

In Late Jurassic time, coeval with Beaufortian rift-related tectonism to the north, Arctic Alaska collided with an island arc south of the present-day Brooks Range. This arc-continent collision resulted in obduction of oceanic crust and the collapse of the outboard margin of the Arctic Alaska plate and the associated imbrication of its Devonian to Triassic sedimentary cover. The sedimentary record of Mesozoic–Cenozoic compressional tectonism is recorded in the Brookian sequence, an Upper Jurassic to Eocene succession characterized by lithic sandstones derived from the ancestral Brooks Range (Figure 2). Brookian strata filled a large east-west-trending peripheral foreland basin with nearly 25,000 feet (7,700 meters) of siliciclastic detritus; the thickness of Brookian strata decreases toward the north, up the south flank of the Barrow arch. Regional seismic data show pronounced clinoform geometries that record the eastward migration of Brookian depocenters. Clinoform reflectors represent mud-prone strata that downlap distal condensed marine shales of the Hue Shale/Gamma-Ray zone. Base-of-slope and slope-apron sandstone successions are important components of clinoform deposits (Figure 3). Topset facies include marine shelf, sand-rich delta-front, and delta-plain facies (Figure 4).

(Figure 2). Beaufortian strata thicken away from the crest of the Barrow arch, toward the north and south. South of the arch, Beaufortian strata are up to 3,200 feet thick (1,000 meters); north of the arch the thickness exceeds 9,500 feet (2,900 meters) in extensional fault-bounded basins. Like Ellesmerian strata, Beaufortian sandstones are quartzose, reflecting derivation from northern and local sources. The Jurassic part of the megasequence is interpreted to record a failed rift episode characterized by down-to-the-south faulting and formation of half grabens, and deposition of an extensive south-thickening (basinward) clastic wedge with distinct clinoform geometries visible on regional seismic data. The Neocomian part of the megasequence records an episode of renewed extension that led to separation of Arctic Alaska from its northern source terrane and opening of the Canada Basin. Uplift during this second period of extension created the rift shoulder–Barrow arch. Widespread erosion along the crest and proximal flanks of the rift shoulder resulted in truncation of older Beaufortian and Ellesmerian strata below a regional Hauterivian—Valanginian breakup unconformity (LCu).

Figure 3. Aerial view of middle Albian turbidites along the Chandler River interpreted as a basin floor fan or slope wedge succession. Residual hydrocarbons present in many sandstone beds at this outcrop suggest that it is part of an exhumed oil field. View toward the east.

Each megasequence includes petroleum source rocks, but the Ellesmerian and Beaufortian sequences were endowed with the richest, most prolific source rocks on the North Slope (Figure 2). Triassic limey shales of the Shublik Formation (Ellesmerian), distal facies in the Jurassic Kingak Shale (Beaufortian), and transgressive shales of the Hauterivian Pebble shale unit (Beaufortian) have sourced most oil and gas accumulations in the region (Bird, 1994). These rocks are widespread in outcrop and the subsurface. Known productive source rocks in the Brookian sequence include the Lower to Upper Cretaceous Hue Shale/Gamma-Ray zone, and mudstones and shales within the Torok and Seabee Formations.

Burial history analysis using wells drilled in the central North Slope show rapid subsidence of the foreland basin starting in Barremian time (Cole and others, 1997), resulting from the northward emplacement of a significant thrust load on the southern margin of the Arctic Alaska terrane. High accommodation in the basin combined with rapid uplift in the orogen led to deposition of a thick post-Barremian succession of Brookian siliciclastic rocks, which, in turn, resulted in maximum burial of Ellesmerian, Beaufortian, and older Brookian source rocks by Campanian time 75 Ma (Bird, 1994).

Figure 4. Aerial view of middle(?) to late Albian (and possible Cenomanian) topset facies in the Nanushuk Formation at Slope Mountain. The Trans-Alaska Pipeline is visible in the distance in the upper left. Outer shelf deposits of the Torok Formation are exposed near the base of Slope Mountain.

The Brookian sediment load and formation of Brookian age structures controlled secondary migration and accumulation of hydrocarbons in present-day reservoirs. Structures in the range-front region of the Brooks Range consist dominantly of north-vergent thrust faults that record hundreds of kilometers of transport. Emplacement of thrust sheets over Brookian foredeep deposits and distal Beaufortian strata in the southern foothills province resulted in complex outcrop-scale folds and thrust faults. Most compressional structures in the Brooks Range and southern foothills belt formed in Late Jurassic—Neocomian time. Structures in the northern foothills belt consist of short-wavelength, thrust-cored anticlines and longer wavelength synclines. These structures typify the Albian—Cenomanian Nanushuk Formation and developed above detachments in the Torok Formation. A similar structural style characterizes Upper Cretaceous strata, where present in the northeastern part of the foothills belt. Beneath the coastal plain north of the foothills belt, Lower and Upper Cretaceous strata are largely undeformed, or are very gently folded without associated thrust faults. Hydrocarbons initially migrated from source rocks at depth in the Ellesmerian and Beaufortian sequences to stratigraphic and combined stratigraphic-structural traps up-section and up-dip on the Barrow arch. Hydrocarbons generated by Brookian source rocks migrated up-dip toward the southwest to reservoirs in base-of-slope and topset positions. Current mapping in the central foothills belt indicates these structures formed in Late Cretaceous and Tertiary time, which suggests a period of remigration to combined structural and stratigraphic traps along the flanks and crest of the Barrow arch. Subaerial exposure of Ellesmerian and selected Beaufortian sandstones beneath the LCu unconformity was critical to porosity enhancement and reservoir development. Post-rift subsidence of the Barrow arch resulted in deposition of the transgressive Pebble shale unit in Hauterivian-Barremian time, creating the topseal for most Ellesmerian and some Beaufortian reservoirs.

Plays are grouped by stratigraphic position and structural style (Figure 2). The most prospective Ellesmerian reservoir targets are located near the Beaufort seacoast and the crest of the Barrow arch, where they lay at depths generally less than 11,000 feet subsea (above the 2% R_0 isograd). Ellesmerian reservoir targets include nonmarine and shallow-marine clastics, and dolomitized shallow- and marginal-marine carbonates in combination stratigraphic-structural traps associated with the LCu. Similarly, attractive Beaufortian targets are located on the south flank and crest of the arch, are present at moderate depths (above the 2% R_0 isograd), are largely undeformed, and include shallow- and marginal-marine quartzose clastics. Jurassic Beaufortian targets will probably be in stratigraphic traps encased in the Kingak Shale; Neocomian Beaufortian targets will be either in stratigraphic or in combination stratigraphic-structural traps. Brookian targets include basin-floor and slope-apron turbidite systems throughout the Colville basin and in fluvial-deltaic sandstones deposited in topset positions in the ➢ continued on page 17 continued from page 15

northern foothills belt (incised valley/lowstand deltas and in highstand structural plays). Significant potential exists for deep-water Brookian targets in stratigraphic traps in the northern foothills and coastal plain (above or near 2% R_0 isograd). Topset reservoir targets in the northern foothills are likely to be in combination stratigraphic-structural traps (also above or near the 2% R_0 isograd). Numerous other plays involving some of the same stratigraphic intervals as those outlined here are present farther to the south, in the southern foothills belt and along the Brooks Range mountain front. These plays most likely involve gas as the primary hydrocarbon phase. ■

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Biographical Sketch

DAVID LEPAIN is a senior geologist in the Energy Section of the Alaska Division of the Geological and Geophysical Surveys (DGGS). His PhD dissertation addressed the regional sedimentology and tectonics of the Carboniferous Endicott Group in the range-front region of the Arctic National Wildlife Refuge. Dave's current focus is the sequence stratigraphy and reservoir potential of the Lower Cretaceous Nanushuk Formation and selected Upper Cretaceous units in the foothills belt south of the National Petroleum Reserve-Alaska. He manages DGGS' NPRA-Foothills program.