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AAPG HEDBERG CONFERENCE
"Deformation History, Fluid Flow Reconstruction and Reservoir Appraisal in Foreland Fold and Thrust Belts"
May 14-18, 2002, Palermo – Mondello (Sicily, Italy)

Variations in Style and Timing of Deformation within the Tertiary Frontal Thrust Zone across Alaska's North Slope, with Implications for Petroleum Geology

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The coastal plain on Alaska's North Slope overlies a spatially- and temporally-varying array of largely-concealed Tertiary structures in the frontal part of the Mesozoic and Tertiary Brookian orogenic belt, including significant targets for future oil and gas exploration. As part of a comprehensive study of the petroleum geology of this region, we have combined a regional network of 2D seismic reflection data with geologic field studies and fission-track analyses, in order to establish a thorough understanding of the variations in structural style and timing of these structures across the North Slope.

Figure 1 illustrates the geographic, and geologic context of the Tertiary frontal structures of the Brooks Range. In contrast to the Jurassic to Cretaceous main (large-displacement) phase of Brookian deformation in which the Brooks Range was constructed in response to collision and convergence between a south-facing passive margin and a volcanic arc to its south, the Tertiary phase of Brookian deformation occurred in response to plate convergence and north-directed terrane accretion in southern Alaska. These structures lie well to the north of the Mesozoic deformation front and modern physiographic mountain front, but terminate south of the well-known Prudhoe Bay Field and other more recent discoveries in relatively undeformed part of the North Slope (Figure 1). In the western part of the North Slope, the deformation front is located onshore, well south of the coast, but in the central North Slope swings northeastward toward the coast, and ultimately passes offshore of northeastern-most Alaska. Onshore, the rocks involved in the frontal zone are mainly foreland basin deposits of the lower Cretaceous to Tertiary Brookian sequence, although pre-Mississippian through Jurassic rocks are locally significant participants. Offshore, frontal-zone structures deform similar-age clastic strata that constitute the passive margin sequence of the Arctic margin of Alaska. The deformation front is Paleogene in age in the western part of the North Slope, and Neogene in the eastern part.

In the western and central part of the North Slope (in the National Petroleum Reserve-Alaska), Brookian strata south of the coastal plain were deformed in a regionally extensive passive-roof duplex (PRD). North of this PRD, prominent anticlines in shallow marine to nonmarine Brookian rocks (topset facies) overlie domains of local structural thickening in mud-rich clinoform facies strata. The structural thickening is balanced at

depth by thrusts that locally ramp up from a detachment in the underlying Jurassic Kingak Shale; these ramps mark the northern extent of the regional Kingak detachment surface, the basal detachment for much of the Brooks Range to the south. There is relatively little internal deformation beneath the intervening synclines, indicating that a regionally continuous roof thrust is not present in this area and that shortening is mainly dissipated upward within in each anticline. Farther north, the deformation front is marked by the tip of a very broad, low-amplitude structurally-thickened welt of mud-rich Torok Formation above a detachment at its base. The shallow-marine to nonmarine sand-prone Nanushuk Group is draped over the welt, forming a broad, subtle anticline. This style of deformation may record the nascent stage in the development of a north-directed frontal triangle zone (=PRD). The lesser degree of shortening here allows preservation of broad relatively unbroken structures that may be viable hydrocarbon traps. With greater amounts of shortening, regional roof and floor thrusts would probably have formed in the Brookian strata bounding an intensely deformed tectonic wedge at the deformation front.

Based on an extensive number of apatite fission track analyses from throughout the North Slope, it is clear that: (1) the main phase of deformation in this incipiently-deformed frontal belt beneath the western and central North Slope occurred at ~65-60 Ma, and (2) deformation throughout the frontal belt probably continued into the Eocene at ~45 Ma. Formation of structural traps appears to have occurred in the Early Tertiary and thus significantly postdated the ~100 Ma time of peak oil generation in the axial part of the Mesozoic foredeep. This suggests that oil accumulations, such as the 70 mmbo Umiat field, likely formed by disruption of earlier-formed stratigraphic accumulations and remigration into higher structural traps. Thus, we regard remigration, accompanied by continued generation of gas at depth, as the favored scenario for hydrocarbon charge for the structures in the western front zone. Seal integrity is the primary risk for hydrocarbon accumulations in this setting.

In the eastern North Slope, Tertiary deformation is dominantly thin-skinned, with PRD geometry and kinematics. In addition, basement-involved deformation within the frontal zone feeds displacement into the thin-skinned PRD. North of the Sadlerochit Mountains in the western part of the Arctic National Wildlife Refuge (ANWR), the deformation front is defined by the northern tip of a prominent east-northeast-trending PRD that is bounded below by a floor thrust near the base of the Brookian section, and bounded above by a north-dipping roof thrust near the base of Eocene strata. The northernmost exposures of deformed rocks in western ANWR lie along the east-northeast-trending Marsh Creek anticline, a fault-bend-fold above a prominent bend in the roof thrust. Buried north-directed basement-involved thrusts north of the Sadlerochit Mountains appear to feed displacement into the thin-skinned system. The latest basement-involved thrusts locally post-date the thin-skinned thrusting. Seismic reflection patterns indicate that all of these thrusts of the frontal zone, including the thin-skinned PRD and the basement-involved thrusts, were principally active in Miocene time.

To the east within ANWR, a northward-younging pattern of thin-skinned deformation is clearly evident. The Aichilik structural high in the southern coastal plain formed in Paleocene time, evidenced by convergence of reflections from Paleocene shallow marine

strata on its flanks. During the Eocene and early(?) Oligocene, thin-skinned thrusting advanced northward, forming a PRD beneath the northeastern part of ANWR. The basement-cored Niguanak high and Aurora dome, the two largest subsurface structures of the North Slope coastal plain, formed in Oligocene to Miocene time above thrust ramps in the pre-Mississippian basement. Overlying, older thin-skinned structures were broadly domed above the Niguanak high, and the basement-involved thrusting transferred new increments of displacement into thin-skinned structures directly to the north. Gentle dips on Miocene strata beneath northeastern-most ANWR, and offshore to the north, strongly suggest that deformation continued through the Miocene. Offshore seismicity may be an indication that contractional deformation continues to the present day. Beneath the present Beaufort Sea coast (north of the easternmost part of the North Slope), the basal detachment lies above the Lower Cretaceous (breakup) unconformity. This detachment descends northward from a depth of about 7 km onshore to about 10 km (sub-sea-level) under the modern continental rise; the northward-dipping offshore portion of the detachment appears to be primarily contractionally- driven, but the influence of large-scale gravity-driven detachment folding cannot be entirely discounted.

The structural and erosional history of the deformed area of the eastern North Slope (ANWR) is not ideal for accumulation and preservation of oil and gas. The critical moment for oil generation and migration within ANWR occurred in the Paleocene and early Eocene. Structural traps were forming in parts of the frontal zone at this time, but the major Neogene pulse of deformation strongly overprinted these earlier-formed structures and would likely have disrupted earlier-formed accumulations. The broad basement-cored Niguanak and Aurora antiforms present attractive exploration targets, but the Missississpian through Triassic Ellesmerian reservoir facies that is present at Prudhoe Bay appears to have been erosionally stripped from the basement across these structures, and the late Oligocene to Miocene formation of these antiforms post-dates oil generation. As in the western North Slope, the most likely scenario for viable oil and gas accumulations in the east would involve remigration of hydrocarbons from older stratigraphic and structural traps into newer, higher structures. The deformed region is mainly gas-prone, based on thermal history and reservoir characteristics, although the northernmost prospects could have been charged by oil from thermally mature Brookian source rocks offshore. Late faulting and fracturing likely compromised the seal in numerous prospects.

In summary, the 700-km-long Tertiary frontal zone of the Brookian orogen is an instructive case-study in regional along-strike variations in structural style and timing. The ages of frontal structures and foreland basin strata vary significantly from west to east (Paleogene structures deforming Cretaceous strata in the west; Paleogene to Neogene structures deforming Tertiary strata in the east). Timing of petroleum generation and maturation varies across the North Slope (mid-Cretaceous in the west, Paleogene in the east), but throughout the North Slope, formation of the youngest structural traps post-dates peak generation and migration. The frontal structures in the western North Slope include a broad area of incipient thin-skinned deformation that lies north of a fully developed passive-roof duplex, whereas the eastern North Slope is characterized by a fully developed passive-roof duplex upon which basement-involved thrusting and folding

have been superimposed. Locally, the late, basement-involved shortening has propagated across the modern continental hinge and deformed the north-facing continental slope and rise of northeastern Alaska.

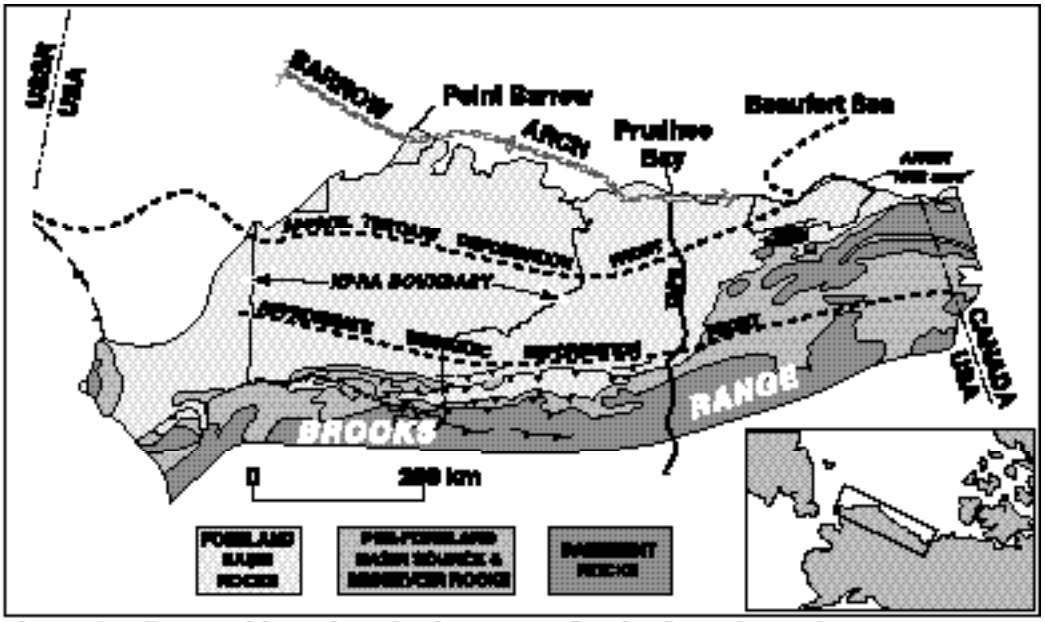

Figure 1. Geographic and geologic context for the frontal Brooks Range structures. Inset map shows location in northern Alaska, USA. The southern limit of foreland basin rocks is the approximate location of the modern physiographic mountain front. NPRA boundary, boundary of the National Petroleum Reserve-Alaska; ANWR "1002 area," boundary of the 1002 area on the coastal plain of the Arctic National Wildlife Refuge; SM, Sadlerochit Mountains; TAPS, Trans-Alaskan Pipeline System.