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Deformation History, Fluid Flow Reconstruction and Reservoir Appraisal in Foreland Fold and Thrust Belts

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Deformational History and Hydrocarbon Potential, Central Brooks Range Foreland Fold and Thrust Belt, Northern Alaska

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New interpretations of regional seismic reflection lines, recent geologic field work, and new apatite fission-track analyses as part of the U.S. Geological Survey assessment of hydrocarbon resource potential of the central North Slope has significantly advanced understanding of the structural framework and kinematic development of the Brooks Range orogen. The Brooks Range is a north-directed fold and thrust belt that forms the southern boundary of the North Slope petroleum province in northern Alaska. Field-based studies have long recognized that large-magnitude thin-skinned folding and thrusting in the Brooks Range occurred during arc-continent collision in the Late Jurassic and Neocomian. Folds and thrusts in the foreland basin, however, deform Upper Cretaceous strata and thus record a younger phase of deformation that apatite fission track data have shown occurred primarily during the Early Tertiary. Few studies have attempted to reconcile these observations and provide an integrated structural and kinematic model for the deformation of this area. Such a model is critical to understanding timing of hydrocarbon maturation and trap development and thus, hydrocarbon potential.

Our interpretations of recently reprocessed regional seismic-reflection data collected in the late 1970’s and early 1980’s show that from the main mountain front northward to near the deformation front under the coastal plain, the basal thrust detachment is located in the Jurassic and Early Cretaceous Kingak Shale in the upper part of the regionally extensive, gently south-dipping, north-derived Mississippian to Early Cretaceous Ellesmerian sequence. Outcrop and seismic data show that near the mountain front, the hangingwall consists of a stacked series of thrust duplexes developed principally in Devonian clastic rocks (Kanayut Conglomerate) and in Mississippian-Pennsylvanian carbonate rocks and chert (Lisburne Group). This stacked succession of duplexes comprises the regionally extensive Endicott Mountains allochthon. To the north, the Endicott Mountains allochthon is overlain by broken formation and melange of late Paleozoic through early Mesozoic basinal strata, oceanic allochthons, and Upper Jurassic and Neocomian syntectonic strata. These strata compose one or more allochthons that are laterally discontinuous and are commonly referred to in composite as “higher allochthons”. Proximal Aptian-Albian clastic strata (Fortress Mountain Formation) rest in apparent unconformity on these rocks and are deformed into gentle “thumbprint” synclines and sharp anticlines cored by north-directed reverse faults. Farther north in the foreland basin, mid-Cretaceous strata are widespread and consist of large thicknesses of strongly deformed strata, including sandstone turbidites and overlying mudstone slope deposits (Aptian-Albian Torok Formation) and overlying, gently folded deltaic strata (Albian-Cenomanian Nanushuk Group). These rocks compose a triangle zone (passive-roof duplex) formed by imbrication of the lower, sandstone-rich part of the Torok Formation beneath less deformed strata of the upper Torok and overlying Nanushuk Group. North of the triangle zone, the frontal part of the deformed belt displays valley and ridge topography controlled by gentle folding above local areas of tectonic thickening in the Torok Formation. Individual folds and underlying thrusts of this belt are locally balanced and are interpreted here as representing an incipient stage of development of a northward propagating triangle zone.

The timing of uplift and denudation along the northern flank of the Brooks Range is constrained by zircon and apatite fission track results from Upper Devonian through Upper Cretaceous sedimentary rocks. Zircon results from outcrop samples within the orogen south of the mountain front record cooling below paleotemperatures >240°C at ~140 Ma, ~120 Ma, ~60 Ma, and ~45 Ma, whereas apatite results record rapid cooling below paleotemperatures ≥110° during discrete episodes at ~100 Ma, ~60 Ma, ~45 Ma, and ~25 Ma. Within the northern foothills and adjoining foreland basin, zircon results from outcrop samples record provenance cooling ages with distinct grain-age populations at ~160 Ma, ~140 Ma, and 120 Ma, whereas apatite results record rapid cooling below paleotemperatures ≥110° at ~100 Ma, ~60 Ma, ~45 Ma, and ~25 Ma. In the northern part of the deformed belt, apatite results from subsurface samples indicate that they were exposed to maximum paleotemperatures in the Late Cretaceous to early Paleocene as a result of subsidence and burial by Cretaceous sedimentary rocks. An especially important result is that apatite grains from the Fortress Mountain Formation near the mountain front are only partially annealed and demonstrate considerably less thermal maturity than found in other mid-Cretaceous strata in the foreland basin.

To explain the stratigraphic, structural, seismic, and fission-track age data, we propose a structural model wherein the deformed belt was formed as the result of two separate north-directed orogenic episodes (Figure 1). The first episode was the Late Jurassic and Early Cretaceous north-facing arc-continent collision that emplaced the Endicott Mountains and higher allochthons by underplating beneath a Jurassic oceanic arc. The allochthons represent the distal outer parts ,whereas the Ellesmerian sequence of the autochthon represents the proximal inner part, of a Late Devonian to Jurassic south-facing, passive margin succession. Because the passive margin succession has a stratigraphic thickness of only 1-4 km, temperatures necessary to anneal apatite and zircon fission track ages were attained only within the orogen where structural thickening produced high thermal maturities.

The allochthons are remnants of shingled, north-thinning deformational wedges emplaced onto the south-dipping autochthon during early (140 Ma) and late Neocomian (120 Ma) time. Their emplacement resulted in construction by Aptian time of a structurally and topographically high-standing region that became the south flank of the Colville foreland basin. Deposition in the basin initially consisted of syntectonic strata, but in Aptian-Cenomanian time, following termination of thrusting, gave way to voluminous sedimentation shed from the south and west. These sediments were derived from the hinterland of the orogen where regional extensional exhumation and cooling occurred from about 110-90 Ma. Sedimentation prograded dominantly longitudinally from west to east along the axis of the basin during the mid-Cretaceous and resulted in deposition of turbiditic bottomset deposits (the lower Torok Formation), followed by mudstone-rich clinoform deposits (upper Torok), and deltaic topset deposits (Nanushuk Group). In the axial part of the basin, where a maximum thickness of over 10 km of sediment accumulated by the end of the Cretaceous, heating due to sedimentary loading caused annealing of apatite grains and thermal maturation of underlying hydrocarbon source beds by 100 Ma. On the south flank of the basin, however, lesser amounts of burial resulted in preservation of thermally immature deposits (e.g., Fortress Mountain Formation).

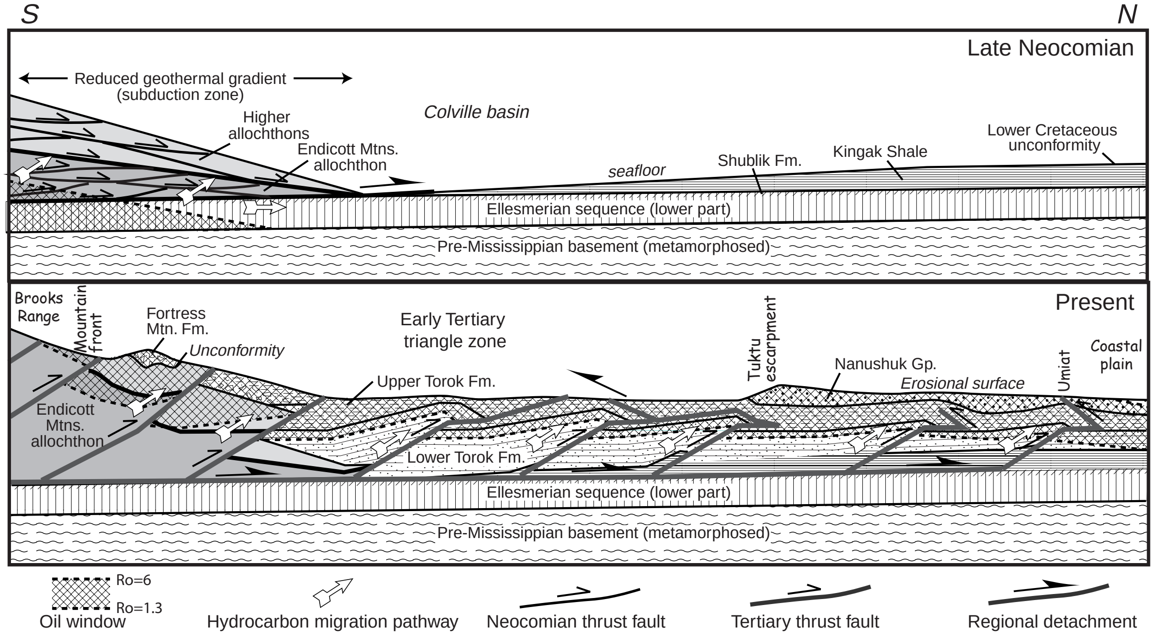

Figure 1. Schematic diagram showing conceptual model for development of the Brooks Range foreland fold and thrust belt. Top, Late Neocomian time following emplacement of deformational wedge and prior to filling of Colville foreland basin in Aptian-Cenomanian time. Bottom, Present relations, following Early Tertiary folding and thrusting and regional denudation of Neocomian deformational wedge and mid-Cretaceous sedimentary fill of Colville basin.

The second, Early Tertiary, episode of north-directed contractional deformation was produced by retroarc thrusting behind a south-facing subduction zone in southern Alaska. The thrusting was deep-seated and involved basement rocks in the Brooks Range, but was thin-skinned in the foreland fold and thrust belt and caused reactivation of some detachments formed initially in the Neocomian (e.g., the Kingak Shale). The renewed deformation resulted in lower magnitudes of shortening than did Neocomian thrusting, but the greater thickness of sedimentary strata involved produced large structural relief and set apatite fission track ages at 60 and 45 Ma over large stratigraphic thicknesses. The shortening propagated along the Kingak detachment well beyond the northern termination of Neocomian deformational wedge and across the axial part of the foreland basin and was mostly accommodated in a passive-roof duplex. To the north in the duplex, linking thrusts between the floor thrust in the Kingak and roof thrust in the upper Torok involved primarily the lower Torok, but to the south, the Neocomian deformational wedge is involved in the duplex. The duplexing produced thrust-related anticlines of lower Torok sandstone units to the north, and significantly shortened the southern flank of the foreland basin on reverse faults to the south. Throughout the deformed belt, regional thermal maturity isograds attained by sedimentary burial prior to Early Tertiary deformation were folded and faulted along with the stratigraphy in which the isograds reside. More than 3 km of denudation has occurred over much of the fold and thrust belt by structural unroofing since the time of maximum sedimentary burial in the Late Cretaceous.

Based on our structural model, we evaluated the hydrocarbon potential of four deformed belt plays: (1) Thrust-belt Play, (2) Lower Torok Structural Play, (3) Deformed Topset Play, and (4) Sub-thrust Ellesmerian Play. Plays 1 and 2 are distinguished by the presence/absence of rocks of the Neocomian deformational wedge, whereas Play 3 occurs entirely above the Torok duplex and mostly in front of the triangle zone and Play 4 in structures in a broad zone of distributed shear beneath the regional Kingak detachment. Major petroleum source rock units found throughout northern Alaska—the Triassic Shublik Formation, Jurassic and Lower Cretaceous Kingak Shale, and gamma-ray zone of the Hue Shale, a condensed section at the base of the overlying Torok Formation— all are present in the deformed belt. Because these units passed through the oil window during sedimentary loading at about 100 Ma in the axial region of the foreland basin, peak generation occurred before formation of structural traps in the Tertiary. Thus, hydrocarbon resources at depth in all plays are likely to be gas. However, the rocks near the present erosional surface are within the oil window, and oil that remigrated upward from older stratigraphic traps during thrusting may be present in shallow structural traps in Plays 1-3 (e.g., Umiat anticline in Play 3 with an oil accumulation estimated at 70 mmbo). Because the source rocks are thick and prolific, the probability of hydrocarbon charge being available in stratigraphic traps in mid-Cretaceous clastic reservoirs is high. Disruption of deep stratigraphic traps and remigration of hydrocarbons to shallower structural traps during thrusting in the Early Tertiary is therefore likely to have been the most common migration pathway in Plays 1-3. Play 1 differs from Plays 2 and 3 in that preservation of hydrocarbon accumulations generated during Neocomian thrusting is possible and because extremely rich source rocks (condensed, stratigraphic equivalents of Shublik and Kingak with TOC>40%, and rich, basinal equivalents of Lisburne carbonate platform deposits, the Kuna Formation) are present in Neocomian allochthons at high structural levels where they remain thermally immature today and could have provided additional hydrocarbon charge at the time of Early Tertiary thrusting.

Uncertainties about the hydrocarbon potential of all four plays stems chiefly from questions about reservoir quality and sealing. Reservoirs in Plays 1 and 4 include both carbonate and clastic strata, whereas reservoirs in Plays 2 and 3 are entirely lithic clastic strata. Reservoir facies in Plays 1, 2, and 4 all display only low to moderate porosity mainly due to post-depositional diagenesis. Regions where porosity has been enhanced by fracturing are thought to have the highest potential for hydrocarbon accumulations. Thick reservoir facies, commonly fault- or erosionally-breached, and problematic seals are the chief questions in Play 3.