CHAPTER BC (Balanced Cross Section)

BALANCED CROSS SECTION, BATHTUB SYNCLINE TO BEAUFORT SEA THROUGH NIGUANAK STRUCTURAL HIGH, ARCTIC NATIONAL WILDLIFE REFUGE (ANWR), NORTHEASTERN ALASKA

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ABSTRACT

This paper presents a geometrically constrained (balanced) cross section that extends northward for 142 km from the Brooks Range to the Beaufort shelf in the northeastern part of the Arctic National Wildlife Refuge (ANWR) in Alaska. The cross section crosses the eastern part of the 1002 area of ANWR where it transects the Niguanak and Aurora dome structural highs. These highs are large domal geologic structures in the subsurface that might have high potential for oil and gas. The cross section was constructed using known geologic relations in the Brooks Range and reprocessed depth sections of the proprietary seismic lines 85-50 and 84-40 from the 1002 Area.

The cross section offers an integrated stratigraphic and structural interpretation of the geology in the frontal part of the northeastern Brooks Range fold-and-thrust belt and a minimum-shortening estimate of the amount of deformation. Principal new interpretations of subsurface stratigraphic relations include: (1) the Ellesmerian sequence, the principal reservoir for the Prudhoe Bay oil field, thins northward to about the apex of the Niguanak high by northward onlap below and increasing erosion from above; (2) the regional Lower Cretaceous unconformity (LCU) is present on the southern flank of the Niguanak high and probably farther north; and (3) the Jago River Formation represents the nonmarine part of a thick, areally extensive, northward thinning uppermost Cretaceous and Paleocene deltaic sequence that was shed northward from the Brooks Range and whose marine equivalents underlie much of the coastal plain. Deformation of these units is interpreted to be underlain by a basal detachment that lies at a depth of about 7 km in pre-Mississippian rocks at its northern end under the coastal plain. Modeling indicates that the basal detachment descends southward to a depth of over 15 km in the Brooks Range. About 72 km of northward displacement is calculated for the transect, with 37 percent shortening in duplexes developed in the Mississippian to Cretaceous Ellesmerian sequence and in the underlying pre-Mississippian rocks and 43 percent shortening in the Cretaceous and younger Brookian sequence. The available age relations indicate that the folding and thrusting began at, or near the end, of the Late Cretaceous at the restored position of the rocks in the southern end of the cross section, and by the Eocene had propagated northward to a position near the present Beaufort Sea coast. Reactivation of thrusting in the Miocene caused renewed uplift in the southern part of the coastal plain and the Niguanak high.

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The Niguanak high and Aurora dome are isolated basement culminations located as much as 50 km north of the regional sharp increase in structural relief within pre-Mississippian rocks at the South 1002 fault system of Grow and others (Chap. NA, Fig. NA1). The isolated basement culminations are interpreted to be bounded by lateral ramps at their eastern and western limits, suggesting that the basal detachment forms a northward-trending trough or fairway for Cenozoic deformation in pre-Mississippian rocks where transected in this study. It is possible that the north-trending trough in the basal detachment allowed the basement-involved deformation to advance to a more northerly position in this area in part because of the presence of the thick Paleocene deltaic section which provided the structural load necessary for a deeper level of detachment.

The stratigraphic-structural model suggests that some of the Paleozoic and Triassic reservoir rocks found in the Prudhoe Bay oil field may be present on the southern flank of the Niguanak high but are unlikely father north. These rocks may be erosionally truncated by the Lower Cretaceous unconformity, potentially forming a stratigraphic trap similar to the one in the Prudhoe Bay oil field. Lower Cretaceous reservoir rocks like those in the Kuparuk River and Point Thomson field might also be expected over parts of the northern part of the 1002 area above the unconformity. A third oil and gas play may lie in deep marine rocks of Paleocene age in the southern part of the 1002 area. These may hold turbidite units that might be prospective for oil and gas if the reservoir quality is good and they have not been excessively breached by the deformation as suggested by this study. These conclusions suggest that significant oil and gas accumulations may be present in the northern part of the eastern 1002 area, particularly on the south flank of the Niguanak high, although a high level of risk is assigned because of questions about the presence or absence of reservoir facies, reservoir quality, and timing of deformation.

INTRODUCTION

The 1002 area of the Arctic National Wildlife Refuge lies in the frontal part of the northward-vergent northeastern Brooks Range fold and thrust belt which constitutes the northeastern salient of the Brooks Range (Rattey, 1985; Kelley and Foland, 1987; Wallace and Hanks, 1990; Hanks, 1993; Wallace, 1993) (Fig. BC1). Blind thrust faults and folds that deform Cenozoic strata characterize the structures found throughout all but the northwestern part of the 1002 area (Bruns and others, 1987; Potter and others, Chap. BD). The deformation is dominantly thin-skinned, but thick-skinned structures involving Proterozoic to Mesozoic rocks are exposed

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throughout the mountains that border the southern boundary of the 1002 area (Wallace and Hanks, 1990; Hanks, 1993; Wallace, 1993). Shortening in the northeastern Brooks Range thrust system, estimated to be less than 100 km (Wallace and Hanks, 1990; Hanks, 1993; Wallace, 1993), is significantly less than that estimated for the older Jurassic and Cretaceous Brooks Range orogen which lies to the south along the axis of the Brooks Range (e.g., Moore and others, 1994).

Despite overall similarities in stratigraphy and structural position, the western and eastern parts of the 1002 area display some notable differences along strike. These include:

1. Seismic basement in the west forms a platform that lies at a depth of about 4-5 km but descends abruptly to a level of about 7-8 km to the east (Grow and others, Chap. NA, Fig. NA1).

2. Although lying at a generally deeper level, seismic basement in the east includes significant, doubly plunging basement-involved uplifts, the Niguanak and Aurora dome structural highs, that rise to a depth of as little as 2.5 km (Grow and others, Chap. NA, Fig. NA1). Similar uplifts are not present in the western part of the 1002 area.

3. Lithic foredeep strata (i.e., the Brookian sequence) that record orogenic unroofing to the south consist of units spanning Cretaceous to Quaternary time in the west. To the east, Brookian strata are apparently dominated by latest Cretaceous and Paleocene deposits that total more than 3 km in thickness (Bird, Chap. GG).

4. The deformation front lies onshore in the western 1002 area, but trends northeasterly to an offshore position over 125 km north of the eastern part of the 1002 area (Grantz and others, 1990). As a result, thin-skinned structures are extensive throughout the entire eastern part of the 1002 area but are restricted to the southern part of the 1002 area to the west.

5. Although the southwestern part of the 1002 area is strongly deformed, complex deformation patterns and locally poor quality of seismic data in the eastern part of the 1002 area make it more difficult to unravel thin-skinned deformation in the east relative to the west.

6. There are significantly more wells and outcrops that provide stratigraphic and structural control in the west than are available to the east in the 1002 area. Several wells in the Canning River region and offshore

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provide ties to seismic lines in the adjacent western part of the 1002 area and allow a relatively robust understanding of the geology there. In addition, numerous field studies conducted in the Sadlerochit and Shublik Mountains south of the western part of the 1002 area (e.g., Knock, 1987; Mull, 1987; Leiggi, 1987; Robinson and others, 1989; Kelley and Foland, 1987; Crowder, 1990; O'Sullivan and others, 1993; Wallace, 1993) furnish abundant information on the stratigraphic and structural architecture present in the western part of the 1002 area. Well data in the eastern part of the 1002 area, in contrast, are restricted to the Aurora-1 well located north of the eastern 1002 area in the Beaufort Sea. A second well, the KIC Jago River-1 well (Fig. BC2), was drilled near the mouth of the Niguanak River but its findings remain confidential. Relevant outcrop studies to the south are restricted to Reiser and others, 1980; Buckingham (1987); Eckstein (1993), and Hanks (1987, 1988, 1989, 1990, 1993), although regional studies by Detterman (1974, 1984), Detterman and others (1975), Molenaar and others (1987), LePain and others (1994), Homza and Wallace (1997) provide some additional stratigraphic and structural information on the area.

Cole and others (Chap. SM) have constructed a north-south balanced cross section and kinematic and thermal model in the western part of the 1002 area. Their cross section, drawing on the earlier balanced cross section of Wallace (1993), uses outcrop, well, and reprocessed seismic data not previously available. In this chapter, I provide a balanced cross section for the eastern part of the 1002 area as a companion to the balanced section of Cole and others (Chap. SM). As did Cole and others, I have drawn on an older balanced section (Hanks, 1990, 1993) and used seismic data recently reprocessed for the assessment of the oil and gas potential of the 1002 area reported in this volume. In addition, well data from the Aurora well located east of the northern end of the section (Fig. BC2) are used as a guide to the stratigraphy in the northern part of the section.

The purpose of constructing the balanced section discussed in this paper is to provide a geometrically constrained cross-sectional model of the geologic relations in the eastern part of the 1002 area. This section can be compared with that of Cole and others (Chap. SM) to the west to understand along-strike variations in the stratigraphy and structure of the 1002 area and the history of sedimentation, deformation, and petroleum generation. In addition to revising the earlier section of Hanks' (1990, 1993) in light of the new seismic and well data, this paper provides the first retrodeformable model for Brookian strata in the eastern part of the 1002 area. The cross section offers an integrated kinematic model for the structural evolution of the 1002 area and adjacent parts of the northeastern Brooks Range fold-and-thrust belt, revises Hanks (1990, 1993) estimate of shortening in the region, and is intended to serve as an aid to the evaluation of exploration plays and prospects in the 1002 area. Because this part of the 1002 area is characterized by complex and inhomogeneous structure, poor stratigraphic control in outcrop and subsurface, absence of marker beds, and abrupt facies changes, the cross section should be considered to be only a simplistic model compared with the actual geologic relations present along the profile. Nonetheless, the simplifications and assumptions detailed below are important because they highlight areas where more information is required.

BALANCED GEOLOGIC CROSS SECTION

The cross section extends northward over a distance of 142 km from a point at the southern margin of the Demarcation Point 1:250,000 quadrangle, about 60 km south-southeast of the 1002 area (N69° 00', W142° 30'), to a point about 15 km north of the mouth of the Jago River in the Beaufort Sea (N70° 15', W143° 14') (Fig. BC2; Plate BC1). This transect is nearly coincident with the sections of Reiser and others (1980) and Hanks (1990, 1993), follows seismic lines 85-50 and 84-40 in the 1002 area, and terminates in the Beaufort Sea at seismic line 719 of Grantz and others (1982). Major structural features crossed by the transect in the northeastern Brooks Range south of the 1002 area include, from south to north, (1) Bathtub syncline, a key erosional remnant of Cretaceous sediments in the core of the northeastern Brooks Range; (2) Mt. Greenough antiform in which lower Paleozoic and Proterozoic rocks are exposed; (3) "the Wall" (Eckstein, 1993) synform, which exposes the Ellesmerian sequence in a tight syncline; and (4) Aichilik River antiform, a second area of exposure of Proterozoic(?) and Lower Paleozoic rocks (Reiser and others, 1980; Wallace and Hanks, 1990) (Fig. BC2). Upper Paleozoic and Mesozoic rocks (the Ellesmerian sequence) are exposed on the north flank of the Aichilik River antiform at Leffingwell Ridge, which forms the range front of the northeastern Brooks Range. To the north under the coastal plain are additional major structural features, including: (1) Okerokovik River monocline, which marks a regionally significant change in structural relief in the subsurface; (2) Sabbath Creek syncline, a composite syncline developed in the Brookian sequence; (3) Aichilik high, a thin-skinned culmination that bounds the Sabbath Creek syncline; (4) Niguanak high, a subsurface high defined at the top of seismic basement; (5) Jago Ridge, a thin-skinned culmination developed above the Niguanak high; and (6) Aurora dome, a second subsurface high defined at the top of seismic basement (Bruns and others, 1987; Grow and others, Chap. NA, Fig. NA1; Potter and others, Chap. BD, Fig. BD2) (Fig. BC2). The Niguanak high and Aurora dome are large structures that were considered to have extremely high potential for oil and gas during the previous U.S. Geological Survey and Bureau of Land Management assessments (Dolton and others, 1987; Callahan and others, 1987). Although well offshore, the northern end of the transect is more than 100 km south of the deformation front of the northeastern Brooks Range foldbelt, which lies in the continental rise of the Canada basin (Grantz and others, 1990, profile 9B). From exposures at elevations of more than 2200 m in the northeastern Brooks Range, lower Paleozoic rocks dip northward to a depth of more than 6100 m beneath the Sabbath Creek syncline (Grow, Chap. NA) indicating a structural relief on the order of 8300 m along the transect.

Bedrock exposures are abundant in the Brooks Range in the southern part of the transect and regional structures are reasonably well constrained by the mapping of Reiser and others (1980) and by Hanks (1987, 1988, 1989, 1993) in the Leffingwell Ridge area. The northern part of the transect lies on the coastal plain, where there are few exposures, and the adjacent submarine Beaufort shelf. Interpretations in this area are based principally on reprocessed depth sections of seismic lines 85-50 and 84-40 (Fig. BC2). Line 85-50 was previously published as a time section in Bird and Magoon (1987, plate 4; see also, Grow and others, Chap. NA, Fig. NA3), and a line drawing of this seismic line is shown on Plate BC1. Line 84-40 remains proprietary and thus a line drawing of it is not included on Plate BC1. Other constraints on interpretations of the northern part of the profile are proprietary shot-hole paleontologic data, proprietary and publicly available vitrinite reflectance results (Bird and others, Chap. VR), offshore seismic data of Grantz and others (1982, 1987, 1990), and paleontologic and thickness data from the Aurora well (Paul and others, 1994; M.B. Mickey, written comm. to M. Keller, 1997; Nelson and others, Chap. WL, Plate WL8). The interpretation presented here also draws from the observations presented in Grow and others (Chap. NA), Potter and others (Chap. BD), and Cole and others (Chap. SM).

STRATIGRAPHY

The stratigraphic sequence in the northeastern Brooks Range and coastal plain is divided into three primary sequences: (1) pre-Mississippian rocks, (2) the Mississippian to Cretaceous Ellesmerian sequence, and (3) the Cretaceous and Cenozoic Brookian sequence (Lerand, 1973; Grantz and others, 1975) (Fig. BC3). A fourth sequence, the Jurassic and Neocomian Beaufortian sequence of the Beaufort shelf, may also be present at the northern end of the transect. The pre-Mississippian rocks are lithologically heterogeneous, variably deformed, and metamorphosed to greenschist facies. In many places, these rocks contain penetrative to semi-penetrative structures that record contractional deformation of the Ellesmerian orogeny in the Early Devonian (Wallace and Hanks, 1990; Anderson and others, 1994; Moore and others, 1994; Bird, Chap. GG). The Ellesmerian sequence overlies the pre-Mississippian rocks on a regional angular unconformity and consists of northerly-derived quartz-rich clastic and carbonate strata deposited on a south-facing continental margin. In contrast, the overlying Brookian sequence consists of lithic sediments shed northward from the Brooks Range orogen into its foredeep during the Brookian orogeny. The Brookian sequence also includes deposits derived from the northeastern Brooks Range foldbelt. The Beaufortian sequence (Hubbard and others, 1987), as suggested by Grantz and others (1990, p. 266), is restricted here to locally derived clastic deposits possibly associated with an episode of failed rifting on the Beaufort shelf.

Regional discussions of this succession and related deformation are provided by Brosgé and others (1962), Bird and Molenaar (1987), Molenaar and others (1987) Grantz and others (1990), Moore and others (1994), and Bird (Chap. GG). The reader is directed to these publications for general information about the stratigraphy of the North Slope and ANWR. The following discussion focuses on the stratigraphy as it pertains to the transect discussed in this paper.

Pre-Mississippian rocks

Pre-Mississippian rocks are exposed in the Mt. Greenough and Aichilik River antiforms along the transect (Fig. BC2). The stratigraphy and age of these rocks are not well understood in detail because of sparse fossils, metamorphism, and structural complexity. In the Mt. Greenough antiform, pre-Mississippian rocks consist of a thick succession of quartz-rich clastic strata, the Neruokpuk Quartzite (Reiser and others, 1978), and overlying chert and phyllite, calcareous, micaceous sandstone, and mafic volcanic rocks and associated carbonate rocks. Late Cambrian trilobites have been recovered from mafic volcanic rocks and carbonate rocks at the structural top of these rocks, suggesting that most of the rocks are Cambrian and/or Proterozoic (Dutro and others, 1972; Reiser and others, 1980). In the Aichilik River antiform, pre-Mississippian rocks consist of a variety of stratified lithologies, including black, pelloidal limestone, ripple-laminated calcareous sandstone, lithic and quartzose sandstone units, argillite, chert, and fine- to coarse-grained volcaniclastic rocks (Hanks, 1989). The age of these rocks is poorly constrained, but is thought to be mostly Proterozoic

(Reiser and others, 1980). Lane (1991) and Kelley and others (1994), however, reported that rocks similar to some of these on the Canadian border span Proterozoic to Devonian time, suggesting that lower Paleozoic rocks may be present along the transect.

Other rocks that may be present in the subsurface along the southern part of the transect include a highly deformed unit of radiolarian chert and phyllite with lesser lithic sandstone, mafic volcanic rocks and limestone that are exposed over an extensive area west of Bathtub syncline (Reiser and others, 1980; Moore and others, 1994). These rocks have yielded Ordovician graptolites (Moore and Churkin, 1984) and may contain strata that represent most of the lower Paleozoic (Reiser and others, 1980). The deformed chert and phyllite unit is unconformably overlain by coarse-grained, nonmarine to marine clastic rocks of Middle Devonian age (Reiser and others, 1980; Anderson and others, 1994; Popov and others, 1994). The clastic rocks, the Ulungarat Formation of Anderson and others (1994), rest on the deformed rocks on a prominent angular unconformity that constrains the main phase of Ellesmerian deformation to pre-Middle Devonian time (Moore and others, 1985; Anderson and others, 1994; Moore and others, 1994). The Devonian clastic rocks themselves are tilted at a shallow angle with respect to overlying Ellesmerian sequence, indicating that another episode of deformation, probably extensional in nature, occurred between the Middle Devonian and Mississippian (Anderson and others, 1994; Moore and others, 1994).

The Devonian Okpilak batholith (Dillon and others, 1987), intrudes pre-Mississippian rocks about 30 km west of the transect (Fig. BC2). Although not exposed along the transect, its structural position would place it in the Aichilik River antiform if projected into the transect. The batholith has played an influential role in Cenozoic deformation in the northeastern Brooks Range by deflecting regional structural trends and forcing a deeper level of detachment (Wallace and Hanks, 1990; Hanks and Wallace, 1990; Peapples and others, 1997).

The nature of pre-Mississippian rocks under the coastal plain along the transect is largely conjectural. On the basis of exposures in the Sadlerochit Mountains (Robinson and others, 1989) and sparse well data west of the Canning River (Dumoulin, Chap. CC), Kelley (Chap. BR) recognizes three east-trending domains in seismic basement in the western part of the 1002 area that may extend eastward into the area of this transect. He suggests that the southern unit consists of carbonate rocks correlative with the Proterozoic Katakturuk Dolomite, Proterozoic, Cambrian, and Ordovician Nanook

Limestone, and Lower Devonian Mt. Copleston Limestone (see Bird, Chap. GG for descriptions of these units), a middle domain that may consist of quartzite and quartzose schist correlative with the Neruokpuk Quartzite, and a northern unit of clastic rocks of lower or middle Paleozoic age.

Because the regional stratigraphy and structure of the pre-Mississippian rocks are poorly understood, they are shown as undifferentiated on Fig. BC3 and Plate BC1 and discussed as seismic and structural basement in the text. Ellesmerian deformation and metamorphism may have made these rocks relatively competent structural units on a regional basis (Wallace and Hanks, 1990). Furthermore, there is evidence that pre-existing structures within the pre-Mississippian units in many places have influenced the location and trend of Brookian structures (Wallace and Hanks, 1990). Pre-Brookian sedimentary layering and penetrative foliation may have produced locally anisotropic fabrics that influenced the resulting geometry of Brookian structures (Hanks, 1993).

Ellesmerian sequence

The Ellesmerian sequence is exposed along the transect in the Bathtub syncline, the “Wall” synform, and at Leffingwell Ridge (Reiser and others, 1980) (Fig. BC2). It consists, from base to top, of the Mississippian Kekiktuk Conglomerate and Kayak Shale of the Endicott Group, the Mississippian and Pennsylvanian Lisburne Group, the Permian and Triassic Sadlerochit Group, Triassic Shublik Formation, Triassic Karen Creek Sandstone, Jurassic and Lower Cretaceous Kingak Shale, and Hauterivian and Barremian pebble shale unit (Fig. BC3). These strata record a Mississippian transgression that deposited nonmarine and paralic sediments (Kekiktuk Conglomerate) followed by black marine shale (Kayak Shale) and carbonate platform deposits (Lisburne Group). The Lisburne Group is disconformably overlain by mainly transgressive shelf deposits (Sadlerochit Group, Shublik Formation, and Karen Creek Sandstone). The overlying Kingak Shale consists of what are interpreted to be fine-grained rift-shoulder deposits that were shed southward from the rift zone that eventually led to the development of the Canada basin (Hubbard and others, 1987). The pebble shale unit is a thin unit of condensed shale that marks the end of Ellesmerian deposition (Bird and Molenaar, 1987).

The Ellesmerian sequence is about 1700 m thick at Bathtub syncline and the “Wall” synform but decreases to about 1300 m at Leffingwell Ridge (Table BC1). On Plate BC1, the Ellesmerian sequence is subdivided into three units: (1) a lower part consisting of the Endicott and Lisburne Groups, (2) a middle part consisting of the Sadlerochit Group, Shublik Formation, and

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Karen Creek Sandstone, and (3) an upper part that consists of the Kingak Shale and pebble shale unit (Fig. BC3). The Kingak Shale is a highly deformed unit, whose stratigraphic thickness is difficult to estimate. Regionally, it thins southward from about 400 m north of Leffingwell Ridge to about 150 m at Bathtub syncline, where it comprises the lower part of the Kongakut Formation of Detterman and others (1975) (Moore and others, 1994) (Table BC1). In this area, the Kingak is too thin to be shown and is included with the middle part of the Ellesmerian sequence on Plate BC1).

Under the coastal plain, the Ellesmerian sequence can be recognized in seismic records on the Okerokovik monocline (Fig. BC2). In this area, the Lisburne Group is interpreted to be expressed as a seismically transparent zone bounded above and below by high amplitude anomalies representing the Endicott Group and Sadlerochit Group (Grow and others, Chap. NA, Fig. NA7). At the longitude of the transect, the Ellesmerian sequence is about 1200 m thick (Plate BC1; Grow and others, Chap. NA, Fig. NA5). North of the Sabbath Creek syncline, it is uncertain whether the Ellesmerian sequence is present in the subsurface (Grow and others, Chap. NA). Seismic data on the south flank of the Niguanak high display a transparent zone that apparently thins northward and nearly pinches out over the shallowest part of the high at a depth of about 3,050 m (10,000 ft) (Plate BC1). This transparent zone is here interpreted to be carbonate rocks of the Lisburne Group. High amplitude anomalies are present above the transparent zone but are mostly absent below it in this area. The disappearance of the lower high-amplitude anomaly can be attributed to northward depositional onlap of the Ellesmerian sequence onto pre-Mississippian rocks so that the Lisburne Group was deposited directly on pre-Mississippian rocks beyond depositional pinch-out of the Endicott Group. Seismic velocities are approximately the same in pre-Mississippian rocks and the carbonate rocks of the Lisburne Group (Grow and others, Chap. NA), so a high amplitude anomaly would not be expected to be found in seismic data if this is the case. Northward onlap of the Ellesmerian sequence onto pre-Mississippian rocks has long been recognized in the central North Slope (e.g., Bird, 1988; Chap. GG, Fig. GG5), the Sadlerochit Mountains (Bird and Molenaar, 1987), and is likely present in the subsurface in the 1002 area west of the Niguanak high (Grow and others, Chap. NA, Figs. NA5, NA8, NA9).

North of the Niguanak high, there is little evidence that the lower and middle parts of the Ellesmerian sequence are present. Rocks of the upper part of the Ellesmerian sequence, the Kingak Shale and pebble shale unit, are exposed in outcrop above the crestal region of the Niguanak high (Bird, Chap. GG). Seismic data and geologic considerations show that these rocks are

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allochthonous and would be restored southward in most models (Molenaar and others, 1987; Potter and others, Chap. BD).

A key question for the construction of Plate BC1 is whether the Lower Cretaceous unconformity (LCU), which lies in the uppermost part of the Ellesmerian sequence beneath the pebble shale unit, extends eastward into the line of transect. This unconformity, interpreted as the “breakup” unconformity associated with opening of the Canada basin in the Hauterivian by Grantz and May (1983), was developed along the nascent margin of the Canada basin. The amount of section removed by the unconformity is variable. In the western part of the 1002 area, the entire Ellesmerian sequence and an unknown amount of pre-Mississippian rocks were removed beneath the LCU (Cole and others, Chap. SM), whereas in the Kuparuk River oil field, about 50 km west of ANWR (Fig. BC1), little or no section is missing by erosion (Carman and Hardwick, 1983). Regionally, the amount of section removed beneath the LCU diminishes southward from a maximum in the Beaufort Sea coastal region, and the unconformity merges with conformable strata at about the southern limit of the coastal plain in the central and western North Slope (Bird, 1985; Bird, Chap. GG, Fig. GG6).

Information bearing on the existence of the LCU along the line of transect is sparse. The large amount of section removed in the northwestern part of the 1002 area, coupled with the position of the northern end of the transect at or near the apex of the rifted margin of the Canada basin (indicated by reversal of dip at the top of pre-Mississippian rocks in the subsurface offshore, Grantz and others, 1990, Plate 9, Profile 9C), suggest that erosion on the LCU was likely. However, no erosion is evident in the northernmost exposures of the Ellesmerian sequence at Leffingwell Ridge and where Ellesmerian strata are best imaged on seismic lines in the south-central part of the 1002 area (Grow and others, Chap. NA). The presence of the LCU, at best, is equivocal along seismic lines on this transect (Plate BC1). Little or no erosion over this interval may be present in the Aurora well (M.B. Mickey, written comm. to M. Keller, 1997) (Nelson and others, Chap. WL, Plate WL8).

For the purpose of construction of the cross section discussed in this paper, I suggest that the LCU has truncated the upper part of the Ellesmerian sequence from a position beneath the Sabbath Creek syncline northward to near the Beaufort Sea. This interpretation is based on two observations: (1) the reflective, upper part of the Ellesmerian sequence (Sadlerochit Group and higher) as interpreted above the southern flank of the Niguanak high on seismic line 85-50 is much thinner than where seen on seismic lines south of the Sabbath Creek syncline, and (2) fossils from the Kingak exposures above the Niguanak high suggest the Kingak is no younger than Middle Jurassic at that location (Detterman and others, 1975; Reiser and others, 1980). The latter evidence may indicate that post-Jurassic strata of the Kingak were removed beneath the LCU at least as far south as the position at which the exposures of the Kingak above the Niguanak high were deposited prior to their northward displacement on thrust faults.

Beaufortian sequence

Fine-grained clastic rocks of Jurassic and Neocomian age are present in the lower 730 m of the Aurora well (M.B. Mickey, written comm. to M. Keller, 1997) (Nelson and others, Chap. WL, Plate WL8). If the remainder of the sedimentary section below the well to the top of seismic basement consists of similar rocks, the unit may be as thick as 2100 m. The presence of Jurassic and Neocomian strata in the Aurora well may indicate that at least the upper part (i.e., the Kingak Shale and pebble shale unit) of the Ellesmerian sequence extends northward beyond the 1002 area into the area of the Beaufort shelf. As explained by Bird (Chap. GG), however, the Jurassic and Lower Cretaceous strata in the Aurora well instead may represent part of an extensional basin that may be analogous to the failed-rift deposits of the Dinkum graben (Grantz and others,1975; 1990). An equivalent of the gamma-ray shale (GRZ), a key marker at the top of the Ellesmerian sequence in ANWR (Bird and Molenaar, 1987) is not present in the well. This observation, coupled with the possibly large thickness and apparent westward disappearance of these deposits on seismic records (Grow and others, Chap. NA; Bird, written comm., 1998) suggest that Jurassic and Neocomian deposits of the Aurora well may represent fill of an distinct basin that may be related to the Dinkum graben. To recognize this possibility in this paper, the Jurassic and Neocomian deposits of the Beaufort shelf are shown as the Beaufortian sequence on Plate BC1.

Brookian sequence

The Brookian sequence forms a thick sedimentary cover of middle Cretaceous to Neogene age that was deposited on the older Proterozoic, Paleozoic, and early Mesozoic successions. Seismic data show that it is extensively deformed in the eastern part of the 1002 area, but abrupt facies changes, absence of marker beds, poorly constrained stratigraphy, sparse outcrops, and incomplete age data make interpretation of the structures difficult. To aid structural analysis of the Brookian for this report, a stratigraphic model was developed that draws on exposures in the Bathtub and Sabbath Creek synclines, data from the Aurora well, seismic data, and shot-hole paleontologic data. Based on these data and observations, the Brookian sequence along the transect is divided into four northward thinning and fining stratigraphic units that consist of (1) middle and Upper Cretaceous deposits, (2) latest Cretaceous and Paleocene deposits, (3) Eocene deposits, and (4) Oligocene deposits (Fig. BC3). Characteristics of these units are as follows.

Brookian sedimentary rocks of middle Cretaceous age form the core of the Bathtub syncline and represent an erosional remnant of the axial part of the eastern Colville basin (Molenaar, 1983; Moore and others, 1994). The Bathtub syncline succession consists of turbiditic strata that thicken upward from thin-bedded, fine-grained turbidites that form the upper 800 m of the Kongakut Formation into thicker, coarser grained turbidites of the 750-m-thick Bathtub Graywacke. Fossils indicate an Aptian to Albian age for the succession (Molenaar and others, 1987; Moore and others, 1994). Vitrinite reflectance data from near the hinge of the Bathtub syncline (Bird and others, Chap. VR) indicate that at least 5 km of Brookian deposits, possibly including Upper Cretaceous deposits, have been removed by erosion.

To the northwest of Leffingwell Ridge, middle and possibly Upper Cretaceous strata are found in the Arctic Creek unit of Molenaar and others (1987). The Arctic Creek unit consists principally of thin-bedded turbidites that are estimated to total about 1100 m in thickness, although stratigraphic thickness is difficult to determine due to deformation (Molenaar, 1983). The Arctic Creek unit has yielded Albian ammonites at the base, but bentonite in the unit has led some workers to conclude that it consists mainly of Upper Cretaceous strata correlative with the Colville Group of the central North Slope (e.g., Mull and Decker, 1993). North of the Sabbath Creek syncline, middle and Upper Cretaceous strata are represented by the Hue Shale. The Hue Shale consists of distal, condensed shale with bentonite and tuff (Bird and Molenaar, 1987; Bird, Chap. GG). It is exposed in scattered outcrops above the Niguanak high (Fig. BC2) and the lower, Albian, part of the unit has been identified in the Aurora well, although in the Aurora well it is not tuffaceous. Strata assigned to the Hue Shale and the underlying late Neocomian pebble shale unit in the Aurora well total less than 300 m (M.B. Mickey, written comm. to M. Keller, 1997) (Nelson, Chap. WL, Plate WL8). The thickness of the same strata near the Niguanak high is not well constrained but is estimated to be 450 m (Reiser and others, 1980). Measured sections document a minimum thickness of only about 50 m in that area (Palmer and others, 1979). The pebble shale unit, a thin shale unit that regionally overlies the LCU, lies beneath the Hue Shale in exposures above the

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Niguanak high. Although part of the Ellesmerian sequence, it is included with the Hue Shale north of Leffingwell Ridge for simplicity in Plate BC1.

The latest Cretaceous and Paleocene unit includes the Maastrichtian and Paleocene Jago River Formation, a thick fluvial-deltaic sequence that totals over 2800 m in thickness (Buckingham, 1987). The Jago River Formation forms topset beds that are well imaged on seismic lines in the southeastern part of the 1002 area. These topset beds define the composite Sabbath Creek syncline (Fig. BC2; Plate BC1; see also Grow and others, Chap. NA, Fig. NA3). Vitrinite reflectance data indicate that about 2 km of section has been removed above the core of the Sabbath Creek syncline, allowing the possibility that the unit may have once been nearly 5 km thick (Plate BC1). Although not identified in the seismic lines in Plate BC1, seismic lines east of the transect display reflectors relatively high in the Jago River Formation that converge outward into the limbs of the Sabbath Creek syncline, suggesting that at least younger parts of the formation were deposited in a piggyback basin that was actively deforming at the time of deposition (Potter and others, Chap. BD, Fig. BD4). The age of the piggyback basin deposits is uncertain, but is presumably late Paleocene (Potter and others, Chap. BD).

Paleocene deposits are sparse in outcrop north of the Sabbath Creek syncline, but probably thin dramatically northward. Vitrinite reflectance data from allochthonous exposures of the Hue Shale in the area of the Niguanak high suggest a maximum burial of about 2-2.5 km (less if maximum burial is due to tectonic causes), and paleontologic data indicate that Paleocene deposits are only about 550 m thick in the Aurora well (M.B. Mickey, written comm. to M. Keller, 1997) (Nelson and others, Chap. WL, Plate WL8).

In the eastern part of the 1002 area, Eocene deposits have been identified in outcrop only in the northernmost exposures along the Jago River (Palmer and others, 1979) (Fig. BC2), but shothole paleontologic data indicate that Eocene deposits are widespread north of latitude 69° 58’ in the area of the transect. The Eocene deposits consist of moderately north-dipping mudstone and siltstone which must lie in fault contact with steeply dipping Hue Shale exposed about 500 m to the south (C.M. Molenaar field notes, Appendix CM; Reiser and others, 1980; Bird, Chap. GG, Plate GG1). In the Aurora well, Eocene strata are thick, totaling nearly 3500 m (M.B. Mickey, written comm. to M. Keller, 1997) (Nelson and others, Chap. WL, Plate WL8).

The upper 725 m of the Aurora well consists of Oligocene and younger deposits (M.B. Mickey, written comm. to M. Keller, 1997) (Nelson and others, Chap. WL, Plate WL8). These strata are correlated seismically with flat-lying strata along the northern part of seismic line 85-50 (Grow and others, Chap. NA, Fig. NA3). The seismic data indicate that Oligocene strata rest unconformably above older, northward dipping rocks along the transect (Plate BC1) and mildly deformed strata in the Aurora well area (K. Bird, written comm., 1998) (Plate BC1).

DEFORMATIONAL STYLE ALONG TRANSECT

It is now widely recognized that the stratigraphy of the northeastern Brooks Range, particularly the location of incompetent shale units that become the site of detachment surfaces, has played an important role in determining the structural style of Brookian deformation (Kelley and Foland, 1987; Wallace and Hanks, 1990; Wallace, 1993; Hanks, 1993; Cole and others, Chap. SM). Map-scale antiforms such as the Mt. Greenough and Aichilik River antiforms, are interpreted as horses within an extensive duplex composed of relatively rigid units of pre-Mississippian rocks caught between a roof thrust along a regional detachment in the Kayak Shale and a floor thrust at depth in pre-Mississippian rocks. Similarly, a higher regional detachment surface near the top of the Ellesmerian sequence in the Kingak Shale has facilitated detachment folding or local duplexing of mechanically competent Ellesmerian units, particularly carbonate rocks of the Lisburne Group, between a roof thrust in the Kingak and a floor thrust in the Kayak Shale. This style of deformation, termed multistoried duplexes by Wallace and others (1997), has resulted in shortening that is expressed in folding and faulting of competent units at multiple structural levels between bounding detachment surfaces in incompetent shale horizons (Wallace and others, 1997). Where a bounding incompetent shale pinches out stratigraphically, the detachment surface ramps upward (forward or hindward) to a higher incompetent unit. This has occurred in the Sadlerochit Mountains, where a map-scale antiform is underlain by a horse composed of a structurally continuous sequence of pre-Mississippian rocks and Ellesmerian sequence because of the northward disappearance of the Kayak Shale (Kelley and Foland, 1987; Robinson and others, 1989; Wallace and Hanks, 1990; Wallace, 1993; Cole and others, Chap. SM). In these areas, the Ellesmerian sequence is deformed with underlying pre-Mississippian rocks in duplexes between detachment surfaces in the Kingak Shale and at depth in pre-Mississippian rocks.

The deformational style present in the Brookian sequence is more complex because these rocks consist of variable proportions of competent sandstone and less competent shale units that undergo abrupt lateral changes of facies. As a result, deformation in the Brookian is thin skinned and locally displays disharmonic folds and internal thrust faults at outcrop scale. Observations of seismic data in the eastern 1002 area nonetheless show that thick sequences of the Brookian rocks locally remain intact between discrete discordant structures (e.g., the topset beds of the Jago River Formation in the Sabbath Creek synform). Shot-hole paleontologic data within areas of incoherent seismic records suggest that imbrication of major stratigraphic units is uncommon and that stratigraphic order is generally preserved between major bounding structures. This suggests that while the rocks are internally deformed, shortening has not been accommodated by an imbricate style of deformation at map scale. These observations instead suggest that the seismically incoherent regions probably reflect the presence of internally deformed clinoform deposits.

Individual map-scale folds in the Brookian sequence generally can be traced in seismic data for no more than about 15 km. Structural culminations, such as the Aichilik high and Jago ridge and depressions such as the Sabbath Creek syncline, are composite structures consisting of multiple folds. Folds observed in outcrop and seismic data vary from open to asymmetric; near vertical and overturned beds are less common. These geometries suggest that map-scale deformation in the Brookian is expressed as fault-bend folds or possibly, detachment folds. As a simplifying assumption for construction of the section, a fault-bend fold style of deformation has been assumed. This interpretation has the advantage of allowing seismically complex areas of Brookian deposits to be modeled as approximately rigid bodies, at least at map scale.

In summary, the cross section presented in this report interprets Brookian deformational style for the entire stratigraphic succession along the transect to be the result of deformation of a mechanically layered medium. The structural relief of individual folds and faults is thus controlled by the thickness of competent strata caught between well-defined detachment surfaces in incompetent, shale-rich units. The detachment surfaces recognized in outcrop and seismic records and along which deformation is modeled in Plate BC1 are shown in Fig. BC3.

CONSTRUCTION OF BALANCED CROSS SECTION

This section of the paper discusses the geologic data and observations and reasoning that were used to construct the balanced section shown in Plate BC1. A number of general assumptions were used to construct the section. These include:

1. The thickness, depth, and orientation of pre-Mississippian, Ellesmerian, and Brookian units can be recognized in the seismic data by their seismic character;

2. Deformation was controlled by discrete detachment surfaces in Brookian as well as Ellesmerian and pre-Mississippian rocks;

3. The stratigraphic succession in the northeastern Brooks Range was deformed according to the general multistory duplex wedge model described by Wallace (1993) and Wallace and others (1997);

4. Structural relief across individual map-scale structures can be modeled with a fault-bend fold and duplex style of deformation;

5. Slope of the basal detachment is 0°;

6. The seismic sections and structural transect are oriented to within about 5° of normal to the strike of the structures;

7. Restorations that require the smallest amount of shortening that satisfy the observed geologic constraints are preferred.

The method of Suppe (1983) for balancing cross sections was used for construction of Plate BC1. The section was constructed on a personal computer and line length and area balancing for all structural units were calculated by computer. Area balancing was within 2 percent, the practical limit of the method used. Details of construction of the section are discussed sequentially by structural position below.

Depth to basal detachment

The depth to basal detachment under the coastal plain is a fundamental parameter that controls the deformational geometry of structures throughout the hindward part of the cross section. Hanks (1990, 1991, 1993) calculated a depth to the basal detachment at 20,000 ft (~6100 m) based on the amount of structural relief on the Niguanak high visible on the published time seismic records available to her (i.e., Bird and Magoon, 1987, plate 4). As she noted, the 20,000 ft depth she used in her section is the *minimum* depth possible for the basal detachment under the coastal plain. Consequently, the amount of shortening, 100.8 km or 45.8 percent over the length of her section, is the *maximum* allowed by the gross geometry of seismic basement under the coastal plain. Thus, the model of Hanks (1990, 1991, 1993) can be regarded as a maximum shortening model. Disadvantages of the maximum shortening model include (1) requirement of a thick antiformal stack of horses of Ellesmerian sequence rocks at the Aichilik River antiform whose existence cannot be independently confirmed, and (2) numerous horses composed of pre-Mississippian rocks in the Mt. Greenough and Aichilik River antiforms. The latter point can be analyzed on existing geologic maps because the basal part of the Ellesmerian sequence (lower Kayak Shale, Kekiktuk Conglomerate, and underlying unconformity) may be expected to be preserved along the top surfaces of pre-Mississippian horses as a consequence of the roof thrust being located within the interior of the Kayak Shale. Examination of the map of Reiser and others (1980) shows few exposures of Kekiktuk and Kayak in the cores of the two antiforms, suggesting that a large number of horses, and hence a large amount of Cenozoic shortening, is unlikely in the pre-Mississippian rocks. However, most of this area is mapped only in reconnaissance and the Kayak and Kekiktuk are thin units that may be difficult to distinguish from pre-Mississippian rocks without detailed mapping (W.K. Wallace, written comm., 1999; C. Hanks, written comm., 1999), so this conclusion should be considered to be tentative.

The good quality depth-converted seismic records available to this study allowed an empirical approach to be used for determination of the depth to detachment under the coastal plain. Relevant observations are as follows: (1) the top of undeformed pre-Mississippian basement beneath the foreland of the thrust belt is imaged at the north end of seismic line 84-40, and lies at a depth of about 23,000 to 25,000 ft (~7000-7600 m); (2) the depth to the top of pre-Mississippian rocks in the synformal low beneath the Sabbath Creek syncline along the line of transect is at about 25,000 ft (~7600 m); (3) regional average depth to pre-Mississippian rocks in the eastern part of the 1002 area both east and west of the transect is about 25,000 ft (~7600 m) (Grow and others, Chap. NA, Fig. NA1); (4) a prominent band of reflections visible within seismic basement and interpreted by Grow and others (Chap. NA) as a lateral ramp underlying Aurora dome, descends eastward from the top of the pre-Mississippian at a depth of 23,000 ft (~7000) on the west flank of Aurora dome to more than 35,000 ft (10,670 m) beneath the core of the structure (Grow and others, Chap. NA); if a lateral ramp, this structure suggests the basal detachment lies at a depth of 35,000 ft or greater; and (5) westward-dipping reflections in seismic basement on the eastern flank of the Niguanak high are interpreted as the upper part of a lateral ramp that extend to a depth of at least 26,000 ft (7900 m) within pre-Mississippian rocks (Grow and others, Chap. NA, Fig. NA4). Taken together, these observations suggest that the top of undeformed pre-Mississippian rocks lie regionally at a depth of 7 to 7.6 km (23,000-25,000 ft) and that the sub-pre-Mississippian basal detachment is located at a depth of approximately 10.7 km (35,000 ft) under the coastal plain.

Using a depth to the top of pre-Mississippian rocks of 7.2 km (~23,600 ft), a best call from seismic line 84-40 near the north end of the transect, iterative modeling using reflectors beneath the Niguanak high and simple fault-bend fold geometry (see below) suggests that the pre-Mississippian section deformed above the detachment is about 4.1 km (~13,500 ft) thick and that the basal detachment lies at a depth of about 11.3 km (37,000 ft). By retrodeforming the pre-Mississippian section as described in the section below, the best-fit model suggests that the basal detachment descends over the length of the section to a depth of 15.6 km (~51,000 ft) south of the Bathtub syncline.

The depth to basal detachment calculated in this paper (11.3 km beneath the coastal plain to 15.6 km in the interior of the northeastern Brooks Range, is significantly deeper than that suggested by Hanks (1990, 1993) (6.1 km beneath the coastal plain to 11.5 km beneath Bathtub syncline) for nearly the same line of section. However, the depth to basal detachment presented here is not as deep as that used by Hanks (1990) for her transect line through the Okpilak batholith about 40 km to the west (10 km beneath the coastal plain descending to 18.5 km beneath the interior of the foldbelt). Cole and others (Chap. SM) used a depth to detachment in the southwestern part of the 1002 area of 8-9 km and, in the central Brooks Range, Fuis and others (1997) determined that a basal detachment of Cenozoic age descends from a depth of 10 km near the front of the Brooks Range to 30 km in the southern Brooks Range. Considering that many workers have ascribed the fundamental tectonic cause of Cenozoic deformation in the northeastern Alaska to far-field effects of subduction in southern Alaska (e.g., Grantz and others, 1991; Lane, 1998) and that a detachment at or near the base of crust allows stress to be transmitted from southern to northern Alaska, a deep level of detachment might be expected as the locus of shortening ascends from depths of about 30-35 km under interior Alaska to the coastal plain in the 1002 area in northeastern Alaska (Plate BC1, cross section A).

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In the interpretation presented here, the basal detachment steps up northward to the top of the pre-Mississippian unit at a depth of 7.2 km (~23,600 ft) beneath the Aurora dome and continues northward under the Beaufort shelf beyond the northern limit of the section.

Retrodeformable model for pre-Mississippian rocks

Seismic line 84-40 and particularly line 85-50 display prominent reflections at the base of the Brookian sequence (Plate BC1, cross section A). These reflections, together with reflections in underlying pre-Mississippian rocks, can be used to model horses in a duplex that deforms the pre-Mississippian rocks under the coastal plain. The duplex is located between a roof thrust at the base of the Brookian sequence and a floor thrust that lies at a depth of about 11.3 km. The most northerly of the horses forms the Aurora dome, whose backlimb is imaged at the northern end of 85-50 and whose forelimb is partly imaged in 84-40. The backlimb of the Aurora dome dips southward at 18° and is assumed to be equivalent in dip to the ramp over which the horse deformed. Forward dips measured on line 84-40 are about 20°. A structural relief of 2.6 km and shortening of 8 km is calculated for the structure.

Developed partly on the backlimb of the Aurora dome, the Niguanak high marks a well-defined horse (Plate BC1, cross section A). High amplitude reflectors on the backlimb of the structure indicate a dip of 15°, a value used to construct the underlying ramp. Forelimb dips are well imaged near the top of the structure and dip northward at 30°. Forelimb dips of about 16° are expected for ramp cutoff angles of 15° (Suppe, 1983), indicating that the structure is more complex than modeled. A similar conclusion was reached by Grow and others from regional seismic data, who interpret a series of south-dipping imbricate structures in the forelimb of the Niguanak high (Chap. NA, Fig. NA3). To account for this complexity, the structure was modeled as a fault-bend fold with an oversteepened forelimb and calculations of bed length were adjusted for the forelimb according to Jamison (1987). A structural relief of 4.1 km and shortening of 12 km is estimated for the structure.

As noted in “Stratigraphy” above, the Ellesmerian sequence is inferred to be present on the southern flank of the Niguanak high antiform as a unit that thins northward by (1) depositional onlap and (2) Early Cretaceous erosional downcutting on the LCU. Because the Endicott Group is inferred to be absent at the base of the Ellesmerian sequence in this area and thus there cannot be a roof-thrust detachment in the Kayak Shale, the Ellesmerian is modeled as a coherent part of the pre-Mississippian horse in the Niguanak structure. A consequence of this interpretation, coupled with the assumption of flat basal detachments in the cross section, is that the thickness of the pre-Mississippian rocks in the Niguanak-high horse increases northward (Plate BC1, cross section B). Thus, with respect to the top of the pre-Mississippian unit, the basal thrust appears to cut downward slightly in the direction of thrusting. Whether this predicted relation can be found in the structure is uncertain and depends on the assumption of constant depth for the sub-pre-Mississippian detachment.

The horse of pre-Mississippian rocks that forms the Okerokovik River monocline (Fig. BC2; Plate BC1, cross section A) represents a change of nearly 5 km in structural relief (see Grow and others, Chap. NA, Fig. NA1 for the regional magnitude and extent of this structure). There can be several causes for this change including (1) stacking of horses, (2) change in horse thickness caused by a ramp in the basal detachment, (3) duplexing above a deeper detachment that lies beneath the sub-pre-Mississippian detachment, or (4) change in deformational style. Through trial and error, a change of horse thickness was found to provide the simplest solution, a conclusion also reached by Hanks (1991, 1993). A ramp in the basal detachment was thus inferred to be located at the leading edge of the restored position of this horse (~km 97-105, Plate BC1, cross section A). The thickness of the horse was calculated from an inflection in dip in Ellesmerian strata clearly visible at the south end of seismic line 85-50 (km 66, Plate BC1, cross section A). Ellesmerian reflectors south of the inflection are approximately flat, whereas to the north reflectors dip northward at about 32°. A ramp angle of 25° and a horse thickness from basal detachment to the sub-Mississippian unconformity of 7.9 km was calculated from these observations. Shortening is estimated to be about 12 km on the structure. Seismic data along the southern margin of the 1002 area clearly image the Ellesmerian sequence, including the Endicott Group, at the top of this horse (e.g. Grow and others, Chap. NA, Fig. NA7) but do not show any detachment or duplication of the Ellesmerian section. For this reason, the regional detachment in the Kayak Shale is interpreted to not be present in the Ellesmerian sequence in this area and the Ellesmerian sequence was modeled with the underlying pre-Mississippian rocks as a single horse. The reason for the absence of the Kayak detachment despite the presence of the Endicott Group is uncertain but may be caused by a northward decrease in the amount of shale in the Kayak, an aspect of the Kayak noted at Leffingwell Ridge by Wallace and Hanks (1990) and Hanks (1991, 1993). The absence of the Kayak detachment in this horse is

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substantiated by observation in the Sadlerochit Mountains of northward stratigraphic discontinuity of the Kayak detachment (Wallace, 1993; Cole and others, Chap. SM).

Pre-Mississippian rocks under the Aichilik River antiform were found to be difficult to model because of constraining surface relations provided by Hanks (1987, 1988, 1989, 1993) and the presence of the ramp inferred to lie at depth (see above). Through trial-and-error, a solution that consists of two horses of pre-Mississippian rocks was found to provide the best fit (Plate BC1, cross section A). The northern horse underlies Leffingwell Ridge and the adjacent coastal plain. Exposures of the Kingak Shale in an extensive series of rivercuts along the Aichilik River about 8 km to the west of the transect (Bird, Chap. GG, Plate GG1) suggests that the Ellesmerian sequence, and hence the top of the underlying horse, is nearly flat. South of Leffingwell Ridge, however, the top of the pre-Mississippian dips shallowly northward (Hanks, 1989, 1993). Although a roof thrust is likely present in the Kayak above this contact, the unit is unusually thin and silty and contains carbonate rocks that may have impeded detachment (Wallace and Hanks, 1990; Hanks, 1991, 1993). On the basis of these observations, the roof thrust in the Kayak is inferred to terminate at depth beneath Leffingwell Ridge (~km 82, Plate BC1, cross section A) midway along the top of the underlying horse of pre-Mississippian rocks. The shallow north dip of the top of the pre-Mississippian south of Leffingwell Ridge is interpreted to have been caused by emplacement of the southern of the two horses along the Kayak detachment beneath a passive-roof formed by the Ellesmerian sequence. The restoration shown in Plate BC1 for the more northern of these horses provides a good fit with the known relations and was modeled as an intact succession of pre-Mississippian and Ellesmerian rocks. The more southerly of the horses, however, was difficult to model precisely and minor adjustments in the shape of the forelimb were necessary to provide an area and bed length (calculated at the sub-Mississippian unconformity) balance of cross sections A and B in Plate BC1. The adjustments in the forelimb may have been caused by oversteepening related to passage over the underlying ramp and adjacent horse. It is hypothesized that the oversteepening may have produced anisotropic strain in the forelimb because of the presence of preexisting Ellesmerian penetrative fabrics and/or sedimentary layering in the pre-Mississippian rocks in this area (Hanks, 1993). The model shown in Plate BC1 was made assuming a ramp angle of 25° and results in shortening of about 6.2 km on the northern horse and 11 km on the southern horse.

The internal character of the Mt. Greenough antiform is not well understood. The reconnaissance map of Reiser and others (1980) and a structure contour map at the sub-Mississippian unconformity constructed by Hanks (1993) shows that along the west fork of the Aichilik River, about 20 km west of the cross section (Fig. BC2), the Mt. Greenough antiform consists of two subsidiary antiforms that may mark two major horses. The structural relief of the southern horse relative to the intervening syncline is small (less than 1 km) and whether these structures extend eastward into the line of transect discussed here is uncertain. Assuming their eastward continuity, Hanks (1991, 1993) modeled these horses as having a thickness of about 5 km and deformed on a floor thrust that lies at a depth of about 7 km below sea level. In their balanced cross section from the same area, however, Homza and Wallace (1997, figure 12) interpreted horses in the pre-Mississippian rocks of the Mt. Greenough antiform as being 1-1.5 km thick and deformed on a floor thrust that lies at about 2 km below sea level. These interpretations suggest that internal deformation of the Mt. Greenough antiform needs to be more carefully assessed and that multiple detachment levels may be present.

For the purpose of this paper, the pre-Mississippian rocks in the core of the Mt. Greenough antiform are modeled using the simplifying assumption that the entire antiform composes a single horse. This assumption requires that the allochthonous pre-Mississippian section has a structural thickness of over 14 km. A thickness of this amount for pre-Mississippian rocks is greater than that calculated for the horses in the Aichilik antiform and requires that a second ramp in the basal detachment must have existed south of the termination of the deformed section. This southern ramp, shown at about km 189-163 in the restored section in Plate BC1 (cross section B), provides a mechanism for the cooling recorded by apatite fission track analysis of rocks from core of the Bathtub syncline (see below).

A second key constraint in modeling pre-Mississippian rocks in the southern part of the cross section is the presence and nature of the Wall synform on the north flank of the Mt. Greenough antiform (Fig. BC2). The base of Ellesmerian strata in the synform lies at a somewhat higher structural level than to the north and the synform is cut by a reverse fault that places pre-Mississippian rocks above most or all of the Ellesmerian sequence on the south. The reverse fault is an unusual breaching thrust that can be traced for more than 125 km across the Demarcation Point 1:250,000 quadrangle (Reiser and others, 1980; Hanks, 1993; Peapples and others, 1997) (Fig. BC2). The interpretation for this area shown on Plate BC1 (cross section A) portrays the pre-Mississippian rocks in the Mt. Greenough antiform as a hindward-rotated horse that breached the roof thrust that lies in the Kayak

Shale. In its initial phase of development, over 13 km of northward shortening is hypothesized to have occurred beneath the Kayak. In the later stage of its development, the thrust migrated to a structurally higher position within the hangingwall, breaking through the roof of the duplex, through the Ellesmerian sequence, and possibly up into overlying Brookian section similar to the Weller thrust in the Sadlerochit Mountains (Wallace, 1993; Cole and others, Chap. SM). The breakthrough is interpreted to have stranded a wedge of pre-Mississippian rocks beneath the Wall synform as shown in Plate BC1 (cross section A). The breakthrough thrust may have developed prior to hindward rotation of the horse above the ramp in the basal detachment that lies at depth beneath its leading edge, or may have been caused by the rotation. About 9 km of shortening is proposed for the later stage of development of the duplex.

As with the southern of the two pre-Mississippian horses in the Aichilik antiform, the horse of pre-Mississippian rocks in the Mt. Greenough antiform was difficult to balance, probably because of oversteepening arising from the ramp in the basal detachment that lies at depth beneath the hangingwall of the duplex. The bedlength of the forelimb of the duplex, mostly unconstrained because of erosion, was modified in order to achieve an area and bedlength balance on the restored section. An initial cutoff angle of 25° was assumed for the horse similar to that calculated under the Sabbath Creek syncline to the north.

Retrodeformable model for Ellesmerian sequence

For reasons described above, the roof thrust that is present regionally in the Kayak Shale is hypothesized to terminate northward beneath Leffingwell Ridge. North of that location the Ellesmerian sequence is likely pinned depositionally to underlying pre-Mississippian rocks and the two units have deformed together. Restoration of the Ellesmerian rocks was therefore combined with that of the underlying pre-Mississippian rocks as discussed above.

South of the northward termination of the roof thrust at Leffingwell Ridge, the Ellesmerian sequence has been deformed above the detachment in the Kayak Shale, and therefore independently, of the duplex developed in the underlying pre-Mississippian rocks. Unfortunately, because of erosion, exposures of the Ellesmerian sequence remain at only three locations along the transect and deformation in the unit cannot be restored in detail except locally. Nonetheless, these exposures may be sufficient to constrain shortening in the Ellesmerian sequence as follows.

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Hanks (1987, 1988, 1989, 1993), who investigated the Ellesmerian section in detail at Leffingwell Ridge, reported a thrust duplication involving much of the Ellesmerian sequence. The duplication is indicated by a large klippe of Kayak Shale through Triassic Karen Creek Sandstone resting structurally on the Kingak Shale (see also Wallace and Hanks, 1990, Fig. 11) (Fig. BC2). This klippe demonstrates that both the Kayak and Kingak acted as major detachment surfaces with shortening being accommodated by a duplex in the intervening section. Assuming an initial cutoff angle for the duplex of 30° following Hanks (1990, 1993), the minimum amount of shortening necessary to explain the observed relations is about 3 km. Because the detachment that serves as a roof thrust in the Kayak Shale is inferred to be pinned just north of this location, much of the displacement on the roof thrust may be backthrusting above the underlying duplex of pre-Mississippian rocks.

Although duplication of the Ellesmerian sequence is demonstrated to have occurred at Leffingwell Ridge, examination of the map of Reiser and others (1980) suggests that thrust duplication of Ellesmerian strata above the Aichilik River antiform may not be common. At the Wall synform on the southern flank of the antiform, the Ellesmerian section is caught in a tight syncline with local out-of-syncline faults but without significant duplication of section by thrusting (Reiser and others, 1980). Thus, the Ellesmerian section above the Aichilik River antiform is portrayed in Plate BC1 (cross section A) with just one thrust duplication: that at Leffingwell Ridge. Additional displacement may expressed in this area, however, by detachment folding of the Ellesmerian sequence. Detachment folds are evident at least locally in Hanks (1993, Fig. 7) but the shortening produced by these folds is difficult to evaluate without information on their amplitude and geometry. For this reason, no attempt was made to portray detachment folds on Plate BC1 and no estimate is made of the amount of shortening represented by these structures.

In the north limb of Bathtub syncline, the Ellesmerian sequence displays evidence of significant amounts of shortening. Assuming an average moderate south dip of 25°, exposures of carbonate rocks of the Lisburne Group as mapped by Reiser and others (1980) on the north flank of the syncline require a thicker section than that measured for the Lisburne Group in the area (Table 1). However, the position of the contacts does not allow for complete duplication of the section. Wallace (1989; written comm., 1999), suggests that shortening there is by asymmetrical detachment folding and minor thrusting of the Lisburne Group. Because available maps do not display these structures, shortening of the Lisburne Group on the north flank of the syncline is approximated on Plate BC1 as a duplex with a floor thrust in the Kayak Shale and a roof thrust near the base of the Sadlerochit Group on Plate BC1 (cross section A). The Sadlerochit Group and overlying sedimentary rocks consist of fine-grained distal deposits in this area. They are portrayed as structurally thickened on Plate BC1 and were restored by area balancing only. About 5.5 km of displacement on the top of the Lisburne Group is necessary to explain the relations in this area.

Structures on the south flank of the Bathtub syncline lie south of the Continental Divide thrust front of Wallace and Hanks (1990), which is marked by the axial trace of the Bathtub syncline. Structures deforming the Ellesmerian section on the southern flank of the syncline are characterized by thrust-truncated detachment folds that have higher displacement than structures to the north and are transitional to the higher displacement structures of the older Brooks Range orogen to the south (Anderson, 1993; Homza, 1992; Homza and Wallace, 1991a,b; Wallace, 1988, written comm., 1999). Deformation between the floor thrust in the Kayak Shale and roof thrust in the Kingak produced the Drain Creek duplex of Wallace and others (1988) (Fig. BC2; Plate BC1, cross section A). Based on examination of the map relations in Reiser and others (1980), deformation in the Drain Creek duplex is approximated as in Plate BC1 as an antiformal stack consisting of three duplications of the Ellesmerian sequence. The three duplications are required to explain the structural relief in the area and represents a minimum displacement of about 11.5 km. No attempt was made to model the uplifted pre-Mississippian rocks at the southernmost extreme of the section, which compose part of the regionally extensive Kongakut River thrust sheet of Wallace (1988).

The amount of shortening in the Ellesmerian sequence that once lay above the Mt. Greenough antiform cannot be directly estimated because of subsequent erosion. However, if the Ellesmerian sequence is restored as described above and the Ellesmerian sequence is assumed to have once been continuous across the Mt Greenough and Achilik River antiforms without any additional duplication, the restored distance of Ellesmerian cover south of the pin at Leffingwell Ridge is nearly identical to the restored distance for underlying pre-Mississippian rocks over the same distance (Table 2, see below). Because of the similarity of shortening between the pre-Mississippian rocks and their cover south of Leffingwell Ridge, no additional shortening was hypothesized for the Ellesmerian sequence in the eroded section that once lay above the two antiforms in Plate BC1. Detachment folding in the Ellesmerian sequence is present along the west fork of the Aichilik River (Homza and Wallace, 1997) and may reasonably be inferred to have once extended eastward into the line section above the Mt. Greenough antiform (Hanks, 1993). If this was the case, it would require that there be more shortening in the Ellesmerian sequence than modeled for the underlying pre-Mississippian rocks. This relation suggests that some of the shortening of the Ellesmerian sequence in the south flank of Bathtub syncline may have been derived from south of the cross section.

Retrodeformable model for Brookian sequence

Because of the poor exposures, lack of marker beds, poor age control, poor stratigraphic control, and complex deformation in the Brookian sequence beneath the coastal plain, the configuration for Brookian deposits shown in Plate BC1 (cross section A) is based on a series of inferences detailed below about Brookian stratigraphy, thickness of units, and deformational style. Although all of the various units shown for the Brookian in Plate BC1 are balanced using line-length and area methods, the deformational model presented here should be regarded as only schematic. Nonetheless, the model outlines a geometrically constrained structural solution that explains most of the known relations along the transect and offers testable hypotheses for future investigations as well as a model for oil and gas assessments.

The Kingak Shale at the top of the Ellesmerian sequence is postulated to have acted as the basal detachment for deformation of the Brookian sequence. This interpretation is supported by (1) its position as roof thrust for Ellesmerian structures at Leffingwell Ridge and regionally elsewhere in the northeastern Brooks Range (e.g., Wallace and Hanks, 1990); (2) the Kingak is strongly deformed and exhibits markedly disharmonic deformation in exposures on the Aichilik River (Schenk and others, Chap. FS, Fig. FS25); (3) the Kingak Shale is the oldest unit exposed in the coastal plain, indicating that thrusts must be rooted at or below this unit; and (4) discordant reflectors are common in the Kingak interval in seismic reflection profiles in the southern part of the coastal plain. If the Kingak is not present to the north because of erosion on the LCU as hypothesized in this paper, the basal detachment likely steps up to the base of the overlying pebble shale unit, Hue Shale, or possibly to the base of the Jago River unit, indicated by discordances in strata above the top of seismic basement over the Niguanak high. Under the Beaufort shelf to the north, the discordant reflectors in seismic line 84-40 suggest that the detachment may step back down into Jurassic deposits of the Beaufortian sequence, following the top of pre-Mississippian basement (Plate BC1, cross sections A).

The oldest and structurally lowest Brookian unit modeled in Plate BC1 (cross section A) is the Arctic Creek unit. This unit consists of thin-bedded turbidites that are interpreted to be the distal equivalents of middle and Upper Cretaceous turbidites deposited in the axis of the Colville basin to the south (e.g., the Bathtub Graywacke and Colville Group; Mull and Decker, 1993). In its type area west of the transect, the Arctic Creek unit comprises a series of imbricated units on the order of 1 km thick (Mull and Decker, 1993). Although poorly exposed, a shallow-dipping outlier of Kingak Shale is exposed apparently above the Arctic Creek unit near the Okerokovik River, about 18 km west of the transect (Fig. BC2; see also Bird, Chap. GG, Plate GG1). This geometry is here interpreted to indicate that the outlier represents a klippe of Kingak Shale that was thrust onto underlying deposits of the Arctic Creek unit. The klippe of Kingak may indicate that the Arctic Creek unit consists of a series of horses in a duplex with a floor thrust in the Kingak. A roof thrust for this duplex is probably located at the base of the overlying Jago River Formation, because: (1) tight, overturned folds are found at the base of the Jago River Formation at VABM Bitty on Sabbath Creek (Schenk and others, Chap. FS, Fig. FS18; for location, see Fig. BC2), (2) discordant reflectors are visible at the base of the Jago River Formation on many seismic lines, and (3) the Jago River Formation is a thick, competent structural unit that would deform differently than the less competent Arctic Creek unit. A conservative model for duplex-related shortening of the Arctic Creek unit between a floor thrust in the Kingak and a roof thrust at the Jago River Formation is shown on Plate BC1. Although balanced for bed length and area using initial cutoff angles of 20°, 15°, and 10° based on assumptions of decreasing thickness and grain size, critical observations about the position(s) of the hypothesized thrusts and cutoff angles are lacking and the model should be regarded as only schematic.

An important observation, however, is that the upper and lower limits of the units that bound the Arctic Creek unit can serve as constraints on its configuration. These data indicate that the structural thickness of the Arctic Creek unit decreases dramatically northward into the axis of the Sabbath Creek syncline. Such thinning might be expected because stratigraphic relations suggest that the turbidite deposits of the Arctic Creek unit thin regionally northward into the basinal deposits represented by the Hue Shale. The transition is here inferred to be located in the axial part of the Sabbath Creek syncline (poorly imaged in the seismic data), but instead could be present in the imbricated units portrayed schematically on the southern flank of the syncline. Because of the dramatic northward thinning, the roof thrust for structural duplication in the Arctic Creek unit is arbitrarily terminated in the axis of the syncline and no internal deformation is shown in the Hue

Shale north of this location. It is possible that the Arctic Creek unit represents the leading edge of a triangle zone developed beneath latest Cretaceous and Paleocene strata in the early Tertiary. This interpretation is supported by (1) presence of a very thick and mechanically competent roof in the Jago River Formation, (2) an underlying detachment in the Kingak Shale, (3) clear evidence for imbrication of the Arctic Creek unit in its type area about 70 km west of the cross section (Mull and Decker, 1993) and possibly in the Okerokovik River area as described above, (4) wedge-like geometry of the Arctic Creek unit in the seismic data, (5) convergent reflections in the Arctic Creek unit in seismic reflection profiles west of the cross section, and (6) the position of the Arctic Creek unit at the leading edge of a fold-and-thrust belt represented by the imbrication described by Mull and Decker (1993). The approximate position of the roof thrust for this triangle zone is shown in the southern part of the 1002 area in Figure BC2.

The distribution and thickness of the latest Cretaceous and Paleocene Jago River Formation are critical factors used in this paper for reconstructing deformation of Brookian strata. The Jago River Formation, defined in outcrop 27 km west of the transect (Buckingham, 1987), forms topset strata that are very well imaged in the Sabbath Creek syncline in seismic line 85-50 (Plate BC1, cross section A). The Jago River Formation could be regarded as allochthonous or an erosional remnant of a local basin (Molenaar and others, 1987), but proprietary shot-hole paleontologic data indicate that latest Cretaceous and Paleocene deposits are widespread above the southern flank of the Niguanak high. Because seismic reflectors in this area are incoherent and not as reflective as in the Sabbath Creek syncline, I hypothesize that the topset strata in the Jago River Formation give way northward into correlative clinoform deposits that extend northward to the area of mapped outcrops of Hue Shale above the Niguanak high (Fig. BC2; see also Bird, Chap. GG, Plate GG1). The clinoform deposits might be expected to be more shale-rich, more susceptible to small-scale structural disruption, and hence to be less reflective than the topset beds to the south. Unfortunately, the transition from topset to clinoform reflectors is not evident in the seismic data and likely was located in Brookian strata eroded from the southern flank of the Niguanak high.

The minimum measured thickness of the Jago River Formation in the Sabbath Creek syncline is over 2.8 km (Buckingham, 1987) and nearly 3.5 km can be estimated in the core of the syncline from seismic data along the transect. Vitrinite reflectance data from exposed rocks in the Sabbath Creek syncline indicate that another 2 km of strata once covered the syncline, but have been eroded away. Some of the latter might have been

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syndeformational deposits correlative with the piggy-back basin deposits reported to the east (Potter and others, Chap. BD; Grow and others, Chap. NA, Fig. NA2), but syndeformational strata are not evident in seismic line 85-50 and adjacent lines to the west. From regional interpretation of thermal data discussed in a following section, a thickness of about 4.5 km is inferred for the Jago River Formation in the area of the Sabbath Creek syncline in Plate BC1. This thickness constitutes nearly the entire thickness of strata allowed by the observed relations in the area. The thickness of the unit must decrease substantially northward, however, to a maximum of about 2-2.5 km in rocks near the crest of the Niguanak high on the basis of estimates of maximum depth of burial from vitrinite reflectance data and fission-track data (O'Sullivan and others, 1993). Additional northward thinning is indicated by the 550-m thickness of Paleocene strata reported from the Aurora well on the Beaufort shelf. Such abrupt northward depositional thinning is consistent with a regional transition from topset strata to clinoform and basinal strata in a northward prograding depositional system and is comparable in scale and amount of thinning to the depositional wedge of Paleocene deposits present west of the Canning River (Bird, Chap. GG, Plate GG3).

Using the thicknesses estimated from the observations described above, a model is constructed in Plate BC1 (cross section A) that portrays the latest Cretaceous and Paleocene strata as a deformed, northward thinning wedge of progradational deltaic strata. Using fault-bend fold geometry, the southernmost antiform in the Aichilik high north of the Sabbath Creek syncline is modeled as a horse composed of latest Cretaceous and Paleocene strata that was displaced about 7-8 km. Initial cutoff angles of 30° were assumed for ramps in these thick units. The thrust along which the displacement occurred has not been identified in outcrop and is predicted to be present in an area lacking bedrock exposures. An alternate interpretation for the rocks coring the antiform that comprises the Aichilik high east of the transect is proposed by Potter and others (Chap. BD, Plate BD3). They suggest that mud-rich rocks coring the antiform comprise an imbricate stack of Lower Cretaceous strata (pebble shale unit and Hue Shale). Their interpretation of the units coring the antiform is not preferred in this paper because of (1) an excessive amount of shortening relative to overlying Tertiary deposits is implied by construction of the Aichilik high with these thin units, and (2) available paleontologic data do not demonstrate the presence of Lower Cretaceous rocks at the surface in the vicinity of the Aichilik high and/or related structures to the west in the vicinity of the line of section discussed here. Potter and others (Chap. BD) additionally suggest that the Aichilik antiform represent a triangle zone with a roof thrust at the base of the Jago River unit. Although the seismic data convincingly support a triangle-zone or passive-roof duplex geometry for this part of the Aichilik high, it is unclear if this geometry should be projected into the line of section because (1) northward dips indicative of a passive-roof are not evident in seismic profile 85-50, and (2) the antiform that composes the Aichilik high where investigated by Potter and others (Chap. BD) appears to terminate east of the line of section and be replaced by different structures that do not display this geometry. Because seismically well-defined triangle zones in the southeastern part of the 1002 area seem to be located beneath the thick and competent topset strata of the Jago River unit, it is possible that passive-roof duplex geometry is replaced by other geometries where the facies of the Jago River Formation change from competent topset strata to less competent clinoform deposits.

Because the outcrops of Kingak through Hue Shale in the area above the Niguanak high lie at a high structural level, they must have been emplaced as the result of significant northward displacement (Molenaar and others, 1987). Although poorly exposed, the outcrop patterns and shot-hole paleontologic data suggest that the Kingak forms the core of a small anticline (Bird, Chap. GG, Plate GG1) beneath the pebble shale unit, Hue Shale, and overlying latest Cretaceous and Paleocene deposits in this area. The distribution of outcrops shown in Bird (Chap. GG, Plate GG1) and proprietary shot-hole paleontologic data suggest that a second small anticline cored at the surface by Hue Shale may be present south of the outcrops of the Kingak Shale on the Jago River. In Plate BC1, these exposures are modeled as the basal part of a thick, duplicated section composed of Kingak through Paleocene deposits with the surface folds cored by Kingak and Hue Shale indicating the position of hangingwall cutoffs. An initial cutoff angle of 30° is assumed for this fault in Plate BC1. The location to which the Kingak and Hue Shale are restored is uncertain, but is guided by (1) the estimated thickness of latest Cretaceous and Paleocene strata and (2) the general, gentle average southward dip of reflections in Brookian strata on the south flank of the Niguanak high. The southward-dipping reflectors approximate the shallow dip of the top of pre-Mississippian rocks on the south flank of the Niguanak high, suggesting that tilting was caused by relatively younger uplift of the underlying Niguanak structural high. This interpretation would also suggest that the stratigraphic section beneath the Kingak thrust remains relatively intact. These considerations suggest that the duplicated section underlain by the Kingak should be restored to a position near km 54 (Plate BC1, cross section A), indicating over 20 km of northward displacement on the underlying thrust. Interestingly, the restored position of the Kingak outcrops approximates the southern limit of the area where downward cutting by the LCU is proposed on the south flank of the Niguanak high from stratigraphic observations (see Stratigraphy, above). It is possible that the relatively large amount of northward displacement on this structure could have been related to northward truncation of the Kingak by the LCU, causing displacement on the Kingak detachment to migrate to a higher structural level by cutting through the entire Cretaceous and Paleocene section. A similar large-displacement thrust has been proposed for the northeastern Sadlerochit Mountains, where truncation of the Kingak by the LCU apparently led to development of an allochthon composed of the Kingak Shale and Kemik Sandstone with at least 10 km of displacement (Mull, 1987; Kelley and Foland, 1987; W.K. Wallace, oral comm., 1999).

An alternate interpretation for the thin-skinned structures above the southern flank of the Niguanak high is presented by Potter and others (Chap. BD). They interpret discordances evident in the seismic data as indicative of an imbricate fan composed of thrust slices of Triassic to Cretaceous rocks (Sadlerochit Group to Hue Shale) (Potter and others, Chap. BD, Plate BD3; see also Bruns and others, 1987). This geometry implies a significantly larger amount of shortening than does the model presented in this paper. The discordances interpreted by Potter and others (Chap. BD) as long, south-dipping thrust faults are here attributed instead to local small-scale folds and faults within the latest Cretaceous and Paleocene section and to stratigraphic features such as clinoform reflections, submarine channels and channel fill, submarine landslides, and toe-of-slope turbidite mounds that are common in strata deposited in the prodelta slope environment inferred for these rocks.

The relations in Brookian strata north of the Niguanak high in the Jago ridge structure are more difficult to constrain. The interpretation presented in Plate BC1 portrays the relations in this area as a triangle zone developed beneath a roof thrust at the base of Eocene strata on the northern flank of the Niguanak high and over the Aurora dome. This interpretation is supported by: (1) outcrop data along the Jago River (Fig. BC2) that indicate that Eocene deposits dip northward above strongly deformed Jurassic to Paleocene deposits (e.g., Molenaar and others, 1987); (2) shot-hole and outcrop paleontologic data that suggest that Eocene deposits lie north of older strata on a single, regional discordant bounding surface (Fig. BC2), (3) seismic data that show a moderate north dip for Eocene strata outside the transect (Potter and others, Chap. BD, Fig. BD3); and (4) magnetic data that indicate magnetically distinct units form the core and roof of the structure and show that strata forming the roof dip moderately northward (Phillips, Chap. AM, Fig. AM10). Accordingly, duplicated sections of Hue Shale and overlying latest Cretaceous and Paleocene deposits that form the core of Jago ridge are shown as composing the triangle zone below a roof thrust at the base of the Eocene strata. The amount of shortening illustrated in Plate BC1 (about 5 km) in the triangle zone is constrained only by inferences about the thickness of the duplicated Cretaceous to Paleocene section and by the structural position of the roof thrust from seismic data and is here regarded as a conservative but only schematic estimate. The roof thrust of the triangle zone is shown to root northward at the top of pre-Mississippian basement beneath highly reflective Beaufortian deposits under the Beaufort shelf. This configuration is proposed because of a prominent north-dipping discordance present at a depth of about 6 km in the highly reflective strata in seismic line 84-40. The large thickness of Beaufortian strata in this area is explained as a section duplicated by the south-vergent thrust that forms the roof thrust of the triangle zone (Plate BC1, cross section A).

Potter and others (Chap. BD) suggest that east of this transect, the triangle zone forming the northern flank of Jago ridge terminates within Paleocene strata instead of Beaufortian strata. The configuration of Potter and others (Chap. BD) is generally consistent with the interpretation presented here (although they use the paleontologic interpretations of Poag (Chap. BI) for the Aurora well, which results in a thicker Paleocene section) and the difference in the northward termination of the structure may be the result of a local change in the detachment level of the floor thrust for the triangle zone. Unfortunately, critical seismic data that would confirm this explanation are not presently available.

CONSTRAINTS ON SHORTENING

Table BC2 shows a comparison of deformed and restored line lengths determined for key units shown in Plate BC1. The top of the pre-Mississippian provides the only measure of the total amount of shortening over the entire length of the section. On the basis of the structural model for pre-Mississippian rocks, about 72 km of shortening is calculated for deformed rocks portrayed in the section on this horizon between reference points A and B (Plate BC1). From the pin at Leffingwell Ridge, where the regional detachment is inferred to terminate in the Kayak Shale, deformation southward in Ellesmerian strata to reference point D represents about 35 km of shortening, the same amount of shortening as calculated at the top of the pre-Mississippian section over virtually the same distance (pin to reference point B). The shortening for latest Cretaceous and Paleocene strata in the Brookian sequence calculated from the truncation of the base of unit TKp in the hangingwall of the Jago ridge triangle zone (reference point E) to the most southerly exposures of this unit on the southern flank of Sabbath Creek syncline (reference point F) represents about 38 km of northward shortening. For comparison, the shortening at the top of the pre-Mississippian unit over the Jago ridge, Niguanak high, and Okerokovik River monocline horses of pre-Mississippian rocks is 31.2 km (reference points A to C). The similarity in shortening in the pre-Mississippian and Brookian duplexes over approximately the same interval is what would be expected for a passive-roof duplex (W.K. Wallace, written comm., 1999)

Although the amounts of shortening for the various intervals are calculated over differing lengths of section and thus have different magnitudes, the percent shortening for the intervals in the pre-Mississippian, Ellesmerian, and Brookian sequences provides a means to compare the shortening despite differences in length examined. Comparison of these values for each of the modeled horizons reveals similar shortening: about 37 percent for the pre-Mississippian and Ellesmerian duplexes and 43 percent shortening for the thin-skinned structures that deform the Brookian sequence (Table BC2). These results were determined from independent sets of observations, because each interval was modeled with minimum shortening of distinct, deformed units separated by roof and floor thrusts above and below, following Wallace (1993) and Wallace and others (1997). The similar results suggest that the modeled strain was approximately the same across the entire section investigated and confirms the cross section in Plate BC1 is a viable cross section.

The estimate of shortening at the top of pre-Mississippian basement is comparable to that published by Wallace (1993) for the northern part of his transect in the Canning River area, but is less than that previously modeled by Hanks in the Aichilik River and Okpilak batholith areas (46%) and by Cole and others (Chap. SM) for the Sadlerochit Mountains (46%).

It is possible that the close correspondence of the shortening calculated for the the duplexes in the pre-Mississippian and Ellesmerian rocks could be serendipitous. For example, the similarity in the shortening for the pre-Mississippian and Ellesmerian units south of the pin at Leffingwell Ridge might indicate either (1) deformation in the Ellesmerian sequence solely represents displacement transmitted hindward along the Kayak roof thrust in response to shortening at depth on the sub-pre-Mississippian basal detachment as implied by the cross section in Plate BC1, or (2) shortening in the Ellesmerian sequence is partly the result of other, unevaluated deformation transmitted into the section from the south. The latter alternative might be indicated by localization of the largest amount of

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shortening modeled in the Ellesmerian in the Bathtub syncline area at the southern end of the transect. This area lies at the Continental Divide thrust front of Wallace and Hanks (1990) and could represent deformation in advance of that thrust front. This alternative would imply that additional shortening, probably in the form of detachment folds, occurred in the Ellesmerian sequence above the erosional level in the Aichilik River and Mt. Greenough antiforms but was not accounted for in the model. In addition, it is kinematically unlikely that backthrust displacement could be transmitted all the way back to Bathtub syncline over the antiformal highs created by emplacement of the basement horses (W.K. Wallace, written comm., 1999).

As a result, the model portrayed in Plate BC1 is regarded as a minimum bound on shortening along the line of section. The minimum bound arises in large part because of the following aspects of the deformational model: (1) the basal detachment under the coastal plain is placed at the deepest level justified by the observed relations in the seismic data; (2) much of the structural relief of pre-Mississippian rocks in the northeastern Brooks Range is explained by ramps in the basal detachment and corresponding thickening of the horses of pre-Mississippian rocks; (3) the minimum number of horses of pre-Mississippian rocks required to explain the observed geologic relations were used to construct the section; (4) internal shortening within the pre-Mississippian horses was not evaluated; (5) thrust duplications in the Ellesmerian sequence were modeled only where observed in erosional remnants of the Ellesmerian sequence; (6) detachment folding of the Ellesmerian sequence was not evaluated, neither in erosional remnants of the Ellesmerian sequence nor where the Ellesmerian is missing due to erosion; (7) the maximum stratigraphic thickness of the Jago River Formation and correlative units (unit TKp) allowed by the outcrop and seismic data was used to construct the section; and (8) internal shortening within the Brookian horses was not evaluated. Any change to the assessment of any of these parameters would probably increase the amount of shortening required by the model. Hanks (1991, 1993), on the other hand, assumed the minimum depth allowed by the gross geometry of pre-Mississippian structures under the coastal plain and thus derived a maximum-shortening model with respect to the pre-Mississippian rocks. The model of Potter and others (Chap. BD), although not balanced, likewise would result in a maximum-shortening model for the thin-skinned deformation under the coastal plain because of the large number of large-displacement thrusts and thin horses hypothesized in the core of the Aichilik high and Jago ridge structural highs. Taken together, these models can provide some estimate of the maximum and minimum bounds of shortening possible along the profile.

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INFERRED TIMING OF DEFORMATION

The age of the deformation modeled in the structural and stratigraphic restoration discussed above and shown in Plate BC1 is important for evaluating the oil and gas potential of the 1002 area. The time when the deformation occurred can be estimated using a number of parameters including thermal data, field relations, and fission track data. These data and their significance are evaluated below.

Predeformational state determined from thermal data

Representative thermal data including vitrinite reflectance data and conodont alteration indicies (Krumhardt, 1994; Bird and others, Chap. VR; unpublished proprietary data) from near the transect are plotted above the erosional profile on cross section A in Plate BC1 and their positions restored according to the structural model in cross section B. For vitrinite data, the empirical equation for determining the depth of burial for vitrinite reflectance data on the North Slope presented in Bird and others (Chap. VR) was used to determine the approximate thickness of eroded strata that once was present at each locality. For conodont data, the maximum temperature attained by the conodonts was taken from Krumhardt (1994) and Bird and others (Chap. VR) and a maximum depth of burial was calculated assuming a geothermal gradient of about 30°C/km (the same geothermal gradient as that used by Cole and others, Chap. SM) for each sample. The approximate thickness of eroded overburden above each vitrinite reflectance and conodont sample was measured from its restored position in cross section B (Plate BC1). If due to burial metamorphism as assumed here, these restorations, shown as red bars above the erosional profile in cross section B (Plate BC1), approximate the maximum height of the stratigraphic column prior to erosion along the transect.

Although the vitrinite and conodont alteration data are not precise gauges of the depth of burial and the calculated maximum thickness of eroded strata is dependent on the restorational model on which they are plotted, the calculated maximum height of the restored stratigraphic column approximates a line of elevation that descends gradually from about 8 km above the datum at the base of the Kingak Shale at the south end of the section to about 6.5 km above the datum north of about km 90 of cross section B (Plate BC1). North of that point, the maximum height of the calculated stratigraphic section descends abruptly northward to a lower elevation of about 2-3 km above the datum. At the northern end of the section, however, vitrinite reflectance data from the Eocene and Oligocene

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sections are from higher stratigraphic positions and indicate only small amounts of previous burial.

The generally consistent level for the height of strata removed by erosion that was determined for Paleocene and older rocks in the central and southern parts of cross section B (Plate BC1) supports the assumption that metamorphism was of burial type, a conclusion previously reached by O'Sullivan and others (1993). Moreover, it provides a measure of corroboration of the structural model shown in Plate BC1 in that the creation of the interpreted structures from the undeformed section accounts for the structural relief needed to attain the observed pattern of unroofing. Farther north, the shape of the top of the calculated section, as modeled by the thermal data, approximates the geometry of a clinoform. Although the original basin morphology may have been influenced by other factors such as thrust loading, the magnitude of the change in modeled thickness is best explained by progradation of a deltaic complex into a deep marine environment. The profile suggests that it is reasonable to infer that a shelf-to-slope break was present in the vicinity of km 80 of cross section B (Plate BC1) prior to deformation. Because the youngest rocks that contribute data to this curve are Paleocene, it is concluded that the calculated curve approximates the depositional profile near the end of Paleocene time. The profile thus is consistent with the earlier inference developed from seismic facies analysis that a Paleocene shelf-to-slope transition must lie in the vicinity of the Aichilik high.

Several ancillary conclusions can also be drawn from the thermal modeling, including the following:

1. The top of the maximum thickness of eroded section in the southern part of cross section B lies at about 1 km above the level of modern deposition (i.e., sea level on the absolute scale) on the Beaufort shelf at the northern end of the section. Deposition to approximately the same level along the entire section suggests that Brookian sedimentation has filled an accommodation space that has been controlled by consistent tectonic processes active over a long period of time;

2. The slightly higher (1km) level of the accommodation space in the southern part of the section probably reflects some combination of factors including (a) local tectonic effect of thrust loading near the Continental Divide thrust front of Wallace and Hanks (1990), (b) passive-margin-related subsidence in Ellesmerian time prior to deposition of the Brookian sequence,

or (c) slight differential uplift along the Barrow arch due to rifting in the Canada basin in the Early Cretaceous prior to Brookian sedimentation.

3. The minimal burial indicated for Eocene and Oligocene strata at the north end of cross section B requires either (a) erosion of older strata (as shown for the Oligocene unit), or (b) thrust emplacement of relatively deep marine strata prior to the deposition of an overlying stratigraphic section (as hypothesized by the backthrusting of the Eocene section). These results imply that only thin Eocene and Oligocene sections were deposited above the Paleocene strata in the Jago ridge structure, a conclusion consistent with the thermally immature vitrinite reflectance data from the Hue Shale above the Niguanak high.

It can be concluded form these observations, coupled with facies information from Brookian sequence rocks (e.g., Molenaar and others, 1987) and analogy with the history of the Colville basin to the west, that until Paleocene time the Brookian sequence was deposited in northward prograding fluvial-deltaic systems that worked to systematically fill the accommodation space north of the Early Cretaceous part of the Brookian orogenic front. The sedimentary record at Bathtub syncline and in the Arctic Creek unit and Hue Shale preserves fragments of the slope and basin of what must have been a significant middle and Upper Cretaceous stratigraphic succession located in the position of the modern-day northeastern Brooks Range. The sedimentary detritus in these deposits presumably was derived from the Brookian orogenic zone to the south. Following deposition of these strata, a major increase in deposition occurred in the latest Cretaceous and Paleocene. This period of active sedimentation marked renewed tectonic activity in the ancestral Brooks Range and heralded latest Cretaceous to Cenozoic deformation in the area of this transect.

Deformational events from field relations and fission-track data

Fission track data from the Mesozoic section in the Bathtub syncline provide the first indication that rocks along the transect were involved in renewed deformation. The data show that the section cooled through the annealing zone for apatite at 62 Ma (Early Paleocene), followed by a younger episode of cooling at 50 Ma (Early Eocene) (O'Sullivan and others, 1993). The cooling events probably represent uplift that was accomplished by erosional unroofing in response to structural thickening in the Ellesmerian and/or pre-Mississippian sections below the sampled strata. If, as is commonly hypothesized in contractional fold belts, deformation at high structural levels in the now mostly missing Brookian section at Bathtub syncline is

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conjectured to have begun prior to the uplift of sub-Brookian rocks dated by the fission-track ages, the earliest deformation may have begun in the latest Cretaceous, coincident with the onset of sedimentation in the Jago River Formation.

To the north, the absolute time of onset of deformation is not yet firmly established, but must be recorded in the piggy-back basin deposits in the upper part of the Jago River Formation (Potter and others, Chap. BD). A tentative late Paleocene age is inferred for these strata by Potter and others, Chap. BD), although there is little age control on these deposits. Convergence in dips on both the northern and southern flanks of the piggy-back basin indicate that deformation synchronous with their deposition occurred on Brookian structures in the adjacent Aichilik high and other Brookian structures to the south that have been subsequently eroded. No deformation in underlying Ellesmerian and pre-Mississippian rocks is indicated in this area at this time. The Paleocene deformation front in the Brookian sequence probably advanced at least as far north as the major thrust duplication that emplaced the Kingak and Hue Shale now exposed above the Niguanak high. If not involved in the deformation, these deposits would have been in position for continued sedimentation and hence to gain higher thermal maturity because of burial metamorphism under younger rocks. A younger, post-Eocene episode of Brookian shortening is required, however, by the backthrust relations shown in the Jago ridge triangle zone because the Eocene strata had to have been deposited before the backthrusting could take place. Oligocene deposits that unconformably overlie the Eocene strata show that formation of the triangle zone occurred prior to the Oligocene. These relations suggest that the Paleocene deposystem now under the coastal plain saw protracted thin-skinned deformation that lasted from the Paleocene to the Eocene.

Deformation in the pre-Mississippian section under the coastal plain in basement-involved structures along the transect probably began after formation of the thin-skinned structures in the overlying Brookian section was largely completed because uplift of the deeper basement-involved structures have deformed the overlying thin-skinned structures. The oldest of the pre-Mississippian horses may be the Aurora dome duplex, which folds the Eocene, but not Oligocene strata, suggesting a Late Eocene age for this structure. Strata in the lower part of the Jago River Formation on the south flank of the Sabbath Creek syncline, in contrast, have yielded apatite fission track ages that average about 23 Ma (Early Miocene) (O'Sullivan and others, 1993). Although taken from Brookian strata, the position of these samples low in the Brookian succession argues that their cooling is related to uplift of the pre-Mississippian horse forming the Okerokovik River monocline, which lies in a structural position hindward of the pre-Mississippian horse at Aurora dome. This relation suggests the possible presence of out-of-sequence thrust faults in the pre-Mississippian rocks in the southern coastal plain. Alternatively, the Okerokovik River horse that lies beneath the southern flank of the Sabbath Creek syncline may have experienced reactivation that folded or tightened the southern limb of the Sabbath Creek syncline, thereby lifting the Jago River Formation through the annealing zone. This horse is thought to be laterally correlative the Sadlerochit Mountains horse to the west, which also experienced Miocene uplift (O'Sullivan and others, 1993). Relatively late movement on the regional flat at this location in the cross section (Plate BC1, cross section A), is mechanically possible only if the horse of pre-Mississippian rocks at the Niguanak high was constructed at the same time. Folding of Oligocene and younger strata visible in seismic data along the western flank of the Niguanak high confirms a Neogene age for the structure. Fission-track data at Leffingwell Ridge indicates a protracted history of uplift-related cooling that extends into the Miocene (J.M. Murphy, written comm., 1998) in that area as well. This may suggest that much of the southern part of the coastal plain, including the Niguanak high, was involved in basement-involved deformation during the Miocene.

CONCLUSIONS AND IMPLICATIONS

In this paper, I have presented an integrated stratigraphic model and geometrically constrained balanced cross section for a north-south transect in the eastern part of the 1002 area and northeastern ANWR. The structural model was constructed using known outcrop relations in the Brooks Range, high quality, newly reprocessed seismic depth sections under the coastal plain and on the Beaufort shelf, and interpretations that result in conservative estimates of shortening. The modeling suggests that deformed rocks at the surface lie on a basal detachment under the coastal plain at a depth of about 7 km at its north end and that the detachment descends southward to a depth of more than 15 km in the Brooks Range. The cross section is a minimum-shortening model which requires 72 km of northward displacement for the 142-km transect and 37 to 43 percent shortening.

Along the profile, the contractional deformation first affected the Brookian sequence in the latest Cretaceous and by the early part of the Paleocene, Ellesmerian and/or pre-Mississippian rocks were involved in the deformation in the southern part of the profile. On the coastal plain, deformation probably was active in the Brookian sequence where it formed a thin-skinned fold-and-thrust belt in the Paleocene and Eocene. Beginning in the Eocene and continuing in Miocene, the deformation involved rocks of the underlying pre-Mississippian basement, resulting in a relatively younger basement-involved structural style. The timing relations indicate that deformation has continued to propagate northward into the Beaufort shelf where the thin-skinned deformation has been active in Neogene and younger time (e.g., Grantz and others, 1987, 1990; Potter and others, Chap. BD).

The presence of duplicated pre-Mississippian rocks under the coastal plain at the Aurora dome and at the Niguanak structural high is surprising because they form nearly isolated uplifts 15-30 km in advance of the regional sharp increase in structural relief located at the Okerokovik monocline and the South 1002 fault system of Grow and others (Chap. NA, Fig. NA1) in the southern part of the coastal plain. The region over which there has been Cenozoic deformation in pre-Mississippian basement in the eastern 1002 area probably forms a northward-elongated zone that begins at the South 1002 fault system at the southeastern margin of the 1002 area and terminates at the leading edge of the Aurora dome in the vicinity of the Beaufort Sea coast. On the west side of this zone, Grow and others (Chap. NA) have described a detachment that descends eastward into the core of the zone to a depth of over 10.7 km (35,000 ft). On the east flank of the zone are westward-descending detachments that are visible on seismic records to depths of 26,000 ft (Grow and others, Chap. NA, Fig. NA4). These observations suggest that the detachment beneath the northward-elongate zone of basement-involved deformation forms a scoop-shaped trough that is bounded on its sides by lateral ramps. The cross section discussed in this paper models a profile along the approximate axis of this trough of basement-involved deformation.

The factors that have led to the development of a northward-trending fairway for Cenozoic deformation in the pre-Mississippian rocks in the eastern 1002 area are unknown. Possibly, a pre-existing zone of structural weakness was present in the pre-Mississippian basement and was excavated by the Cenozoic deformation. Such a zone of north-south weakness may have been produced by the Ellesmerian orogenic event in the lower Paleozoic, or possibly during opening of the Canada basin in the Early Cretaceous, particularly if opening was by rotation centered in the McKenzie delta, located only a short distance away to the east. However, the structural grain of pre-Mississippian rock units in the subsurface of the coastal plain is interpreted by Kelley (Chap. BR) to trend east-west, normal to the trend of the fairway and thus argues against such a relation. Alternatively, Wallace

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and Hanks (1990) have argued that the Okpilak batholith to the west of the fairway may have served as an obstacle to the northward progress of deformation. This suggests that the batholith may have provided a strain shadow to deformation of pre-Mississippian rocks under the coastal plain in the vicinity of the Hula Hula low (see Grow and others, Chap. NA, Fig. NA1 for location), thus impeding deformation of pre-Mississippian basement rocks. In this view, the absence of basement deformation in the Hula Hula low represents the regional anomaly in the northward extent of deformation of basement rocks rather than the presence of the northward outliers of basement-involved structures at Aurora dome and Niguanak high as discussed above. While the alternative of Wallace and Hanks (1990) has many compelling aspects, it does not provide a reason for the eastward termination of the basement culminations against the undeformed pre-Mississippian basement in the Demarcation subbasin to the east (Fig. BC2; Grow and others, Chap. NA, Fig. NA1).

A third alternative, the possibility that the depth to detachment may have been influenced by the thickness of overlying stratigraphic section at the time of the deformation, is suggested here. Examination of seismic records in the 1002 area suggests that the maximum thickness of the Jago River Formation, estimated here to be nearly 5 km, may be located along the southeastern margin of the 1002 area. If the Jago River Formation and its correlatives form a regionally significant fluvial-deltaic complex as argued in this paper, it is possible that the Jago River Formation was a major point for debauchment of sediment in the Paleocene and built a delta northward into a marine basin. It is suggested that this delta may have provided a significant structural load not present to the east or west along strike. The structural load, particularly after thickening during the initial phase thin-skinned deformation in the Paleocene, may have driven the basal detachment of the thrust-belt to a locally deeper level as a function of the thickness of the structural wedge and allowed it to advance northward beyond the regional limit of basement-involved deformation that was present in the early Tertiary.

The balanced cross section presented in Plate BC1 is a well constrained integrative model that offers very specific predictions of the geology under the coastal plain that have applications to assessment of oil and gas potential. For example, the model suggests that parts of the Ellesmerian section, the major petroleum reservoir at Prudhoe Bay, may be present on the south flank of the Niguanak high. Depending on how much section was eroded by the LCU from the top of the Ellesmerian, the Sadlerochit Group, including possibly coarse-grained facies analogous to the Ivishak, may still be preserved in this area. Due to onlap at the base Ellesmerian sequence, however, it is hypothesized that the Lisburne Group may consist of nearshore facies and that the Endicott Group probably is not present. Erosion of the Ellesmerian sequence by the LCU, coupled with the southward dip on the flank of the Niguanak high, nonetheless may provide a stratigraphic trap analogous to the one in the Prudhoe Bay field if reservoir units in the Sadlerochit and Lisburne are preserved beneath the unconformity. Second, it is suggested that erosion on the LCU in the late Neocomian, interpreted to have occurred along the transect north of approximately km 55 on Plate BC1 (cross section A), allows the possibility that clean sandstone reservoirs such as that in the Kuparuk C interval in the Kuparuk River field, might be present. These reservoir units would be expected to form local accumulations just above the unconformity and could be distributed discontinuously over its entire extent. Third, the large thickness of the latest Cretaceous and Paleocene deltaic depositional system proposed here allows the possibility that significant reservoirs may be present in the Brookian sequence. The relatively simple deformational style modeled here provides hope that any reservoirs present in these rocks remain unbreached by deformation. Because the shelf-slope transition for Paleocene rocks is hypothesized to be located in the vicinity of the Aichilik high, the most likely Brookian plays in Paleocene rocks in the 1002 area are suggested to be toe-of-slope turbidite mounds. Nonetheless, the lithic character of these sandstones might remain impediments to reservoir quality. Finally, there is a possibility that oil generated in the Tertiary strata of the Beaufortian sequence and/or the Hue Shale in the Demarcation subbasin to the east or the Barter subbasin to the north (Bird Chap. GG, Plate GG1), may have migrated up dip into the Jago ridge and/or Aurora dome structures. Oil seeps at Angun Point and Cape Manning (Fig. BC2) may substantiate the possibility of this petroleum system.

The impact of the timing of deformation on hydrocarbon generation and migration in the play concepts mentioned above is variable. The Ellesmerian strata probably had a shallow initial southward dip during the time of maximum burial and hydrocarbon generation in Shublik and Hue Shale source rocks that lay in the oil window in the area of the present Brooks Range prior to deformation in the Paleocene. Any reservoir facies present in the Ellesmerian sequence in the Niguanak-high area (e.g., Lisburne, Sadlerochit, Kemik Sandstone-like units) may have formed stratigraphic traps that could have been filled by northward migration of hydrocarbons prior to the deformation. Thrusting and southward tilting of the Niguanak-dome horse in the Miocene, although well after the time of maximum burial and hydrocarbon generation, may have served to increase

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the trap size and concentrate petroleum accumulations. However, any thrusting along faults that acted as basal detachments to thin-skinned structures or roof thrusts associated with formation of the Niguanak high and Aurora dome at the top of the pre-Mississippian section may have caused breaching of the trap seals and spillage of any pre-existing hydrocarbon accumulations. Likewise, deformation is likely to have had only a degrading effect on any petroleum accumulations present in stratigraphic traps in the Brookian sequence that may have been filled with hydrocarbons generated from Shublik and Hue Shale source rocks from the south. The deformation, on the other hand, could have enhanced hydrocarbon migration from Beaufortian and Hue Shale source rocks located in the oil window in the Barter and Demarcation subbasins during the Tertiary by creation of structural relief, migration pathways, and structural traps in the frontal zone of the thin-skinned foldbelt (i.e., Jago ridge).

In sum, the model suggests that the oil and gas resources, particularly on the south flank of the Niguanak high, may be significant. Questions, however, about the northward extent of the Ellesmerian sequence, the presence or absence of the LCU, reservoir quality, the timing of deformation, and effect of deformation on pre-existing hydrocarbon accumulations caused a high level of risk to be assigned to hydrocarbon plays in the Niguanak and Aurora dome structures (Grow and others, Chap. P10).

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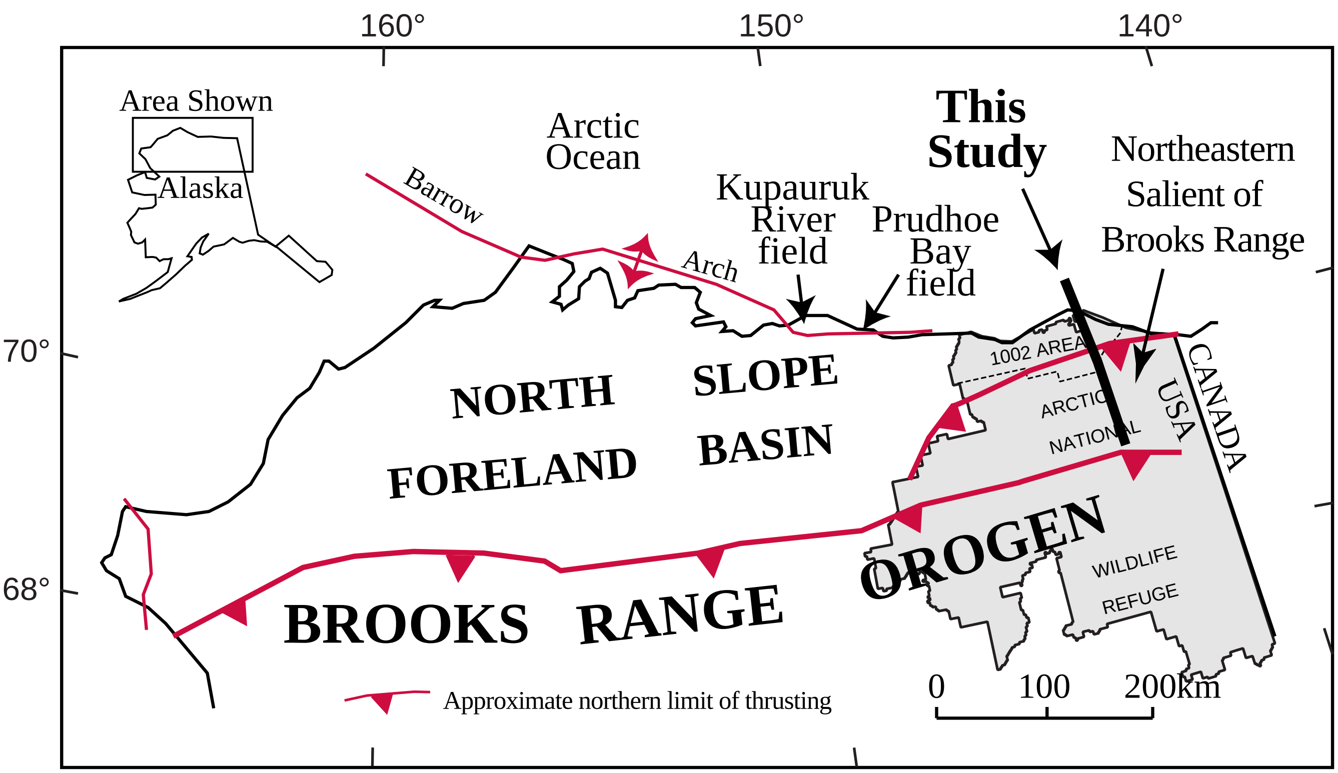

Figure BC1. Map showing location of structural-stratigraphic transect discussed in this paper.

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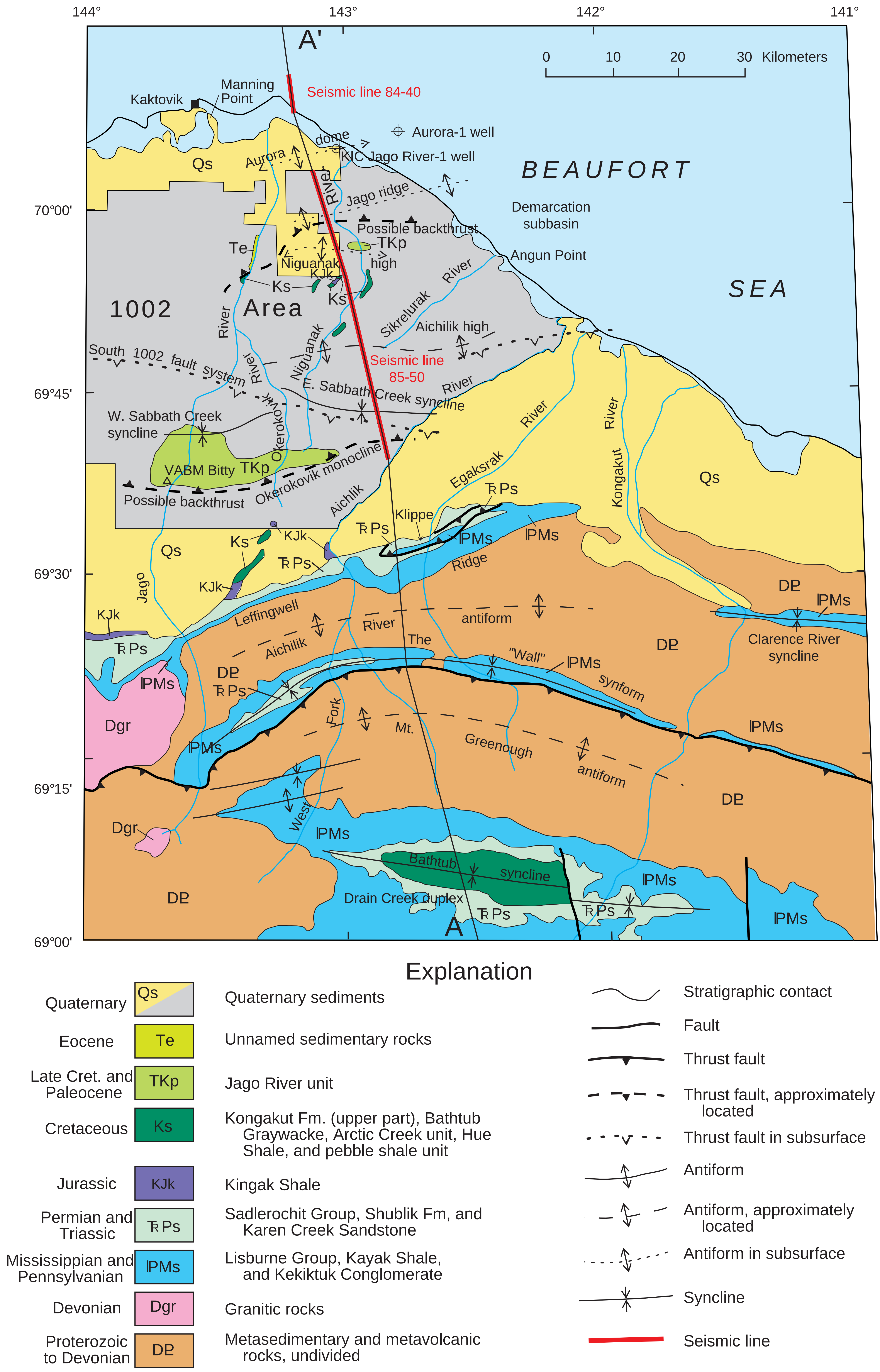

Figure BC2. Simplified geologic map of the northern Arctic National Wildlife Refuge, showing locations of structural transect in Plate BC1 and other features mentioned in text.

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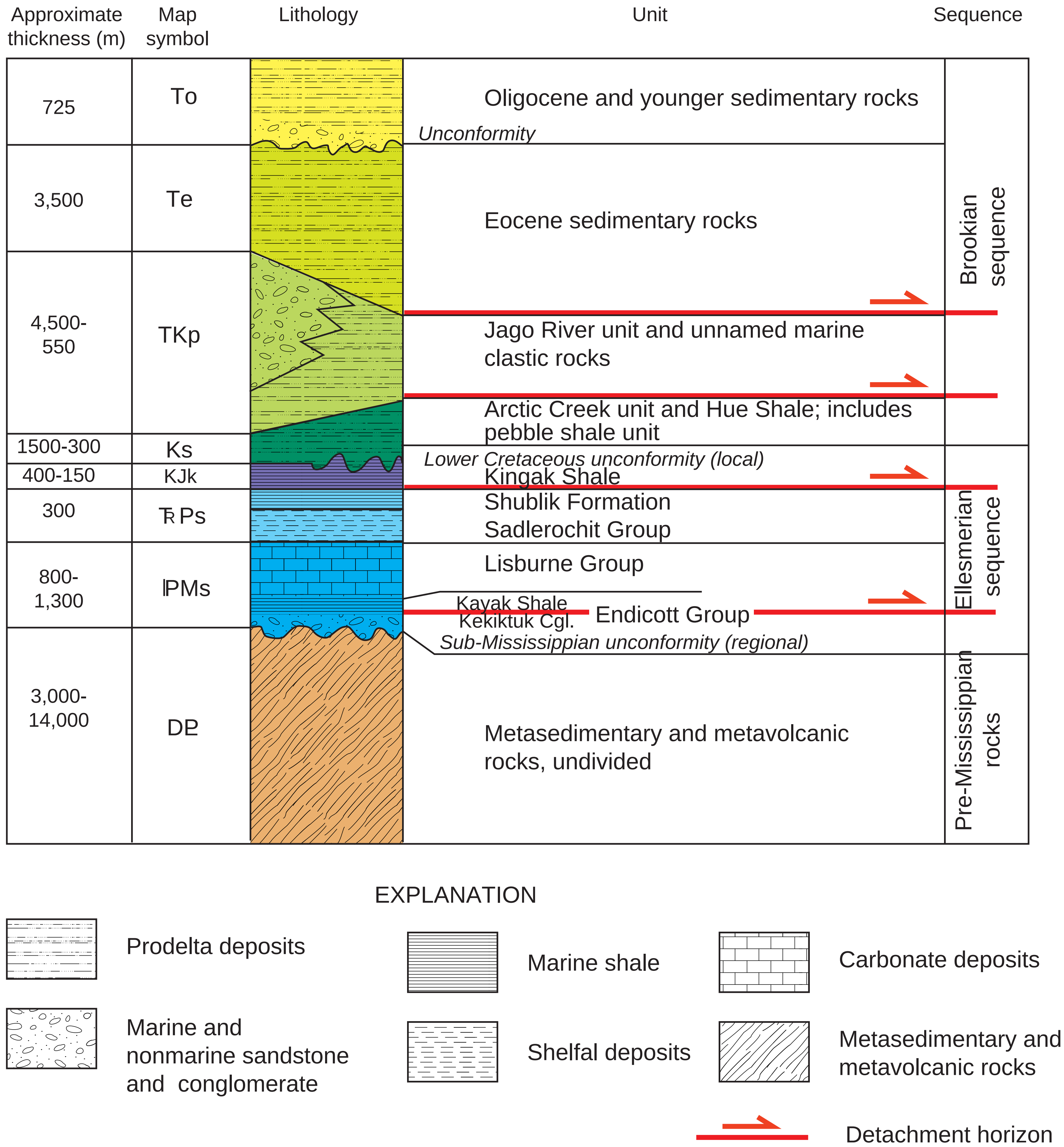

Figure BC-3. Generalized composite stratigraphy and detachment horizons along structural transect. Thicknesses are not to scale.

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Table BC1. Measured thicknesses in meters for units shown in Plate BC1 at various localities along transect. Sources of data: Detterman (1974, 1984), Eckstein (1993), Armstrong and Mamet (1975), Moore and others (1994), M.B. Mickey (written comm. to M. Keller, 1997).

Formation	Unit	Bathtub Ridge	The "Wall" synform	Leffingwell Ridge	Sabbath Creek syncline, south flank	Niguanak high	Aurora well
Oligocene strata	To	ND	ND	ND	ND	NE	725
Eocene strata	Te	ND	ND	ND	ND	NE	3500
Jago River unit and other latest Cretaceous and Paleocene strata	TKp	ND	NP?	NP	3500*†	NE	550
Arctic Creek unit, Hue Shale, Bathtub Graywacke and upper Kongakut; includes pebble shale unit	Ks	1150*	NP	NP	1500?	300?	300
Kingak Shale; Beaufortian sequence (shown in bold)	KJk	150	NP	400	400†	100?	**730**
Shublik Formation and Sadlerochit Group	TrPs	420	350	410	250†	ND	ND
Lisburne Group, Kayak Shale, and Kekiktuk Conglomerate and Kayak Shale	PMs	1100	1300	900	800†	ND	ND

Abbreviations: ND, Not deposited; NP, Not preserved; NE, Not exposed, *, Partial section; †, Thickness from seismic data

Table BC2. Comparison of distances for key horizons in deformed and restored cross sections in Plate BC1 and calculations of amount and percent of shortening. See Plate BC1 for position of reference points.

Part of cross section measured	Deformed length	Undeformed length	Shortening (length)	Shortening (percent)
Top of pre-Mississippian, footwall cutoff in Aurora dome (reference point A) to south end of section (reference point B)	124 km	195.8 km	71.8 km	36.7%
Top of pre-Mississippian, footwall cutoff in Aurora dome (reference point A) to trailing edge of horse at Okerokovik River monocline (reference point C)	62.7 km	93.9 km	31.2 km	33.2 %
Top of pre-Mississippian rocks, pin at Leffingwell Ridge to southern end of section (reference point B)	59.3 km	94.3 km	35.0 km	37.1%
Top of Lisburne Group, pin line at Leffingwell Ridge to breaching thrust at south end of section (reference point C)	58.1 km	93.0 km	34.9 km	37.5%
Base of latest Cretaceous and Paleocene deposits, hangingwall cutoff in roof of Jago Ridge triangle zone (reference point E) to south flank of Sabbath Creek syncline (reference point F)	50.0 km	87.7 km	37.7 km	43.0%

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U.S. DEPARTMENT OF INTERIOR
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OPEN-FILE REPORT 98-34
PLATE BC1

Explanation

Brookian Sequence

- To — Oligocene to Recent sedimentary rocks
- (wavy line) — Eocene sedimentary rocks
- Te — Unconformity
- TKp — Latest Cretaceous and Paleocene sedimentary rocks (includes Jago River Formation)
- Ks — Cretaceous sedimentary rocks (includes Bathtub Graywacke, Arctic Creek unit, Hue Shale, and pebble shale units)
- (wavy line) — Lower Cretaceous unconformity (LCU), inferred to be locally present north of Sabbath syncline

Ellesmerian and Beaufortian Sequences

- KJk ? KJb — Jurassic to Lower Cretaceous sedimentary rocks. KJk - Kingak Shale; KJb - Beaufortian sequence
- TrPs — Permian to Upper Triassic sedimentary rocks (Sadlerochit Group and Shublik Formation; includes Kingak Shale in Bathtub Ridge area)
- IPMs — Mississippian and Pennsylvanian sedimentary rocks (Kekiktuk Conglomerate north of Leffingwell Ridge, if present, Kayak Shale, and Lisburne Group)
- (wavy line) — Sub-Mississippian unconformity

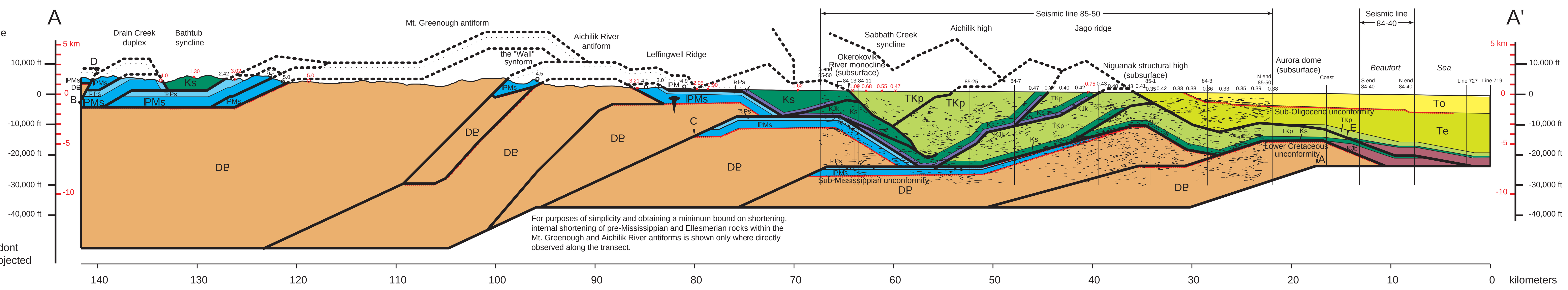
Pre-Mississippian rocks

- DP — Proterozoic to Lower Devonian metasedimentary rocks; includes Kekiktuk Conglomerate south of Leffingwell Ridge

Contacts and Symbols

- Stratigraphic contact
- Fault
- Unconformity
- Seismic reflections
- Pinpoint, indicating unfaulted, depositional contact
- D — Reference point. See text for explanation
- 5.0 / 4.0 — Location of conodont sample and conodont alteration index (CAI). Red symbols projected onto profile from outside of transect
- 2.42 / 3.02 — Location of vitrinite sample and vitrinite reflectance data. Locations of proprietary data not shown. Red symbols projected onto profile from outside of transect
- 5.6 km — Approximate depth of burial calculated from CAI and vitrinite reflectance data assuming geothermal gradient of 30 /km.

A. Balanced Cross Section, Bathtub Ridge to Beaufort Sea, Arctic National Wildlife Refuge, Alaska



B. Structural-Stratigraphic Restoration of Cross Section

BALANCED CROSS SECTION AND STRUCTURAL STRATIGRAPHIC RESTORATION, BATHTUB SYNCLINE TO BEAUFORT SEA THROUGH NIGUANAK STRUCTURAL HIGH, ARCTIC NATIONAL WILDLIFE REFUGE, ALASKA

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1999