Chapter BD (Brookian Deformation)

STYLE AND TIMING OF THRUST-FAULTING IN THE 1002 AREA, ARCTIC NATIONAL WILDLIFE REFUGE

by Christopher J. Potter[1], William J. Perry[1], John A. Grow[1], and Myung W. Lee[1]

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[1] U.S. Geological Survey, MS 939, Denver, Colorado 80225

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ABSTRACT

Thrust faulting and folding of Brookian, Ellesmerian, and Franklinian rocks are apparent on seismic reflection profiles across the coastal plain in the 1002 area of the northernmost Arctic National Wildlife Refuge. This contractional deformation represents the northernmost part of the northeastern Brooks Range orogen. The deformation front trends east-northeast across the 1002 area, such that the southern third of the westernmost part of the 1002 area is strongly deformed, whereas the entire north-south width of the easternmost part of the 1002 area is strongly deformed. Thin-skinned thrusting is pervasive in the deformed part of the 1002 area. Additionally, in parts of the 1002 area, basement-involved thrusts are significant structural elements.

In the western part of 1002, the dominant style of thin-skinned thrusting is that of a passive-roof duplex, which is essentially a large north-driven triangle zone bounded below by a detachment (floor thrust) near the base of the Brookian section, and bounded above by a north-dipping backthrust (roof thrust) near the base of the Eocene. The east-northeast-trending Marsh Creek anticline records rollover on Eocene strata across a prominent bend in the roof thrust. Buried basement-involved thrusts ("South 1002 thrust system") are present north of, and parallel to, the structures that bound the north edge of the Sadlerochit uplift. These basement-involved structures appear to feed displacement into the thin-skinned system, and locally, late basement-involved thrusts post-date the thin-skinned thrusting. Both the basement-involved thrusts and the thin-skinned passive-roof duplex that underlies the Marsh Creek Anticline were principally active in Miocene time.

In the eastern part of the 1002 area, a northward-younging pattern of thin-skinned deformation is apparent. Converging patterns of Paleocene reflectors on the north flank of the Sabbath syncline indicate that the Aichilik high and the Sabbath syncline formed in Paleocene time; the "triangle-zone" geometry of thrusts beneath the Aichilik high suggest that this was the location of the deformation front in Paleocene time. During Eocene and early(?) Oligocene time, thin-skinned thrusting advanced northward over the present location of the Niguanak high. A passive-roof duplex occupied the frontal part of this system. The Kingak and Hue Shales exposed above the Niguanak high were transported into their present structural position during Eocene to Oligocene motion on the long thrust ramps above the present south flank of the Niguanak high.

In the northeastern 1002 area, the large basement-cored structures of the Niguanak high and Aurora dome formed in Oligocene time, deforming the overlying thin-skinned structures and feeding a new increment of displacement into thin-skinned structures directly to the north. Deformation continued through the Miocene above a detachment in the Franklinian basement. Offshore seismicity may be an indication that contractional deformation continues to the present day.

INTRODUCTION

An extensive array of largely blind thrust faults and folds underlies most of the coastal plain within the 1002 area of the northernmost Arctic National Wildlife Refuge. These structures, found mainly within the Brookian section but also affecting underlying Ellesmerian and Franklinian rocks, compose the frontal part of the northeastern Brooks Range fold and thrust belt. (for stratigraphic overview, see Chap. GG). Although the main axis of the Brooks Range (100-250 km south of the 1002 area) records hundreds of kilometers of dominantly north-vergent Middle Jurassic to Early Cretaceous shortening, the northeastern Brooks Range within the Arctic National Wildlife Refuge is a younger (Cretaceous? and mainly Cenozoic) orogenic element that has undergone less than 100 km of principally north-vergent shortening (Wallace and Hanks, 1990). The blind structures beneath the coastal plain are the northward continuation of the northeastern Brooks Range thrust system illustrated in cross sections presented by Wallace (1993), Hanks (1990, 1993), and Hanks and Wallace (1990).

This report summarizes interpretations of the style and timing of the thrusting beneath the 1002 area, based on our analysis of the regional network of proprietary seismic reflection data collected during 1984 and 1985 (Foland and Lalla, 1987). We have developed a comprehensive interpretation of the areal and temporal variations in thin-skinned structural patterns beneath the coastal plain, incorporating and building upon some of the themes previously introduced by Bruns and others (1987) and Kelley and Foland (1987). The structural interpretation presented here is aided by newly reprocessed versions of the seismic reflection data (Chap. SP) and by results of new potential-field studies (Chaps. AM, GR). New timing constraints are provided by the application of seismic-stratigraphic approaches summarized by Houseknecht and Schenk (Chap. BS).

The Brookian thrust structures that underlie the 1002 area are of two types: (1) thrust faults that involve pre-Mississippian metasedimentary rocks; and (2) thin-skinned thrusts that lie entirely within the Brookian and Ellesmerian sequences (and are primarily confined to the Brookian beneath most of the

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1002 area). Structures of both types are evident on geologic maps of the region (e.g., Bader and Bird, 1986) (Fig. BD1). The east-west trending Sadlerochit and Shublik Mountains, in which pre-Mississippian rocks are extensively exposed just south of the 1002 area, are bounded on their north sides by major basement-involved thrusts, and contain other subsidiary east-west striking basement-cutting thrusts and reverse faults. Geologic map patterns (Robinson and others, 1989) strongly imply that the Sadlerochit uplift has breached a formerly continuous east-northeast-trending thin-skinned duplex, or zone of duplexes (Fig. BD1), in which the Kemik Sandstone is repeatedly thrust-imbricated above a detachment in the underlying Kingak Shale and beneath a roof thrust in the pebble shale (Meigs, 1989; Kelley and Foland, 1987) . The Kemik duplex zone is exposed west of the Shublik Mountains, in Ignek Valley between the Shublik and Sadlerochit Mountains, and just north of the eastern part of the Sadlerochit Mountains, where it continues into the southernmost part of the 1002 area (Fig. BD1). North of there, the east-northeast trending Marsh Creek anticline (Fig. BD1) records thin-skinned deformation and is the only major bedrock structure exposed on the coastal plain within the western part of the 1002 area.

Basement-involved thrusts identified in the subsurface have an east-west strike throughout the 1002 area (Figs. BD2, NA1), just as they do in the Sadlerochit and Shublik Mountains and in other parts of the northeastern Brooks Range (Wallace and Hanks, 1990). In the western and central parts of ANWR, the subsurface thin-skinned thrusts and folds trend east-northeast, similar to thin-skinned structures mapped at the surface in the area (Fig. BD2). In the eastern part of the 1002 area, however, the thin-skinned structures have an easterly trend (Fig. BD2), consistent with a regional change in trend of structures eastward toward Canada. Within the 1002 area, there are three major thin-skinned culminations, which are actually composite structures; these are named the Marsh Creek anticline, the Aichilik high, and Jago ridge (Fig. BD2). Between these major culminations, there are many minor thrust-related structural highs in the Brookian section.

SEISMIC INTERPRETATION OF THRUST STRUCTURES IN THE WESTERN PART OF THE 1002 AREA

In the western part of the 1002 area, north of the Sadlerochit Mountains, a map of subsurface fold and thrust structures reveals an interference pattern between basement-involved structures that parallel the east-west trending Sadlerochit mountain front, and thin-skinned structures that parallel the east-northeast trending Marsh Creek anticline (Fig. BD2). As a guide to our overall interpretation of this pattern, we present an interpretation of seismic line 84-10 (Fig. BD2, Plate BD1), because it illustrates many fundamental seismic-reflection characteristics of the stratigraphy and structure of this part of the 1002 area.

Seismic line 84-10

Seismic line 84-10, interpreted in Plate BD1, provides clear evidence for both basement-involved and thin-skinned thrust faulting. The following discussion of this seismic line proceeds from south to north. In the southern part of the seismic line, the Franklinian basement, characterized by a relatively unreflective to chaotic seismic character, is overlain by a reflective sequence that we correlate with the lower part of the Brookian section. The Ellesmerian sequence is erosionally omitted in this part of the southern 1002 area (Fig. NA5). The top of the Franklinian (here referred to as the LCU, lower Cretaceous unconformity, because the Ellesmerian has been erosionally removed) is cut by north-vergent reverse or thrust faults on the southern part of the seismic section, as are the Franklinian and Ellesmerian rocks in the Sadlerochit Mountains exposed immediately to the south. In the southern part of the reflection section four stacked thrust faults (*a*, Plate BD1) are interpreted in the Franklinian basement. These faults are marked by prominent, gently south-dipping reflections in the Franklinian, and by small offsets of the LCU. These basement-involved thrusts appear to cut only the very lowest part of the Brookian section. For this reason, we infer that a detachment near the base of the Brookian probably was the roof thrust for a basement duplex composed of the four stacked thrust faults, and there was only minor younger disruption of this surface by reactivated thrust faulting. This interpretation implies that the basement-involved duplex at the south end of line 84-10 transferred most of its displacement northward along a thin-skinned detachment near the base of the Brookian section. The basement duplex appears to have produced well over 5000' of total vertical relief on the top of pre-Mississippian basement.

Shallower strata and structures are obscure on the south end of this seismic line because of the locally poor data quality. Southeast of line 84-10, a detachment in the Jurassic to Lower Cretaceous Kingak Shale underlies a duplex containing thirteen horses of imbricated and folded Lower Cretaceous Kemik Sandstone (Fig. BD1; Meigs, 1989); higher detachments are documented as well, at the top of the Ellesmerian (pebble shale) and in the lower part of the Brookian section (Hue Shale). The northward, down-dip continuation of this complex geology is represented by one detachment surface interpreted above the basement on the southern end of the seismic

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section, with dashed splays coming up from it (*b*, Plate BD1), but there are probably several levels of detachment.

The reflective Brookian section is folded in a broad syncline on the south half of Plate BD1. Beneath the south-dipping north limb of this syncline, there is a wedge-shaped domain of discontinuous, locally arcuate reflections with a southerly to subhorizontal dip. This pattern overlies a strong reflection doublet at about 2.5 s (*c*, Plate BD1) which likely corresponds to the LCU. We interpret the thick stack of south-dipping, discontinuous, locally arcuate reflectors above the LCU to be imbricated Brookian sedimentary rocks above a detachment that lies at or near the base of the Brookian. Discordant relations between south-dipping packets of reflectors in the Brookian section are interpreted as thrust faults that have imbricated the section.

Above, and north of, the imbricated Brookian section, is a north-dipping, less deformed set of reflectors representing topset and foreset Brookian facies (Plate BD1). Using stratigraphic correlations established with the regional seismic reflection network tied to wells west of the Canning River, these reflectors correlate with Eocene through Miocene sequences A through C of Houseknecht and Schenk (see Chap. BS). They are tilted above the imbricate Brookian stack, and flatten to subhorizontal dips in the northern part of Plate BD1, where the underlying imbricate stack diminishes in thickness to a feather edge. The base of the less deformed Brookian strata, approximately at the base of the Eocene, must be a detachment surface, as it consistently is discordant to the underlying imbricate stack. Thus, the imbricate stack is within a duplex, with a flat floor thrust near the base of the Brookian section, and a north-dipping roof thrust that underlies the less deformed Eocene section.

Specifically, the duplex on line 84-10 has the geometry of a passive roof duplex (Banks and Warburton, 1986). This is a system that is essentially identical to an Alberta-foothills-style triangle zone (Jones, 1982) in which displacement along a flat basal detachment is not transferred to the surface along forward-breaking imbricates. Instead, at a certain point (represented by the tip of the imbricate wedge) shortening is accommodated rearward, along a backthrust that bounds the top of the thrust-imbricated wedge. Thus the rocks above the roof thrust are passively tilted toward the north and uplifted as the imbricate stack is constructed by thrusting at depth, and deformation advances forward (northward) through continuing insertion of the imbricate wedge beneath the cover rocks.

Kelley and Foland (1987) interpreted the imbricate stack within the passive-roof duplex to be composed of mud-rich Cretaceous and Paleocene rocks, based on surface geology exposed in the Katakturuk River drainage, north of the Sadlerochit Mountains and west of line 84-10. Unfortunately, this monotonous and thoroughly deformed volume of rock does not contain recognizable stratigraphic markers that allow calculation of the amount of thrust-related shortening. We believe there are many more thrusts than are depicted in Plate BD1, but there is not sufficient stratigraphic definition to constrain their locations.

Two north-vergent thrusts cut the top of the basement and the inferred detachment beneath the tapering wedge of the passive roof duplex (*d*, Plate BD1). Similar thrusts are apparent on other seismic lines across the Marsh Creek anticline. A south-vergent thrust (*e*, Plate BD1) displaces and gently arches the top of the Franklinian basement and the lower part of the Brookian section at or near the tip (north edge) of the passive-roof duplex.

Evolution, configuration and age of the Marsh Creek anticline

The structural style of line 84-10 typifies the western part of the 1002 area. The passive-roof duplex system dominates the thin-skinned structure in the western part of the 1002 area. The top of the prominent steeper segment of the roof thrust marks the location of the east-northeast -trending Marsh Creek anticline. This anticline records rollover on Eocene strata over a bend in the roof thrust of the passive-roof duplex. Although this structure is mapped at the surface as a simple plunging anticline, it is clear from several seismic lines that the core of this anticline is cut by numerous faults and it is, in detail, a complex structure. Near the down-plunge (east-northeastern) end of the structure, as defined by both outcrop and seismic data, the structure appears to be simpler, as evidenced by a well-defined anticline that involves Eocene reflectors on a seismic line across this part of the anticline. High-resolution aeromagnetic data reveal anomaly patterns that faithfully reflect the structure of the Marsh Creek anticline (Chap. AM). The most prominent positive magnetic anomaly, produced by a highly magnetic Eocene layer, defines a plunging anticline pattern that is locally disrupted as if cut by faults, supporting similar interpretations from the reflection data. The magnetic data (Chap. AM) show similar east-northeast - trending folded patterns to the south of the Marsh Creek anticline, which apparently preserve folding patterns above the roof thrust of the passive roof duplex; these folds are also seen in the seismic reflection data.

The amount of shortening within the passive-roof duplex can be calculated using an area-balance approach. The roof thrust is localized near the base of

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the Eocene, and the basal detachment is near the base of the Brookian section, so the deformed wedge is essentially composed of the pre-Eocene part of the Brookian section. The deformed wedge, as imaged on seismic lines, is up to 15,000 feet thick and 10-12 miles long (shorter and thinner in the southwestern part of the Marsh Creek Anticline). Considering that the undeformed thickness of this section is 4,000'-5,000', we calculate that the passive-roof duplex beneath the Marsh Creek anticline records 12-15 miles of shortening where it is best developed (east of line 84-10), and less shortening (under ten miles) to the east. Because the southward extent of the roof thrust has been removed by erosion, these are minimum figures. The magnitude of shortening associated with the passive-roof duplex that controls the Marsh Creek anticline attenuates to the southwest. Near the southwest corner of the 1002 area, on line 84-6, the deformed wedge that defines the passive-roof duplex is relatively small, and the Eocene reflectors above the wedge form a simple anticline (Plate BD2). Southwest of this location, the Marsh Creek anticline loses definition.

Seismic reflection patterns record the timing of growth of the Marsh Creek anticline. Uniformly northwest-dipping Eocene reflections, forming inclined "railroad-track-like" patterns, are hallmarks of the north flank of the Marsh Creek anticline on all seismic lines. The tilting of these strata demonstrates that the Marsh Creek anticline is a post-Eocene structure. Unpublished proprietary seismic reflection data contain fanning patterns in Oligocene through early Miocene strata on the north flank of the Marsh Creek anticline, demonstrating that this structure grew in late Oligocene to early Miocene time.

South 1002 fault system in the southwestern 1002 area: relation to Marsh Creek anticline

The basement-cutting faults identified near the south ends of lines 84-10 and 84-6 (Plates BD1 and BD2) lie in a zone, 9-13 mi (14-21 km) north of the Sadlerochit mountain front, comprising three separate thrust segments in a right-stepping *en echelon* pattern (Fig. BD2). This zone of faulting, named the "south 1002 fault system" by Grow and others (Chap. NA) is evident on all of the north-northwest- trending seismic lines (structural dip lines) in this part of the 1002 area. This fault system produced 5000 ft (1500 m) or more of structural relief on the pre-Mississippian unconformity on lines 84-6 and 84-10. Structure contour maps by Grow and others (Chap. NA) illustrate the regional relief on the top of pre-Mississippian basement produced by this basement-cutting thrust system.

The structural interpretations of seismic lines 84-10 and 84-6 (Plates BD1 and BD2) strongly suggest that basement-involved thrusting transferred displacement northward into the thin-skinned passive-roof duplex that underlies the Marsh Creek anticline. On some unpublished proprietary seismic reflection lines, there is clear evidence for late "breakthrough" reverse faults that cut through, and displace, the thin-skinned detachment near the base of the Brookian section. These late breakthrough structures do not appear to be uniformly developed across the south 1002 fault system in the southwestern part of the 1002 area. In summary, we interpret the basement-involved "south 1002 thrust system" to have been intimately involved with the evolution of the thin-skinned thrust system to its north, and to have outlasted the thin-skinned thrusting.

SEISMIC INTERPRETATION OF THRUST STRUCTURES IN THE CENTRAL PART OF THE 1002 AREA

Although the Marsh Creek anticline dies out in the central part of the 1002 area, the passive-roof duplex style of deformation continues across this region (Fig. BD2). The overall trend of the thin-skinned structures continues on the north-northeast trend that typifies the Marsh Creek anticline to the west.

Figure BD3 illustrates an interpretation of the northern part of seismic line 84-20. Topsets and foresets of Oligocene sequence B (Chap. BS) overlie a thrust-imbricated lower section, that in turn is underlain by a detachment near the base of the Brookian. Houseknecht and Schenk (Chap. BS) interpret an unconformity between sequence B and the underlying thrust-imbricated Eocene and Paleocene rocks. This surface is regionally correlative with a well-defined unconformity mapped offshore. On this seismic line, we infer the presence of a roof thrust that is essentially a detachment surface localized along the unconformity (detachment along the base of Sequence B). Beneath this roof thrust, the structural style shown in this figure strongly resembles a classic forward-propagating duplex (Boyer and Elliot, 1982). The complete structural style, based on examination of several seismic lines across this part of the 1002 area, is better described as a passive-roof duplex with both backthrusts and forward-propagated thrusts in the duplex roof (Banks and Warburton, 1986). The 1.5 s of relief on the base of sequence B in the south part of Fig. BD3 was probably produced by stacking of thrust sheets beneath the roof thrust, producing a local culmination in the roof.

In the northern half of Fig. BD3, two thrust faults (one north-vergent (*a*) and one south-vergent (*b*)) affect the Oligocene section above the roof

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thrust. The north-vergent thrust, interpreted as a listric thrust fault, produced rollover in the topset beds in the hanging-wall. The south-vergent thrust is inferred to have a ramp-flat pattern, based on the apparent fault-bend fold in the topset and foreset strata in its hanging-wall. These thrusts appear to sole into the roof thrust at the base of the Oligocene section, or a slightly shallower detachment.

Two minor north-vergent thrust faults offset the top of the pre-Mississippian basement and the basal Brookian detachment (*c* in Fig. BD3).

In the southern part of the central 1002 area, a prominent basement-cutting thrust zone (part of the south 1002 fault system; Chap. NA) bounds the north side of the buried eastern continuation of the Sadlerochit uplift, although it is not well-defined on the seismic reflection lines. Poor data quality prevents careful analysis of basement-involved or thin-skinned structures in this south-central area.

SEISMIC INTERPRETATION OF THRUST STRUCTURES IN THE EASTERN PART OF THE 1002 AREA

In the eastern part of the 1002 area, the principal basement-involved structural elements include the south 1002 fault system and the Niguanak and Aurora domes, two major domes to the north that are underlain by major north-vergent basement thrusts (Chap. NA). Principal thin-skinned structural elements include the Sabbath syncline, the Aichilik high, a north-vergent imbricate stack across the top of the Niguanak high, and Jago ridge (Fig. BD2). All of these structural elements are present on seismic line 84-30 (Plate BD3). Although this line passes over the eastern flank of the Niguanak high (the single structure of perhaps the greatest exploration interest within the 1002 area) , rather than over the center of this structure, the generally good data quality provides valuable examples of our interpretations of the style and timing of deformation in the eastern part of the 1002 area.

Seismic line 84-30

Sabbath syncline and Aichilik high. The southernmost part of line 84-30 (Plate BD3) contains a prominent syncline-anticline pair developed in Brookian rocks, termed the Sabbath syncline and the Aichilik high. Figure BD4 is a generalized line drawing that shows geologic relations interpreted from proprietary seismic reflection lines across these structures. The Sabbath syncline contains over 10,000 ft of shallow-marine to nonmarine sedimentary rocks of the Jago River Formation (Buckingham, 1985). These

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rocks were dated with plant fossils by Spicer (Buckingham, 1985), who reported Maastrichtian *Equisetum* in the lower 1000 feet of the section, in the southern part of the Sabbath Creek syncline. Spicer (R. A. Spicer, Open University, United Kingdom, 1997, written communication to W.J. Perry) stated that this genus has limited use for precise age determinations as it is so long ranging. Plant fossils from the upper half (and possibly much of the lower half) of the Jago River Formation are Paleocene. Within the Paleocene part of the section, there is a pronounced convergence of reflections on the north flank of the Sabbath syncline (south flank of Aichilik high; Plate BD3 and Fig. BD4). From this observation, we conclude that the Aichilik high was growing during the Paleocene, and that the Sabbath syncline represents a largely Paleocene piggyback basin behind and above the growing Aichilik high. The internal structure of the Aichilik high, in which south-dipping packages of reflections have progressively steeper dips in the structurally higher and hindward parts of the uplift, is consistent with the geometry of a small triangle zone or passive -roof duplex, bounded above by a smooth north-dipping roof thrust (Plate BD3 and Fig. BD4). The imbricate stack within the Aichilik triangle zone is inferred to be shale-rich on the basis of reflection character, deformation style and especially because the Aichilik high corresponds to a negative gravity anomaly (Chap. GR). We interpret the imbricate stack to be composed of Hue Shale and pebble shale, and the underlying detachment (Plate BD3 and Fig. BD4) to lie in the pebble shale. As triangle zones are typical of thrust fronts, it appears likely that the Aichilik high was near the Paleocene front of the Brookian thrust belt.

Another syncline is apparent in Brookian strata just north of the Aichilik high (Plate BD3). On some seismic lines, possible convergence of Paleocene reflections on the south flank of this syncline (above the north flank of the Aichilik high) may suggest Paleocene growth relations, similar to those on the south flank of the Aichilik high.

Beneath the Sabbath syncline, the Ellesmerian section is not obvious on 84-30 (Plate BD3) but it is present as a reflective section that is at least partially involved in thrusting on unpublished seismic lines, about 7 mi. southwest of the south end of this seismic line (Figs. NA1 and NA5). The top of the pre-Mississippian is tentatively identified, based on locally prominent reflections (Plate BD3). It appears to be cut by several thrust faults beneath the Aichilik high of line 84-30 (Plate BD3, Fig. NA1), with a cumulative throw of about 4000 feet.

South-dipping thrust faults between Aichilik high and Niguanak high. North of (and beneath) the syncline that is directly north of the Aichilik high, there is a uniformly south-dipping seismic reflection fabric that lies south of, and above, the prominent domed reflector between 2 and 3 s that defines the Niguanak high (Chap. NA).

This south-dipping reflection fabric strongly suggests the presence of long north-vergent thrust faults reaching from a deep detachment at 2.0 to 2.7 s (near the base of the Brookian section), to the present day surface above the Niguanak high (Plate BD3). (Depth to detachment is constrained by depth to the top of pre-Mississippian basement, summarized in Fig. NA1). As with the imbricated Brookian section in the western part of the 1002 area, there are no real marker horizons that allow rigorous geometric interpretation.

Allochthonous Ellesmerian rocks may be imbricated with Brookian strata in south-dipping thrust slices north of the south 1002 fault system, based on patterns evident in nearby unpublished proprietary seismic data. The long south-dipping thrusts above the south flank of the Niguanak high are probably thrust ramps, evidenced by the gently dipping fabric (discordant to the dip of the thrusts) that characterizes the panels between the inferred thrusts. This interpretation is corroborated by seismic reflection patterns on nearby seismic lines.

Niguanak high. The central part of line 84-30 is dominated by the Niguanak high, a large dome expressed in this seismic profile as a broad arch that deforms a prominent reflector interpreted as the top of Franklinian basement. As discussed in Chapter NA, the domed Franklinian rocks within the Niguanak high may have been internally imbricated during Brookian deformation, forming a basement duplex.

Thin-skinned fold-thrust structures that affect Brookian (and some Ellesmerian) rocks across the top of the Niguanak high were detached from the Franklinian basement, and appear to have pre-dated the formation of the Niguanak high. An erosionally breached Brookian passive-roof duplex (shown in map view in Fig. BD2) is interpreted from seismic lines across the Niguanak high. On line 84-30, and on other nearby seismic lines, there is an erosional window through the roof thrust, so that the seismic reflection geometry above the basement dome resembles a north-vergent imbricate fan with no overlying roof thrust. As discussed above, the thrusting above the south flank of the Niguanak high appears to be ramp-dominated. Across the top and north flank of the Niguanak high, reflection patterns in the deformed Brookian section flatten; individual thrust slices are identified on the basis of discordant reflection patterns suggesting the presence of ramp-flat geometry (Plate BD3). The regional doming of the basal detachment surface (which

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overlies and mimics the broadly arched top of the Franklinian), as well as the erosional breaching of the shallow roof thrust across the top of the Niguanak high, require that the broad basement doming post-dated the shallower thin-skinned thrusting.

Along seismic lines to the west that cross the highest part of the Niguanak dome, outcrops of Kingak and Hue equivalents near Niguanak ridge (near NH in Fig. BD1) require that at least one thrust sheet carried Jurassic and Cretaceous shales (Kingak, and Hue equivalents) to a shallow structural position. We do not know if this relation also applies along 84-30 (east flank of the Niguanak high), because there is insufficient bedrock exposure at this location. In any case, the volume of imbricated strata above the pre-Mississippian in the Niguanak high is dominated by Brookian rocks, above a detachment near the base of the Brookian.

North of the Niguanak high, the seismic data are represented only as an interpreted line drawing because data in this area are proprietary. Approximate stratigraphic ties to the Aurora 1 well are shown; these well ties are discussed in detail by Grow and others (Chap. NA).

Jago ridge. Directly north of and above the Niguanak high, a thick north-vergent imbricate wedge corresponds to Jago ridge, a long east-west trending thin-skinned culmination. The north margin of the Jago ridge imbricate wedge, on this and other seismic lines, includes an abrupt north-dipping boundary between a deformed sedimentary wedge and relatively undeformed lower Tertiary strata to the north. Upper Eocene(?) and Lower Oligocene(?) reflectors dip to the north above the thoroughly deformed imbricate wedge (location *a*, Plate BD3). At the north end of the seismic line, there is evidence for a thin thrust-bounded wedge inserted northward within the Paleocene section (location *b*, Plate BD3). These characteristics strongly suggest that the passive-roof duplex is present in this area, as on seismic lines to the east. On other seismic lines in this vicinity, evidence for a passive-roof duplex is less obvious.

Upper Eocene(?) and Lower Oligocene(?) reflectors at location *a* (Plate BD3) are tilted above an inferred roof thrust, whereas relatively flat-lying upper Eocene(?) and Oligocene(?) reflectors (location *b*, Plate BD3), overlie the tapering imbricate wedge at the north end of Plate BD3. There also appears to be modest Eocene stratigraphic thinning on the north flank of the Jago ridge (Plate BD3). This implies that the passive roof duplex here is actually a composite structure, recording two different periods of motion. The thinly tapered imbricate wedge at the north end of the cross-section appears to have developed in Eocene time, and the prominent bulge in the

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roof thrust, overlain by dipping reflections at *a*, appears to record the development of a younger north-directed triangle zone. This latter deformation is constrained as Oligocene in age because it involves probable lower Oligocene reflectors, and is overlain by nearly horizontal Miocene and upper Oligocene reflectors.

The basement-cutting Niguanak thrust, which underlies the broad basement high, was probably coeval with the latter part of the thin-skinned imbrication of Jago ridge (and the thin-skinned deformation across the top of the Niguanak high). Line 84-30 clearly images a basement-cutting thrust that offsets the top of pre-Mississippian basement and the detachment near the base of the Brookian section. This is the thrust above which the top of the pre-Mississippian is domed. As it propagated up into the (already) deformed Brookian section, its displacement appears to have fed into the thin-skinned passive roof duplex. It does not appear to have cut Eocene reflectors that overlie the passive-roof duplex roof thrust, so it may have driven a wedge of Paleocene (and early Eocene?) strata forward, producing the prominent bulge in the roof thrust (near location *a*, Plate BD3). If this bulge in the roof thrust records motion on the Niguanak thrust, the Niguanak thrust is Oligocene in age.

Jago ridge: timing

Detailed stratigraphic interpretations (Chap. BS) for Brookian strata on the flanks of the Jago ridge (Fig. BD2) on seismic lines in the northeastern 1002 area provide important additional constraints on timing of deformation. Figure BD5, a line drawing that generalizes a short segment of proprietary reflection data on the south flank of Jago ridge near its west end, shows evidence for Eocene, and principally Oligocene growth of Jago ridge, and for continuing deformation in late Oligocene and younger time, as described below.

The chaotic reflection patterns in the lower right part of Fig. BD5 are the imbricated Brookian rocks at the southern edge of Jago ridge. The deepest south-dipping reflections are Eocene bottomset strata (within sequence C, Chap. BS) that appear to downlap the edge of the Jago ridge. A downlap relation here would require that the chaotic reflection patterns, inferred to record thrust imbrication, formed in Eocene or older time. Alternatively, the south-dipping top of the chaotic reflection patterns represents a roof thrust above a passive-roof duplex, in which case the southerly dip on this surface would represent post-Eocene deformation. (The diachronous evolution of Jago Ridge, inferred above to explain patterns on line 84-30 (Plate BD3), would allow either interpretation for Fig. BD5). A local erosional surface is interpreted near the top of the Eocene at about 5000 ft depth. This would require that the Jago ridge was a slightly positive topographic element in late Eocene time. Oligocene reflections above this erosional surface are interpreted as foresets overlain by topsets, all tilted back to the south from their original depositional dips. The upward transition from foresets to topsets (which defines a south-dipping surface from 4,500 to 6,500 feet across the southern (left) half of Fig. BD5) documents Oligocene shelf-edge progradation (within lower part of sequence B, Chap. BS; Fig. BSG2).

The topsets are dramatically cut by a surface representing an Oligocene shelf-edge step-back (within sequence B, Chap. BS); this north-dipping surface is present at 0-2,500 feet across the center part of Fig. BD5. This sharp break has two-fold significance: (1) it represents a significant relative sea-level fluctuation, with the end result that the shelf edge stepped landward, resulting in foreset deposition above the "shelf-edge step-back" surface in this location; (2) this rapid relative sea-level rise appears to have been preceded by a pulse of uplift and relative sea-level fall, resulting in southward tilting and erosional truncation of the topset section, before re-establishment of clinoform deposition (i.e., this is an angular unconformity). Most of the southward tilting of the Eocene through lower Oligocene section occurred during the hiatus associated with this Oligocene unconformity, as the dip of Oligocene topsets beneath the shelf-edge step-back surface is only a few degrees gentler than the dip of Eocene bottomsets that directly overlie the chaotic reflectors of Jago ridge.

The uppermost (Oligocene) clinoforms in Fig. BD5 prograded over the top of the thrust-imbricated Jago ridge, apparently not influenced by it, demonstrating that by this time Jago ridge was no longer a positive structural element. It is not clear whether or not these uppermost clinoforms are slightly back-tilted. We conclude that growth of Jago ridge apparently took place during Eocene through Oligocene time, culminating in the Oligocene, coeval with the shelf-edge step-back. The most pronounced growth of the structure occurred in the Oligocene. Seismic lines in the area show a northward tilting of Miocene strata, indicating that there was continued regional deformation, though less intense, in Miocene time.

DISCUSSION

Evolution of Brookian thrusting across the Niguanak high

Jurassic and Cretaceous shales exposed on the Niguanak ridge area of the coastal plain (Fig. BD1) are key to structural interpretations for two reasons: (1) they provide geologic control on the lithologies involved in the imbricate

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structure above the Niguanak dome; and (2) thermal maturity and apatite fission track data for these rocks (Magoon and others, 1987; O'Sullivan and others, 1993) provide constraints on thermal history. The thermal data show that the imbricates are thermally immature and have not been subjected to temperatures higher than 60°C for more than 1 m.y. This implies a maximum depth of tectonic or sedimentary burial of 1-2 km (O'Sullivan and others, 1993). These observations, and the deformational timing deduced from line 84-30 (Plate BD3), are placed in the context of a generalized interpretation across the Niguanak area in a series of schematic cross sections in Figure BD6.

Figure BD6-A illustrates the concept that the Aichilik high represents the frontal triangle zone of the Brookian thrust belt in Paleocene time. To the south of this diagrammatic section, the basal detachment has ramped up above the Ellesmerian, from the deeper stratigraphic levels it occupies to the south. As discussed above, the volume of rock within the Aichilik high consists dominantly of Hue shale and pebble shale, and seismic reflection patterns in the Sabbath syncline demonstrate that it was a nonmarine to shallow marine piggyback basin at this time.

In Eocene and early(?) Oligocene time, represented by Fig. BD6-B, an imbricate stack, involving the Brookian section as well as Kingak-equivalent shales such as those exposed in the Niguanak ridge area, has propagated to the north, across the current Niguanak high, as far north as the current position of the Jago ridge (although Jago ridge attained most of its current structural relief in Oligocene time, as implied by Fig. BD5).

Figure BD6-C illustrates Oligocene development of basement-cored anticlines (including the Niguanak and Aurora domes). As the Niguanak thrust is inferred to have transferred its displacement northward into the thin-skinned passive-roof duplex, this time period also corresponds to renewed development of the Jago ridge passive-roof duplex directly north of the Niguanak high.

The Kingak and Hue Shales, presently exposed at Niguanak ridge, were transported into their present structural position during Eocene (to Oligocene?) motion on the long thrust ramps above the south flank of the Niguanak high (Fig. BD6-B, BD6-C). Prior to that, they were most likely involved in Paleocene thrusting beneath the Aichilik high (or at an equivalent structural level; Fig. BD6-A). The Paleocene position of these rocks (BD6-A) prior to their Eocene to Oligocene ramp-dominated upward transport, represents the deepest structural level that these rocks experienced.

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Present-day continuation of this thrust belt (not depicted in Fig. BD6) may be manifested as upper crustal earthquakes with epicenters offshore to the north of ANWR. Earthquake epicenter locations (Fig. BD7) offshore support an interpretation of continued north-directed shortening of the northeastern Brooks Range, with the present-day deformation front in the offshore, north of the 1002 area.

Summary of the timing of deformation in the 1002 area

We briefly summarize our conclusions on the timing of deformation beneath the 1002 area, and then discuss these in light of the fission-track studies of O'Sullivan and others (1993).

In the eastern part of the 1002 area, our analysis of the seismic reflection data demonstrate a Paleocene to present(?) pattern of progressively younger thin-skinned structures toward the foreland (Fig. BD6). Superimposed upon this are the younger basement-involved thrusts in the southeastern part of the 1002 area and in the Niguanak/Aurora area. The basement-involved thrusting in the southeastern part of the 1002 area (Plate BD3) is post-Paleocene (because basement-involved faulting cuts Paleocene structures) but beyond that the age of these structures is indeterminate. In the Niguanak area, we have presented an interpretation that the basement-involved thrusts are Oligocene in age.

In the western part of the 1002 area, east-west-striking basement-involved faulting parallel to (and north of) the Sadlerochit mountain front appears to have been synchronous with, and partly later than, late Oligocene to Early Miocene development of the east-northeast trending Marsh Creek anticline. It is not clear whether the Marsh Creek anticline developed synchronously with, or later than, the northeast-trending "Kemik duplex" thin-skinned structures that are mapped north of the Sadlerochit Mountains, and in Ignek Valley and vicinity. If the thin-skinned structures in this region evolved in a standard "forward propagation" of thin-skinned deformation, the "Kemik duplex" would be older than the Marsh Creek anticline.

Based on regional analyses of apatite fission track data, O'Sullivan and others (1993) identified rapid cooling (=uplift) events at ~62 Ma, ~45 Ma and ~23 Ma in the northeastern Brooks Range. These dates presumably represent times of shortening-related uplift that punctuated the Cenozoic evolution of the northeastern Brooks Range thrust belt. O'Sullivan and others (1993) proposed that the Marsh Creek anticline and the Kemik duplex system belong to an early (about 45 Ma) thin-skinned phase of deformation in the 1002 area, and that the Sadlerochit Mountains uplift typify a ~23 Ma

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uplift event. Our interpretations on the timing of structures would place both the Marsh Creek anticline and the east-west striking basement-involved structures near the 23 Ma “event.” This in turn would allow the Kemik duplex to be quite young as well (though still pre-23 Ma), although there are no definitive data on that.

To place all of the major structural elements described in this paper in the context of cooling ages reported by O’Sullivan and others (1993), the Paleocene development of the Aichilik high may be one expression of the 62 Ma deformation (also expressed by deformation in the Bathtub Ridge area to the south). We report no distinct deformation that may fall into the 45 Ma “event”, although there was an evolving thrust system in the eastern part of the 1002 area throughout the Eocene. The growth of the Jago ridge, primarily an Oligocene event, appears to fall into a time frame between the 45 and 23 Ma “events.” It is possible that all of the young basement-involved thrusts throughout the 1002 area (along with the Marsh Creek anticline) evolved around 20-25 Ma (near the 23 Ma “event”), although some, such as the Niguanak thrust, may be somewhat older. There is a consistent pattern of basement-involved thrusting postdating thin-skinned thrusting at any given place; this is a common and expected pattern in thrust belts. To summarize, the apatite fission-track ages reported by O’Sullivan and others (1993), as well as our analyses of the reflection data, provide evidence for pulses of shortening and uplift during the hinterland-to-foreland progression of deformation. Because the two techniques date distinctly different deformation-related phenomena, somewhat different pulses of deformation are measured by the two techniques.

There is a striking contrast in the temporal and spatial patterns of thin-skinned Brookian deformation in the 1002 area. The Marsh Creek anticline and other east-northeast trending structures in the western and central part of the 1002 area (Fig. BD2) are late Oligocene to Miocene in age, whereas in the eastern 1002 area there is the regular south to north (Paleocene to present?) progression of ages for thin-skinned deformation discussed above. The thin-skinned structures in the east are east-trending. This pattern makes more sense when one realizes that the Marsh Creek anticline projects to the east-northeast “in front of” the older Jago ridge, and that the Aichilik high projects to a position well south of any younger thin-skinned structures documented in the western part of the 1002 area. Thus, in a general way, a northward progression of thin-skinned deformation through time is a reasonable characterization of the 1002 area. Locally this generalization breaks down, where east-northeast-trending Miocene structures interfere with east-trending Eocene to Oligocene structures in the central part of the 1002 area (Fig. BD2).

Wallace and Hanks (1990) noted that east-northeast trends (which probably developed normal to the direction of tectonic transport) appear to characterize structures in the northeast Brooks Range that do not involve sub-Mississippian rocks, whereas easterly trends (inherited form the predominant basement fabric) characterize structures in which the sub-Mississippian rocks are involved. This generalization applies well to the western part of the 1002 area, yet in the eastern part of the 1002 area, thin-skinned structures have an easterly orientation, as noted above. This may be explained by the involvement of sub-Mississippian basement in younger, deeper thrusts beneath the older thin-skinned structures in the eastern 1002 area, well to the north of the northern limit of significant basement-involved thrusting in the western 1002 area. In the eastern part of the 1002 area, the earlier-formed thin-skinned thrusts may have been re-oriented into easterly strike directions due to the development of later basement-involved thrusts such as the Niguanak thrust.

REFERENCES CITED

Bader, J.W., and Bird, K.J., 1986, Geologic map of the Demarcation Point, Mt. Michelson, Flaxman Island, and Barter Island quadrangles, northeastern Alaska: USGS Miscellaneous Investigations Series Map I-1791, scale 1:250,000, 1 sheet.

Banks, C.J., and Warburton, J., 1986, ‘Passive-roof’ duplex geometry in the frontal structures of the Kirthar and Sulaiman mountain belts, Pakistan: Journal of Structural Geology, v. 8, p. 229-237.

Boyer, S.E., and Elliott, D., 1982, Thrust systems: AAPG Bulletin, v. 66, p. 1196-1230.

Bruns, T.R., Fisher, M.A., Leinbach Jr., W.J., and Miller J.J., 1987, Regional structure of rocks beneath the coastal plain: *in* Bird, K.J., and Magoon, L.B., eds., Petroleum Geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska, U.S. Geologic Survey Bulletin 1778, p. 249-254.

Buckingham, M.L., 1985, Stratigraphy, petrology, and depositional environments of the Upper Cretaceous to Lower Tertiary Sabbath Creek section, Arctic National Wildlife Refuge (ANWR), Alaska: MS thesis, University of Alaska, 120 p.

Foland, R.L., and Lalla, D.J., 1987, Seismic reflection data acquisition, processing, and interpretation: *in* Bird, K.J., and Magoon, L.B., eds., Petroleum Geology of the northern part of the Arctic National

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Wildlife Refuge, northeastern Alaska, U.S. Geologic Survey Bulletin 1778, p. 235-244.

Grantz, A.,Dinter, D. A., & Culotta, R. C., 1987, Structure of the continental shelf north of the Arctic National Wildlife Refuge: *in* Bird, K.J., and Magoon, L.B., eds., Petroleum Geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska, U.S. Geologic Survey Bulletin 1778, p. 271-276.

Hanks, C.L., 1990, Balanced cross sections of the Aichilik River and Okpilak batholith regions, northeastern Brooks Range, Alaska: Alaska Division of Geological and Geophysical Surveys Public-data file 90-2a, 12 p., 3 figs., 2 plates.

Hanks, C.L., 1993, The Cenozoic structural evolution of a fold-and-thrust-belt, northeastern Brooks Range, Alaska: Geological Society of America Bulletin, v. 105, no. 3, p. 287-305.

Hanks, C.L., and Wallace, W.K., 1990, Cenozoic thrust emplacement of a Devonian batholith, northeastern Brooks Range -- involvement of crystalline rocks in a foreland fold-and thrust belt: Geology, v. 18, p. 395-398.

Jones, P.B., 1982, Oil and gas beneath east-dipping underthrust faults in the Alberta foothills, *in* Powers, R. B., ed., Geologic studies of the Cordilleran thrust belt - 1982**:** Rocky Mtn. Assoc. Geologists, v. 1, p. 61-74.

Kelley, J.S., and Foland, R.L., 1987, Structural geology and framework geology of the coastal plain and adjacent Brooks Range: *in* Bird, K.J., and Magoon, L.B., eds., Petroleum Geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska, U.S. Geologic Survey Bulletin 1778, p. 255-270.

Magoon, L.B., Woodward, P.V., Banet Jr., A.C., Griscom, S.B., and Daws, T.A., 1987, Thermal maturity, richness, and type of organic matter of source-rock units: *in* Bird, K.J., and Magoon, L.B., eds., Petroleum Geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska, U.S. Geologic Survey Bulletin 1778, p. 127-180.

Meigs, A.J., 1989, Structural geometry and sequence in the eastern Sadlerochit Mountains, northeastern Brooks Range, Alaska: Master of Science thesis, University of Alaska, Fairbanks, 220 p.

Click here or on this symbol in the toolbar to return.

O'Sullivan, P.B., Green, P.F., Bergman, S.C., Decker, J., Ruddy, I.R., Gleadow, A.J.W., and Turner, D.L., 1993, Multiple phases of Tertiary erosion and uplift and erosion in the Arctic National Wildlife Refuge, Alaska, revealed by apatite fission track analysis: American Association of Petroleum Geologists Bulletin, v. 77, p. 359-385.

Robinson, M.S., Decker J., Clough, J.G., Reifenstuhl, R.R., Bakke, A., Dillon, J.T., Combellick, R.A., and Rawlinson, S.A., 1989, Geology of the Sadlerochit and Shublik mountains, Arctic National Wildlife Refuge, northeastern Alaska: Alaska Division of Geological and Geophysical Surveys Professional Report 100, scale 1:63,360, 1 sheet.

Wallace, W.K., 1993, Detachment folds and a passive-roof duplex -- examples from the northeastern Brooks Range, Alaska, in Solie, D.N., and Tannian, F., eds., Short Notes on Alaskan Geology 1993: Alaska Division of Geological and Geophysical Surveys Geologic Report 113, p. 81-99.

Wallace, W.K. and Hanks, C.L., 1990, Structural provinces of the northeastern Alaska Brooks Range, Arctic National Wildlife Refuge, Alaska: American Association of Petroleum Geologists Bulletin, v. 74, p. 1100-1118.

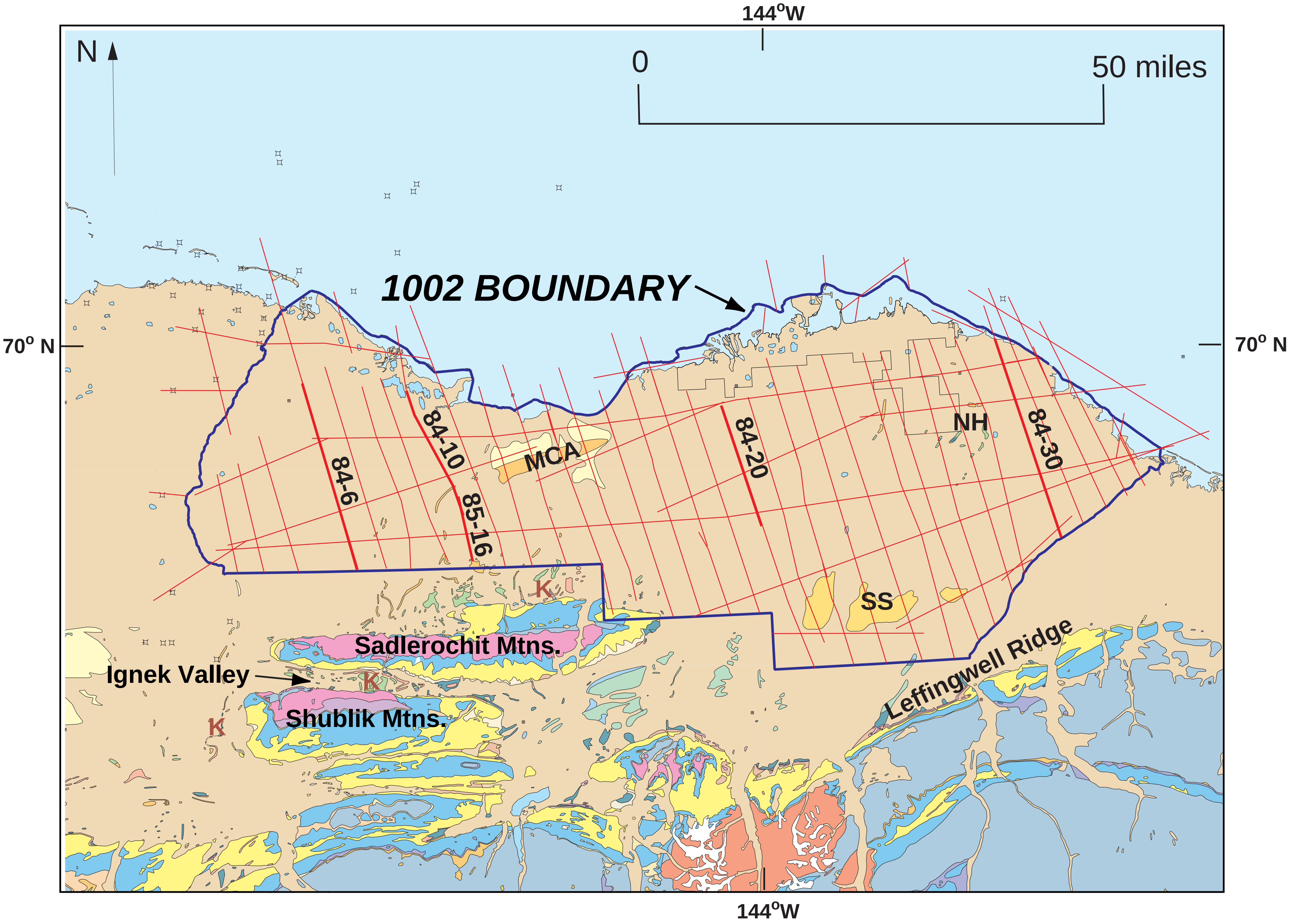

Figure BD1. Geologic map of the ANWR 1002 area and the surrounding region, based on Bader and Bird (1986). Map explanation for the geologic units is in Plate GG1. K, location of exposures of Kemik duplex. MCA, Marsh Creek anticline. NH, Niguanak high. SS, Sabbath syncline. Seismic lines are shown in red; seismic lines 84-6, 84-10/85-16, 84-20, 84-30 are interpreted in Plates BD1 through BD3, and in Fig. BD3.

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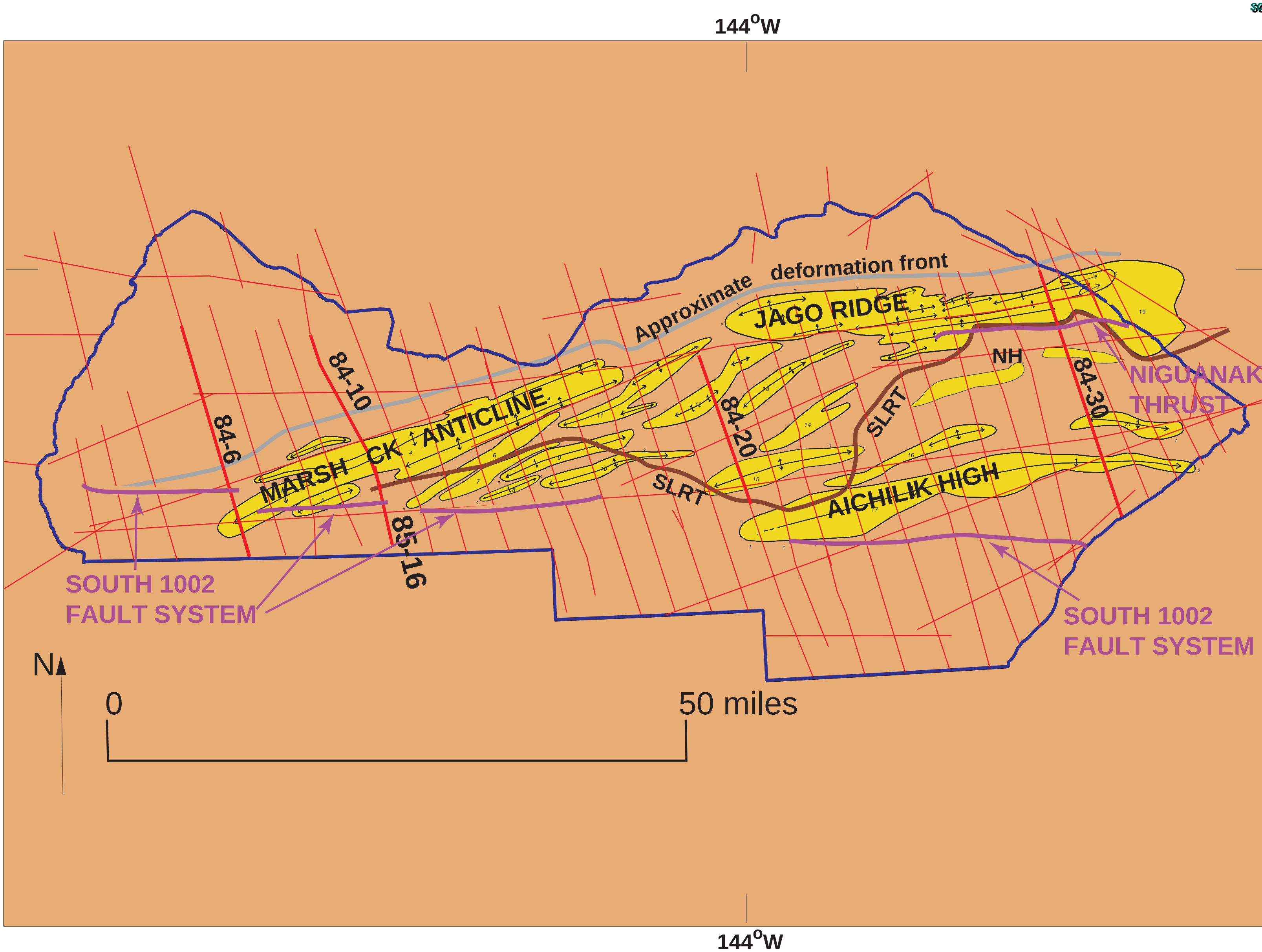

Figure BD2. Generalized map of the ANWR 1002 area showing structural culminations (in yellow) produced by thin-skinned thrusting. The large Marsh Creek and Jago ridge culminations are actually composite structures that contain many smaller culminations. Seismic lines are shown in red; seismic lines 84-6, 84-10, 84-20, 84-30 are interpreted in Plates BD1 through BD3, and in Fig. BD3. NH, Niguanak high. SLRT, southern limit of the (erosionally breached) roof thrust on the passive roof duplex in the eastern part of the area. Purple lines represent principal basement-cutting thrust faults (mapped at hanging-wall cutoff of the top of the pre-Mississippian basement).

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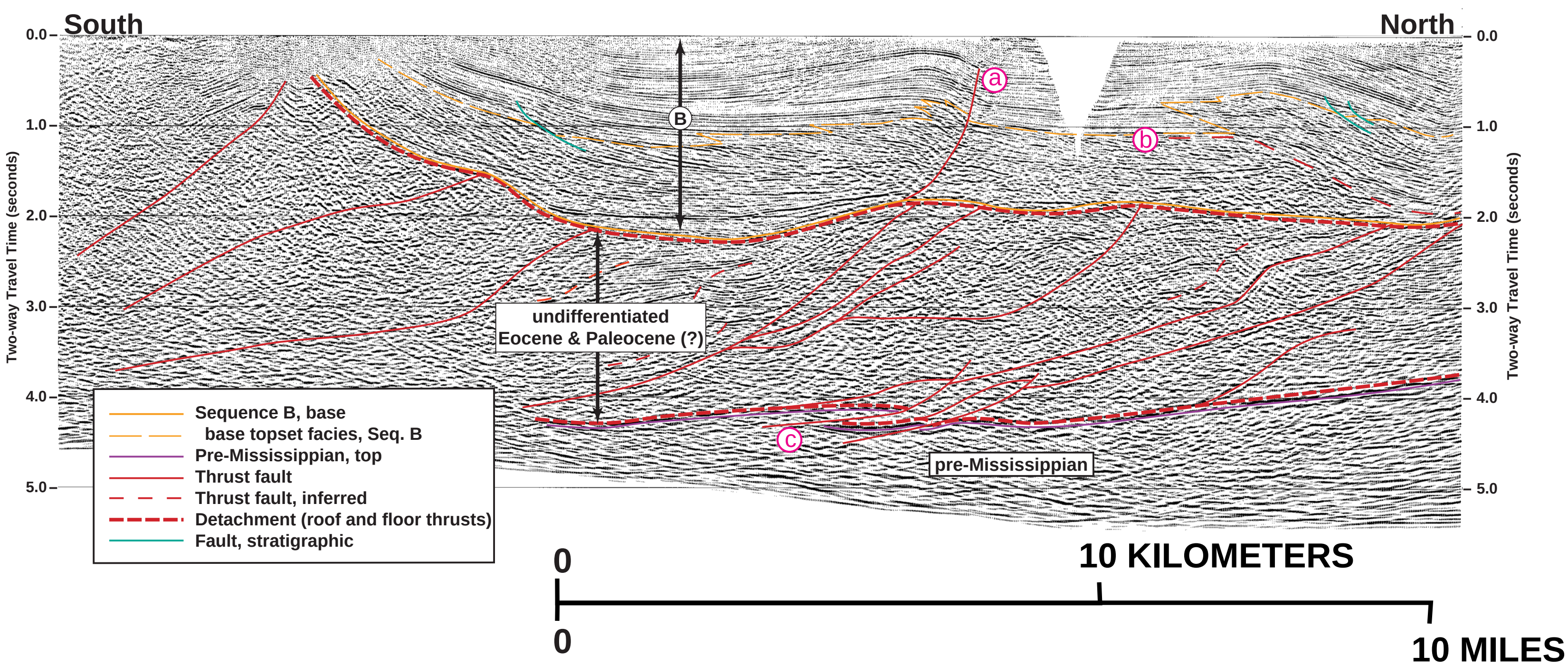
Figure BD3



North end, Seismic line 84-20

Figure BD3. Northern part of seismic line 84-20, showing thrust-duplex geometry in the central part of the 1002 area.

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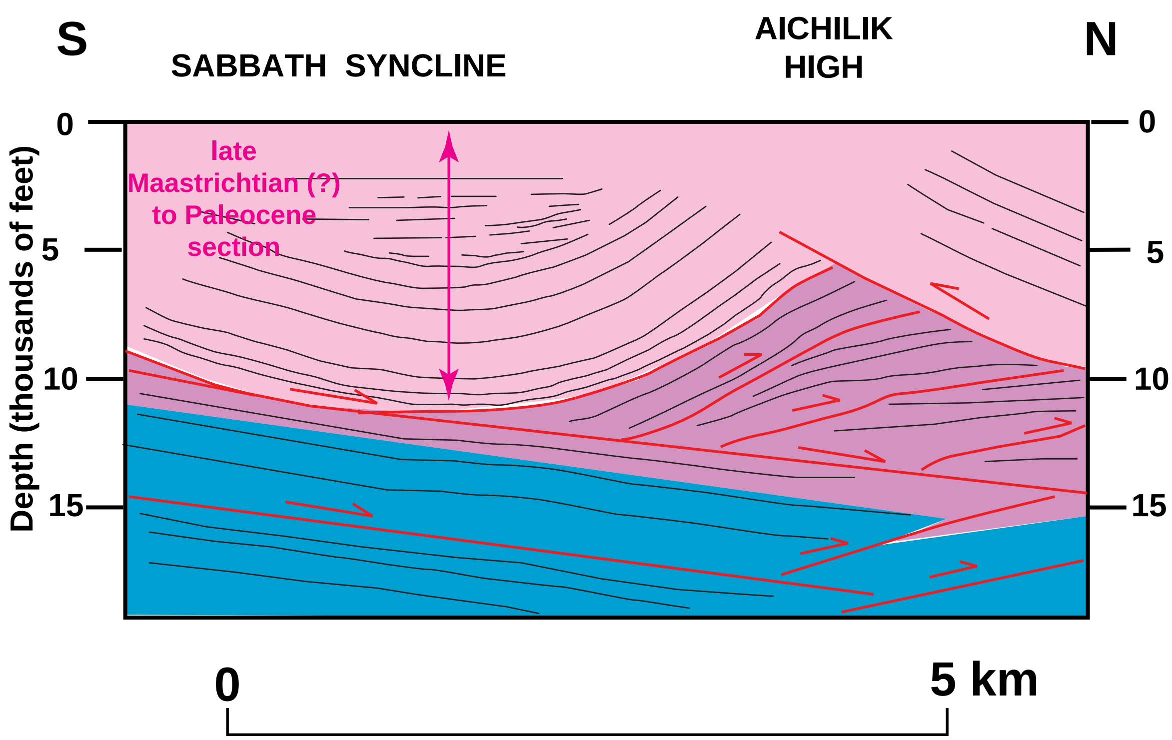

Figure BD4. Line drawing, based on seismic reflection data, showing detail of the structural and stratigraphic relations beneath the Aichilik high and the northern flank of the Sabbath syncline, demonstrating Paleocene growth of the Aichilik high. Lavender, Maastrichtian? to Paleocene section; Violet, Hue Shale and pebble shale; Blue, Hue Shale and pebble shale and upper part of Ellesmerian.

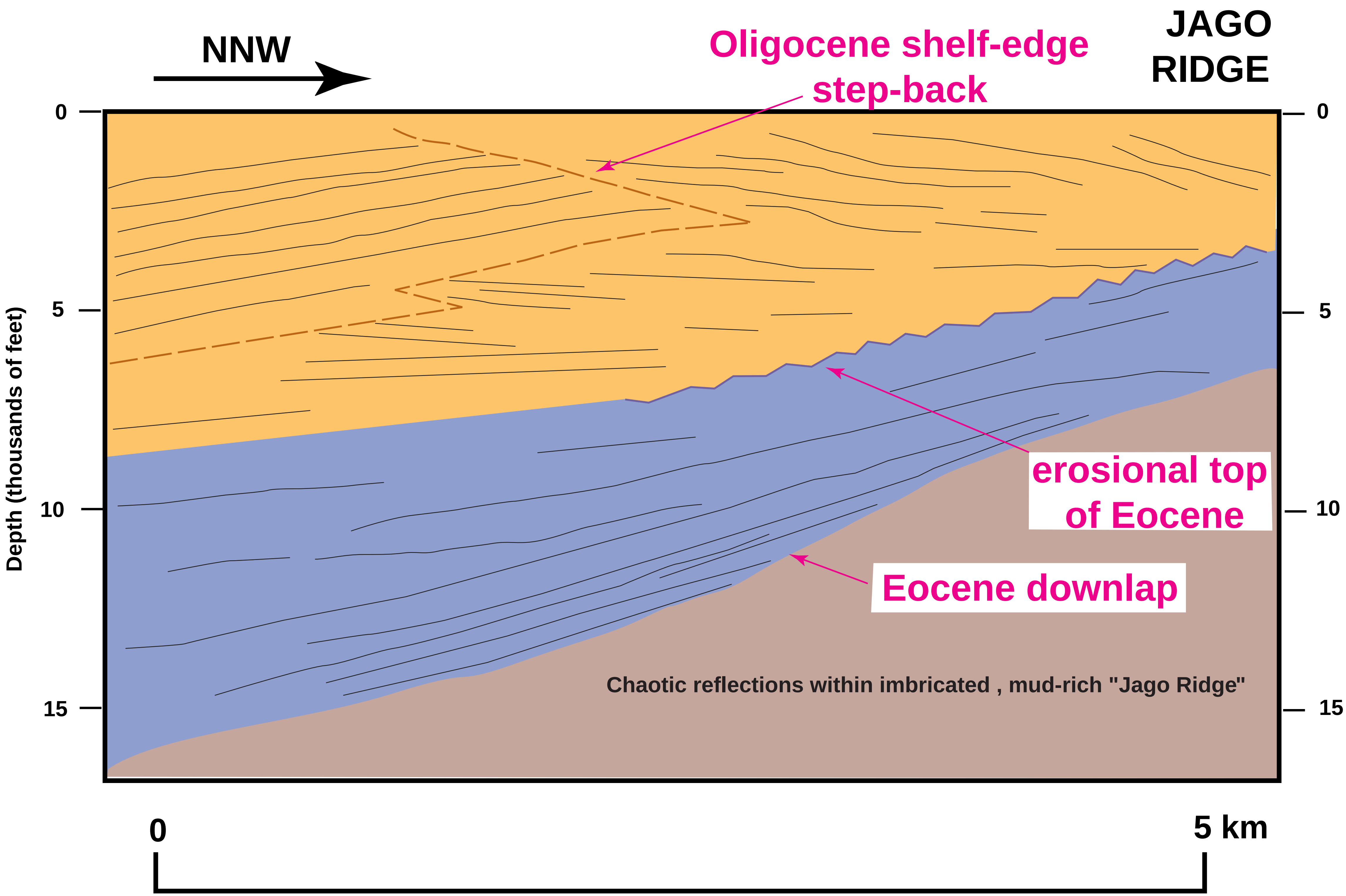

Figure BD5. Line drawing based on a short segment of seismic reflection data on the western margin of Jago ridge, showing Eocene downlap, an erosional surface at the top of the Eocene, an angular unconformity corresponding to the Oligocene "shelf-edge step-back," and Oligocene foresets prograding across the top of the Jago ridge.

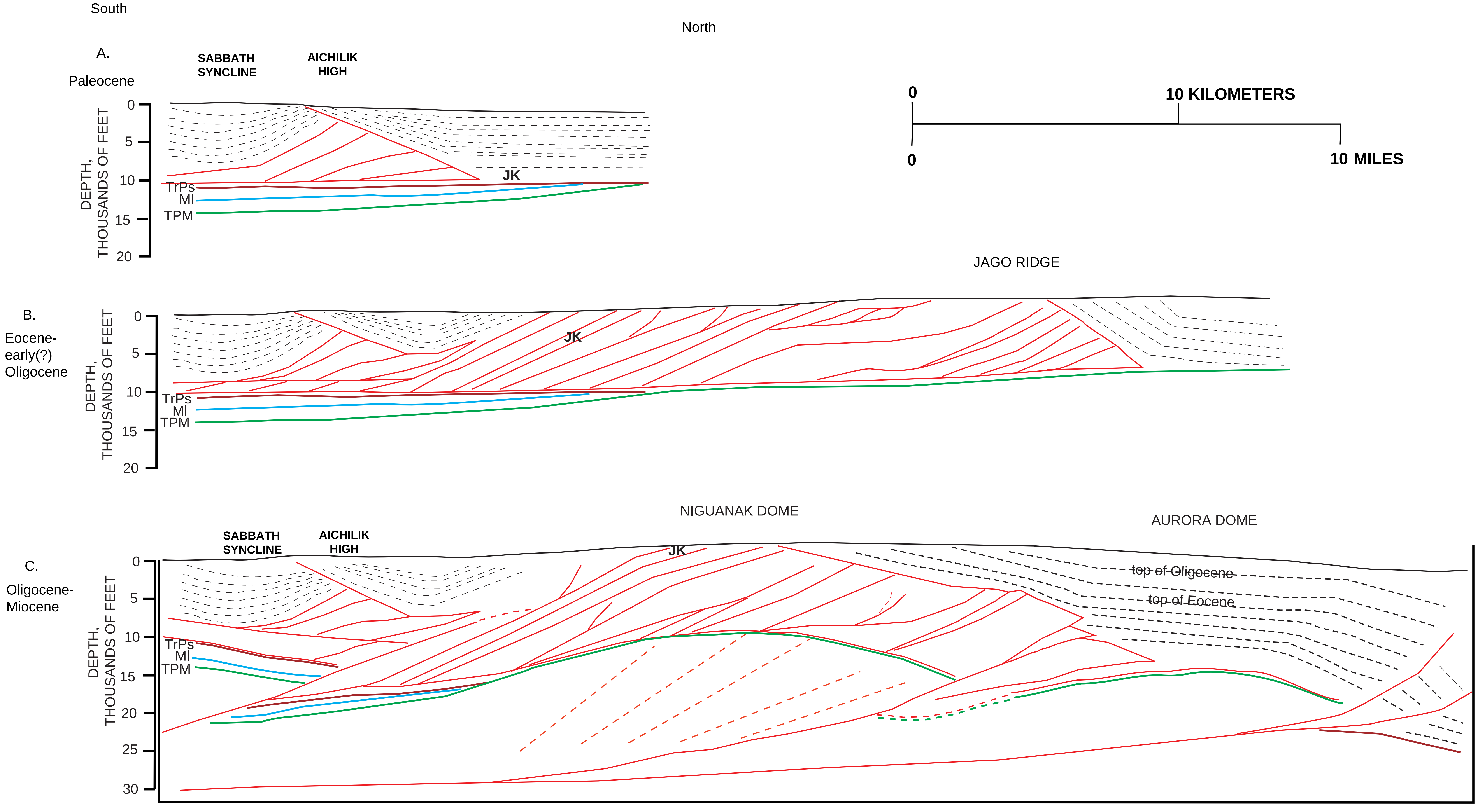

Figure BD6. Evolution of the structures along a north-south transect across the eastern part of 1002. TPM, top of pre-Mississippian; Ml, top of Lisburne Group; TrPs, top of Permian and Triassic Sadlerochit Group and Triassic Shublik Group.
(a) Paleocene frontal triangle zone (Aichilik high), with Sabbath syncline as a piggyback basin to the south; JK indicates Paleocene position of the Jurassic and Cretaceous shale units that are presently exposed near Niguanak Ridge.
(b) Eocene to Oligocene development of ramp-dominated thrust structure to the north of the Aichilik high, transporting strata equivalent to the Cretaceous Hue and Jurassic Kingak shales to shallow structural levels, and development of Jago Ridge frontal triangle zone.
(c) Oligocene to Miocene basement-involved thrusting and folding forming the Aurora dome, Niguanak dome, and the major basement thrust in southeastern 1002. Three basement-involved thrust ramps sole into a detachment near 30,000' in depth (Chapter NA). JK indicates position of the Jurassic and Cretaceous shale units that are presently exposed near Niguanak Ridge.

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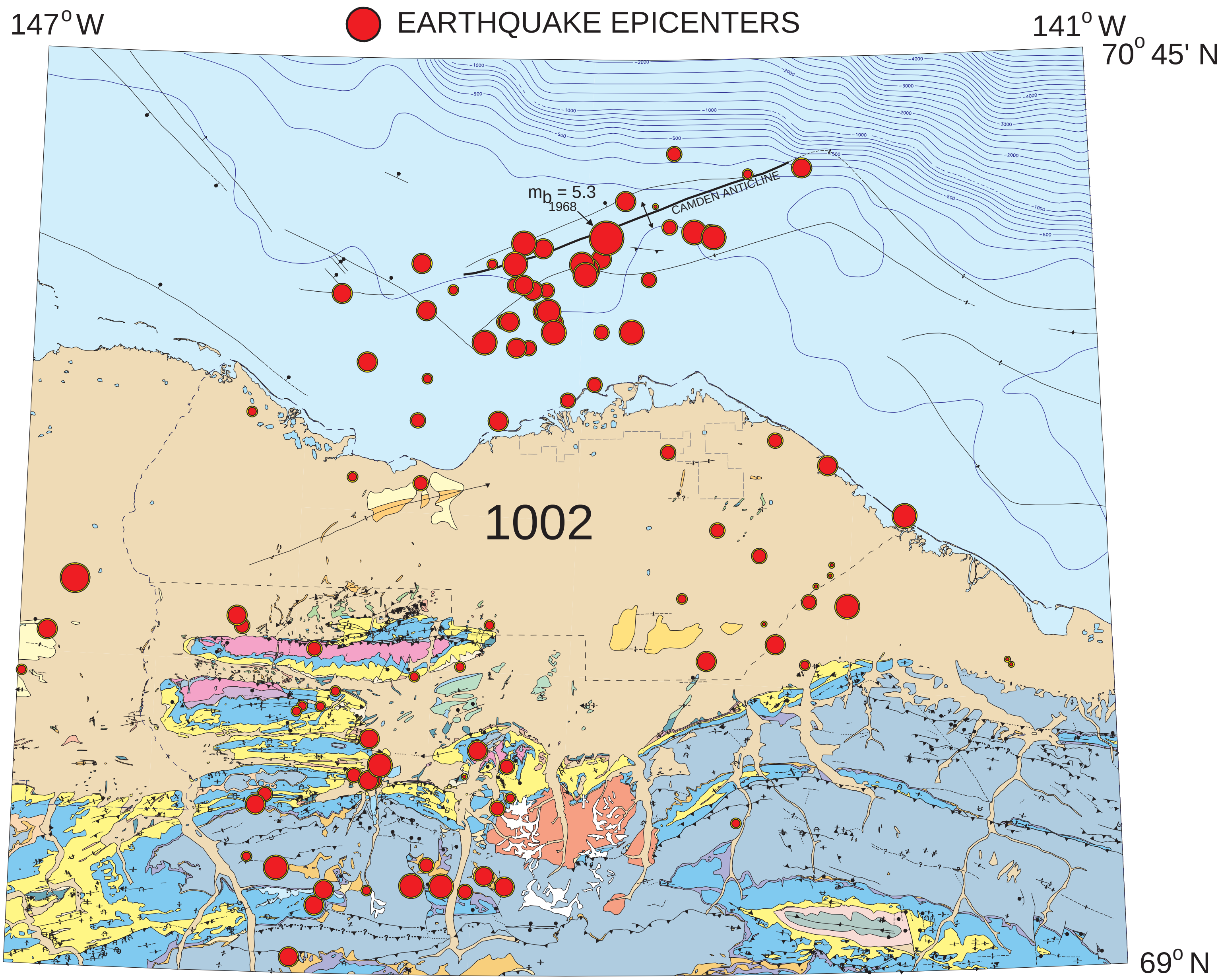

Figure BD7. Locations of 107 earthquakes detected by the Canadian Geological Survey and the U.S. Geological Survey in the vicinity of the 1002 area between 1966 and 1997. Red circles show locations of epicenters; size of circles indicates magnitudes (m_b) which range from 2.4 to 5.3. Their depths range from 10 to 33 km. 104 of the focal depths were between 10 and 20 km with 68 of these calculated assuming a depth of 18 km. No detailed studies of depths or focal mechanisms are available. These data were provided by Madeleine Zirbes of the U. S. Geological Survey's National Earthquake Information Center in Golden, Colorado. For geologic map explanation see Plate GG1. The location of the Camden anticline and other offshore structures is from Grantz and others (1987), who first noted the seismicity in the vicinity of the Camden anticline. The offshore bathymetry contours are in 100-foot intervals from sea level to a depth of 1000 feet and 200 foot-intervals below 1000 feet.

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Plate BD1

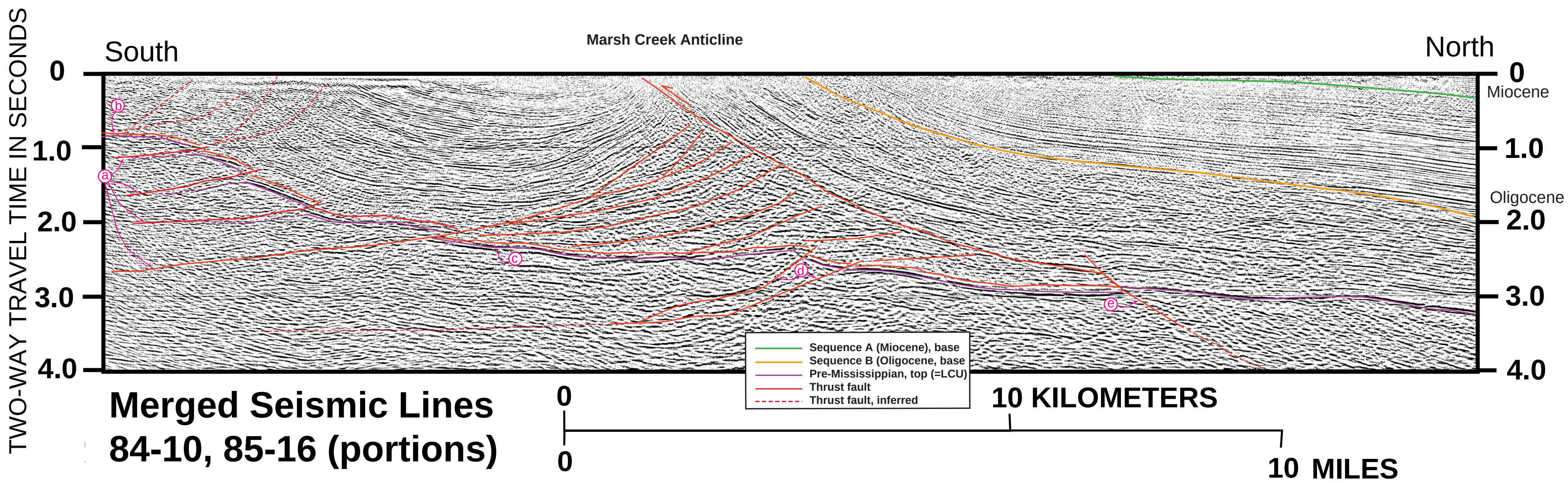

Plate BD1. Interpretation of merged seismic line 84-10 and 85-16, showing passive-roof duplex geometry. Because the Ellesmerian sequence has been erosionally truncated by the Lower Cretaceous unconformity (LCU) in this part of the 1002 area, the top of the pre-Mississippian is coincident with the LCU. See text for details. Miocene and Oligocene sequences at north end of seismic line are based on seismic reflection tie to West Staines State 2.

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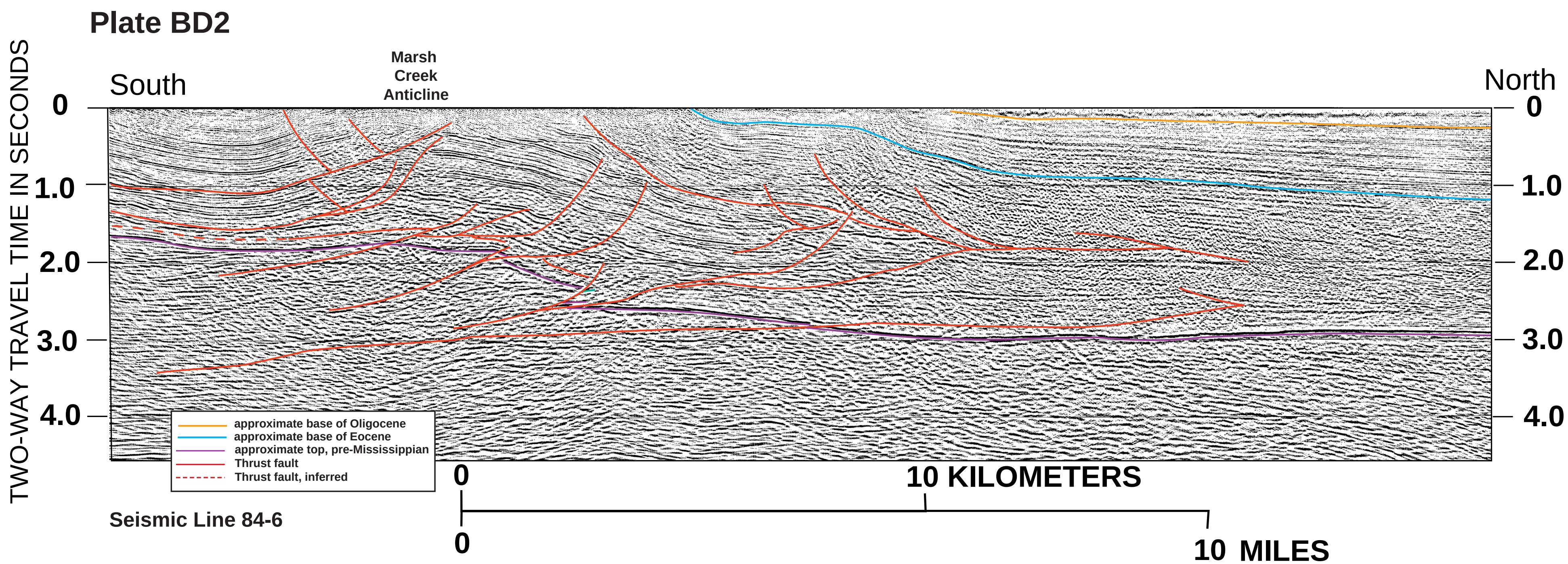

Plate BD2. Part of seismic line 84-6, showing superposition of the thin-skinned Marsh Creek anticline above the principal basement-involved reverse fault, at the point where these two trends (Marsh Creek anticline and basement-involved thrusting) intersect.

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Plate BD3

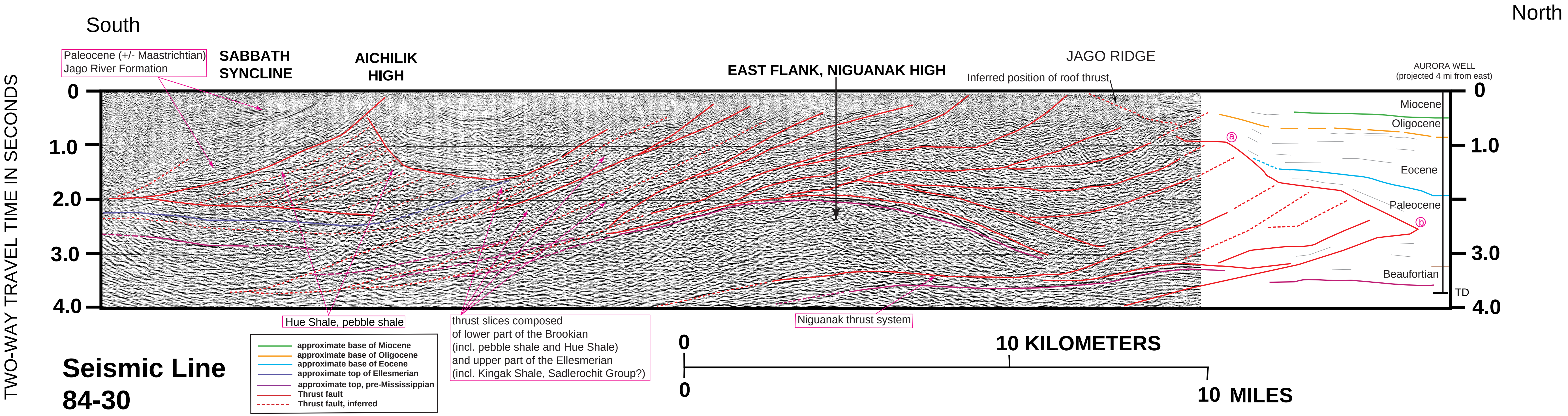

Plate BD3. Seismic line 84-30, illustrating the structure across the Sabbath syncline, Aichilik high, eastern flank of the Niguanak high, and onto the Aurora dome, with ties to the Aurora 1 well. See text for details.