CHAPTER NA (Niguanak and Aurora Structures)

STRUCTURAL FRAMEWORK AND LITHOLOGIC COMPOSITION OF THE NIGUANAK HIGH AND THE AURORA DOME

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FIGURES

[Figures NA2-NA5 and NA6-NA9 have two parts. Part a shows the seismic profile with interpretive overlay, part b is without the interpretive overlay.]

ABSTRACT

The Aurora dome and Niguanak high in the northeastern 1002 area are the largest structural prospects mapped in the ANWR seismic surveys. The north-verging Niguanak thrust system underlies the Niguanak high, separating it from the Aurora dome. Seismic reflection profiles suggest that both the Aurora dome and Niguanak high structures are imbricate thrust stacks, primarily composed of Franklinian rocks, and that a deeper-level detachment underlies the Aurora dome and extends beneath the outer continental shelf.

The seismic velocities derived during the reprocessing of the ANWR profiles and the gravity modeling indicate that the rocks composing the Niguanak high and Aurora dome have relatively high velocities and high densities. Seismic reflection profiles indicate that the Beaufortian rift sequence penetrated in the Aurora 1 well is restricted to the east flank of the Aurora dome. The Ellesmerian sequence may be present on the southeastern flank of the Niguanak high, however, the possibility of the Ellesmerian sequence extending to any part of the Aurora dome is very low. The Franklinian sequence, especially massive carbonates such as the Katakturak dolomite, and/or Devonian clastic rocks are likely to predominate within the Niguanak high.

INTRODUCTION

The Niguanak high and the Aurora dome are large structures in the northeastern part of the 1002 area (Fig. NA1) which 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). These highs were prospect 18 (previously referred to as the Tapkaurak high by Foland and Lalla, 1987, Plate 3; herein referred to as the Aurora dome because of the subsequent drilling of the Aurora 1 well) and prospect 19 (Niguanak high), which had estimated areas of 227,000 and 130,000 acres, respectively (Table 23.1 of Callahan and others, 1987). For that assessment, the crests of these highs were estmated at approximately 13,500 and 9,800 feet, respectively, and the lowest closing contours were 24,000 and 17,000 feet, respectively. Most of the Aurora dome underlies the lands of the Kaktovik Inupiat Corporation (KIC), Alaskan State waters, and offshore Federal waters, while most of the

Niguanak high underlies the onshore Federal part of the 1002 area (Molenaar, 1987; Fig. 1.1).

The KIC 1 exploration well on the Aurora dome (Fig. NA1) was drilled by Chevron USA Inc. in KIC lands on the southeast flank of the Aurora dome prior to the 1987 assessment of the 1002 area, but all of the information from that well remains proprietary and unavailable for this assessment. The Aurora 1 well was drilled after the previous assessment on the east flank of the Aurora dome in Federal waters in the winter of 1987-88, approximately 6 miles northeast of the KIC 1 well. It was drilled by the Tenneco Oil Company to a depth of 18,325 feet, and information from that well has been released to the public (Paul and others, 1994). Although it had some shows of oil and gas, the well was plugged and abandoned, and its Federal offshore lease has been relinquished.

In this chapter, the information from the Aurora 1 well is tied to the seismic reflection profiles in the eastern the part of the 1002 area, and we will review its impact on our understanding of the structural framework and lithologic composition of the Niguanak high and Aurora dome. Finally, we will discuss the implications of these new data and interpretations for the current oil and gas assessment.

Details of seismic acquisition over the 1002 area by the industry consortium are given by Foland and Lalla (1987). The processing of the seismic data used in this chapter is described by Lee and others (Chap. SP).

STRUCTURAL FRAMEWORK AND MAJOR FAULT SYSTEMS

During the current oil and gas assessment, prospect maps were prepared for the top of the Franklinian sequence (or top of the pre-Mississippian, the TPM) (Fig. AO5) within the undeformed Franklinian (Chap. P6), deformed Franklinian (Chap. P7), and the Niguanak/Aurora plays (Chap. P10). The seismic reflection off the top of the pre-Mississippian metasedimentary basement rocks is generally the strongest reflection event on the seismic profiles and is a mappable seismic horizon over more than 80 percent of the 1002 area. A prospect map was also required for the top of the Ellesmerian sequence in order to map prospects for the Ellesmerian play. An isopach map for the Ellesmerian sequence was prepared to show the distribution of this sequence, which was limited to the western and southern parts of 1002. The mapped prospects provided a minimum number for estimating the total population and size of possible prospects for each play because the seismic grid spacing was approximately 3 x 6 miles and smaller prospects could be missed in this survey.

A structural framework map (1:500,000 scale) of the TPM, based on the seismic lines published in USGS Bulletin 1778 (Bird and Magoon, 1987), has been prepared to illustrate the regional structural and tectonic framework of the 1002 area (Fig. NA1) which shows the depth to the TPM below sea level with a smoothed color shading. Nevertheless, this smoothed map delineates the major structural highs and lows formed during the thrusting and folding of the Franklinian sequence. The general location of the Niguanak high (NH) and the Aurora dome (AD) can also be seen in the northeastern part of the 1002 area.

For the assessment, interpretations for TPM and the upper part of the Ellesmerian sequence were made for all ANWR seismic profiles where reliable horizons could be mapped. In practice, the highest mappable part of the Ellesmerian on the seismic profiles was the Sadlerochit Group and Shublik Formation (Fig. AO5), where alternating sand and shale units generate a band of high amplitude reflections. The overlying Kingak Shale and Lower Cretaceous units are generally either too thin to resolve on the seismic profiles or are involved in complex thin-skinned imbricate thrusting which appears as transparent zones above the band of Sadlerochit and Shublik reflections in the eastern part of the 1002 area.

The seismic grid spacing determines the smallest size exploration prospect that can be mapped with any seismic survey. For instance, if the seismic survey was at a 1 x 1 mile grid interval, 1/2-mile sampling should resolve all features of a 1-mile diameter or larger. Since the actual seismic grid was closer to 3 x 6 miles (Foland and Lalla, 1987; Fig. 17.1; Potter and others, 1998; Fig. BD1) and, in practice, our sampling interval was 1 mile, only features larger than 2 miles in diameter (~3 square miles or ~2000 acres in size) could be resolved along the present seismic profiles. If it is assumed that a two-dimensional seismic profile can actually detect side echoes out to 1/2 mile on either side of the profile, 2 x 4 mile rectangular features could go undetected with a 3 x 6 mile grid. Therefore, exploration prospects of 8 square miles (5,000 acres) could be missed with this 3 x 6 mile seismic survey. In fact, the ANWR seismic grid is not at a uniform 3 x 6 mile spacing and has one data gap in the northwestern part of the 1002 area which is approximately 8 x 8 miles in dimension. Even if it were assumed that a two-dimensional seismic profile could detect side echoes out to 1 mile on either side of the profile, a 6 x 6 mile feature (36 square miles or 22,500 acres) could escape detection in that area. For the oil and gas plays in this assessment, prospects smaller than 2,000 acres were found to have very little chance of making an oil accumulation of 50 million barrels. In this oil and gas assessment, it was assumed that prospects between 2,000 and 20,000 acres in size were missed by the ANWR seismic grid. Therefore, the estimates for the total number of prospects in an assessed play was sometimes 2 to 4 times the number of prospects actually mapped, with the increases almost exclusively in the 2,000 to 20,000 acre range.

Approximately 1500 velocity analyses were derived during the reprocessing of all the ANWR lines (Lee and others, Chap. SP; Fig. SP11). The stacking velocities were smoothed in 250 msec time intervals and in 300 shot point intervals to prepare tables of average velocity to time values. The average velocity to the TPM was also mapped to generate a velocity grid for converting the reflection times into depths. The average velocity values to the TPM had an extremely large range within the 1002 area, from 9,200 ft/sec in the north to 16,100 ft/sec in the southeast (Fig. SP11

The 1:500,000 scale version of the TPM map in Figure NA1 was prepared by sampling the reflection time to the TPM at a 5,500 ft interval (50 shot points) along the seismic lines released in USGS Bulletin 1778 and then gridding these data at a spacing of approximately 2.5 miles (4,000 m). This gridding interval allows resolution of features with a length of 5 miles or larger.

Structural relief on the top of the pre-Mississippian (TPM)

The shallowest TPM in the 1002 area is 4,000 feet below sea level along the southern border immediately north of the Sadlerochit Mountains, while the deepest TPM in the 1002 area is over 31,000 feet below sea level in the Hulahula Low (HHL, Fig. NA1). With parts of the eastern Sadlerochit Mountains more than 4,000 feet above sea level, the total relief on the TPM between the mountains and the HHL is over 35,000 feet in a horizontal distance of only approximately 20 miles. In the northwestern part of the 1002 area, the TPM on the Barrow Arch (BA) is less than 14,000 feet below sea level and is plunging to the east-southeast. Just southwest of the 1002 area, in the deepest part of the Colville Basin (CLVB), the TPM is more than 19,000 feet below sea level. Between the south-eastward extension of the BA and the subsurface northern extension of the Sadlerochit Mountains, a saddle at 16,000-17,000 feet below sea level separates the Barrow arch from the Sadlerochit high. In the eastern 1002 area, the TPM rises from the Hulahula low to less than 9,000 feet below sea level to form the Niguanak high, with the Aurora dome forming a secondary high about 15,000 feet below sea level to the north. Grantz and others (1987, 1990) have described the Demarcation Subbasin (DSB) and the Barter Subbasin (BSB) in the Beaufort Sea north of the 1002 area that lie southeast and northwest of the Aurora dome, respectively, beneath the continental shelf. Seismic activity beneath the outer continental shelf near the Camden Anticline on the north side of the Barter Subbasin (north of Fig. NA1) indicates that the modern locus of deformation lies offshore (Grantz and others, 1987, 1990; Potter and others, Chap. BD, Fig. BD7).

In the southeastern 1002 area, an east-plunging anticline on the TPM reaches a depth approximately 19,000 feet below sea level and is the eastward extension of the Sadlerochit Mountains (Fig. NA1). South of the southwestern part of the 1002 area, several exploration wells have tested the west plunging nose of Sadlerochit Mountains where gas discoveries have been made at the Kavik gas field (see Kavik 1 well southwest of the 1002 area, Fig. NA1) and the Kemik gas field, which is about 20 miles southwest of Kavik 1 well.

The Aurora dome and Niguanak high in the northeastern 1002 area are the largest structural prospects mapped in the ANWR seismic surveys. The north-verging Niguanak thrust system underlies the Niguanak high, separating it from the Aurora dome (Foland and Lalla, 1987; Bruns and others, 1987). Seismic reflection profiles discussed later in this chapter (as well as Potter and others, Chap. BD) suggest that both the Aurora dome and Niguanak high structures are imbricate thrust stacks, primarily composed of Franklinian rocks, and that a deeper-level detachment underlies the Aurora dome and extends beneath the outer continental shelf.

Above 16,800 feet below sea level, the Niguanak high and Aurora dome separate into two discrete highs with crests at 8,800 and 14,800 feet below sea level, respectively. The dimensions of the two highs above 16,800 feet are 11 x 21 and 9 x 23 miles (118,000 and 103,000 acres), respectively. Below 16,800 feet, however, these two features merge into a single closed structure that continues to 19,000 feet below sea level. The dimensions of the two prospects down to 19,000 feet are 15 x 25 and 16 x 32 miles

(195,000 and 257,000 acres), respectively. The total area of the combined high above 19,000 feet below sea level is approximately 450,000 acres. Although the combined area estimate for these two highs by Callahan and others (Table 23.1;1987) was approximately 360,000 acres, both estimates have large uncertainties mainly caused by projection of the highs into the KIC lands along with State and Federal waters, where the seismic profiles were either short, unconnected pieces, or unavailable for this assessment. Because of their uniquely large size and heights of closure, the Aurora dome and Niguanak high were considered to be the most attractive oil and gas prospects in the previous assessment. In the current assessment, the Niguanak/Aurora Play (Chap. P10) again deals with these large prospects.

Major fault systems in and around the 1002 area

The major faults offsetting the TPM are dominated by north-verging thrust faults with numerous small-scale backthrusts (Fig. NA1). Because of the 3 x 6 mile seismic line spacing, the mapping of the smaller fault trends is very difficult and more than one interpretation is frequently possible. The faults depicted in Figure NA1 represent the medium and larger fault trends. Although this fault map is in general agreement with the maps presented in Bulletin 1778 (Fig. 19.3, Bruns and others, 1987; and Plate 3, Foland and Lalla, 1987), there are a number of subtle differences. An alternative map interpretation is also given by Kelley (Chap. BR) where some of the smaller and intermediate size faults are shown differently than those presented in Figure NA1. Because of uncertainties inherent in the 3 x 6 mile grid and limitations for detail in a 1:500,000 scale map, the faults in Figure NA1 are schematic and do not attempt to accurately show smaller scale features or prospects.

In the western part of the 1002 area, where the Brookian thin-skinned compressional deformation is minimal, the seismic profiles show fairly strong reflections from within the Franklinian metasedimentary rocks; these include south-dipping reflections in the southwestern 1002 area and north-dipping reflections in the northwestern 1002 area (Fisher and Bruns, 1987). The reflections in the northwestern 1002 area form an antiform within the Franklinian. Kelley (Chap. BR) has noted that the fabrics within the Franklinian in the north-central 1002 area actually dip more towards the north-northeast rather than due north as implied by Fisher and Bruns (1987). Dip symbols with approximate dip angles for the fabrics within the Franklinian are also summarized in Figure NA1. Kelley has suggested that

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Brookian offsets of the TPM occur frequently along the fabric within the Franklinian, and that some of the Brookian faults are probably reactivated pre-Mississippian faults.

A zone of east-west, north-verging thrust faults crossing the entire width of the southern 1002 area will hereafter be referred to as the "south 1002 fault system." The fault system is distributed over a 4 to 6 mile zone in the west. In the south-central 1002 area, near the AN 84-14 seismic line, the fault system is narrow and steep with approximately 8,000 feet of relief over a two-mile wide zone (Fig. NA1). In the southeastern 1002 area, the eastern end of the Sadlerochit Mountain forms a plunging anticline while the main hanging-wall of the fault system becomes a monocline dipping approximately 30° to the north. Here the fault system appears to form the boundary between the southeastern part of the Hulahula Low and the monocline. In the most southeastern part of the 1002 area, the fault system is steeper again at the south end of seismic line AN 85-50, appearing to pass eastward out of the 1002 area.

A zone of north-verging thrusts along the northern flank of the Niguanak High will hereafter be referred to as the Niguanak thrust system. Again the 3 x 6 mile grid does not permit detailed mapping of all the faults, but an imbricated stack of thrust sheets appears to form both the Niguanak High and the Aurora Dome (see additional discussion below). An arcuate detachment fault around the north flank of the Aurora Dome is inferred from the seismicity offshore (Potter and others, Chap. BD; Fig. BD7), although the ANWR seismic surveys did not go far enough to the north of the Aurora Dome to demonstrate this interpretation unequivocally.

AURORA DOME AND AURORA WELL

The Aurora 1 well was drilled offshore on the east flank of the Aurora dome, approximately 6 miles east-northeast of the onshore KIC 1 well (no data released to date). The stratigraphic section encountered in the Aurora well included 15,480 feet of Tertiary sedimentary rocks overlying 2,845 feet of Middle Jurassic through Lower Cretaceous clastic sedimentary rocks, the latter of which have been interpreted as Beaufortian rift deposits associated with the opening of the Canadian Basin and the subsidence of the continental margin along northern Alaska (Paul and others, 1994; Poag, Chap. BI, Plate BI1 and BI2; Bird, Chap. GG, Fig. GG3). The Jurassic strata included approximately 850 feet of Kingak Shale equivalent. The Lower

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Cretaceous strata include, in ascending order, approximately 860 additional feet of Kingak Shale equivalent, 170 feet of Kuparuk sand, 510 feet of Pebble shale, and 450 feet of Hue Shale (Nelson and others, Chap. WL, Plate WL8). The Lower Cretaceous Unconformity (LCU) separates the pebble and Hue shales. The Tertiary strata include 8,120 feet of Paleocene rocks, 4,810 feet of Eocene rocks, 900 feet of Oligocene rocks, and 1,380 feet of Miocene rocks.

Seismic profile AN 84-30 (Fig. NA2) trends south-southwest across the east flank of the Aurora dome (Fig. NA1). The north end of profile AN 84-30 lies 4 miles south-southwest of the Aurora well. The basal Tertiary unconformity (herein referred to as the BTU) separates the Paleocene from the Lower Cretaceous at a depth of 15,480 feet in the Aurora well, and is a strong sub-horizontal seismic event with a reflection time of about 3.15 sec near the well and at the north end of AN 84-30. In theory, the LCU should be about 70 msec below the BTU, but the frequency content of the reflection returns from this depth are too low to separate these two events. Although the profile does not go far enough to the north to observe the north flank of the Aurora dome, the south flank of the dome and the Niguanak high are clearly observed. The BTU is somewhat discontinuous, but appears to be depressed down to about 2.7 sec (~22,000 feet below sea level) beneath the leading edge of the Niguanak thrust. The tops of the Paleocene and Eocene intervals are at 7,360 and 2,550 feet in the Aurora well, respectively (1.65 and 0.70 sec at the north end of AN 84-30). Potter and others (Chap. BD; Plate BD3) suggest that a tapering thrust wedge has been driven northward into the Paleocene strata (i.e., a passive-roof duplex) and has gently tilted the upper Paleocene and Eocene strata within the Aurora dome. The relatively undisturbed Paleocene and Eocene strata near the well were gently tilted during the Oligocene or later, while the shallow thin-skinned deformation in the Jago ridge (above the Niguanak high) appears to have begun to grow before the end of the Eocene (Potter and others, Chap. BD).

The BTU is the strongest seismic reflection event on the east flank of the Aurora dome (Fig. NA2). There are also a number of strong reflection horizons in the Paleocene. The Mesozoic strata, which occurs between 3.15 and 3.60 seconds on the seismic reflection profiles near the Aurora well, have a weak to moderate seismic reflection response. Below 18,325 feet or 3.60 seconds in the reflection profiles, the seismic reflection response decays gradually without any strong, continuous reflection events. In the 1987 USGS oil and gas assessment, the BTU seismic reflection event at 3.15

seconds in the vicinity of the Aurora well was interpreted as the top of the pre-Mississippian Franklinian sequence, as well as the top of the entire Aurora dome (prospect 18).

The subhorizontal reflections between 3.15 and 3.60 sec at the north end of AN 84-30 (Fig. NA2) correlate with the Beaufortian Jurassic and Lower Cretaceous clastic sedimentary rocks drilled at the Aurora well (15,480 to 18,325 feet below sea level). Beneath the strong 3.60 sec reflection at the north end of AN 84-30, discontinuous sub-horizontal seismic reflection horizons are observed (and also are seen on other seismic lines near the Aurora well) down to more than 4.2 sec (~23,000 feet below sea level) without any strong terminal event signaling the top of the Ellesmerian or Franklinian sequences. Moving south along AN84-30, the BTU again descends to about 3.6 sec beneath the leading edge of the Niguanak thrust sheet(s). Beneath and sub-parallel to the BTU, there are another 0.5 sec (~3,000 feet) of discontinuous reflection events on this profile with slightly weaker seismic events decaying gradually at greater depth. Although the reflection data below the BTU are discontinuous on AN 84-30, other profiles on the east flank of the Aurora dome also suggest that the Beaufortian section dips south and does not change thickness appreciably before being overridden by the thrust sheet(s) forming the Niguanak high. Since the Aurora well did not penetrate through the base of the Beaufortian rift sequence and the seismic profiles do not delineate a base for this sequence, it is uncertain how thick the Beaufortian section is or what underlies it.

While Beaufortian sediments intersected in the Aurora 1 well and observed on the north end of line AN 84-30 (Fig. NA2) indicate a thickness of Beaufortian section of 3,000 feet or more on the southeast flank of the Aurora dome, other seismic lines over the east flank of the Aurora dome, which remain proprietary, suggest that Beaufortian rocks thin westward and may pinch out before reaching the crest of the Aurora dome. Seismic reflection velocities (see section below) and densities inferred from gravity modeling (Saltus and others; Chap. GR) for the rocks beneath the strong reflection event which defines the top of the Aurora dome are considerably higher than the Beaufortian section in the Aurora well. Therefore, higher density and higher velocity rocks such as the Franklinian and/or Ellesmerian sequences appear to be the dominant lithology within the Aurora dome. Therefore, the Beaufortian rocks penetrated in the Aurora well and observed on the AN84-30 seismic profile may be restricted to the east flank of the dome and are not the dominant lithology within it.

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The north ends of the other seismic profiles and one east-west profile over the south flank of the Aurora dome (all of which remain proprietary), suggest that the Aurora dome below the TPM is composed of multiple north-verging thrust sheets. The apparent dip of faults on east-west profiles is dominantly eastward. The deepest of the detachment zones visible on any of the seismic lines intersects the TPM low on the west flank of the Aurora dome, where it meets the north edge of the Hulahula low (~ 23,000 feet below sea level). This deep detachment surface has apparent east dip and is more than 35,000 feet deep beneath the east flank of the Aurora dome, i.e. a large scale lateral ramp in an east-west section. This deeper level detachment is inferred to extend northward under the Aurora dome and is referred to as the Aurora thrust system in Figures NA1 and NA2a. The seismic character above this deep detachment and the upper surface of the Aurora dome suggested complex folding and thrusting of sedimentary rocks.

Gravity models over the Aurora dome and Niguanak high indicate that these two highs are composed of rocks having densities averaging more than 2.7 g/cc (Saltus and others, Chap. GR). Seismic velocities derived during reprocessing the seismic lines over these two highs indicate that the average velocities of the rock units within the highs are approximately 16,500 feet/sec (Lee and others, Chap. SP; see further discussion below). These density and velocity data are higher than the values measured by well logs for the Beaufortian rocks in the Aurora well and, therefore, suggest that the Beaufortian sequence is not a dominant lithology in either the Aurora dome or Niguanak high. The velocity and density data are more compatible with the Franklinian sequence or older sedimentary rocks such as the Ellesmerian sequence or the Devonian clastic rocks than with the Beaufortian sequence.

In seismic profiles over the Aurora dome and Niguanak high, their upper surface was provisionally mapped as the TPM. This surface merges gradually with the well-defined TPM mapped in the western and central part of the 1002 area along the eastern edge of the Hulahula low (Fig. NA1). This provisional TPM and the BTU appear coincident over the Aurora dome. The velocity and density data preclude the Beaufortian sequence as a dominant lithology within the dome, and the Ellesmerian sequence appears to pinch out south of the Niguanak high. Although the compositions of the Aurora dome and Niguanak high are not known with certainty, the Franklinian sequence and/or pre-Mississippian rocks are the most likely candidates. Therefore, for convenience, the upper surfaces of the Aurora dome and Niguanak high are referred to as the TPM in the following discussions in spite of the uncertainties concerning the actual lithologies beneath this surface.

In summary, the evidence is contradictory concerning which of the lithologic units underlies this "TPM" within the Aurora dome and Niguanak high. Although the density and velocity data appear more persuasive in favor of the Franklinian rocks, there is sufficient uncertainty with all these methods that further research is warranted. A more detailed review of the velocity and density data will be made later in this chapter.

NIGUANAK HIGH

Similar to the Aurora dome, the Niguanak high appears as an elongate east-west feature on the structural framework map of the top of the pre-Mississippian metasedimentary rocks (Fig. NA1). The entire Niguanak high is approximately 15 miles in its north-south dimension and 25 miles in its east-west direction at approximately 19,000 feet below sea level. From its crest at 8,800 feet below sea level down to 16,800 feet, it is clearly separated from the Aurora dome, as discussed above. Deeper than 16,800 feet, the Aurora dome and Niguanak high merge into a composite, northwest-trending ridge with closure down to 19,000 feet below sea level. The combined area of both the Niguanak high and Aurora dome is approximately 450,000 acres.

Jurassic and Cretaceous shales outcrop at the surface in the Niguanak Ridge area in the northeastern part of the 1002 area (Bader and Bird, 1987). These shales were involved in the thin-skinned Brookian thrust system and were detached and transported from south of the Niguanak high (Chap. BD). These rocks exposed at the surface in Niguanak Ridge happen to overlie, but are separate from, the deeper Niguanak high which is more broadly folded and thrusted. The rocks underlying the Niguanak high are probably dominantly Franklinian, but subsidiary components of Beaufortian rocks are also likely as well as other possible lithologies. Kelley (Chap. BR) has also suggested that Devonian clastic rocks are a dominant or significant lithology underlying both the Aurora dome and Niguanak high. Ellesmerian rocks, based on evidence discussed in a subsequent section of this chapter, are unlikely to be a significant component of the rocks underlying the Niguanak high.

The AN 84-30 seismic profile, which was discussed in the previous section on the Aurora well, also crosses the east flank of the Niguanak high where the TPM is approximately 12,000 feet below sea level (Fig. NA1 and NA2). The AN 85-50 north-south seismic profile crosses the crest of the Niguanak high where it is shallower than 10,000 feet below sea level (Fig. NA3). The shallowest TPM observed on the seismic profiles over the crest of the Niguanak high was 8,800 feet below sea level. These two north-south profiles over the Niguanak high give the impression that the high is a simple, asymmetric fold overlying the low-angle north verging Niguanak thrust system. Other north-south profiles suggest a more complex feature composed of a stack of several imbricated thrusts.

Seismic profile AN 85-1 is an east-west section across the Niguanak high (Fig. NA4). The TPM rises from below 3.0 sec in the west to 1.6 sec near the crest of the Niguanak high and then drops down to more than 4.0 sec deep in the Demarcation sub-basin on the east. Although the AN85-1 profile does not go far enough to the west to demonstrate it, the total structural relief on the TPM from the Hulahula low (4.3 sec) to the crest of the Niguanak high is 2.7 sec or approximately 20,000 feet. This profile also suggests a more complicated stack of imbricate thrust faults underlying the Niguanak high. Other seismic profiles over the crest of the Niguanak high suggest the high is more complexly faulted than shown on the AN 84-30 and AN 85-50 north-south profiles (Fig. NA1, NA2, and NA3). Therefore, we interpret the Niguanak fault system is actually a complex zone of north-verging thrusts.

The TPM on the south flank of the Niguanak high descends gradually to a depth of approximately 20,000 feet below sea level (3.1 sec) in the eastern end of the Hulahula low (Fig. NA1), where the quality of the seismic reflection data is generally poor (Figs. NA2 and NA3). The reflection data show a saddle just north of the south 1002 fault system which separates the Niguanak high from the uplifted high area southeast of the 1002 area. This saddle is approximately 19,000 feet deep and connects northeastward into the Demarcation subbasin (Fig. NA1). This saddle is the spill point for the deepest closing contour around the Niguanak high and Aurora dome. However, because of the relatively poor data quality in this area and the 3 x 6 mile grid spacing, the details of the fault patterns in the southeastern part of the 1002 area are unknown.

LITHOLOGIC COMPOSITION

In the 1987 assessment of the 1002 area, the Niguanak high was inferred to be composed of rocks of both Franklinian sequence and Ellesmerian sequence, while the Aurora dome was inferred to be composed of primarily Franklinian sequence rocks (Callahan and others, 1987; Table 23.1). Although approximately 2,800 ft of Beaufortian sequence rocks were encountered in the bottom of the Aurora well, the significance of this well for inferring the overall composition of the Aurora dome and the Niguanak high remains problematic. The following section will review the mapped distribution of the Ellesmerian sequence within the 1002 area and inferences derived from seismic velocity, gravity, and magnetic data concerning the composition of these two large structural highs.

Ellesmerian sequence in the 1002 area

The Ellesmerian sequence is present along the southwestern and southeastern border of the 1002 area (Fig. NA5). The Beli Unit 1 well, just southwest of the 1002 area, reached total depth within the Lisburne Group, and seismic line AN 84-5 provided a firm calibration for the Lisburne Group, Sadlerochit Group, and the Shublik Formation (Fig. NA6). The Endicott Group was not penetrated at the Beli well, but its highly reflective character above the angular unconformity on top of the pre-Mississippian is quite distinctive on seismic line AN 84-5 as well as other profiles just west of the 1002 area. The typical seismic signature of the Ellesmerian has three components: (1) a deeper high reflectivity zone of Endicott Group clastic rocks separated from the Franklinian rocks by an angular unconformity (the reflections within the Franklinian dip 20 to 30º south with respect to this unconformity), (2) an intermediate transparent zone of the Lisburne Group, and (3) an upper high reflectivity zone composed of the Sadlerochit Group and Shublik Formation. The Kingak Shale (the Jurassic and Lower Cretaceous part of the Ellesmerian Sequence) is thin or absent in the southwestern 1002 area, where it has been truncated by the Lower Cretaceous Unconformity (LCU).

While the Ellesmerian is more than 5,000 feet thick just southwest of the 1002 area, it is erosionally truncated by the LCU less than 10 miles east of the western 1002 area border (Fig. NA5). A 15-mile wide zone along the southern border of the 1002 area in the vicinity of seismic line AN 84-6 detected none of the seismically distinctive part of the Ellesmerian at all. If

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the Jurassic and Lower Cretaceous part of the Ellesmerian sequence is present here, it is not distinguishable from the younger Brookian sedimentary rocks in the seismic data.

In the south-central and southeastern 1002 area, the distinctive Endicott, Lisburne, and Sadlerochit-Shublik part of the Ellesmerian Sequence is again clearly mappable (Fig. NA5) in spite of complex thin-skinned detachments above it. Although the Ellesmerian is truncated near the south end of seismic line AN 84-10 (south end merged with AN 85-16; see Potter and others, Chap. BD, Plate BD1), it thickens systematically to the east along the southern border of the 1002 area (Fig. NA5). Seismic profile AN 85-15 runs east-west along the southeastern border of the 1002 area and clearly demonstrates the characteristic seismic signature of the Ellesmerian (Fig. NA7). Although our interpretation of AN 85-15 is in agreement with the original description of this profile by Bruns and others (1987, Plate 4), the seismic reprocessing has improved the data quality of AN 85-15 and other lines in the southeastern 1002 area and allowed us to map the Ellesmerian sequence with much greater certainty than was possible for the 1987 assessment (Fig. NA5). The AN 85-15 profile crosses the south ends of seismic profiles AN 84-20 and AN 84-24 (Figs. NA8 and NA9), both of which cross the eastward plunging nose of the Sadlerochit Mountain (Fig. NA1). Both seismic profiles show northward thinning of the Ellesmerian. The thinning of the Ellesmerian section in this area appears to be due to depositional onlap rather than to erosional truncation by the LCU, which occurs along the western boundary of the 1002 area.

In the eastern end of the Hulahula low, the south end of the AN 84-30 profile begins north of the south 1002 fault system (Fig. NA2). The seismic data quality at the south end of this line, as well as four other profiles to the east, are too poor to demonstrate the presence or absence of the Ellesmerian sequence.

In summary, the recently reprocessed seismic profiles in the southeastern 1002 area reveal the distinctive seismic signature of the middle and lower parts of the Ellesmerian sequence (Endicott Group up through the Shublik Formation) which thins northward from ~6,000 feet along the south border of the 1002 area to less than 1,500 feet before reaching the south 1002 fault system (Fig. NA5). Although most of the seismic profiles in the southeastern 1002 area do not have sufficient resolution to determine whether this thinning is due to deposition or erosional truncation, it appears

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that depositional thinning can be demonstrated on the best profile in this area. As much as 10,000 feet of the Ellesmerian sequence may be present where tectonic thickening occurs due to folding and faulting of the Franklinian and the attached Ellesmerian section. In areas not affected by tectonic thickening, the Ellesmerian along the southern border of the 1002 area increases eastward from ~4,000 feet to ~6,000 feet in thickness.

The implications of these data are that there is very low probability of Ellesmerian rocks occurring on the west or south flanks of the Niguanak high or any part of the Aurora dome. Because the thickest Ellesmerian occurs along the southeast border of the 1002 area (Fig NA5) and the seismic data north of the south 1002 fault system is poor in this area, there is a slightly greater probability of Ellesmerian occurring on the southeast and east flanks of the Niguanak high. However, since there is no characteristic Ellesmerian seismic signature there, the probability of the presence of Ellesmerian rocks is still low.

Lithologic information based on seismic velocities

The seismic profiles on the southeast flank of the Aurora dome and north of the Niguanak fault system, which are tied to the Aurora 1 well, show that the Beaufortian sequence in that area is probably 3,000 feet or more in thickness with no clear bottom. Other seismic profiles to the west of the AN 84-30 profile (Fig. NA1), however, indicate that the Beaufortian penetrated in the Aurora well thins rapidly to the west and pinches out east of profile AN 85-50. Therefore, the Aurora well does not answer the question concerning the nature of the dominant lithologies in these two large structures.

The seismic velocities derived during the reprocessing and the gravity models have been prepared and analyzed to see if additional constraints could be obtained. Velocity analyses were made every 50 shot points (5,500 feet) on the seismic profiles during the reprocessing in order to optimize the restacking and for the conversion of reflection times to depth (Lee and others, Chap. SP). Random noise in the individual stacking velocities was smoothed over 250 msec time windows and 300 shot point windows and then converted into interval velocities. The smoothed interval velocities were overlaid on top of page size displays of the seismic profiles in order to facilitate the comparison of the velocities with the sedimentary strata and structures seen in the profile. In this section, we will review the velocity data for the Aurora dome and Niguanak high and compare them to well-log

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values measured in the major rock units and lithologies (Nelson and others, Chap. WL).

In the northwestern part of the 1002 area where Brookian and Ellesmerian sequences are undeformed, the velocities for the AN 84-1 profile change laterally and in depth in a gradual, geologically reasonable manner (Fig. NA10). The velocities for the western end of seismic profile AN 84-1 indicate that the upper 0.3 sec are in the range of 11,000 to 13,000 ft/sec, which is in good agreement with the permafrost layer measured in well logs and seismic check shots. There is a velocity inversion below the permafrost where the velocities decrease to ~8,000 ft/sec at 0.3 sec, which is reasonable, based on well data west of the 1002 area. From there down to 2.6 sec (base of the Brookian sequence lying on the TPM at west end of the profile), the interval velocities increase to ~14,000 ft/sec. From 2.6 to 3.5 sec, the inferred Franklinian sequence has velocities ranging from 15,000 to more than 18,000 ft/sec. The velocities on profile AN 84-1 also show anomalously high values near the base of the Brookian sequence under the Canning River. This is caused by rapid lateral changes in the permafrost near any major river, which distort the seismic ray paths and the velocity measurements. Velocity profiles are noisier within 1-2 miles of their ends (see west end of AN 84-1), where the common-depth-point (CDP) fold is deteriorating. Velocities for seismic profiles less than 6 miles long were generally unreliable. With the exception of the line ends (or short lines) and the permafrost perturbations near rivers, the interval velocity profiles were generally geologically reasonable in the undeformed part of the 1002 area.

Although the interval velocity data for seismic profiles in the deformed part of the 1002 area had a higher noise level than in the undeformed area, the vertical and lateral velocity changes there were also generally reasonable and consistent with parallel and crossing profiles. A north-south velocity profile over the Niguanak high and up the south flank of the Aurora dome for the AN 85-50 seismic line (Fig. NA11; see Fig. NA1 for location and NA3 for normal seismic display) shows shallow velocities (first 1 sec) at the north end in the range of 8,000 ft/sec or less, which is typical of all the north-south profiles in the vicinity of the Aurora dome. The shallow velocities increase southward up into the 11,000 to 15,000 ft/sec range, generally with the lower values in synclines and higher values in the anticlines, which is also typical of the deformed area. The low velocity at 1.4 sec near the south end of AN 85-50 is not reliable due to decreasing CDP fold at the end of the line. The interval velocities between 1.7 and 2.5 sec, within the upper part of the Niguanak high, are in the 15,000 to 17,000 ft/sec range with velocities of over 18, 000 ft/sec below 2.5 sec (the velocity decrease below 3.5 sec is not reliable because of weak reflection returns and insufficient offset to the distal seismometer groups). The velocities below the TPM on the south flank of the Aurora dome are in the 15,000 to 17,000 ft/sec range, which are similar to the velocities in the upper part of the Niguanak high.

An east-west smoothed velocity profile over the Niguanak high for the AN 85-1 seismic line (Fig. NA12) shows values below 9,000 ft/sec in the first 1 sec all across this profile, which is consistent with the north end of the AN 85-50 line and all the other seismic lines over the Aurora dome. The shallow low velocity zone deepens at the east end of the profile in the Demarcation sub-basin, again consistent with other profiles along the northeast boundary of the 1002 area. The velocities below the TPM across the Niguanak high are again in the 15,000 to 17,000 ft/sec range except for the highest tip of the Niguanak high where the velocity is ~14,000 ft/sec because the lateral and vertical smoothing operation was too coarse and smeared out the data.

Because of the shallow deformation and the possibility of side echoes off structures out of the plane of the profile, the uncertainty for the velocity estimates within the deformed area is significantly greater than in the deformed area. Although we do not presently have sufficient well control to calibrate this uncertainty or to estimate a standard deviation, it could easily be plus or minus 1,500 ft/sec or more.

Lithologic information based on gravity data

The regional isostatic gravity map reveals an east-west gravity low through the central and northern part of the 1002 area with -50 mGal anomalies in the northwestern part of the 1002 area and over the Demarcation Sub-basin just northeast of the 1002 area (Saltus and others, Fig. GR3 and Plate GR1). The anomalies decrease to -20 mGal along the southern border of the 1002 area and become positive (+10 to +20 mGal) in the mountains south of the 1002 boundary. Large positive anomalies (+50 to +80 mGal) also occur over the middle and outer continental shelf north of the 1002 area. The east-west gravity low through the 1002 area is interrupted by a northwest trending anomaly over the Niguanak high and Aurora dome (approximately -15 and -20 mGal, respectively). The Niguanak high is approximately 5 mGal more positive than the Aurora dome, and both structures are 30 to 35 mGal more positive than the east-west low which they interrupt.

A north-south gravity model over the Niguanak high and Aurora dome along the AN 85-50 seismic profile and an east-west gravity model across the northern part of the 1002 area (Saltus and others, Fig. GR9 and GR10) indicate that the average density of the two structures is between 0 and 0.2 g/cc more dense than the basement rocks (absolute densities of 2.7 to 2.9 g/cc if 2.7 is assumed for basement, which is mostly Franklinian) outcropping south of the 1002 area. The north end of the model for the AN 85-50 seismic profile required a +0.3 g/cc layer (absolute density of 3.0 g/cc) between 6 and 14 km deep under the outer continental shelf. North-south models in the central and western part of the 1002 area also required a +0.3 g/cc mass beneath the outer continental crust (Saltus and others, Fig. GR6, GR7, and GR8). Although the models beneath the outer continental shelf did not include any offshore seismic data control, the +0.3 g/cc anomalous mass is an indication that the gravity data is sensing the transition to oceanic crust (with shallower mantle) to the north as well as anomalously dense or shallow crustal rocks beneath the outer continental shelf north of the 1002 area.

Although the gravity modeling can be improved in the future by integration of the offshore seismic data, offshore well density control, and three-dimensional modeling software, the present models are strong evidence that the average density values for the Niguanak high and Aurora dome are equal to or denser than the basement rocks which crop out south of the 1002 area.

Lithologic information based on magnetic data

Analysis of the aeromagnetic survey over and around the 1002 area using lowpass, bandpass, and highpass filtering (wavelengths longer than 10.8 km, between 1.7 and 10.8 km, and less than 1.7 km, respectively) reveal significant magnetic sources in the near-surface sedimentary horizons (wavelength < 1.7 km) as well as significant sources at intermediate depths between the near-surface and the TPM (Phillips, Chap. AM; Fig. AM6 and AM7). The intermediate sources are interpreted as possible thrusted and folded Brookian sedimentary rocks. The lowpass magnetic anomaly map shows a broad low amplitude negative anomaly over the eastern third of the 1002 area, including and surrounding the Niguanak high, which does not have an obvious magnetic expression. The lowpass magnetic map shows a broad low-amplitude positive over the Aurora dome.

The minimum estimates of depth to magnetic source over the Niguanak high are 2-3 km below sea level, close to the crest mapped with the seismic profiles. However, the lack of an obvious magnetic expression for the high suggests that the rocks forming the crest of the high are relatively non-magnetic. This would favor sedimentary rocks over intrusive or volcanic rocks as the dominant lithology within the Niguanak high. While the minimum depth-to-magnetic-source estimates over the Aurora dome are 2-3 km below sea level (1-2 km above the crest mapped with the seismic profiles), the maximum depth-to-magnetic-source estimates over the dome are 6-7 km below sea level (2-3 km below the crest mapped with the seismic profiles). Thus, like the Niguanak high, the Aurora dome falls within the range of depths permissible for magnetic basement sources. Unlike the Niguanak high, the Aurora dome appears to be associated with a significant positive magnetic anomaly. This suggests that the Aurora dome is more likely to contain intrusive or volcanic material than is the Niguanak high.

DISCUSSION

Seismic profiles over the Niguanak high clearly indicate an imbricate stack of north-verging thrust sheets below the TPM, as interpreted by Foland and Lalla(1987) and Bruns and others (1987). Although the seismic line coverage over the Aurora dome is less complete than over the Niguanak high (and few of these lines are publicly available), those lines generally suggest that the Aurora dome is also composed of a complex imbricate stack of thrust sheets. The Niguanak high and Aurora dome are separated by the Niguanak thrust system which is a complex zone that can not be mapped in detail with the presently available 3 x 6 mile spaced seismic survey. Earthquake activity beneath the outer continental shelf near the Camden anticline (Grantz and others, 1987: Potter and others, Chap. BD, Fig. BD7) indicate that a deeper level of detachment also underlies the Aurora dome and extends offshore.

The seismic velocities derived during the reprocessing of the ANWR profiles and the gravity modeling indicate that the rocks below the TPM and composing the Niguanak high and Aurora dome have high velocities and high densities. The aeromagnetic data indicate that the rocks composing the Niguanak high are relatively non-magnetic, precluding mafic igneous rocks but not most sedimentary or silicic igneous rocks. Well lithified Paleozoic rocks from the Franklinian sequence, Ellesmerian sequence, or Devonian clastic units (Kelley, Chap. BR) would be compatible with these velocity, density, and magnetic properties. However, based on the thinning of the Ellesmerian sequence observed in the southeastern part of the 1002 area (Fig. NA5), it is unlikely that the Ellesmerian sequence extends far enough north to reach the western or southern flanks of the Niguanak high. The eastward thickening of the Ellesmerian sequence in the southeastern corner of the 1002 area, combined with marginal seismic resolution, allow the possibility of the Ellesmerian sequence being present on the southeastern flank of the Niguanak high. The possibility of the Ellesmerian sequence extending to any part of the Aurora dome is very low. By process of elimination, the Franklinian sequence, especially massive carbonates like the Katakturak dolomite, and/or Devonian clastic rocks are likely to be the predominant constituent within the Niguanak high.

However, because of the broad, low-amplitude, positive magnetic anomaly over the Aurora dome, the presence of weakly magnetized igneous or metamorphic rocks within or beneath it can not be precluded. Deformed Franklinian sequence rocks with mineralized fault zones could also be the magnetic sources, which could be between 2 and 7 km below sea level. Therefore, the range of possible lithologies which compose the Aurora dome is poorly constrained.

Although more than 2,500 feet of Beaufortian sequence sandstones and shales were penetrated in the bottom of the Aurora well, the seismic reflection profiles indicate that this rift sequence is restricted to the east flank of the Aurora dome. Seismic profiles, which remain proprietary, show that the Beaufortian section drilled at the Aurora well thins rapidly to the west and merges with the strong reflection event which was mapped as the top of the Aurora dome. Although the reflection off the basal Tertiary unconformity (BTU) in the Aurora well was mapped as the TPM in the previous assessment, the discrepancy appears to be restricted to the wedge of Beaufortian sequence on the east flank of the dome. Because the results of the KIC 1 well have not been released to date, it is unknown whether it encountered either the Beaufortian sequence and/or Paleozoic sedimentary or metasedimentary rocks.

Uncertainties in the seismic reflection interpretation and the tie to the Aurora well are inevitable because the seismic reflection survey over the central and northern part of the Aurora dome consists mainly of short and unconnected profiles (Fig. BD1). The seismic coverage here is much sparser than the main part of the ANWR survey where the average line spacing is 3 x 6 miles. While the seismic velocity estimates for the rocks composing the Niguanak high and Aurora dome (below the TPM) average approximately 16,500 ft/sec, deviations of plus or minus 10% are likely. Finally, while the gravity models indicating 2.7 g/cc or more average density within the Niguanak high and Aurora dome are consistent with the high velocity estimates, the models are not unique and a more comprehensive integration with the offshore seismic reflection and well data is needed in order to confirm these model densities.

CONCLUSIONS

Although the reprocessed seismic profiles and the velocity data derived in the reprocessing provided significant improvements on many details of the Niguanak high and Aurora dome, the overall sizes and depths of these two large structural highs are in good agreement with the estimates in the previous assessment (Foland and Lalla, 1987; Bruns and others, 1987; and Callahan and others, 1987). The improved velocity model (Lee and others, Chap. SP; Fig. SP11) demonstrated large lateral velocity variations within the 1002 area which resulted in shifts in the depth to the TPM by more than one thousand feet in comparison to the previous study. Therefore, the depths to crests and deepest closing contours for the two highs changed from the previous study. This resulted in a moderate increase in the overall size of the highs in comparison with the 1987 assessment; 195,000 versus 130,000 acres for the Niguanak high and 257,000 versus 226,000 acres for the Aurora dome, respectively. However, the overall agreement between the two assessments in size and depths of these two highs is good.

The major faults offsetting the TPM within the 1002 area interpreted in this assessment (Fig. NA1) are also in general agreement with the previous assessment (Foland and Lalla, 1987; Plate 3), although some details are clearly different. The difference in most cases is due primarily to a combination of ambiguities imposed by the 3 x 6 mile spacing of the seismic survey and by poor seismic data quality in very complexly deformed areas. The faults interpreted in this chapter also differ in some details from those of Kelley (Chap. BR). These are reasonable differences of interpretation which could only be resolved by a closer spaced seismic survey and/or the use of the high resolution seismic data acquisition systems which have been developed since these data were collected in 1985. The differences in interpretation of faulting in the vicinity the Niguanak high and Aurora dome do not significantly impact the oil and gas assessment of the two prospects.

The interpretation of the Niguanak high below the TPM (and/or BTU) as an imbricate stack of thrusts presented in this chapter is in agreement with the interpretation of Bruns and others (1987; Plate 4) for the AN 85-1 seismic profile, which runs east-west across the crest of the Niguanak high (Fig. NA4). Some of the seismic profiles over the Aurora dome were reprocessed down to 8 seconds for the current assessment, and the improved resolution on these profiles indicate that the Aurora dome is also a complex imbricate stack of thrusts. While the USGS received permission from the industry consortium to show reprocessed seismic profiles for lines shown in the 1987 assessment report (AN 84-30 and AN 85-50, which only reach the south flank of the Aurora dome), the best seismic lines over the Aurora dome remain proprietary. Since AN 84-30 and AN 85-50 do not give a representative picture of the Aurora dome, we can only summarize our interpretation of this feature. The Aurora dome appears to be composed of multiple north-verging thrust sheets with predominantly east-dipping lateral ramps. The deepest detachment zone for these imbricated thrusts, which can be resolved in the seismic data, is at least 35,000 feet below sea level beneath the eastern border of the 1002 area. The deeper thrusts may extend beneath the north flank of the Aurora dome, and the deepest may feed into the active deformation offshore in the vicinity of the Camden anticline (Potter and others, Chap. BD, Figs. BD6 and BD7).

While the Beaufortian sequence encountered in the Aurora well initially suggested the possibility that the Aurora dome may be composed of predominantly Beaufortian thrusts sheets, the high velocity and high density estimates below the TPM (and/or BTU) appear to rule out the Beaufortian as a predominant lithology. The seismic reflection data near the Aurora well show that the Beaufortian section penetrated in the well does not change thickness to the south, but does pinch out rapidly to the west. While the seismic reflection data could be interpreted with more Beaufortian sequence underlying this pinched-out wedge, the density and velocity data suggest the underlying material is not Beaufortian. Although the magnetic data can rule out mafic igneous rocks within the Niguanak high, the magnetic data do permit weakly magnetized rocks within the Aurora dome. Either non-magnetic sedimentary rocks or non-magnetic silicic igneous or volcanic rocks are consistent with the magnetic data over the Niguanak high. A wide

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range of weak-to-moderately magnetized sedimentary, igneous, or metamorphic rocks may be present within the Aurora dome. Since silicic igneous rocks are absent in the vicinity of the 1002 area, silicic igneous rocks are unlikely. Although both Franklinian and Ellesmerian sequence rocks are consistent with the velocity, density, and magnetic constraints, the fact that the Ellesmerian appears to pinch out well south of the Niguanak high (Fig. NA5) eliminates it as a probable candidate. Therefore, the Paleozoic sedimentary rocks such as the Franklinian sequence are probably the dominant lithologies composing the Niguanak high and Aurora dome. The Devonian clastic wedge interpreted beneath the northern part of the 1002 area by Kelley (Chap. BR) would also be compatible with the geophysical constraints.

Although the extensive geophysical coverage and information from the Aurora well provide constraints suggesting the Franklinian sequence or Devonian clastic wedge as the most probable lithologies within the Niguanak high and Aurora dome, uncertainties remain on this question. The significance of the imbricated thrusts in creating separate compartments for smaller hydrocarbon accumulations within either prospect is dependent on whether the faults are sealing or are migration pathways. In this assessment, the uncertainties concerning the dominant lithology and its effect on compartmentalizing were taken into account by allowing two possible scenarios for the Niguanak-Aurora play. The first scenario assumed two large prospects, and the second assumed many prospects or compartments (Fig. P10-1).

ACKNOWLEDGMENTS

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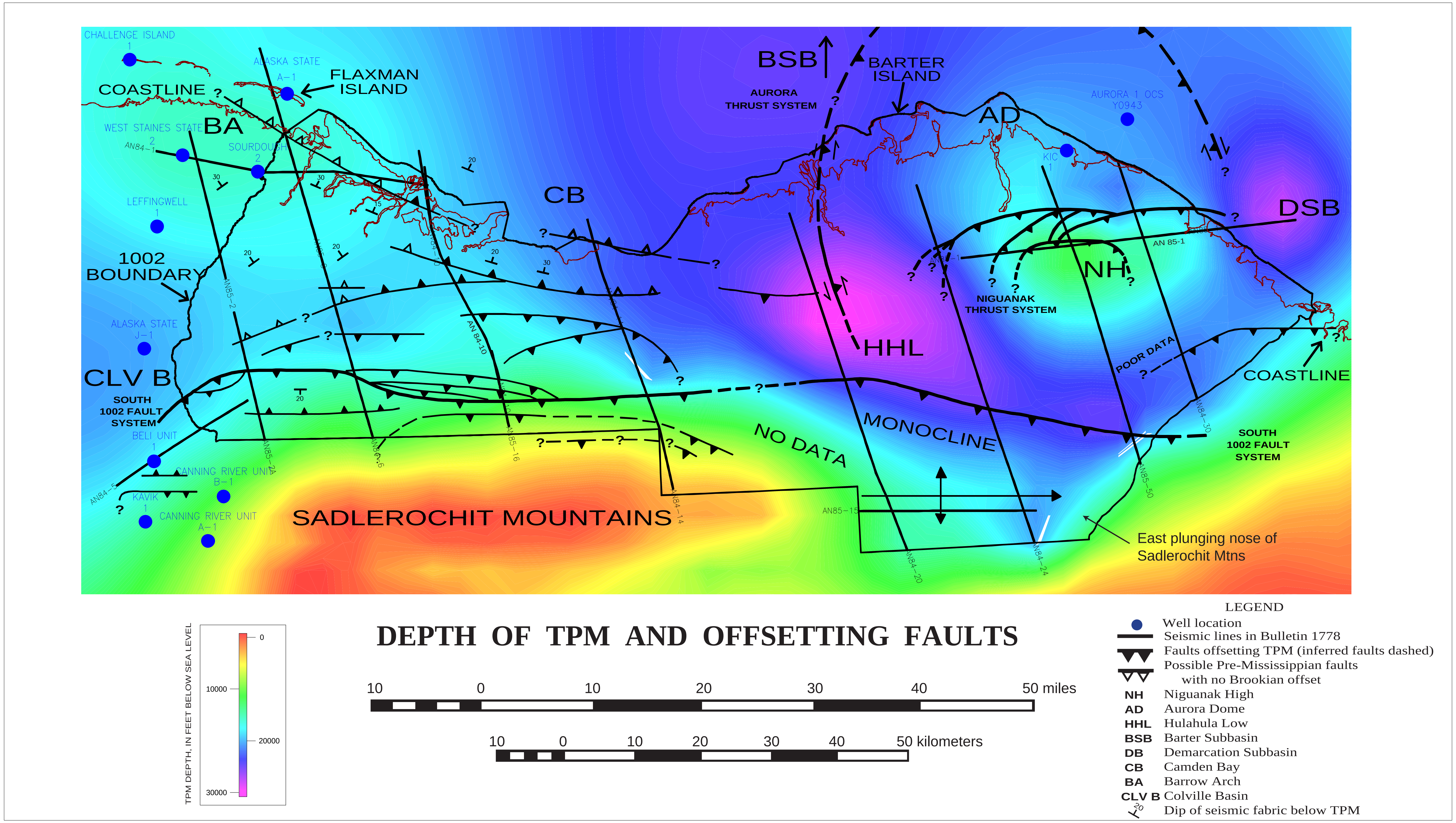

Figure NA1. The major fault systems offsetting the top of the pre-Mississippian (TPM) or Franklinian sequence within the 1002 area of the Arctic National Wildlife Refuge (ANWR) are superimposed on a base map showing the smoothed depth to the TPM. The base map was prepared with a grid spacing of 4,000 meters (~2.5 miles) using only the seismic reflection profiles shown in black, which were released in U. S. Geological Survey (USGS) Bulletin 1778 Plates 3, 4, and 5). Additional outcrop and well data for the TPM was also used. The resulting map has smoothed out structural features shorter than 5 -miles in diameter, but the larger structural highs and lows within and surrounding the 1002 area are still clearly represented. Although this interpretation of fault locations is based on all ANWR seismic lines, which had an average line spacing of 3 x 6 miles (north-south and east-west lines respectively), alternative interpretations of the fault trends are possible (see Kelley, Chapter BR).

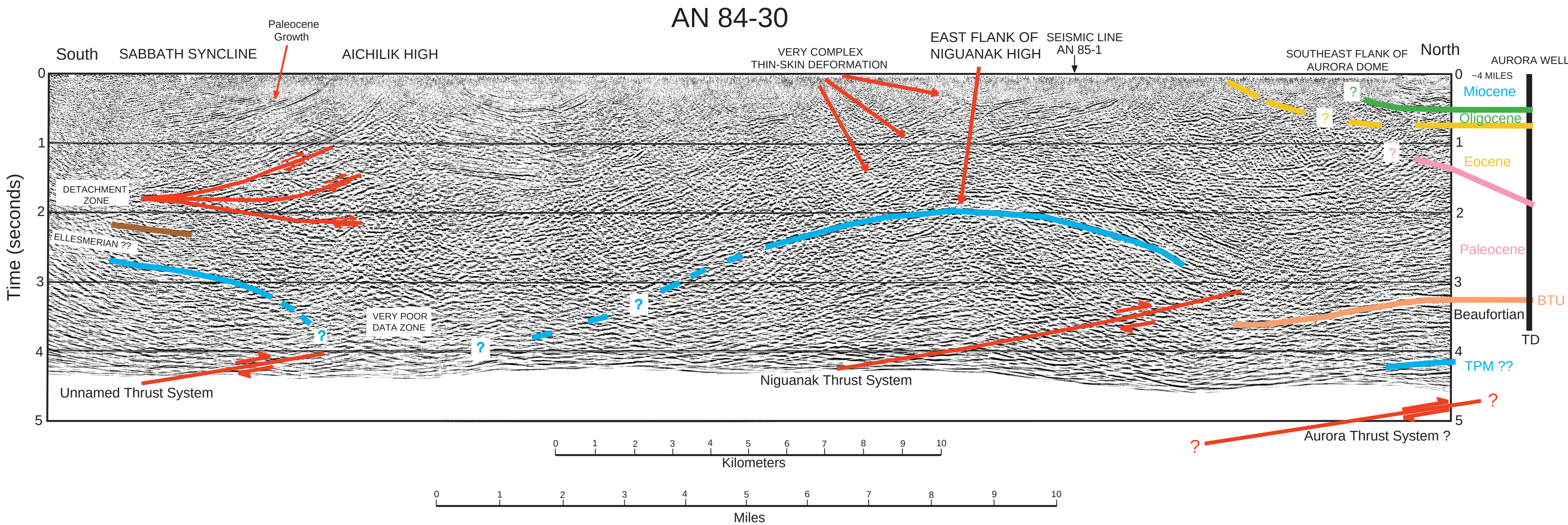

Figure NA2a. Seismic profile AN 84-30 with interpreted features. The AN 84-30 seismic profile ended ~4 miles south of the Aurora well. While the Beaufortian section penetrated in the well appears relatively uniform in thickness on this profile, other unreleased seismic profiles suggest that the Beaufortian section penetrated at the Aurora well pinches out to the west before reaching the crest of the Aurora dome (Fig. NA1). Because gravity models over the Niguanak high and Aurora dome (Saltus and others, Chapter GR) indicate that these two large structures have densities of 2.7 g/cc or greater, the dominant lithologies in the highs are probably pre-Mississippian sedimentary rocks rather than the Beaufortian sequence. The location of the Aichilik high is shown in Figure BD2. The ages for the stratigraphy at the north end of the profile are defined by the Aurora well (Nelson and others, Chapter WL; Plate WL8). BTU, the basal Tertiary unconformity. TPM, top of the pre-Mississippian. TD, total depth. Seismic line AN 85-1 is shown in Figure NA4. See Plate BD3 for the details of the shallow thin-skinned deformation. Figure NA2b is shown without the interpretation overlay.

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AN 84-30

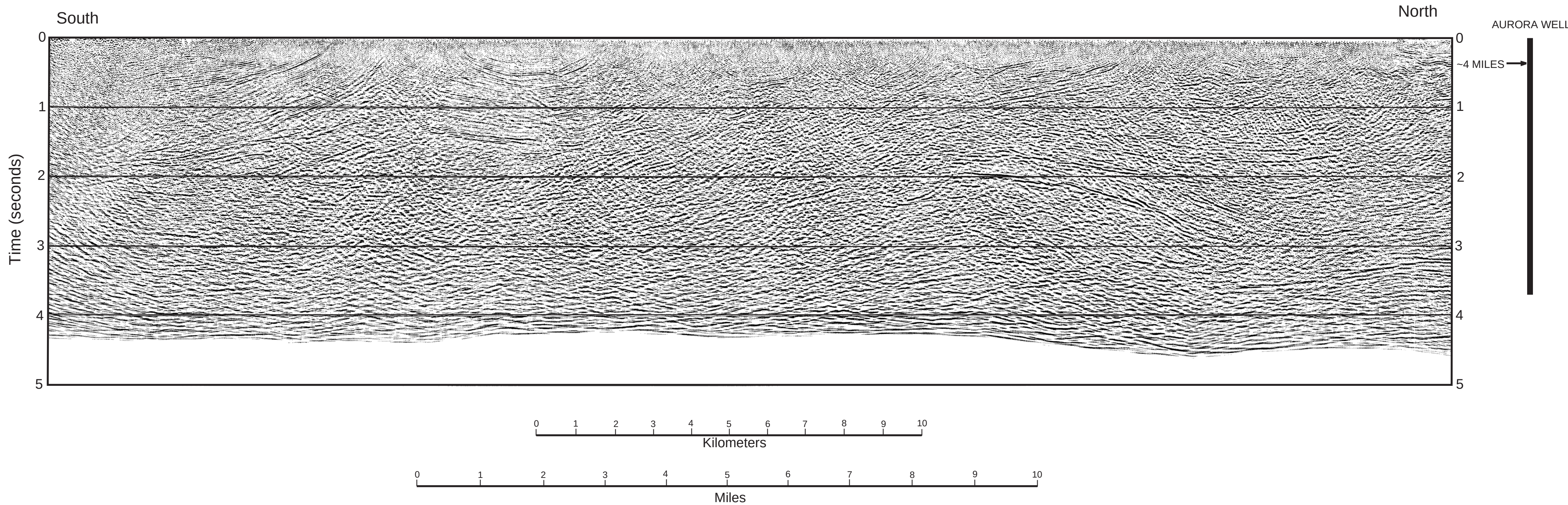

Figure NA2b. Seismic profile AN 84-30 without the interpretive overlay.

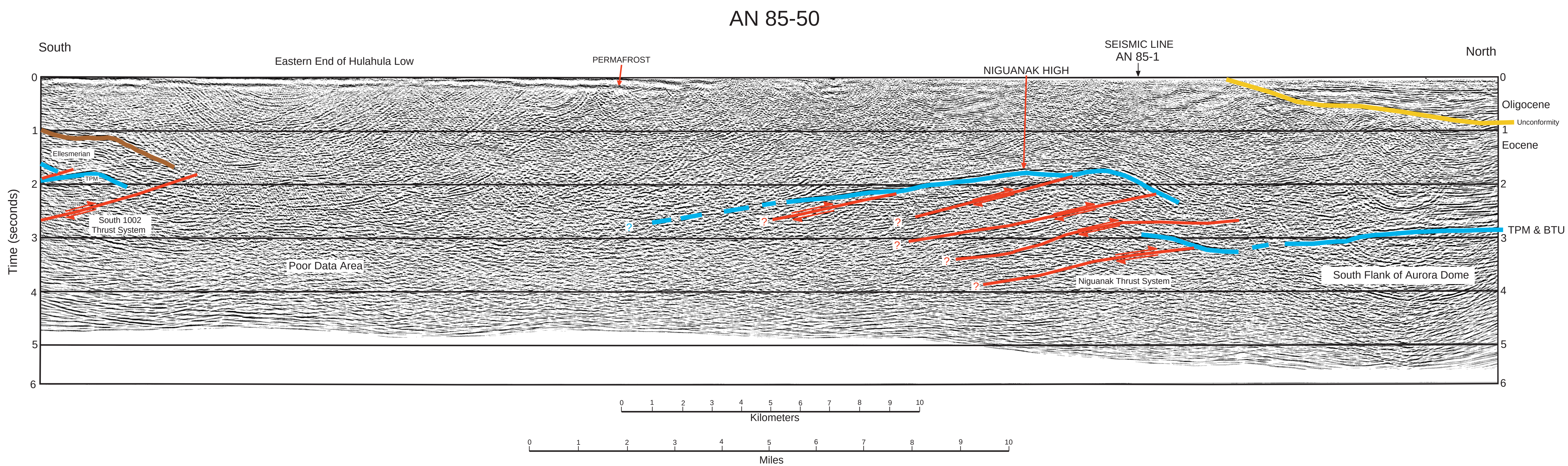

Figure NA3a. The AN 85-50 seismic profile crosses the crest of the Niguanak high and the south flank of the Aurora dome (Figure NA1). This north-south seismic profile and the east-west seismic profile AN 85-1 (Figure NA4) suggest that the Niguanak high is a stack of multiple thrust sheets. Other seismic profiles over the Aurora dome also suggest that it is a composite stack of thrust sheets. The deformation is too complex to permit detailed mapping of the internal thrusts faults with the existing 3 x 6 mile seismic survey. Figure NA3b is shown without the interpretation overlay.

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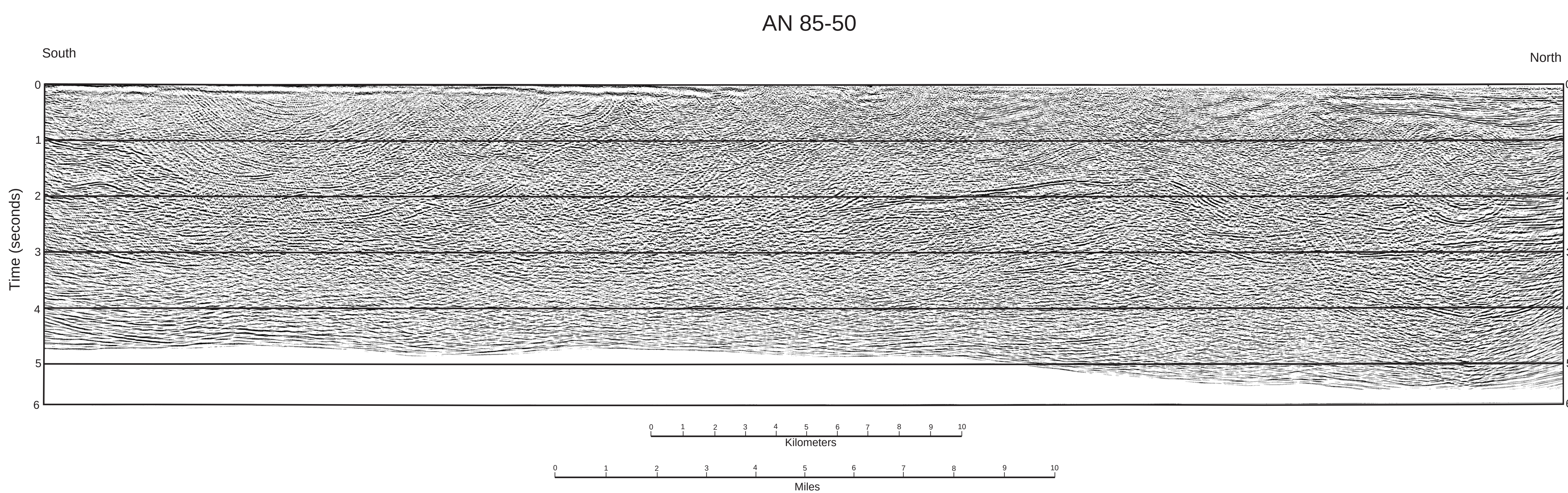

Figure NA3b. Seismic profile AN 85-50 without the interpretive overlay.

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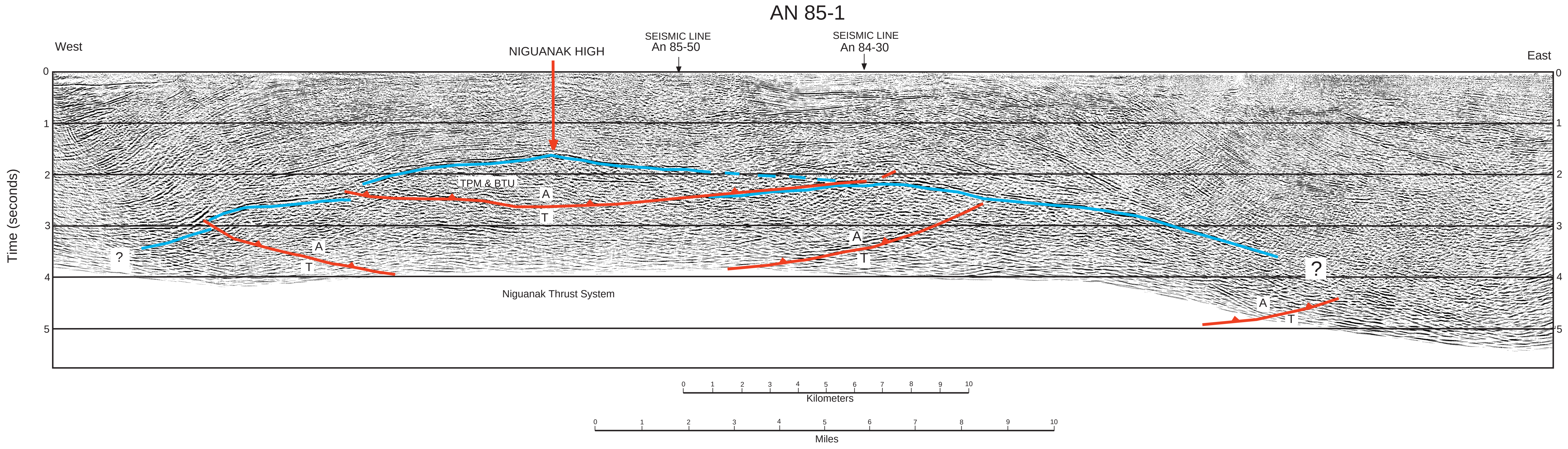

Figure NA4a.. Seismic profile AN 85-1 runs east-west across the crest of the Niguanak high (Figure NA1). The interpretation of multiple internal thrust sheets within the Niguanak high for this profile was originally suggested by Bruns and others (1987; Plate 4). Figure NA4b is shown without the interpretation overlay. Letter A indicates displacement away from viewer, T indicates displacement toward viewer.

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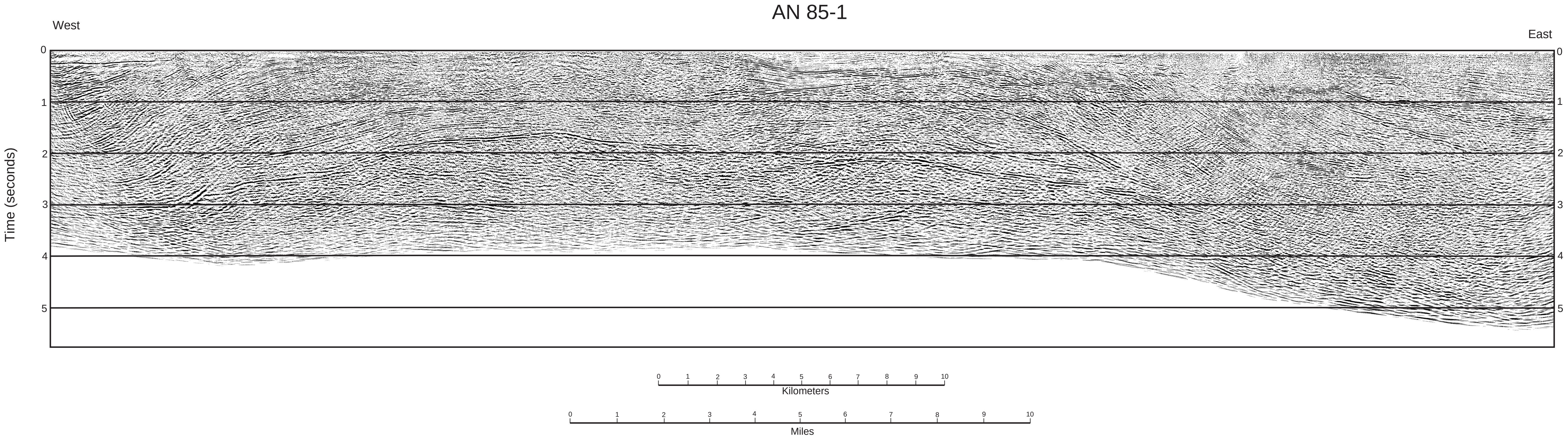

Figure NA4b. Seismic profile AN 85-1 without the interpretive overlay.

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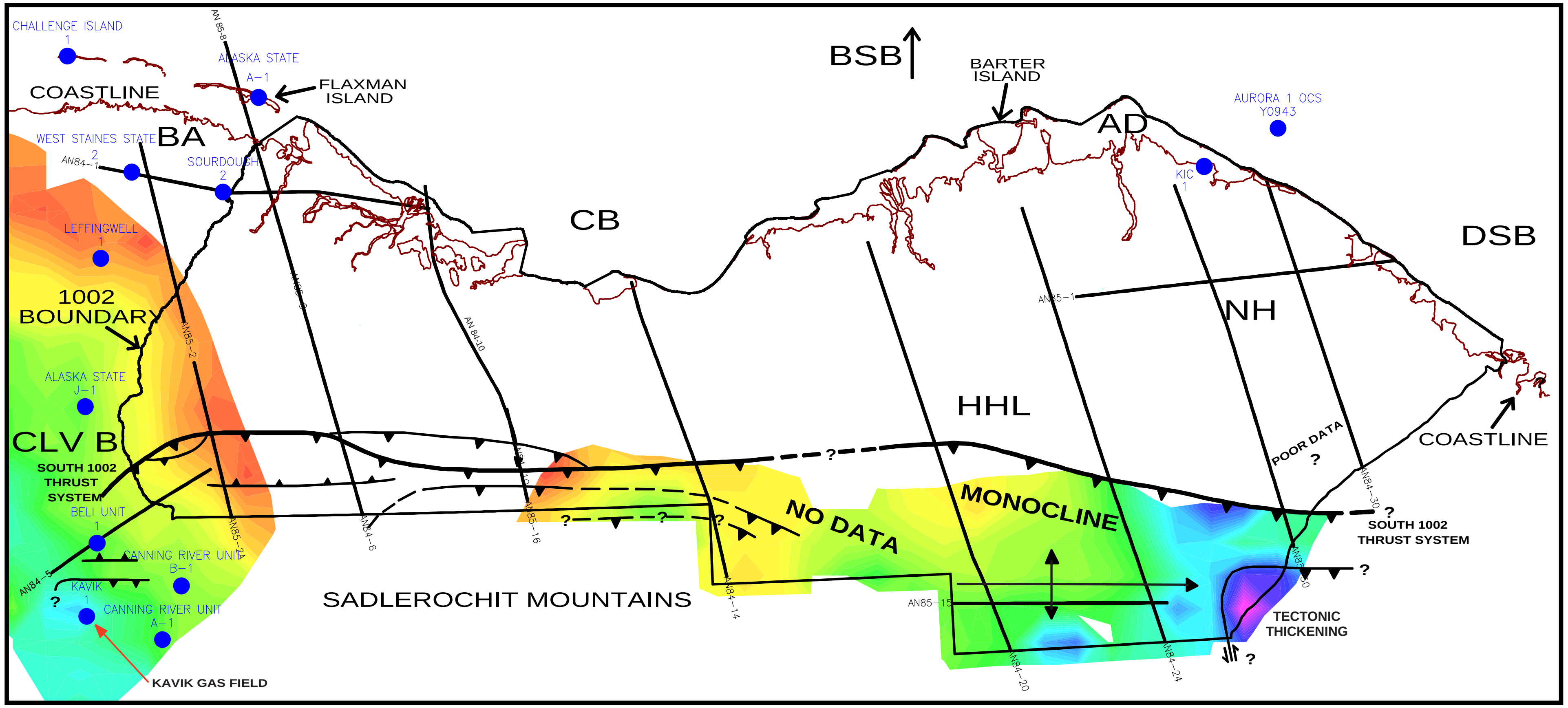
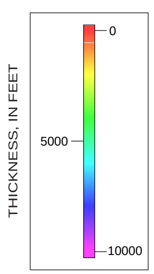
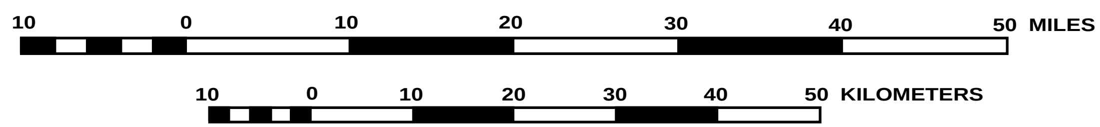




ISOPACH MAP OF THE ELLESMERIAN SEQUENCE



EXPLANATION

	Seismic lines in Bulletin 1778
	Faults offsetting TPM
NH	Niguanak High
AD	Aurora Dome
HHL	Hulahula Low
BSB	Barter Subbasin
DSB	Demarcation Subbasin
CB	Camden Bay
BA	Barrow Arch
CLV B	Colville Basin

Figure NA5. Isopach map showing the seismically mappable Ellesmerian sequence in the 1002 area of the Artic National Wildlife Refuge. This includes the basal Endicott Group, Lisburne Group, Sadlerochit Group, and the Shublik Formation. The younger Jurassic and Early Cretaceous part of the Ellesmerian sequence is usually detached into thin-skin thrusts and folds that are impossible to discriminate from the deformed Brookian sequence in the seismic data. In the western part of the 1002 area, the Ellesmerian sequence thins due to erosional truncation by the Lower Cretaceous Unconformity (LCU) and is missing along the southern border in the western quarter of the 1002 area. In south-central and southeastern 1002, the depositional thickness of the Ellesmerian sequence is more than 5,000 feet on some seismic lines (see Figures NA6, NA7, NA8, and NA9), and tectonic thickening to 10,000 feet was seen in the southeastern corner of the 1002 area. In the area south of the Niguanak high, the Ellesmerian sequence appears to thin by depositional onlap (rather than erosional truncation) and does not appear to extend north of the South 1002 thrust system with the possible exception of the south end of the AN 84-30 seismic line where the seismic data quality was poor (see Fig. NA2 and Plate BD3).

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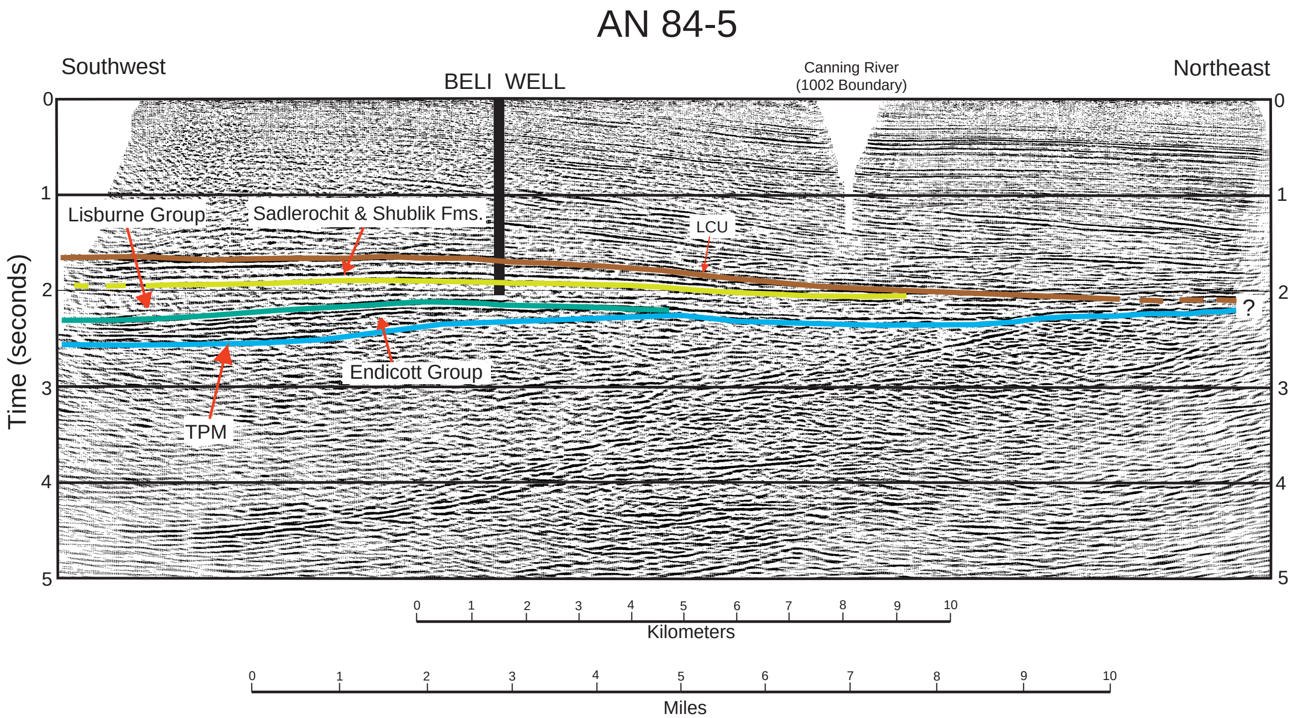

Figure NA6a. Seismic profile AN 84-5 lies in the southwest corner of the 1002 area and ties to the Beli well (Figure NA1). The Beli well terminates within the carbonates of the Lisburne Group, which typically have a non-reflective or transparent seismic reflection signature or character. The overlying clastic lithologies of the Sadlerochit Group and Shublik Formation typically have a highly reflective seismic character, as do the underlying clastic lithologies of the Endicott Group. The Ellesmerian sequence in the southwestern part of the 1002 area (Figure NA5) thins northward and eastward by erosional truncation of the Lower Cretaceous Unconformity (LCU) (Bird, Chapter AO). Figure NA6b shows the seismic profile without the interpretation overlay.

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AN 84-5

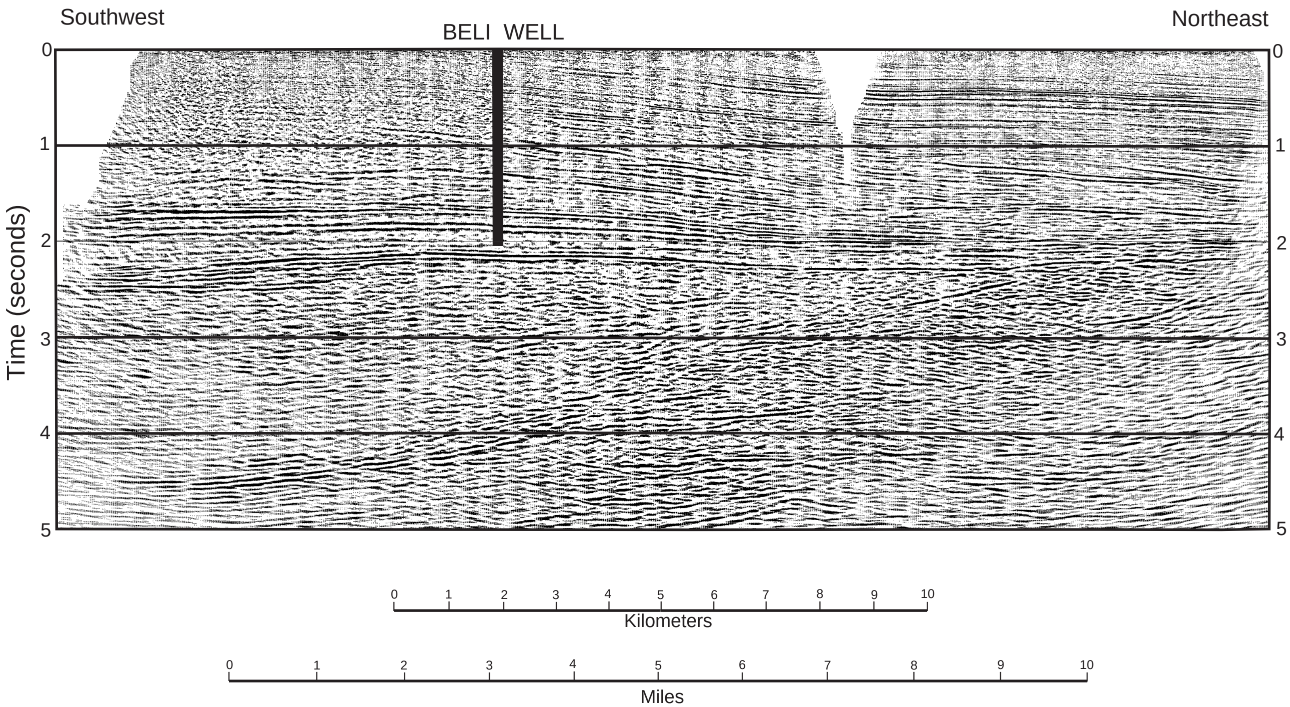

Figure NA6b. Seismic profile AN 84-5 without the interpretive overlay.

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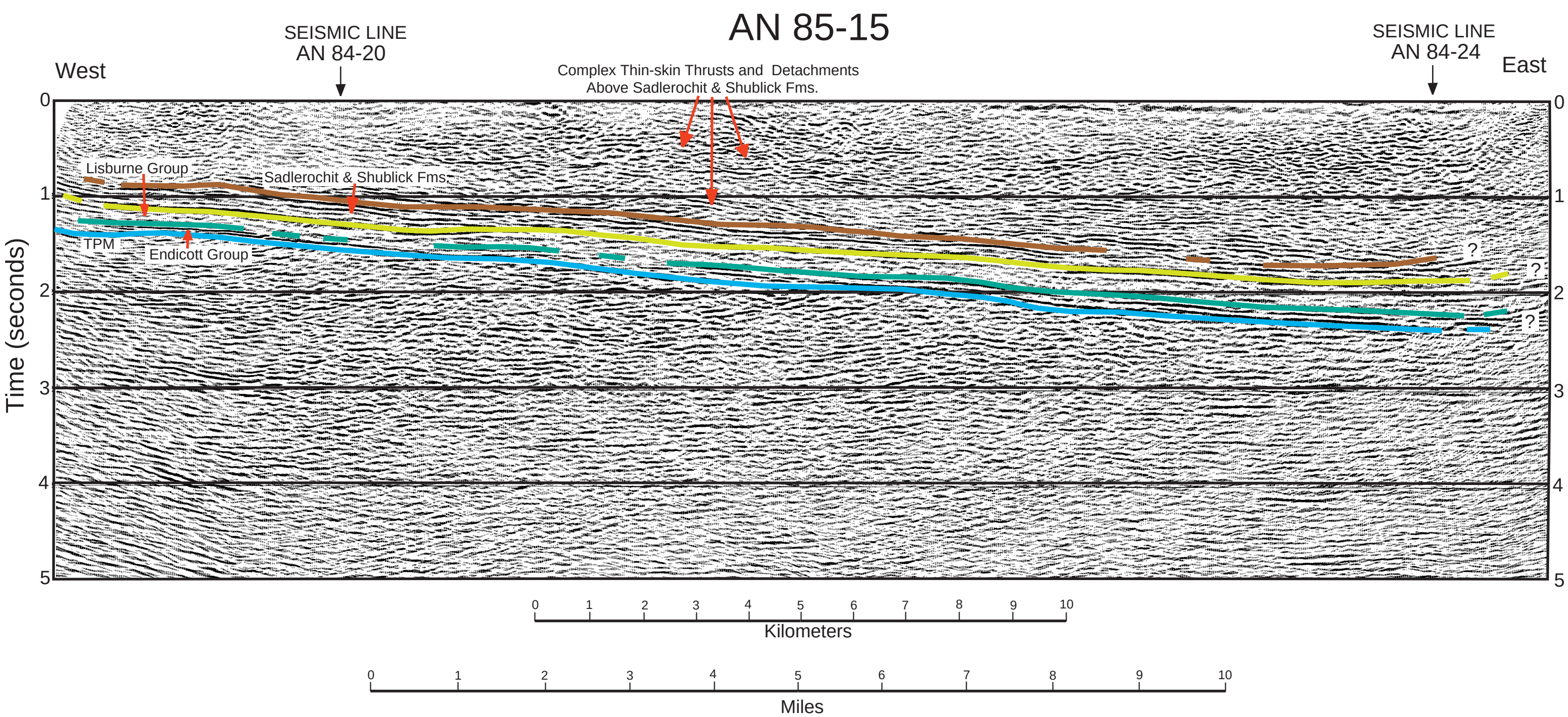

Figure NA7a. Seismic profile AN 85-15 runs east-west in the southeastern part of the 1002 area (Figure NA1). The typical seismic character of the Endicott Group, Lisburne Group, Sadlerochit Group, and Shublik Formation (Figure NA6) is well displayed on this profile, as originally interpreted by Bruns and others (1987). Figure NA7b is shown without the interpretation overlay.

AN 85-15

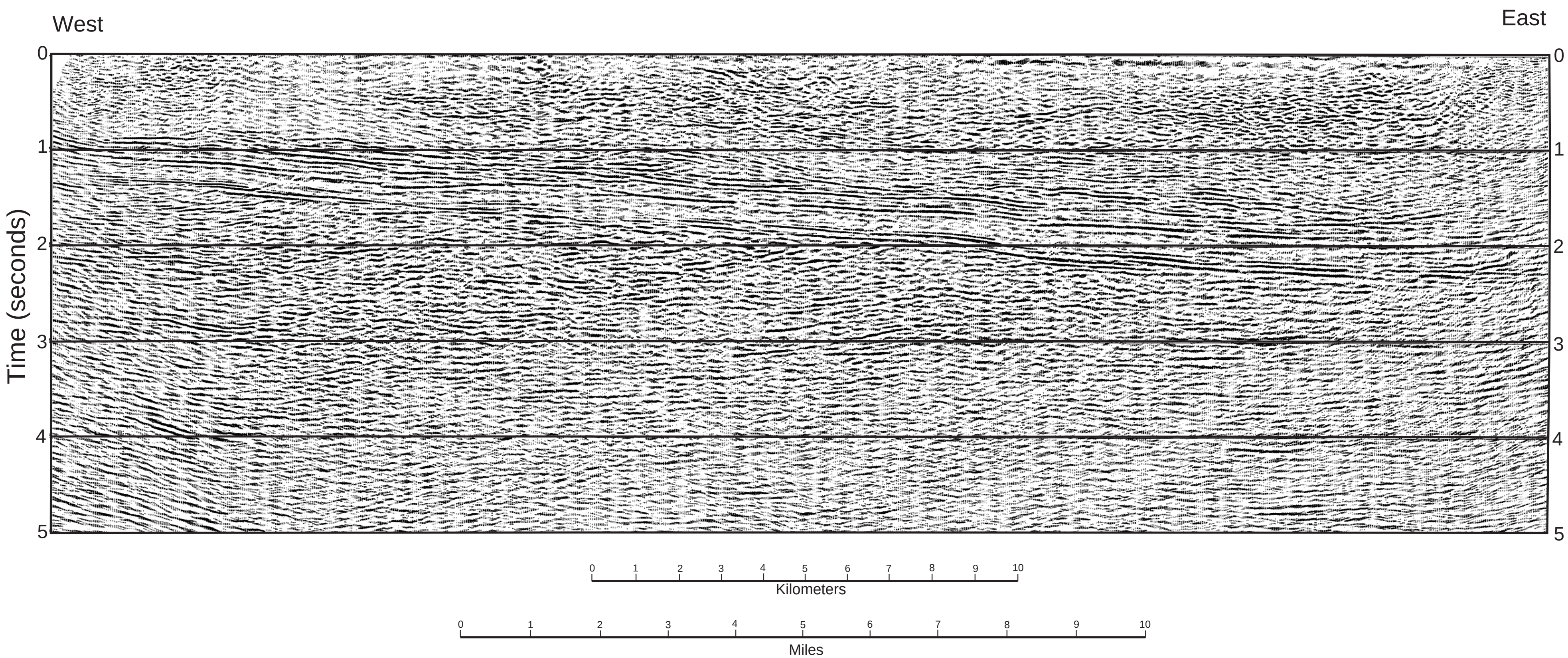

Figure NA7b. Seismic profile AN 5-15without the interpretive overlay.

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South End of AN 84-20

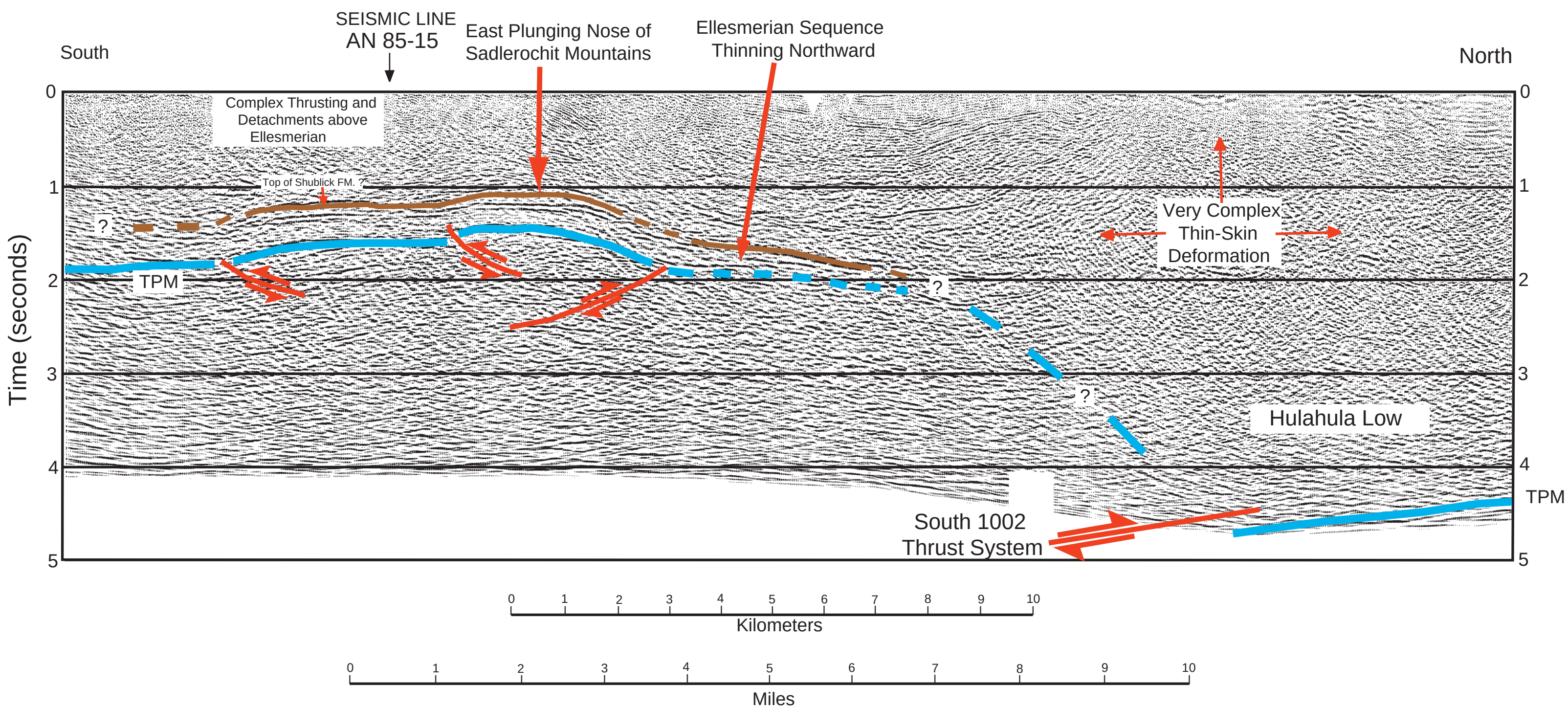

Figure NA8a. The south end of the AN 84-20 seismic profile shows the typical seismic characteristics of the Ellesmerian sequence near the southern border of the 1002 area (Figure NA1 and NA5), but the Ellesmerian sequence thins northward and appears to pinch out near the northern edge of the South 1002 thrust system. The east-plunging nose of the Sadlerochit Mountains is also clearly displayed on this profile. Seismic profile AN 84-24 (Figure NA9) displays a similar profile about 12 miles to the east of this profile. Figure NA8b is shown without the interpretation overlay.

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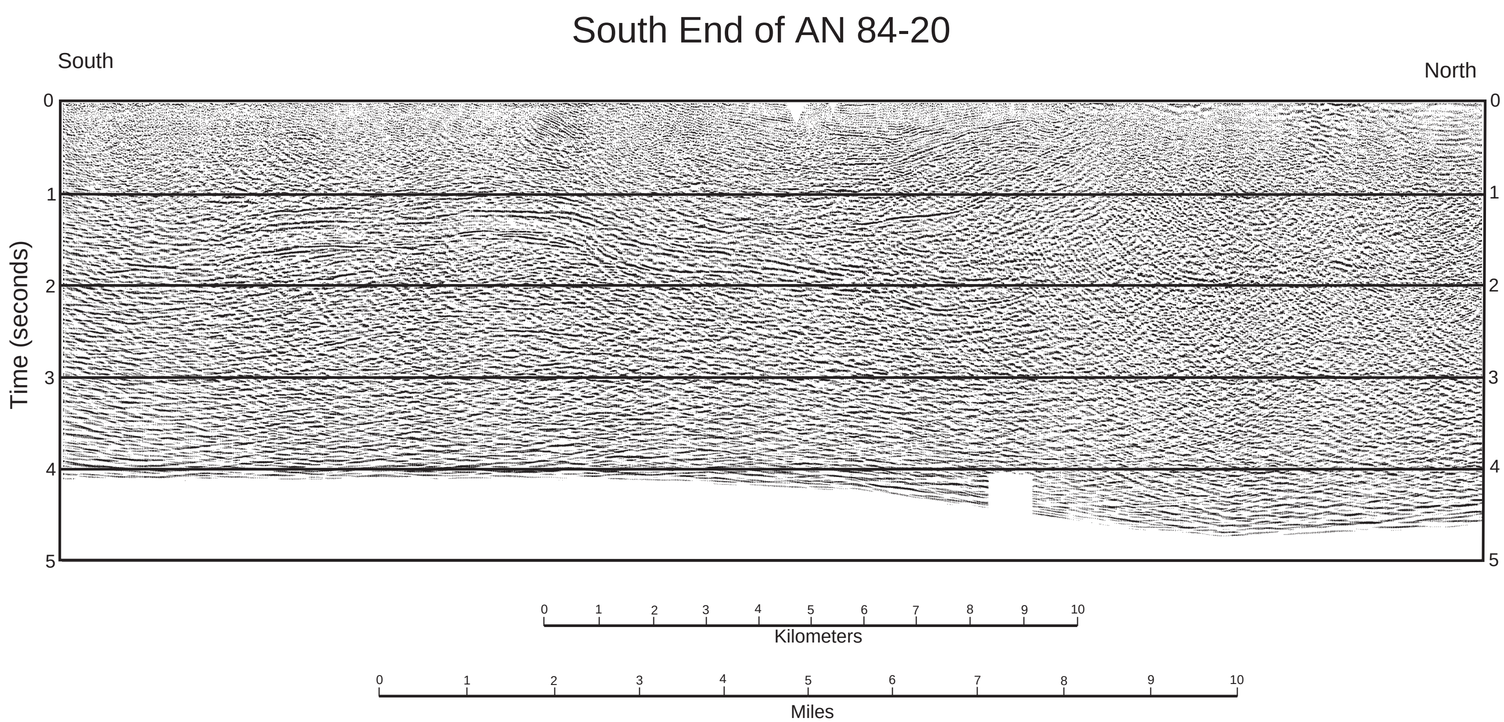

Figure NA8b. Seismic profile AN 84-20 without the interpretive overlay.

South End of AN 84-24

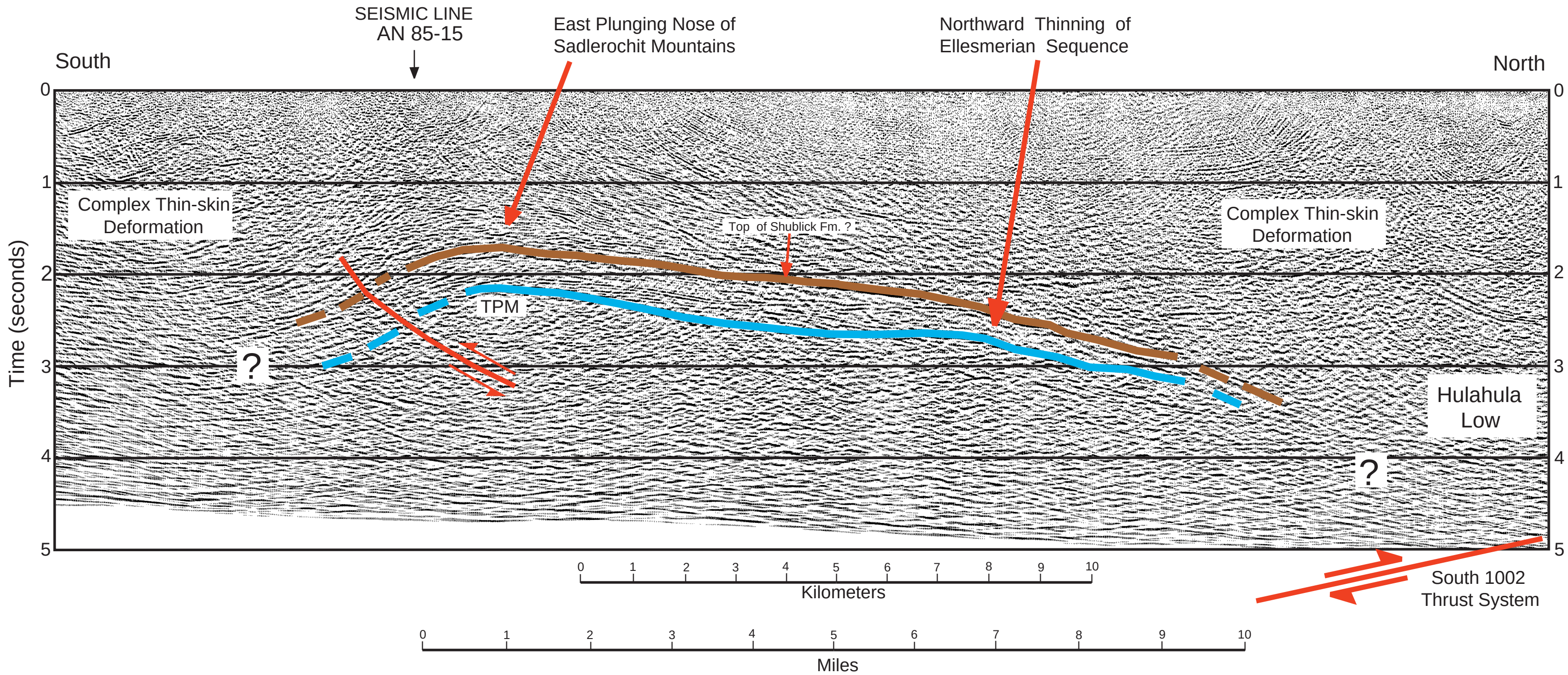

Figure NA9a. The AN 84-24 seismic profile also dislpays the northward thinning of the Ellesmerian sequence. Although the northward thinning of the Ellesmerian sequence is clearly displayed on both the AN 84-20 and the AN 84-24 profiles, the data quality for these profiles is marginal for determining whether the thinning is due to erosional truncation or depositional onlap. The highest quality north-south profile in this area has not been released for publication, but it suggests that depositional onlap thinning is occurring in the south-eastern part of the 1002 area in contrast to the erosional truncation thinning in the southwestern part of the 1002 area (Figure NA5 and NA6). Figure NA9b is shown without the interpretation overlay.

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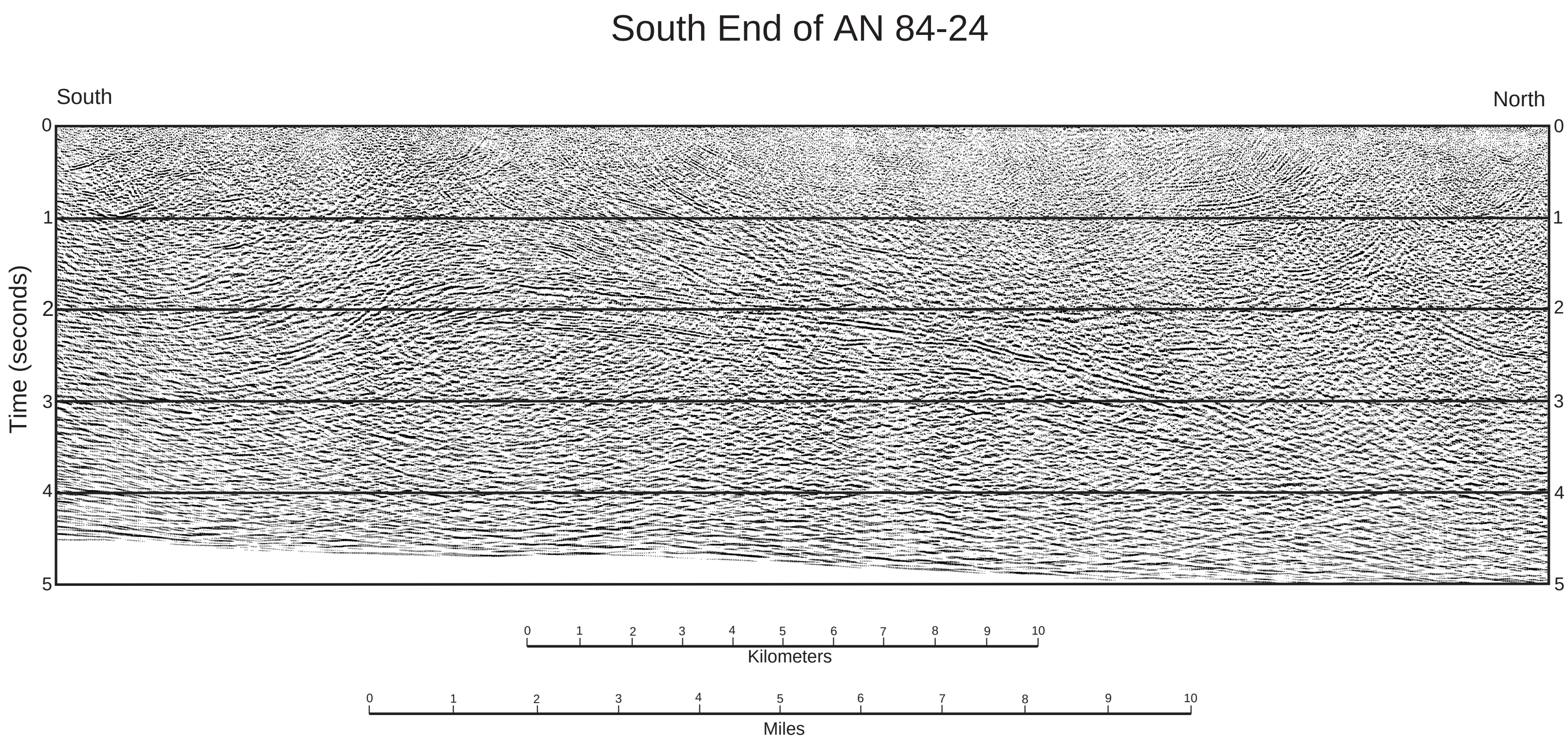

Figure NA9b. Seismic profile AN 84-24 without the interpretive overlay.

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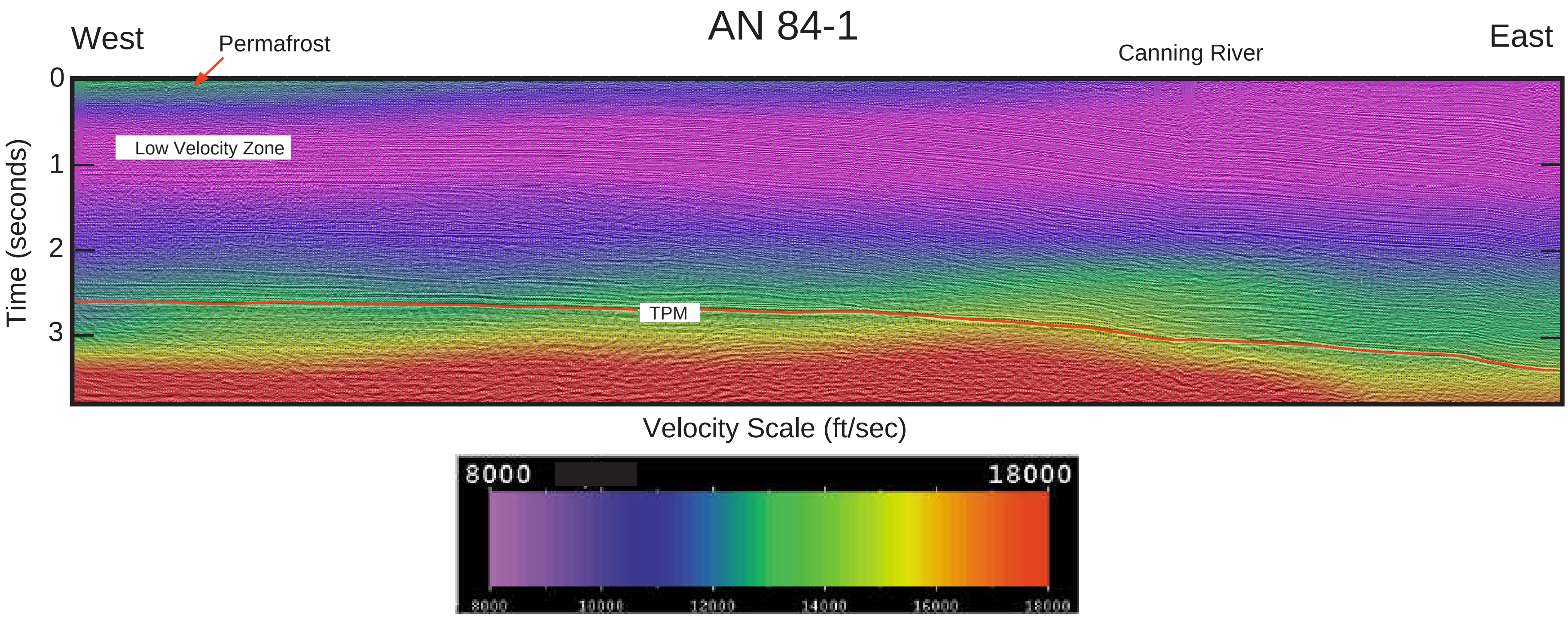

Figure NA10. The smoothed interval velocity profile for the AN 84-1 seismic profile demonstrates well behaved gradual velocity gradients which are typical in the undeformed northwestern part of the 1002 area where the seismic data quality was extremely good. AN 84-1 is ~25 miles long (see Fig. NA1 for location). The permafrost (~13,000 ft/sec) disappears near the Canning River, which causes a travel time delay of up to 0.3 second relative to thick permafrost area to the west (south on north-south profiles). The distortion of ray paths near the Canning River also causes an erroneous high velocity anomaly just above the TPM beneath the Canning River. TPM, top of the pre-Mississippian.

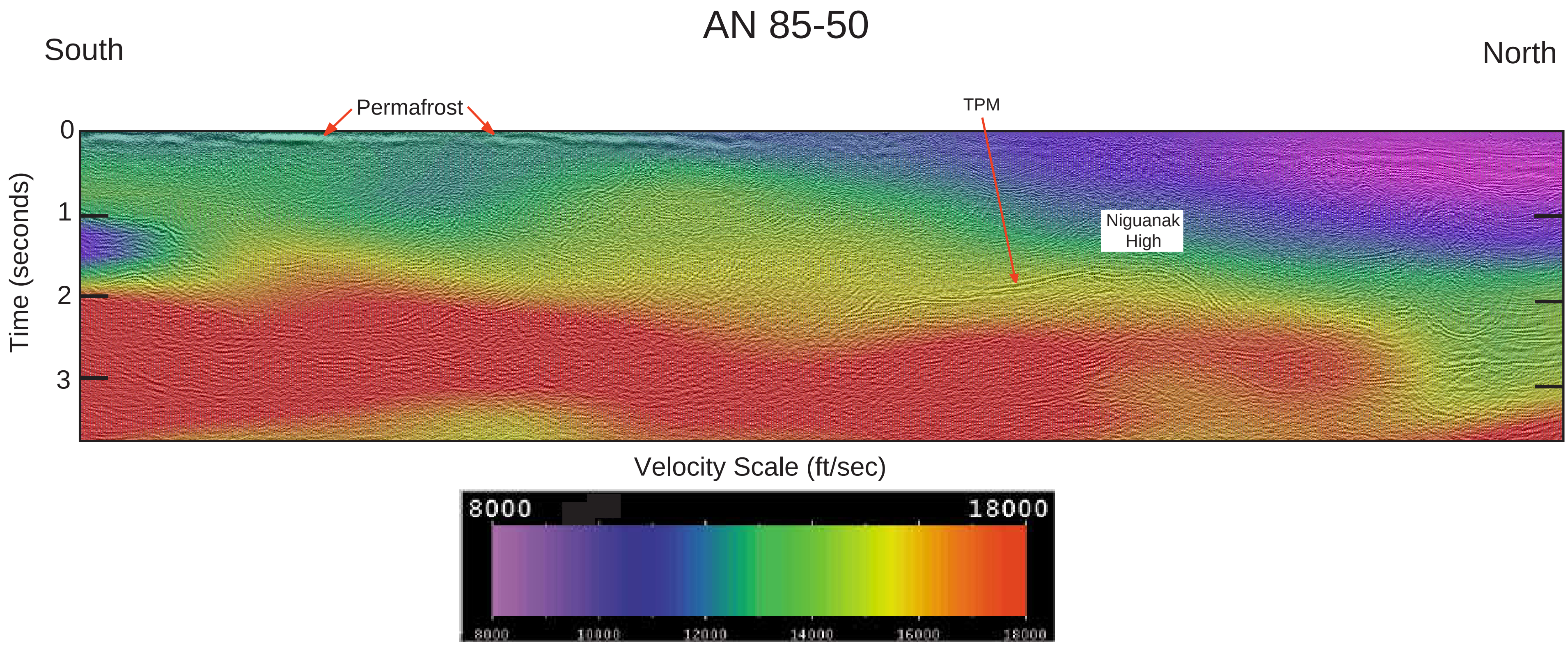

Figure NA11. This is a smoothed interval velocity profile for seismic line AN 85-50, which crossed north-south over the crest of the Niguanak high. AN 85-50 is ~29 miles long (see Fig. NA1 for location). The shallow velocities decrease from ~13,000 ft/sec in the south to ~8,000 ft/sec in the north, near the coastline where the permafrost disappears. Although the velocity data were generally not as good in the deformed part of the 1002 area as in the undeformed part due to complex ray paths through the shallow thin-skin deformation, systematic velocity trends were observed from north to south and from shallow to deep. The velocities beneath the crest of the Niguanak high were consistently between 15,000 to 18,000 ft/sec for all of the north-south seismic profiles over the Niguanak high. Due to the smoothing over 250 msec time windows, the transition beneath the TPM (top of the pre-Mississippian) appears more gradual than the true velocities must be. The low velocities between 1.0 and 1.6 sec at the south end of AN 85-50 are probably an edge effect due to low CDP fold and/or raypath distortion.

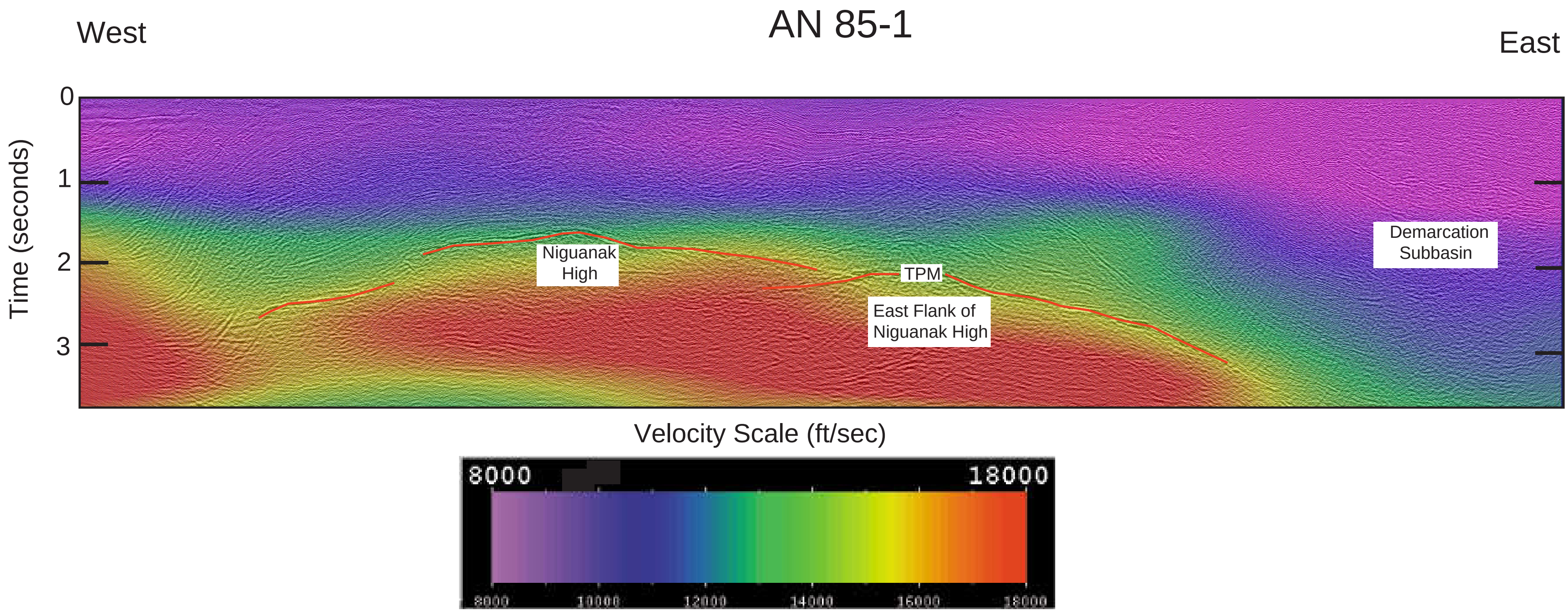

Figure NA12. The smoothed interval velocity profile along east-west seismic profile AN 85-1 shows velocities between 8,000 - 9,000 ft/sec in the upper 0.5 sec across the entire line with little or no indication of significant permafrost in this area. AN 85-1 is ~30 miles long (see Fig. NA1 for location). The low velocity zone extends nearly down to 2.0 sec at the east end of this profile, in the Demarcation Sub-basin. As with the north-south seismic profiles over the Niguanak high (Fig. NA11), the interval velocities beneath the crest of the Niguanak high are between 15,000, - 18,000 ft/sec. The very topmost part of the high appears to have velocities as low as 14,000 ft/sec, but this is an artifact caused by the lateral smoothing algorithm. Discreet interval velocity measurements between the crest of the Niguanak high and deeper intermittent reflection events were also consisitently between 15,000 -18,000 ft/sec. TPM, top of the pre-Mississippian.