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DEPOSITIONAL HISTORY AND SEISMIC STRATIGRAPHY OF LOWER CRETACEOUS ROCKS, NATIONAL PETROLEUM RESERVE IN ALASKA AND ADJACENT AREAS

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ABSTRACT

The addition of much seismic and well data since 1974 in National Petroleum Reserve in Alaska has aided considerably in understanding the depositional history of Lower Cretaceous rocks in that part of the Colville basin. These rocks range in thickness from in excess of 7,000 m along the basin axis on the south to about 1,200 m on the Barrow arch along the north coast. Seismic and well data indicate that early Neocomian strata on the north flank of the basin consist of southward prograding marine shelf and slope sequences of shale with minor sandstone units. Uplift, erosion and subsequent transgression by the pebble shale unit on the northernmost flank of the basin in late Neocomian time terminated the northern provenance. Following pebble shale deposition, the basin was downwarped and little, if any deposition occurred on the north flank until distal deep-water deposits of the Torok Formation onlapped and downlapped the south-dipping flank in mid or late Albian time.

The depositional history of the south flank of the Colville basin is inferred from outcrop data. Turbidites of the early Neocomian Okpikruak Formation were derived from the ancestral Brooks Range on the south, and subsequently were thrust northward to their present position in late Neocomian or Aptian time. The early Albian Fortress Mountain Formation, which is as much as 3,000 m thick and consists largely of deep-water deposits, unconformably overlies the Okpikruak and older rocks on the southernmost flank of the basin. Filling of the Colville basin occurred in mid to late Albian time as thick prodeltaic and deltaic deposits of the Torok Formation and Nanushuk Group, respectively, prograded across the basin from the south on the south side of the basin, but principally from the west-southwest over most of the basin.

Regional subsidence (or sea-level rise) and subsequent transgression by the Upper Cretaceous Colville Group approximately coincided with the termination of Early Cretaceous deposition.

INTRODUCTION

Lower Cretaceous rocks, which are widespread throughout National Petroleum Reserve in Alaska and adjacent areas north of the Brooks Range, make up the major part of the thick sedimentary fill of the Colville basin. These strata range from deep-water flyschoid deposits to shallow-marine and nonmarine deltaic deposits. The addition of much seismic and well data since 1974 has aided considerably in understanding these rocks in the subsurface. These latest data resulted from an active exploration program begun in 1974 by the U.S. Navy in Naval Petroleum Reserve No. 4 (NPR-4). In 1977, the Reserve was transferred to the jurisdiction of the Department of the Interior and the area became known as National Petroleum Reserve in Alaska (NPRA). The U.S. Geological Survey took over the continuation of the exploration program at that time. The additional data include over 20,000 kilometers of seismic lines covering much of NPRA with a 10-20 km grid, and 28 exploratory wells for a total of over 50 wells in and adjacent to NPRA (fig. 1). The purpose of this report is to present an interpretation of the depositional history of Lower Cretaceous rocks in NPRA and adjacent areas based on the latest seismic and well data, and on information reported from outcrops in the southern part of the Colville basin.

Many studies have been made of the Cretaceous rocks that crop out in the foothills belt north of the Brooks Range. Some of this work is included in Gryc and others (1956), Chapman and Sable (1960), Detterman, Bickel, and Gryc (1963), Patton and Tailleur (1964), Chapman, Detterman, and Mangus (1964) and Ahlbrandt, Huffman, Fox, and Pasternak (1979). The earlier studies established the stratigraphic sequence in a structurally complex area in which many of the outcrops are limited to discontinuous river cuts or ridge tops. Because of structural complications, direct correlations into the subsurface could be made only with the Nanushuk and Colville Groups in the northern foothills, where several Nanushuk tests were drilled in the late 1940's and early 1950's. Payne and others (1951) presented a synthesis of all the data applying to the NPRA area. Later, Collins and Robinson (1967) made a subsurface study using data from the available wells, mostly Nanushuk tests. With the aid of recent seismic lines and many well penetrations, additional subsurface stratigraphic studies have been made of the Nanushuk Group and associated strata by Bird and Andrews (1979) and Molenaar (in press). Interpretations made of the basin geometry and depositional history of units in those reports will be repeated here in context with the overall Lower Cretaceous depositional history.

In the discussion of the depositional history of the different units, well data, including paleontology, and seismic data are used almost exclusively to interpret relations in the northern foothills and coastal plain areas. Surface data and some well data are used in the southern parts of the northern foothills, and surface data are used exclusively to interpret the depositional history in the southern foothills and Brooks Range.

Seismic data are fair to good in most of the coastal plain area where the structure is simple. In the northern foothills, tracing seismic reflections is more difficult, especially in the shallower part of the section because of structural complications in the thrust-faulted anticlines.

The quality of the seismic data across the structurally complex southern foothills area is inadequate to correlate stratigraphic units of the outcrop area of the southern foothills with subsurface units of the less structurally complex areas to the north. However, certain consistent depositional patterns evident on north-south seismic lines in the coastal plain and northern foothills are extrapolated into the areas of poor-quality seismic data in the southern foothills. Consequently, stratigraphic relations in that area are highly interpretative.

STRATIGRAPHIC ANALYSES AND METHODS

The discussion of each formation or rock unit is aimed at placing the different lithologies or units in a meaningful stratigraphic sequence in relation to the overall depositional history. This is accomplished by interpreting the depositional environments of each unit in context with their ages and lithologies, and relating them to the physical relationships as depicted by seismic data. Specific age data on some of the stratigraphic units are sparse or subject to interpretation. The ages used in this report are those generally accepted or published, except for new data acquired on some of the wells which required some reinterpretation. Figure 2 shows the generalized temporal relations of the stratigraphic units discussed in this report.

For purposes of regional synthesis and facies projection, the depositional environments of the various sedimentary units or facies are divided into three categories; these are nonmarine, shallow-water marine, and deep-water marine. By recognizing these three categories, each unit can be placed in its proper paleogeographic position in relation to the depositional basin at that particular time. The three major facies usually are coeval with each other in the overall depositional pattern, although in some cases a shallow marine facies may be bypassed or a nonmarine facies may not be preserved along the basin edge. This occurs in the orogenic deposits such as the Fortress Mountain Formation in some areas (Molenaar and others, 1981). Seismic sections in the northern part of NPRA show the coeval stratigraphic relationships clearly. Shallow marine and nonmarine strata are represented by topset reflectors. Slope deposits are represented by inclined foreset reflectors that dip basinward at angles of less than a degree to as much as 6 degrees as measured from topset reflectors. Deep-water basinal deposits are represented by bottomset reflectors and the lower part of foreset reflectors. In effect, the profiles of correlative topset, foreset and bottomset reflectors represent the compacted depositional profile of the basin. At the time of deposition, the angle and topographical relief of the basin slope were somewhat greater.

In the discussion of the stratigraphic units, the terms topset and shelf, foreset and slope, and bottomset and basinal are used interchangeably. These terms correspond to undaform, clinoform, and fondoform, respectively, of Rich (1951).

Two prominent seismic reflectors that are mappable over most of the coastal plain and northern foothills areas have provided excellent datums with which to relate underlying or overlying seismic stratigraphic horizons. One seismic reflector represents the pebble shale unit of Neocomian Age, and the other reflector is from the top of the Triassic Shublik Formation. Except for the pebble shale unit in the southern part of its mapped area, both units are considered to be time synchronous, and to have been deposited on a near-horizontal surface.

The seismic-stratigraphic terms used in this paper are from Mitchum (1977, p. 205). Toplap refers to the termination of strata against overlying topset beds as a result of nondeposition, i.e., sedimentary bypassing, with perhaps only minor erosion. This could be caused by a relative stillstand of sea level, or, if erosion is involved, by a temporary relative sea level drop. Downlap refers to a base-discordant relation in which initially inclined (foreset) strata terminate downdip against an initially horizontal or inclined surface. Onlap refers to a base-discordant relation in which initially horizontal strata terminate progressively against an initially inclined surface, or in which initially inclined strata terminate progressively updip against a surface of greater initial inclination.

In the northern part of NPRA, where the structure is simple, the number of well penetrations and close spacing of seismic lines provide excellent data for interpreting the overall depositional history, especially of the Torok-Nanushuk section. Interpretations can be made with a fair degree of confidence on (1) stratigraphic correlations, (2) progradational directions, (3) basin slope angle, (4) paleobathymetry of basin, and (5) width of the basin shelf.

Much of the interpretation of the depositional history of the Lower Cretaceous rocks of the Colville basin is based on the cross sections shown in figures 3 and 4, and 6A to E. Figures 3 and 4 show the inferred depositional relations across the Colville basin at 3 different periods during Early Cretaceous time. Although these cross sections are based on data in the eastern part of NPRA and adjacent areas, similar depositional patterns are indicated throughout NPRA. In addition, because there are much more data available for the Nanushuk Group and Torok Formation, 5 more-detailed, interpretive stratigraphic cross sections for these units are shown in figures 6A to E.

LOWER CRETACEOUS ROCKS

General

The Colville basin is filled largely with a thick section of Lower Cretaceous siliciclastic rocks. The basin is asymmetric and is bounded on the south by the Brooks Range orogenic belt. The gentle north flank of the basin is bounded by the Barrow arch, which during earliest Cretaceous time was part of a mildly positive area, and later during most of Cretaceous time, was a passive submarine ridge that separated the Colville basin from the continental margin and the Canada basin, an oceanic basin to the north.

The Lower Cretaceous section ranges in thickness from about 1,200 m in northeastern NPRA to over 7,000 m in the basin axis in the southern foothills. Two general types of source areas for these rocks are recognized. A southern and west-southwest source area that contributed lithic-rich clastics dominated sedimentation throughout Early Cretaceous time. These rocks are known as the Brookian sequence. A northern source area, which was the dominant or only source area prior to Cretaceous time, contributed primarily finer clastics during earliest Cretaceous time on the north flank of the basin. Rocks derived from this northern provenance are more quartzose and mineralogically mature, and are called the Ellesmerian sequence.

Some of the Lower Cretaceous stratigraphic units of the Colville basin are not present over the entire basin. Some are facies equivalent of each other and some units are restricted geographically; coeval strata being represented by condensed sections or depositional hiatuses. The units involved are, in generally ascending order, a previously unnamed Neocomian shale unit in northern NPRA herein assigned to the Kingak Shale, the Okpikruak Formation and an unnamed clay shale unit of the southern foothills, the informally named pebble shale unit or member of the Kongakut Formation, the Fortress Mountain Formation of the southern foothills, the Torok Formation, and the Nanushuk Group (fig. 2). The uppermost part of the Nanushuk ranges into the Upper Cretaceous (Cenomanian).

With the exception of part of the Nanushuk Group and a small part of the Fortress Mountain Formation, all Lower Cretaceous rocks of the Colville basin are considered to be marine in origin.

Neocomian (Early Cretaceous) Part of Kingak Shale

In the northern part of the coastal plain of NPRA, the Kingak Shale of Jurassic age and older rocks underlie the regional pebble shale unconformity as indicated by well and seismic data. The truncation plain of the unconformity cuts progressively older strata from south to north toward the Barrow arch. Conversely, progressively younger strata are preserved under the unconformity to the south in the coastal plain and northern part of the northern foothills. Foraminiferal and palynological data from wells in those areas indicate that shale of Neocomian Age is present below the unconformity (NPRA Palynology and Micropaleontology Reports, 1980). The thickest well penetration of the pre-pebble-shale-Neocomian section was in the Tunalik No. 1 well on the west where it is 754 m (2,475 ft) thick. The amounts penetrated by other wells and the approximate subcrop limit of these Neocomian strata under the pebble shale unconformity are shown in figure 1. The pre-pebble-shale-Neocomian section consists of dark-gray to black micaceous marine shale containing minor floating fine sand grains, and includes a small amount of sandstone in the western part of the area. Because this Neocomian section is lithologically similar to, and appears to be part of, the same gross depositional cycle as the underlying Kingak Shale of Jurassic age, it is herein recommended that it be included in the Kingak Shale.

The Kingak Shale was named by Leffingwell (1919, p. 179) for shale exposures on the southeast side of the Sadlerochit Mountains in northeastern Alaska. At that locality the Kingak is all Jurassic in age; however it underlies the regional Early Cretaceous or pebble shale unconformity in that general area (Detterman and others, 1975, p. 21) similar to the relations noted in the northernmost part of NPRA. In the Bathtub Ridge area 110 km southeast of the type area, a clay shale unit at least 100 m thick containing Valanginian (Early Cretaceous) fossils underlies the Kemik Sandstone and pebble shale unit (Detterman and others, 1975, p. 22). Also, in the Kemik Creek area 95 km west-southwest of the type area, a Berriasian fossil, *Buchia subokensis*, was collected from shale at least 200 m below the Kemik Sandstone (Molenaar, unpublished data). In addition, on the east bank of the Shaviovik River a few km farther southwest, a possible *Buchia sublaevis* of Valanginian Age was collected a few meters beneath the Kemik Sandstone. This shale has been mapped as Kingak Shale (Keller and others, 1961), and appears to be continuous with underlying shale of Jurassic age. As in the NPRA area, it appears that progressively younger shale is preserved under the unconformity to the south from the type area. Therefore, the inclusion of the pre-pebble-shale-Neocomian strata in the Kingak is logical and will simplify nomenclature problems throughout northern Alaska.

Foraminiferal and palynological data in the northern part of NPRA indicate that the Neocomian shale overlies shale of Kimmeridgian to Tithonian (Late Jurassic) Age in the east, and shale of Oxfordian (Late Jurassic) Age on the northwest. Whether this break on the west represents an unconformity, a depositional hiatus i.e., a toplap relationship, or an as yet inadequately sampled condensed section is unknown. The missing Kimmeridgian-Tithonian section or depositional hiatus on the west may be similar to apparently missing Jurassic intervals that have been indicated within the Kingak elsewhere (Imlay and Detterman, 1973, p. 12).

A suggestion of a toplap relation within the Upper Jurassic part of the Kingak Shale is indicated on seismic line line 7X-75-G-1182 south from the Inigok No. 1 well. This corresponds to a depth of about 11,000 ft (3,353 m) in the well. Similar relations may occur in the Cretaceous part also, but seismic reflections are not prominent enough to document a toplap relationship. The main depositional feature, as indicated by moderate to weak seismic reflections, however, is that the total Kingak Shale, as defined above, is a southward prograding shelf and slope sequence as shown in figures 3 and 7. The northern (Ellesmerian) provenance, the clastic source for earlier formations, still existed in early Neocomian time.

Paleontologic data from wells and seismic data indicate that the truncated northern limit of the Cretaceous portion of the Kingak Shale trends west-northwest from approximately midway between the Inigok No. 1 and East Teshekpuk No. 1 wells (fig. 1). To the south of this line, seismic reflections indicate the Cretaceous portion to be part of a shelf sequence, i.e., topset beds, that grade into south-dipping slope beds to the south and possibly into southwest-dipping slope beds on the far west. Two zones containing thin sandstone beds, which occur in the lower or middle part of the slope facies according to seismic data, were penetrated in the Tunalik No. 1 well on the west. One zone at 12,500 to 12,600 ft (3,810 to 3,840 m) in the well had a significant gas show. Also, immediately below the pebble shale unconformity in this well is a 160-m-thick sandstone and shale zone that appears to either be at a shelf break, or in the upper part of the slope as indicated by seismic data.

In the northern part of the northern foothills, the Cretaceous part of the Kingak downlaps to within 100 m of the Triassic Shublik reflector. Similarly, the underlying Jurassic part of the Kingak grades from shelf (topset) beds to slope (foreset) beds, but the shelf break is farther north than that indicated for the Cretaceous part. To the south the Jurassic part is a thin condensed section or is missing owing to deep water nondeposition. Correspondingly, the Cretaceous part is thicker to the south in the northern part of of the northern foothills even though the interval between the pebble shale and Shublik reflectors remains fairly uniform in most of this area (fig. 3). However, farther south the total Kingak Shale thins markedly as the overlying pebble shale unit converges toward the underlying Shublik Formation (figs. 3 and 8).

The present slope angle of the foreset beds of the Kingak in relation to topset beds is gentle, ranging from less than 1 degree to slightly greater than 2 degrees. The water depth in which the basinal or condensed Kingak bottomset beds were deposited was somewhat greater than the 400 to 900 m indicated by the present relief on the compacted south-dipping foreset beds.

Neocomian Rocks of the Southern Foothills

General

There is no control on the Neocomian section between the northern foothills and outcrops of coeval strata along the southern part of the southern foothills. In the southern foothills, the strata are involved in complex structural relations, and two separate facies of early Neocomian age are recognized. One is a thin clay shale unit containing thin lenses of coquina limestone. This unit is considered to be a stable shelf facies (Jones and Grantz, 1964, p. 1472; Brosgé and Tailleur, 1971, p. 82), and is informally referred to as the clay shale unit in this report. The second facies is a thick turbidite sequence known as the Okpikruak Formation. In some areas, it appears that the Okpikruak Formation overlies the clay shale unit, but fossils indicate the Okpikruak is the same age as, or older than the clay shale unit. Evidently, the Okpikruak Formation had been thrusted to its present position from an original position many km to the south relative to underlying autochthonous rocks (Mull and others, 1976, p. 24).

Okpikruak Formation

The Okpikruak Formation of Neocomian Age was named for a sequence of interbedded graywacke sandstone and shale that occurs in thrust slices along the structurally complex north side of the Brooks Range (Gryc and others, 1951, p. 159). Because of structural complexities, a complete section of Okpikruak is not exposed at any one locality so the full thickness of the formation is unknown. The thickest measured section is about 580 m (Patton and Tailleur, 1964, p. 447).

The Okpikruak Formation is a basinal turbidite deposit of Brookian origin, i.e., southern source. Although some conglomerate is present, especially in the lower part (Patton and Tailleur, 1964, p. 446), much of the sandstone in the Okpikruak is fine to very fine grained and occurs in thin graded beds. In most outcrop sections, sandstone makes up only 10 to 25 percent of the section although a few sections contain as much as 60 percent sandstone (Patton and Tailleur, 1964, p. 446). The remaining portions are siltstone and shale. In the submarine fan facies model as described by Mutti and Ricci Lucchi (1972), most of the Okpikruak Formation outcrop belt would be considered an outer-fan or distal facies.

In addition to the thin-bedded turbidite sequence, Mull, Tailleur, Mayfield, and Pessel (1976, p. 25) described an associated sedimentary chaos or olistostrome that occurs in many areas along the front of the Brooks Range. This unit would indicate a more proximal position to the ancestral Brooks Range front. The juxtaposition of these different Okpikruak facies may be the result of thrust displacement of different thrust sheets.

On the basis of the fossils *Buchia okensis, B. subokensis, B. crassicollis* and *B. sublaevis*, the Okpikruak Formation is considered to be of Berriasian to Valanginian Age (Jones and Grantz, 1964, p. 1464).

Inasmuch as the Okpikruak Formation exposed in the outcrop belt is largely a distal, deep-water, basinal facies, and partially coeval rocks are a condensed section of probable shallow marine shales, it appears that Okpikruak facies would not occur anywhere in the subsurface north of the outcrop belt. It is interpreted in figure 3 as having originated far south of its present position, and subsequently having been thrust northward to its present position. The Okpikruak could conceivably underlie Paleozoic rocks in much of the present-day Brooks Range.

Clay Shale Unit

The clay shale unit or coquinoid limestone-bearing shale unit has been reported from many localities along the Brooks Range front. In many places, this unit has been described as resting directly on Triassic rocks, and in some places on a thin Jurassic shale section with no intervening Okpikruak turbidites (Jones and Grantz, 1964, p. 1471). Because of the structural complexities and the subdued nature of outcrops of the clay shale unit, no accurate measurements of its thickness are available. Most descriptions indicate it is thin, possibly 100 m (Brosgé and Tailleur, 1971, p. 84). The top is usually covered or is overlain by the Fortress Mountain Formation or by overthrusted older rocks.

Crane and Wiggins (1976, p. 2177) suggested the name Ipewik Formation for the clay shale unit in the central and western Arctic region. In the western part of NPRA and farther west, a quartz sandstone unit, which they called the Tingmerkpuk member, was included in the Ipewik. The presence of a clean quartz sandstone in an area that far south is anomalous. It is very dissimilar from the typical lithic-rich or graywacke sandstones typical of southern source or Brookian units, and is more typical of Ellesmerian rocks. Perhaps it had a source to the northwest. Another possibility is that it was derived from the sandy Utukok Formation of the Lisburne Group, or older Devonion clastics, that may have been exposed in nearby thrust sheets (C. G. Mull, oral communication, 1981).

The clay shale unit of the central southern foothills area consists predominantly of black clay shale containing minor lenses of coquinoidal limestone (Brosge and Tailleur, 1971, p. 84). The coquinoid limestone lenses are as much as 2 m thick and are composed almost entirely of broken bivalve shells. The fossils have been identified as *Buchia sublaevis* of Valanginian Age (Jones and Grantz, 1964, p. 1464). The occurrence of fragmented *Buchias* in coquina beds suggests that they were deposited in relatively shallow water, i.e., a shelf environment. Jones and Grantz (1964, p. 1474), and Brosge and Tailleur (1971, p. 82) suggest that an intra basin medial sill or ridge separated the orogenic foredeep to the south, where the Okpikruak turbidites were deposited, from the broad shale basin to the north. Figure 3 shows this interpretation.

An alternate interpretation would be that the clay shale unit may be a distal condensed basinal section of Kingak Shale. This would eliminate the postulated intra-basin, medial sill, but would necessitate that the *Buchias* flourished in water depths of at least 600 m. This is unlikely (D. L. Jones, oral communication, 1981). Still another interpretation would be that the fragmented-*Buchia* beds were displaced from a shelf position into deeper water.

Pebble Shale Unit

The pebble shale unit, an informal but well-known stratigraphic unit of Neocomian Age, is a widespread unit that is present throughout most of the North Slope of Alaska. It is an important unit because (1) its base marks a major regional unconformity throughout northernmost Alaska, (2) it represents the termination of northern source (Ellesmerian) clastics, and (3) it is a distinctive low-velocity shale that can be mapped seismically over most of the area. Hence, it is a good mappable unit in which to relate depositional units above and below. In the northern part of NPRA the pebble shale unit is 70 to 125 m thick, and consists predominantly of organic marine shale containing distinctive floating quartz and chert sand grains and rare pebbles scattered throughout. Locally, a basal transgressive sandstone as much as 15 m thick is developed. This sandstone is probably equivalent to the Kemik Sandstone that crops out in northeastern Alaska. However, its contemporaniety and continuity cannot be demonstrated at this time. Its development may be related to the underlying lithology, e.g., the Ivishak Sandstone being eroded in front of the advancing Neocomian sea.

The rare chert and quartzite pebbles that are scattered throughout the pebble shale unit are an enigma. Rather than being concentrated only at the base of the unit as is common in transgressive shale units, they are scattered throughout most of the unit. The pebble shale unit undoubtedly represents slow deposition over a broad area over a long period of time. Perhaps the pebbles may have been rafted by floating shore ice, kelp or logs, or perhaps they may have been stomach stones from marine vertebrates such as ichthyosaurs.

The pebble shale unit is easily recognizable on gamma-ray and transit-time logs of wells by the abrupt higher transit times and high gamma-ray deflection compared to shales of the overlying Torok Formation and the underlying Kingak Shale. The high gamma-ray deflection is much higher in the upper part of the pebble shale unit, and that part of the unit is frequently referred to as the gamma-ray zone. Both the high gamma-ray radiation and the high transit time may be due at least in part, to the high organic content of the shale.

In northernmost NPRA, the unconformity at the base of the pebble shale unit truncates progressively older rocks from south to north. To the south, however, seismic facies relationships suggest that the erosional unconformity dies out into a conformable shelf and slope facies. In the northern part of NPRA, seismic data show the pebble shale unit as a shelf sequence, but to the south, seismic lines in the westernmost part of NPRA show what is interpreted to be a broad shelf break and slope in which the pebble shale reflector converges toward the Shublik (Triassic) reflector to the south (fig. 8). The Shublik reflector maintains a more constant south dip. The position of the shelf break over which the pebble shale unit was deposited is shown in figure 1. This shelf break can be seen on several of the north-south regional condensed seismic sections.

Micropaleontologic data from wells drilled in NPRA suggest that the pebble shale unit is Hauterivian to Barremian in age (NPRA Palynology and Micropaleontology Reports, 1980). Megafossil data in the NPRA area are lacking, but data have been reported from the Bathtub Ridge area in northeastern Alaska 360 km east of NPRA (Detterman and other, 1975, p. 25). In that area, the Hauterivian ammonite *Simbirskites* sp. occurs in the Kemik Sandstone Member, which underlies the pebble shale member. The pebble shale contains only a few poorly preserved pelecypods of possible Aptian to Albian Age. Inasmuch as the Kemik Sandstone is considered here as part of the pebble shale depositional cycle, it seems more likely that the pebble shale unit is Hautervian to Barremian in age, as suggested by the micropaleotologic data. It is possible, however, that the upper part of the pebble shale unit is a condensed section of Aptian to lower Albian strata.

If the suggested Hauterivian to Barremian age is correct, the pebble shale unit is younger than the clay shale unit and Okpikruak Formation of the southern foothills area. In that area, however, the pebble shale unit has not been recognized with certainty in outcrops. This may be due to its having lost its identifying characteristics, i.e., the floating sand grains and pebbles, or possibly to lack of good outcrops of the soft-weathering shale unit. Another possibility is that thrusting and subaerial erosion was occurring during upper Neocomian time, or strata equivalent to the pebble shale unit were removed by subsequent erosion in the southern part of the southern foothills. Farther north in the southern foothills, however, deep-water facies of the Fortress Mountain Formation overlie or are in close proximity to the clay shale unit in some areas, such as near Brady about 9 km from the mouth of the Kiligwa River in south-central NPRA (Tailleur and Kent, 1953, p. 12). In those areas, the pebble shale unit may either be represented by a condensed section, or possibly time-equivalent strata are included in the lower part of the Fortress Mountain Formation. Additional data are needed on the age of the lower part of the Fortress Mountain Formation in those areas.

Aptian Rocks

Following Neocomian deposition, the Colville trough was significantly downwarped and little, if any, sedimentation occurred in the coastal plain and northern foothills areas on the north flank of the basin until mid or late Albian time. The downwarping affected the entire north flank of the basin, and the south dip apparently steepened to the south as indicated by structure maps on both the pebble shale and Triassic reflecting horizons (NPRA Summary Report: Interpretation of Seismic Data, FY 78).

Deep-water bottomset or basinal beds of Albian Age onlap the south-dipping pebble shale unit as indicated by seismic reflectors in the northern half of the northern foothills (figs. 7 and 8). In the outcrop belt of the southern foothills, the Fortress Mountain Formation of early Albian age apparently unconformably overlies folded Neocomian and older rocks. Large-scale thrusting and folding evidently occurred during Aptian time. Whether or not rocks of Aptian Age were deposited in the Colville basin is not known. Fossils of this age are unknown in northern Alaska. This may be because (1) rocks of Aptian Age are not exposed in northern Alaska, (2) Aptian fossils have not been differentiated from Neocomian or Albian forms, or (3) rocks of Aptian Age are a deep-water unfossiliferous facies. It appears likely that Aptian strata are present as a deep-water facies in the axial part of the

Colville basin. It is also possible that some of the Fortress Mountain Formation may be Aptian or even older in age in the axial part of the basin.

Foraminifera tentatively assigned to the Aptian have been reported from wells in the coastal plain area (NPRA Palynology and Micropaleontology Reports, 1980), but strata in which these foraminifers occur can be traced seismically into beds of Albian Age. The strata thought to be Aptian are a deeper water facies of Albian beds higher on the slope or shelf (figs. 6B to D).

Fortress Mountain Formation

The Fortress Mountain Formation of early Albian Age was named for a thick section of shale, sandstone and conglomerate that unconformably overlies folded Neocomian and older rocks in a broad structurally complex belt along the southern foothills (Patton and Tailleur, 1964, p. 452). The Fortress Mountain formation is about 3,000 m thick at the type section on and adjacent to Castle Mountain 85 km south of Umiat. It is doubtful that the formation is that thick in other areas even though it is incompletely exposed. Thickness variations can be explained by penecontemporaneous folding and local unconformities reported in the southern part of the outcrop belt (Patton and Tailleur (1964, p. 456; Tailleur and others, 1966; Chapman and others, 1964; and Molenaar and others, 1981).

The Fortress Mountain Formation is largely a deep-water orogenic deposits although some of the southernmost exposures are nonmarine in origin. The Fortress Mountain deposits range from fluvial, submarine canyon and inner-fan channel facies on the south to outer-fan and basin-plain facies to the north within the complexly folded outcrop belt of the southern foothills (fig. 4). (See Molenaar, Egbert and Krystinik (1981) for a more detailed discussion of the Fortress Mountain Formation.) It is apparent that facies changes are rapid and that the coarse clastics of the Fortress Mountain Formation grade into and intertongue with shale of the lower part of the Torok Formation to the north. Also, there is much depositional onlap and thinning between the outcrop belt in the southern foothills and the little-deformed belt in the northern part of the northern foothills, where stratal relations can be seen seismically (figs. 4, 7, and 8).

Because the Fortress Mountain Formation becomes thinner bedded and finer grained to the north within the southern foothills, the differentiation between Fortress Mountain and Torok Formation is arbitrary. The placement of this contact in the subsurface in the northern foothills is also complicated by the occurrence of thin-bedded turbidites in the Torok that were derived from Nanushuk deltas to the west or southwest (figs. 4 and 6A). For this reason, Molenaar, Egbert, and Krystinik (1981) recommended that the Fortress Mountain name be dropped as a subsurface unit in the northern foothills and areas to the north. The deep-water sandstones are then included in the Torok Formation and referred to informally as lower Torok sandstones.

Torok Formation

General

The Torok Formation of Albian Age included all strata above the Okpikruak Formation and below the Nanushuk Group as originally defined (Gryc and others, 1951, p. 160). Later, Patton (1956, p. 219) separated out the southern facies, which crop out in the southern foothills and contain a large percentage of sandstone and conglomerate, and called that part the Fortress Mountain Formation. The Torok was retained for the dominantly shale facies that crops out in the northern half of the southern foothills. At the type section in the vicinity of the Chandler River and Torok Creek, an incomplete section of Torok Formation about 1,830 m thick was measured (Patton, 1956, p. 222). The lower part of this section may include distal facies of the upper part of the Fortress Mountain Formation. Because of discontinuous scattered outcrops, structural complications, and intimate intertonguing of the two formations or facies, the mapped contact between the two units in the field is rather arbitrary.

Except for small areas in the northern foothills, where the uppermost part of the Torok Formation is exposed, the Torok is a subsurface formation in the northern foothills and coastal plain areas. Seismic and well data in those areas indicate that the Torok Formation ranges in thickness from about 6,000 m on the south near the Colville River to less than 900 m on the Barrow arch (fig. 10). The thick section on the south includes temporally equivalent-strata of the Fortress Mountain Formation. In constructing the isopach map (fig. 10), attempts were made to remove at least part of the apparent thickening associated with compressional folding and thrust faulting within the Torok shale in the northern foothills. This was accomplished by subtracting the structural relief of the anticlines developed in the overlying Nanushuk Group. The underlying pebble shale reflector beneath the surface anticlines is generally a south-dipping surface (NPRA Summary Report: Interpretation of Seismic Data, FY 78) and is not involved in the folding of the overlying rocks in most of the structures. The folds in the overlying strata apparently are due to incompetent folding or shale flowage caused by the surfacing or dying out upwards of thrust faults within the incompetent Torok shales. Even though all the tectonic thickening in the Torok may not have been accounted for in the southern part of the northern foothills, there is no doubt that the total section thickens markedly to the south from the coastal plain area.

Northern Foothills Area

Much of the southward thickening of the Torok Formation is due to the addition of older Torok beds at the base of the formation (fig. 4). Post-pebble shale onlap, apparently from the south, is clearly shown on north-south seismic lines in the southern part of the coastal plain and northern foothills area (figs. 7 and 8). As much as 1,250 m of section wedges out by onlapping the south-dipping pebble shale unit between the area of the Wolf Creek No. 3 well in the anticlinal belt of the Northern Foothills and the zero edge north of the Inigok No. 1 well, a distance of about 80 km. Similar rates of onlap occur across the entire belt. The average calculated acute angles made by the wedge range from 0.9 to 1.2 degrees. Inasmuch as the onlapping wedge was probably almost flat when deposited, the acute angle of the wedge approximates the south dip of this part of the basin during lower Torok time (less the effects of compaction). The wedge apparently thickens farther to the south, but structural complications in the anticlinal belt preclude seismic definition.

The Inigok No. 1 well penetrated about 150 m of the onlapping wedge, the Oumalik No. 1 well penetrated about 800 m, and the Seabee well penetrated about 1,100 m. The section in these wells is composed of interbedded shale, siltstone, and fine- to very fine grained sandstone, and is interpreted to be basin-plain distal turbidite and shale deposits. The lower part of the wedge was probably derived from the ancestral Brooks Range and is probably equivalent to the Fortress Mountain Formation. However, most if not all of the 800 m penetrated in the Oumalik No. 1 well and all of the 150 m in the Inigok No. 1 well can be traced seismically into westerly dipping foreset (slope) beds and into topset Nanushuk Group deltaic deposits. This indicates that strata equivalent to the Fortress Mountain Formation are probably limited to an area no farther north than the northern foothills.

In addition to the upper part of the apparently northward onlapping wedge being traceable to westerly dipping prodelta slope beds of the Nanushuk delta, there is evidence that the lower part of the wedge was also deposited by east-northeasterly flowing currents. Direction features in distal turbidites of Fortress Mountain outcrops in the northern part of the southern foothills indicate a dominance of east-northeast flowing turbidity currents (Molenaar, Egbert, and Krystinik, 1981).

Coastal Plain Area

The Torok Formation in the northern part of NPRA is represented on seismic lines by, in ascending order, bottomset (basinal), foreset (slope), and topset (shelf) reflectors. The beds represented by these reflectors are time equivalent to each other. Basinal beds can be traced into slope, shelf, and indeed, into deltaic deposits of the Nanushuk Group (figs. 6A-C and 9). In effect, the profiles of these correlative seismic reflections represent the depositional profile of the basin, less the subsequent compaction of the sediments.

The basinal beds of the Torok Formation range in thickness from about 150 m to 700 m in the coastal plain area and thicken to the south, where they include the apparently northward onlapping wedge. The bottomset beds consist of shale, siltstone and thin beds of fine- to very fine grained sandstone. The sandstone beds are thought to be turbidites derived from the temporally equivalent Nanushuk delta to the west-southwest (Molenaar, in press). The water depth in which the basinal beds were deposited is indicated by the calculated present 450 to 1,000 m relief of the slope-foreset beds plus (1) the amount of additional post-depositional compaction of the already deposited and partially compacted sediments below the shelf break and (2) the water depth of the shelf break; the latter was probably no more than 50 to 75 m.

Slope beds make up the major part of the Torok Formation in the coastal plain area. These beds range in thickness from 450 to 1,000 m and consist mostly of shale and siltstone with minor thin sandy zones. The seismic reflectors in this foreset sequence are caused by sandy intervals or low-velocity shale beds (Molenaar, in press). Foreset bedding is best seen on seismic lines in the east and northeast parts of NPRA. In the western part, these features are obscure and less numerous, partly because of poor seismic data in the shallow Nanushuk-Torok interval. Some foresetting can be seen, however, as far west as the Tunalik No. 1 well where the foreset beds are at a much lower angle than to the east. The foreset dip angles, which were calculated relative to the topset beds, range from less than 2° on the west to between 4° and 6° on the east and northeast part of NPRA (figs. 6A-D). These calculations were made on the steeper upper parts of the foresets averaged over at least 4 km of horizontal distance. The variation in slope angle is probably related to the rate of deltaic progradation of coeval Nanushuk deposits. The greater the rate of progradation, the steeper the slope angle. The relief of the foresets from top to base is 450 to 1,000 m, which is the thickness of the slope deposits.

The shelf beds of the Torok Formation consist of shale and siltstone with occasional thin sandstone beds, and range in thickness between a few m to as much as 335 m. This range is due to the balance or imbalance between rates of deposition and rates of subsidence. Also, because the upper part of the Torok grades into, and intertongues with shallow marine sandstones of the Nanushuk Group, the selection of the Nanushuk-Torok contact is arbitrary in many areas.

Robinson, Rucker, and Bergquist (1956, p. 223) applied the name Oumalik Formation to the section between 4,860 and 10,880 ft (1,481 and 3,316 m) penetrated in the Oumalik test well No. 1, and they also applied the name Topagoruk Formation to the section between 1,350 and 3,900 ft (411 and 1,189 m) penetrated in the Topagoruk test well No. 1. Because the Oumalik is now recognized as Torok Formation (fig. 6A), and the Topagoruk is part of the highly time-transgressive transition zone between the Torok Formation and Nanushuk Group (fig. 6B), it is herein recommended that the Oumalik and Topagoruk names be abandoned.

In the northeastern part of NPRA in the area from the Fish Creek wells to beyond the Atigaru Point No. 1 well, the lower part of the Torok is disturbed as indicated by seismic data (fig. 6D). Inasmuch as this interval is laterally adjacent to bottomset beds and underlies foreset and bottomset beds, the disturbed interval is thought to have been caused by large-scale submarine slumping. In some of this area, the pebble shale unit is missing, at least in part, indicating either that it was involved in the slumping, or that it was scoured by submarine currents which may have triggered the subsequent slumping. In either case, the areal association of the slumping and scouring suggests that they were caused by related events.

In the northern part of NPRA where the data are well displayed, bottomset beds downlap onto or near the pebble shale unit (figs. 6B-D and 9). Because these bottomset beds can be correlated seismically to beds of late Albian age, the hiatus or thin interval of Torok between these downlapping beds and the pebble shale unit is interpreted to be a deep-water condensed or non-depositional zone representing part of Neocomian, all of Aptian and much of Albian time. The thickness of this interval is less than the resolution of the seismic data, that is, less than 25 m. Strata represented by this time period may indeed be included in the upper part of the pebble shale unit. This starved depositional system is interpreted to have occurred as a result of the deeper part of the Colville basin to the south receiving all the sediments derived from the south and southwest after deposition of the pebble shale unit. This is shown seimically by the progressively northern onlap of older Torok strata including probable equivalents of the Fortress Mountain Formation (fig. 4). It wasn't until the latest stages of the Nanushuk-Torok depositional cycle that the Colville basin was filled enough for sediments to reach the northern part of NPRA. A similar depositional pattern continues to the northeast of the Nanushuk depositional limit in younger Cretaceous and Tertiary formations. On seismic lines in the northeastern part of NPRA, topset, foreset, and bottomset bedding can be seen in the overlying shales of the Colville Group (figs. 6D and 9). In the Prudhoe Bay area, bottomset beds of the Colville Group downlap onto or near the pebble shale unit (Bird and Andrews, 1979, p. 35).

Nanushuk Group

General

The Nanushuk Group of Albian to Cenomanian Age is a thick deltaic deposit that crops out in the northern foothills and is present in much of the subsurface in the western and central North Slope. It ranges in thickness from at least 3,444 m in outcrops at Corwin Bluff (Smiley, 1969) along the Chukchi Sea on the west to a pinchout edge in the area of the present Colville delta on the east (fig. 11). The thickest subsurface penetration is about 1,900 m (top eroded) in the Tunalik No. 1 well on the west.

The lower part of the Nanushuk consists of a thick sequence of intertonguing shallow marine sandstones and neritic shales and siltstones that grade seaward into the Torok Formation. The upper part of the Nanushuk Group consists of a dominantly nonmarine facies of paludal shale, coal, and fluvial sandstone that grades into the marine facies. Conglomerate is present, primarily in the fluvial facies, in the southern part of the outcrop belt, which is more proximal to the source.

Two delta systems were recognized in outcrop studies by Ahlbrandt, Huffman, Fox, and Pasternack (1979, p. 17); the Corwin or western delta, and the Umiat or southern delta. Both deltas were river dominated, but to a lesser extent in the Umiat delta. The Corwin delta was a high-constructional delta and had a low sand-high mud content in contrast to the Umiat delta. Paleocurrent directions in outcrops (fig. 12), indicate that the Corwin delta was probably derived from a source area to the southwest. Because the Corwin delta dominated the depositional patterns of the Nanushuk Group, a source area encompassing a large drainage area probably extended far to the west or southwest in the area of the present Chukchi sea or beyond. (Molenaar, in press). The Umiat delta had a source to the south in the ancestral Brooks Range. In addition to the Umiat delta, there were probably many small deltas emanating from the ancestral Brooks Range (fig. 13).

On seismic sections, the Nanushuk Group is represented by topset reflectors that can be traced seaward into offshore or deeper water deposits of the Torok Formation (fig. 9). These relations are shown by five cross sections that correlate the Lower Cretaceous rocks in most of the wells throughout NPRA and adjacent areas (figs. 6A-E). The correlations in these sections are based on lithology and seismic data. The datum used is the base of the overlying Colville Group where it is present. In other areas, assumed near-horizontal time-correlative beds or reflections in the lower part of the Nanushuk Group between adjacent wells are used.

On the cross sections, the Nanushuk Group is divided into a lower dominantly marine facies and an upper dominantly nonmarine facies to show the lateral relationships. These major facies are the basis for the differentiation of most of the formations of the group. The relationships and names of the formational units of the group that were described by Detterman (1956) from outcrops in the Colville River area southeast of NPRA, and by Sable (1956) from outcrops on the west side of NPRA are portrayed on the cross sections. Two of the cross sections (figs. 6D and E) are tied to outcrop sections south of Umiat where some of these units were orignally named. The outcrop sections are portrayed in a very generalized way to show the gross facies relationships.

The Ninuluk Formation of Cenomanian Age occurs in the upper part of the Nanushuk Group in the outcrop belt in the Chandler River-Killik River area (Detterman, 1956; Detterman, Bickel and Gryc, 1963; and Chapman, Detterman and Mangus, 1964). It is a marine unit that intertongues with the nonmarine Niakogon Tongue of the Chandler Formation (of the Nanushuk Group), and attains a thickness of as much as 350 m (Detterman and others, 1963, p. 264). As portrayed on the cross sections (figs. 6D and E), it is interpreted as representing deposition by the southern-source Umiat delta during the time of the initial Colville transgression farther north. In other words, the Umiat delta was still actively aggrading after the east-northeastward prograding delta to the north became inactive and was being transgressed by the Colville sea.

Depositional Patterns

Seismic data indicate that the major part of the Nanushuk delta prograded east-northeastward across the subsiding Colville basin. This is indicated by foreset dip directions in the underlying prodelta slope deposits of the Torok Formation (fig. 12). The overall prograding regressive sequence was interrupted many times by marine transgressions due in part to delta shifting, but more importantly, to episodic pulses of basin subsidence. Except for the amount of compaction of underlying sediments, basinal subsidence (or relative sea level rise) is necessary to deposit thick multicyclic shallow marine sequences, or to account for the upward change in stratigraphic position (stratigraphic rise) of the sequence during progradation. As a result, the Nanushuk is not one simple regressive sequence but a composite of intertonguing shallow marine shale, shallow marine sand and subaerial delta-plain deposits.

The total incremental stratigraphic rise (a measure of relative sea-level rise and (or) basin subsidence) of the base of the Nanushuk from the Tunalik No. 1 well on the west to the Atigaru Point No. 1 well on the east, a distance of 350 km, is about 2,100 m. However, subsidence was not uniform throughout the basin as indicated by less and (or) later subsidence of the Barrow arch. This is based on the following evidence and reasoning: (1) Greater subsidence is required to accomodate the thicker Nanushuk-Torok section in areas to the south and west than in areas of the Barrow arch to the north and northeast. (2) Inasmuch as both the basinal and the shelf beds were probably essentially flat when deposited, differential subsidence during Nanushuk-Torok time is necessary to account for some of the basinal beds of the Torok dipping west or southwest (toward the depositing currents) in respect to the later-deposited overlying shelf beds. These features are shown in figures 6B and C. Indeed, much of the differential subsidence of the basin may be due to differential sediment loading.

During most of the Nanushuk-Torok depositional cycle, the Barrow arch was a passive submarine high that separated the Colville basin from the Canada basin to the north. Thus, the Barrow arch was partly responsible for the easterly directed progradation of the deltaic system. The Corwin delta, however, is considered to have played the major part in influencing the direction of progradation.

Sedimentary bypassing or even minor beveling of shelf sediments in the Nanushuk-Torok interval is suggested by apparent toplap relations indicated by some seismic lines. The dominant pattern, however, is one of constructional progradation. The width of the prodelta shelf of the Corwin delta ranged between 75 and 150 km as shown on the cross sections. This is determined by closely correlating seismic data to the marine-nonmarine boundary or transition interpreted in well logs, and tracing a seismic reflections to the shelf break.

Because of the relatively greater subsidence on the south side of the basin, the southern-source deltas probably did not extend very far to the north. The growth of the Umiat delta southeast of NPRA, however, coincided with the presence of the prodelta shelf of the larger easterly prograding western delta so that the southern-derived clastics could be distributed along the north-northwesterly trending shoreline and shelf, probably by longshore currents (fig. 13). It is postulated that during late Nanushuk time, wave action and longshore currents increased because of the more open marine conditions that prevailed after the Barrow arch subsided enough to lose its silling effect on the Colville basin. It is further postulated that prior to that time, marine circulation was somewhat restricted in the Colville basin. This may account for the low marine energy and the relative paucity of good marine fauna in much of the Nanushuk in the western part (Molenaar, in press).

Thus the eastern part of NPRA along the alignment of the Umiat, Inigok and Simpson wells has thicker, better sorted, cleaner sandstone units. In addition, the sand contribution from the Umiat delta was relatively richer in quartz (Bartsch-Winkler, 1979, p. 64), especially farther north where labile constituents probably were removed by winnowing and abrasion. Alternate hypotheses for the thicker sandstone buildups along that trend may be that increased wave energy concentrated sand into thicker units, or that the influx of a western fluvial system in late Nanushuk time was responsible for the increase in sand percentage. Evidence for such a fluvial system is lacking, however, because of erosion of that part of the section to the west.

In the area of Dease Inlet southeast of Pt. Barrow, a large incised canyon or valley, known as Simpson Canyon, has cut out the Nanushuk Group and much of the Torok Formation in the subsurface (figs. 6E and 13). This canyon, which is filled with shale of the Colville Group, is considered to be cut by submarine processes during the late stages of the Nanushuk regression (Payne and others, 1951). After the Nanushuk delta had prograded across the Barrow arch, and was open to the Canada basin to the north, a canyon-cutting phase was probably initiated. Sea level rise and the Colville transgression terminated the regression and the canyon cutting. This transgression marks the beginning of the Upper Cretaceous cycle of deposition. Some of the deltaic clastics of this cycle in the area south of Umiat, however, are included in the Nanushuk Group.

SUMMARY OF DEPOSITIONAL HISTORY

Earliest Cretaceous sedimentation in the northern part of NPRA was a continuation of the Jurassic cycle of deposition. This is represented by the southward prograding Ellesmerian shelf and slope shale sequence of the Kingak Shale. On the south side of the Colville basin, turbidites of the Okpikruak Formation were deposited in front of the ancestral Brooks Range orogen, which may have been initiated in Jurassic time. Partly coeval or slightly younger rocks in the area of what is now the southern foothills are represented by a thin condensed section of black shale containing coquinodal limestone beds. Because of the inferred shallow marine environment for the coquina beds, a medial ridge or sill is envisioned to have separated the Okpikruak turbidite basin to the south from the Ellesmerian shale basin to the north.

In mid-Neocomian time, relative uplift in northernmost Alaska, subsequent erosion, and transgression by the Hautervian-Barremian(?) pebble shale unit terminated the Ellesmerian depositional cycle. To the south the pebble shale unit apparently grades to a conformable shelf and slope sequence towards the axis of the Colville basin, where definitive seismic or other subsurface data are lacking. On the structurally complex south side of the Colville basin, there are no reported strata of late Neocomian age. Large-scale deformation and thrusting may have been initiated at that time.

After pebble shale deposition in the northern part of NPRA, the Colville basin was significantly downwarped. Thus the north flank of the basin was isolated from the influx of Brookian clastics until the basin was filled from the south or southwest. This is characteristic of Cretaceous sedimentation throughout northern Alaska. In the northern NPRA area, significant post-Neocomian deposition did not occur until late Albian time.

Large-scale deformation and thrusting continued during Aptian time in the ancestral Brooks Range orogen on the south. Aptian-age rocks are not known with certainty in northern Alsaka. Undoubtedly, however, there must have been Aptian deposition in the axial portion of the Colville basin. Parts of the Fortress Mountain Formation, which is a thick orogenic, largely deep-water deposit on the south flank of the basin, may be in part Aptian in age, although it is generally considered to be early Albian. The Fortress Mountain grades into the lower part of the Torok Formation to the north. During Albian time, deep-water basin-plain deposits of the Torok onlapped the south-dipping late Neocomian pebble shale unit on the north flank of the Colville Basin. Deposits representing the intervening time are either absent or are a thin condensed section and may be included in the uppermost part of the pebble shale unit.

Final filling of the Colville basin occurred in mid to late Albian time, and is represented by pro-delta shale and thin-bedded turbidite deposits of the Torok Formation and overlying deltaic deposits of the Nanushuk Group. Although some of the Nanushuk deltaic deposits prograded to the north on the south side of the basin, the main delta prograded to the east-northeast, almost parallel with the Colville basin axis. A large source area is postulated to have existed to the south-southwest in the area of the present

Chukchi Sea and Hope basin area and perhaps even farther to the southwest. The Barrow arch, which was a passive high in Albian time may have influenced the direction of progradation.

Regional subsidence (or sea level rise) and subsequent transgression marks the termination of Early Cretaceous deposition and closely corresponds to the beginning of a Late Cretaceous cycle of deposition.

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Table 1.—*Location of wells shown in figure 1, and stratigraphic data on Nanushuk Group, North Slope, Alaska*

[?, data not resolved; ± approximate top of section; + eroded top of Nanushuk Group, incomplete section]

Loc. No.	Well Name	Location Sec.	T.	R.	Nanushuk Top (ft)	Base (ft)	Thickness (ft)	(m)
1	USN Umiat -1	34	1 N.	2 W.	915	2,840	165[1]	355[1]
2	USN Skull Cliff C.T.-1	23	18 N.	22 W.	10	450	440+	134+
3	USN Umiat -2	3	1 S.	1 W.	80	1,060	980	299
4	USN Simpson -1	32	19 N.	13 W.	20	980	960	293+
5	USN South Barrow -1	28	23 N.	18 W.	70	695	625+	190
6	USN Fish Creek -1	15	11 N.	1 E.	2,890	4,110	1,220	372
7	USN Oumalik -1	30	6 N.	16 W.	20	2,770	2,750+	838+
8	USN Meade -1	19	8 N.	22 W.	45	3,450	3,405+	1,038+
9	USN East Oumalik -1	13	5 N.	15 W.	35	2,970	2,935+	895+
10	USN Simpson C.T. 31	36	19 N.	11 W.	220			
11	USN East Topagoruk -1	12	14 N.	14 W.	90	2,280	2,190+	667+
12	USN Titaluk -1	23	1 N.	11 W.	40	3,500	3,460	1,055
13	USN Gubik -1	20	1 N.	3 E.	3,350	4,005	655	200
14	USN Topagoruk -1	25	15 N.	16 W.	50	2,150	2,100+	640+
15	USN Knifeblade-2A	2	4 S.	12 W.	0		1,805+	500+
16	USN Kaolak-1	25	7 N.	34 W.	113	5,205	5,092+	1,552+
17	USN Square Lake-1	2	2 N.	6 W.	1,630	3,940	2,310	704
18	USN Grandstand-1	32	5 S.	1 E.	110	1,070	960+	293+
19	USN Wolf Creek-3	2	1 S.	7 W.	30	3,575	3,545+	1,080+
20	British Petroleum Shale Wall-1	1	5 S.	5 E.	1,080	3,150?	2,070?	631?
21	Sinclair Little Twist-1	34	3 S.	4 W.	0	3,075	3,075+	937+
22	British Petroleum Kuparuk-1	1	2 S.	5 E.	5,365	6,330	965	294
23	British Petroleum Itkillik-1	11	1 N.	6 E.		Not present		
24	McCulloch Colville U-2	15	1 S.	1 E.	1,765	2,820	1,055	322
25	Texaco-Newmont E. Kuparuk-1	10	2 S.	8 E.	6,680	6,860	180	55
26	Gulf Colville Delta-1	9	13 N.	6 E.		Not present		
27	Pan Am. Aufeis-1	30	3 S.	11 E.	2,450	3,474	1,025	312
28	USN Cape Halkett-1	5	16 N.	2 W.	3,118	4,235	1,117	340
29	Forrest Lupine-1	13	4 S.	14 E.	?	?		
30	Texaco W. Kurupa-1	33	6 S.	14 W.	0	1,730	1,730+	527+
31	Texaco E. Kurupa-1	9	7 S.	6 W.	0	2,190	2,190+	667+
32	USN East Teshekpuk-1	16	14 N.	4 W.	1,585	3,100	1,515	462
33	USN So. Harrison Bay-1	6	12 N.	2 E.	3,220	4,220	1,000	305
34	USN Atigaru Pt.-1	19	14 N.	2 E.	3,470	4,400	930	283
35	USN W.T. Foran-1	13	17 N.	2 W.	3,480	4,380	900	274
36	USN South Simpson-1	22	17 N.	12 W.	50±	1,915	1,865+	568+
37	USN West Fish Creek-1	11	11 N.	1 W.	2,550	3,915	1,365	416
38	Texaco Tulugak-1	26	5 S.	3 E.				
39	USGS Drew Pt.-1	26	18 S.	8 W.	1,230	3,200	1,970	600
40	USGS North Kalikpik-1	3	13 N.	2 W.	2,395	3,470	1,075	328
41	USGS Kugrua-1	8	14 N.	26 W.	100	2,330	2,230+	680+
42	USGS South Meade-1	31	15 N.	19 W.	50±	2,490	2,440+	759+
43	USGS East Simpson-1	18	18 N.	10 W.	350	2,690	2,340	713
44	USGS Peard-1	25	16 N.	28 W.	50±	2,470	2,420+	738+
45	USGS J.W. Dalton-1	14	18 N.	5 W.	2,660	4,135	1,475	450
46	USGS Inigok-1	34	8 N.	5 W.	2,250	3,935	1,685	514
47	USGS Ikpikpuk-1	25	13 N.	10 W.	150	2,950	2,800	853
48	USGS Tunalik-1	20	10 N.	36 W.	50±	6,250	6,200+	1,890+
49	USGS Seabee-1	5	1 S.	1 W.	280	1,300	1,020	

1 Fault repetition of 760 ft (232 m) has been removed.

Table 2.—*Location of outcrop sections of Nanushuk Group shown in figure 1, North Slope, Alaska*

[+, incomplete section]

Loc. No.	Outcrop name	Location T.	Location R.	Nanushuk thickness (m)	Source
1	Corwin Bluff	6-7 S.	53-56 W.	4,723+ 3,444+	Chapman and Sable, 1960. Smiley, 1969.
2	Barabara Syncline	1 N.-2 S.	44-45 W.	3,110+	Chapman and Sable, 1960.
3	Kokolik Warp Syncline	3-4 S.	40-41 W.	2,091+	Ahlbrandt and others, 1979.
4	Elusive Syncline	13 N.	33 W.	1,977	Chapman and Sable, 1960.
5	Carbon Creek Anticline	2 S.	28 W.	786+	Ahlbrandt and others, 1979.
6	Colville River	5 S.	15-17 W.	1,911+	Chapman and others, 1964.
7	Kurupa River	6 S.	12-14 W.	1,728+	Huffman and others, [in press].
8	Knifeblade Ridge	3-4 S.	12 W.	1,452+	Brosge and Whittington, 1966.
9	Killik River	5-6 S.	6-7 W.	1,361+	Detterman and others, 1963.
10	Chandler River-Tuktu Bluff	7-8 S.	1-2 W.	1,426 1,871+	Do. Huffman and others, [in press].
11	Type Grandstand	6 S.	4 E.	812+	Do.
12	Rooftop	7 S.	6-7 E.	375+	Do.
13	Nanushuk River	9 S.	6 E.	1,097+	Detterman and others, 1963.
14	Marmot Syncline	8 S.	13 E.	853+	Huffman and others [in press].
15	Lupine River	4 S.	14 E.	563+	Do.

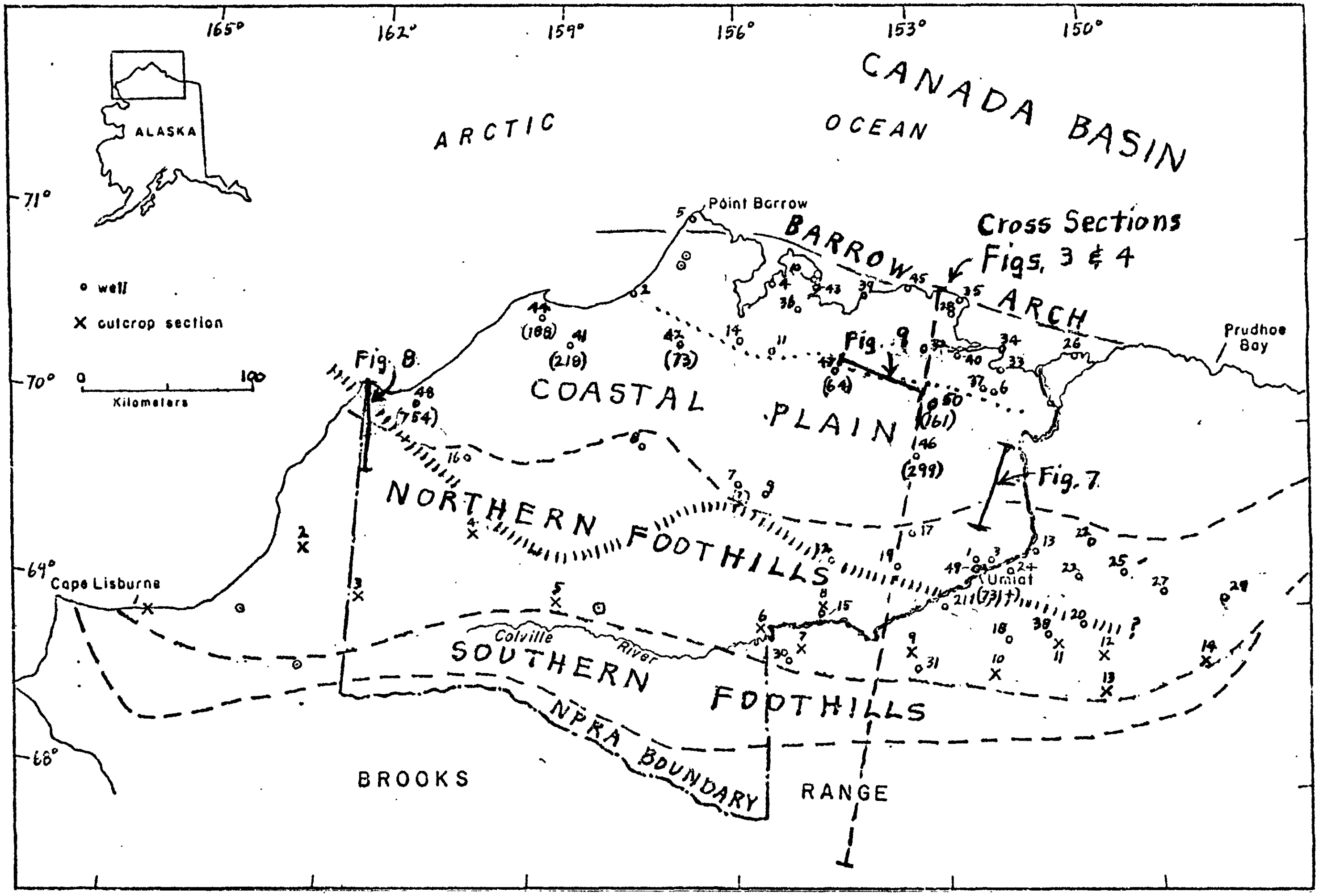

Figure 1.--Index map of the NPRA and adjacent areas showing physiographic subdivisions, wells, and lines of cross sections of figures 3 and 4, and seismic sections of figures 7, 8, and 9. Dotted line is approximate subcrop of the Jurassic-Cretaceous boundary under the mid-Neocomian unconformity. Hashured line is approximate position of the shelf break (and southernmost limit of mid-Neocomian unconformity) over which the pebble shale unit was deposited. Numbers by wells are penetrations in meters of the Cretaceous part of the Kingak Shale based on paleontology. Refer to tables 1 and 2 for identification of wells and outcrop sections.

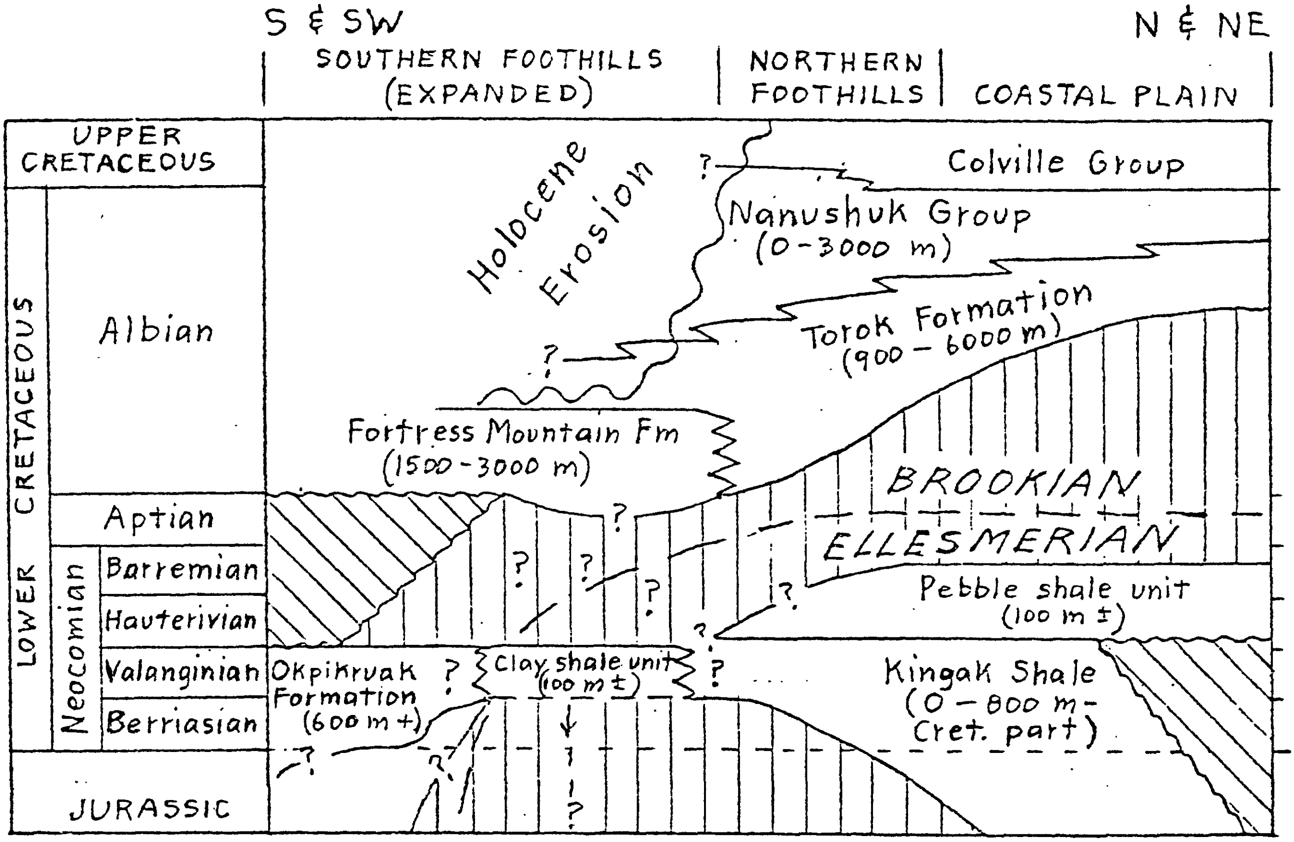

Figure 2.--Time-stratigraphic nomenclature chart of Lower Cretaceous rocks across NPRA and adjacent areas. Diagonal-hatched pattern represents eroded section; vertical-hatched pattern represents nondeposition or condensed section. Time scale is not uniform.

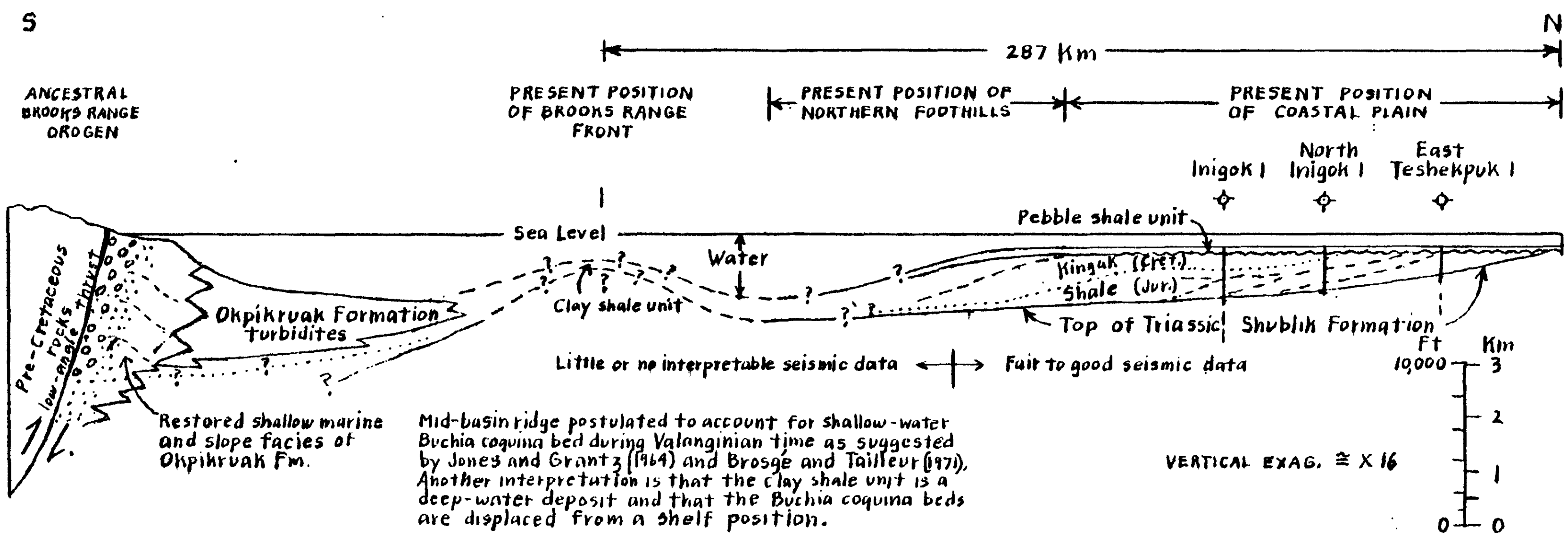

Figure 3.--Restored cross section across Colville basin showing Lower Cretaceous rocks at end of pebble shale (Neocomian) time. Dotted line approximates Cretaceous-Jurassic boundary and, in north half of section, dashed lines represent bedding traces as indicated by seismic data. South half of section is conjectural. Palinspastic restoration is not meant to be rigorous. See figure 1 for location of section.

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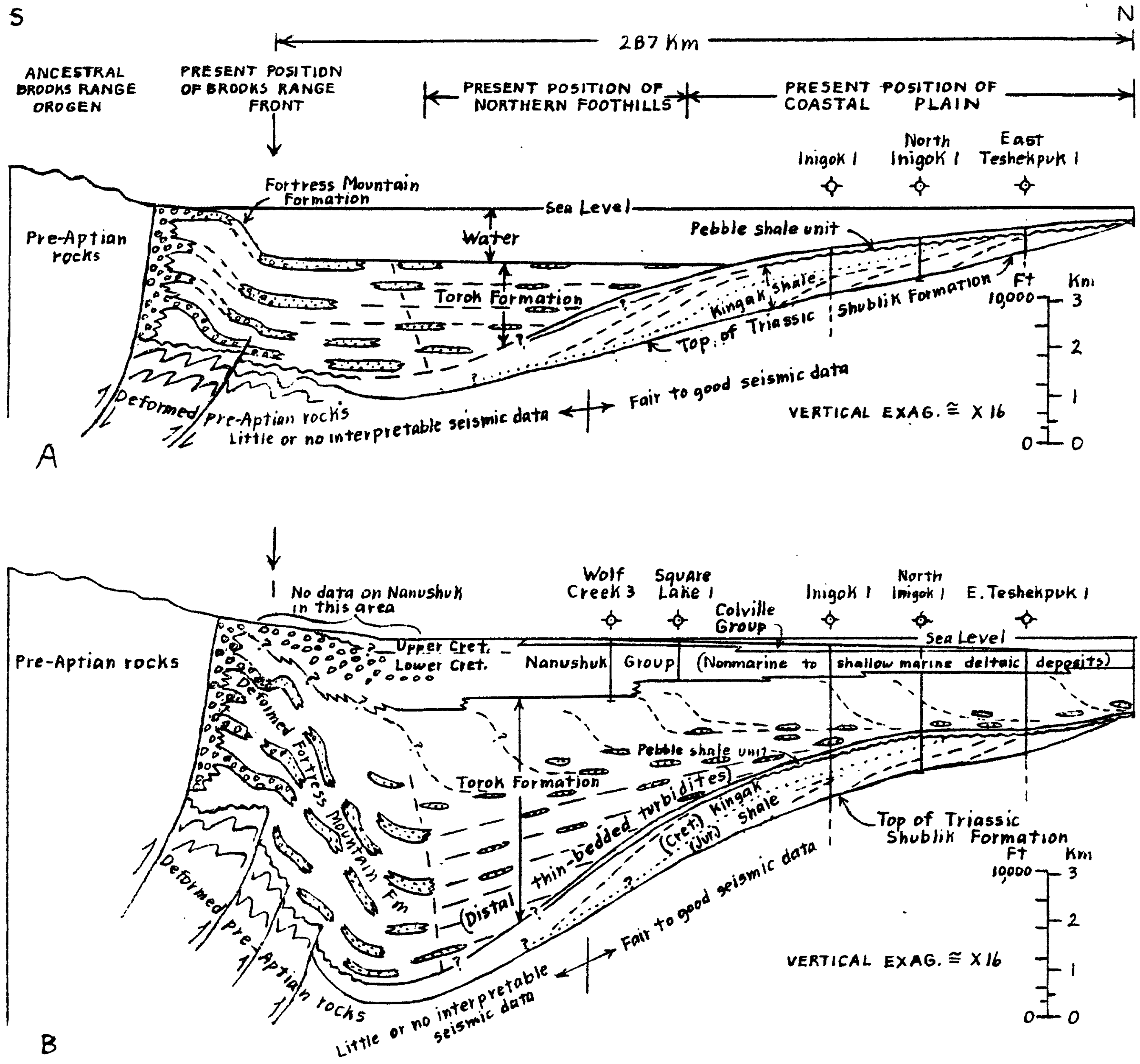

Figure 4.--Restored cross sections across Colville basin showing Lower Cretaceous rocks at (A) end of Fortress Mountain-lower Torok (early Albian) time, and (B) end of Nanushuk (Cenomanian-early Turonian(?) time. In north half of sections, dotted line approximates Cretaceous-Jurassic boundary, and dashed lines represent bedding traces as indicated by seismic data. South half of sections is diagrammatic. In A, horizontal beds in upper left are alluvial and shallow-marine facies, tilted beds are slope shales and submarine canyon facies, and lower horizontal beds are basinal shale and turbidite facies. In B, turbidites in lower part of Torok Formation are shown diagrammatically to illustrate relations with Fortress Mountain Formation. Line of section is oriented at an oblique angle to progradation direction of Nanushuk-Torok interval. See Figure 1 for location of section.

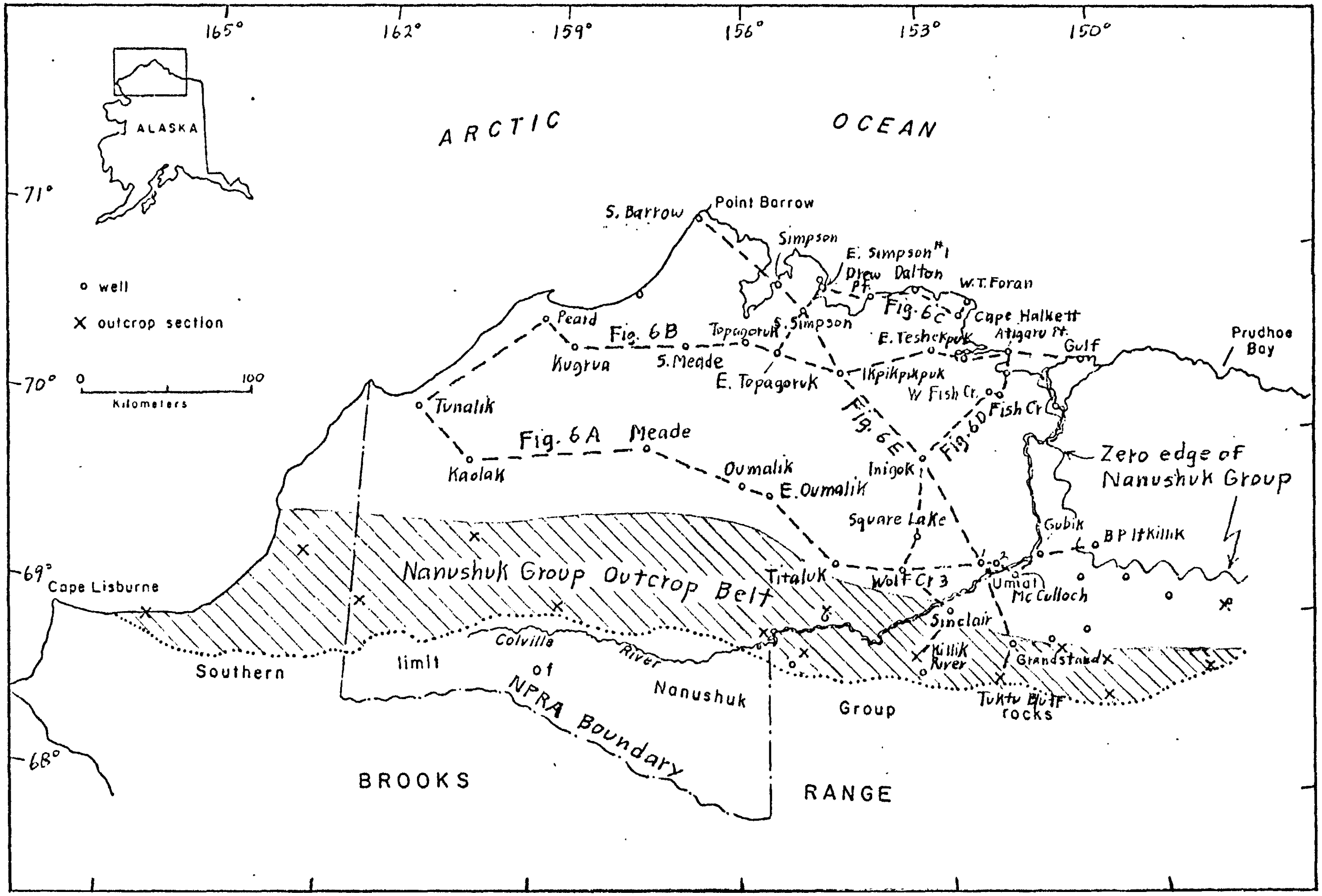

Figure 5.--Index map of NPRA and adjacent areas showing lines of stratigraphic cross sections of Nanushuk-Torok interval (figs. 6A - E), eastern extent of Nanushuk Group, and selected Nanushuk Group wells and outcrop sections. Cross-hatched area is Nanushuk Group outcrop belt. Refer to figure 1 and tables 1 and 2 for identification of wells and outcrop sections.

CAPTIONS FOR FIGURES 6A-E

Stratigraphic cross sections of Nanushuk Group and Torok Formation through most of wells in NPRA. See figure 5 for location of sections. Horizontal distance between wells or sections is indicated. Well depths are numbered at 1,000-ft intervals. Vertical exaggeration is approximately 58 X. SP, spontaneous potential; R, resistivity; GR, gamma ray; TT, transit time. Dashed lines are correlations of miscellaneous beds or reflectors. Dip angle of foreset beds in respect to topset beds is indicated. Datum is base of Colville Group (Seabee Formation) where it is present; otherwise datum generally conforms to topset beds.

6A.--Stratigraphic cross section across northern foothills.

6B.--Stratigraphic cross section across northern coastal plain.

6C.--Stratigraphic cross section across northeastern coastal plain.

6D.--South to north stratigraphic cross section across the eastern part of NPRA.

6E.--Southeast to northwest stratigraphic cross section across the northeastern part of NPRA.

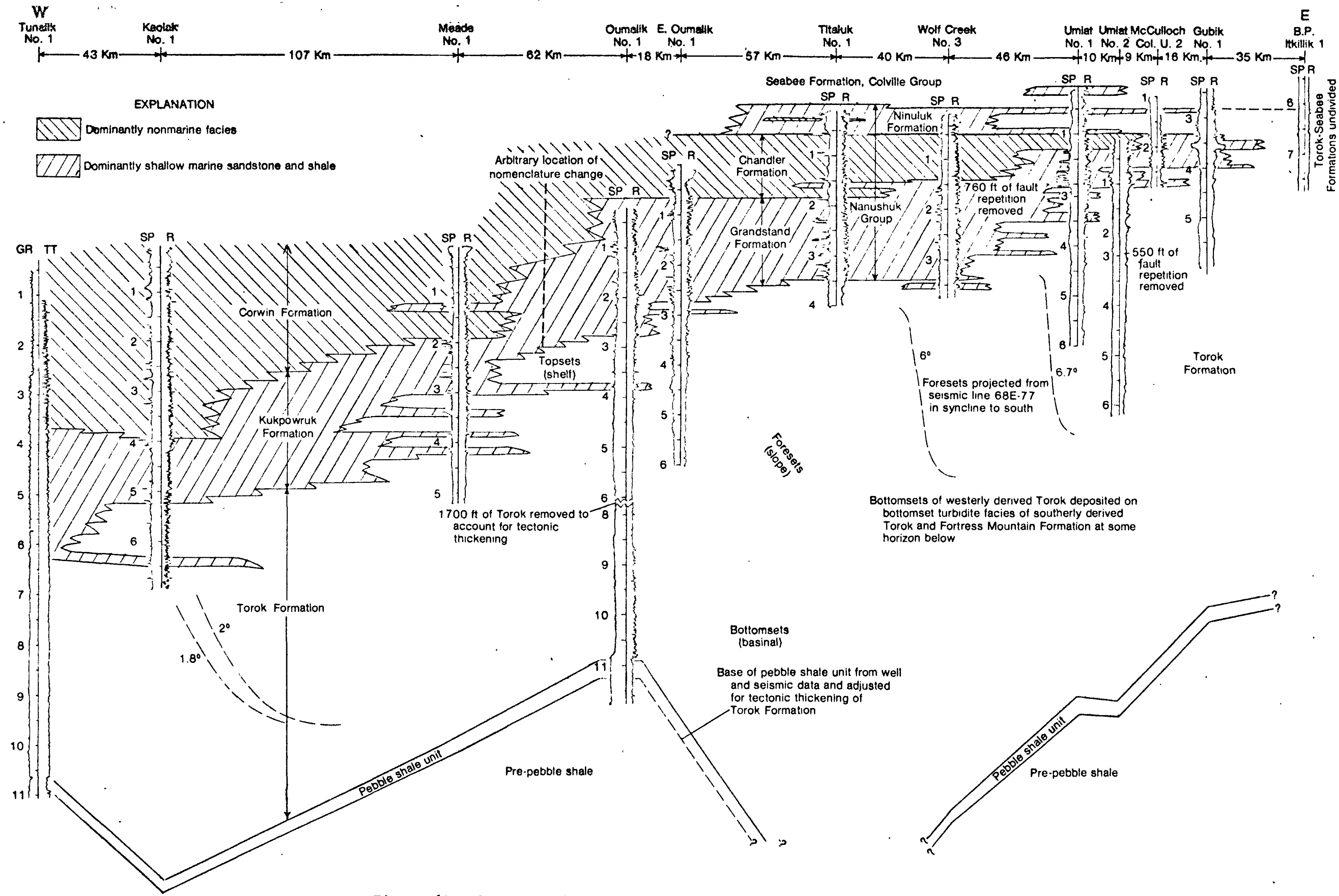

Figure 6A.--Stratigraphic cross section across northern foothills.

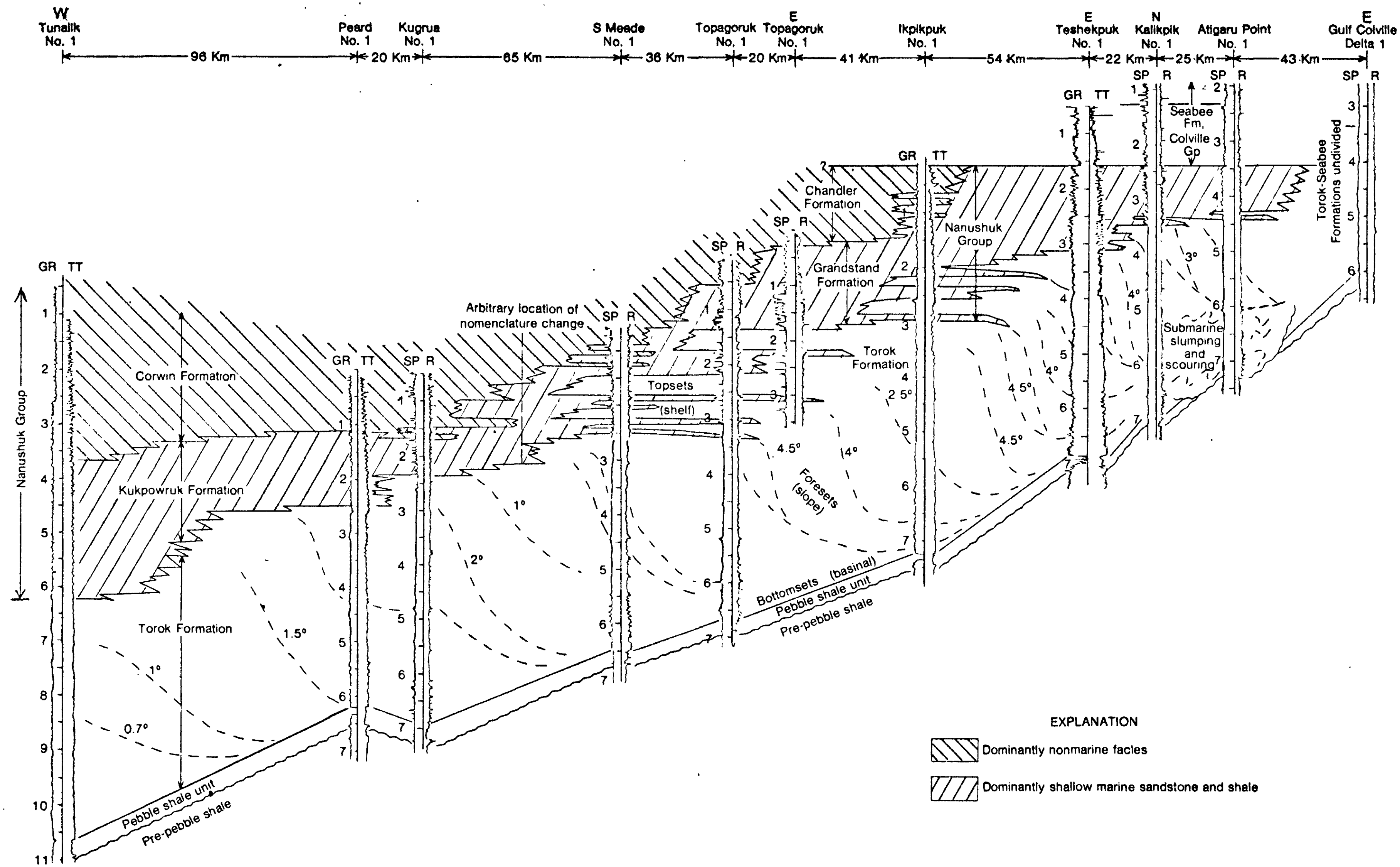

Figure 6B.--Stratigraphic cross section across northern coastal plain.

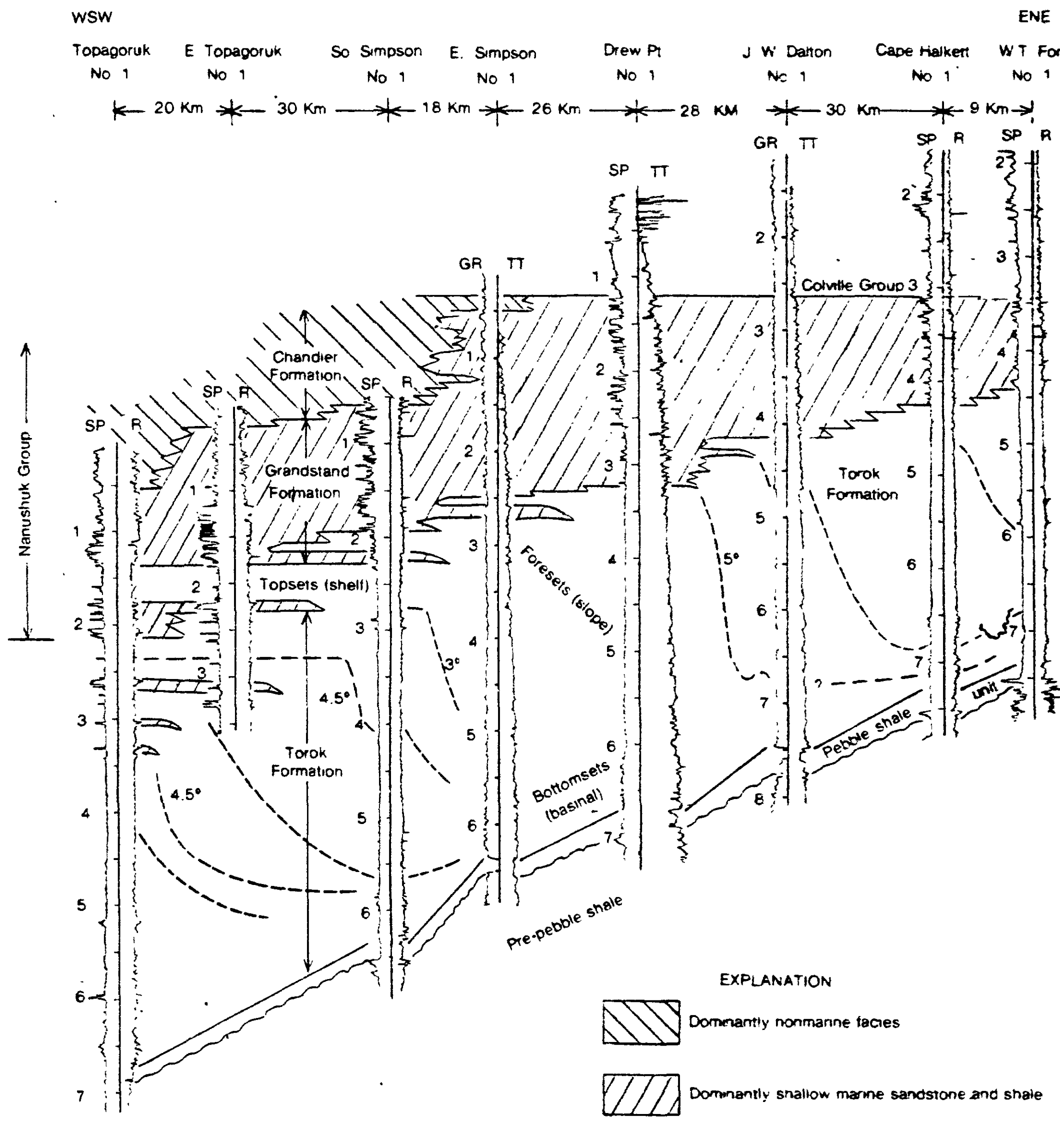

Figure 6C.--Stratigraphic cross section across northeastern coastal plain.

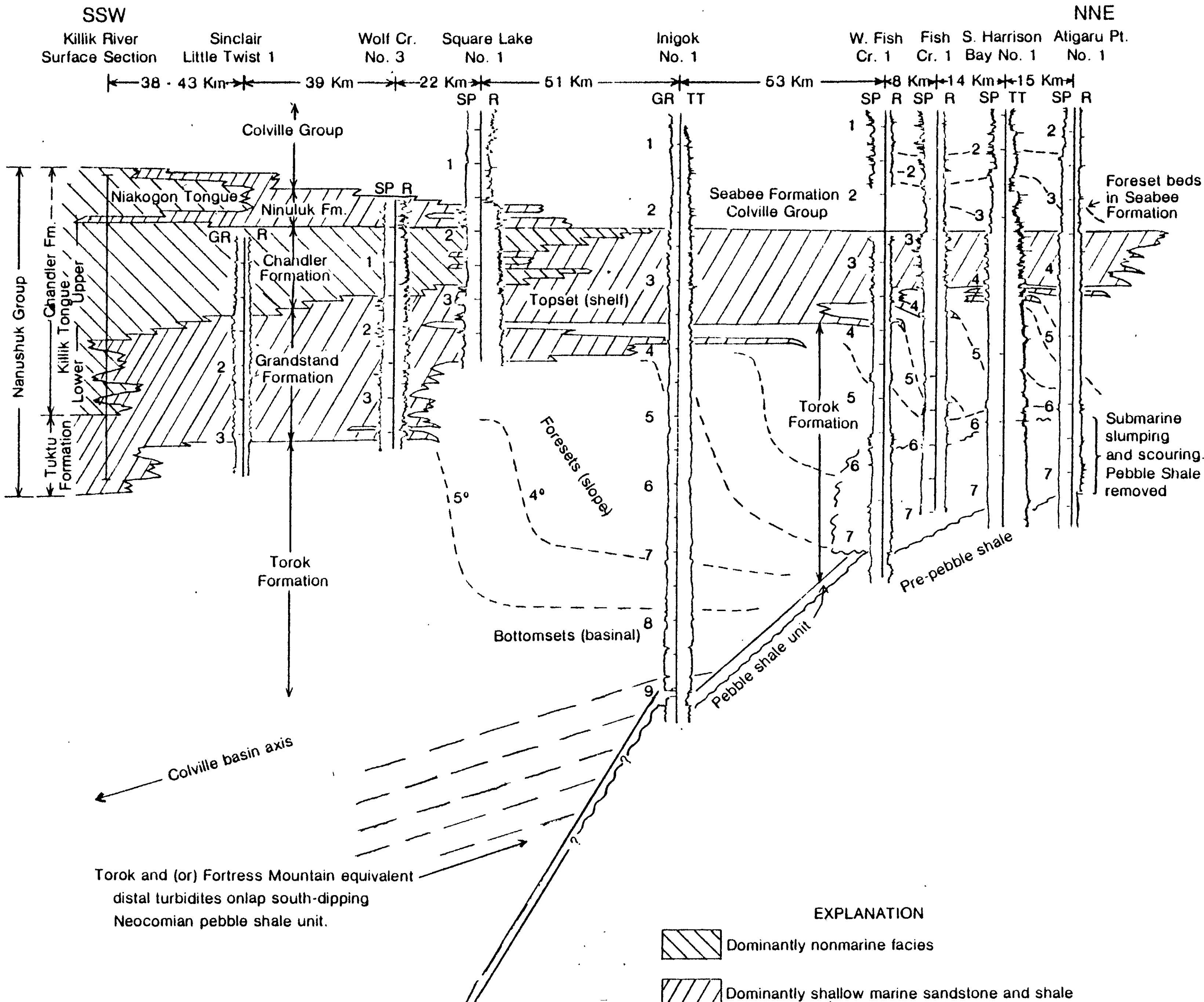

Figure 6D.--South to north stratigraphic cross section across eastern NPRA.

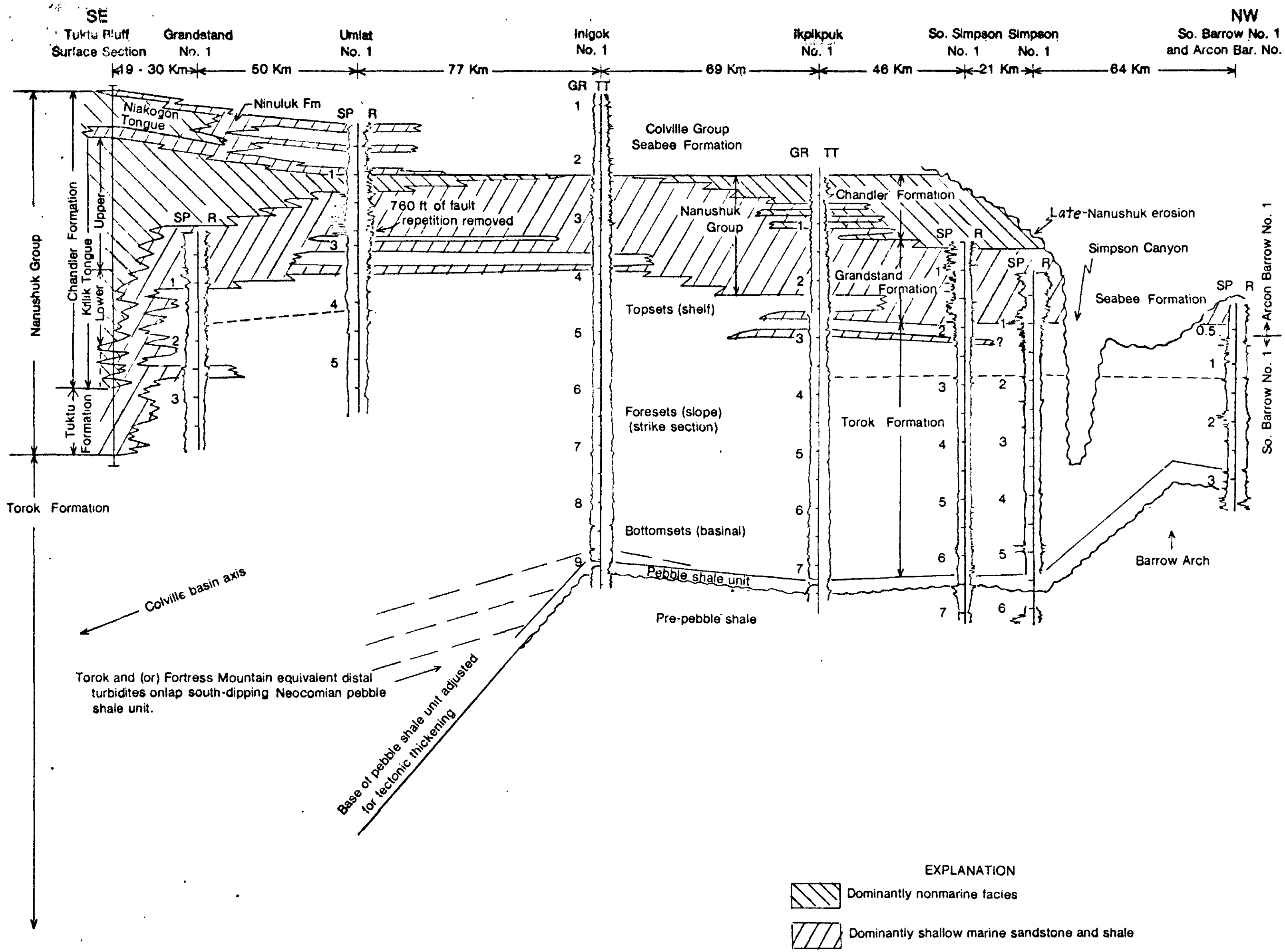

Figure 6E.--Southeast to northwest stratigraphic cross section across northeastern NPRA.

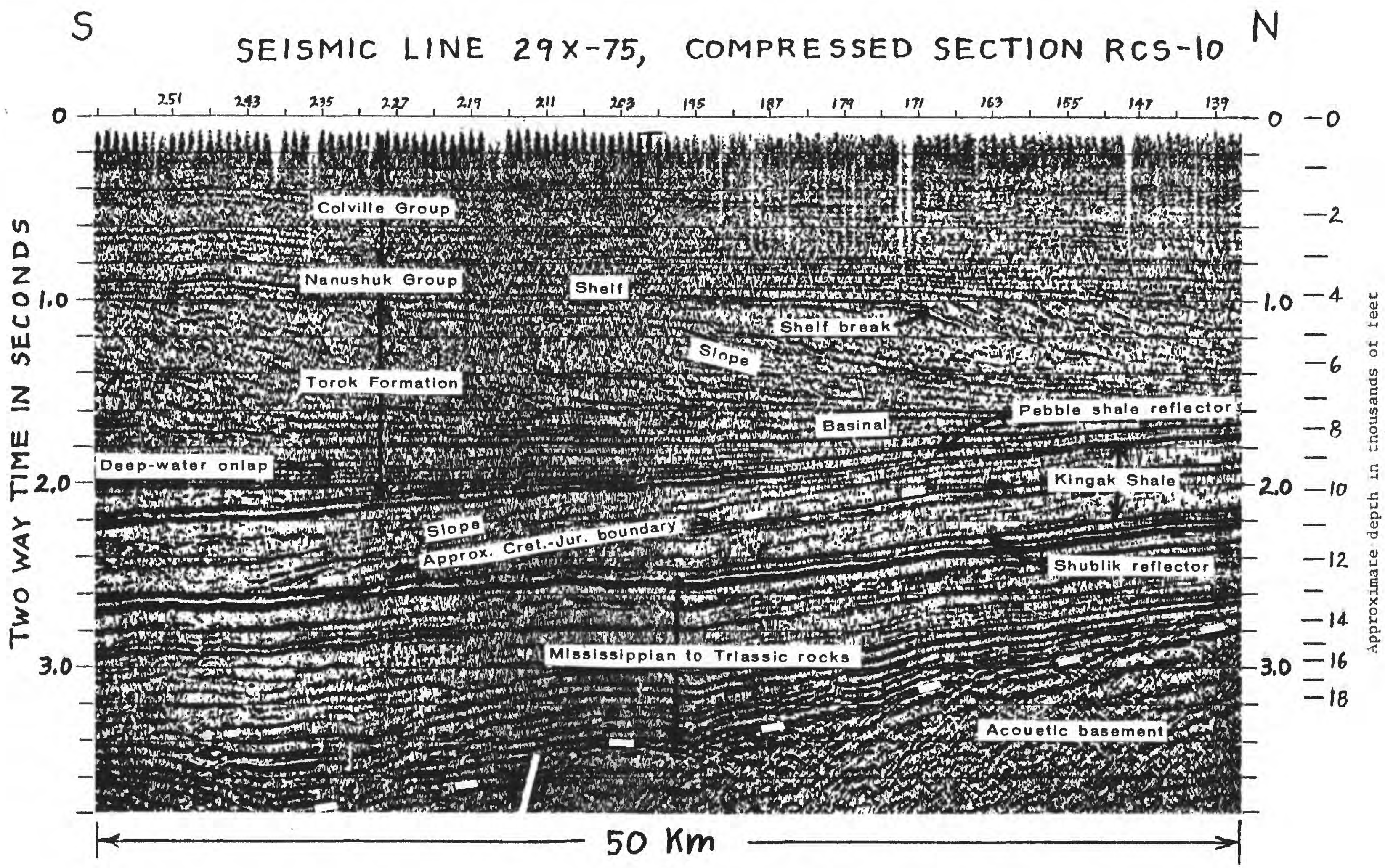

Figure 7.---Seismic section in eastern part of the NPRA showing (1) southward prograding shelf and slope deposits of the Kingak Shale, (2) approximate Cretaceous-Jurassic boundary within the Kingak Shale, (3) lower part of the Torok Formation onlapping south-dipping pebble shale unit, and (4) relationships of shelf, slope, and basinal deposits (topset, foreset, and bottomset beds) of the Torok-Nanushuk interval. Line of section is oriented at an oblique angle to progradation direction of the Torok-Nanushuk interval. Numbers above section are shot-point numbers. See figure 1 for location of section.

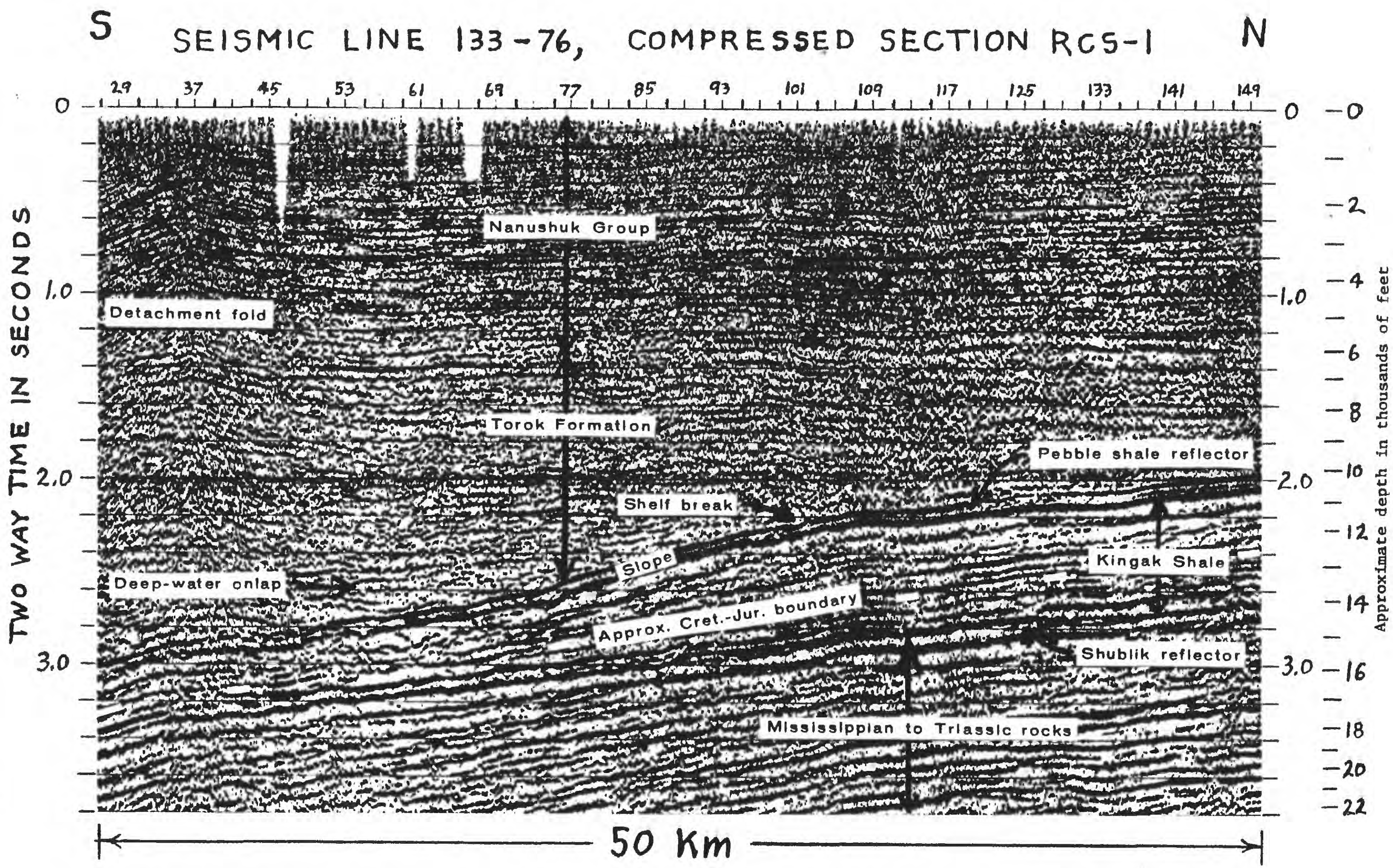

Figure 8.--Seismic section in western part of the NPRA showing (1) gradual shelf break and slope relations of the pebble shale unit to the Triassic Shublik Formation, (2) southward thinning of the Kingak Shale, (3) approximate Cretaceous-Jurassic boundary within the Kingak Shale, and (4) lower part of the Torok Formation onlapping south-dipping pebble shale unit. Foreset beds in Torok are not present or are dipping at a very low angle in this part of the basin. Also, line of section is oriented about 60 degrees to dip of foreset beds. Numbers above section are shot-point numbers. See figure 1 for location of section.

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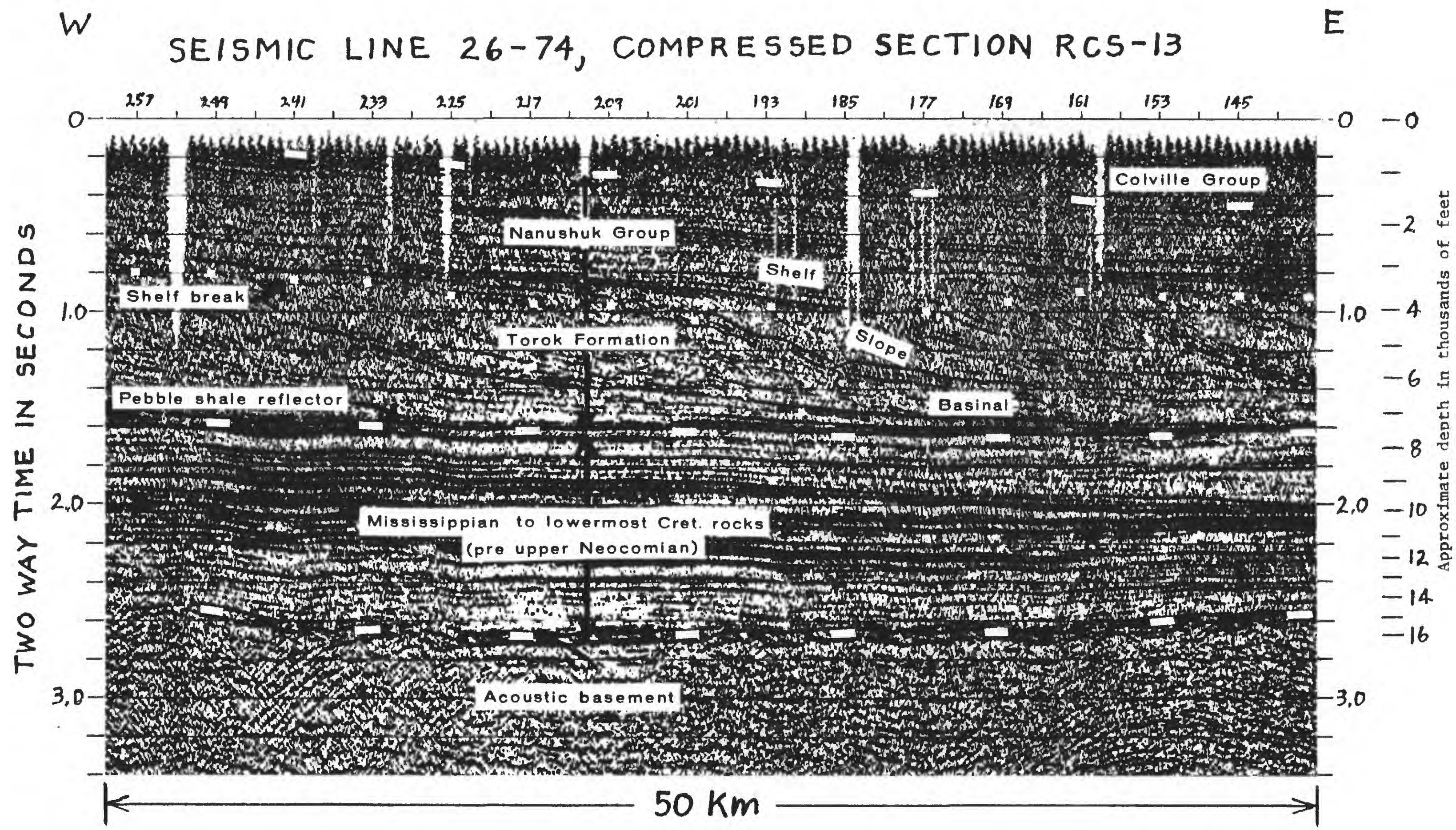

Figure 9.--Seismic line in northeastern part of the NPRA showing progradation and stratigraphic relationships of shelf, slope, and basinal deposits (topset, foreset, and bottomset beds) of the Torok-Nanushuk interval. Dots represent position of shelf break. Note stratigraphic rise of shelf break from west to east. Numbers above section are shot-point numbers. See figure 1 for location of section.

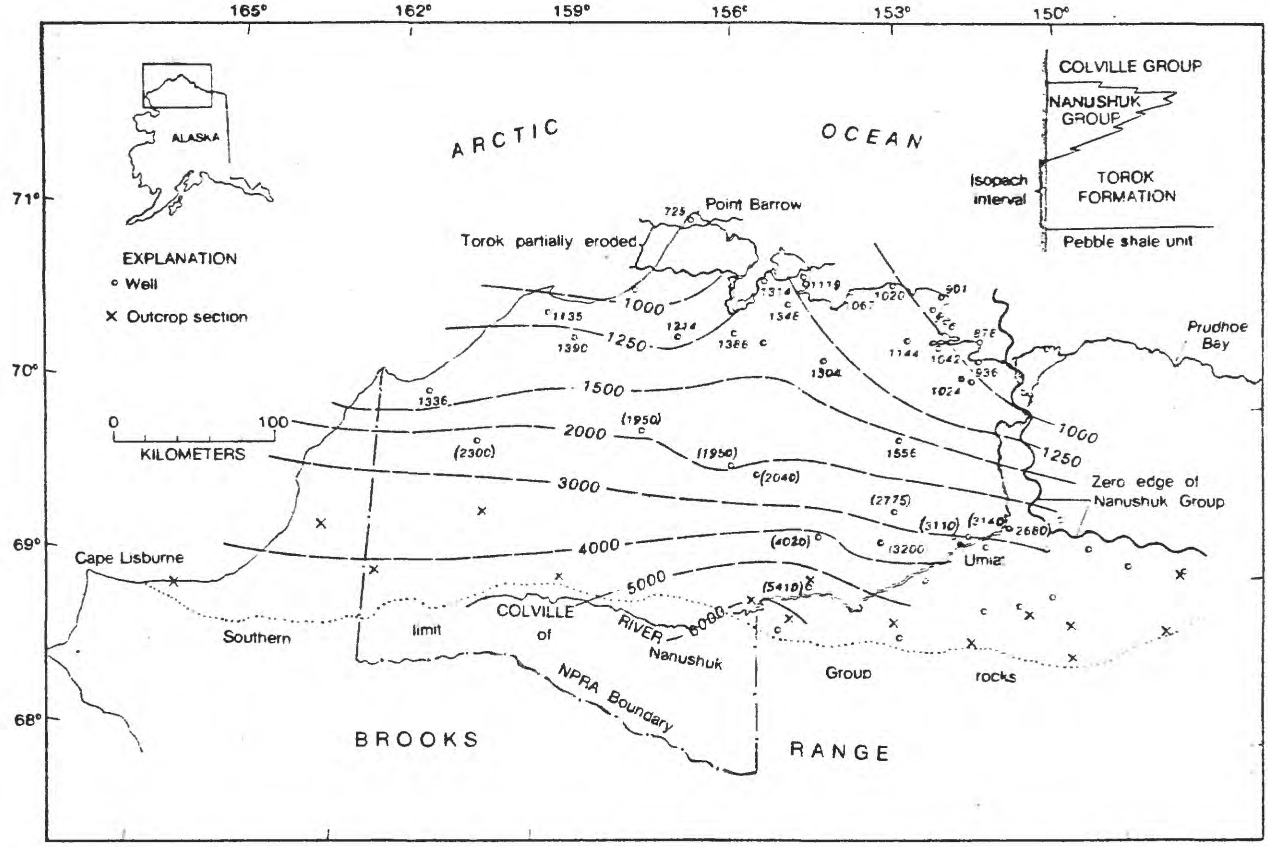

Figure 10.--Isopach map of Torok Formation (modified from Bird and Andrews, 1979). Numbers beside wells indicate thickness of Torok Formation; thickness values in parenthesis have been corrected (approximately) for tectonic thickening in thrust-faulted anticlines. Isopach interval is 250, 500 and 1000 m. Refer to table 1 and figure 1 for identification of wells.

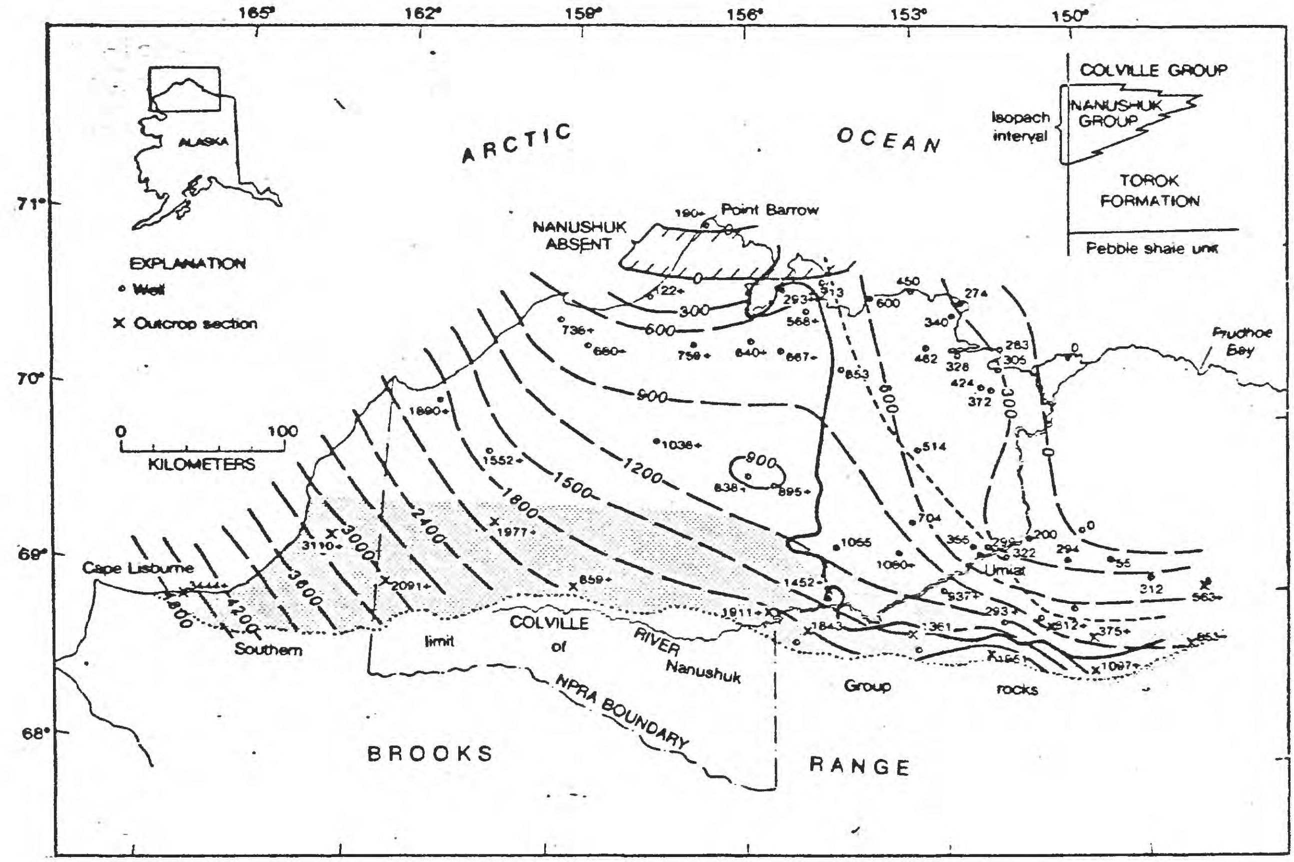

Figure 11.--Isopach map of Nanushuk Group. Short dashed line is seaward extent of subaerial plain deposits, and heavy solid line is present western and southern limit of Colville Group. Shaded area is Nanushuk outcrop belt. (Modified from Bird and Andrews, 1979). Numbers beside control points indicate thickness of Nanushuk Group; a plus after number by wells indicates minimal thickness owing to top of Nanushuk having been eroded. A plus after number by outcrop section indicates an incomplete section of Nanushuk. Isopach interval is 300 m. Refer to tables 1 and 2, and figure 1 for identification of wells and outcrop sections.

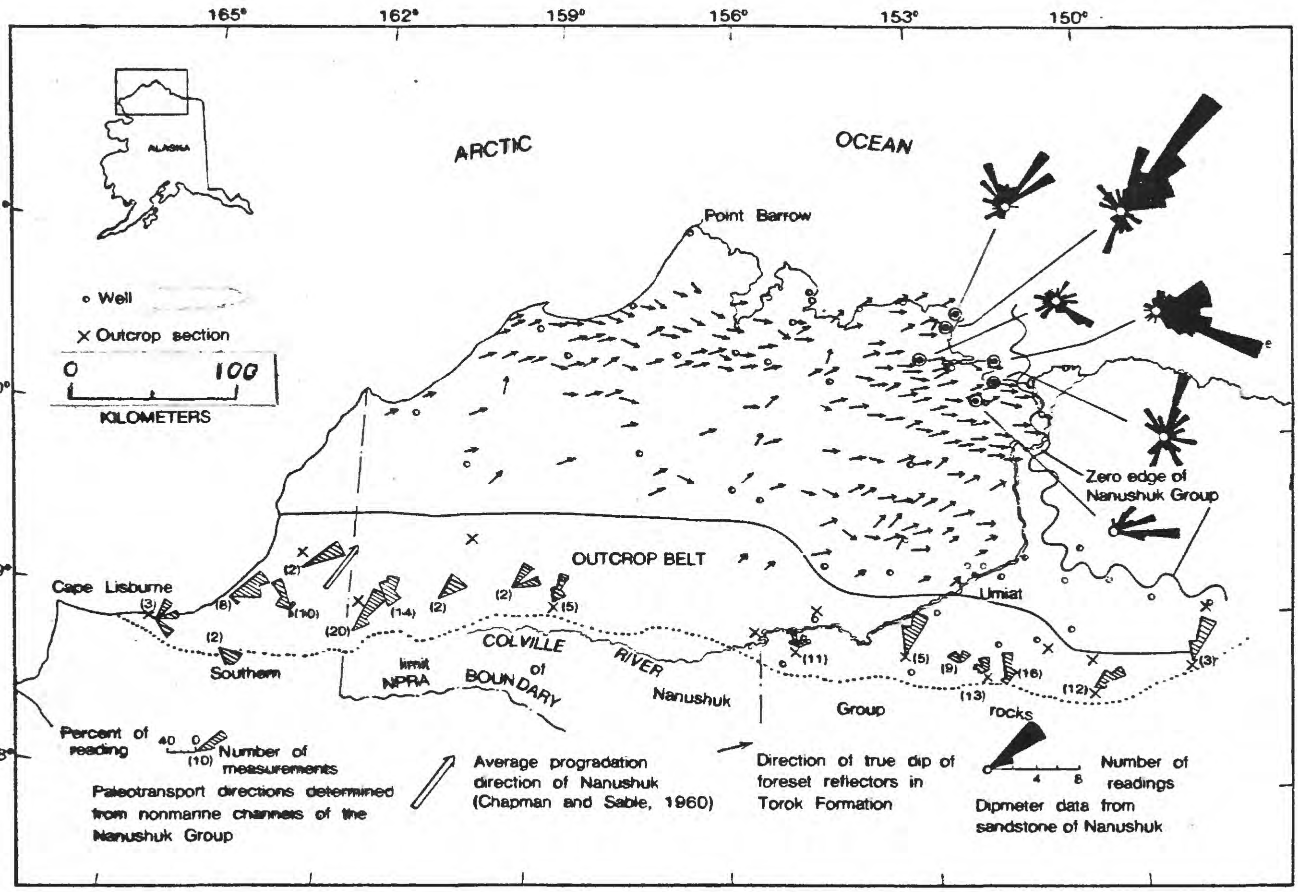

Figure 12.--Plot of directional data from seismic foreset dips in Torok Formation, dipmeter data from Nanushuk Group sandstones, direction of Nanushuk progradation from outcrop (Chapman and Sable, 1960), and direction of plunge of symmetrically filled nonmarine channels of the Nanushuk Group as measured by Ahlbrandt and others (1979) and Huffman and others (in press) (modified from Bird and Andrews, 1979).

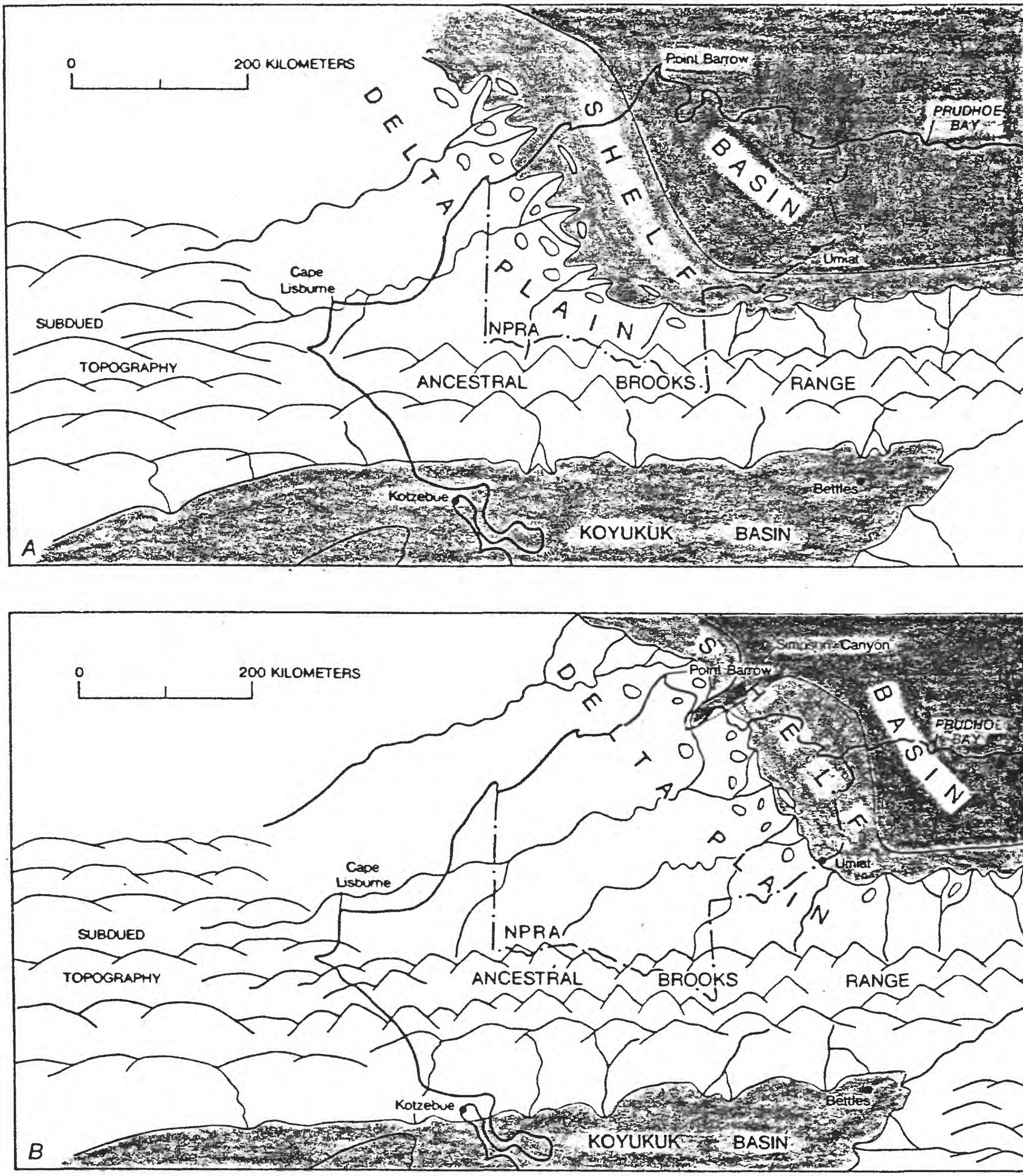

Figure 13.--Inferred paleogeographic maps of a part of northern Alaska and adjacent areas at (A) mid-Nanushuk time and (B) latest Nanushuk time (maximum regression).