

# Sequence stratigraphy, biotic change, $^{87}\text{Sr}/^{86}\text{Sr}$ record, paleoclimatic history, and sedimentation rate change across a regional late Cenozoic unconformity in Arctic Canada<sup>1</sup>

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**Abstract:** Eustasy, tectonics, and climate contributed to a remarkable Miocene–Pliocene regional unconformity in the Beaufort–Mackenzie area of Arctic Canada. The unconformity extends from beneath deep basin turbidites on the continental rise, upslope across an erosional paleocontinental shelf, onto the cratonic margin as a regional paleosurface (peneplain) in the Mackenzie Delta area, and into pediment surfaces cut into the orogenic highlands of the Richardson Mountains. The unconformity was initiated by shelf exposure during latest Messinian or earliest Pliocene eustatic lowstand and was accentuated by tectonic uplift from the culmination of a major Late Miocene compressional pulse on the basin margin. Palynomorph, benthic foraminiferal, strontium isotopic, paleomagnetic, and radiometric data document the climatic and chronological events surrounding the unconformity. A widespread hardground (K-59 limestone) occurs at the unconformity and caps the Late Miocene Akpak Sequence. The hardground yields the benthic foraminifera *Cibicides grossus*, a regional marker in the Arctic Pliocene, and the bryozoan *Aeonella* sp. aff. *A. polystomella*, previously known from temperate North Atlantic environments. The  $^{87}\text{Sr}/^{86}\text{Sr}$  data and new biostratigraphic data indicate that the *C. grossus* Zone in the Beaufort–Mackenzie area may be younger than previously estimated, ranging into the earliest Pleistocene. Late Miocene regional uplift across the cratonic margin, coupled with eustatic lowstand followed by Early Pliocene tectonic quiescence and dry cool climatic conditions, combined to produce widespread erosion (pediments and peneplanation). Rapid erosion contributed to the >4 km-thick, Pliocene–Pleistocene Iperk Sequence and a 23-fold increase in sedimentation rates relative to the Early and Middle Miocene.

**Résumé :** L'eustatisme, la tectonique et le climat ont tous contribué à une remarquable discordance régionale Miocène–Pliocène dans la région Beaufort–Mackenzie de l'Arctique canadien. La discordance débute sous les turbidites de bassins profonds sur le glacis continental, remonte la pente à travers une plate-forme d'érosion paléocontinentale, se retrouve sur la marge du craton en tant que paléosurface régionale (pénéplaine) de la région du delta du Mackenzie et sur les surfaces de pédiment découpées dans les hautes terres orogéniques des monts Richardson. La discordance a commencé par l'exposition de la plate-forme au cours du dernier bas niveau, au Messinien terminal ou au Pliocène précoce, et elle a été accentuée par un soulèvement tectonique, au Miocène tardif, soit la culmination d'une forte impulsion de compression sur la bordure du bassin. Des données palynomorphiques, de foraminifères benthiques, de strontium isotopique, ainsi que paléomagnétiques et radiométriques documentent les événements climatiques et chronologiques qui entourent la discordance. Une surface rubéfiée (calcaire K-59) se retrouve à la discordance et forme le sommet de la séquence Akpak, du Miocène tardif. La surface rubéfiée fournit le foraminifère *Cibicides grossus*, un marqueur régional pour le Pliocène dans l'Arctique, et le bryozoaire *Aeonella* sp. aff. *A. polystomella* auparavant trouvé dans des environnements tempérés de l'Atlantique Nord. Les données de  $^{87}\text{Sr}/^{86}\text{Sr}$  et de nouvelles données biostratigraphiques indiquent que la zone *C. grossus* dans la région Beaufort-Mackenzie peut être plus jeune qu'estimée antérieurement, allant jusqu'au début du Pléistocène. Le relèvement régional sur l'ensemble de la marge du craton, au Miocène tardif, jumelé au bas niveau eustatique suivi d'une quiescence tectonique au Pliocène et des conditions climatiques fraîches et sèches, tout s'est combiné pour produire une érosion à grande échelle (pédiment et pénéplanation). L'érosion rapide a contribué à la séquence Iperk, d'une épaisseur >4 km, datant du Pliocène–Pléistocène et à une augmentation des taux de sédimentation de l'ordre de 23 fois ceux au Miocène précoce et moyen.

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## Introduction

Regional unconformities have long been utilized as fundamental boundaries for the separation of rock stratigraphic units (Sloss 1963, 1988), but few if any studies have documented the distribution of an unconformity from the deep sea to the orogenic highlands. In this study, we attempt to do so. The sub-Iperk Sequence unconformity, of latest Miocene to earliest Pliocene age, occurs in the Beaufort–Mackenzie Basin of Arctic Canada, and is traceable from pediment surfaces and a regional terrace in the orogenic highlands of the Richardson Mountains, across a broad piedmont surface or denudation surface that truncates the stable craton. The unconformity continues northward as a subaerial erosional surface cutting the continental shelf, as shown by conspicuous shelf margin erosion on seismic profiles. At the base of the continental slope, the unconformity is overlain by a thick turbidite complex in the deep basinal deposits of Canada Basin. We know of no other example of an unconformity traced out in such entirety.

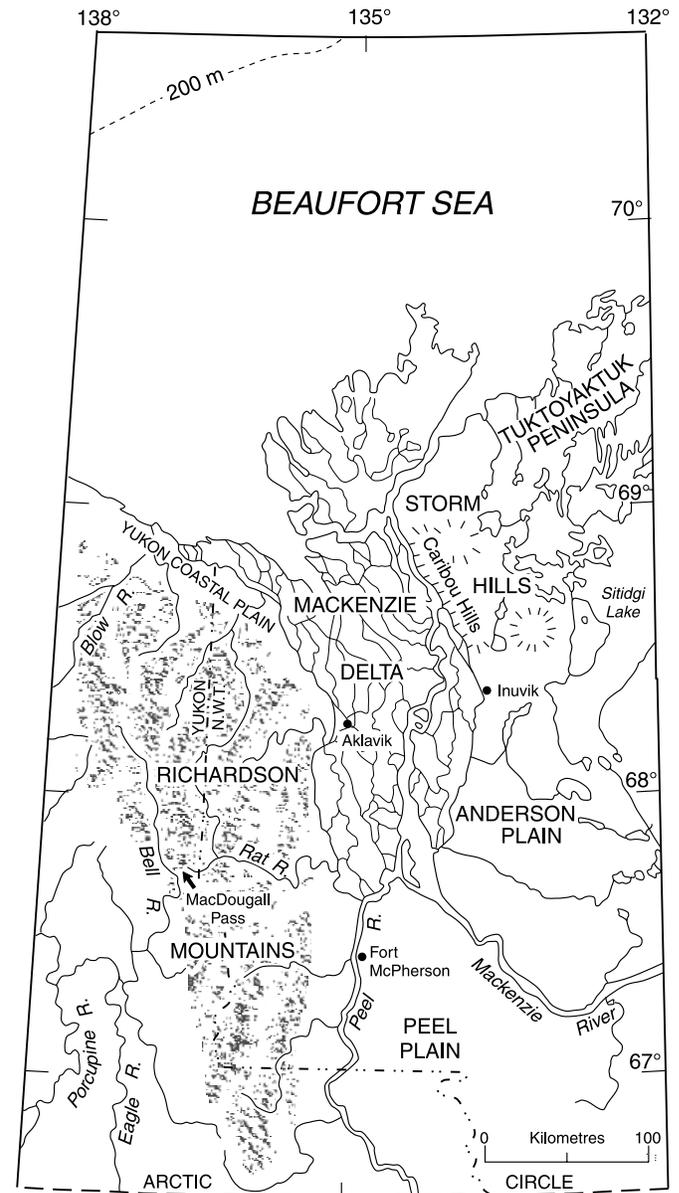
The sub-Iperk Sequence unconformity extends far beyond the confines of the Beaufort–Mackenzie region and is probably recognizable on a circum-Arctic scale and beyond. As such, it ranks as a first-order sequence boundary and represents a significant event in earth history. We define a first-order sequence boundary by several criteria listed previously by Embry (1993). On the continent and the shelf, a first-order sequence boundary marks a surface of widespread subaerial erosion. It is recognizable throughout numerous basins on an interregional scale, even globally. Rocks that have undergone significantly higher degrees of tectonic deformation underlie it. It is followed by a significant transgressive episode. It separates markedly different depositional regimes or patterns. And, it is a boundary of pronounced faunal and floral change. Given the significant breadth of geological phenomena involved, documentation of the first-order sequence boundary can best be accomplished through regional multidisciplinary studies. In this paper, we therefore examine the unconformity in terms of geomorphology, sequence stratigraphy, seismic stratigraphy, paleontology (benthic foraminifera and pollen and spores), and the strontium isotope record ( $^{87}\text{Sr}/^{86}\text{Sr}$ ).

## Geographical and geological setting of Beaufort–Mackenzie area

The Beaufort–Mackenzie area comprises several physiographic elements, including the Richardson Mountains, the Yukon Coastal Plain, the Mackenzie Delta, the Caribou Hills on the northwestern margin of Anderson Plain, and the continental shelf, slope, and rise beneath the Beaufort Sea (Fig. 1).

Richardson Mountains were erected during the late Maastrichtian to the Middle Eocene by compressional tectonics of the Brookian Orogeny. During much of the Cenozoic, a broad piedmont plain extended from the Richardson Mountains across the Yukon and Anderson plains towards the Beaufort Sea. This piedmont plain, however, is now dissected by the Mackenzie River which is a relatively young, late Quaternary physiographic feature, which originated in the late stages of the Wisconsin Glaciation. Prior to the late Cenozoic glaciations, the main drainage pattern from the

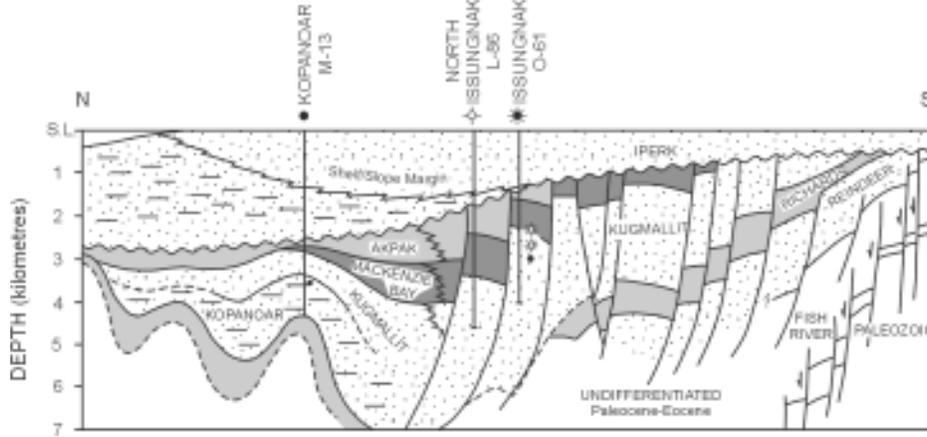
**Fig. 1.** Geographic map of the Mackenzie Delta bordered by the Beaufort Sea, the Richardson Mountains, and the stable cratonic plains.



Richardson Mountains to the Beaufort Sea was dominated by the northeastward flowing paleo-Porcupine and Peel rivers (Duk-Rodkin and Hughes 1994). We emphasize that the modern physiographic setting, which is dominated by the Mackenzie Delta, is quite different from the ancient Miocene and Pliocene configurations.

The Beaufort–Mackenzie Sedimentary Basin contains Albian to Holocene sediments with a maximum thickness in the order of 15 km. The basin extends from the edge of the Richardson Mountains into the subsurface of the Mackenzie Delta and Beaufort Sea. Its origins lie in thermal subsidence associated with the formation of Canada Basin in the Early Cretaceous (Embry and Dixon 1990, 1994). Deposition has generally migrated seaward (northward) through time in a succession of thick prograding deltaic complexes.

**Fig. 2.** Structural cross-section, Mackenzie Delta to Beaufort Sea, and Cenozoic stratigraphic sequences. Line of section shown in Fig. 3. Predominant sandstone units are shown by stippled pattern, mudstones with stipples and bars. Predominantly mudstone and fine-grained rocks are indicated by darker screened pattern. S.L., sea level.

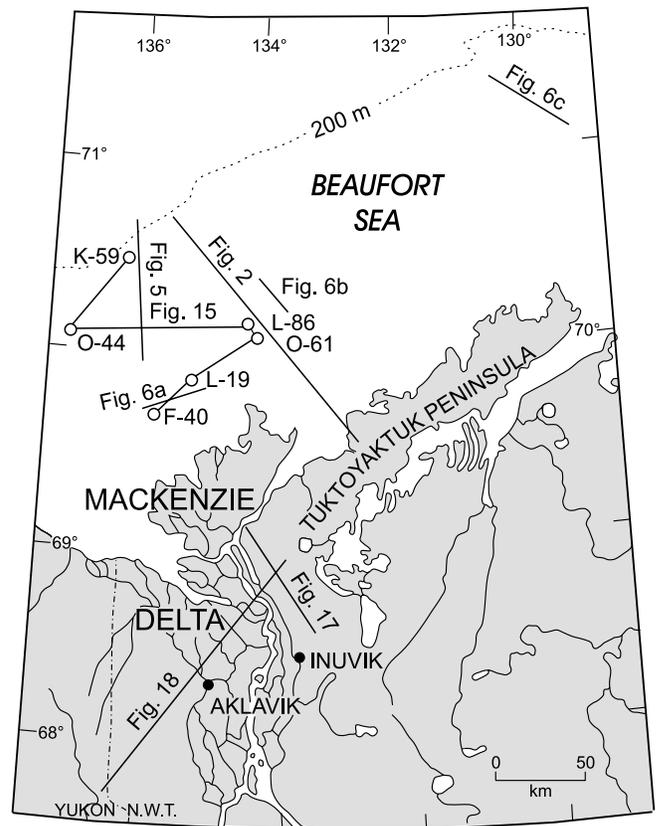


During the Miocene to Pleistocene, three major depositional sequences were developed in Beaufort–Mackenzie Basin: the Mackenzie Bay Sequence of latest Oligocene to Middle Miocene age; the Akpak Sequence of Late Miocene age; and the Iperk Sequence of Pliocene–Pleistocene age (Fig. 2, location shown on Fig. 3). The Mackenzie Bay and Akpak sequences reach thicknesses of about 1000 m. The Iperk Sequence, in contrast, is more than 4000 m thick. Since the Iperk spans a much shorter time interval, it is apparent that the Iperk Sequence is atypical and represents anomalously high rates of erosion and deposition.

The Mackenzie Bay Sequence is widely developed in the subsurface of Beaufort–Mackenzie Basin. Outcrop terrestrial equivalents are rare, but have been described from the Ballast Brook Formation on Banks Island (Fyles et al. 1994), unnamed Middle Miocene beds on Porcupine River north-eastern Alaska, the Usibelli Group of the Alaska Range, and the Kenai Group of Cook Inlet, Alaska (White and Ager 1994). The Akpak Sequence is only known from the subsurface and has a more limited distribution affected by erosional truncation around the basin margin. The Iperk Sequence is a pervasive, thick package distributed throughout the subsurface with thinner outcrop equivalents wedging out on the basin margin around the Mackenzie Delta area and northeastward in the sediments of the Beaufort Formation and other deposits of the continental terrace wedge bordering the Arctic Archipelago.

Together, the Mackenzie Bay, Akpak, and Iperk sequences and regional equivalents hold an important record of the sedimentary and biotic responses to climatic deterioration in the arctic region (Fig. 4). The Mackenzie Bay Sequence yields palynological evidence of a rich thermophilous flora indicative of warm moist temperate terrestrial climates (*Carya*, *Castanea*, *Juglans*, *Liquidambar*, etc.), with a peak in climate and canopy density occurring during the early Middle Miocene (White et al. 1997). The absence of much of that thermophilous flora in the overlying Akpak Sequence indicates climatic cooling but with indicators of moist climatic conditions still present (*Tsuga*). Iperk floras indicate cool dry climatic conditions with a flora dominated by *Pinus*, *Picea* and *Betula*. Parallel patterns are shown in the foraminiferal distribution with the Mackenzie Bay Sequence

**Fig. 3.** Location of cross-sections, seismic lines, and topographic profiles presented in this paper.

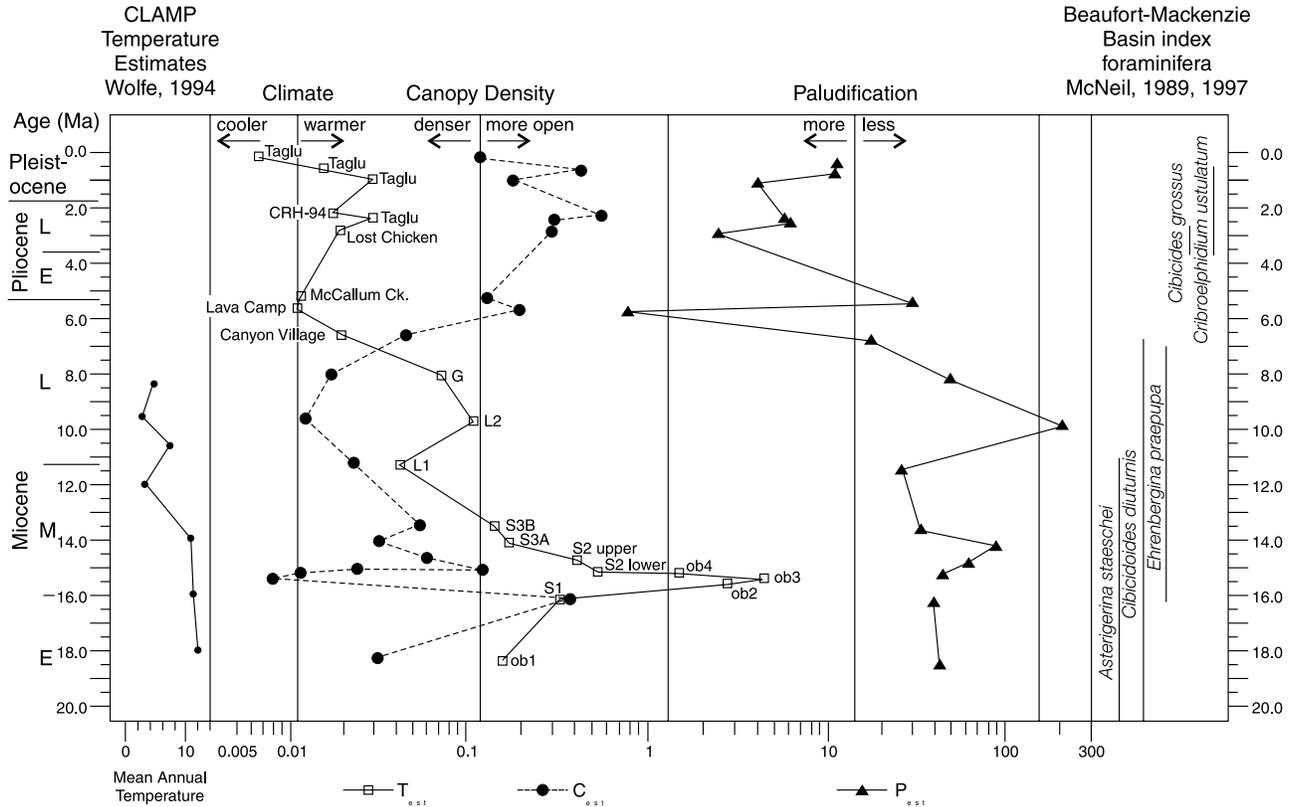


containing warm water genera such as *Asterigerina*, the Akpak containing longer ranging, colder-water-tolerant species surviving from the Middle Miocene, and the Iperk containing a newly introduced boreal assemblage following a complete faunal turnover at the Akpak–Iperk sequence boundary.

**Previous evidence from the High Arctic**

Early recognition of a regional arctic unconformity can be found in the works of Tozer (1955, 1960 p. 14), who

**Fig. 4.** Interpretation of vegetation and climatic parameters produced by drawing ratios of pollen and spore taxa from continental sections with independent age estimates in northern northwest Canada and Yukon Territories and Alaska;  $T_{est}$  (warm/cool trees) indicates changes in climatic temperature,  $C_{est}$  ((shrubs plus herbs)/trees) indicates changes in forest canopy openness and,  $P_{est}$  (terrestrial angiosperms/*Sphagnum*) indicates changes in site paludification (cover by saturated organic matter). Interpretation is based on the direction of change, rather than on the absolute magnitude. Due to several factors, especially differential pollen productivity of taxa, the performance of the ratios are not linear measures of the underlying parameters (White et al. 1997).



recognized a “remarkable sheet of unconsolidated sediment,” referred to as the Beaufort Formation, occurring from Banks Island to Meighen Island in the Arctic Archipelago and resting unconformably on early Cenozoic or Cretaceous rocks. Tozer (1955) reported remains of *Picea* and *Pinus* in the Beaufort Formation and considered it to be of late Cenozoic (Pliocene) age. Later work on Banks Island (Hills 1969; Hills et al. 1974) revealed unconsolidated sediments similar to the Beaufort Formation that yielded plant fossils of undisputed Miocene age, in particular, the walnut *Juglans eocinerea* Hills et al. These Miocene beds occupied the lower part of the “Beaufort Formation” on Banks Island and occurred below an erosional angular unconformity. Considerable confusion followed regarding the age (Miocene and (or) Pliocene) and correlation of the “Beaufort Formation” (Dixon et al. 1992). Resolution of this problem came with the work of Fyles et al. (1994), who restricted the use of the name Beaufort Formation to Pliocene deposits and introduced the name Ballast Brook Formation for the Miocene deposits on Banks Island.

### Previous evidence from Beaufort-Mackenzie Basin

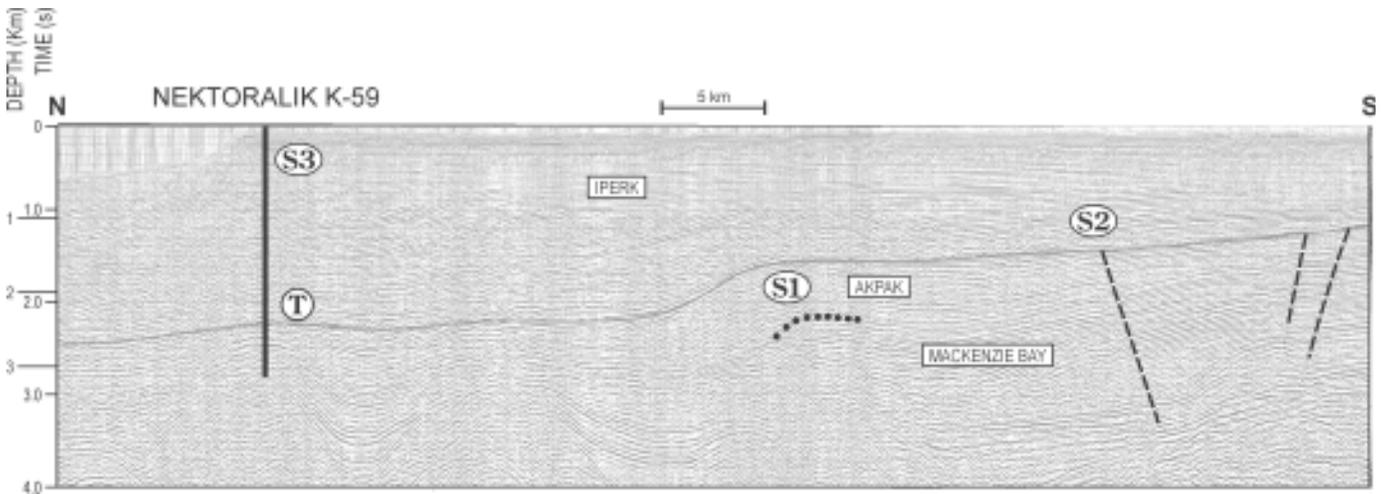
In the Beaufort-Mackenzie Basin, seismic profiles (Lane and Jackson 1980; Jones et al. 1980) revealed a conspicuous

regional unconformity in the upper Cenozoic sediments. Poor biostratigraphic control, however, resulted in contrasting age assignments. Lane and Jackson (1980), for example, recognized the “Beaufort Sequence” of Late Oligocene to Pleistocene age and Jones et al. (1980) introduced the name Iperk Sequence for the same strata and assigned a Miocene to Holocene age.

Jones et al. (1980) noted that the “Paleogene-Neogene” unconformity was erosional around the basin margins, locally representing considerable erosion, but within the basin, uplift was thought to be insufficient to raise the unconformity to sea level. Deeper in the basin, they noticed that the unconformity decapitated Paleogene structures as a result of significant submarine erosion and that turbidites and debris flows were interbedded with deep-water clays above the unconformity. Jones et al. (1980) introduced the name Iperk Group for the 4000 m-thick pile of sediments above the unconformity. Although the Iperk sediments were poorly dated at that time, it was estimated by Jones et al. (1980) that 90% of the Iperk Group was deposited prior to Quaternary glaciation.

In the Mackenzie Delta area, Young and McNeil (1984) recognized the Pliocene-Pleistocene Nuktak Formation unconformably overlying Miocene and older units. Young and McNeil (1984) also recognized a Miocene “Beaufort Formation” beneath the Nuktak Formation, but these beds were

**Fig. 5.** Seismic reflection profile across Beaufort Sea shelf and upper slope (location in Fig. 3). Solid (horizontal) line indicates sub-Iperk unconformity; dashed lines indicate faults truncated at the unconformity; dotted line indicates paleoshelf margin position at the top of the Mackenzie Bay Sequence. Shelf margin positions indicated by S1 (top Akpak, Late Miocene), S2 (lower Iperk, Late Pliocene), and S3 (top Iperk, Pleistocene). Turbidite fan deposits (T) occur in basinal portion of lower Iperk. The Nektoralik K-59 well (solid dark vertical line) penetrated slope and basinal deposits in the Iperk and older sequences.



later shown to be Oligocene gravels of the Kugmallit Formation by Dixon et al. (1992).

Despite the confusion over the age of certain units, a clear expression of a regional unconformity was noted in numerous arctic studies from the work of Tozer (1955) onwards. In 1982, McNeil et al. made the first attempt to explain the significance of this conspicuous unconformity. Using foraminiferal and palynological data combined with regional geological evidence, they deduced that the unconformity was developed most likely during the Late Miocene or Early Pliocene; that it appeared to coincide with eustatic sea-level drop during the Messinian; that it marked a complete microfaunal turnover and the introduction of cool-water assemblages; that the flora changed dramatically from a cool-temperate, deciduous–coniferous–bryophyte assemblage to a boreal coniferous–bryophyte assemblage; and that the emerging Miocene mountains of southeastern Alaska contributed to a cooler continental climate in the Mackenzie region.

More recent investigations by McNeil (1989, 1990), Dixon et al. (1992), Duk-Rodkin and Hughes (1994), and Fortin and Blasco (1996) coupled with detailed geological, geophysical, paleontological, and stable isotope data presented herein, provide for a much clearer look at the full extent and significance of the regional unconformity that is so conspicuously developed in the Beaufort–Mackenzie Basin and surrounding areas of the Arctic. White et al. (1997) have further considered the contribution of regional tectonics and global climatic events to late Neogene climatic cooling in the study region.

### Seismic stratigraphy

Seismic reflection data provide the best regional perspective of the sub-Iperk unconformity and late Cenozoic strata across the Beaufort–Mackenzie Basin. To illustrate this point and show the variable depth and nature of the unconformity surface beneath the Beaufort Sea, one regional seismic pro-

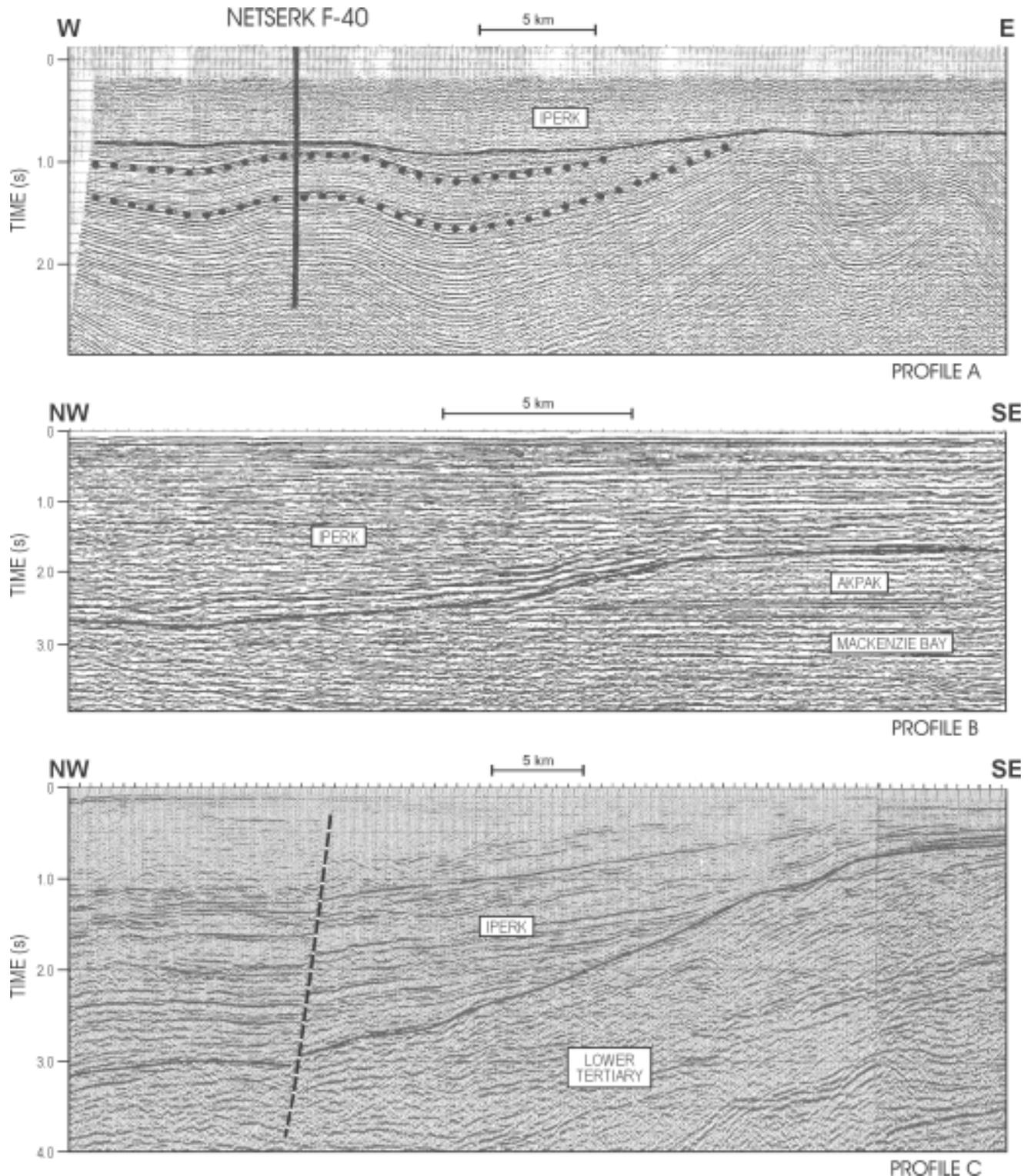
file (Fig. 5) and three shorter profiles (Fig. 6 profiles A–C) have been selected.

In the regional, downdip profile (Fig. 5), shelf strata of the Mackenzie Bay and Akpak sequences are moderately deformed by extensional faulting beneath the unconformity in the south. Basinward, to the north, equivalent strata in deep-water continental rise facies are folded into compressional anticlines. Development of the sub-Iperk unconformity coincided with, or followed, a Late Miocene tectonic phase of regional deformation, uplift, and erosion (Lane and Dietrich 1995). Strata above the unconformity are generally undeformed, indicating that Pliocene–Pleistocene sedimentation coincided with a period of relative tectonic quiescence.

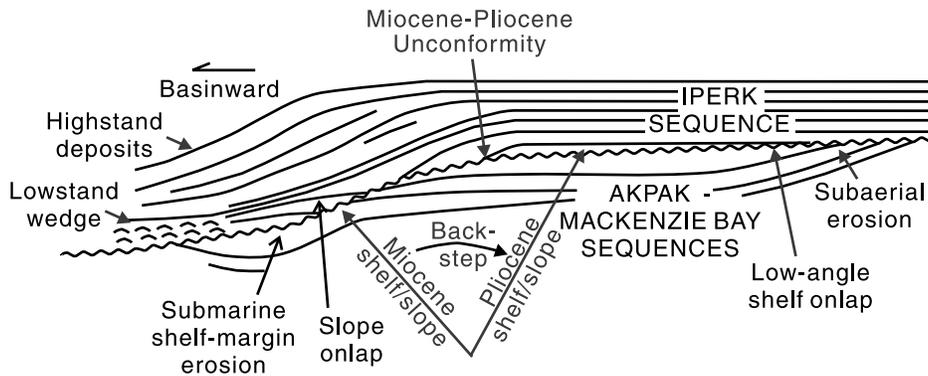
The regional seismic profile (Fig. 5) also outlines progradational clinoform configurations in late Cenozoic sequences, delineating linked-shelf, continental-slope, and basin settings. The vertical dimensions of slope clinoforms indicate bathymetric relief of some 1000–1200 m between shelf and basinal settings in the Iperk and Akpak sequences (not corrected for compaction). Similar bathymetric relief is observed between the present-day outer Beaufort Sea shelf and the base of the continental slope (Pelletier 1987). The vertical separation between the Late Miocene shelf margin and Pliocene shelf margin indicates a relative change in sea level across the unconformity of about 400 m. The positions of paleoshelf margins (shelf–slope breaks) indicate that the post-unconformity transgression resulted in a major 15–20-km back-stepping or landward shift of the shelf margin above the unconformity.

Later in the Pliocene, thick deposits of the Iperk Sequence prograded up to 120 km basinward from the position of the Miocene Akpak shelf margin, filling much of the outer Beaufort–Mackenzie Basin (Dixon 1996). In central parts of the basin, the rate and extent of Pliocene progradation greatly exceeded that of the Miocene (Figs. 2, 5). Reflection clinoform patterns in the Iperk sequence exhibit complex sigmoid-oblique geometries, characteristic of high-energy depositional systems (Fig. 5). These reflection patterns are

**Fig. 6.** Seismic reflection profiles (A, B, C) illustrating variable expressions of the Miocene–Pliocene unconformity (locations in Fig. 3). Unconformity marked by solid (horizontal) lines. Profile A illustrates truncation of Akpak and Mackenzie Bay sequences at sub-Iperk unconformity and dramatic difference in structural deformation across the unconformity surface. Dotted lines mark top and base of Miocene Mackenzie Bay Sequence. The Netserk F-40 well (solid dark vertical line) encountered Late Pliocene nonmarine sediments above the sub-Iperk unconformity. See text (seismic stratigraphy) for discussions. Profile B illustrates downcutting of the sub-Iperk slope unconformity into Miocene Akpak and Mackenzie Bay shelf sequences. Profile C illustrates onlap of deep-marine Iperk strata onto the Miocene–Pliocene unconformity. Dashed line in profile C marks a Late Pliocene normal fault that offsets the unconformity.



**Fig. 7.** Schematic cross-section showing sequence stratigraphic relationships above and below the sub-Iperk Sequence unconformity.



consistent with well data indicating coarse-clastic deltaic sediments in the topset portion of the Iperk Sequence. At the base of the Iperk Sequence, in the basin setting, thin, deep-water turbidites form a lowstand wedge lying unconformably on older strata (Fig. 5). The Nektoralik K-59 well encountered about 35 m of fine grained turbidite sandstones in the lowermost part of the Iperk Sequence (Dixon and Snowdon 1979). These sandstones at the Nektoralik location are located some 20 km basinward of the paleocontinental slope (Fig. 5). In the shelf area, reflections immediately above the unconformity are parallel to the unconformity surface, indicating relatively rapid transgression and minimal tilting of the unconformity surface in this area.

Figure 6 provides several views of features associated with the unconformity, from nonmarine to deep-marine settings. In the nonmarine setting, a strike section (Fig. 6 profile A) illustrates subaerial erosion and truncation of folded Akpak and Mackenzie Bay strata. At Netserk F-40, there is a 30 or 40 m-thick section just above the unconformity that is barren of foraminifera, suggesting either terrestrial or shoreface sedimentation. Figure 6 profile B illustrates pronounced submarine slope erosion that partially truncates the Mackenzie Bay Sequence and entirely truncates the Akpak Sequence. Figures 6 profiles A and B indicate the Late Miocene erosional event removed up to several hundred metres of Miocene shelf sections, in both subaerial and submarine settings. Figure 6 profile C illustrates onlap of about 1000 m of deep-marine strata of the Iperk Sequence onto the sub-Iperk slope unconformity.

A composite summary of the sequence stratigraphic relationships of upper Cenozoic strata, collated from the illustrated seismic profiles and numerous others in the region is shown in Fig. 7.

On a seismic time structure map of the unconformity surface (Fig. 8), the position of the Late Miocene shelf margin is marked by an arcuate-shaped zone of steep contour gradients, indicating abrupt northward (basinward) deepening of the unconformity surface. The steepest gradients occur along the northeast-aligned segment of the slope (from 130°W to 132°W), which reflects an underlying tectonic hingeline influence (Dixon and Dietrich 1990). The seismic structure contours (Fig. 8) also reveal several small reentrants in the slope area that may represent submarine canyons cut into the Miocene outer shelf. An anomalous, base-of-slope high in the area of the Nektoralik K-59 well on Fig. 8 is a structural

feature, associated with diapiric uplift of deep-seated shale cored anticlines (Fig. 5).

### Carbonate hardground (K-59 limestone)

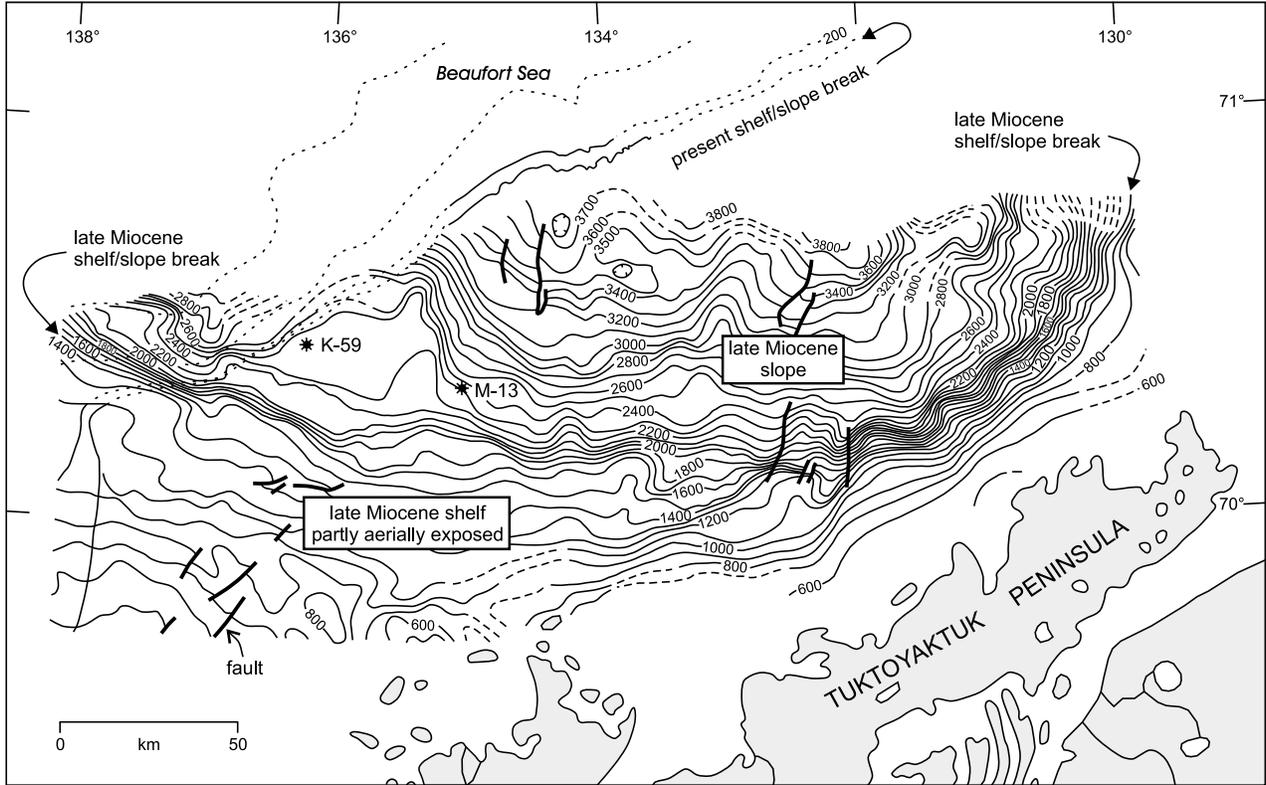
A thin microcrystalline limestone was observed on top of the Miocene section just below the sub-Iperk unconformity in the Nektoralik K-59 and Ukalerk C-50 wells (Dixon and Snowdon 1979; Jones et al. 1980; and McNeil et al. 1982). Jones et al. (1980) noted that it was composed of secondary aragonite, enriched in O<sup>18</sup> and depleted in C<sup>13</sup> (unfortunately no data supplied). This distinctive carbonate unit, referred to here as the K-59 limestone, received little more attention as the basin sequences were studied in more detail (Dixon et al. 1992), but a detailed examination of well cuttings at the unconformity has revealed that the unit is widespread in the Beaufort-Mackenzie Basin as indicated on Fig. 9. The thickness of the K-59 limestone can be determined from mechanical logs with an accuracy of plus or minus 1 m. Using well logs, Dixon and Snowdon (1979) reported a thickness of 6 metres in the Nektoralik K-59 well and McNeil et al. (1982) reported 8.9 metres in the Ukalerk C-50 well.

We now interpret the limestone as a carbonate hardground formed during a time of sediment starvation and sediment bypass that affected the basin. The hardground provides a very good marker of the distribution of marine sedimentation at the time of the unconformity. Its stratigraphic position at the sequence boundary underlying conspicuous turbidites and lowstand deposits also provides important evidence of the processes that took place at the time of unconformity and the sedimentary processes that followed (Figs. 10a, 10b).

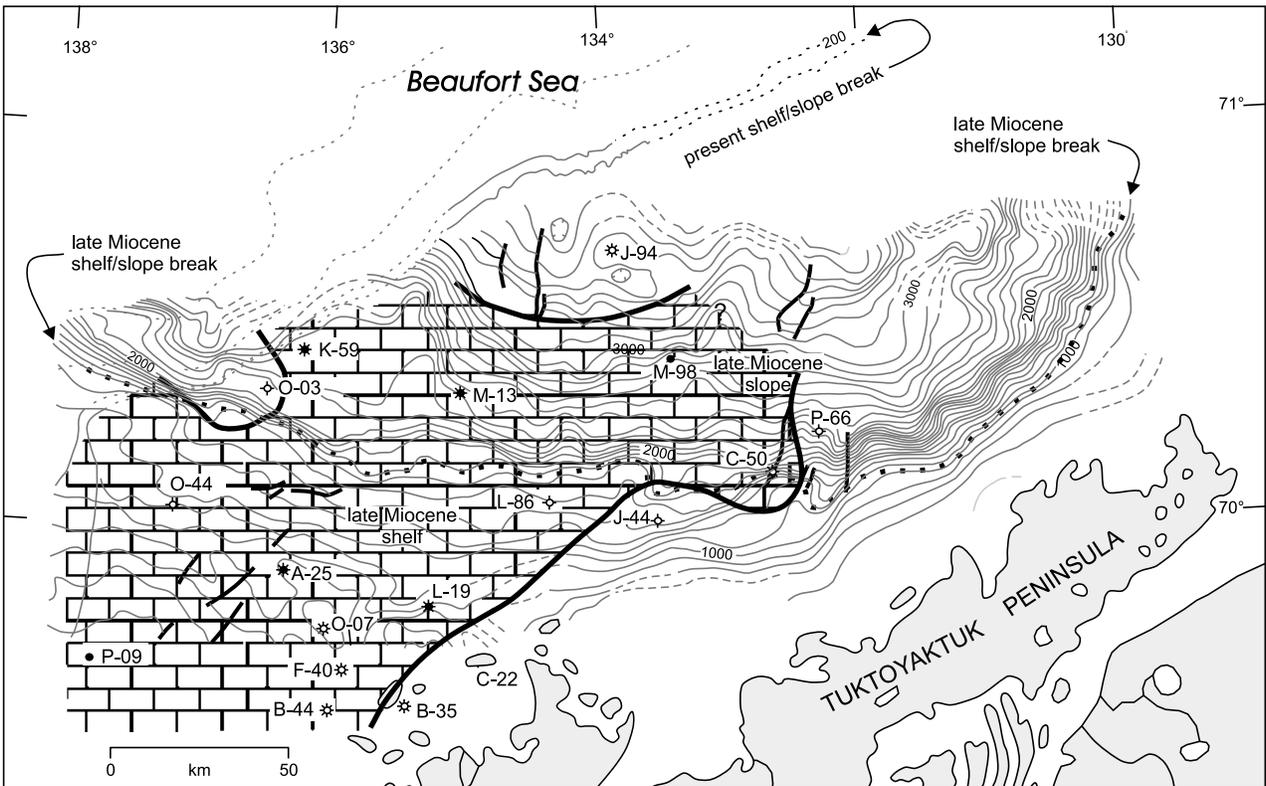
Stratigraphic and paleontological evidence clearly indicates that the carbonate hardground postdates the Akpak and Mackenzie Bay sequences. Not enough is known about the detailed distribution of the carbonate to indicate if it underwent contemporaneous erosion in certain areas. Its consistent occurrence in numerous wells, however, indicates that it was deposited as a widespread blanket or drape.

The K-59 hardground has now been recognized in 12 wells (Fig. 9). Well cuttings provide abundant chips of the limestone which were examined for their microfaunal content, but only one well, Issungnak O-61, proved to be fossiliferous, yielding foraminifera, scaphopods, ostracods, and bryozoans. The foraminifera are enclosed in limestone

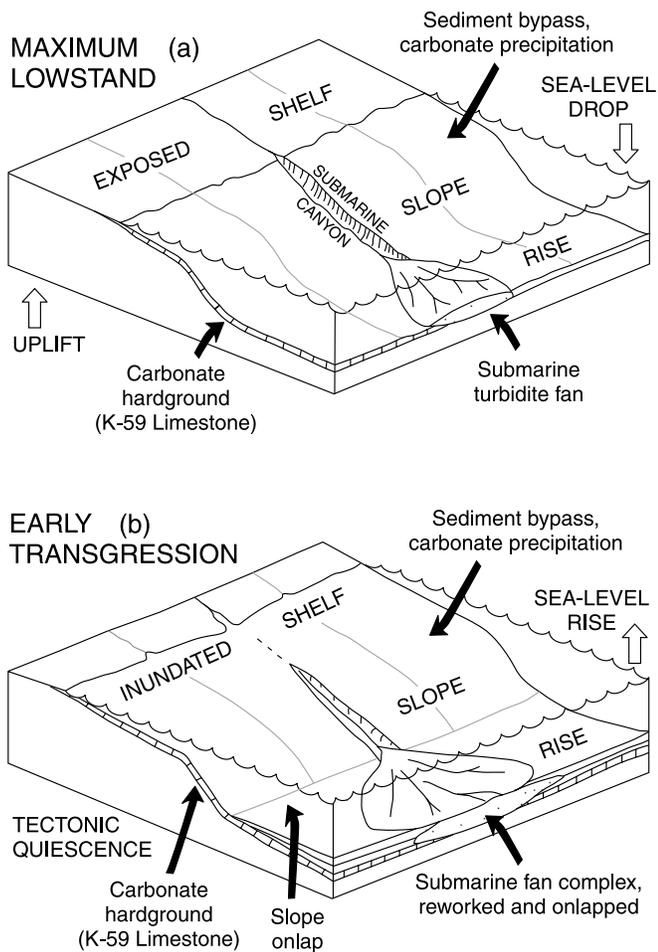
**Fig. 8.** Time structure contour map of the sub-Iperk Sequence unconformity for the offshore central part of Beaufort–Mackenzie Basin, showing the configuration of the continental margin at the end of the Miocene. Faults are indicated by heavy lines. (Modified from Fortin and Blasco 1996).



**Fig. 9.** Distribution of the carbonate hardground (K-59 limestone) superimposed on the time-structure contour map of the sub-Iperk Sequence unconformable surface (Fig. 8).

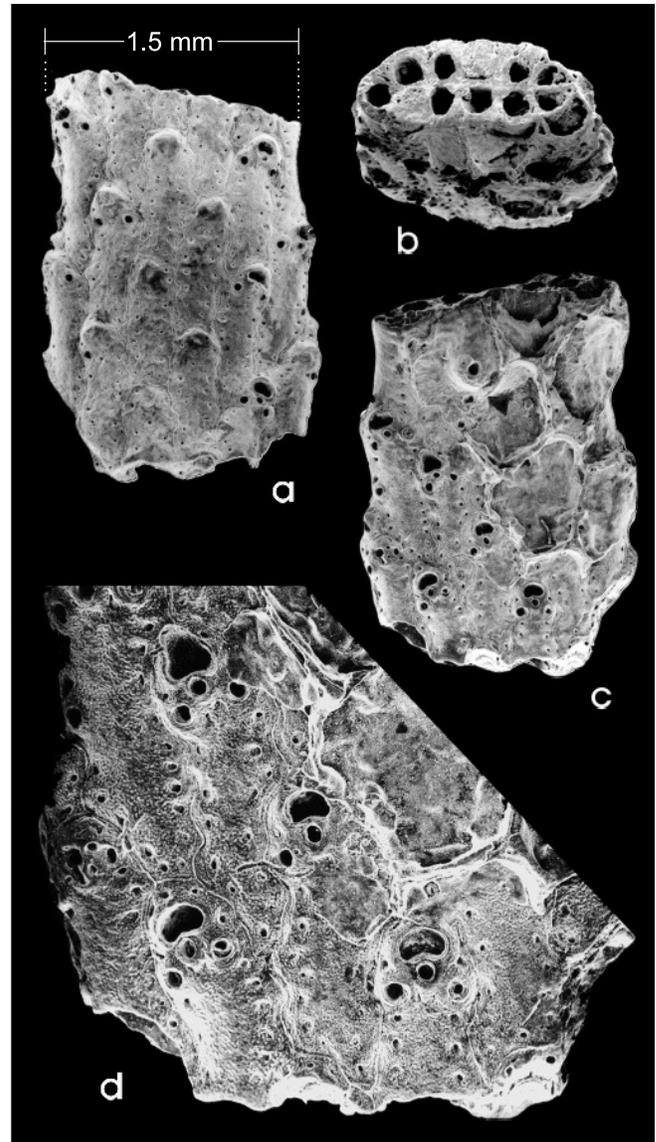


**Fig. 10.** Schematic models of deposition (a) at the time of maximum sea-level lowstand and (b) during the early transgression.



matrix and difficult to identify, but specimens of *Cibicides grossus* ten Dam and Reinhold, *Haynesina?* sp., and a large inflated specimen of *Miliolinella?* have been identified. The remaining microfauna consists of numerous fragments of an unornamented scaphopod shell, several specimens of an unidentified smooth-surfaced ostracod, and numerous fragments of a distinctive branching cheilostomate bryozoan species (Fig. 11) tentatively identified as *Adeonella* sp. aff. *A. polystomella* (Reuss), which ranges from Eocene to Recent (Moissette 1997). The scaphopod suggests open-marine conditions during deposition of the K-59 hardground. The hardground provided a unique and favourable substrate for colonization by bryozoans, which are otherwise not typical of the Arctic Cenozoic fossil record. All previous records of *A. polystomella* are from warm temperate shelf deposits of Europe and the Mediterranean. Recent occurrences are known from the eastern Atlantic Ocean (Angola to the Canary Islands). Tentatively, the occurrence of *A. sp. aff. A. polystomella* in the Beaufort–Mackenzie area suggests influence from a relatively warm Atlantic water mass, possibly representing the mid-Pliocene climate peak ca. 3 Ma (Dowsett and Poore 1991). Palynomorphs in the K-59 carbonate hardground at the Nektoralik K-59 well, however, consist of *Picea*, *Pinus*, and *Betula*, suggesting that the

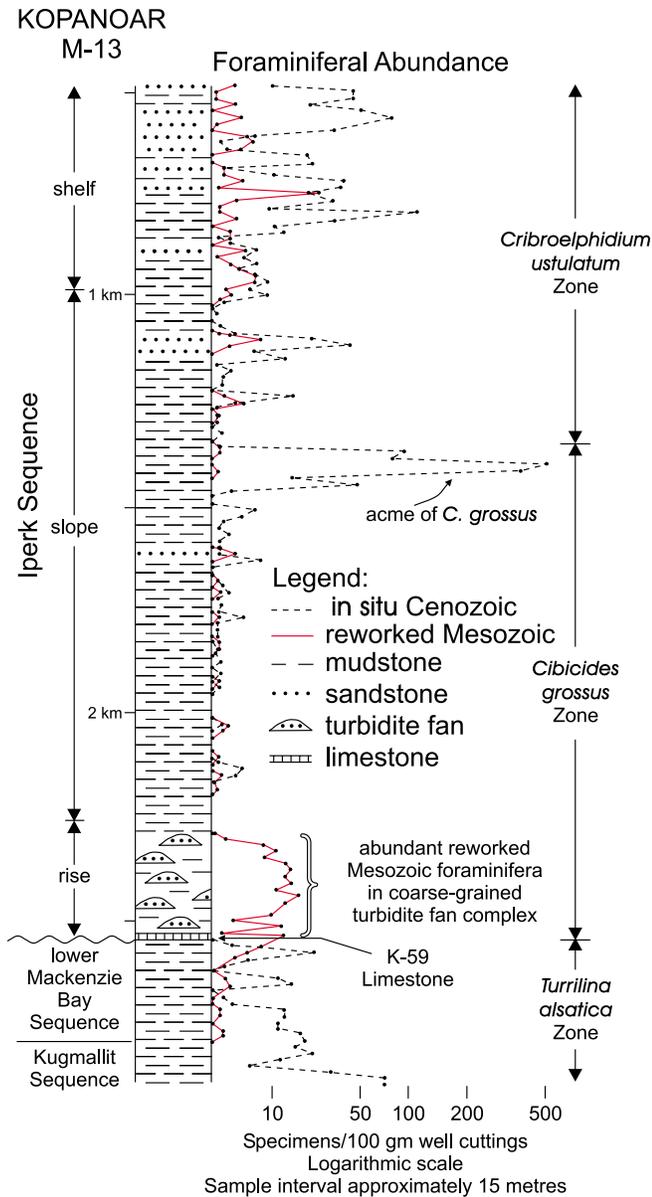
**Fig. 11.** Fragment of the branching cheilostomate bryozoan, *Adeonella* sp. aff. *A. polystomella* (Reuss) from the Issungnak O-61 well at 1305–1325 m (GSC locality C-86839). GSC type collection number 68813. (a, c) Frontal views of the zooid fragment (22x). (b) Transverse view. (d) Enlarged frontal view (51x). Identification by P. Moissette (personal communication, 1998).



neighbouring terrestrial climate was relatively cool. The ostracod appears to be *Cytheropteron paralatissimum* Swain, which is thought to have become extinct ca. 2.4 Ma (Fyles et al. 1998).

The carbonate hardground yields no traces of the prolific foraminiferal assemblages that are present below the unconformity. Its limited microfauna and microflora are significant, however, because they represent the first organisms to recolonize the basin after the climatic and environmental change at the end of the Miocene. The occurrence of *C. grossus*, *A. sp. aff. polystomella*, and the sparse pollen assemblage are of critical importance in deciphering the time span of the unconformity and the paleoenvironmental context of the K-59 limestone.

**Fig. 12.** Distribution of in situ calcareous benthic foraminifera and reworked Mesozoic foraminifera in well cutting samples of the Kopanoar M-13 well, middle shelf Beaufort Sea. Reworked foraminifera are predominantly silicified agglutinated specimens concentrated in the deep-water turbidite fan deposits and shelf sands of the Iperk Sequence.



Lowstand turbidity deposits in the deeper part of the Beaufort–Mackenzie Basin followed deposition of the carbonate hardground. Seismic profiles have been used to document the distribution of the lowstand wedge in the area of the Kopanoar M-13 well (Dixon et al. 1992) and other areas of the basin. In the Kopanoar M-13 well, the lowstand deposits are devoid of in situ fossils but contain an abundance of reworked foraminifera as plotted in Fig. 12. Seismic profiles indicate that the lowstand deposits onlap older, pre-unconformity, slope deposits and pinch out upslope on the unconformable surface.

Reworked Mesozoic foraminifera in the lowstand deposits at Kopanoar M-13 show classic effects of diagenetic alter-

ation (McNeil 1997), indicating that they were derived from terrains of much higher thermal maturity. The tests of the agglutinated foraminifera are thoroughly silicified and alteration colours (Foraminiferal Colouration Index (FCI) of McNeil et al. 1996) typically range from FCI 7 to 8. These preservational features are diagnostic of a source area that was originally buried to depths in the order of 6 km and temperatures in the order of 150°C or more (burial diagenetic zones C or D of McNeil 1997). This evidence indicates that the turbidites were largely sourced from orogenically deformed and tectonically uplifted strata of the Richardson Mountain area rather than the less deeply buried and thermally immature cratonic areas to the southeast.

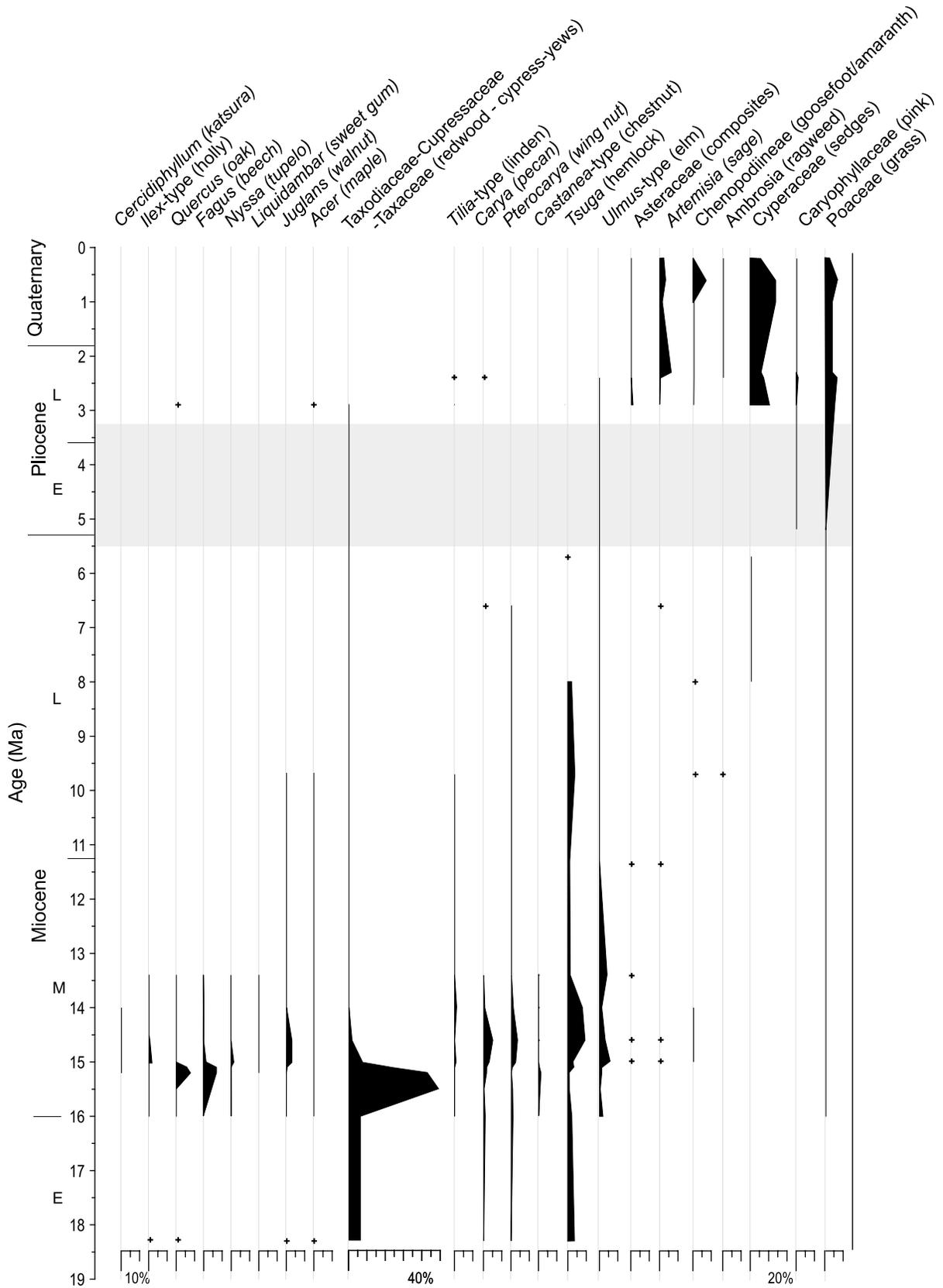
### Floral and faunal change across the sub-Iperk unconformity

The palynological and foraminiferal records have been examined relative to the sub-Iperk unconformity (Figs. 13, 14). Together these fossil groups provide ample evidence of significant change in the terrestrial and marine environments leading up to and following the sub-Iperk Sequence unconformity event. Four generalized biotic assemblages distinguish four climatic phases in the Middle Miocene to Pleistocene sequences of the Beaufort–Mackenzie area. The first assemblage of palynomorphs and foraminifera reflects warm climatic conditions that peaked in the early Middle Miocene. The second assemblage reflects a cooling trend from the Middle Miocene oscillating through the Late Miocene and culminating in a low point at the latest Miocene. A complete foraminiferal turnover and a palynological change indicating drier, possibly cooler climates in the Early Pliocene distinguish the third assemblage. The fourth assemblage is diagnostic of the cool climatic conditions of the latest Pliocene to Pleistocene glacial periods. The sub-Iperk unconformity appears to have been directly associated with drier cooler climatic conditions at the end of the Miocene and pronounced oceanographic changes responsible for complete microfaunal turnover.

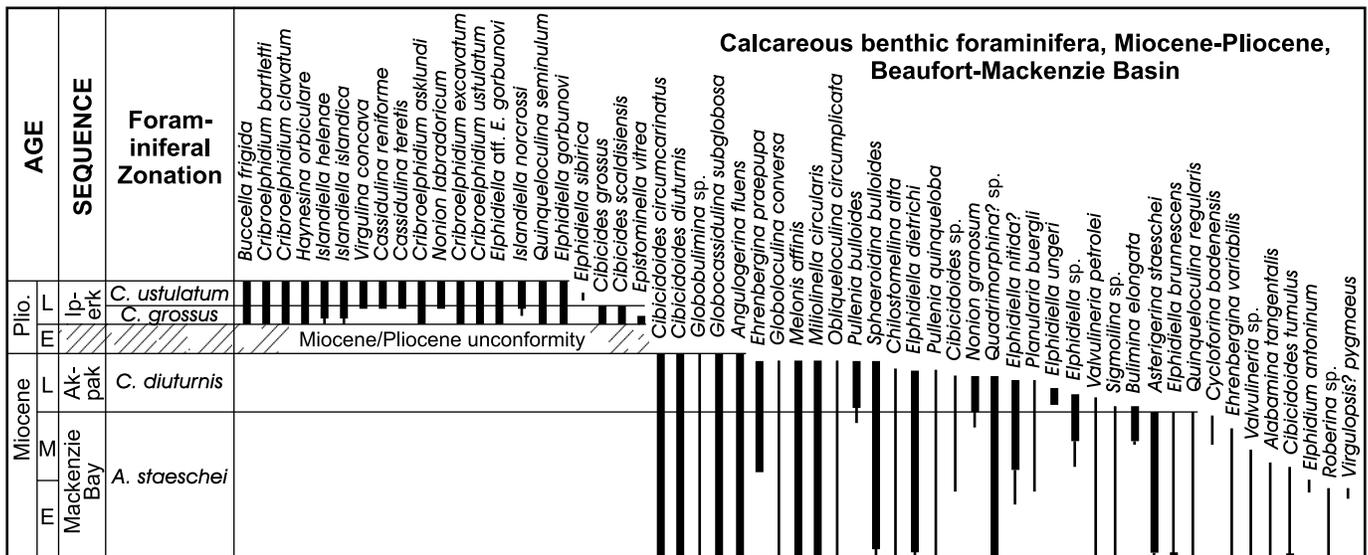
Evidence of a warm climatic interval during the Early to Middle Miocene is now well documented by plant megafossils and palynomorphs. This includes the walnut *Juglans eocinerea* in the Ballast Brooks Formation on Banks Island (Hills et al. 1974), Taxodiaceae stumps associated with temperate hardwood palynomorphs recovered from a 15.2 Ma outcrop section on the Porcupine River (White and Ager 1994; White et al. 1997), palynomorphs in the Beaufort Sea subsurface (White 1989), and palynomorphs and plant megafossils in the Nenana coalfield (Leopold and Liu 1994) and Cook Inlet (Wolfe 1994) of south central Alaska.

In the Beaufort–Mackenzie area, palynomorph assemblages in the Miocene Mackenzie Bay and Akpak sequences are generally impoverished and masked by an abundance of recycled material. Analysis of several well-documented terrestrial sections (White et al. 1997) provides strong evidence of humid temperate conditions. Thermophilous taxa documenting this warm climatic episode include *Quercus* (oak), *Fagus* (beech), *Tilia* (linden), *Liquidambar* (sweet gum), *Carya* (pecan), *Castanea* (horse chestnut), *Juglans* (walnut), *Pterocarya* (wing nut), *Ginkgo* (ginkgo), *Tsuga* (hemlock), and Taxodiaceae–Cupressaceae–Taxaceae (redwood, cypress,

**Fig. 13.** Relative abundance of selected pollen and spore taxa from continental sections with independent (radiometric, paleomagnetic) age estimates in northern Northwest and Yukon Territories and Alaska (White et al. 1999). Grey band indicates approximate time affected by unconformity. Plus (+) symbol indicates palynomorph relative abundance of less than one percent.



**Fig. 14.** Distribution of calcareous benthic foraminifera in the late Cenozoic of the Beaufort–Mackenzie Basin illustrating a complete foraminiferal turnover from the Miocene to Pliocene. Compiled from McNeil (1996, 1997). Grey band indicates Early Pliocene gap in the fossil record due to unconformity. Relative abundance is schematic: narrow vertical bars represent approximately one to five specimens, thicker bars represent more than 5 specimens. Plio., Pliocene.



yews). White and Ager (1994) estimated a mean annual temperature of 9°C for the peak period of warmth, ca. 15.2 Ma.

Though not as strongly indicated, the benthic foraminiferal fauna also provides evidence of temperate conditions by the presence of the dominantly warm-water genus *Asterigerina* and relatively high species diversity for such a high-latitude site. Figure 14 illustrates the foraminiferal succession through the Miocene Mackenzie Bay and Akpak sequences in the Beaufort–Mackenzie Basin. The succession is characterized by a gradual disappearance (some extinctions) of foraminiferal species. Worsening climatic conditions are indicated by the disappearance of *Asterigerina staeschei* at the Mackenzie Bay – Akpak sequence boundary. A further indicator of climatic deterioration is indicated by the domination of longer ranging, presumably colder-water-tolerant, species in the Akpak Sequence. At the Akpak–Iperk boundary, even these longer ranging taxa are finally terminated.

Palynomorph distributions in the Miocene follow a similar trend to the foraminifera, but with a more conspicuous change in the late Middle Miocene marked by the disappearance of the thermophilous taxa (Fig. 13). Some of these taxa have minor occurrences in Late Miocene sediments of the Akpak Sequence, but the Late Miocene palynoflora is clearly dominated by longer ranging species of alders, birch, pines, and spruce (White et al. 1999). The continued presence of *Tsuga* suggests that climates remained moist although much cooler during the Late Miocene in this area.

Floristically, the unconformity at the Akpak–Iperk boundary is not as dramatically represented as in the foraminifera, which underwent a complete turnover. The disappearance of several key palynomorphs, however, is significant of further climatic change. The rarity or absence of *Tsuga*, *Abies*, and *Taxodiaceae–Cupressaceae–Taxaceae* indicate drier, cooler climatic conditions at the time of the unconformity and following it. Rare occurrences of these taxa in the lower Iperk Sequence are interpreted as reworked or transported into the area.

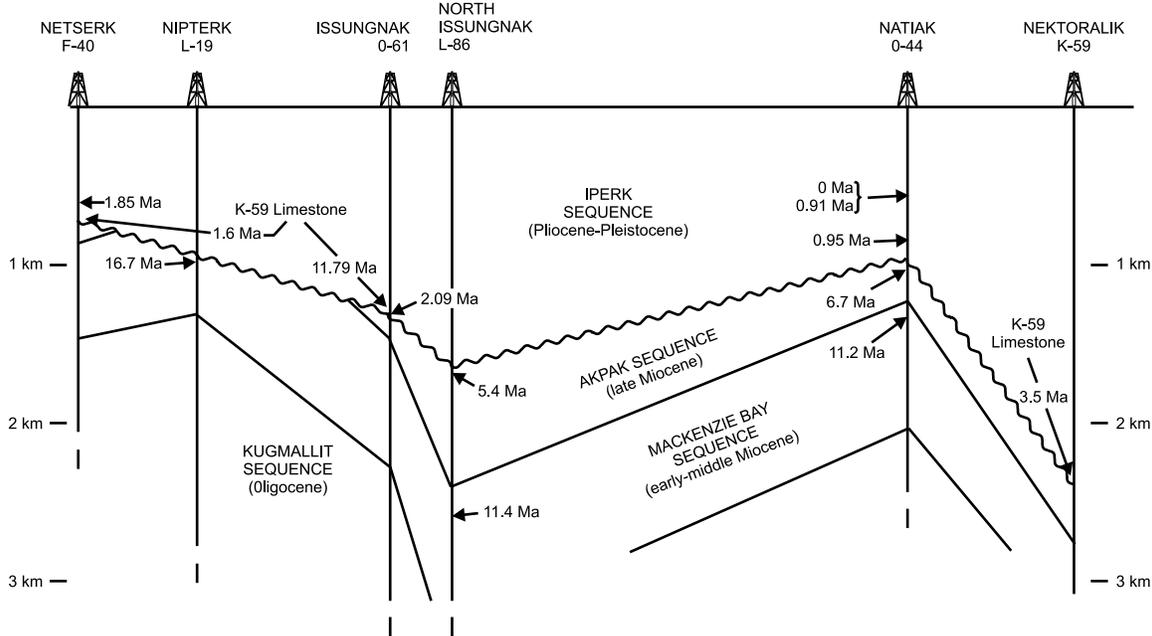
The bulk of the Iperk Sequence consists of thick prograding highstand deposits. These slope and shelf sediments contain foraminifera of the *Cibicides grossus* and *Cibicides ustulatum* interval zones. In arctic regions, the *C. grossus* Zone is dated at approximately 2.5 to 3.4 Ma. Feyling-Hanssen (1980), McNeil (1990), and Fyles et al. (1998) considered that the *C. grossus* assemblage developed during a time of climatic amelioration prior to the Late Pliocene continental glaciations on Greenland beginning at 2.4 Ma.

Numerous lines of evidence suggest that the *C. grossus* Zone represents a sea-level highstand within the Pliocene. The zone is very widespread in the arctic regions (McNeil 1990; Feyling-Hanssen 1980) and occurs at relatively high elevations of 110 to 120 m a.s.l. on northern Ellesmere Island (Fyles et al. 1998). The Pliocene is well known for its warm interval, ca. 3 Ma, and concurrent sea-level highstand. Apparently, the *C. grossus* Zone is the arctic expression of this event. Although *C. grossus* represents a period of amelioration during the Pliocene, it also represents the third phase in Neogene climatic deterioration as outlined in this paper. In spite of climatic amelioration, tectonically induced continentality probably prevented thermophilous taxa from reoccupying the region (White et al. 1997, 1999), ensuring the dominance of coniferous and herbaceous plants.

The final step in the Arctic Cenozoic climatic deterioration is represented by the introduction of boreal-arctic microfaunas of the *Cibicides ustulatum* Zone, which occupy the upper part of the Iperk Sequence in the Beaufort–Mackenzie Basin. Foraminiferal assemblages of this zone existed during the glacial–interglacial stages of the late Cenozoic and are not considered in this study which focuses on the preglacial Miocene–Pliocene record.

Palynological analysis of the Iperk Sequence is made difficult by an impoverished in situ palynoflora and an abundance of recycled palynomorphs introduced by the rapid and widespread erosional events that characterized Iperk deposition.

**Fig. 15.** Strontium isotope ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) age estimates for calcareous benthic foraminifera and micritic limestone in Miocene and Pliocene sequences of the Beaufort–Mackenzie Basin. Age estimates of 5.4 to 16.7 Ma in the Mackenzie Bay and Akpak sequences conform closely to previous biostratigraphic age determinations. Strontium values from the K-59 limestone vary widely and may have been affected by sediment pore water. Strontium age estimates for the Iperk Sequence range from 0 to 2.09 Ma, which is younger than age estimates of 2.5 to ~3.5 Ma based on benthic foraminifera.



**Table 1.**  $^{87}\text{Sr}/^{86}\text{Sr}$  data.

Well name	Sample interval	$^{87}\text{Sr}/^{86}\text{Sr}$ ratios	Age (Ma)	Sample material
Issungnak O-61	1305–1325 m	0.709096±6	2.09	<i>Cibicides grossus</i>
Issungnak O-61	1305–1325 m	0.709116±4	1.6	K-59 limestone
Natiak O-44	560–630 m	0.709151±6	0.91	<i>Cibicides grossus</i>
Natiak O-44	590–630 m	0.709197±8	0	<i>Islandiella islandica</i>
Natiak O-44	841–874 m	0.709149±4	0.95	<i>Cibicides grossus</i>
Natiak O-44	976–1048 m	0.708973±5	6.7	<i>Cibicoides</i> , <i>Elphidiella</i> , miliolids
Natiak O-44	1279–1312 m	0.798882	11.2	<i>Asterigerina</i> , <i>Elphidiella</i>
Nektoralik K-59	2258 m	0.709048±14	3.5±1.5	K-59 limestone
Netserk F-40	637–649 m	0.709107±6	1.85	<i>Elphidiella gorbunovi</i>
Netserk F-40	732–762 m	0.708872±6	11.79	K-59 limestone
Nipterk L-19	940–950 m	0.708730±6	16.76	<i>Asterigerina</i> , <i>Elphidiella</i>
North Issungnak L-86	1565–1640 m	0.709031±4	5.4	<i>Cibicoides</i> , <i>Pullenia</i> , nodosarids

However, analysis of continental sections has clarified the pattern of vegetation adaptation to temperature decline (White et al. 1997, 1999). Although weakly indicated and difficult to document from well cuttings, there is some indication that palynomorphs paralleled the foraminiferal changes seen in the *C. grossus* and *C. ustulatum* zones (White 1989). The lower Iperk Sequence contains a probable flora of larch and pine, and these diminish in the upper Iperk, where the palynoflora is dominated by spruce, birch, alder and open habitat herbs, such as the asters and the grasses.

**Strontium isotope analysis**

Strontium isotope ratios ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) were analysed for 13 calcareous benthic foraminiferal samples of 50 to 100 speci-

mens taken from the upper Mackenzie Bay, Akpak, and Iperk sequences and 3 samples of K-59 limestone (Fig. 15, Table 1). Methodology was identical to that outlined by McNeil and Miller (1990). Samples were carefully selected from the best possible cuttings samples to attain visually unaltered, in situ foraminiferal calcium carbonate. Selecting species that were either at the top of their stratigraphic range, or at the abundance acme, eliminated or minimized contamination by caved well cuttings. Age estimates were determined by correlation to a Neogene standard curve (Farrell et al. 1995) established from Ocean Drilling Project (ODP) Site 758. The  $^{87}\text{Sr}/^{86}\text{Sr}$  record from the Holocene to the Miocene has been summarized by Hodell et al. (1990) and Hodell et al. (1991). They note that periods of relatively rapid change in strontium isotope ratios occurred from 0 to 2.4 Ma, from 4.5 to 5.5 Ma, and 8 to 16 Ma, thus providing

potential for chronostratigraphic resolution. Resolution potential is poor (i.e., little isotopic change) during the middle Pliocene from 2.4 to 4.5 Ma. Increased ratios beginning at 2.4 Ma and younger reflect late Cenozoic glaciations, lower sea level, and increased continental weathering.

The oldest samples examined were from the upper Mackenzie Bay Sequence in the Natiak O-44, Nipterk L-19, and North Issungnak L-86 wells. Foraminifera analysed were dominantly species of *Asterigerina* and *Elphidiella*. Mackenzie Bay samples 10 and 12 from Natiak O-44 and North Issungnak L-86 (Fig. 15) yielded similar  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of  $0.709031 \pm 4$  and  $0.708806 \pm 11$  and an age estimate of 11.2 and 11.4 Ma. These ages compare well with the foraminiferal age estimate of Middle Miocene for the uppermost Mackenzie Bay Sequence (upper *Asterigerina staeschei* Zone of McNeil 1989). The  $^{87}\text{Sr}/^{86}\text{Sr}$  strontium value at Nipterk L-19 was considerably lower at  $0.708730 \pm 6$ , indicating an estimated age of 16.7 Ma and suggesting that the Middle Miocene deposits of the Mackenzie Sequence are removed by erosion. This is consistent with independent geological–seismic interpretations, indicating that the Iperk Sequence rests on a subaerially exposed unconformity surface at the Nipterk L-19 site.

The Akpak Sequence is developed in fewer wells than the underlying Mackenzie Bay Sequence and in some wells the foraminiferal carbonate is slightly corroded. Fortunately, the Natiak O-44 and North Issungnak L-86 wells provided good-quality assemblages consisting of nodosarids, miliolids, *Cibicides*, and *Pullenia* suitable for strontium isotope analysis.

Independent foraminiferal age determination for the Akpak Sequence established the Akpak as Late Miocene (McNeil 1989). Consideration of global event stratigraphy suggested that the sub-Iperk unconformity began at the time of the Messinian event (McNeil et al. 1982). Recently, White et al. (1997) showed floral impoverishment at ca. 5.2 and 5.7 Ma, indicating a cool climatic interval consistent with Messinian temperature and eustatic effects possibly linked to the unconformable boundary between the Akpak and Iperk sequences.

Strontium isotope ratios of  $0.708973 \pm 5$  and  $0.709031 \pm 4$ , near the top of the Akpak Sequence in the Natiak O-44 and North Issungnak L-86 wells, indicate ages of 5.4 and 6.7 Ma. Since the Akpak strata in these two wells is thick and apparently as complete a section as exists in Beaufort–Mackenzie Basin, the ages represent the youngest age (latest Messinian) for strata below the sub-Iperk unconformity. The strontium age estimates also confirm previous interpretations, indicating that the sub-Iperk unconformity was initiated at the same time as the glacially driven sea-level events that triggered the Messinian crisis in the Mediterranean area. The Beaufort–Mackenzie and the Arctic Ocean Basin, however, could not have been restricted in the manner that the Mediterranean Basin was during the Messinian event. The K-59 limestone more likely represents clastic sediment starvation, but the presence of a precipitated carbonate unit in precisely the same relative stratigraphic position has some parallels with the precipitation of evaporites in the desiccated Mediterranean Basin.

The K-59 limestone was analysed for strontium isotopes in the Netserk F-40, Nektoralik K-59, and Issungnak O-61

wells and ratios of  $0.708872 \pm 6$ ,  $0.709048 \pm 14$ , and  $0.709116 \pm 4$  provide age estimates of 11.79, 3.5, and 1.6 Ma, respectively. The 3.5 Ma age is compelling because it matches the age estimate derived from foraminiferal biostratigraphy. The wide variance in strontium age estimates for the K-59 hardground is most likely explained by incorporation of pore water strontium into the carbonate hardground. Diachrony of the K-59 hardground is possible, but a time range of 10 million years is considered unrealistic considering age constraints above and below.

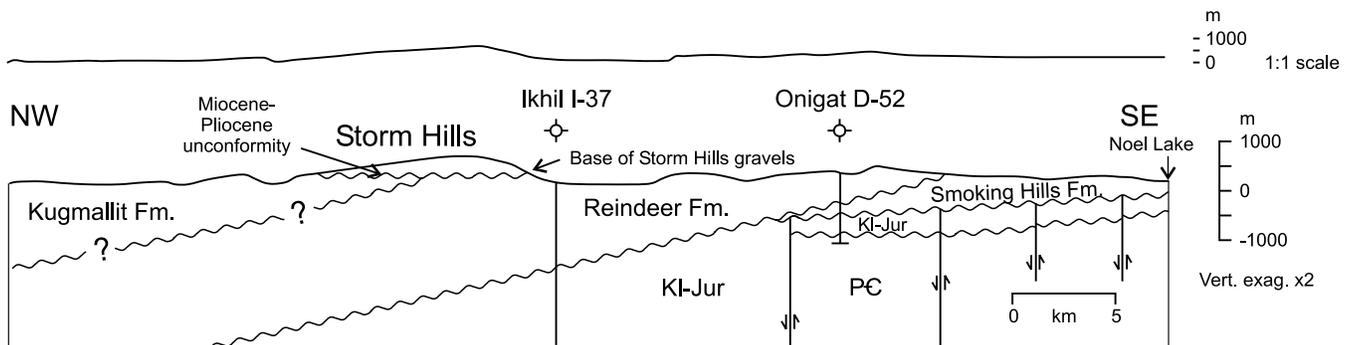
Five samples of foraminiferal calcium carbonate from the Iperk Sequence were analysed for strontium isotope ratios. Two objectives were sought after in these analyses. The first was an attempt to achieve an independent age estimate for the timing of marine transgression recorded in the lower Iperk Sequence. The second objective was to determine the age of the *Cibicides grossus* Zone in the Beaufort–Mackenzie Basin. However, results from the strontium analyses of the Iperk Sequence were equivocal.

In general, strontium isotope age estimates from foraminiferal calcium carbonate samples in the Iperk Sequence produced younger ages than were predicted. The stratigraphically oldest samples came from the *Cibicides grossus* Zone at Issungnak O-61 and Natiak O-44. In Issungnak O-61, at 1305–1325 m, a ratio of  $0.709096 \pm 6$  indicates an age estimate of 2.09 Ma. In Natiak O-44, a ratio of  $0.709149 \pm 4$  indicates an age of 0.95 Ma. Perhaps, the *C. grossus* zone spans an approximate time interval of 1–2 Ma. Previous biostratigraphic age estimates for the *C. grossus* Zone in Arctic North America, however, ranged from 2.4 to 3.5 Ma based on the paleomagnetic record, isotope data, climatic history, and interregional correlations (Feyling-Hanssen 1980; McNeil 1990; and Fyles et al. 1998). These age estimates, however, were influenced partly by ages assigned to the apparently equivalent *C. grossus* Zone (NB15 of King 1983) in the North Sea Basin. King (1989, fig. 9.13) later revised the age of *C. grossus* in the North Sea to latest Pliocene – earliest Pleistocene, which is more in accord with the age estimates provided from  $^{87}\text{Sr}/^{86}\text{Sr}$  in *C. grossus* of the Beaufort–Mackenzie Basin. King (1989) also recognized diachrony in the last occurrence of *C. grossus*, highlighted by younger last occurrences in deeper water.

We have no conclusive answer for resolving the discrepancies in age estimates for the Iperk Sequence. It could be that the regional biostratigraphic correlations and climatic interpretations were incorrect. Downhole caving of younger material may have been a factor, although samples were deliberately chosen to avoid this problem. The margin of error from  $^{87}\text{Sr}/^{86}\text{Sr}$  data for the mid-Pliocene is also substantial at  $\pm 2$  million years based on the compilation by Farrell et al. (1995).

Previous analysis of the age of *C. grossus* in the Arctic centred also on its extinction (locally) at the time of continental glaciation in North America, i.e., 2.4 Ma. However, the foraminiferal distributions from Natiak O-44 (435 to ~670 m) indicate an anomalous association of “warm-water” *C. grossus* with colder water microfaunas (i.e., *Islandiella islandica*, *Islandiella helenae*, and *Cassidulina reniforme*). The putative “cold-water” assemblage, represented by *I. islandica*, was analysed separately from specimens of *C. grossus*. The *Islandiella* sample yielded a high ratio corresponding to a

**Fig. 17.** Profile and geological cross-section through the Storm Hills area, east of the Mackenzie Delta. The sub-Iperk Sequence unconformity truncates Oligocene–Eocene and older strata and is overlain by the Pliocene Storm Hills gravels (Iperk Sequence).



**Fig. 16.** The Caribou Hills Escarpment, upper surface cut by a regional planation surface, east margin of the Mackenzie Delta. Foreground shows the East Channel of the Mackenzie River with reflections from the adjacent escarpment. Topographic relief from water surface to the planation surface is approximately 200 m.



Holocene age (0 Ma), and the *C. grossus* sample yielded a ratio indicating an age of 0.91 Ma, essentially the same as the 0.95 age for *C. grossus* 300 m lower in the well (841–874 m). There are at least three possible interpretations of this data. The range of *C. grossus* could be younger than previously thought, *C. grossus* could be reworked from older strata, or *I. islandica* could be caved (although its uppermost occurrence in the Natiak O-44 is no higher than 335 m).

The stratigraphically highest sample examined for strontium isotope content in the Iperk Sequence consisted of *Elphidiella gorbunovi* from the Netserk F-40 well, considered to be stratigraphically above the *C. grossus* Zone (McNeil 1996). A ratio of  $0.709107 \pm 6$  corresponds to an age estimate of 1.85 Ma. The date seems to be more in agreement with preconceived biostratigraphic age estimates for the Beaufort–Mackenzie Basin, but the other age estimates of 0.95 and 2.09 Ma for *C. grossus* cannot easily be reconciled with the supposed younger occurrence of *E. gorbunovi* dated at 1.85 Ma. Inconsistencies in the strontium isotopic data within the Iperk Sequence are difficult to resolve from the data at hand. Multiple working hypotheses on

the chronostratigraphy of Iperk Sequence will have to be employed until further data becomes available.

### Correlation from subsurface to surface

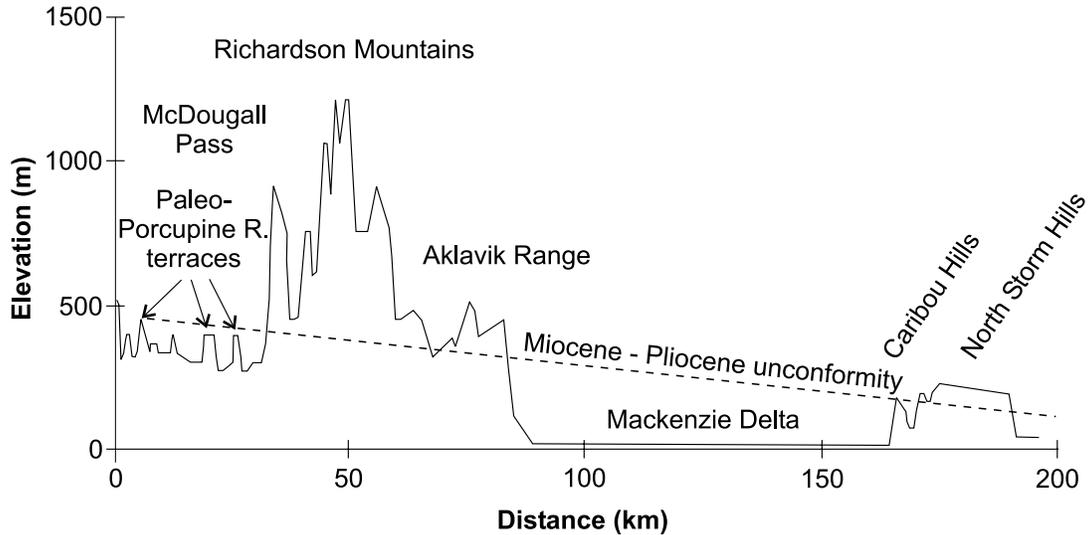
An abundance of data for assessing the sub-Iperk unconformity exists in the subsurface of the Beaufort Sea and Mackenzie Delta, but interpretation of the unconformity on land to the south and southwest in the Mackenzie Delta is more difficult because the record is preserved only in erosional remnants. Nonetheless, the sub-Iperk unconformity can be traced from the subsurface south to the Caribou Hills on the southeast margin of the Mackenzie Delta. In the subsurface offshore, the unconformity is buried by up to 4 km or more of Iperk Sequence sediments, but they become progressively thinner southward, condensing and wedging out, as the unconformity truncates progressively older strata (Fig. 2). Shale compaction studies by Issler (1992) indicated that up to 3 km of pre-Iperk strata have been eroded in the Mackenzie Delta area. Much of the Iperk Sequence may be comprised of this eroded material. Projection of the unconformity southward into the Caribou Hills suggests that the unconformity has bevelled the Caribou Hills, forming a regional plateau along the east side of the Mackenzie Delta (Fig. 16). This planation surface is essentially identical to the classical pedimentation surface illustrated by King (1967). To the east of the Caribou Hills Escarpment, the erosional surface is overlain by Pliocene gravels of the Storm Hills in an angular, unconformable relationship (Fig. 17).

### Pediments and terraces of the Richardson Mountains

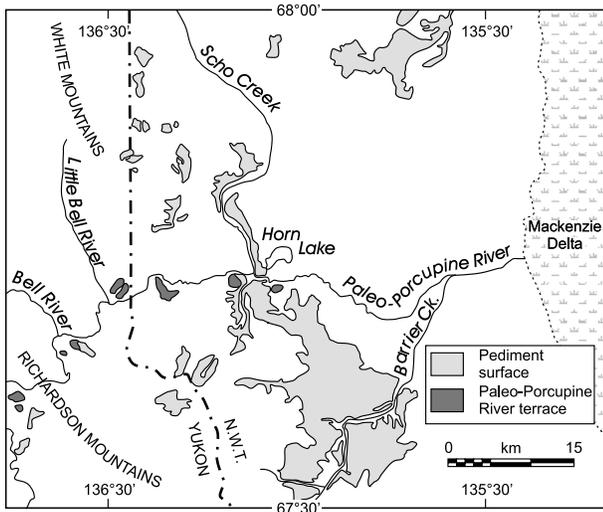
A topographic profile from the Caribou Hills plateaux across the Mackenzie Delta to the Richardson Mountains (Fig. 18), coupled with maps of remnant terraces and widespread pediment surfaces (Fig. 19), provides the final link for correlating the regional sub-Iperk unconformity from the deep sea to the cratonic highlands.

A conspicuous feature of the profile is the occurrence of terraces defining a planation surface far above the modern river and delta, implying removal of a large volume of sediment from the Mackenzie Delta area. This erosion occurred during the Late Pleistocene (Wisconsin) glaciation, and was

**Fig. 18.** Topographic profile illustrating the position of the regional erosional paleosurface (Miocene–Pliocene unconformity) from McDougall Pass area of the Richardson Mountains projected across the Mackenzie Delta to the Caribou Hills and Storm Hills (re-drawn from Duk-Rodkin and Hughes 1994).



**Fig. 19.** Pediment surfaces and river terraces of the paleo-Porcupine River along the eastern flanks of Richardson Mountains.



responsible for forming the modern Mackenzie Valley, which is therefore a relatively young topographic feature (Duk-Rodkin and Hughes 1994). Prior to the late Quaternary, regional drainage to the Mackenzie Delta included the Porcupine River system of the northern Yukon, which drained eastward via McDougall Pass (Figs. 1, 19) in the central Richardson Mountains (Duk-Rodkin and Hughes 1994). Seismic data document the preglacial channel of the Porcupine River that lies beneath about 150 m of drift in the McDougall Pass area (Hunter 1979).

Remnants of a much older valley floor, which we interpret as the Miocene–Pliocene unconformity, occur along the flanks of McDougall Pass, and in its western approaches. These spectacular erosional terraces (Fig. 20) are now upwarped as much as 240 m above present river level and

**Fig. 20.** Terrace of the paleo-Porcupine River cut across a tilted fault block of Permian clastics and carbonates, McDougall Pass area, Richardson Mountains, Horn Lake in the foreground. Terrace horizon indicated by arrows.



390 m above the floor of the preglacial valley. In the glaciated areas, the pediments (terraces) comprise scoured bedrock benches with a thin, discontinuous cover of glacial drift (Figs. 21, 22). In unglaciated areas to the west, alluvial terraces of paleo-Porcupine River are cut into pediment surfaces (Fig. 19). There are three levels of pediment formation (the oldest being of Late Miocene age) recorded in the western slopes of Richardson Mountains (Fig. 23) and five in the British Mountains (L. Lane, personal communication, 1997). The pediments, or erosional terrace remnants, record a regional base level and are classically related to periods of tectonic quiescence in semiarid or arid environments. Both of these conditions were met at the end of the Miocene and into the Early Pliocene. Regional studies in the Beaufort–Mackenzie indicate cessation of tectonic activity at the end of the Miocene (Dixon et al. 1992; Lane and Dietrich 1995). Palynological records show a marked trend towards increased

**Fig. 21.** Erosional unconformity (bedrock terrace of the paleo-Porcupine River) overlain by Laurentide glacial outwash deposits, Grafe Creek, near the front of the Canyon Ranges, Mackenzie Mountains.



paludification and decreased canopy cover following the Miocene (White et al. 1997).

Evidence of this old erosional surface is found farther south in the Mackenzie Mountains and in west-central Yukon. In the Mackenzie Mountains pediment surfaces marking the unconformity have been mapped as far south as 64°N latitude. Here, pediments extend along valley sides, and they are developed on bedrock of the Upper Cambrian – Lower Ordovician Franklin Mountain Formation.

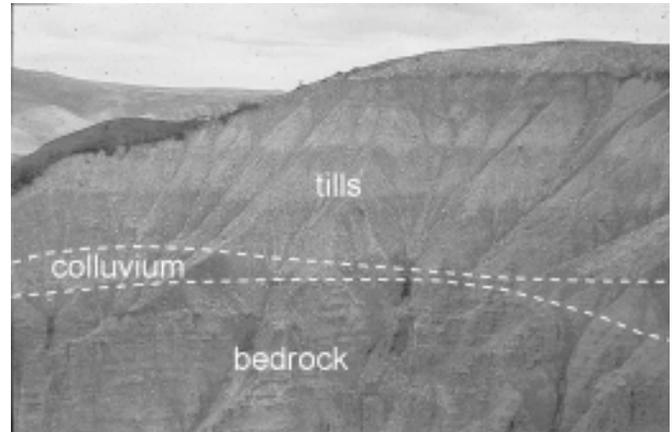
The maximum known age for sediments above the erosional surface is at least Gaussian (2.58–3.58 Ma), but most likely pre-Gaussian. This is based on colluvium yielding a normal polarity overlying a pediment surface in the Canyon Ranges of the Mackenzie Mountains, south of the Richardson Mountains (Duk-Rodkin et al. 1996). The pediment surface and colluvium (Fig. 21) is overlain by magnetically reversed glacial sediments of Matuyama age, such that the pediment-forming erosional event likely predates the Gauss, but postdates the Messinian (based on subsurface  $^{87}\text{Sr}/^{86}\text{Sr}$  data, Fig. 15). Equivalent surfaces can be seen throughout the Canyon Ranges at about 950 m a.s.l. (Fig. 22). Glacial sediments (tills and (or) outwash) generally overlie these pediments.

Subaerial evidence of the Miocene–Pliocene unconformity is also found in the Tintina Trench of west-central Yukon, north of the Yukon River (Fig. 24). Here, a conformable sequence of pre-glacial Pliocene fluvial beds and Pliocene to middle Pleistocene glacial strata overlies tilted Miocene fluvial deposits (Duk-Rodkin and Barendregt 1997; Duk-Rodkin 1997). The deformation of the Miocene strata is related to a major period of extensional faulting along the trench. Subsequent regional denudation and aggradation resulted as streams adjusted to the newly established base level (Duk-Rodkin 1997).

### Sedimentation rates

Multiple lines of evidence indicate that sedimentation rates were dramatically increased in the Beaufort–Mackenzie Basin following regional denudation at the end of the Miocene. The Miocene Mackenzie Bay and Akpak se-

**Fig. 22.** Pediment surface developed on bedrock of Upper Cambrian – Lower Ordovician Franklin Mountain Formation. Pediment capped by colluvium (Gauss, normal polarity) and overlain by glacial tills (Matuyama, reversed polarity), Little Bear River, Canyon Ranges.



**Fig. 23.** Multiple, low-angle, pediment terraces along the east slopes of the Richardson Mountains.

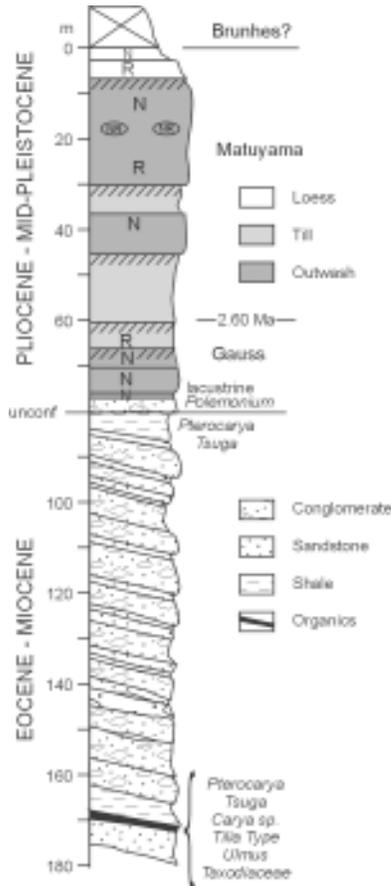


quences, which span about 15 million years, have a maximum thickness in the order of 1 km. The approximately 3.5 million years Iperk Sequence, in contrast, has a maximum thickness greater than 4 km. In view of the significance of sedimentation rates for basin analysis and hydrocarbon generation, an attempt is made here to quantify sediment accumulation rates for the Mackenzie Bay, Akpak, and Iperk sequences (Fig. 25).

Quantification of sedimentation rates requires an accurate knowledge of the age and thickness of sedimentary units. These calculations are complicated by the fact that sediment thickness changes with time as a result of compaction during burial. To remove the effects of compaction, it is necessary to restore or “decompact” sedimentary units to their original thickness at the time of deposition using a technique called “back-stripping” (e.g., Steckler and Watts 1978; Bond and Kominz 1984).

Sediment compaction is assumed to be a mechanical process involving the rearrangement and closer packing of sediment grains. With this assumption, which is reasonable for

**Fig. 24.** Schematic profile of tilted Miocene strata unconformably overlain by horizontal strata of fluvial and glacial deposits Gauss and younger age, north side of Tintina Trench.



the clastic sequences of the Beaufort–Mackenzie region, sediment thickness change can be directly tied to porosity loss. Commonly, sediment compaction is parameterized using empirical porosity–depth functions (e.g., Magara 1980), but uncertainties in compaction coefficients has led to errors in tectonic subsidence and estimated sedimentation rates, particularly if generic compaction curves are used (Gallagher 1989). These errors can be reduced if porosity–depth relations are established for the study area. Shale and sandstone compaction equations were determined for distinct compaction zones within the Beaufort–Mackenzie area using sonic log data calibrated with core porosity data (Issler 1992, 1996). Although porosity is commonly considered to vary exponentially with depth, the Beaufort–Mackenzie sandstone and shale porosity data are best fit using simple linear equations. Unfortunately, the shallowest portions of the sedimentary section (<500 m) were rarely logged, and where logs are available, readings have been adversely affected by poor borehole conditions related to permafrost. Therefore, Hamilton’s (1976) porosity–depth curve for terrigenous silt and clay was used to characterize shale compaction over this depth interval.

Decompaction was carried out layer by layer using the approach of Sclater and Christie (1980), modified to account for linear as opposed to exponential sediment compaction. Sediments were decompacted by stepping backwards in time

and sequentially removing progressively older and more deeply buried layers. As each surface layer is removed, the next underlying layer is brought to the surface and the thickness of this layer and all remaining layers is adjusted in accordance with the porosity–depth relations. Each layer may be composed of different proportions of sandstone and shale, and therefore compaction coefficients must be recalculated for each layer to account for these lithological variations. This is accomplished by linearly combining sandstone and shale compaction coefficients in proportion to sandstone and shale abundance.

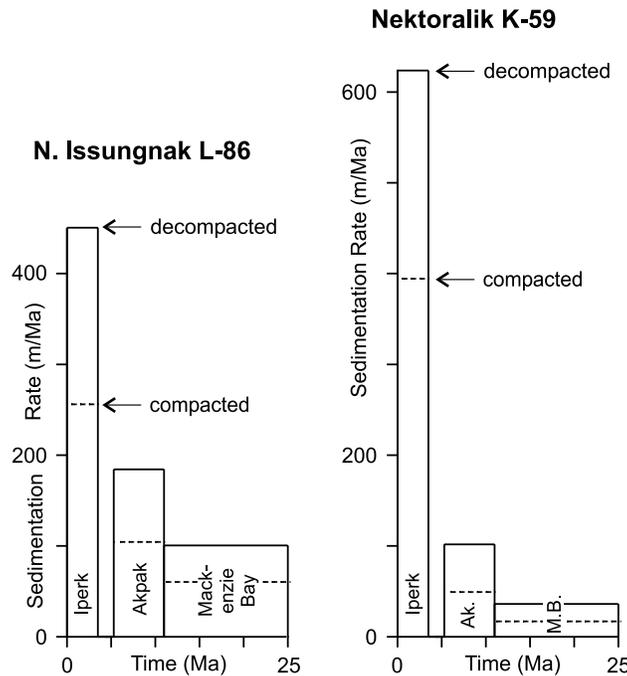
Sedimentation rates, both compacted (zero porosity) and decompacted (“self-compacted” at surface), have been calculated for two wells (Fig. 25) in contrasting sedimentary environments. The compacted sedimentation rate compensates for lithologically related variations in porosity and it represents the amount of solid material that has accumulated in a given time interval. The decompacted sedimentation rate corresponds to a partially compacted surface layer, and therefore it provides a minimum estimate of the true sedimentation rate. The porosity of the decompacted layers varies with their thickness and lithology, and therefore it is difficult to compare decompacted sedimentation rates for layers with differences in these properties. When estimating relative changes in sediment accumulation rates for different time intervals, it is better to use compacted sedimentation rates because they normalize out these differences in porosity.

In the North Issungnak L-86 well (Fig. 25), which is representative of shelf sedimentation, decompacted (compacted) sedimentation rates increased from 100 m/million years (60 m/million years) in the Mackenzie Bay Sequence to 450 m/million years (256 m/million years) in the Iperk Sequence. In the Nektoralik K-59 well, the sedimentation rate for these same units increased from 36 m/million years (17 m/million years) to 624 m/million years (394 m/million years). Increased rates of sedimentation through the Mackenzie Bay, Akpak, and Iperk sequences appear to coincide with climatic cooling through the late Cenozoic and basin margin uplift at the end of the Miocene. At Nektoralik K-59, sediment accumulation rates increased by a factor of 23 between the Early–Middle Miocene and Pliocene. Rates have been calculated using 3.5 Ma as the estimated age for the base of the Iperk Sequence, but there is some uncertainty over its maximum age. Strontium age estimates suggest the base is closer to 2 Ma, in which case the calculated sedimentation rates could increase by a factor of up to 1.8.

## Discussion

The major factors controlling landscape evolution and sedimentary deposition (tectonism, eustasy, and climate) appear to have reinforced each other to produce a remarkable regional paleosurface that extends from pediment surfaces in the Richardson Mountains, northwards along a planation surface cutting into the Aklavik Range of the Richardson Mountains, across the adjacent stable craton, and onto the Beaufort Sea continental shelf. The paleosurface extends downslope to the continental rise, as far basinward as seismic images extend.

**Fig. 25.** Sedimentation rates calculated for the Iperk, Akpak, and Mackenzie Bay sequences in the North Issungnak L-86 and Nektoralik K-59 wells. Dashed line indicates compacted rate; solid line indicates decompacted rate. Note that the base of the Mackenzie Bay Sequence at the Nektoralik location is projected at 2900 m below sea floor (~85 m below well total depth) from regional isopach trends.



It is often debated which factor was the controlling influence in the development of unconformities and sedimentary sequences. Tectonics and eustasy are typically at the forefront of the discussions (Vail et al. 1977; Cloetingh 1986; Miall 1986; Posamentier et al. 1988). Burton et al. (1987) have written a very clear exposition on the problems of untangling a multivariate system concluding that “geological judgement” must ultimately be relied on, because not enough of the variables can be measured with assurance. In the Neogene, however, the oxygen isotope record as influenced by continental–alpine glaciation reduced much of the uncertainty, because the eustatic factor can be more accurately assessed. In the Beaufort–Mackenzie Basin, there is a substantial amount of data to assess the tectonic, sedimentation, and climatic history. The geochronology of the Beaufort–Mackenzie Basin and neighbouring continental area is not highly refined, but the biostratigraphic record from foraminifera and palynomorphs coupled with limited data from the strontium isotopic, paleomagnetic, and radiometric records is adequate to establish the timing of most of the important events.

Relatively thin sedimentary sequences (Mackenzie Bay and Akpak sequences) dominated by marine sediments were deposited in the Beaufort–Mackenzie Basin through the entire Miocene. Landward, these sequences are largely absent by erosion and are only preserved in isolated areas of adjacent Yukon, Alaska, and the Arctic Islands. The chronology and climate of the Miocene sequences is fairly well established through several independent data sets, including palynology, foraminiferal biostratigraphy, radiometrics, and strontium isotope chronostratigraphy.

During the Middle Miocene a warm climatic peak (ca. 15 Ma) was attained in northwest Canada and Alaska (White

et al. 1997) in harmony with global climates of the time. The palynomorph record indicates that the peak was followed at first by a rapid climatic decline, then a less rapid, but steady, climatic decline through to the end of the Middle Miocene (White et al. 1997). The global oxygen isotope record for the Middle Miocene indicates that there were a series of high-amplitude shifts from 13.6 to 11.7 Ma that corresponded to glaciation events on Antarctica and sea-level drops of 50–100 m (Abreu and Anderson 1998). The declines in sea level and climate culminated near the Middle–Late Miocene boundary, temporally close to the sequence boundary between the Mackenzie Bay and Akpak sequences. Of the two factors (eustasy and climate), it is more likely that eustasy is the proximate cause of the sequence boundary and the abrupt basinward shift in facies at the boundary. A Middle Miocene tectonic event has not been identified as a cause.

The Mackenzie Bay – Akpak sequence boundary may thus correspond to the large sea-level drop at 10.5 Ma, noted on the Haq et al. (1987) curve. By comparison, a similar major Middle–Late Miocene hiatus has been documented on east-coast U.S.A. (Olsson and Melillo 1987; Miller et al. 1996). For this sequence boundary and others in the Oligocene and Miocene of the east-coast continental shelf, Miller et al. (1996) considered that there was sufficient evidence to confirm a causal link between ice volume, sea level, and sequence boundaries.

During the Late Miocene, the Akpak Sequence was deposited in the Beaufort–Mackenzie. Slope clinofolds of the Akpak Sequence indicate basinward progradation of about 5 km. Palynomorphs and benthic foraminifera indicate the Late Miocene was cooler than the Middle Miocene. Palynomorphs of the region indicate a slight warming towards

the middle of the Late Miocene, but substantial cooling by the latest Miocene. A decrease in the diversity of the calcareous benthic foraminifera and the disappearance of the genus *Asterigerina* in the Akpak Sequence suggest cooler marine waters during the Late Miocene. In the Beaufort–Mackenzie region, a major phase of tectonic deformation also occurred in the Late Miocene and was characterized by folding and thrust faulting (Lane and Dietrich 1995). They considered that regional uplift associated with the culmination of the deformation resulted in the major unconformity below the Pliocene Iperk Sequence. Climatic conditions in the Beaufort–Mackenzie region also reached a critical point at the end of the Miocene as White et al. (1997) record this as the coolest point reached during the Miocene. Herbs and shrubs became more important in the palynological assemblages suggesting a cooler–drier climatic with canopy cover notably decreased and paludification contrasting from high to low. Climatic conditions in this region of the Arctic were strongly influenced by tectonic uplift in southern Alaska, driving the Beaufort–Mackenzie region into increasing continentality (McNeil et al. 1982; White et al. 1997). In the Gulf of Alaska, this event is marked by the first evidence of tidewater glaciation in the Yakataga Formation between 6.7 and 5.0 Ma (Lagoe et al. 1993).

The age of the sediments at the top of the Miocene record in the Beaufort–Mackenzie Basin is critical to the chronology and interpretation of the unconformity. In the absence of planktonic foraminifera and other standard paleontological indices, or magnetic, or radiometrics, the strontium isotope record has been relied upon to date the latest Miocene sediments. The two youngest dates estimated from calcareous benthic foraminifera were 5.4 and 6.7 Ma, both within the Messinian. High-amplitude, positive shifts in the composite oxygen isotope record are a well-documented feature of this period and widely interpreted as rapid sea-level drops in the order of 100 m. Peak amplitudes shifts, i.e., Antarctic glaciation and sea-level fall, occurred at 4.8 and 5.2 Ma, according to Abreu and Anderson (1998, Table 2). This would have resulted in widespread earliest Pliocene exposure of Messinian aged continental shelves globally. In the Beaufort–Mackenzie region the effects of sea-level fall would have been compounded by regional uplift (Lane and Dietrich 1995) and climatic change (White et al. 1997). Eustasy, however, was probably the immediate and major driving force behind the unconformity–sequence boundary.

The chronologies of events following the initiation of the unconformity are more difficult to resolve. A substantial amount of erosion took place at the unconformity surface. The Akpak Sequence has been removed entirely in many areas of the basin, and, at the Nipterk L-19 well, for example, the erosional surface cuts into the Early–Middle Miocene *Asterigerina staeschei* Zone of the Mackenzie Sequence corroborated by a strontium age estimate of 16.7 Ma just below the erosional surface. At Nipterk L-19 and many other locations in the Beaufort Sea (Fig. 9), the erosional surface is blanketed by a carbonate hardground referred to as the K-59 limestone. The K-59 limestone yielded erratic strontium isotope results, very few palynomorphs, and a few benthic foraminifera, including *Cibicides grossus*, an arctic regional Pliocene index. Strontium isotope age estimates from the lower part of the Iperk Sequence varied between 0.95 Ma

and 2.09 Ma, which was considerably younger than a biostratigraphic estimate of 3.5 Ma based on the occurrence of the *C. grossus* Zone (2.4 to ~3.5 Ma) at the base of the Iperk Sequence. On land, the oldest date above the unconformable surface was of Gaussian (2.58–3.58 Ma) or older age based on the recognition of a normal magnetic record in colluvium on the pediment surfaces. It seems, therefore, that the unconformable gap was in the order of 1.7 million years, from ~5.2 to ~3.5 Ma.

The global sea-level curve of Haq et al. (1987) shows a prolonged sea-level highstand immediately following the lowstand in the Messinian until the mid-Pliocene. The smoothed oxygen isotope record for this period (5.2 to present) shows a series of rapid alternations with increasingly heavier isotopes indicating cooler, probably glacial, conditions in the Antarctic. In the Beaufort–Mackenzie area, the Pliocene and Pleistocene are recorded in the sediments of the Iperk Sequence. Seismic stratigraphy indicates that the transgressive facies of the Iperk Sequence rapidly overlapped the erosional shelf of the Beaufort Sea. A prodigious 120-km progradation then followed as the Iperk Sequence built out northward into the Beaufort Sea. This increased sedimentation rate and extensive progradation was sourced from a regional planation and pedimentation of the highlands to the south towards Richardson and Mackenzie mountains. Reworked foraminifera of Mesozoic age show evidence of thermal alteration compatible with that of the orogenically deformed Richardson Mountains. Tectonic quiescence after Late Miocene uplift and cooler climatic conditions in the Pliocene as indicated by palynological records provided the prerequisites for this regional planation. Sedimentation rates relative to the Akpak sequences increased by up to 8 times for the wells examined. The contrast in sedimentation rates between the Iperk and the Mackenzie Bay Sequence is even greater. If the Iperk Sequence is considered to span a 3.5 million year history, then it represents a 20-fold increase in sediment accumulation rate relative to the Early–Middle Miocene.

Comparable progradation events are known from other Pliocene sequences on the continental margins of North America. On the eastern Canadian continental shelf, Piper and Normark (1989) recognized a Late Pliocene canyon cutting event followed by a several fold increase in sedimentation rates. Similarly, in the Gulf Coast of Mexico, Morton and Ayers (1992) recognized an abrupt introduction of lowstand deposits, at approximately 3 million years, followed by rapid outbuilding of a broad continental platform that prograded basinward approximately 110 km. In the Gulf of Alaska, sedimentation rates increased to as much as 6.2 km/million years at approximately 3.5–3.0 Ma in the upper Yakataga Formation.

The similarity in timing and characteristics of these events points to continental wide controls on uplift, climate, and erosion. Erosional and sedimentation rates were so high during this period that accompanying deposition on the Beaufort Sea shelf and slope generally masked the effects of eustatic change during much of Late Pliocene and Pleistocene.

## Summary of events

Eustasy, tectonics, and climate all played a role in the development of a regional erosional paleosurface separating

Miocene and Pliocene strata in the Beaufort–Mackenzie area of Arctic Canada. The sequence of events from the Middle Miocene through the Pliocene has been deciphered as follows:

1. Late Cenozoic climates have declined in an oscillatory manner from a warm optimum, ca. 15.2 Ma. At peak warmth, palynomorph assemblages within the Mackenzie Bay Sequence were characterized by abundant thermophilous taxa. Contemporaneous foraminiferal assemblages contained warm-water genera such as *Asterigerina* in abundance.
2. Strontium isotopes and biostratigraphic data indicate that the sequence boundary separating the Mackenzie Bay Sequence from the overlying Late Miocene Akpak Sequence is approximately coincident with a major phase of Antarctic glaciation and eustatic sea-level fall towards the end of the Middle Miocene.
3. Palynomorph assemblages indicate that the Late Miocene climate oscillated but cooled dramatically by latest Miocene time (ca. 5.7 Ma). Foraminiferal diversity decreased during the Late Miocene with the longer ranging, apparently cool-water-tolerant, species surviving. The Late Miocene was also the time of the culmination of a major tectonic pulse documented by folding and faulting of the Akpak Sequence and uplift of the margins of the Beaufort–Mackenzie Basin.
4. A regional unconformity occurs at the top of the Miocene Akpak Sequence throughout the Beaufort–Mackenzie Basin. The unconformity extends southward on land, where it is recognized as a regional planation surface ending at pediment surfaces cut into the Richardson Mountains.
5. Several lines of evidence (strontium isotopes, radiometric data, palynomorphs, and foraminifera) indicate that the unconformity was initiated during or at the end of the Messinian. Rapid exposure of the continental shelf, accentuated by tectonic uplift of the basin margin, caused the unconformity, which ranks as a first-order sequence boundary separating the Akpak and Iperk sequences. Seismic profiles indicate subaerial exposure and erosion of the continental shelf, canyon cutting of the slope, and turbidite deposition at the base of the slope.
6. The K-59 limestone forms a carbonate hardground capping the eroded Miocene Mackenzie Bay and Akpak sequences in the offshore area. Strontium isotopes age estimates are highly variable for this carbonate, but other lines of evidence suggest an age ca. 3.5 Ma. A complete benthic foraminiferal turnover occurs at the K-59 limestone, as the first species typical of the late Cenozoic Arctic appear and the last of a once diverse assemblage of Miocene benthic foraminifera disappears. The carbonate also contains the temperate bryozoan *Adeonella* sp. aff. *A. polystomella*, previously known only from the Atlantic area, suggesting a warm period in the Pliocene.
7. Tectonic quiescence of the regionally uplifted basin margins toward the southwest, coupled with climatic change to cooler, drier conditions in the Pliocene, contributed to widespread denudation now observed in the dissected regional planation surface and pediments of

the Richardson and Mackenzie mountains. Pediments in the Mackenzie Mountains contain a veneer of colluvium with normal magnetic polarity and are considered to be of Gaussian (2.58–3.58 Ma) age or older.

8. Pliocene–Pleistocene sedimentation rates increased dramatically in the Beaufort–Mackenzie area and across much of the North American continent. Depositional rates for the Pliocene–Pleistocene Iperk Sequence increased by as much as 23 times relative to the Early to Middle Miocene Mackenzie Bay Sequence. Similar changes in depositional rates have been recorded off east-coast Canada, the Gulf of Alaska, and the Gulf of Mexico in the Pliocene.

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