ARCTIC
VOL. 43, NO. 4 (DECEMBER 1990) P. 301-313

Tertiary Marine Events of the Beaufort-Mackenzie Basin and Correlation of Oligocene to Pliocene Marine Outcrops in Arctic North America[1]

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(Received 19 June 1989; accepted in revised form 19 March 1990)

ABSTRACT. The benthic foraminiferal succession from the Beaufort-Mackenzie Basin of arctic Canada reflects many of the major oceanographic and climatic events of the Tertiary. The Paleocene-Eocene epochs are characterized by restricted marine circulation and pronounced foraminiferal endemism. Paleogeographic reconstruction illustrates that the Paleocene-Eocene Arctic Ocean was markedly different from its modern counterpart and it is thus referred to as the "Arctic Gulf." Marine connections between the Arctic and Atlantic oceans were broadened and deepened during the Oligocene. The Arctic Gulf thus evolved into a modern Arctic Ocean configuration by sea floor spreading in the Greenland-Norwegian Sea.

The Oligocene index, *Turrilina alsatica* Andreae, appeared in the arctic regions concurrent with increased circulation between the North Atlantic and Arctic oceans. In the Beaufort-Mackenzie subsurface, *Turrilina alsatica* has proven to be a widespread and reliable zonal index. In outcrop, it is known from only one locality, the Nuwok Member of the Sagavanirktok Formation on Carter Creek, Alaska.

During the Miocene, increased circulation between the Arctic and Atlantic oceans was further established, and a moderate warming trend developed after a cool early Oligocene episode. The foraminifer *Asterigerina staeschei* (Franke) is an abundant and widespread marker of this phase of arctic marine history. *Asterigerina staeschei* became extinct in the middle Miocene in both the arctic and North Atlantic regions. In the Beaufort-Mackenzie Basin, many associated species ranged through into the late Miocene but disappear abruptly at the terminal Miocene unconformity. Major faunal and depositional sequence changes mark this as one of the most significant events in arctic Tertiary history, and the unconformity itself was caused by a widespread relative drop in sea level.

A major faunal turnover in the Pliocene is characterized by *Cibicides grossus* ten Dam and Reinhold, which first appeared in the early Pliocene but became extinct through the North Atlantic and arctic regions at approximately 2.4 Ma, closely approximating the climatic deterioration and initiation of continental glaciation in the late Pliocene. *Cibicides grossus* has a widespread distribution in arctic North America, occurring in the subsurface of the Beaufort-Mackenzie Basin and in outcrops of the marine tongue of the Beaufort Formation on Meighen Island, in unnamed strata on White Point of northwest Ellesmere Island, on eastern Baffin Island, and on eastern and northern Greenland.

Key words: benthic foraminifers, Tertiary, arctic North America, paleoceanography, *Turrilina, Asterigerina, Cibicides*

RÉSUMÉ. La série de foraminifères benthiques du bassin Beaufort-Mackenzie de l'Arctique canadien témoigne de nombreux événements océanographies et climatiques importants du Tertiaire. Les époques du Paléocène et de l'Éocène sont caractérisées par une circulation marine limitée et par un endémisme marqué des foraminifères. Une reconstruction paléographique montre que l'océan Arctique du Paléocène-Éocène était très différent de sa forme moderne, de sorte qu'il est appelé le "golfe Arctique". Les liaisons marines entre l'Arctique et l'Atlantique se sont élargies et approfondies pendant l'Oligocène. Le "golfe Arctique" s'est donc transformé en un océan Arctique moderne par l'étalement du fond marin dans la région du Groenland et de la mer de Norvège.

L'indice de l'Oligocène, *Turrilina alsatica* Andreae, est apparu dans les régions arctiques pendant une période de circulation accrue entre l'Atlantic Nord et l'Arctique. Dans la subsurface du bassin Beaufort-Mackenzie, *Turrilina alsatica* s'est avéré un indice zonal répandu et fiable. Par contre, il n'affleurerait qu'à un endroit, dans le membre Nuwok de la Formation de Sagavanirktok au ruisseau Carter, en Alaska.

Pendant le Miocène, la circulation entre les océans Arctique et Atlantique s'est intensifiée, et une tendance modérée au réchauffement est apparue après un épisode de froid de l'Oligocène ancien. Le foraminifère *Asterigerina staeschei* (Franke) est un marqueur abondant et répandu de cette phase de l'histoire marine de l'Arctique. *Asterigerina staeschei* a disparu au Miocène moyen des régions de l'Arctique et de l'Atlantique Nord. Dans le bassin Beaufort-Mackenzie, un grand nombre d'espèces associées ont survécu au Miocène tardif, mais ont disparu soudainement à la discordance terminale du Miocène. D'importantes modifications de la faune et des séquences de sédiments indiquent que cet événement a été l'un des plus marquants de l'histoire tertiaire de l'Arctique. Selon une hypothèse, la discordance terminale du Miocène aurait été causée par une baisse eustatique du niveau de la mer.

Durant le Pliocène, un important changement faunique est caractérisé par *Cibicides grossus* (Dam et Reinhold), apparu au début du Pliocène et disparu d'Amérique du Nord et de l'Arctique depuis 2,4 Ma environ, à peu près à l'époque de la détérioration du climat et du début de la glaciation continentale vers la fin du Pliocène. *Cibicides grossus* est très répandu en Amérique du Nord, dans la subsurface du bassin Beaufort-Mackenzie et les affleurements de la langue marine de la Formation de Beaufort dans l'île Meighen, dans des couches non identifiées de la pointe White dans le nord-ouest de l'île Ellesmere, dans l'est de l'île de Baffin, et dans l'est et le nord du Groenland.

Mots clés: foraminifères benthiques, Tertiaire, Amérique du Nord arctique, paléocéanographie, *Turrilina, Asterigerina, Cibicides*

РЕФЕРАТ. Бентическая фораминиферовая последовательность бассейна Бофорта-Маккензи в Арктической Канаде отражает многие из наиболее важных океанографических и климатических событий третичного периода. Палеоцен и эоцен характеризуются ограниченной морской циркуляцией и четко выраженным эндемизмом фораминифер. Палеогеографическая реконструкция показывает, что в палеоцене и эоцене Северный Ледовитый океан выглядел совсем иначе, чем в настоящее время, и больше заслуживал названия "Северного Ледовитого залива". Морские проливы, соединявшие Северный Ледовитый и Атлантический океаны, расширились и углубились в олигоцене. "Северный Ледовитый залив" превратился таким образом в современный Северный Ледовитый океан за счет спрединга дна Гренландско-Норвежского моря.

Руководящий вид олигоцена, *Turrilina alsatica* Andreae, появился в арктических районах одновременно с усилением циркуляции между Северной Атлантикой и Северным Ледовитым океаном. В подповерхностной зоне бассейна Бофорта-Маккензи *Turrilina alsatica* — широко распространенный и надежный зональный руководящий вид. В обнажениях этот вид обнаружен только в одном месте: в пачке Нувок формации Сагаванирктоk на реке Картер крик, Аляска.

В миоцене циркуляция между Северным Ледовитым и Атлантическим океанами усилилась еще больше. В эту эпоху имело место умеренное потепление, пришедшее на смену похолоданию, наблюдавшемуся в раннем олигоцене. Фораминифера *Asterigerina staeschei* (Franke), широко распространенный и встречающийся в больших количествах вид, служит маркером этой фазы истории Северного Ледовитого океана. *Asterigerina staeschei* вымерли в среднем миоцене как в Северном Ледовитом океане, так и в северных районах Атлантики. В бассейне Бофорта-Маккензи многие сопряженные виды прослеживаются до позднего миоцена, но неожиданно исчезают на уровне конечного миоценового несогласия. Крупные изменения в составе фауны и в осадочном комплексе указывают на то, что это несогласие отражает одно из

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самых значительных событий в истории третичного периода. Предполагается, что оно было вызвано эвстатическим падением уровня моря.

Крупный оборот в фауне плиоцена ознаменовался появлением *Cibicides grossus* ten Dam анд Реинчолд. Этот вид появился в раннем плиоцене и вымер в Северной Атлантике и Северном Ледовитом океане примерно 2,4 миллиона лет тому назад — почти тогда же, когда в позднем плиоцене началось ухудшение климата и континентальное оледенение. Вид *Cibicides grossus* широко распространен в арктических районах Северной Аме-рики: в подповерхностной зоне бассейна Бофорта-Маккензи и в обнажениях морского языка формации Бофорта на острове Миен, в безымянной толще на мысе Уайт Пойнт в северо-западной части острова Элсмир, в восточной части острова Баффинова Земля и в восточных и северных районах Гренландии.

Ключевые слова: бентические фораминиферы, третичный период, арктические районы Северной Америки, палеокеанография, *Turrilina, Asterigerina, Cibicides*

INTRODUCTION

The information presented in this paper is a summary of biostratigraphic-paleogeographic events of arctic Tertiary history documented mainly by benthic foraminiferal assemblages, in particular those of Oligocene to Pliocene age. The distribution and interpretation of marine rocks, deciphered from foraminiferal distributions, is of fundamental importance in understanding the geological history of the arctic regions during the Tertiary. At present, the most comprehensive record of marine Tertiary sedimentation in the Arctic comes from the Beaufort-Mackenzie Basin (Fig. 1), where petroleum exploration during the past 25 years has provided samples for an extensive foraminiferal data base. Seven foraminiferal assemblages have been recognized in Tertiary strata of the Beaufort-Mackenzie Basin (Fig. 2), each recording a discrete episode of marine sedimentation, ultimately reflecting the major tectonic and oceanographic events of Tertiary arctic North America.

Biostratigraphic resolution is a fundamental problem in the Arctic because of the general absence of standard indices such as planktonic foraminifers and nannoplankton. In this context, three species of benthic foraminifers have become particularly important — *Turrilina alsatica* Andreae, *Asterigerina staeschei* (Franke), and *Cibicides grossus* ten Dam and Reinhold. In combination with their associated foraminiferal and palynomorph assemblages, each of these species provides a significant amount of information on Tertiary history. They occur abundantly in the Arctic, are readily recognizable, have widespread nearly isochronous last appearance datums, and occur outside the Arctic in regions of the North Atlantic. Their respective extinction levels at the end of the Oligocene, within or near the end of the middle Miocene, and at the end of the early late Pliocene provide regionally and easily recognizable "chronologic" datums. Their widespread distributions and last appearance datums (LADs) serve to document the major oceanographic changes of the period and provide a means to correlate geographically isolated outcrops of Tertiary strata in the Arctic Coastal Plain.

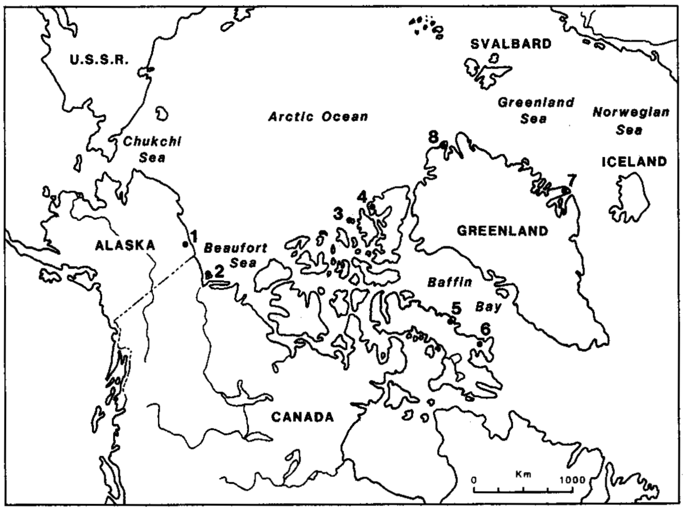

FIG. 1. Location map of foraminifer-yielding marine Oligocene to Pliocene sections in the Arctic Ocean region of North America. 1=Carter Creek, Alaska; 2=Beaufort-Mackenzie Basin; 3=Meighen Island; 4=White Point, Ellesmere Island; 5=Clyde Foreland; Baffin Island; 6=Qivituq Peninsula, Baffin Island; 7=Lodin Elv, Greenland; 8=Kap København, Greenland.

Although this paper deals mostly with Oligocene to Pliocene foraminiferal biostratigraphy, a brief summary of Paleocene-Eocene history is presented as an introduction to later events and to emphasize the pronounced changes that mark Tertiary arctic history.

TERTIARY EVENTS AND THE BEAUFORT-MACKENZIE BASIN RECORD

Paleocene-Eocene

It is well established that the Paleocene-Eocene interval (66.4–36.6 Ma) was a time of remarkably favourable climatic conditions. Wolfe (1978, 1980) has summarized that during the Eocene broad-leaved evergreen vegetation such as palms and cycads existed to about 60°N. Rich assemblages of pollen, including angiosperm pollen of deciduous hardwoods, have been recovered from the Paleocene-Eocene terrestrial formations of arctic Canada (Ioannides and McIntyre, 1980; Doerenkamp *et al.*, 1976), redwood forests (*Metasequoia*) proliferated in the Arctic Archipelago (McMillan, 1986), and Eocene crocodilian remains have been recovered from Ellesmere Island at approximately 77° (Estes and Hutchison, 1980). The oxygen isotope record (Fig. 3) from Atlantic deep-sea drilling sites also clearly indicates warm climatic conditions in the Paleocene and Eocene (Miller *et al.*, 1987).

Unfortunately, the warm, humid climates (warm temperate?) that supported rich floral assemblages at this time did not go hand in hand with a rich marine record of benthic foraminiferal assemblages. The relatively poor Paleocene-Eocene marine record is characterized by dominantly agglutinated foraminiferal assemblages, made up mostly of arctic-endemic species. Agglutinated foraminifers, which are single-celled organisms with a test constructed of grains of sediment bound by organic cement, are generally less reliable for stratigraphic purposes than calcareous benthic foraminifers or planktonic foraminifers that have secreted calcite tests.

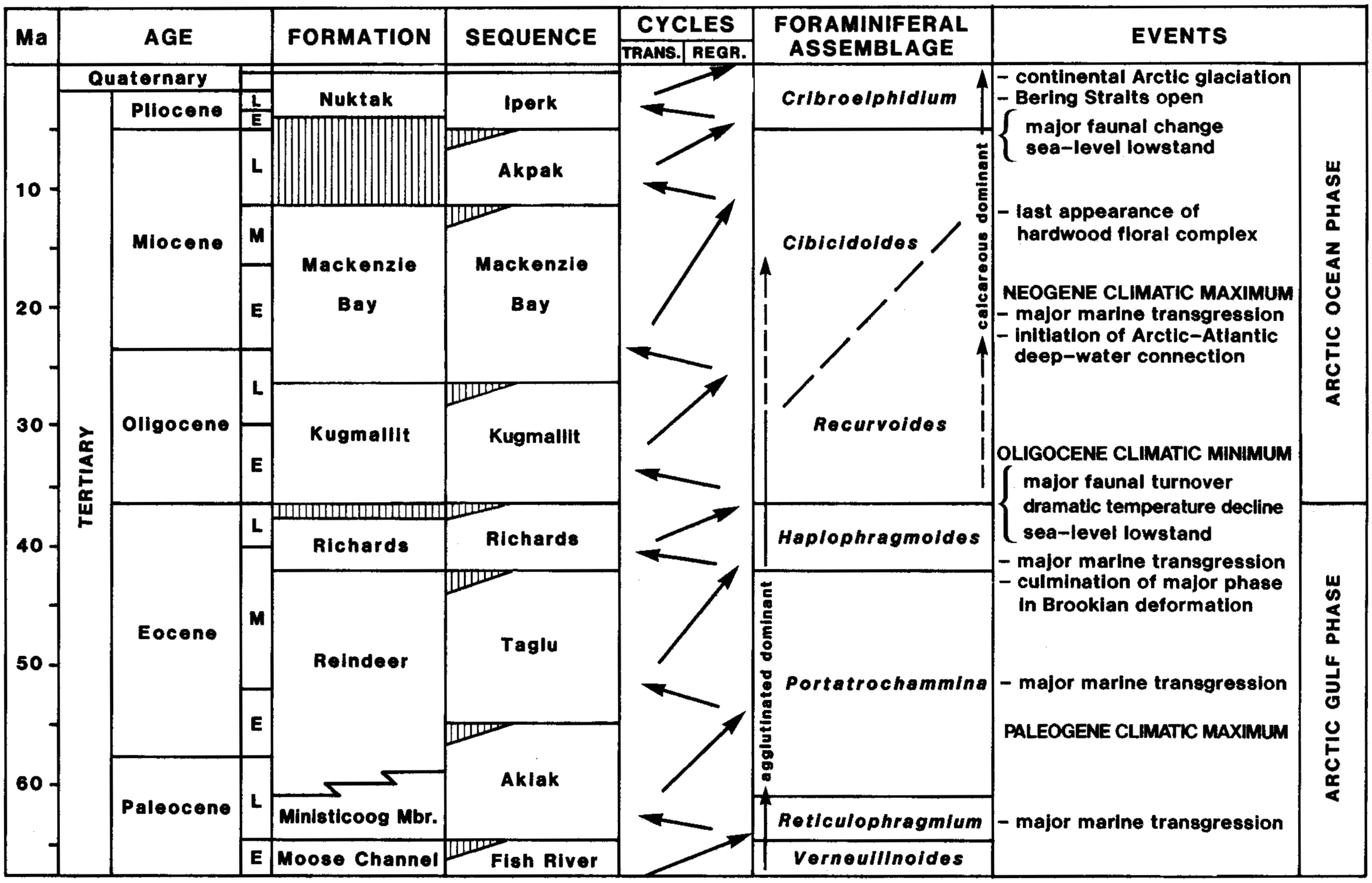

FIG. 2. Stratigraphic summary of the Tertiary succession in the Beaufort-Mackenzie Basin related to tectonic, oceanographic, and climatic events or episodes. Transgressive-regressive trends supplied courtesy of J. Dixon. Foraminiferal assemblages after McNeil (1989).

Paleogeographic reconstructions for this time period by Briggs (1987) indicate that the paleo-Arctic Ocean was a severely restricted marine basin. Its configuration is so different from present that I refer to it as the "Arctic Gulf." On the paleogeographic base map (Fig. 4), the Arctic Gulf was connected to southern oceans by the restricted Turgai Straits (trending north-south through western Siberia) and by the restricted Greenland-Norwegian Straits. Three major marine transgressions can be documented from the Beaufort-Mackenzie Basin during this time span (Fig. 2): a "mid-" Paleocene transgression represented by the Ministicoog Member (lower Aklak sequence) of the Moose Channel Formation, an early Eocene transgression represented by marine beds in the Taglu sequence, and a mid- to late Eocene transgression represented by the Richards sequence.

Microfossil assemblages from these units have been documented by Petracca (1972), Staplin (1976), Young and McNeil (1984), and McNeil (1985, 1988b, 1989). The assemblages represent a boreal Paleocene-Eocene biogeographic province that was probably circum-arctic in extent, stretching approximately from the area of the Alaska-Chukotka land bridge to the present-day area of Svalbard (Fig. 4). The restricted, isolated nature of this phase of arctic marine history is amply demonstrated by the nature of the foraminiferal assemblages of the Beaufort-Mackenzie Basin. Young and McNeil (1984) have summarized these assemblages as being dominantly agglutinated, completely lacking in planktonic species, low in species diversity, and endemic to the Arctic. The endemic Arctic Gulf assemblages have been only partly described. Examples include *Reticulophragmium borealis* (Petracca) in the Paleocene, *Portatrochammina* sp. 2450 of McNeil (1989) in the early to middle Eocene, *Cyclammina cyclops* McNeil, *Haplophragmoides* sp. 2000 of McNeil (1989), and *Jadammina statuminis* McNeil in the late Eocene. These foraminifers and their assemblages differ markedly from cosmopolitan Paleocene-Eocene assemblages that include, for example, *Haplophragmoides walteri* (Grzybowski), *Recurvoides walteri* (Grzybowski), *Reticulophragmium amplectens* Grzybowski, *Rzehakina epigona* (Rzehak), and *Spiroplectammina spectabilis* (Grzybowski).

Interpretation of oxygen isotope records (Fig. 3) from the deep-sea Atlantic indicates that a temperature decline in the order of 7°C occurred gradually from the early Eocene maximum to the latest Eocene, when the temperature plummeted by 5°C near the Eocene-Oligocene boundary.

Oligocene

The transition from the Eocene to Oligocene is marked globally by a complex of biological and physical changes (Pomerol and Premoli-Silva, 1986). In the Beaufort-Mackenzie Basin, for example, a pronounced unconformity separates the Eocene Richards sequence from the Oligocene Kugmallit sequence (Dixon *et al.*, 1985). The early Tertiary endemic agglutinated microfaunas are replaced above this unconformity by agglutinated and calcareous benthic

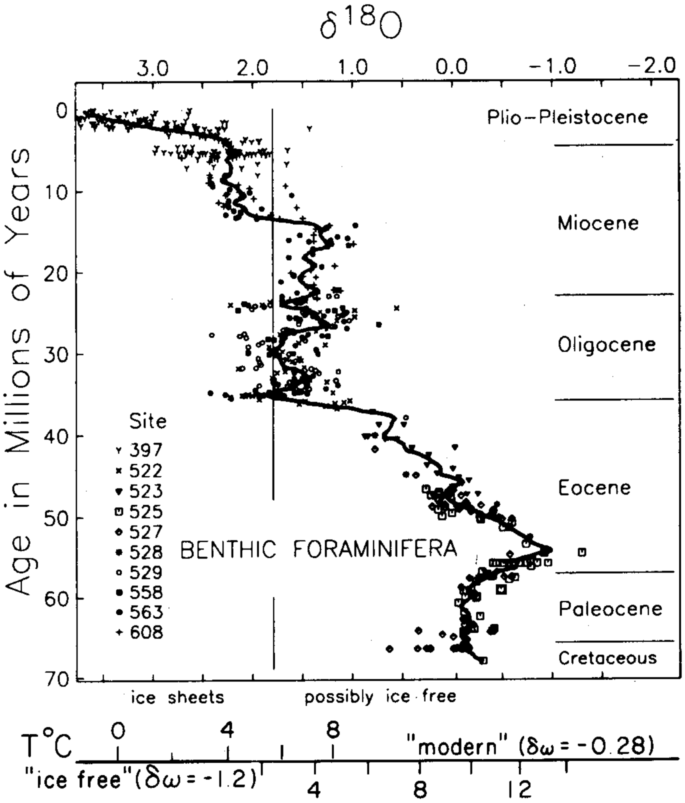

FIG. 3. Composite benthic foraminiferal oxygen isotope record for Atlantic deep-sea drilling sites (after Miller *et al.*, 1987, with permission of the American Geophysical Union).

foraminifers that show affinities to North Atlantic and northwestern European assemblages. Examples include *Alabamina tangentalis* (Clodius), *Budashevaella multicameratus* Voloshinova, *Cibicidoides eocaenus* (Gümbel), *Gyroidina soldanii* d'Orbigny, *Melonis affinis* (Reuss), *Nuttallides* sp. 1414, *Rotaliatina mexicanus* Cushman, *Turrilina alsatica* Andreae, and *Valvulineria petrolea* (Andreae). Some of these species are also known from the Pacific Ocean Basin, but connections with the Pacific are unlikely based on paleogeographic reconstruction (Briggs, 1987) and my direct observations of Oligocene microfaunas from Kamchatka and westcoast Canada, which indicated no similarites between Pacific and arctic assemblages.

The occurrence of North Atlantic affinity microfossils (e.g., *Turrilina alsatica*) in the Oligocene Kugmallit sequence is thus thought to reflect Arctic-Atlantic microfaunal migrations that were initiated by the submergence of the Greenland-Iceland-Farroe bridge and establishment of Arctic-North Atlantic deep-water connections during the early Oligocene (Talwani and Eldholm, 1977; Eldholm and Thiede, 1980).

The paleogeographic reconstruction of the Miocene (Fig. 5) by Briggs (1987) illustrates a major reorganization of the arctic-North Atlantic paleogeography, which was initiated in the Oligocene. This event or episode marks the end of the restricted early Tertiary Arctic Gulf and the beginning of the Oligocene to Holocene Arctic Ocean with well-established connections to the North Atlantic.

Based on North American fossil leaf records, Wolfe (1971, 1978) demonstrated a climatic decline in the early Oligocene, which he referred to as the most dramatic climatic event in Northern Hemisphere Tertiary history. Wolfe estimated that the decline in mean annual temperature was as great as 12-13°C in Alaska at latitude 60°N. Norris (1982) recognized the absence of thermophylic angiosperm taxa in early to mid-Oligocene strata from the subsurface of the Beaufort-Mackenzie Basin and interpreted this as an indication of a significant cooling relative to the Eocene. Importantly, Norris also recognized an amelioration of climate, to warm temperate, in the late Oligocene. The occurrence of the genus *Nuttallides*, a member of the warm-water subfamily Asterigerinacea, in upper Oligocene strata of the Beaufort Sea also suggests relatively warm climatic conditions at this stage of arctic history.

Miocene

The transition from Oligocene to Miocene is marked by important changes in the calcareous benthic foraminifers, including the disappearance of numerous species (e.g., *Anomalinoides* sp. 1400 of Dietrich *et al.*, 1989; *Nuttallides* sp. 1414 of McNeil and Miller, 1990; and *T. alsatica*). The precise dates of these last appearance datums is not known. Revets (1987) reported the extinction of *T. alsatica* in the middle late Oligocene (approximately 27.0 Ma). However, strontium isotope correlations (McNeil and Miller, 1990) have indicated an age of 23.8 Ma for *T. alsatica* and associated benthic foraminifers in the Nuwok beds at Carter Creek, North Slope, Alaska. The introduction of *Asterigerina staeschei*, which is abundant through lower to middle Miocene strata in the Beaufort-Mackenzie Basin, is representative of the changes that occurred during the early Miocene. *Asterigerina* strongly suggests relatively warm oceanographic conditions (McNeil *et al.*, 1982). The first appearance datum for *A. staeschei* is difficult to determine from well cuttings

FIG. 4. Eocene world paleogeography (base map after Briggs, 1987, with permission of Elsevier publishers). The early Tertiary "Arctic Gulf" nurtured the development of a Paleocene-Eocene arctic endemic province (indicated by diagonal lines). The Arctic Gulf had restricted connections to southern oceans by the Greenland-Norwegian Straits and the Turgai Straits.

FIG. 5. Miocene world paleogeography (base map after Briggs, 1987, with permission of Elsevier publishers). Establishment of the modern Arctic Ocean began in the early Oligocene with the opening of the North Atlantic by sea floor spreading between Greenland and Norway. The diagonal lines indicate the geographic extent of the Oligocene to Miocene arctic faunal province.

in the Beaufort-Mackenzie Basin, but it may have occurred as early as the latest Oligocene.

The early to mid-middle Miocene (23.7–14 Ma) is well documented as the climatic maximum for the Neogene (Kennett, 1982). This has been determined from several lines of evidence, one of which is the oxygen isotope record (Fig. 3) from Atlantic deep-sea drilling sites. The arctic expression of this warm climatic episode is documented by the Hills *et al.* (1974) report of walnuts (*Juglans eocineria*) in abundance in lower to middle Miocene strata on Banks Island. Wolfe (1978:700) also noted that global evidence exists for a relatively warm late Oligocene to late Miocene, in particularly the late early to early middle Miocene. Palynological evidence supporting a relatively warm Miocene episode has also been presented by White (1989), who recognized mixed hardwood-coniferous palynofloras typical of temperate regimes in late Oligocene to middle Miocene strata of the Beaufort Sea. Interestingly, White's (1989) palynomorph distributions in the Issungnak O-61 well suggest a climatic decline across the interval 1505–1775 m, which is *prior to* the last appearance datum of *A. staeschei* at the upper boundary of the Mackenzie Bay sequence (1455 m).

The *Asterigerina*-bearing Mackenzie Bay sequence is overlain by the Akpak sequence. Foraminiferal assemblages of the Akpak sequence are characterized by the *absence* of *A. staeschei*, but many other species such as *Cibicidoides* sp. 800 of McNeil (1989) range through the Mackenzie Bay and Akpak sequences, suggesting conformity and similarity of oceanographic conditions, although slightly cooler. The occurrence of *Ehrenbergina praepupa* in the Akpak sequence was used by McNeil (1988a) to suggest a late Miocene age. A late Miocene arctic cooling trend was also suggested by Wolfe and Leopold (1967), who noted that coniferous forests began to occupy increasingly larger areas of the uplands of Alaska by the late Miocene. Pinaceae-dominated palynomorph assemblages in the late Miocene Akpak sequence (White, 1989) of the Beaufort-Mackenzie Basin also attest to cooler climatic conditions relative to the early and middle Miocene.

Terminal Miocene Unconformity

Miocene strata are terminated abruptly in the Beaufort-Mackenzie Basin by a regional unconformity, followed by a pronounced microfaunal change. This event, which McNeil *et al.* (1982) alluded to as probably coinciding with eustatic lowering of sea level, is one of the most conspicuous stratigraphic breaks in the arctic Tertiary record. Its cause remains speculative, but there is no doubt that a marked change in *relative sea level* occurred and that water mass characteristics, and probably climates, were markedly different before and after this event. Stratigraphic relationships observed in seismic profiles indicate regional erosion on the shelf at about the same time lowstand turbidite facies of the Pliocene-Pleistocene Iperk sequence were being deposited in bathyal environments. An abundance of reworked microfossils in the lowstand facies, and the Iperk in general, attests to rapid and significant rates of erosion.

Pliocene

Impoverished palynofloras, characterized by dominance of coniferous pollen, suggest that boreal climatic conditions prevailed during the Pliocene (McNeil *et al.*, 1982). Matthews (1987, 1989), documented a forest-tundra plant megafossil assemblage from early Pliocene beds of the Beaufort Formation on Meighen Island and concluded that some form of tundra flora probably existed around the arctic basin for much of the Pliocene. Benthic calcareous microfaunas of the Pliocene are characteristic of cool boreal (but not arctic) waters, with many species ranging to the Holocene.

A major Pliocene marine transgression and interregional continuity of marine conditions is documented by the widespread distribution of the calcareous benthic foraminifer *Cibicides grossus* (North Sea to Beaufort Sea). Extinction of *C. grossus* at about 2.4 Ma coincides approximately with the onset of widespread glaciation in the late Pliocene-Pleistocene interval (Feyling-Hanssen, 1985; Feyling-Hanssen *et al.*, 1982; Ruddiman and Raymo, 1988). Based on floral and faunal evidence from the Kap København Formation on northeastern Greenland (82°30′N), Funder *et al.* (1985) have shown that the Pliocene epoch ended with the existence of a forest-tundra terrestrial environment associated with glaciomarine conditions of sedimentation in the absence of a perennial ice cover.

OLIGOCENE-PLIOCENE OUTCROP RECORD

In contrast to the subsurface sections of the Beaufort-Mackenzie Basin, outcrop exposures of marine strata of a Tertiary age younger than Eocene are rare around the marginal rim of the Arctic Ocean Basin, but those that do occur have yielded valuable biostratigraphic information (Fig. 6). In arctic North America, only a handful of such localities are known at present. In the Arctic Islands and Greenland, these localities include the Lodin Elv Formation deposits on

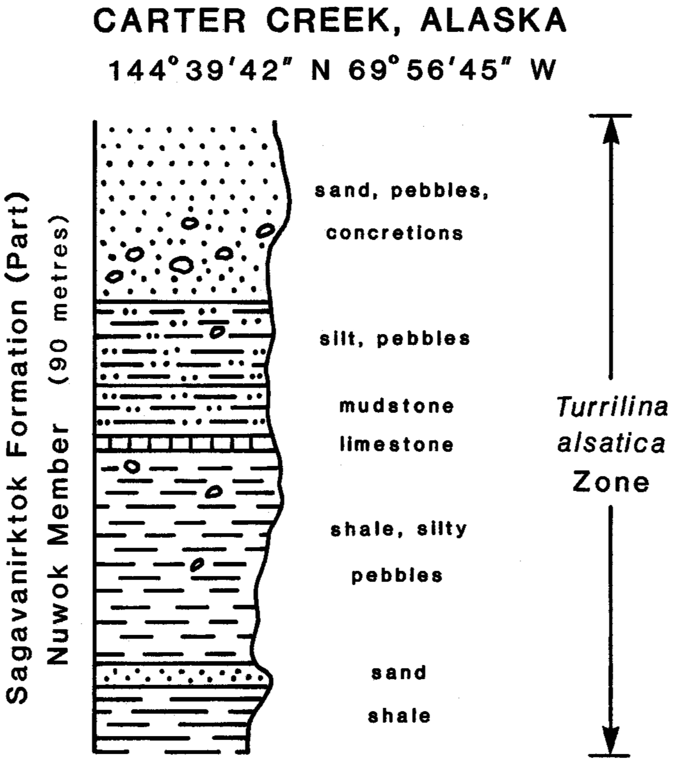

FIG. 6. Chronostratigraphic position of selected Oligocene, Miocene, and Pliocene calcareous benthic foraminifers from several localities in arctic North America. Time scale after Snelling (1985). Informal species numbers after McNeil (1989) and Dietrich *et al.* (1989).

eastern Greenland (Feyling-Hanssen *et al.*, 1983), the Kap København Formation on the northern tip of Greenland (Feyling-Hanssen, 1987), the Clyde Foreland Formation and the Qivituq Peninsula deposits of eastern Baffin Island (Feyling-Hanssen, 1976, 1980, 1985), unnamed strata at White Point, northwestern Ellesmere Island, and marine clays assigned to the Beaufort Formation on Meighen Island. To the west, the only exposure of marine Tertiary strata younger than the Eocene, and excluding the uppermost Pliocene/Pleistocene Gubik Formation, comprises the beds assigned to the Nuwok Member of the Sagavanirktok Formation along Carter Creek, Alaska (Todd, 1957).

NUWOK MEMBER AT CARTER CREEK, ALASKA

The occurrence of Tertiary marine strata in northeastern Alaska has been known since Leffingwell (1919) and Dall (1919, 1920) reported marine macrofossils from the "Nuwok formation" on Carter Creek about 2.4 km south of the coast at an elevation of 46 m (Detterman *et al.*, 1975). MacNeil (1957) and Todd (1957) considered these faunas to be Miocene or Pliocene age, but McNeil *et al.* (1982) assigned an Oligocene age, pointing out Todd's (1957) critical misidentification of *Turrilina alsatica* Andreae (an Oligocene index) as *Buliminella curta* Cushman (from the Miocene of California). Several other corrections to Todd's microfaunal list must also be emphasized to avoid further confusion in age determinations. *Nonion labradoricum* (Dawson) (an arctic Quaternary species) is not present at Carter Creek; Todd's (1957: Pl. 1, Fig. 17) illustrated specimen is an unnamed species of *Chilostomellina*. Todd's illustration of "*Cibicides perlucidus* Nuttall" includes one representative of *Nuttallides* and several species of *Cibicidoides*, including *Cibicidoides eocaenus* (Gümbel), a cosmopolitan bathyal Eocene-Oligocene species according to Van Morkhoven *et al.* (1986). The occurrence of *Nuttallides* sp. 1414 of Dietrich *et al.* (1989), previously wrongly assigned to the microspheric generation of *Eponides binominatus* Subbotina by McNeil *et al.* (1982), is of considerable importance, since it, as a member of the subfamily Asterigerinacea, suggests relatively warm oceanographic conditions during the late Oligocene in the Arctic.

The Nuwok Member (Fig. 7) is only known from a single outcrop locality. Detterman *et al.* (1975:37-39) described the section as consisting of 1) a basal cross-bedded sandstone containing thin-shelled pelecypods, 2) a middle part consisting of marine mudstones and siltstones, including thin limestone interbeds, and 3) an upper part consisting mostly of sand. Recently, Brouwers and Marincovich (1988) reported ostracode and molluscan assemblages from the Nuwok Member, which they dated as late Neogene, citing generalized comparisons to east coast United States faunas. Disintegrated and washed sediment residues from the Nuwok, courteously supplied to the author by E.A. Brouwers, indicate that almost the entire member yields common to abundant foraminifers similar to the assemblage Todd (1957) described from two samples in the lower part of the Nuwok. Diversity and specimen abundance decrease upwards through the Nuwok, but diagnostic species such as *T. alsatica* (Fig. 8:5,6) are essentially continuous throughout the member. There is no indication of reworked foraminifers and the preservation is among the best I have observed in the Beaufort Sea area. The Nuwok is rich in fine mascerated plant debris of terrestrial origin. One sample, which was barren of microfossils, yielded abundant coal, amber, and plant fragments.

The generic composition of the assemblage, as illustrated by Todd (1957), is suggestive of normal marine salinities. A neritic paleoenvironment is considered most likely based on Detterman's assessment of the stratigraphy of the section and

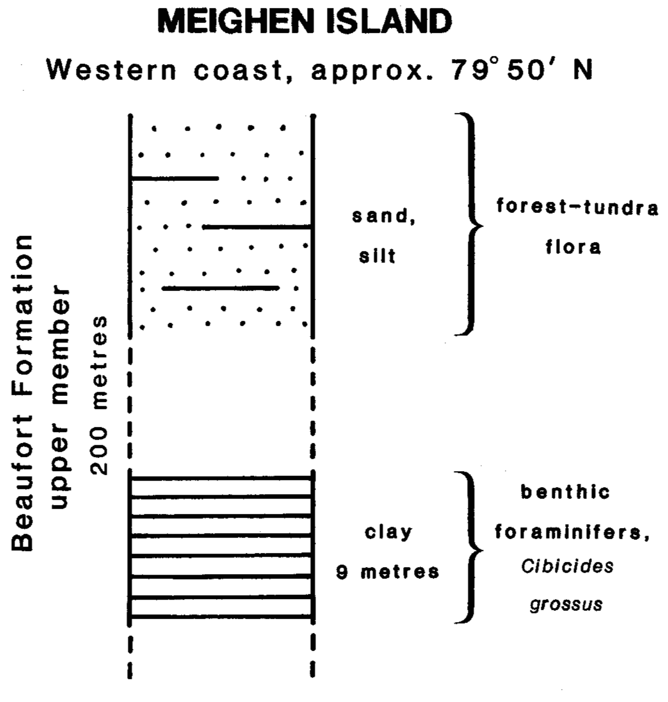

FIG. 7. Lithological succession in the type Nuwok Member at Carter Creek, Alaska (modified from Detterman *et al.*, 1975). See Figure 1 for location.

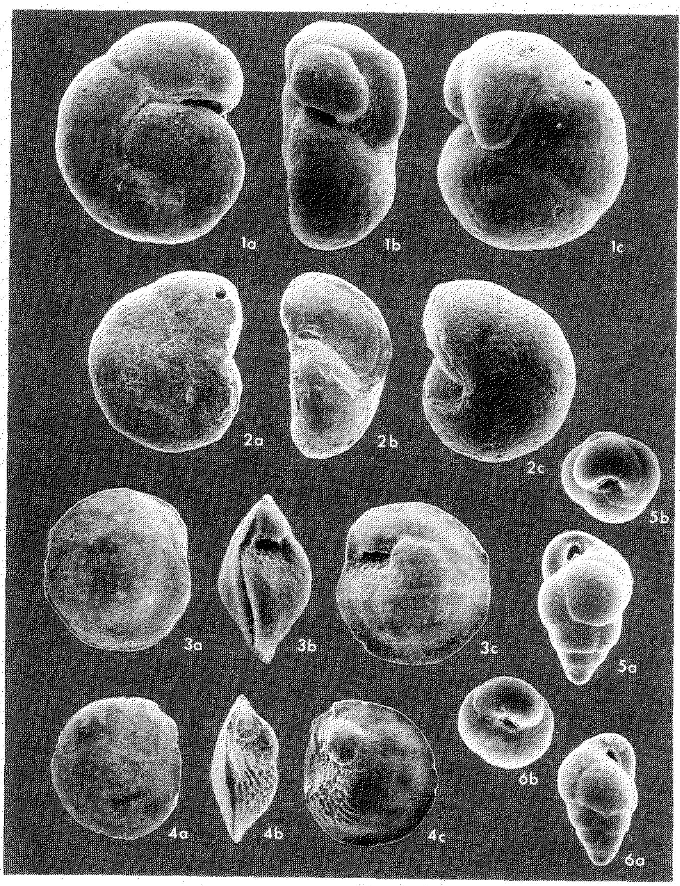

FIG. 8. Illustrated specimens are stored in the type collections of the Geological Survey of Canada (GSC), Ottawa.

1-2. *Cibicides grossus* ten Dam and Reinhold, from GSC Locality O-48222 at White Point, Ellesmere Island. 1) Hypotype GSC 89536, X58, (a) spiral view, (b) edge view, (c) umbilical view. 2) Hypotype GSC 89537, X59, (a) spiral view, (b) edge view, (c) umbilical view.

3-4. *Asterigerina staeschei* (Franke), from well cuttings of the Dome Natiak O-44 well between 1489 and 1507 m, Beaufort Sea, GSC Locality C-137749. 3) Hypotype GSC 89538, X66, (a) spiral view, (b) edge view, (c) umbilical view. 4) Hypotype GSC 89539, X77, (a) spiral view, (b) edge view, (c) umbilical view.

5-6. *Turrilina alsatica* Andreae, from the Nuwok Member, Sagavanirktok Formation, Carter Creek, Alaska. 5) Hypotype GSC 89540, X69, (a) lateral view, (b) apertural end view. 6) Hypotype GSC 89541, X57, (a) lateral view, (b) apertural end view.

the presence of abundant terrestrial material in the section. Brouwers and Marincovich (1988) concluded that the ostracode and mollusc assemblages represented inner-shelf environments and that the ostracodes indicated a shallowing upward trend.

A variety of ages have been assigned to the Nuwok Member, but regardless of the exact chronological age, its foraminiferal assemblage can be correlated easily and objectively with the relatively complete Tertiary foraminiferal section from the nearby subsurface of the Beaufort-Mackenzie Basin. Briefly stated, the Nuwok microfauna equates with the *Turrilina alsatica*-bearing zone that is widespread immediately underlying the early to middle Miocene zone of *Asterigerina staeschei*. Until recently, calcareous microfaunas considered to be older than those at Carter Creek were poorly known from the Beaufort-Mackenzie Basin. However, drilling of the Dome Edlok N-56 well, situated in the western area of the Canadian Beaufort Sea (Dietrich *et al.*, 1989), revealed an Oligocene section that can be divided into lower and upper subdivisions, with the upper Oligocene being comparable to the Carter Creek section. The lower Oligocene section differs in containing *Cancris* cf. *C. subconicus* Terquem and species of *Brizalina and Rectobolivina*. Dietrich *et al.* (1989) have illustrated this microfauna from the Edlok N-56 well and assigned an early Oligocene age on the basis of *C.* cf. *C. subconicus*, which marks the lower Oligocene in the North Sea Basin (King, 1983).

The foraminiferal age determinations of late Oligocene for Nuwok strata have been substantiated recently by correlation of Nuwok strontium isotope ratios ($^{87}Sr/^{86}Sr$) to the standard Oligocene chronostratigraphy documented in deep-sea drilling studies in the North Atlantic Ocean (McNeil and Miller, 1990). Strontium isotope correlations indicate that the Nuwok was deposited within an interval from at least 23.8 to 27.0 Ma. Considerable reliance can be placed on these age estimates because the isotopic change was relatively pronounced during the Oligocene, providing a steeper gradient to the isotopic curve and hence greater potential for accuracy (McNeil and Miller, 1990).

The only other reports of marine Oligocene strata in the Arctic Ocean basin have come from Spitsbergen (Feyling-Hanssen and Ulleberg, 1984) and from a borehole in northern Chukotka (Gudina, 1984). Although limited data are available for comparison, both these localities yield foraminiferal assemblages comparable to those in the Beaufort-Mackenzie Basin, indicating a fairly uniform circum-Arctic Oligocene biogeographic province.

BEAUFORT FORMATION, MEIGHEN ISLAND, ARCTIC ISLANDS

There are no known exposures of marine Oligocene, Miocene, or Pliocene rocks from Carter Creek (lat. 70°N) to Meighen Island (lat. 80°N), high in the Arctic Islands (Fig. 1). At Meighen Island, Matthews (1987) has described the lower Pliocene Beaufort Formation as consisting of approximately 220 m of unconsolidated sand, silt, and clay (Fig. 9). Plant megafossils indicative of a forest-tundra environment were recovered for the most part stratigraphically above a clay unit, considered to be a marine tongue of the Beaufort Formation, outcropping in the southern part of the island (Matthews, 1987). The marine clay, exposed at two sites (approximately 79°48′N, 99°22′W) situated approximately 2.5 km from the western coast along an unnamed stream, was sampled by L.V. Hills, who recovered calcareous benthic foraminifers from two samples. The foraminiferal collection was referred to B.E.B. Cameron, who reported an assemblage suggestive of an early Pliocene age (Cameron, pers. comm. 1973). Foraminiferal species identified in a re-examination of this collection are listed in Figure 6.

In agreement with earlier determinations of Cameron (pers. comm. 1973) and Matthews (1987), an early Pliocene age seems most likely for the marine tongue of the Beaufort Formation on Meighen Island. Matthews (1989), however, noted the possibility of the deposit being late Miocene in age on the basis of strontium isotope determinations from the bivalve *Arctica*. This seems unlikely in view of the complete dissimiliarity of this microfauna with that of the Miocene microfaunas of the *Cibicidoides* assemblage in the Beaufort-Mackenzie Basin or with the Miocene microfaunas of the North Atlantic region, notably the North Sea area as described by King (1983).

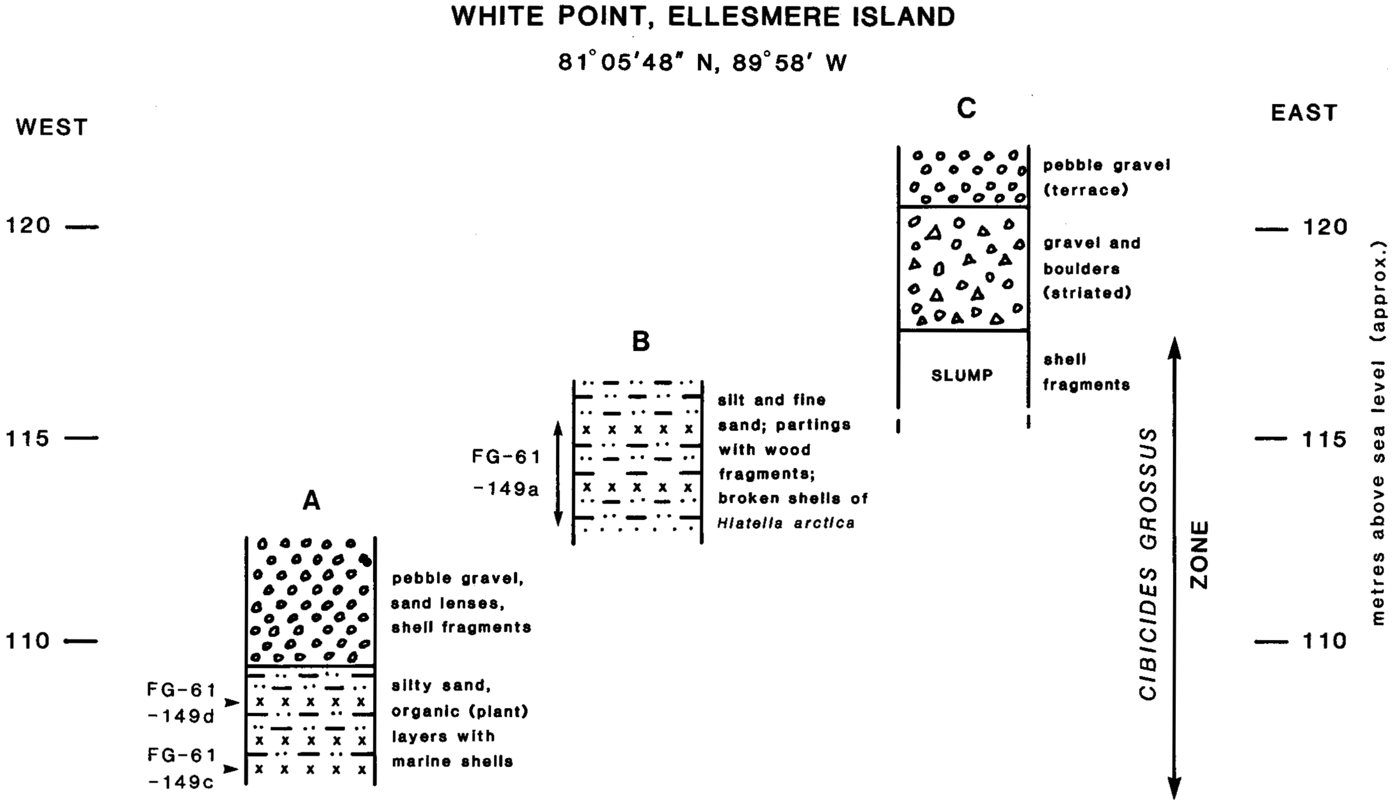

FIG. 9. Schematic representation of stratigraphy of the Beaufort Formation on Meighen Island (compiled from Matthews, 1987, and L.V. Hills, pers. comm. 1987). See Figure 1 for location.

Most of the foraminifers from the Beaufort marine tongue have a potential range of Pliocene through Quaternary, but an important exception is *Cibicides grossus* (Fig. 8), which establishes a Pliocene age for this deposit. *C. grossus* is well documented in apparently slightly younger Pliocene sections on Baffin Island (Feyling-Hanssen, 1980, 1985), east Greenland (Feyling-Hanssen *et al.*, 1982) and in the North Sea Basin (King, 1983). *C. grossus* became extinct with the climatic deterioration of the Late Pliocene (Feyling-Hanssen *et al.*, 1982), which is dated at approximately 2.4 Ma on the basis of %$CaCO_3$ and $\delta^{18}O$ values from Deep Sea Drilling Project (DSDP) cores of the North Atlantic (Ruddiman and Raymo, 1988). The first appearance datum for *C. grossus* is less precisely known but probably occurred in the early Pliocene. King (1983) illustrates its appearance in the North Sea Basin in the late early Pliocene. Feyling-Hanssen (1980:170) recounted previous records of *Cibicides grossus* in Miocene sections in the Netherlands, but information from both the Beaufort Sea and North Sea areas suggests its range is restricted to the Pliocene.

The *C. grossus* zone, as described by Feyling-Hanssen, is different in species composition relative to the *C. grossus* occurrence on Meighen Island. The Baffin Island occurrences, for example, include common to abundant specimens of *Buccella frigida, Cassidulina reniforme, C. teretis*, and *Cribroelphidium subarcticum*, all of which are absent at Meighen Island. The differences are probably explained by the *C. grossus*-yielding marine tongue being older and representing a warmer climatic regime than beds assigned to the *C. grossus* zone of Feyling-Hanssen. A more refined age than early Pliocene cannot be determined from the existing foraminiferal data.

WHITE POINT LOCALITY, NORTHWEST ELLESMERE ISLAND

Unnamed silts and sands underlying gravels (Fig. 10) at an approximate elevation of 122 m near White Point, Ellesmere Island, have yielded well-preserved foraminifers diagnostic of the *Cibicides grossus* zone as recognized by Feyling-Hanssen (1980, 1985) and Feyling-Hanssen *et al.* (1982) on Baffin Island and eastern Greenland. The samples were collected by J.G. Fyles in 1961 and a radiocarbon date of approximately 38 600 was derived from bivalve shells (Dyck and Fyles, 1963). Since the age of *Cibicides grossus* is probably greater than 2.4 Ma, the radiocarbon date probably is an infinite age.

A detailed stratigraphic description of the deposit near White Point is not presently available, but a brief account was presented by Dyck and Fyles (1963). A schematic illustration (Fig. 10) of the lithologic succession was provided by J.G. Fyles (pers. comm. 1988).

The foraminiferal collection was derived from a composite sample taken from exposures A and B (FG-61-149a,c,d shown in Fig. 10). Numerous marine ostracodes and bivalves were also recovered from this locality, but other than the identification of *Hiatella arctica* and radiocarbon dating, no work has been done on these fossils. Foraminifers recovered from these deposits are listed in Figure 6. The assemblage clearly documents the presence of the *Cibicides grossus* zone of Feyling-Hanssen (1980) at the White Point locality. This zone is distributed widely in high-latitude Pliocene deposits, including the North Sea Basin (King, 1983), eastern Greenland (Feyling-Hanssen *et al.*, 1982), and eastern Baffin Island (Feyling-Hanssen, 1980, 1985). Its occurrence in the Soviet Arctic has also been documented by Slobodin *et al.*

Ma	5 10 15 20 25 30 35							STRATIGRAPHIC UNITS AND LOCALITY
EPOCH	PLIOCENE		MIOCENE			OLIGOCENE		
	L	E	L	M	E	L	E	
Buccella tenerrima	●							unnamed beds, White Point, Ellesmere Island
Cassidulina teretis	●							
Cibicides grossus	●							
Cibicides scaldisiensis	●							
Cribroelphidium albiumbilicatum	●							
Cribroelphidium asklundi	●							
Cribroelphidium bartletti	●							
Cribroelphidium excavatum	●							
Cribroelphidium subarcticum	●							
Cribroelphidium ustulatum	●							
Elphidiella cf. *E. gorbunovi*	●							
Glandulina cf. *G. laevigata*	●							
Guttulina glacialis	●							
Haynesina orbiculare	●							
Melonis barleeanum	●							
Quinqueloculina seminulum	●							
Cibicides grossus		●						Beaufort Formation, Meighen Island
Cribroelphidium excavatum		●						
Cribroelphidium ustulatum		●						
Elphidiella cf. *E. gorbunovi*		●						
Haynesina orbiculare		●						
Miliolinella subrotunda		●						
Quinqueloculina seminulum		●						
Asterigerina staeschei				●	●			Akpak and Mackenzie Bay sequences, Beaufort–Mackenzie Basin
Cibicidoides sp. 800			●	●	●			
Ehrenbergina praepupa			●	●				
Alabamina tangentalis						●		Nuwok beds, Carter Creek, Alaska
Anomalinoides sp. 1600						●		
Chilostomellina sp.						●		
Cibicidoides eocaenus						●		
Melonis affinis						●		
Nuttallides sp. 1414						●		
Turrilina alsatica						●		
Valvulineria petrolei						●		
Brizalina sp. 1435							●	lower Kugmallit sequence, Edlok N–56 well, Beaufort Sea
Cancris cf. *C. subconicus*							●	
Rectobolivina sp. 1464							●	

FIG. 10. Stratigraphy of unnamed Pliocene deposits yielding *Cibicides grossus* at White Point, northwestern Ellesmere Island (data provided courtesy of J.G. Fyles, based on 1961 field work). See Figure 1 for location.

(1986), who described it in early late Pliocene (approximately 2.3–3.3 Ma) deposits in Taymyr Peninsula.

The assemblage at White Point compares most closely with the microfauna that Feyling-Hanssen *et al.* (1982) reported from member A of the Lodin Elv Formation in eastern Greenland, in that *C. grossus* is associated with abundant *Cassidulina teretis* (*C.* cf. *C. teretis* of Feyling-Hanssen *et al.*). In other sections of the *C. grossus* zone at Clyde Foreland and Qivituq Peninsula on Baffin Island, *C. teretis* occurs only rarely and is abundant only above *C. grossus*, where it is used to distinquish the *C. teretis* zone. These and other differences in the detailed assemblage composition between these areas are probably environmentally controlled.

Most of the species associated with *C. grossus* range through the Pliocene and Pleistocene and are of limited chronostratigraphic significance through that interval. *C. grossus*, however, is the important exception. A minimum age for its last appearance datum (LAD) is fairly well constrained by data from the North Sea Basin. *C. grossus* disappears in the late Pliocene (King, 1983). The precise age datum was probably about 2.5 Ma, based on data from the Netherlands, where *C. grossus* disappears in the Reuverian stage, below the Reuverian/Praetiglian boundary dated paleomagnetically at about 2.3 Ma (Feyling-Hanssen, 1980, 1987; Van Montfrans, 1971). Feyling-Hanssen *et al.* (1982) have noted that *C. grossus* disappeared with the climatic deterioration of the late Cenozoic and that therefore its LAD could be diachronous, perhaps slightly older in the higher latitude arctic occurrences. As previously noted, a minimum date of 2.4 Ma constrains the LAD for *C. grossus* in eastern Greenland, based on DSDP data from the North Atlantic.

It should also be noted that a Quaternary age was assigned to the *C. grossus* zone in the lower Clyde Foreland Formation on eastern Baffin Island on the basis of amino acid ratios in mollusc shells (Andrews and Miller, 1984). Andrews (1989) later referred to Feyling-Hanssen's (1985) Pliocene age determination, commenting that the amino acid kinetics were such that an age of greater than 1 Ma was probable for these deposits and that a Pliocene age was also possible. Some diachroneity in the LAD of *C. grossus* is likely, but regional foraminiferal correlations still favour a minimum age of 2.4 Ma.

A maximum age for the *Cibicides grossus* zone at White Point is less well constrained, but an age at approximately the early/late Pliocene boundary is likely, based on extrapolations from east Greenland. The Lodin Elv Formation contains the *C. grossus* zone in association with bivalves of Pacific affinity (e.g., *Mya truncata*). It is thought (L.N. Marincovich, Jr., pers. comm. 1987) that the Pacifican molluscs could not have entered the arctic regions prior to the opening of the Bering Straits (approximately 3.3 Ma). MacNeil (1965) has documented the Pacifican molluscs in sections in Iceland, and Gladenkov (1981) has dated the first appearance of Pacifican molluscs at Iceland at approximately 3.0 Ma.

SUMMARY

The Beaufort-Mackenzie Basin of arctic Canada contains a relatively complete Tertiary record of marine sedimentation. Benthic foraminiferal assemblages from those sediments changed dramatically through time, largely in response to large-scale tectonic, oceanographic, and climatic changes. The early Tertiary paleo-setting differed greatly from the modern Arctic, and to emphasize that contrast, this early period is referred to as the Arctic Gulf phase. The Arctic Gulf was a restricted, relatively warm ocean body connected to the Atlantic and Tethyan areas by shallow, narrow seaways during the Paleocene and the Eocene. A more modern Arctic Ocean configuration evolved during the Oligocene as connections with the Atlantic were broadened and deepened with seafloor spreading in the North Atlantic. In detail many changes occurred in the benthic foraminiferal assemblage during the Oligocene and Miocene, but underlying similarities in the benthic foraminiferal assemblages indicate some continuity through this period of time. Changing climatic trends, closely paralleling global oxygen isotope trends, have been documented by palynological assemblages, macrofloras, and benthic foraminifers. The major trends include a dramatic deterioration in the climate near the Eocene-Oligocene boundary, a relatively cool early Oligocene, followed by a warmer late Oligocene to middle Miocene phase, culminated by cooling in the late Miocene. The Miocene record is terminated abruptly by a regional unconformity that underscores a virtually complete change in the benthic foraminiferal assemblage. The cause of the terminal Miocene unconformity is still speculative, but it might be interpreted as a eustatic drop in sea level caused by massive glaciation in Antarctica beginning at about 6 Ma. Pliocene calcareous benthic foraminiferal assemblages occur in strata above the unconformity. These assemblages are generally similar to those of the Quaternary, indicating some oceanographic continuity in this phase of arctic Cenozoic history. Important changes in the benthic assemblages occur, however, to mark the climatic deterioration and onset of continental glaciation in North America at 2.4 Ma.

Of the many benthic foraminiferal species in Tertiary strata of arctic North America, three stand out as being particularly useful in establishing a regional biostratigraphic framework for Oligocene to Pliocene strata. They are *Turrilina alsatica*, *Asterigerina staeschei*, and *Cibicides grossus*.

T. alsatica has a documented range of late Eocene to late Oligocene. In the Beaufort-Mackenzie Basin, it occurs in the Kugmallit sequence and the lowermost Mackenzie Bay sequence. The only known equivalent in outcrop in arctic North America yielding *T. alsatica* occurs in the Nuwok Member of the Sagavanirktok Formation on Carter Creek, Alaska.

A. staeschei has been reported from middle Oligocene to Miocene beds in the North Atlantic region but has a likely range of early to middle Miocene. It occurs in the Beaufort-Mackenzie Basin within the Mackenzie Bay sequence and signifies a relatively warm climatic period, as has been postulated previously on the basis of plant megafossils. There are no known outcrops in the Arctic yielding *A. staeschei*. Many early to middle Miocene foraminiferal taxa range higher into the upper Miocene Akpak sequence of the Beaufort-Mackenzie Basin, but their ranges are truncated abruptly at the terminal Miocene unconformity.

Cibicides grossus has been reported from Miocene and Pliocene strata, but close scrutiny of previous records indicates that its range is most likely early Pliocene to earliest late Pliocene. In the Beaufort-Mackenzie Basin, it occurs in the lower and middle parts of the Iperk sequence or equivalent strata of the Nuktak Formation. It occurs in numerous outcrops in arctic North America, including the marine tongue of the Beaufort Formation on Meighen Island, unnamed strata in White Point on northwest Ellesmere Island, on eastern Baffin Island, and on northern and eastern Greenland. The last occurrence datum for *C. grossus* coincided approximately with the late Pliocene climatic deterioration and onset of continental glaciation at approximately 2.4 Ma.

ACKNOWLEDGEMENTS

I would like to thank J.V. Matthews, Jr., of the Geological Survey of Canada (GSC), Ottawa, for encouraging me to present foraminiferal data from the Beaufort-Mackenzie Basin at the 1987 Denver workshop on Late Cenozoic stratigraphy and paleoenvironments. J.G. Fyles (GSC, Ottawa) generously provided me with samples and stratigraphic descriptions for unnamed Pliocene strata on White Point, Ellesmere Island. I am indebted to Institute of Sedimentary and Petroleum colleagues J. Dixon (stratigraphy/sedimentology), J.R. Dietrich (seismic stratigraphy), D.J. McIntyre (palynology), and J.M. White (palynology) for sharing their expertise in discussions on the Beaufort Sea stratigraphy and palynology. The constructive comments from R.W. Feyling-Hanssen, of the Geological Institute, Aarhus University, Denmark, and Yu.B. Gladenkov, of the Geological Institute, USSR Academy of Sciences, Moscow, and two anonymous reviewers are gratefully acknowledged. Technical support was ably provided by B.J. Davies and D.R. Then (drafting), J.N.Y. Wong (SEM operator), and W.B. Sharman (photography).

APPENDIX. SYNONOMIES, OCCURRENCES, AND REMARKS FOR SELECTED SPECIES OF BENTHIC FORAMINIFERS

Correlations of marine Oligocene to Pliocene strata in arctic North America have been based on several stratigraphically significant foraminifers species tied into the constraints of "event" stratigraphy. Biostratigraphy is an empirical science that draws on a long history of previous records of fossil occurrences. Many of these details are tedious for the non-specialist, but they form the basis for subsequent interpretations and are therefore included in this appendix. Three species in particular have proven to be useful in establishing a generalized framework for correlation of widely separated rock exposures. They are *Turrilina alsatica* Andreae, *Asterigerina staeschei* ten Dam and Reinhold, and *Cibicides grossus* ten Dam and Reinhold.

Turrilina alsatica Andreae, 1884 (Fig. 8:5,6)

Turrilina alsatica Andreae, 1884:120, Pl. 8, Fig. 18; Cushman and Parker, 1947:56, Pl. 15, Fig. 3; Batjes, 1958:125-126, Pl. 4, Fig. 15; Hansen, 1973:Figs. 3, 4b, 5b, 6b, 7b; Hughes, 1981: Pl. 15.1, Fig. 11; Gradstein and Agterberg, 1982:Pl. 5, Fig. 2, possibly Fig. 3; McNeil *et al.*, 1982: Pl. 2, Fig. 21; King, 1983: Pl. 2, Fig. 27; Young and McNeil, 1984: Pl. 4, Fig. 14; McNeil, 1985: Pl. 1, Fig. 6; Revets, 1987:321, 325, Pl. 1, Figs. 1-6, Pl. 2, Figs. 1-4; McNeil, 1989:Pl. 1, Fig. 6.

Buliminella curta Cushman, Todd, 1957:Pl. 28, Fig. 20.

Illustrated specimens. Hypotype, GSC (Geological Survey of Canada) specimen 89540, Fig. 8:5, maximum length 0.59 mm, from 59 m above base of type section of Nuwok Member, Sagavanirktok Formation, Carter Creek, Alaska. Hypotype GSC 89541, Fig. 8:6, maximum length 0.61 mm, from 59 m above base of type section of Nuwok Member, Sagavanirktok Formation, Carter Creek, Alaska.

Occurrence. Upper Eocene (rare) to upper Oligocene. Revets (1987) reported a stratigraphic range of middle upper Eocene to middle upper Oligocene. *Turrilina alsatica* was originally recorded from middle Oligocene in the Alsass region of Germany by Andreae (1884). Todd (1957) reported it from the Nuwok Member of the Sagavanirktok Formation on the North Slope of Alaska but erroneously referred to it as *Buliminella curta* Cushman (a species originally described from the Miocene of California). The Nuwok Member was dated Miocene or Pliocene by Todd (1957), but that age is undoubtedly wrong. An Oligocene age was determined for the Nuwok Member by McNeil *et al.* (1982) based largely on the presence of *T. alsatica*. Batjes (1958) recorded *T. alsatica* from the middle Oligocene Boom clay of Belgium and the correlative Septaria-clay in nearby Germany. Additional middle Oligocene records from northwestern Europe have been documented in Denmark by Hansen (1973) and in the North Sea by Hughes (1981). King (1983) recorded its range in the North Sea Basin to be from upper Eocene to upper Oligocene. On the other side of the North Atlantic, Gradstein and Agterberg (1982) reported it from the Oligocene of the Labrador Shelf and northern Grand Banks. In the Arctic, it was recorded by Feyling-Hanssen and Ulleberg (1984) from "upper Middle" Oligocene strata at Sarsbukta, western Spitsbergen, in the island group of Svalbard. It has been recorded extensively in Oligocene deposits of the Beaufort-Mackenzie Basin by McNeil *et al.* (1982), Young and McNeil (1984), and McNeil (1985). Its last appearance datum, estimated at >23.7 Ma, forms the upper boundary of the *Turrilina alsatica* interval zone in the Beaufort-Mackenzie Basin (McNeil, 1989).

Remarks. *Turrilina alsatica* is uniform in morphology and presents little problem for identification. The genus *Turrilina* was recently reviewed by Revets (1987), who presented clear illustrations of the apertural detail in *T. alsatica*, showing the distinctive serrated apertural lip and internal tooth plate of the species.

The closely allied species *Turrilina andreae* Cushman is probably also present in the Beaufort-Mackenzie Basin and in the Nuwok Member outcrop at Carter Creek. In fact, Todd's (1957:Pl. 28, Fig. 19 only) illustration of "*Buliminella curta*" is in part probably referrable to *T. andreae*. This species has not been discriminated in collections from the Beaufort Sea as yet, but it is likely present. Its range is confined to a span of middle lower to upper Oligocene.

Asterigerina staeschei (Franke) (Fig. 8:3,4)

Asterigerina guerichi Franke, Staesche and Hiltermann, 1940:Pl. 49, Figs. 12-13; Batjes, 1958:159-160, Pl. 10, Fig. 6; Gradstein and Williams, 1976:18-19; de Meuter and Laga, 1976:142, Table 2; Jansa *et al.*, 1977:Pl. 3, Fig. 1.

Asterigerina staeschei ten Dam and Reinhold, 1941a:222, Pl. 1, Fig. 2; ten Dam and Reinhold, 1942:91, Pl. 7, Fig. 2; Bettenstaedt *et al.*, 1962:375, Pl. 54, Figs. 22, 23; Doppert, 1980:Pl. 17, Fig. 3; Hughes and Jenkins, 1981:276, Pl. 9.1, Figs. 3-5; King, 1983:23, Pl. 3, Figs. 4-6; McNeil, 1989:Pl. 1, Fig. 5.
Asterigerina ex gr. *guerichi* (Franke), Gradstein and Agterberg, 1982:Pl. 6, Figs. 10-14.
Asterigerina guerichi s.l. (Franke), McNeil *et al.*, 1982:Pl. 3, Fig. 1; Young and McNeil, 1984:Pl. 5, Fig. 2.
Asterigerina sp., Staplin, 1976:Pl. 1, Fig. 6.
Asterigerina guerichi (Franke) (*staeschei* variety), McNeil, 1985:Pl. 1.

Illustrated specimens. Hypotype GSC 89538, Fig. 8:3, maximum diameter 0.65 mm; hypotype GSC 89539, Fig. 8:4, maximum diameter 0.49 mm; both from cuttings of the Beaufort Sea Dome Natiak O-44 well between 1489 and 1507 m (Mackenzie Bay sequence).

Occurrence. *Asterigerina staeschei* has been recorded from uppermost "middle" Oligocene to upper Miocene strata. There are, however, inconsistencies in the age determinations and taxonomic separation of *A. staeschei* from *A. guerichi*. A review of previous work indicates that *A. staeschei* should be considered an index of the lower to middle Miocene.

The following are the published records of *A. staeschei* recognized as a distinct taxon or as a variant of *A. guerichi*. *A. staeschei* was first recognized from lower and middle Miocene strata from the Netherlands, Belgium, and Germany by ten Dam and Reinhold (1941a, 1942). In northwestern Europe, it has been recorded since from upper Oligocene to middle Miocene of Belgium and Germany by Batjes (1958), from uppermost middle Oligocene to upper Miocene of northern Germany (common only in lower and middle Miocene) (Bettenstaedt *et al.*, 1962), from the upper Oligocene (rare) to middle Miocene of the Netherlands by Doppert (1980), from the lower Miocene offshore northern Scotland by Hughes and Jenkins (1981), and from the lower to middle Miocene of the North Sea Basin by King (1983). It was also recorded but not illustrated from the lower and middle Miocene of northern Belgium by de Meuter and Laga (1976) and from the Norwegian continental shelf by Skarbø and Verdenius (1986).

In wells offshore eastern Canada, Gradstein and Williams (1976), Jansa *et al.* (1977), and Gradstein and Agterberg (1982) have recorded *A. guerichi* (probably including mostly the *A. staeschei* morphotype) from Miocene strata of the Labrador Shelf and Grand Banks areas.

In the Beaufort Sea area, *A. staeschei* has been recorded in undifferentiated uppermost Oligocene to middle Miocene strata of the Mackenzie Bay Formation/seismic sequence by McNeil *et al.* (1982), Young and McNeil (1984), and McNeil (1985). Its last appearance datum, estimated at >10.4 Ma, forms the upper boundary of the *Asterigerina staeschei* interval zone in the Beaufort-Mackenzie Basin.

Remarks. *Asterigerina staeschei* has had a history of differing taxonomic interpretations and has been referred to as either a single taxon or as a variety or morphological variant of *Asterigerina guerichi* (Franke). *A. staeschei* differs from *A. guerichi* primarily in having a greater convexity and a more pronounced peripheral keel. Ten Dam and Reinhold (1941a, 1942) first proposed that *A. guerichi s.s.* was an index of the middle and upper Oligocene and that *A. staeschei* was an index of the middle Miocene. Batjes (1958:159), however, noted that the Miocene sands near Antwerp carried mostly *staeschei* but with examples of *guerichi* as well and that the late Oligocene Voort sand yielded examples of both morphotypes. More recently, King (1983) has summarized the *Asterigerina* distribution in the North Sea Basin, finding *A. staeschei* in the lower to middle Miocene and *A. guerichi* primarily in the upper Oligocene, but rarely just above and below.

Microfaunas from the Beaufort-Mackenzie Basin reveal that only the "*staeschei*" morphotype is present and that its range is restricted to the lower to middle Miocene. In Oligocene sections where the possibility of well-cavings can be eliminated, *A. staeschei* is absent (i.e., in the Dome Edlok N-56 well [Dietrich *et al.*, 1989] and in the Oligocene *Turrilina alsatica*-yielding outcrops at Carter Creek Alaska).

There seems little question that, in general, the "*staeschei*" morphotype is characteristic of the Miocene, whereas the *guerichi* morphotype is characteristic of the Oligocene (in Europe), and that the two should be recognized as separate species. *Asterigerina guerichi* and *A. staeschei* might not be useful in determining the Miocene/Oligocene boundary, because they likely evolved across that interval and left a gradational series of morphotypes. The uppermost occurrence or last appearance datum for *Asterigerina staeschei* is taken to be approximately the middle/late Miocene boundary based on King's (1983) determinations for the North Sea Basin and assessment of neighbouring northwestern European published data.

Cibicides grossus (ten Dam and Reinhold) (Fig. 8:1,2)

Cibicides lobatulus (Walker and Jacob) var. *grossa* ten Dam and Reinhold, 1941b:62, Pl. 5, Figs. 5a-c, Pl. 6, Figs. 1a-c.
Cibicides rotundatus Stschedrina, Feyling-Hanssen, 1976:354, Pl. 3, Figs. 1-3, Pl. 4, Figs. 1-2.
Cibicides grossa ten Dam and Reinhold, Feyling-Hanssen, 1980:Pl. 1, Fig. 1, Pl. 5, Figs. 1-6; Young and McNeil, 1984:Pl. 5, Figs. 5a-c; McNeil, 1985:Pl. 1, Figs. 4a-c.
Cibicides grossus ten Dam and Reinhold, King, 1983:4, Figs. 6, 12; McNeil, 1988a:Pl. 2, Figs. 1a-c; McNeil, 1989:Pl. 1, Fig. 3.

Illustrated specimens. Hypotype GSC 89536, Fig. 8:1, maximum diameter 0.98 mm; hypotype 89537, Fig. 8:2, maximum diameter 0.82 mm; both from unnamed Pliocene strata at White Point, Ellesmere Island, GSC locality O-48222.

Occurrence. *Cibicides grossus* has been documented only in Pliocene strata from neritic facies of the North Atlantic and Arctic Ocean. It was first recorded in the lower Pliocene Diestien beds and middle Pliocene Scaldisien beds of the Netherlands by ten Dam and Reinhold (1941b). *C. grossus* has been recorded since from Pliocene beds of the lower Clyde Foreland Formation on eastern Baffin Island (Feyling-Hanssen, 1976, 1980), from Pliocene deposits in Qivituq Peninsula on the east coast of Baffin Island, from North Sea benthonic zone NSB 15 dated latest early Pliocene to early and middle late Pliocene by King (1983), from lower Pliocene beds now assigned to the Iperk sequence in the Beaufort Mackenzie Basin by Young and McNeil (1984), McNeil (1985), and McNeil (1988a) (*C. grossus* was originally recorded erroneously from Miocene beds of the Beaufort-Mackenzie Basin in publications by McNeil.) Its last appearance datum, estimated to be >2.4 Ma, forms the upper boundary of the *Cibicides grossus* interval zone in the Beaufort-Mackenzie Basin (McNeil, 1989).

Van Voorthuysen (1950) recorded *C. grossus* from the middle Pliocene and middle Miocene (rarely) in a boring at Zaandam in the Netherlands. Van Voorthuysen's illustrations show only the umbilical view of *C. grossus*, which is inadequate for identification. Re-examination of the Zaandam material would be necessary to clarify the distribution of *C. grossus*, particularly the Miocene recordings. It is likely that the Zaandam occurrences are limited to the Pliocene. Doppert (1980) has recorded *C. grossus* from the late Pliocene and late Miocene of the Netherlands (the Breda and Oosterhout formations), but the specimen illustrated more closely resembles *Cibicides scaldisiensis* ten Dam and Reinhold. Skarbø and Verdenius (1986) have reported *C. grossus* in upper Pliocene sediments of the Norwegian continental shelf. *Cibicides grossus* has also been recorded from lower member A of the Kap København Formation on northern Greenland (Feyling-Hanssen, 1987).

Remarks. *Cibicides grossus* was originally referred to as *Cibicides lobatulus* (Walker and Jacob) var. *grossa* by ten Dam and Reinhold (1941b). It clearly differs from the thin, planoconvex, irregularly shaped *lobatulus*, which is strongly flattened on its spiral side. The species might be assignable to *Heterolepa* in view of its granular wall structure and lack of attachment surface on the spiral side. The closely associated *Cibicides scaldisiensis*, however, has what appears to be a flat attachment surface and a granular wall. This leaves only the matter of wall structure, granular versus radial, as the determining feature for generic assignment. Since it has been demonstrated that wall structure may differ within one genus (Hansen, 1973), no change of generic status is warranted.

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