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Arctic Oceanic Climate in Late Cenozoic Time

Yvonne Herman and David M. Hopkins

Summary. Faunal and lithologic evidence is used to reconstruct paleoceanographic events over the last 4.5 million years. The inception of perennial sea-ice cover is dated at about 0.7 million years.

Several significant global climatic and tectonic events affected the evolution of Arctic oceanic climates during late Cenozoic time. The terminal Miocene temperature decline, culminating in the major expansion of the Antarctic ice sheet, and the concomitant worldwide lowering of sea level that resulted in the isolation of the Mediterranean Sea about 5 million years ago (*1*) may have been synchronous with the onset of glaciation at high latitudes in the Northern Hemisphere. At that time, the Bering land bridge completely isolated the Arctic from the Pacific Ocean (*2–5*), and because circulation in the world ocean was primarily latitudinal, there was probably little interchange between Atlantic and Arctic waters (*6*).

The sudden appearance of a flood of Pacific mollusks in Iceland indicates that the Bering land bridge was breached about 3.5 million years ago (*7, 8*). These events coincided approximately with the emergence of the Isthmus of Panama, completed about 3 million years ago (*9*), which resulted in a salinity contrast between salty North Atlantic and somewhat fresher North Pacific surface waters (*10*) and in the reorientation of oceanic circulation to a more vigorous south-north current. The Gulf Stream as we know it today may have evolved at about this time (*6*): The overall consequence of these events was the persistent influx into the western part of the Arctic Ocean basin of low-salinity North Pacific water through the Bering Strait (*11*) and the influx of a much larger volume of salty Atlantic water into the eastern part of the Arctic basin by way of the Norwegian Sea (*10*).

This change in oceanic circulation led to intensified atmospheric circulation. Increased transport of moist air over an open and relatively warm North Atlantic Ocean to adjoining subpolar highlands evidently resulted in the episodic development of local ice sheets large enough to lower sea level as much as 40 meters as early as 3.4 million years ago (*12*). The situation is somewhat analogous to the abortive high-latitude glaciation recorded about 115,000 years ago during an early phase of the last glaciation (Wisconsin/Würm) (*13*). Continental ice sheets at least two-thirds as large as those of the late Pleistocene developed about 2.4 million years ago, shortly after the beginning of the Matuyama reversed epoch (*12, 14*). Latitudinal temperature gradients increased gradually, and by late Pliocene time the modern marine faunal provinces were established (*15*).

Sedimentary Record in the Arctic Basin

The continuous sedimentary record representing roughly the last 4.5 million years is preserved in deep-sea cores raised from bathymetric highs by the Lamont-Doherty Geological Observatory (LDGO) from ice platforms drifting over the central part of the Arctic basin (Fig. 1 and Table 1). Despite certain ambiguities, the radiometric dates (*16*) and magnetic stratigraphy (*17*) of these cores together with biostratigraphic and lithologic correlations (*18–20*) provide control points for the time framework of this Pliocene and Pleistocene sequence (Fig. 2). Three major climatic regimens, here represented by three stratigraphic units, can be recognized within this time interval. Rates of sedimentation were very low (1 to 3 millimeters per 1000 years) in all three units.

The oldest unit (unit III) comprises sediments deposited between approximately 4.5 and 2.5 million years ago and consists of fairly well sorted red clays containing manganese and micronodules. The botryoidal micronodules, which constitute up

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to 60 percent of the coarse fraction (> 62 micrometers), are very similar to Greenslate's (*21*) "juvenile" micronodules in the Pacific basin. Small but significant amounts of ice-rafted quartz sand grains have also been recognized throughout unit III. The grains exhibit surface features consistent with a cycle of glacial abrasion prior to their transport to this region (*22*). Faunal remains constitute less than 1 percent of the coarse fraction (Fig. 2). The planktonic foraminifers are dominated by a robust, left-coiling, polar *Globigerina pachyderma* population, some of which are corroded. Fragmentary tests are abundant, and the solution-susceptible tests of juvenile specimens are rare in unit III. Scattered occurrences of low-latitude planktonic foraminifers in this unit as well as in the "foraminifera-poor" layers of units II and I were noted in earlier publications (*18-20, 23, 24*) (Figs. 2 to 4). Their presence was suggested to be due to transport by ocean currents from the Atlantic and Pacific during periods of more active water exchange between the Arctic and adjacent oceans (*23*) or to transport by shelf ice (*25*).

Benthonic foraminifers are represented by solution-resistant, deep-water agglutinated forms and robust calcareous elements (*24*). A few shallow-water shelf foraminifers, indicating transport by icebergs or shelf ice, are also present. The top of unit III appears to lie a short distance below the boundary of the Gauss normal and the Matuyama reversed epochs (*19, 20, 24*) and is about 2.5 million years old.

Table 1. Locations, depths, and lengths of cores.

Core	Latitude	Longitude	Depth (m)	Length (cm)
D.St.A.2	83°52′N	168°12′W	1521	206
D.St.A.4	84°21′N	168°49′W	2041	116
D.St.A.5	84°28′N	169°04′W	1934	125
D.St.A.6	85°15′N	167°54′W	1842	88
T3-66-S-8	75°41.4′N	158°00′W	864	108
T3-66-S-33	75°50.4′N	162°59′W	2047	225
T3-67-2	79°06.3′N	175°34′W	1982	312
T3-67-3	79°11′N	175°09′W	2285	380
T3-67-4	79°22.7′N	174°46′W	1760	272
T3-67-9	79°37.9′N	172°07′W	2237	356
T3-67-11	79°34.9′N	172°30′W	2810	250
T3-67-12	80°21.9′N	173°33′W	2867	374

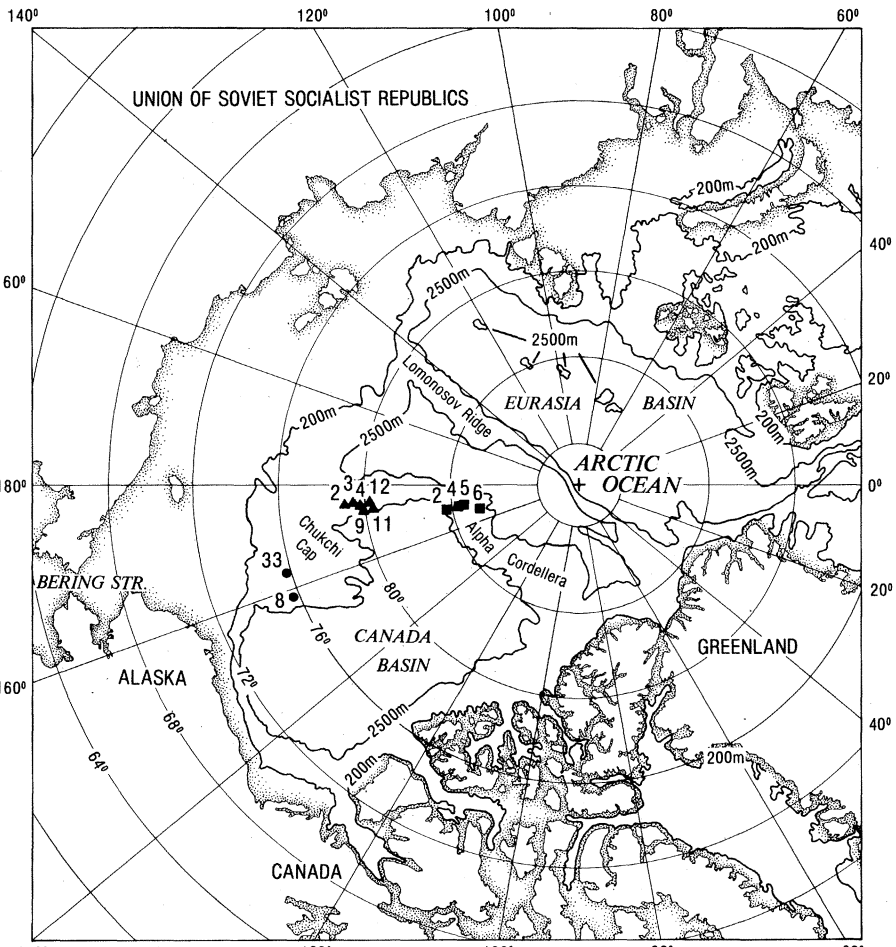

Fig. 1. Arctic Ocean and surrounding lands, showing locations of cores and other places mentioned in the text. (■) D.St.A. 2, 4, 5, and 6; (●), T3-66 cores; (▲) T3-67 cores.

The boundary between units III and II is sharp and clear, being defined by simultaneous lithologic and faunal changes. The sediments of unit II consist of tan silts, devoid of iron- and manganese-rich micronodules, with abundant coarse ice-rafted debris. The planktonic foraminifers are dominated by *Globigerina egelida* followed by *Globigerina quinqueloba*. These two extant solution-susceptible subpolar species comprise up to 99 percent of the total foraminiferal fauna of unit II in cores raised from depths less than 2400 m, but decrease considerably in relative abundance in deeper water sediments (*26*) (Figs. 2 and 3). *Globigerina egelida* presently inhabits the Labrador Sea during summer months and the North Atlantic slope water during winter (*27*). It was gradually replaced by the cosmopolitan euryhaline-eurytherm *G. quinqueloba* (*28*), and about 0.9 to 0.7 million years ago *G. quinqueloba* became the predominant taxon (*26, 28*) (Fig. 3). The right-coiling subpolar *G. pachyderma* complex attains highest frequency in the sediments of unit II (*19, 20*) (Fig. 4). The benthonic foraminifers include both deep-water and shallow-water forms. Among the latter, *Elphidium* spp., endemic to continental shelves, are abundantly represented (*19, 20*) and constitute as much as 50 percent of the benthonic fauna in some samples (*26*) (Figs. 3 and 4). Deep-water species are varied, both calcareous and arenaceous elements being common (*19, 20*). The top of unit II lies near the top of the Matuyama reversed epoch and is between 0.9 and 0.7 million years old (*19, 20*).

The boundary between units II and I is defined by changes in the composition of the foraminiferal fauna and by the appearance of sharp and frequent fluctuations in the abundance of foraminiferal tests (*19, 20, 24*) (Figs. 2 to 4). The planktonic foraminifers of unit I are dominated by a left-coiling polar *G. pachyderma* complex. Layers rich in *G. pachyderma*, similar to those now being deposited in the Arctic basin, appear for the first time near the bottom of unit I and recur at several higher levels (Figs. 2 and 3), and coarse, ice-rafted particles are a major component of the sediments. *Globigerina egelida* is replaced by *G. quinqueloba*, which appears sporadically and is especially abundant near several of the transitions between foram-rich and foram-poor zones (Figs. 2 and 3); it is significant that this species can tolerate large salinity and seasonal temperature fluctuations (*26*). Benthonic foraminifers are varied and include shallow-water species (*19, 20*) (Figs. 3 and 4).

Interpretation

Three different oceanographic-climatic regimes are represented by the three stratigraphic units preserved in deep-sea cores from the central Arctic basin. The predominance of cold-water elements in the fauna of unit III suggests that surface water in the Arctic Ocean was hardly warmer than at the present time. Ice-rafted sand grains and rare shallow-water benthonic foraminifers indicate that glaciers reached tidewater at times, calving icebergs that drifted across the Arctic basin and released incorporated debris to the sea floor.

Although the fauna suggests surface temperatures as low as today's, other features of the sediments of unit III indicate that the structure of Arctic water masses must have been quite different from that of later periods.

1) Extensive solution of calcareous foraminifera indicates that the carbonate compensation level (CCL) was shallower than it was during deposition of units II and I.

2) The reddish color of unit III sedi-

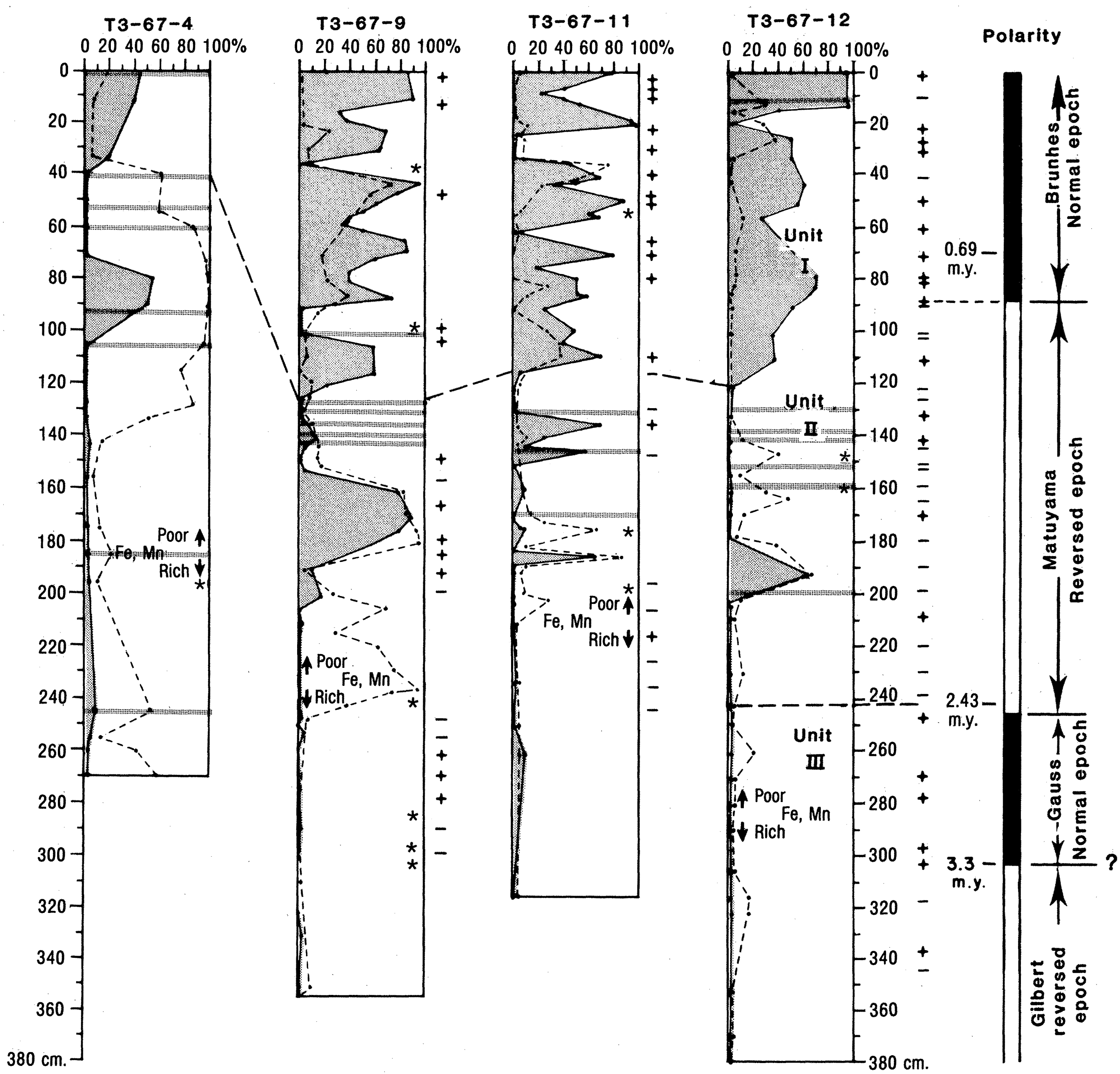

Fig. 2. Paleomagnetic time scale (right) and percentage of microfauna in coarse fraction (> 62 μm) in cores T3-67-4, T3-67-9, T3-67-11, and T3-67-12. In core diagrams, shaded areas are microfauna; white areas are clastic particles. Dashed line is the percentage of the total planktonic foraminiferal population composed of *Globigerina quinqueloba* and *G. egelida*. Dark horizontal bands are zones in which benthonic foraminifers constitute > 10 percent of the total fauna. (*) Low-latitude planktonic foraminifers; (+, −) magnetic polarity determinations (*17*). [Modified from Herman (*24*)]

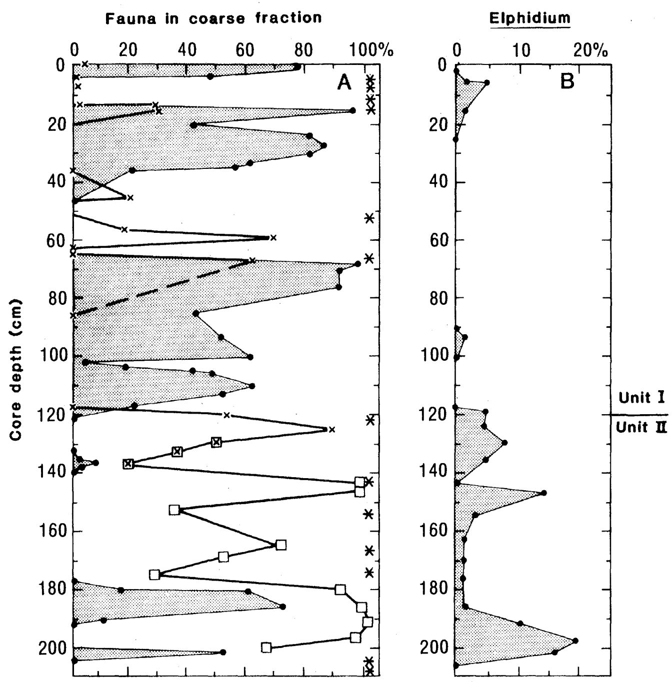

Fig. 3. Core D.St.A.2. (A) Percentages of microfauna in the coarse fraction (> 62 μm). Shaded areas are microfauna; white areas are clastic material. (×) Percentages of *Globigerina quinqueloba* of the total planktonic foraminiferal fauna; (□) percentages of *G. egelida* of the total planktonic foraminiferal fauna; (*) low-latitude planktonic foraminifers. (B) Percentages of *Elphidium* spp., a shallow-water genus, of the total benthonic foraminiferal fauna. Core depth is in centimeters. [Modified from Herman (*19*)]

ments indicates oxidation of bottom sediments. Evidently there was good vertical mixing, a lack of pronounced stratification of water masses, and oxygenation of bottom waters.

3) The presence of manganiferous micronodules: phyto- and zooplankton are important in the marine biogeochemical cycle because they are able to extract various elements (such as manganese) present in seawater at very low concentration levels and concentrate them in their skeletal structures, tissues, and fecal pellets. Furthermore, these organisms are capable of transporting such elements from various water masses to the sea floor (*29*), where they become available to benthonic organisms which further concentrate them. Agglutinated benthonic foraminifers utilize the manganese and iron in their shell construction (*21*). All manganiferous micronodules examined had agglutinated foraminifers as nuclei, much like the micronodules from Pacific sediments described by Greenslate (*21*). An interesting implication of the biogenic origin of the manganiferous micronodules in the Pliocene Arctic is that surface water biological production must have been greater than it is today, precluding the existence of a perennial ice cover. The extremely low sedimentation rates below the CCL enhanced the concentration of micronodules in unit III.

Water temperatures during unit III time were certainly cold, but just how cold remains uncertain. The near absence of the right-coiling *G. pachyderma* complex suggests surface waters as cold as those of the present time. However, the presence of *G. egelida* in the sediments of unit III in shallow core T3-67-4 (Fig. 2) strongly suggests water temperatures seasonally above the freezing point. Perhaps the absence of this solution-susceptible subarctic species in deeper cores is due to dissolution during a period of elevated CCL. In any case, faunal composition and lithology suggest that water temperatures were very low, vertical mixing was intense, and biological production was greater than today's during the deposition of unit III sediments. Some oceanographers (*10*) contend that a perennial sea-ice cover could not form over the deep Arctic basin in the absence of a well-defined density stratification. We believe that, because of strong vertical mixing or warmer surface temperatures, there was no perennial sea-ice cover on the Arctic basin during the accumulation of unit III.

The microfaunal evidence of cold surface water in the Arctic basin is compatible with indirect biogeographic evidence concerning the nature of shelf waters 3.5 million years ago. The mollusk assemblage that dispersed at the time out of the Pacific and into the North Atlantic Ocean by way of the Bering Strait and the Arctic Ocean (*7, 8*) consists almost entirely of species whose nearest relatives are still present throughout all except the northernmost part of the eastern Chukchi Sea (*30*), and several of these species extended their ranges into the Beaufort Sea during the last interglacial interval (*31*). The implication is that during deposition of unit III, water temperatures of the Arctic Ocean were comparable to those of late Pleistocene interglacial intervals, and possibly only slightly warmer than they are now.

A major oceanographic and climatic threshold was crossed about 2.5 million years ago. The much greater abundance of coarse ice-rafted debris in unit II indicates a great increase in the frequency and intensity of glaciation on adjoining land masses, and the sporadic high abundances of *Elphidium* in cores raised from isolated bathymetric highs indicate that glaciers episodically gouged material from the continental shelves and dropped it far from land. As illustrated in Figs. 3 and 4, the frequency of *Elphidium* spp. is much higher in Matuyama sediments, a relatively mild period (*32*), than in Brunhes, when global temperatures were lower. The lack of manganese micronodules and the change in sediment color from red to tan indicates lessened biological production, poorer oxygenation of bottom waters, and lessened vertical circulation. Thus the base of unit II evidently records the inception of a strong salinity-density stratification in the Arctic (*19, 20, 24*) probably as a consequence of the sudden dilution of surface water by the influx of large quantities of thawing icebergs and glacial meltwater coupled with intensified river runoff during an early deglaciation at Arctic latitudes. The water temperatures indicated by the planktonic foraminiferal faunas of unit II are incompatible with the presence of a perennial Arctic ice pack, but a seasonal ice cover may have been present. Seasonal ice would enhance the salinity stratification by reducing mixing due to wind shear, by excluding heavy saline water from surface layers during freezing, and by diluting the surface low-salinity layer when the ice melted in summer. The influx through the Bering Strait of the low-salinity water of the Alaska Current may have contributed to the persistence of a salinity-density stratification throughout the time represented by unit II.

The stability of water layers restricted vertical convection, especially during the warm months. Nutrient recycling by upwelling was minimal, and consequently plankton production was very low. Foraminiferal production would have been further decreased during the episodically lowered salinities of Arctic deglacial episodes (*G. quinqueloba* is one of the rare species adapted to low salinities).

The boundary between units II and I records another climatic threshold. The disappearance of *G. egelida* and decrease in proportion of right-coiling *G. pachyderma* indicates that water temperatures dropped to present-day levels.

The perennial Arctic ice pack probably originated at that time. The alternation of sediments rich and poor in foraminifera apparently records fluctuations in plankton production related to changes in surface water salinities, nutrients, and the thickness and continuity of the Arctic ice pack. The several stratigraphic levels at which *G. quinqueloba* (which tolerates salinity fluctuations) reaches high frequencies probably record dilution of surface water due to the floating of ice shelves and glacial ice sheets previously grounded on Arctic continental shelves and increased river runoff (*19, 20, 24*) during sea-level rises associated with abortive deglaciations at high latitudes (*13, 33*).

Conclusion

During most of the time of accumulation of unit III between about 4.5 and 2.5 million years ago, the Arctic Ocean basin was a relatively isolated water mass with no exchange with the Pacific and only limited exchange with the North Atlantic. Clark (*34*) has repeatedly asserted that the Arctic Ocean has been covered continuously with perennial ice from middle Cenozoic time to the present and that the ice cover was much thicker during the deposition of the foram-poor beds than it is today. Now the ice attains thicknesses of 3 to 4 m at the end of winter, decreasing to about 2 to 3 m in summer (*35*). Field observations and theoretical calculations indicate that sea ice reaches an equilibrium thickness at about 4 m (*36*). Furthermore, evidence exists for much drier climates during glacial episodes in the north polar region as a direct consequence of reduced snowfall, increased continentality of land areas broadened by lowered sea level (*33*), and reduced moisture when ice covered extensive land and ocean areas. Moreover, the evidence of intense vertical mixing and relatively high biological production precludes the existence of perennial ice during the deposition of unit III, although there is strong evidence for very cold surface water during this time of elevated CCL. Recently discovered calcareous nannofossils in unit III sediments as well as in foram-poor zones and in transition sediments between foram-poor and foram-rich zones also preclude the existence of a perennial ice cover during the deposition of these sediments (*37*) and strongly support the interpretation of Herman (*19, 20, 24*) concerning the evolution of Arctic oceanic climate during the last 5 million years.

The occurrence of ice-rafted sand grains in unit III sediments indicates that glaciers developed in high latitudes before 4.5 million years ago (*22*). The earliest glacial sediments in the Norwegian-Greenland Sea were estimated to be approximately 3 million years old by correlating these sequences with lower latitude North Atlantic climatic events (*38*). As global temperatures were slightly higher in the early Pliocene (before 2.5 million years) than later (*32*), the absence of subpolar solution-susceptible *G. egelida* and *G. quinqueloba* from cores raised in water depths greater than 2400 m is probably due to their dissolution during a time of elevated CCL.

Unit II records a drastically altered oceanographic regime that developed shortly after the elevation of the Isthmus of Panama and the inception of a more vigorous Gulf Stream. The development of salinity-density stratification may have been associated with a warming pulse superimposed upon the late Pliocene cooling trend, suggesting that stratification was not caused by the initiation of a perennial cover of sea ice and also that the inception of stratification did not immediately result in the development of perennial ice pack. The increasing inputs of low-salinity water through the Bering Strait and of salty Atlantic water through the Norwegian Sea seem quantitatively inadequate and probably too gradual to account for the inception of a density stratification in the Arctic basin, but together with the large inflow from Arctic rivers, they may have constituted necessary preconditions that led to density stratification after a triggering event. The triggering event was probably deglaciation with consequent massive melting of icebergs and ice shelves after the first major high-latitude continental glacial event (*38*). Although not perennial, a thin ice layer possibly covered the Arctic basin during part of the year and would have helped maintain the density stratification. Formation and melting of seasonal sea ice extending along the coast may have also contributed to a very gradual vertical stratification (*39*).

The reduced surface-water biological production during the Matuyama reversed epoch was probably due to low

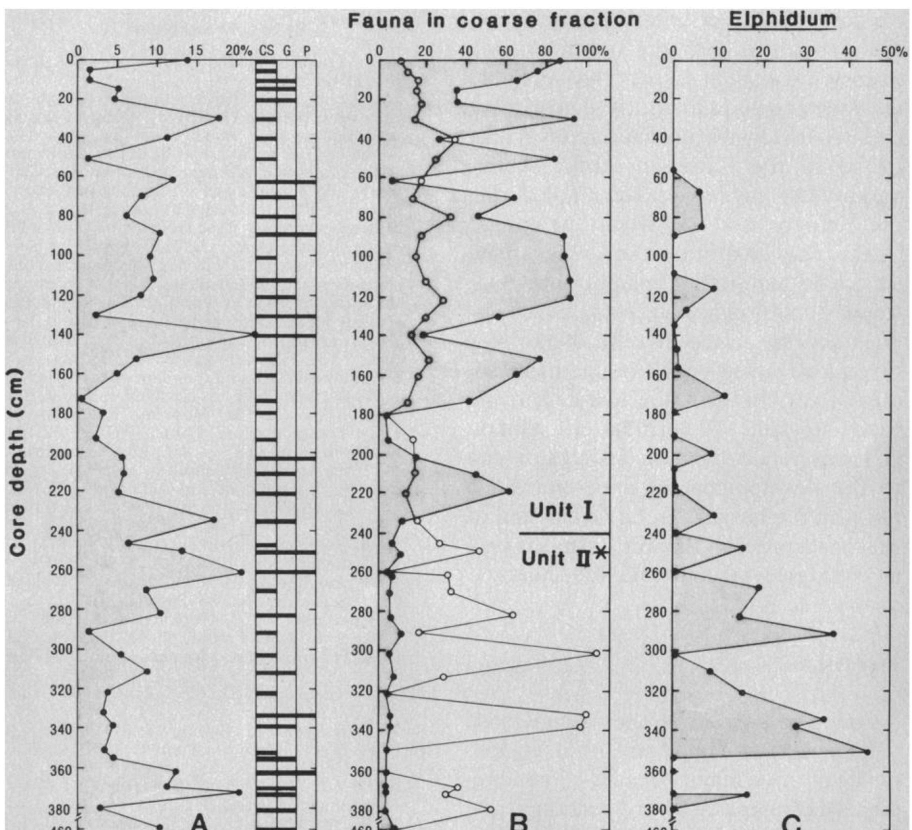

Fig. 4. Core T3-67-3. (A) Percentage of coarse fraction (> 62 μm). *CS*, coarse sand; *G*, granules; *P*, pebbles. (B) Percentage of microfauna in the coarse fraction (> 62 μm). Shaded areas are microfauna; white areas are clastics; values are indicated at the top of the diagram. (○) Percentage of dextral *Globigerina pachyderma* of the total *G. pachyderma* population; values are indicated on the abscissa at the bottom of the diagram. (*) Low-latitude planktonic foraminifers. (C) Percentage of *Elphidium* spp. out of the total benthonic foraminiferal fauna. Core depth in centimeters. [Modified from Herman (*19*)]

availability of nutrients and to decreased salinity, to which very few open ocean planktonic foraminifera are adapted. Density stratification was most pronounced during summer and early fall when ice melting and river runoff are most intense and coincide with the plankton production seasons.

Linked with the continued late Pleistocene global refrigeration trend, another major climatic threshold was crossed with the inception of a perennial sea-ice cover about 0.9 to 0.7 million years ago, at the beginning of the period of deposition of unit I; this coincided with the initiation of a pattern of frequent glacial-deglacial cycles at middle latitudes. The reduction in abundance of *Elphidium* in unit I may reflect less active or less extensive glacial erosion on Arctic continental shelves, perhaps because of the failure of the Arctic Ocean as a moisture source after the appearance of a perennial Arctic ice pack, or because of a more restricted ice shelf drift over the Arctic following the appearance of a perennial ice cover.

Pliocene as well as early and middle Pleistocene sediments exposed around the shores of the Arctic basin should contain records of climatic events that are compatible with the oceanographic history postulated here. Two possible examples come to mind: (i) the early but undated extensive glaciations of Banks Island in the Canadian Arctic Archipelago (*40*) may have taken place during the time of unit II, when the Arctic Ocean was cold but lacked a perennial ice cover; and (ii) the first appearance of steppe-tundra plants, insects, and mammals shortly before the end of the Matuyama reversed epoch in sediments of the Ol'yor Suite of the lower Kolyma River lowland of northeastern Siberia (*41*) may reflect climatic desiccation due to the development of a perennial ice pack on the nearby Arctic Ocean and of seasonal sea ice in subarctic seas, as well as of extensive continental ice sheets.

Discussion

Sediment cores from the Arctic Ocean yield significant faunal and lithologic evidence of three major oceanic-climatic regimes during the last 4 or 5 million years. The evolution of these regimes appears to have been linked to major global climatic, hydrologic, and tectonic events.

The record begins near the time of a major global cooling phase about 5 million years ago, marked by the latest large expansion of the East Antarctic ice sheet and by a concomitant eustatic sea level drop. The Arctic Ocean of this time was cold but free from perennial sea ice. This regime, which continued through the time of the opening of the Bering Strait, the emergence of the Isthmus of Panama, and a reorganization of ocean circulation about 3.5 million years ago, was followed by a sharp temperature decline approximately 3 million years ago (*38*).

A climatic threshold was crossed in the Arctic Ocean about 2.5 million years ago with the development of sharp density-salinity stratification. Although density stratification may be a precondition for the establishment of perennial sea ice, active ice-rafting and dominance of subpolar planktonic foraminifera suggest that there was no perennial ice cover during the period of the second regime between 2.5 and 0.7 million years ago.

Another oceanic-climatic threshold was crossed approximately 0.7 million years ago with the inception of a perennial sea-ice cover. This event marks the period of deposition of sediments representing the third and most recent climatic-oceanic regime (*42*).

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