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20. We thank J. S. Olson, W. R. Emanuel, and P. A. Delcourt for discussions and reviews. We also thank R. L. Burgess for providing forest inventory maps. This research was supported by the National Science Foundation's Ecosystem Studies Program under interagency agreement DEB 77-26722 with the U.S. Department of Energy under contract W-7405-eng-26 with Union Carbide Corporation. This is Environmental Sciences Division, Oak Ridge National Laboratory publication No. 1586.

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Episodic Ice-Free Arctic Ocean in Pliocene and Pleistocene Time: Calcareous Nannofossil Evidence

Abstract. *Today's ice cover (2 to 4 meters thick) over the Arctic Ocean provides a shadow that prevents coccolithophorids (photosynthetic, planktonic algae) from living there. Sparse, low-diversity, but indigenous coccolith assemblages in late Pliocene to mid-Pleistocene (but not Holocene) sediments imply deep penetrating warm currents or an ice-free Arctic Ocean, or both, as those layers were being deposited.*

The climatic history of the Arctic has been a matter of debate ever since the study of its sediments commenced. The early Soviet investigators (*1*), using "radium distribution," estimated that the rates of sedimentation were ~ 1.2 to 2 cm per 10^3 years and interpreted the uppermost foraminiferal-silty layer (10 to 15 cm thick), which covers vast areas of the sea floor, as representing postglacial deposits and the underlying foraminifera-poor beds as representing colder, glacial sediments (*1*). However, uranium series isotope dates (*2*) and the magnetic stratigraphy of Lomonosov Ridge and Alpha Cordillera cores (*3, 4*) indicate that the sedimentation rates are only 1 to 3 mm per 10^3 years. Herman (*5, 6*) has argued that the "foram-poor" layers deposited intermittently during the Brunhes magnetic epoch and throughout most of the Matuyama epoch represent milder periods than those of today, possibly seasonally ice-free intervals. Clark (*7*), on the other hand, has held that the Arctic has been covered continuously with perennial sea ice from middle Cenozoic time to the present, and that the foram-poor layers were not typical of intervals milder than the present but actually were laid down during times when the ice cover was thicker than today's, which ranges from 3 to 4 m at winter's end to 2 to 3 m at summer's end (*8*).

Field observations and theoretical calculations indicate that sea ice reaches an equilibrium thickness at about 4 m (*9*). Furthermore, evidence exists for much drier climates during the peaks of glacial periods, probably due to a sharp drop in evaporation, reduced snowfall, and reduced moisture when ice covered extensive land and ocean (*10*), precluding the existence of a thicker ice cover than today's.

We report here on the discovery of calcareous nannofossils (skeletal remains of planktonic unicellular photosynthetic golden brown algae) in sedimentary cores from the crest and flank provinces of the Alpha Cordillera raised by Lamont-Doherty Geophysical Observatory (LDGO) scientists, on drifting ice platforms (Table 1 and Fig. 1). This discovery supports the hypothesis of an episodic warmer, possibly ice-free Arctic Ocean. Foraminiferal data and magnetic stratigraphy have been published (*5, 6, 11*) for most cores. Within the time interval of $\sim 4.5 \times 10^6$ years, recorded in the longest core, three major climatic regimes are recognized, represented here by climatic units I, II, and III (Fig. 1). Thirty-one samples taken from eight cores were examined, six of which contained nannofossils (Fig. 1); these samples were selected from core tops and from downcore levels representative of the three climatic regimes. The earliest unit (III) consists of fairly well sorted manganese micronodule–bearing red clays with small but significant amounts of ice-rafted minerals (*12*). The planktonic foraminifera are dominated by polar, left-coiling *Globigerina pachyderma* complex, some of which are corroded. Benthonic foraminifera are represented by deep-water elements (*5, 6*). Neither coccoliths nor discoasters were found in these red clays. The boundary between units II and III coincides with the Gauss-Matuyama boundary (*6, 11*) (Fig. 1) and is defined by lithological and faunal changes. The change from "red clays" to tan silts with abundant coarse, ice-rafted debris is accompanied by faunal change. The planktonic foraminiferal fauna is dominated by the extant, solution-susceptible *Globigerina egelida* and *G. quinqueloba*, which constitute up to 99 percent of the fauna of the shallower cores (< 2400 m). Today, *G. egelida* inhabits the Labrador Sea during summer and the North Atlantic slope water in winter (*13*). *Elphidium*, endemic to continental shelves, constitutes up to 50 percent of the benthonic foraminiferal fauna, further evidence of the large-scale ice-rafting during the Matuyama. We believe that these changes $\sim 2.4 \times 10^6$ years ago record a drastic alteration in the oceanographic regime, namely, the initiation of density stratification, a precondition for the formation of sea ice.

One specimen each of *Dictyococcites minutus*, a small cosmopolitan species ranging from Eocene to Pleistocene, and *Discoaster woodringi*, a generalized Eocene to Pliocene representative of the thermophilic discoasters, were found in core T3-67-9 at 238 to 239 cm. They come from the same level in which warm-water planktonic foraminifera were found (*5, 6, 11*) and probably represent Tertiary forms ice-rafted along with *Elphidium* spp. from shallow-water outcrops by drifting ice. The sediments of unit II were deposited during the Matuyama epoch, a time of low global temperatures, milder than those of the following Brunhes epoch (*5, 6, 11, 14*). The boundary between units I and II, defined by both faunal and lithological changes, occurs near the Brunhes-Matuyama boundary (Fig. 1). Five of the six nannofossiliferous samples are within unit I. Another climatic threshold was crossed about 0.9×10^6 years ago when perennial sea-ice cover developed over the Arctic Ocean, as indicated by the first occurrence of a "*G. pachyderma*-rich" layer similar to that being deposited today on the floor of the Arctic basin. Brunhes sediments are composed of alternating foram-rich and foram-poor layers. We interpret the foram-rich layers as representing conditions similar to those prevailing today (perennial sea-ice cover) and the foram-poor layers as indicative of short, mild, possibly seasonally ice-free, lower salinity intervals, comparable to those of the Matuyama epoch. The planktonic fauna of unit I is dominated by the polar left-coiling *G. pachyderma* complex. However, *G. quinqueloba*, which is capable of withstanding low salinities, attains high frequencies near several of the boundaries between foram-rich and foram-poor layers. Benthonic foraminifers are varied, and ice-rafted debris is scattered throughout Brunhes sediments (*6, 11*).

Coccoliths occur very sparsely ($\simeq 1$ per 10^4 silt-size grains) in five foram-poor layers and in one foram-rich sample transitionally above a foram-poor bed (Fig.

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Table 1. Locations, depths, and lengths of cores. For an index map, see (*6*).

Core	Latitude	Longitude	Depth (m)	Length (cm)
Dst A2	83°52′N	168°12′W	1521	206
Dst A4	84°21′N	168°49′W	2041	116
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

1). They were not found in foram-rich (ice-covered) surface sediments. Four of the five coccolith-containing samples from this interval [Dst A2 (39 to 40 cm), T3-67-3 (112 to 113 cm), T3-67-9 (60 cm), and T3-67-2 (3 to 4 cm)] contain the extant Pleistocene guide fossil *Gephyrocapsa carribeanica*, one of the most cold-tolerant and cosmopolitan species of the Pleistocene *Gephyrocapsa* complex (*15*). The youngest coccolith assemblage occurs in core T3-67-2 (3 to 4 cm). The upper Pleistocene is missing in this case, so that the sample is mid-Brunhes in age (*16*). This is the only sample that contains the subarctic *Coccolithus neohelis*, the temperate-subarctic *C. pelagicus*, and the cosmopolitan *Cyclococcolithina leptopora*. Samples Dst A2 (39 to 40 cm), Dst A2 (45 to 46 cm), and T3-67-3 (112 to 113 cm) also contain very small (< 2 μm) unidentified elliptical placoliths. Two of the samples [Dst A2 (39 to 40 cm) and T3-67-9 (60 to 61 cm)] also contain representatives of the *Dictyococcites minutus* complex [*D. minutus* and similar small (3 to 4 μm) placoliths (*17*)]. The published stratigraphic range of the *D. minutus* complex is early Eocene through Pliocene (*17*), but Worsley (*18*) noted similar forms in the north Pacific off Kamchatka in sediments of late Pliocene age. Therefore, these cold-tolerant forms might have persisted into the Pleistocene in polar seas where they have not as yet been searched for. Sample Dst A2 (45 to 46 cm), only 6 cm below a sample with Pleistocene calcareous nannofossils, contains obviously displaced early- to mid-Cenozoic *Reticulofenestra bisecta* and early Cenozoic *Chiasmolithus* sp., as well as the late Cretaceous *Broinsonia* sp. in Brunhes sediments. As it contains no exclusively Pleistocene coccoliths, ice-rafting of older shelf sediments is the likely source of the nannoflora, as all are known from higher latitudes (*18*).

The discovery of sparse coccoliths in Arctic basin deposits and in late Pliocene and Pleistocene sediments and their absence from Recent sediments provides new support for Herman's hypothesis (*5, 6, 11*) of deeper penetration of low-latitude warm currents into the Arctic or of an ice-free Arctic, or both, during periods represented by the foram-poor zones. As these calcareous algae require sunlight to photosynthesize their food, a thick ice cover [such as exists today or thicker, as proposed by Clark (*7*)] would have precluded their survival in the Arctic Ocean. The ecologic tolerance of living coccolithophorids suggests that sunlight, temperature, and salinity are the most important factors controlling their distribution, and that these three parameters covary with latitude (*15, 19, 20*). However, the standing crop in the north Pacific subarctic province north of 50° (*20*) can be higher by as much as an order of magnitude than for any other province. The occurrence of large populations of *Coccolithus pelagicus, Cyclococcolithina leptopora*, and *Emiliania huxleyi* (*19*) in core-top sediment samples in the Norwegian Sea north of the Arctic Circle suggests that an appreciable fraction of high-latitude standing crops can be preserved in underlying sediments. The large populations are attributed to high nutrient levels produced by upwelling in these two areas (*19, 20*); light availability, and not temperature or salinity, is probably the controlling factor in high-latitude coccolith distribution. The low surface salinity (< 32 per mil) and temperature (< 5°C) of the subarctic Pacific and Norwegian Sea north of the Arctic Circle, where these species have been found in great abundance in both the water column and surface sediments, further substantiate this contention. Therefore, although nannofossil species diversity decreases with latitude, populations do not and may in fact increase until very large, nearly monospecific populations are attained north of the polar front. In view of this, only light remains to limit the distribution of these hardy forms, either in the form of Arctic night (which seasonally limits populations) or a perennial sea-ice shadow (which totally limits them). It is evident that overall coccolith accumulation has been exceedingly low and irregular throughout the Brunhes epoch. However, our success rate in finding them (6/31 or ≃ 20 percent) suggests that future searching will probably reveal more occurrences. Furthermore, as corrosive deeper waters completely destroy individually settling coccoliths (*20*), the four indigenous assemblages we observed within the Brunhes interval must either have been rapidly transported from surface-water to the sediment-water interface by fast-settling fecal pellets (*20*) or have been ice-rafted into the area as constituents of larger sediment particles

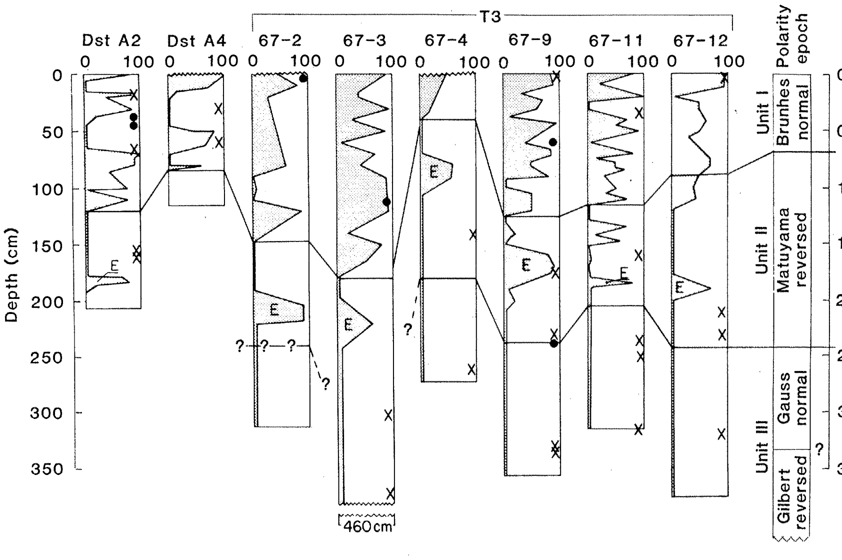

Fig. 1. Nannofossils found in eight cores. Shaded areas represent the percentages of the microfauna, and white areas represent the clastic material in the coarse fraction (< 63 μm); X, coccoliths looked for and not found; ●, coccoliths found; *E, Globigerina egelida* zone. Polarity epochs and absolute time scale plotted on right margin are modified from (*4*). Core depths are given on the left margin.

gouged from Arctic Ocean shelf strata (*21*). We speculate that coccoliths may have accumulated relatively rapidly during intense blooms accompanying short warming events. Without bioturbation, the stratigraphic record of a recurring series of such events would resemble a varved sequence with each of the coccolith-rich layers being perhaps a fraction of a millimeter thick. However, bioturbation by bottom-dwelling organisms [perhaps to a depth of 30 cm subbottom (*22*)] would mix the thin coccolith-rich layer with thick sub- and superjacent coccolith-free layers, thereby greatly diluting the observed coccolith abundances and defocusing the stratigraphic record to a resolution of perhaps 50,000 years. The occurrence of rare specimens in transition zones, between the foram-rich and foram-poor layers in cores T3-67-2 and T3-67-3, is attributed to vertical mixing in sediments by burrowing organisms and bottom currents. If these results are representative of Arctic sediments as a whole, the strong possibility exists that low-diversity populations of coccoliths have sporadically invaded the Arctic Ocean throughout the Cenozoic. A detailed study of these populations will provide a valuable tool with which to unravel the complex paleoclimatic history of the Arctic.

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Late Wisconsin Climate of Northern Florida and the Origin of Species-Rich Deciduous Forest

Abstract. Species-rich mesic forest covered northern Florida as early as 14,000 radiocarbon years before present. It probably originated in deciduous tree populations already present locally in conifer forest between 24,000 and 18,600 years before present. The cold, dry Late Wisconsin climate ended before 14,600 years before present. A transitional warm, dry phase preceded a precipitation increase at 14,000 years before present.

The number of long pollen records from middle and low latitudes is still insufficient for validation of paleoclimatic reconstructions derived from CLIMAP data and other climate-simulation models (*1*). In the southeastern United States, several pollen sites (*2*) reflect conditions much colder and drier than at present during the Late Wisconsin "equilibrium" climate about 18,000 radiocarbon years before present (B.P.) rather than the wetter midsummer conditions simulated (*1*). At White Pond, South Carolina (*3*) (Fig. 1), boreal coniferous forest was replaced by mesic broad-leaved forest at 12,800 years B.P. At Lake Annie in southern Florida, however, neither boreal conifers nor broad-leaved forest is recorded; instead, the flora indicates a dry but not necessarily cold climate after 37,000 years B.P. (*4*). It was desirable to study a geographically intermediate site to determine more closely the southern limit reached by boreal conifers, the place and time of origin of the mesic broad-leaved forest, and the climatic history of the Florida peninsula.

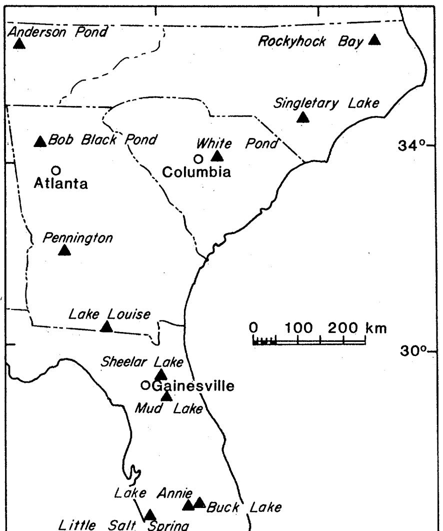

Fig. 1. Location of sites referred to in the text.

Few of the many limestone sink lakes in Florida and southern Georgia (Fig. 1) (*5*) have long records of uninterrupted sedimentation. The relatively shallow modern lakes seem to have been dry before 8500 years B.P. (*6*), because the water level in the main Floridan aquifer in Ocala Limestone was lower during Late Wisconsin glaciation. In the Holocene, the lakes were again flooded as the water table rose. At Buck Lake, shallow-water sediments rich in *Brasenia* (water lily) seeds dated to 8270 ± 50 years B.P. (sample QL-1172) overlie a sandy bottom 2040 cm below the modern lake surface. At Little Salt Spring (*7*), the water level was 26 m below the present spring surface 12,000 years ago. Thus lake muds older than 8500 years B.P. may be found only in sink lakes at least 20 m deep controlled by the Floridan aquifer.

Sheelar Lake (*8*) near Gainesville in