Biostratigraphy and late Cenozoic paleoceanography of the Arctic Ocean: Foraminiferal, lithostratigraphic, and isotopic evidence

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ABSTRACT

Detailed studies of benthonic foraminifera, stable isotopes, and lithofacies in cores from the southeastern Alpha Ridge, central Arctic Ocean, reveal some new aspects of Arctic Ocean paleoceanography. High ratios of benthonic to planktonic foraminifera are found in most of the Quaternary sediment units, and ratios of 1:1 appear to characterize the Arctic deep-water sediments. Benthonic foraminifera in the carbonate mud unit M show a succession of calcareous species reflecting increased influx of Norwegian Sea bottom water to the Arctic Ocean during the past 0.4 m.y. Foraminiferal and lithological data indicate less-uniform sedimentation during a warmer interval from 0.4 to 0.6 Ma, when most of the silty lutite unit L was deposited at the CESAR site. Lower Pleistocene units J to I contain less limestone and more dolomite, and they contain a uniform faunal assemblage with low numbers of calcareous foraminifera. Upper Pliocene units H to AB contain rare limestone and relatively large amounts of dolomite and quartz sand. Middle to upper Pliocene units AB to A3 are marked by abundant sand-sized ferromanganese-coated particles, which in many cases have a silt nucleus; hence, much of the coarse sand in these units does not indicate increased ice rafting. The Pliocene sediments mostly contain a low-diversity assemblage of agglutinated foraminifera, but a mixed calcareous/arenaceous fauna occurs in a short interval above the Matuyama-Gauss boundary (2.4 Ma).

Stable-isotopic curves occur within sequences which broadly correspond to stages 1-9 of the global record; below stage 9, the record is discontinuous. Strong vertical mixing apparently prevailed during most of the Pliocene and early Pleistocene, then decreased during the past 0.4 m.y. owing to damping by a perennial ice cover. Isotopic and foraminiferal data, however, suggest that an interval of perennial sea ice also occurred during the late Pliocene at the time of the earliest glacial event recorded in the North Atlantic.

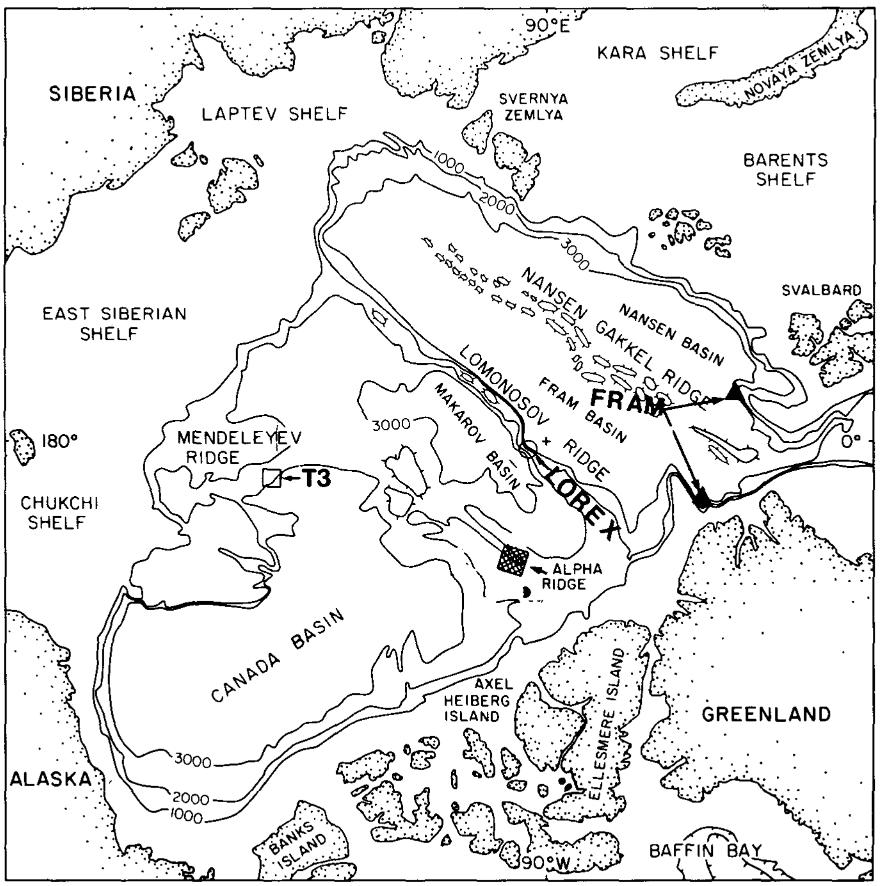

Figure 1A. Location map of the Arctic Ocean and important core sites.

Additional material for this article (tables) may be obtained free of charge by requesting Supplementary Data 8902 from the GSA Documents Secretary.

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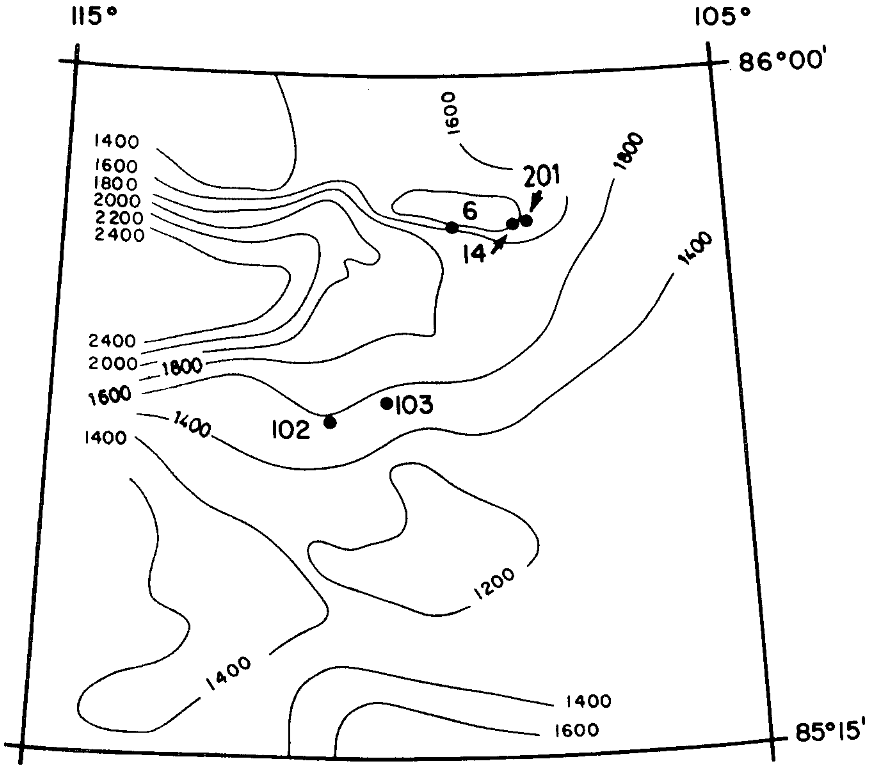


Figure 1B. Detailed bathymetry (in meters) of the CESAR study area (cross-hatched in 1A). The T-3 experiment covered much more area than is shown in the enclosed square in A—the area shown is that from which come some of the cores we discuss.

INTRODUCTION

The Arctic Ocean is a mediterranean polar sea which is presently covered by about 13 million km^2 of quasi-stable ice 3 m thick. Seasonal and annual changes in the ratio of polar sea ice to open water profoundly influence Northern Hemisphere weather conditions (Crowley, 1984; Hills, 1983). Several studies of Arctic Ocean sediment cores (Herman, 1974; Herman and O'Neill, 1975; Herman and Hopkins, 1980; Clark, 1982; Zahn and others, 1985; Boyd and others, 1984; Markussen and others, 1985) therefore have aimed at determining the relation between the paleoceanographic history of the Arctic Ocean and Northern Hemisphere glaciations. Data in this paper refine and modify some earlier interpretations, and one core provides a sufficiently long record to compare with the North Atlantic Deep Sea Drilling Project (DSDP) site 552A for the late Pliocene.

Recent studies have used oxygen isotope data from planktonic foraminifera (Zahn and others, 1985; Duplessy and others, 1984; Morris and Clark, 1986) or time-series analysis of carbonate cycles (Boyd and others, 1984) as a basis for paleoceanographic models. Results originally led to apparently conflicting interpretations: cores from the Eurasian Basin (Markussen and others, 1985) showed an isotope stratigraphy which appeared to be synchronous with that of the eastern North Atlantic Ocean during the past approximately 50,000 yr. Cores from Alpha Ridge showed cyclical changes in carbonate (Boyd and others, 1984), palynofacies, and stable isotopes (Mudie and Jackson, 1985), with a predominant periodicity of 100 or 400 ka (thousand years) and with a minor 41-ka component during the past 0.7 m.y. Isotope data for a core from the Canada Basin abyssal plain (Duplessy and others, 1984) revealed fluctuating spectral power frequencies which apparently reflected variable resolution due to changes in sedimentation rates during the past 0.3 m.y.

Various explanations were proposed to account for these conflicting data, such as regional variations in surface water temperature and salinity, uncertain stratigraphic correlation between regions of the Arctic Ocean, and differences in methods used for dating and definition of units. New data, however, clearly show that different parts of the Arctic Ocean are characterized by different sedimentation regimes (Macko and Aksu, 1986; Marquard and Clark, 1987).

To avoid some of the problems referred to above, several new approaches were used in this study. (1) Cores were selected from basin and ridge sites within a 50 × 25 km area of the Alpha Ridge (Fig. 1) for which acoustistratigraphic data allow regional mapping of surficial lithofacies; (2) high-resolution quantitative studies were made of benthonic foraminifera to delimit stratigraphic range zones; (3) stable isotopes were measured for benthonic foraminifera as well as planktonic forms; and (4) mineralogical studies were made of the coarse sediment fraction (greater than 63 μm) to distinguish between biogenic and clastic components, as only the latter truly reflects amounts and sources of ice-rafted detritus (IRD).

The purposes of this paper are to document our lithological and benthonic foraminiferal studies in detail, to provide interpretations of regional biofacies variations, and to discuss the main features of our stable-isotope and biostratigraphic data in terms of paleoenvironmental changes and the late Cenozoic history of the Arctic Ocean ice cover.

MATERIAL AND METHODS

Gravity cores and piston cores were collected from the Alpha Ridge during occupation of the Canadian Expedition to Study the Alpha Ridge (CESAR) ice camp in 1983 (Mudie and Jackson, 1985). Field and laboratory methods of handling the cores are given by Mudie and Blasco (1985). The two longest gravity cores (CESAR cores 102 and 103) from the graben floor were selected for detailed comparison with the longest gravity core (CESAR core 201) and a piston core (CESAR core 14) from the plateau on the crest of the eastern Alpha Ridge. High-resolution acoustic profiles were obtained at or near these core sites by means of a 3.5-kHz sounder and a 40-cu.-in. air gun. Sample volumes of 10 cm^3 were taken at 1-cm intervals in the gravity cores and down to 70 cm in core 14; the rest of core 14 was sampled at 2.5-cm intervals. Sediment was wet sieved through a 0.5-mm screen (no. 35 mesh) to remove coarse sediment and washed on a 0.063-mm screen (no. 230 mesh) to retain the foraminifera and sand fraction. Samples from cores 102 and 201 were examined for benthonic foraminifera in a liquid suspension (alcohol and water), as no samples had large amounts of sand. The wet samples were split using a special wet splitter (Thomas, 1985), so that no more than 1,000 individuals were present in any one subsample. Samples from core 14 were dried, and an "Otto" microsplitter was used to split them for microfossil studies. Stable-isotope measurements were made on the planktonic foraminifer *Neo-*

globoquadrina pachyderma(s) in the size range 150–250 μm and on the benthonic species *Oridorsalis umbonatus*. Delta $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios were determined using a Cambridge 602D mass spectrometer with an internal reproducibility of 0.05‰. Methods are detailed in Scott and others (1986a). Laboratory standard is Carrara Marble calibrated to universal PDB standard for us by N. J. Shackleton (Cambridge University).

This paper contains no taxonomic descriptions because the critical species are illustrated in Lagoe (1977). D. B. Scott and G. Vilks (unpub. data) have made a detailed taxonomic study of Arctic surface material that justifies the following combinations: *S. horvathi* = *S. horvathi* plus *Epistominella* spp. of Lagoe, *E. tumidulus* = *E. tumidulus horvathi* in Lagoe, *R. charlottensis* = *R. charlottensis* plus *Ceratobulimina arctica* in Lagoe, *O. umbonatus* = *Eponides tener* in Lagoe, and *B. hensoni* = *B. elegantissima hensoni* in Lagoe.

RESULTS

Bottom Topography

Cores 102 and 103 are from the south side of the Alpha Ridge graben at water depths of 1,555 and 1,585 m, respectively. Bottom relief at these sites is highly variable (Fig. 2A and 2B), owing to the presence of both large- (100 m high) and small-scale (<5 m) hummocky mounds of unconsolidated sediment. The small hummocks lack coherent internal reflectors (Fig. 2B); hence, they are probably mud-flow deposits rather than drift waves. Cores 201 (1,485 m) and 14 (1,370 m) were obtained from a plateau about 4 km wide which surrounds the northern Alpha Ridge crest at depths between ~1,350 and 1,500 m (Fig. 2A). Seismic profiles show conformable, strongly stratified sediments throughout this area. Core 201 is from the middle of a shallow basin, where sharp continuous subsurface reflectors are evident. Core 14 is from the plateau top about 6 km southeast of core 201 (Fig. 2A), where reflectors pinch and swell to enclose parcels of semi-transparent sediment over distances of ~500 m.

The importance of these seismic data is that they show relatively continuous sedimentation in the area for at least the time period investigated herein. Sub-bottom irregularities (for example, Fig. 2B) were formed prior to 0.73 Ma, as cores 102 and 103 have similar late Pleistocene records.

Lithostratigraphy and Age

The four cores obtain similar sequences of lithological units (Fig. 3), which have been dated and correlated using magnetostratigraphic and palynostratigraphic methods (Aksu, 1985a; Mudie, 1985; Aksu and Mudie, 1985; D. B. Scott and K. D. MacKinnon, unpub. data for core 201). Additional chronological control was obtained for core 102. (1) ^{14}C ages were measured by the tandem accelerator micromass method, using *Neogloboquadrina pachyderma*(s) hand picked from the >150 micron fraction at 2–3 and 5–6 cm core depths; (2) an aminostratigraphy was obtained (Macko and Aksu, 1986) from the allo-isoleucine ratios of 10 samples of *N. pachyderma*(s) hand picked from the 125–250 micron size fraction in units M and K. Together, these data firmly establish that the average sedimentation rate is about 1 mm/ka, with maximum rates of 1.5 to 3 mm/ka being possible for some intervals.

The lithostratigraphy of the CESAR cores is described in detail elsewhere (Mudie and Blasco, 1985; Dalrymple and Maas, 1987). Herein, we report only the results of new studies related to the paleoenvironment of the sediment.

Unit M. Unit M is a dark brown mud with one to three sandy carbonate layers. The carbonate layers have been designated as marker beds, PW2, W2, and W3 (Clark and others, 1980); their extensive occurrence in cores from the western Arctic Ocean indicates paleoceanographic events of a regional magnitude, although the number and thickness of the carbonate beds are locally variable (Fig. 3).

On a dry-weight basis, unit M contains about 20%–40% detrital sand and gravel, with limestone rock fragments making up 40%–80% of the gravel fraction (Fig. 4). The sand (5%–20%) is mainly angular quartz and feldspar grains, with V-shaped chatter marks indicating a glaciogenic origin. Most of the carbonate is biogenic and consists of abundant well-preserved foraminiferal tests and variable amounts of calcite fragments. Aragonite is also found as the pteropod *Limicina helicina*, which occurs from the surface to the top of PW2. Unit M lies in the upper Brunhes normal polarity chron (Aksu and Mudie, 1985). Accelerator micromass spectrometer dates provide the following radiocarbon ages for core 102: 31,000 ± 290 yr B.P. for 2–3 cm depth (Beta-12230) and 54,000 ± 1,042 yr B.P. for 5–6 cm depth (Beta-12231).

Unit L. Unit L is a light olive-brown fine sandy mud with a grayish coarse sand lamina at the base (subunit L1 in Fig. 3). Silty mud with biogenic carbonate marks the top of the lithofacies (subunit L5 in Fig. 3), but carbonate is rare or absent in the rest of unit L. In the CESAR cores, the fine structure of unit L is highly variable (Fig. 3). Ridge cores (CESAR 11–15) contain 22 to 27 cm of yellowish silty mud with some gray sandy layers or mottles. In core 14, the sandy subunit L1 is overlain by silt with discontinuous clay laminae, followed by silty mud with two thin sandy laminae containing rare planktonic foraminifera (Fig. 3). In core 201, subunit L1 is overlain by silty mud with three sandy laminae near the base. The lowest two laminae contain common pyrite, Fe-Mn particles, and infilled microfossil fragments; the uppermost lamina also contains rare foraminifera.

Unit L is significantly longer (38–45 cm) in cores 102 and 103 from the Alpha Ridge graben, and more fine structure is present (Fig. 3). Subunit L1 contains rare gravel and foraminifera. This sandy bed is overlain by yellowish silt with gray streaks, small white flecks, and rare rust-colored spots (subunit L2). X-radiographs show silty or fine sandy laminae alternating with thin (1 mm) clay laminae. In core 103, microlaminae are also found near the top of unit L (Fig. 3), but subunit L2 is not repeated in core 102. Subunit L2 is overlain by yellowish mud with gray sandy streaks or mottles (subunit L3), with the mineralogy being similar to the yellowish silt in core 201. In the graben cores, a brown fine sand lamina occurs near the middle of subunit 3, but no coarse sandy laminae are present like those found in the ridge cores.

Unit L contains 20%–30% detrital sand, most of which consists of roughly equal amounts of quartz and feldspar (Fig. 4). The quartz sand is a mixture of well-rounded frosted grains, angular grains with fresh chatter marks, and heavily iron-stained grains, which suggests multiple sources of sand transport for this unit. Hematite and volcanic minerals are also common throughout unit L, suggesting increased input of sediment eroded from volcanic bedrock outcrops on the Alpha Ridge. Large mica flakes are present in some intervals. Carbonate is rare and consists mainly of foraminiferal tests and traces of limestone at the top of the unit. Unit L lies within the lower part of the Brunhes magnetochron.

Units K and J. The brown muds in units K and J are similar to those of unit M in percentage of detrital sand and biogenic carbonate, but they contain 30%–80% quartz or feldspar and less limestone. Dolomite fragments and rock fragments make up most of the gravel fraction. The Brunhes-Matuyama boundary (0.73 Ma) occurs near the top of the carbonate marker bed W1 in unit K. Unit J is lighter brown and has a higher content of coarse sand (>375 μm) than does unit K. It contains the pinkish carbonate marker bed PW1. A short-lived normal polarity excursion at or just below the top of unit J is tentatively correlated with the top of the Jaramillo event, thus providing an age of about 0.91 m.y. for unit J/K boundary (Aksu and Mudie, 1985).

Units I and H. The sandy brown muds of units I and H contain more gravel (mainly dolomite and rock fragments) than do the other lithofacies. The sand contains <10% calcite, and

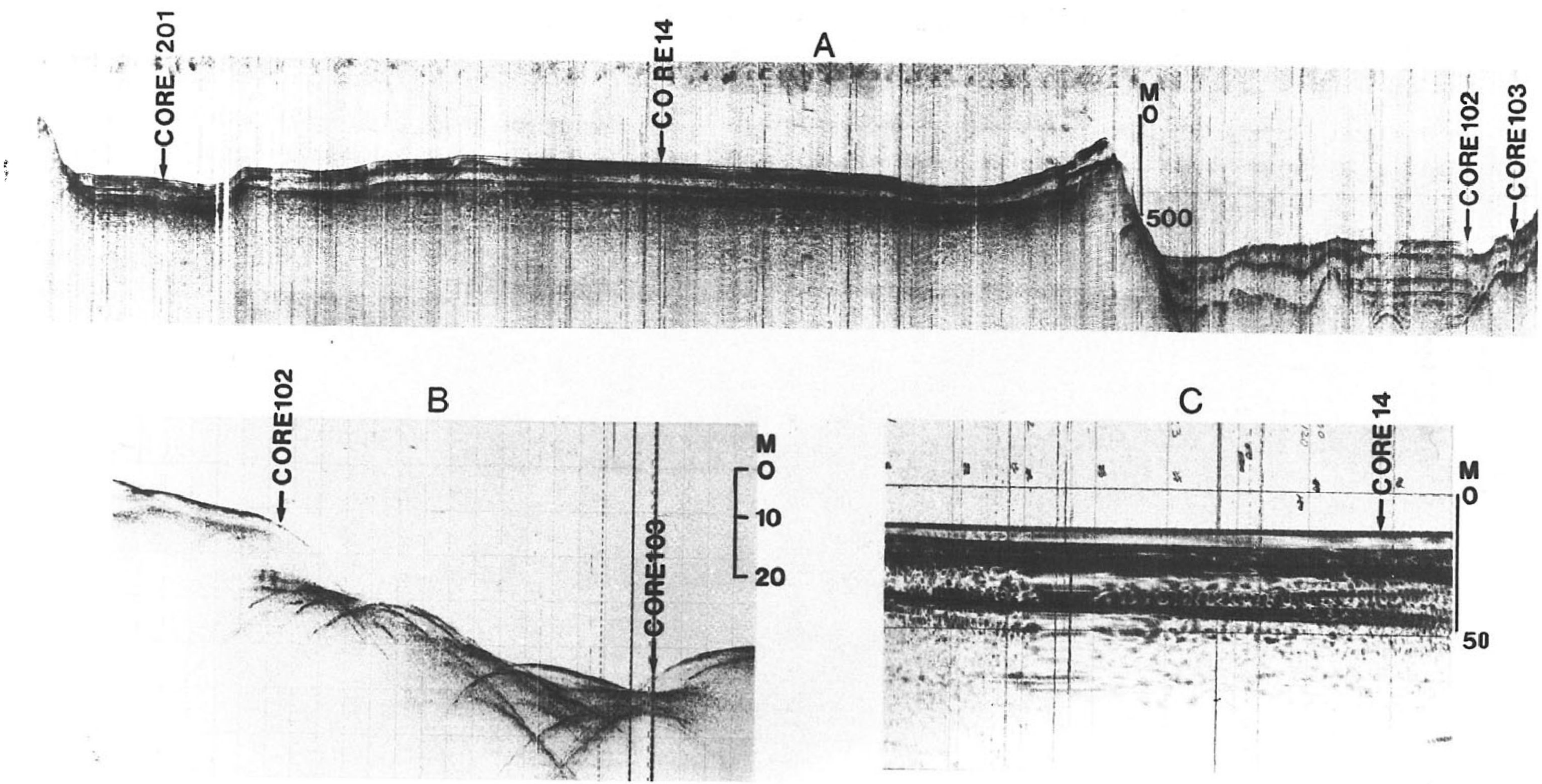


Figure 2. A. Air-gun seismic profile across the northern Alpha Ridge and graben, with the locations of all the cores in this study.
B. 3.5-kHz seismic profile in the graben near cores 102 and 103.
C. 3.5-kHz seismic profile on the Alpha Ridge at the site of core 14.

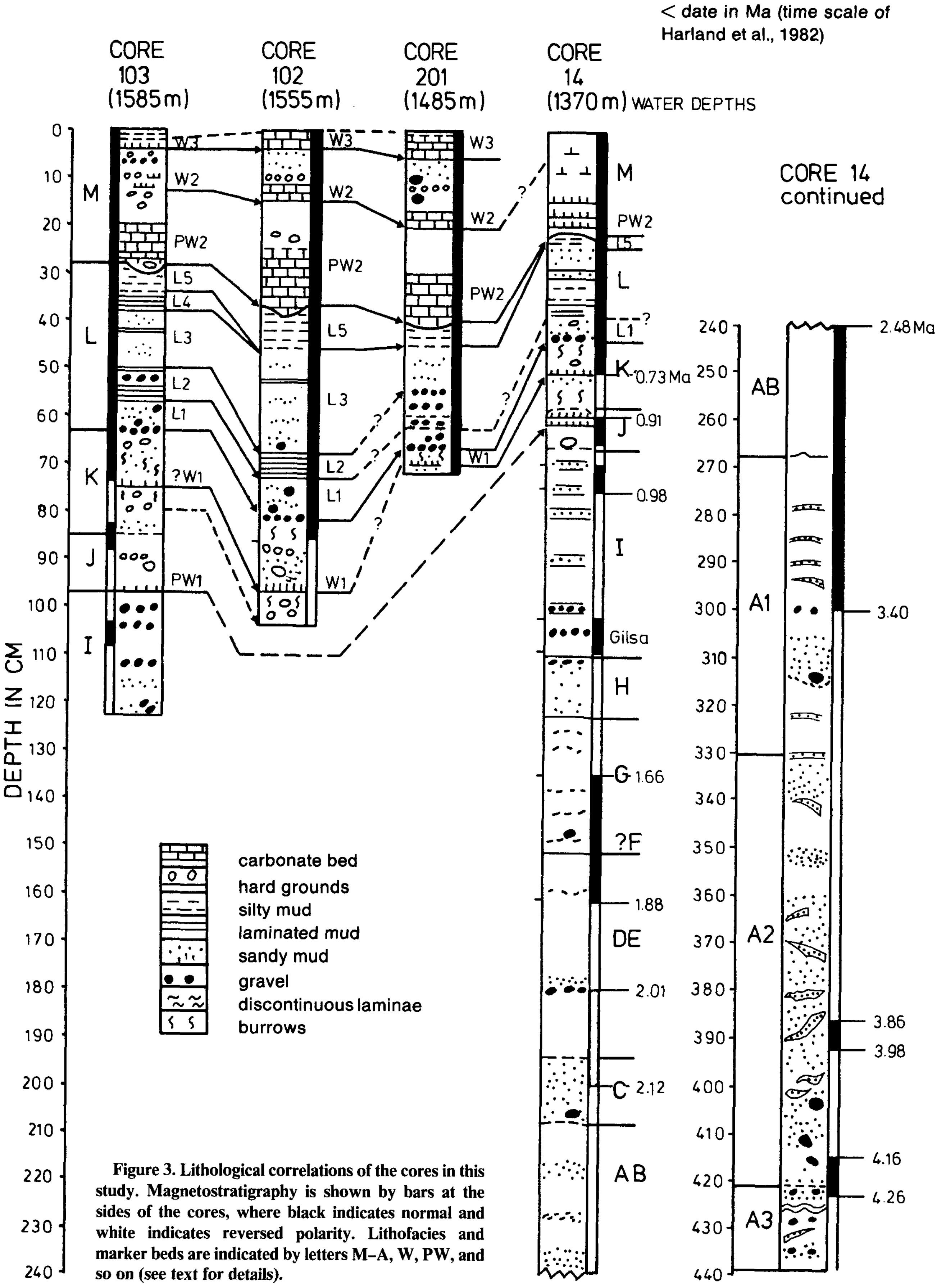


Figure 3. Lithological correlations of the cores in this study. Magnetostratigraphy is shown by bars at the sides of the cores, where black indicates normal and white indicates reversed polarity. Lithofacies and marker beds are indicated by letters M–A, W, PW, and so on (see text for details).

limestone is rare; however, dolomite is common in the coarsest fraction, and therefore, the total carbonate content remains high. In unit I, 5%–20% of the grains are heavily coated with ferromanganese. Unit H is a reddish sandy bed with common hematite and volcanic minerals. A short normal-polarity interval occurs at the top of unit I (Aksu and Mudie, 1985), which probably corresponds to the base of the Jaramillo event (ca. 0.98 Ma). The boundary between units I and H is marked by another normal interval which is correlated with the Gilsa event (1.63–1.64 Ma).

Units G, F, DE, and C. The lithofacies units G, F, DE, and C contain ~10%–20% sand and mottled silty mud layers. Rare gravel- to pebble-sized clasts are present, including dolomite and metamorphic rock fragments. Carbonate content is low and is mostly dolomite, with rare limestone in unit DE. Ferromanganese-coated grains are common. The magnetostratigraphic sequence (Fig. 3) is typical of the Olduvai and Reunion events in the lower Matuyama polarity interval, and it provides an age of ~1.80 m.y. for the gray sandy layer marking unit F and ~2.0 m.y. for unit C.

Unit AB. Unit AB is mainly a mottled brown silty mud with a very low carbonate content. The central portion, however, is faintly banded with yellowish or reddish sandy beds containing calcareous foraminifera. This carbonate sand interval marks the Matuyama-Gauss boundary (2.48 Ma); it also marks the start of a major decrease in detrital quartz, feldspar, and volcanic minerals (Fig. 4) and the occurrence of abundant (>80%) sand-sized ferromanganese particles, most of which have a nucleus of coarse silt or finer sediment.

Units A1, A2, and A3. Units A1, A2, and A3 are dark brown muds with about 20%–30% sand and coarser clasts, including rare gravel- to pebble-sized dropstones. More than 80% of the sand consists of ferromanganese-coated silt or fine sand. Agglutinated foraminifera and large mica flakes make up most of the remaining coarse fraction, with carbonate being present only as rare, poorly preserved (corroded and manganese coated) planktonic foraminifera. The paleomagnetic record shows a polarity reversal in the middle of unit A1 (Fig. 3) which probably marks the Gauss-Gilbert boundary (3.40 Ma).

Benthonic Foraminiferal Stratigraphy

As discussed briefly already, these foraminiferal findings are the first high-resolution benthonic data from the central Arctic Ocean. Unfortunately, because of space limitations, we can present only summary diagrams for each core; complete data tables are available for each core from the Geological Society of America Data Repository.[1]

Core 102. Gravity core 102 (103 cm long) is from the graben floor at 1,555 m water depth. Assemblage A (0–10 cm) shows the highest diversity in the core, being dominated by *Stetsonia horvathi* (60%–70%) along with significant percentages (4%–20%) of *Valvulinera arctica*, *Eponides tumidulus*, *Oridorsalis umbonatus*, and *Buliminella hensoni* and traces of *Robertinoides charlottensis*, *Bolivina arctica*, *Triloculina trihedra*, *Planulina wuellerstorfi*, and *Quinqueloculina* spp. (Fig. 5). In assemblage B (10–26 cm), *V. arctica* drops below significant levels (<1% or absent), and *S. horvathi* becomes more dominant (>80%), whereas other species remain the same. The base of this biofacies is marked by the first occurrence of *E. tumidulus* in significant percentages (that is, >1%). Assemblage C (26–31 cm) records the oldest significant occurrence of *O. umbonatus*, and it includes the youngest peak in the relative abundance of *B. arctica*. Assemblage D (31–37 cm) is marked by high percentages (18%–53%) of *B. arctica*, and the base of this interval is the oldest significant occurrence (>1%) of *B. hensoni*. Assemblage E (37–49 cm) is marked by a small peak of *V. arctica* and a low-diversity fauna dominated by *S. horvathi* and *B. arctica*. Assemblage F (49–80 cm) is characterized by rare foraminifera which are mainly shallow-water species (*Elphidium* spp.) that appear to be transported in subunit L1 (75–80 cm). Planktonics are also rare in this assemblage. Assemblage E abruptly reappears at the top of unit K (81 cm) and continues to the base of the core at 103 cm.

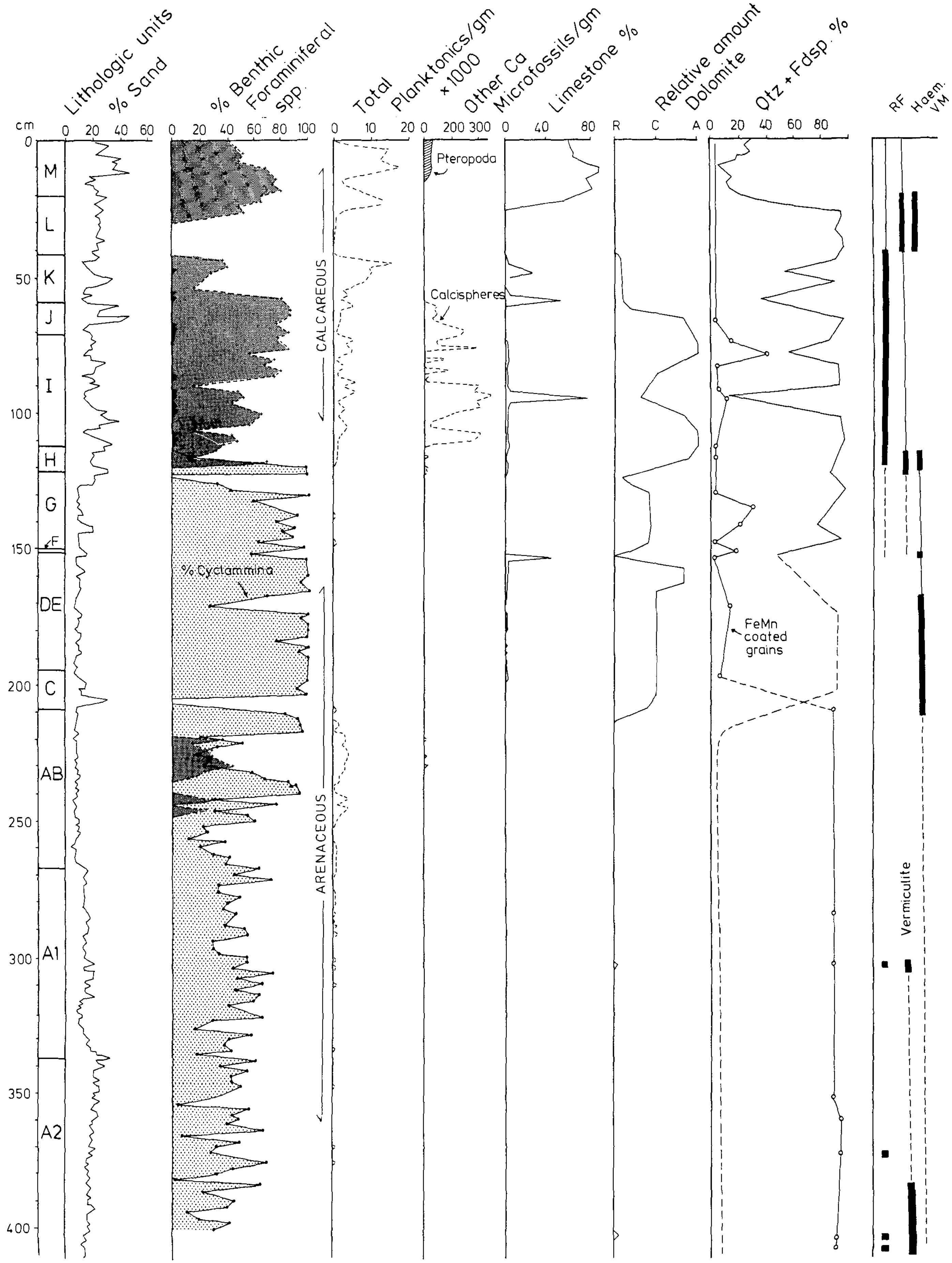
Total numbers of benthonic foraminifera are extremely variable, ranging from 0 to 241,000/10 cm^3. Numbers are generally high in assemblage A (30,000–70,000) but show a major decrease (900–8,000/10 cm^3) at 7–9 cm. High numbers persist from 10 to 46 cm, where they drop below 1,000/10 cm^3, then disappear in a barren section of assemblage F (50–81 cm). Low numbers also occur at the base of unit L, but they rapidly increase at 81 cm and are high (25,000–50,000) in assemblage E except for a short barren interval at 95–97 cm. Aksu (1985b) reported total numbers of benthonics from core 102 at least one order of magnitude lower than those found in our study, resulting in B:P ratios of 1:10 compared to ratios of as high as 3:1 that we observe at selected intervals. This difference may be due to the difficulty of recognizing the small forms, such as *Stetsonia horvathi*, which are easily overlooked.

Core 201. Core 201 is a shorter gravity core (71 cm) from the Alpha Ridge crest at a water depth of 1,485 m. The same foraminiferal assemblages observed in core 102 are present in this core, although assemblage E is truncated at the base (Fig. 6). Assemblage A occurs at 0–10 cm, assemblage B at 10–30 cm, assemblage C at 30–35 cm, assemblage D at 35–38 cm, assemblage E at 38–49 cm, and assemblage F at 49–64 cm, and assemblage E reoccurs from 64 cm to the base of the core. Assemblage E in this core differs in that the *V. arctica* component is not as distinct as in core 102. Assemblage F is also noticeably shorter in this core than in core 102, and assemblage E extends up into the base of unit L.

Total numbers in this core are lower than in core 102, ranging from 0 to 20,000/10 cm^3, but fluctuations in numbers show similar trends. Higher numbers occur from 1–7 cm, from 9–45 cm, and from 64 cm to the base; low numbers occur at 7–9 cm and at 45–50 cm; there is a barren zone at 50–64 cm. The short low-number interval found at the base of core 102 was not penetrated by this core. Planktonics occur in numbers similar to those in core 102, but B:P ratios are lower because the number of benthonics is lower in this core (1:3).

Core 14. Piston core 14 (440 cm) is from the Alpha Ridge at 1,370 m water depth. Although the surface sediment layer was not recovered, the faunas at the top of this core are almost identical to those in the corresponding lithofacies of 102 and 201. Assemblage A occurs from 1 to 10 cm, assemblages B and C at 10–16 cm (*O. umbonatus* and *E. tumidulus* have their first significant occurrences together in this core), assemblage D at 16–20 cm, assemblage E at 20–26 cm, and assemblage F at 26–43 cm, and assemblage E reoccurs from 43 to 54 cm (Fig. 7). A slightly different assemblage, E1, occurs at 54–86 cm, with significant percentages of *B. hensoni* and greatly reduced numbers of *B. arctica*. Planktonics in E1 are so rare that no isotope values could be obtained. Assemblage E reoccurs at 86–94 cm. In the middle of this interval (91 cm), planktonics become sufficiently abundant to obtain isotope values. Foraminiferal assemblage G occurs from 94 to 118 cm; it is marked by the occurrence of *Brizalina pseudopunctata*. Near the base of this assemblage, there is a unique interval in which *Fursenkoina fusiformis* becomes relatively common. Assemblage H occurs at 118–218 cm and is characterized by low numbers of agglutinated species and lack of both calcareous benthonic and planktonic foraminifera. Between

[1]The data tables may be obtained free of charge by requesting Supplementary Data 8902 from the GSA Documents Secretary.



Lithologic units
% Sand
% Benthic Foraminiferal spp.
Total Planktonics/gm ×1000
Other Ca Microfossils/gm
Limestone %
Relative amount Dolomite
Qtz + Fdsp. %
RF
Haem.
VM
cm
M
L
K
J
I
H
G
F
DE
C
AB
A1
A2
CALCAREOUS
ARENACEOUS
% Cyclammina
Pteropoda
Calcispheres
FeMn coated grains
Vermiculite

Figure 4. Summary of main sedimentologic parameters for sand and coarser sediment in CESAR core 14. Relative abundance of dolomite clasts is indicated by rare (R = <5%), common (C = 6%–20%), abundant (A = >20%). RF = metamorphic rock fragments, haem. = hematite grains, VM = volcanic minerals. Note that from 65–90 cm and below 120 cm, planktonics/gm are actual numbers (*not* times 1,000).

219 and 250 cm, there are low numbers of a fauna similar to assemblage D, and a short interval of assemblage H occurs at 235–240 cm. Assemblage H reoccurs at 250 cm and extends to the base of the core.

Total numbers of foraminifera can be divided into two groups (Fig. 7); above 118 cm, numbers vary from 0 to 63,000 individuals/5 cm^3, and below 118 cm, numbers vary from 0 to 109/5 cm^3. In the upper 118 cm, most of the variations in foraminiferal numbers are similar to those in the gravity cores except the 64- to 90-cm interval of lowered benthonics and rare planktonics. The very low numbers in assemblage H do not correspond to any modern or late Pleistocene assemblages in the present Arctic Ocean. The B:P ratios are similar to those in core 102 in the upper units but virtually infinite in the Pliocene except the short interval at 2.4 Ma.

STABLE ISOTOPES

Data for stable isotopes are less complete than for the faunal assemblages because several intervals contain too few specimens for reliable isotope measurements. Delta $^{18}O/^{16}O$ and $^{13}C/^{12}C$ values were obtained for both planktonic and benthonic forms in cores 102 (Fig. 5) and 201 (Fig. 6) and for planktonic forms from core 14 (Fig. 7). The benthonic record (*O. umbonatus*) extends only to 40 cm, below which core depth the species is rare.

Planktonic Oxygen Isotopes—Core 102 and 201

Vertical changes in the isotopic curves are highly compressed, as expected for an area of very low sedimentation (~1 mm/1,000 yr). This compression makes it difficult to resolve the boundaries of paleoclimatic events with a duration of 10 ka (= 1 cm depth) or less, for example, substages within interglacial stage 5. With bioturbation depths of 1 cm or more, fine-scale correlation between cores cannot be expected. The isotope stratigraphy is illustrated by the sequence in core 102 (Fig. 5), where we recognize stage 1 (0–1 cm), stages 2–4 (2–8 cm), stage 5 (8–12 cm), stage 6 (12–15 cm), stage 7 (15–20 cm), stage 8 (20–38 cm), and stage 9 (38–49 cm). Values range from +0.5 to +3.5 ppm. To correlate the oldest stages with certainty, we need detailed dating control for the barren interval of unit L. At present, however, magnetostratigraphic, palynostratigraphic, and aminostratigraphic data (Aksu and Mudie, 1985; Macko and Aksu, 1986) show that the sedimentation rate is about 1 mm/1,000 yr above the Brunhes/Matuyama boundary. The same range of $^{18}O/^{16}O$ values and sequences can generally be observed in equivalent lithofacies of cores 201 and 14, although it should be noted that the top 8 cm of the piston core (core 14) was not recovered.

Although the planktonic isotope stratigraphy for core 102 shows the same general trends as those reported by Aksu (1985b), heavier $^{18}O/^{16}O$ values were found by Aksu (1985b), especially in the upper 30 cm. This may reflect his use of all size ranges of planktonics, including the large specimens. Above 30 cm in core 102, the proportion of specimens greater than 250 μm is relatively high. Larger planktonics, which live deeper in the water column, generally give heavier values (Williams and others, 1981). In addition, bioturbation may add significant noise to the signal. For example, at the stage 1/stage 2 boundary, duplicate analyses of one sample show a $1^0/_{00}$ variation between replicates (Fig. 5). This variation probably reflects bioturbation in an interval where rapid changes are recorded within a short vertical distance. This magnitude of signal mixing may occur at all glacial-interglacial boundaries in cores from the Alpha Ridge, and it highlights the need for continuously spaced sampling to delimit isotopic stages. Even with continuous sampling, however, events of $<1^0/_{00}$ isotopic magnitude in the planktonic record may not be discernible, and signal to noise would increase with greater depths of bioturbational mixing. The general similarity of isotopic values and light/heavy events found in all three cores from the Alpha Ridge, however, indicates that a regional paleoenvironmental signal is recorded despite the high signal:noise ratio.

Benthonic Oxygen Isotopes—Cores 102 and 201

The isotope signal for the benthonic foraminifera (*O. umbonatus*, Figs. 5 and 6) in cores 102 and 201 shows the same general pattern as does the planktonic record except the curves are smoother and the amplitude of change is much lower ($+4.2^0/_{00}$ to $+4.8^0/_{00}$). These records show that essentially synchronous isotopic events are recorded by both the planktonic and benthonic faunas but that fluctuations in the signals for the surface water layer are far greater than those for the more stable bottom waters.

Planktonic Oxygen Isotopes—Core 14

Benthonic foraminifera were not analyzed in core 14 because *O. umbonatus* is common down to only 10 cm. The planktonic isotope stratigraphy from 0–65 cm in core 14 (Fig. 7) essentially corresponds to that of core 102, with the upper 10 cm of this core (W3 carbonate marker) missing. The interval from 65–90 cm contains too few planktonics for isotopic analysis. Samples just above the Pliocene-Pleistocene boundary (91–98 cm) show light oxygen isotopic values (+0.041 to +0.725 ppm), suggesting both melt-water input and higher temperatures. Values obtained from this interval may be artificially light, however, as smaller specimens (>125 μm) were used to obtain sufficient numbers for analysis. Below 98 cm, there were insufficient specimens for analysis except for a wide interval (218–235 cm) where specimens were combined to give an average value of +2.465 ppm for $^{18}O/^{16}O$. This value indicates average conditions slightly colder than at present for an early interval in the late Pliocene and suggests a short period of perennial ice cover.

Carbon Isotopes

The $^{13}C/^{12}C$ ratios for all cores show values which are mostly positive for the planktonics ($+0.5^0/_{00}$ to $1.5^0/_{00}$) and mostly negative for the benthonics ($0^0/_{00}$ to $-1.5^0/_{00}$), but the trends track their oxygen isotopic counterparts. This difference in ranges of carbon values between benthonics and planktonics is typical for all deep-sea areas in which surface waters are depleted in ^{12}C owing to preferential uptake of the lighter isotope during primary production. The $^{13}C/^{12}C$ values of *N. pachyderma*(s) and *O. umbonatus* in the Alpha Ridge cores, however, are about $1^0/_{00}$ heavier than those in the Norwegian Sea (Jansen and Erlenkeuser, 1985), presumably reflecting the lower productivity of the Arctic surface water. Glacial-interglacial shifts in carbon values for *N. pachyderma*(s) are also about $0.5^0/_{00}$ larger than those found in the Norwegian Sea. This may indicate a greater reduction of primary productivity of the Arctic Ocean during glacial stages. Other factors, for example, reduced ocean-atmosphere CO_2 exchange or organic carbon influx from ice-rafted sediment, could also account for these differences in carbon ratios. Detailed interpretation of the Alpha Ridge carbon isotope records therefore is not warranted at present.

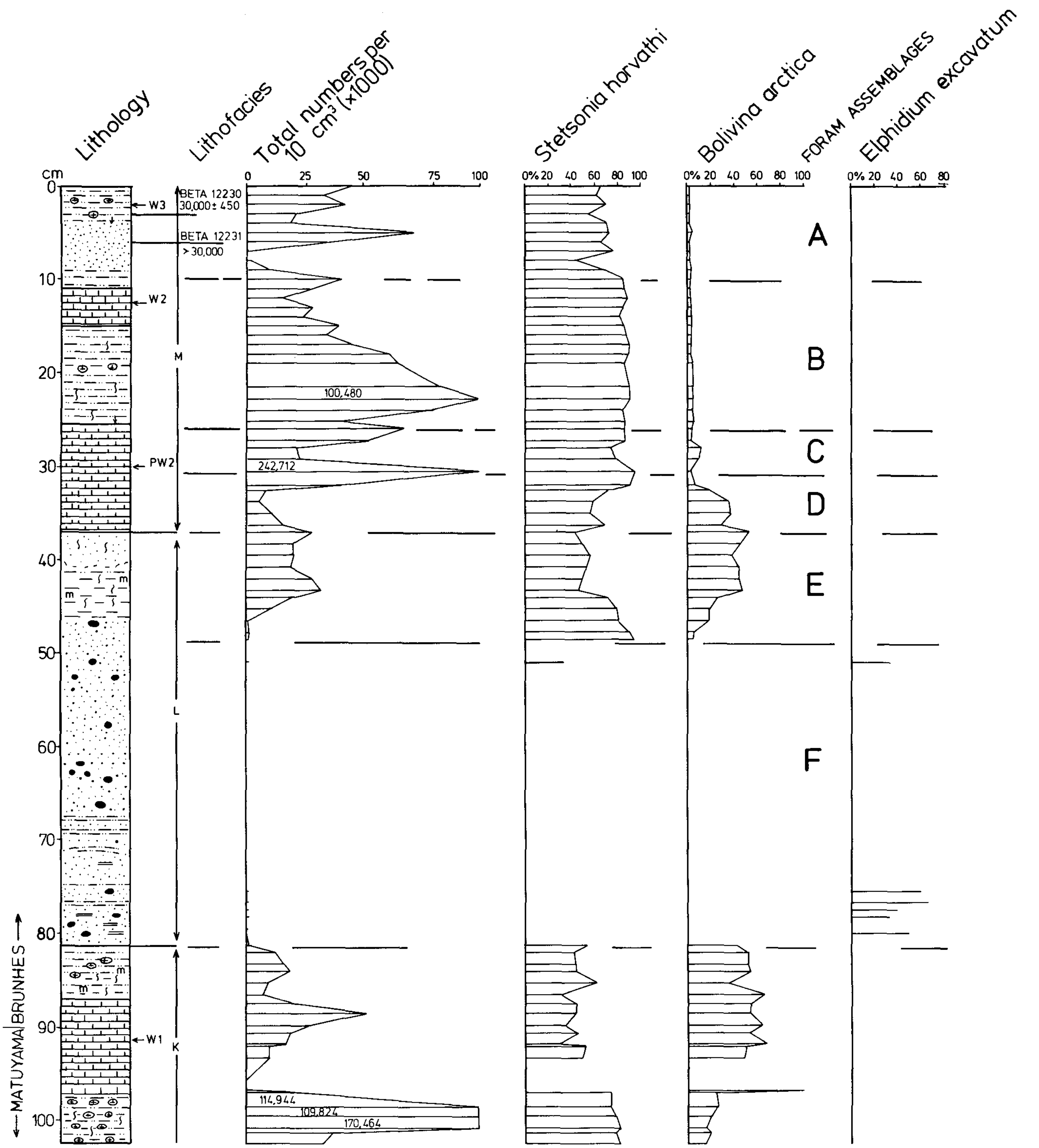


Figure 5. CESAR core 102 lithology, percentage and total number of occurrences of benthonic foraminifera, and stable-isotope values (in per mil relative to PDB) for benthonic and planktonic foraminifera. BETA numbers indicate ^{14}C dates. Large letters refer to foraminiferal assemblages described in text.

INTERPRETATION AND DISCUSSION

Present Benthonic Faunas

Few studies have reported quantitative data on benthonic foraminifera in the Arctic Ocean. The numbers of planktonics (P) and benthonics (B) reported by Aksu (1985b) for Alpha Ridge give B:P ratios of 1:10, similar to those found in open-water North Atlantic sites. Morris and Clark (1986) also suggested that benthonics are uncommon in Arctic sediments. Our data for the CESAR cores and other studies on surface sediments from a wide range of water depths from 800 to 4,000 m (D. B. Scott and G. Vilks, unpub. data) indicate that the opposite is true, with B:P ratios in many cases exceeding 1:1. These high B:P ratios have also been observed in

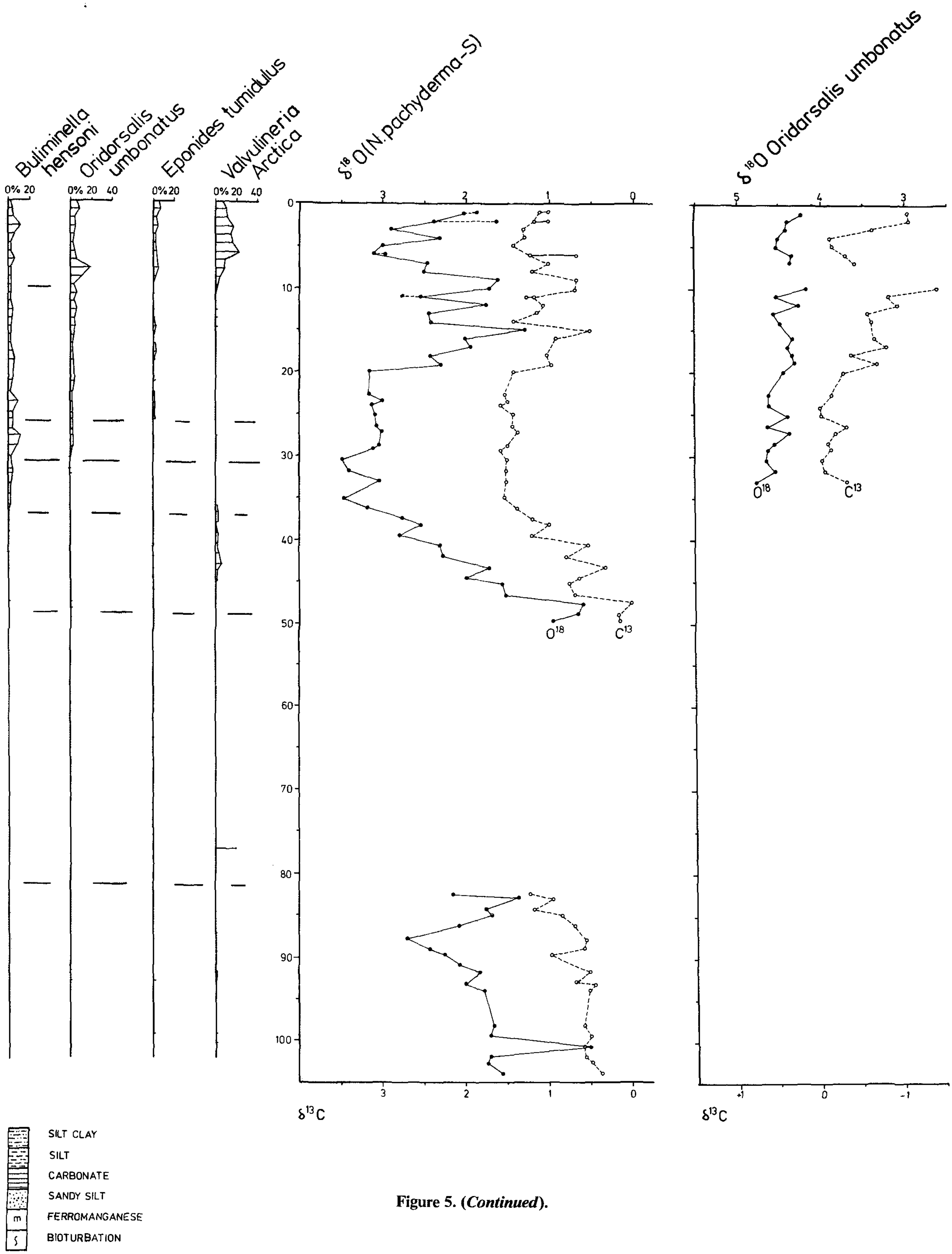


Figure 5. (*Continued*).

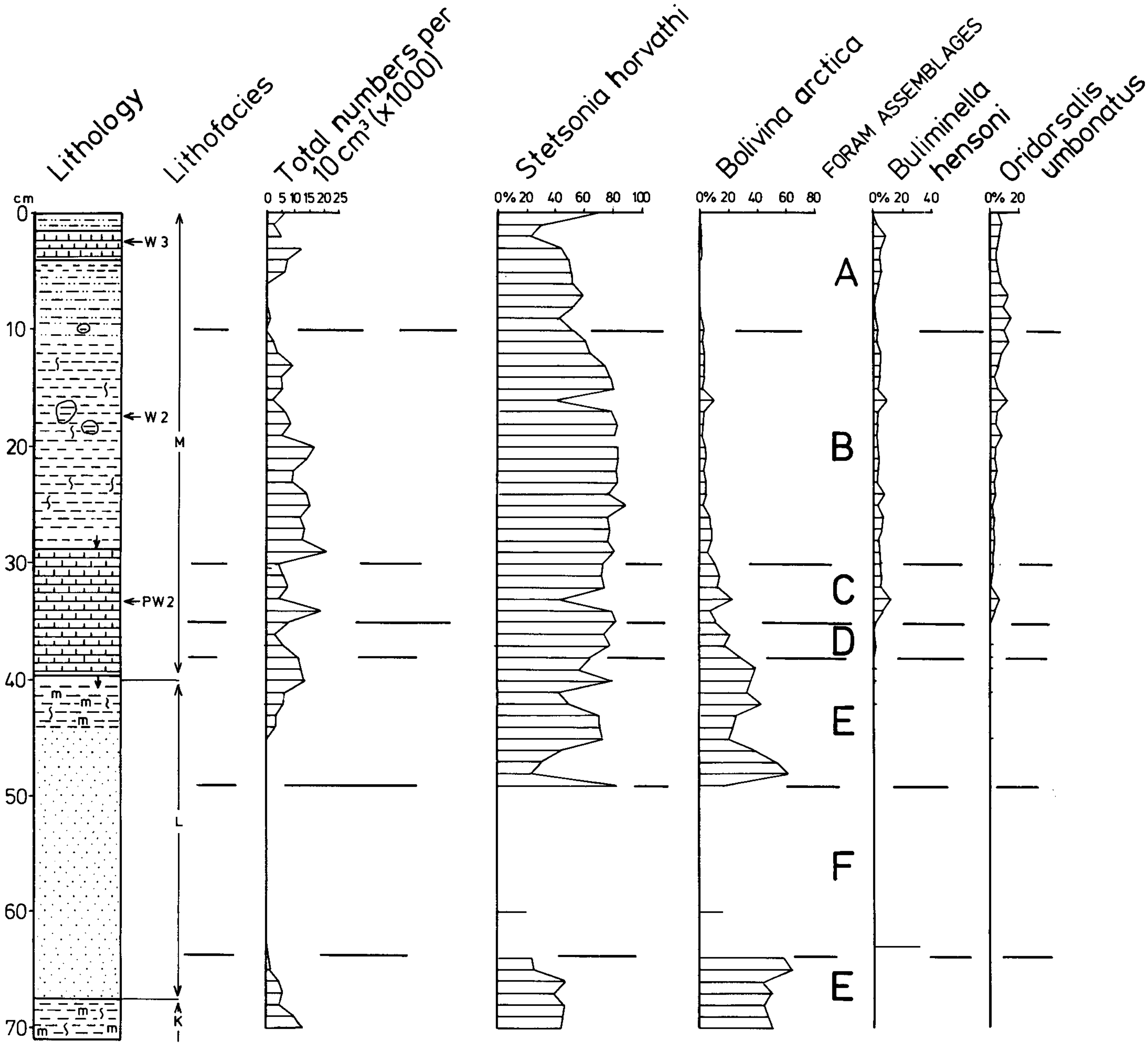


Figure 6. CESAR core 201 lithology, percentage and total number of occurrences of benthonic foraminifera, and stable-isotope values (in per mil relative to PDB) for benthonic and planktonic foraminifera. Large letters refer to foraminiferal assemblages described in text.

sections of Baffin Bay cores in periods when we suspect Baffin Bay was ice covered (Scott and others, 1986b, 1988), and we suggest that these high B:P ratios can be correlated with perennial ice cover. The implication is that bottom-water productivity may be less affected by ice cover than is surface-water productivity, although it is impossible to quantify this at present. Regardless of productivity rates, however, it appears that the Arctic Ocean B:P ratios differ from most oceanic values. Hence, the high B:P ratios may provide a good index for distinguishing perennial ice-covered deep-sea environments from areas with partially ice-covered or open conditions.

Interpretation of the benthonic paleoecology and biostratigraphy of the CESAR cores is based primarily on descriptions of modern foraminiferal distributions (Green, 1960; Vilks, 1969; Lagoe, 1977) and data from Fram Expedition, CESAR, and Lomonosov Ridge Experiment (LOREX) surface-sediment samples (D. B. Scott and G. Vilks, unpub. data). The CESAR cores are all from water depths greater than 1,300 m. These locations are well below the present Arctic seasonal layer from 0–200 m and below the intermediate Atlantic water layer from ~200–750 m (Jones and Anderson, 1986) or 1,300 m (Aagaard and others, 1985). The present Arctic bottom water (ABW) is thought to originate on the Arctic continental margins, where dense, cold brines result from sea-ice formation (Aagaard and others, 1985; Jones and Anderson, 1986). This water sinks and is the main source of ABW in the western Arctic Ocean. Although there is input to the surface

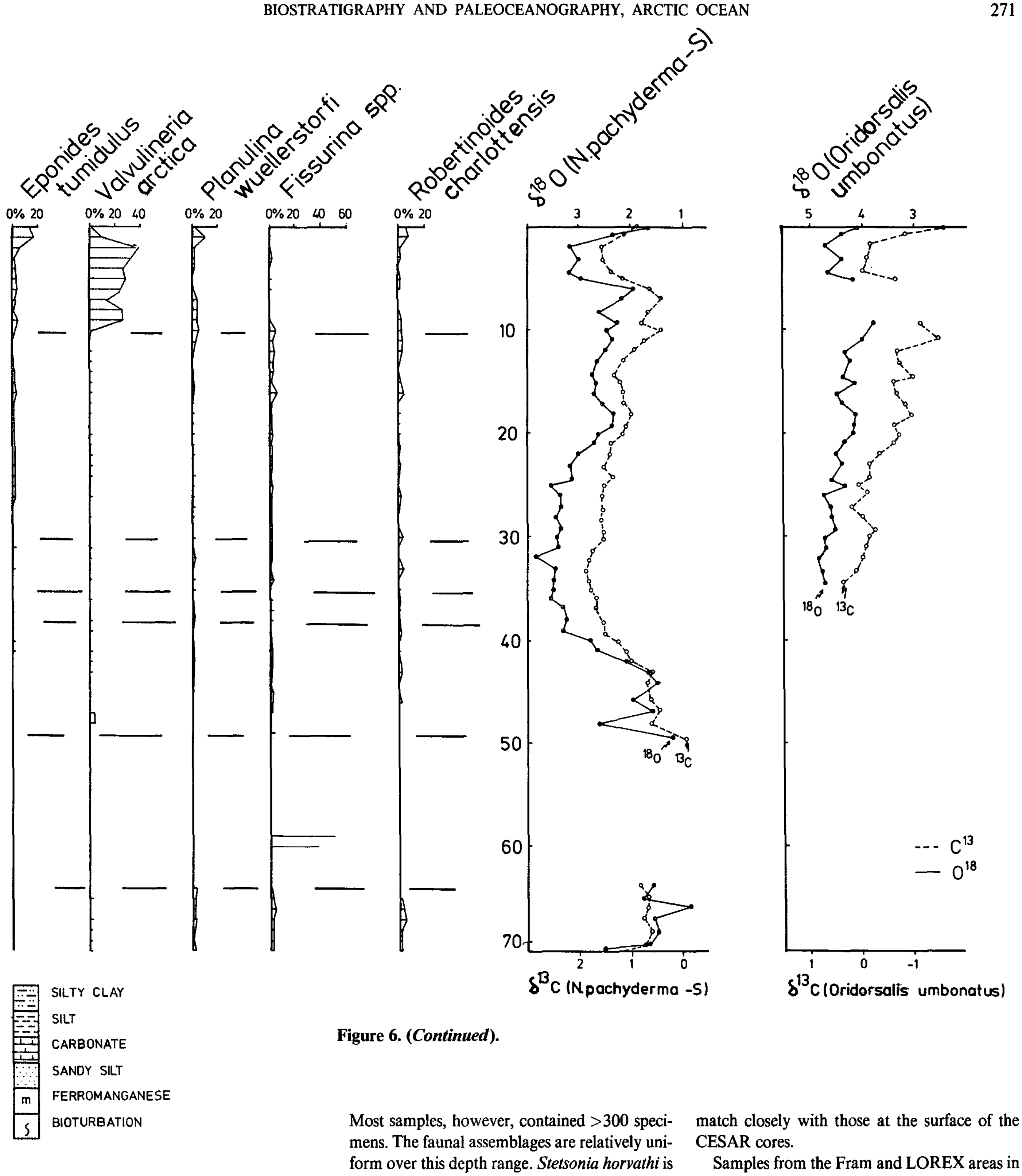


Figure 6. (*Continued*).

and intermediate water from the North Atlantic and the Bering Sea, these sources lose their identity in the ABW.

Samples studied by Lagoe (1977) cover water depths of 1,000 to 3,800 m in the western Arctic. Relative abundances of species are reported, but total numbers per sample are not given. Most samples, however, contained >300 specimens. The faunal assemblages are relatively uniform over this depth range. *Stetsonia horvathi* is dominant (60%–80%) throughout, with varying but significant percentages of *Oridorsalis umbonatus*, *Buliminella hensoni*, *Eponides tumidulus*, *Valvulinera arctica*, and *Triloculina* spp. Significant numbers of *Bolivina arctica* (5% or more) occur at only 6 stations, and those may be erosional surfaces because *B. arctica* is rare elsewhere in the present Arctic Ocean. The southern Alpha Ridge assemblages of Lagoe (1977) match closely with those at the surface of the CESAR cores.

Samples from the Fram and LOREX areas in the eastern Arctic Ocean have many of the same species found in the western Arctic (Lagoe, 1977), but three distinct assemblages are present (D. B. Scott and G. Vilks, unpub. data). Water depths sampled range from 795 m in the Fram Basin to more than 4,000 m in the Makarov Basin (Fig. 1). In water depths of less than 1,000 m in the Fram Basin, a primarily agglutinated fauna is found which contains *Reophax* spp.,

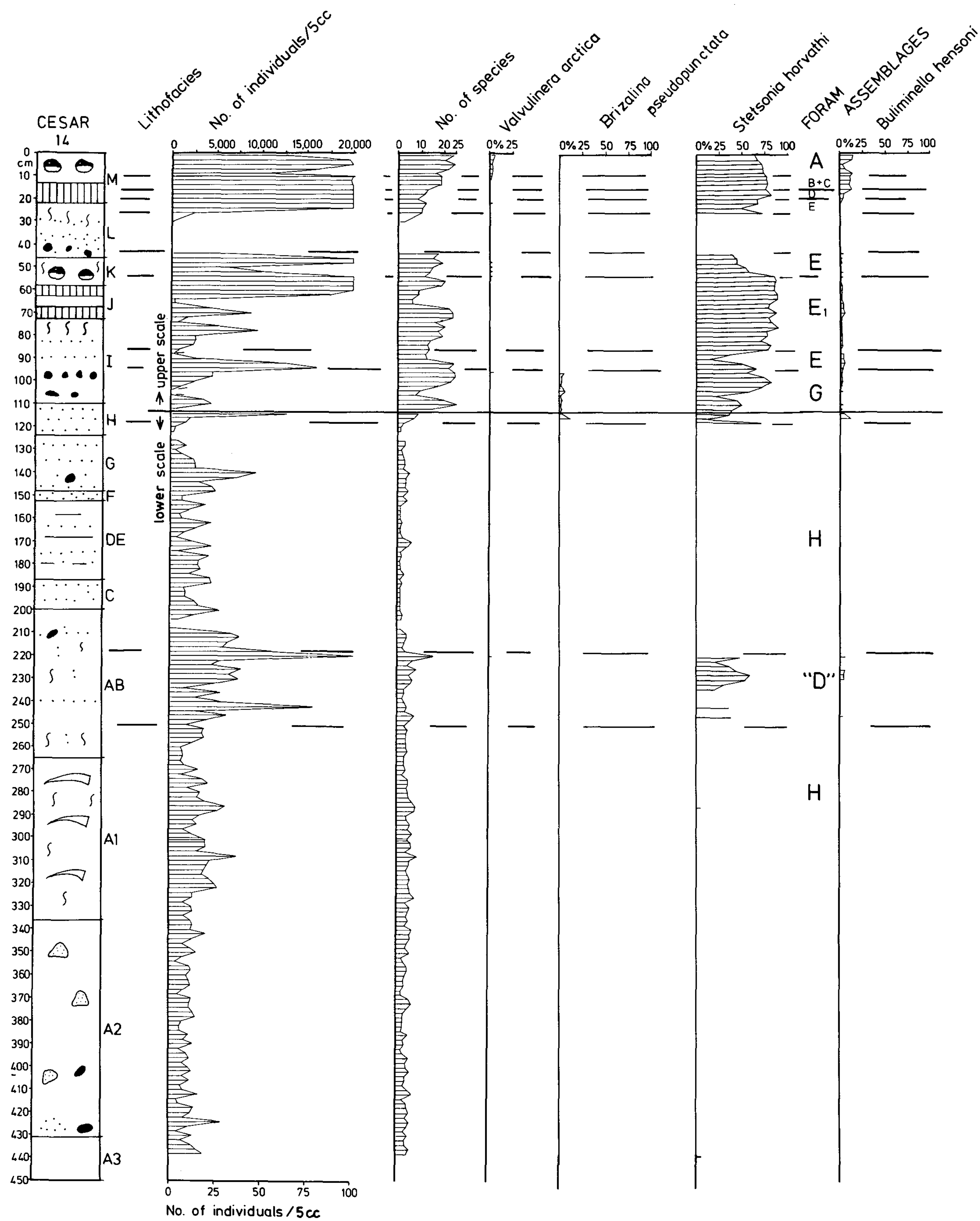


Figure 7. CESAR core 14 lithology (symbols same as in Fig. 3), percentage and total number of occurrences of benthonic foraminifera, and stable-isotope values (in per mil relative to PDB) for planktonic foraminifera. *Stetsonia horvathi* and *Epistominella arctica* are combined in this figure from the original data to conform with Figures 5 and 6; these two forms are considered conspecific, but Cole separated the two forms in core 14. Letters A–H refer to foraminiferal assemblages described in text.

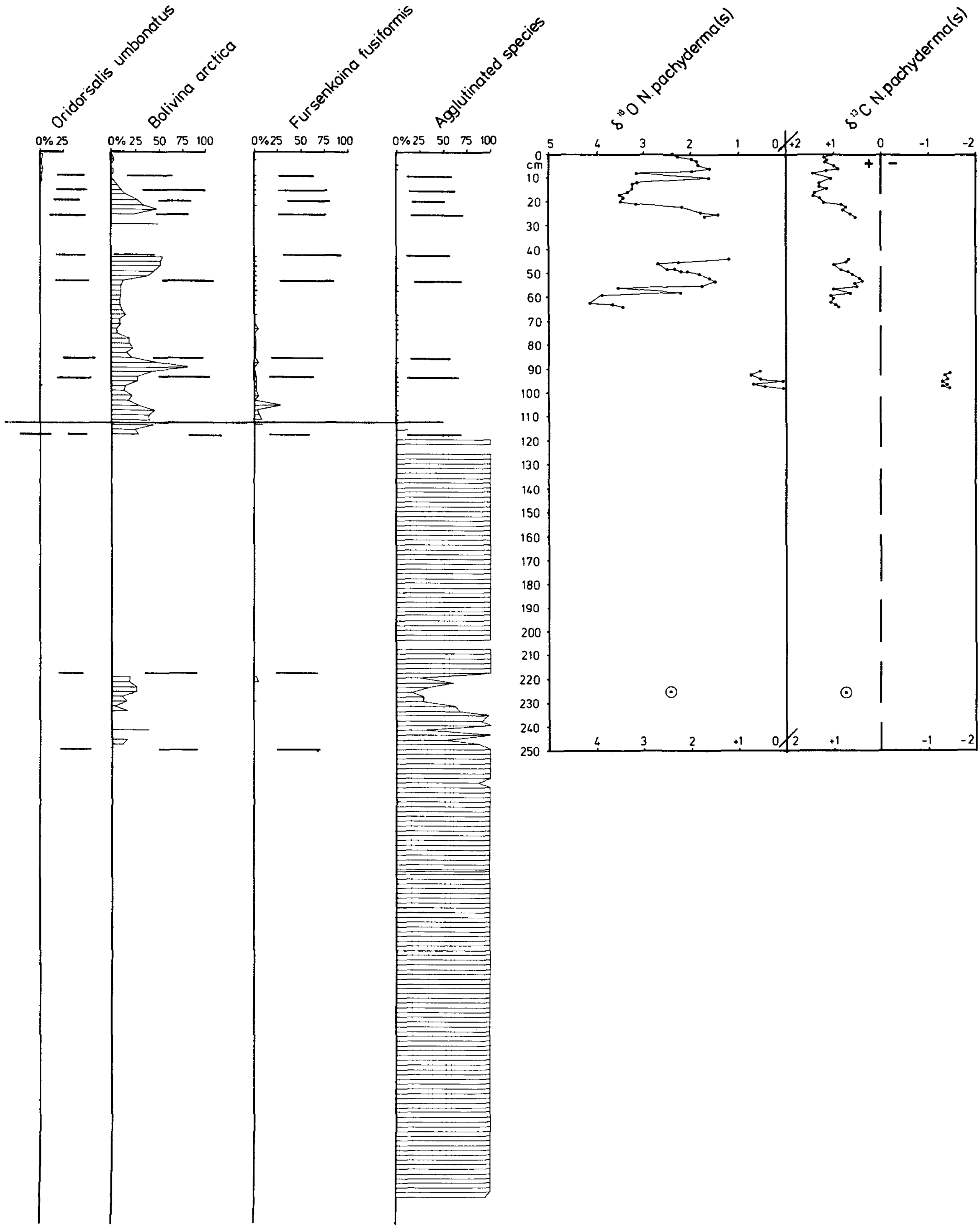


Figure 7. (*Continued*).

Hyperammina spp., *Psammosphaera fusca*, *Rhizammina algaeformis*, *Saccammina difflugiformis*, *Trochammina* spp., and *Adercotryma glomerata*, together with a sparse calcareous fauna (mostly shallow-water species; for example, *Islandiella teretis* and *Cassidulina reniforme*). Low numbers of poorly preserved planktonic specimens indicate that the depth range of 795–1,000 m (lower Atlantic water) in the Eurasian Basin is not conducive to carbonate preservation. Between 1,000 and 3,000 m, a mixed fauna occurs, with strong components of both agglutinated and calcareous species, together with abundant planktonics. The calcareous species are similar in composition to Lagoe's (1977) samples, but the Fram Basin contains a more significant agglutinated element. Below 3,500 m in Fram Basin, a low-diversity deep-water fauna composed of *S. horvathi* and *Triloculina* spp. is found, with *Stetsonia* in many cases composing as much as 95% of the benthic fauna. Other species typical for similar depths in the Canada Basin are absent or rare (<1%) in the Fram Basin.

Total numbers for these assemblages vary, being lowest in the agglutinated assemblages (200–1,000/10 cm^3), highest in the mixed fauna (2,000–20,000/10 cm^3), and relatively high in the *Stetsonia* fauna (2,000/10 cm^3). All these numbers are low compared to those for most samples in the CESAR cores.

The surface faunas in Fram Basin reflect some fundamental differences between the water mass characteristics of the Eurasian and Canada Basins. First, the agglutinated fauna found between 795 and 1,000 m is not present on the Alpha Ridge or at any of Lagoe's (1977) sites. This probably reflects more mixing of corrosive, lower-salinity water in the Eurasian Basin than in the Canada Basin (Aagaard and others, 1985; Thiede and others, 1987). Second, the low-diversity fauna found from 3,500 to 4,000 m is important for two reasons: (i) it shows that biogenic carbonate can be produced and preserved in the Arctic Ocean below 4,000 m and (ii) that this particular fauna is unique to the deepest part of the present-day eastern Arctic Ocean. The unique composition of the fauna suggests that there is little input to the deepest parts of the Fram Basin from the Norwegian-Greenland Sea. Aagaard and others (1985), however, have shown that the Arctic is the source for deep, dense water that is exported southward, and recent findings of *S. horvathi* in some Norwegian Sea sediments recovered from Leg 104 of the Ocean Drilling Program (ODP) drilling (L. Osterman, 1987, personal commun.) appear to support this interpretation.

Paleoenvironmental and Biostratigraphic Interpretation for the Central Arctic

The CESAR core data show that substantial changes in benthonic foraminiferal assemblages are recorded in the Pliocene-Pleistocene sediments of the central Arctic Ocean. The Alpha Ridge data are from a small area and narrow depth range, but because of the relatively shallow sills restricting the deep Arctic circulation, it is unlikely that events occurred earlier in deeper parts of the western Arctic Ocean. Furthermore, they must have occurred earlier in the eastern Arctic because Atlantic water has to pass through the Fram Basin before reaching the Alpha Ridge. Earlier work by O'Neill (1981) provided a qualitative biostratigraphy for the western Arctic Ocean; quantitative work in this paper allows detailed interpretations which illustrate a more complex sequence of faunal events.

There are no modern analogues for some of the older assemblages, for example the *Stetsonia-B. arctica* assemblage E. On the basis of the first significant occurrences (>1%) of North Atlantic benthonic foraminiferal species, however, the most dynamic Pleistocene interval of the Arctic Ocean appears to be in the past 300,000 yr (base of stage 8, top of unit L to the surface). This interval corresponds to the carbonate-rich unit M and the persistent presence of detrital limestone, which probably reflects influx of IRD from the Canadian Arctic and northwest Greenland (Amos, 1985).

In this late Pleistocene interval, many typical North Atlantic species (for example, *Oridorsalis umbonatus* and *Eponides tumidulus*) begin to appear on the Alpha Ridge in significant percentages (>1%), replacing the endemic species, *B. arctica*. Two Arctic endemic deep-water species, *B. hensoni* and *V. arctica*, also have their first significant occurrences here; these species are useful as stratigraphic markers, but little is known about their ecology. The first North Atlantic species to appear is *O. umbonatus*, which characterizes glacial intervals in the Norwegian Sea (Streeter and others, 1982) and presently occurs at depths of 1,000–3,000 m in the Norwegian Sea (Belanger and Streeter, 1982). In all cores, this species first appears in the PW2 carbonate bed. The isotope records appear to indicate early stage 8 (~300 ka), which roughly agrees with the estimated age of 350 ka based on a sedimentation rate of ~1 mm/ka. The next North Atlantic species to appear, *E. tumidulus*, is recorded in the Norwegian Sea (Belanger and Streeter, 1982) at water depths in most instances greater than 3,000 m. This species is also a common component of deep-sea faunas studied in other areas of the North Atlantic (for example, Schafer and Cole, 1982; Hermelin and Scott, 1985; Schroeder, 1986). Although *E. tumidulus* is never a dominant component of typical faunas, it appears to prefer deeper water than does *O. umbonatus*. The last North Atlantic species to appear in the Alpha Ridge cores is *P. wuellerstorfi*, which dominates the interglacial intervals in the Norwegian Sea (Streeter and others, 1982) and presently has the same depth range as *O. umbonatus* but is more dominant above 2,000 m (Belanger and Streeter, 1982). Significant numbers of this species, together with *V. arctica*, appear in the CESAR cores during isotopic stage 5, which is the warmest late Pleistocene interval. It is notable that the species *Nuttallides umbonifera* does not appear in the Arctic Ocean or Norwegian Sea surface sediments, although it is a dominant species in the present North Atlantic at depths below 3,000 m. This species also occurs in assemblage B of cores 102 and 201 (isotope stages 5–8). This occurrence corresponds to some of the heaviest oxygen values in the Arctic cores and may signal limited inflow or regional formation of dense, cold, saline bottom water similar to Antarctic bottom water (AABW) in the North Atlantic.

With respect to the paleocirculation of the Arctic Ocean, it is important to determine why these species are not present in the Arctic throughout the Pleistocene, as this ocean basin has been connected to the Atlantic by the Greenland-Svalbard Channel during the past 20 m.y. (Thiede, 1980). The depth dependence of benthonic foraminifera which characterize the water masses suggests that faunal migration was controlled by the Greenland-Svalbard Channel, which presently has a maximum depth of about 2,600 m. Either deepening of this channel or increased flow of Norwegian Sea water into the Arctic Ocean would allow increasing amounts of deep-water Norwegian Sea species to enter the Arctic Ocean. It appears that the threshold depth for species to reach the Alpha Ridge is marked by the first arrival of *O. umbonatus* in the middle–late Pleistocene. Prior to deposition of unit M, the Alpha Ridge was isolated from influence of the Norwegian Sea, and at this time, the central Arctic contained a relatively low-diversity fauna similar to that presently found in the deep parts of the Eurasian Basin.

Paleoenvironmental interpretation of the sediments in unit L at the Alpha Ridge is problematical, as both arenaceous and calcareous benthonic foraminifera and planktonic forms are rare or absent, although palynomorphs are common (Mudie, 1985). Morris and Clark

(1986) suggested that increased sedimentation rates at the start of interglacials were responsible for lower numbers of foraminifera. Some intervals in the CESAR cores with low numbers of foraminifera are also associated with interglacial conditions (for example, 8–10 cm in cores 102 and 201), or the transition to glacial in the early Pleistocene of core 14 (65–90 cm), but these sediments are not completely barren of microfossils. There is no evidence of a major change in sedimentation rate at the Alpha Ridge CESAR sites, however, which could account for the low numbers of foraminifera in unit L. Conditions that formed the barren zone of unit L apparently do not exist today in the Arctic. The modern area that most closely resembles the carbonate-poor aspect of unit L is found above 1,000 m in the Eurasian Basin, where seasonal mixing of low-salinity surface and Arctic Atlantic water dissolves the carbonate (Aagaard and others, 1985; Thiede and others, 1987); hence, only agglutinated species and shallow-water benthonics (probably transported downslope and rapidly buried) survive in this area. Low numbers of shallow-water calcareous benthonics are found at the base of unit L in cores 102 and 201; agglutinated forms are absent.

Some diagenesis may be indicated by the lack of detrital carbonate and the presence of hematite in unit L. The finely laminated sediments, however, may reflect periodic strong bottom turbulence and vertical mixing which could suspend the nepheloid layer. If the bottom sediment was periodically mixed upward into the corrosive Atlantic intermediate layer, as presently occurs in Summer ice-free areas of Fram Strait, calcareous foraminifera would dissolve. Deep-water arenaceous foraminifera also could not live in an unstable environment of this type. This model not only accounts for the extraordinary absence of foraminifera in unit L on the Alpha Ridge, but it also explains the variable thickness and structure of unit L (Fig. 3), and the presence of pollen and dinoflagellates which are not affected by carbonate dissolution. The presence of fresh-water algae (*Pediastrum*) indicates higher fluvial runoff and lower surface-water salinity (Mudie, 1985). The prevalence of hematite and volcanic minerals in unit L (Fig. 4) also suggests stronger bottom-current erosion of the volcanic outcrops on the Alpha Ridge.

Other evidence which supports this model includes the following factors: (1) Light $^{18}O/^{16}O$ values at the top and base of unit L indicate full interglacial conditions, and relatively light $^{13}C/^{12}C$ values above and below the barren zone indicate higher primary productivity or influx of terrigenous carbon, as expected for warmer climatic conditions and more fluvial input. (2) Unit L is highly variable in thickness, both within and between basin and ridge areas, which would be expected if sedimentation involved periodic bottom-current winnowing. (3) If the absence of calcareous foraminifera in unit L was due to only a long period of carbonate-free bottom water, an agglutinated fauna would be present; the lack of any fauna therefore suggests a prolonged series of disruptive events. (4) The global isotope record of Shackleton and Opdyke (1973) shows that isotopic stages 9–15 are marked by relatively long interglacial intervals and brief glacial events. Hence, most of unit L apparently corresponds to a long interval of relatively small glacial oscillations, during which time the Arctic Ocean, at least over the Alpha Ridge, may have been largely ice free.

Unit K marks the reoccurrence of sediments rich in detrital limestone, and it again contains a fauna similar to assemblage E above the low-carbonate unit L. In the lower Pleistocene lithologic units J and I of core 14, assemblages E, E1, and G occur, but total numbers are lower on average than in upper units, particularly planktonics.

Dolomite and metamorphic rock fragments dominate the coarse sediment fraction in unit I, suggesting increased influx of IRD from berg ice calved from Ellesmere Island and Greenland (Amos, 1985). The occurrence of calcispheres (calcareous dinoflagellate cysts) in this interval (Fig. 4) may also indicate relatively warm, low-salinity surface water (Mudie, 1985). The $^{18}O/^{16}O$ values for unit I also indicate a major melt-water interval.

The base of unit I and the top of unit H (94–118 cm) are characterized by high numbers of *F. fusiformis* in assemblage G. This calcareous species is apparently associated with low-oxygen sub-ice environments off eastern Canada (Scott and others, 1984; Schroeder, 1986). The presence of this species in assemblage G suggests that the present highly oxygenated bottom-water regime was not established in the Arctic Ocean until the end of the Gilsa event (ca. 1.63 Ma) in the early Pleistocene.

At the base of unit I, there is a major turnover of foraminiferal faunas, with totally agglutinated assemblage H occurring below 118 cm, except in the interval from 220–250 cm. Assemblage H is similar to that presently found above 1,000 m water depth in the Eurasian Basin, but total numbers are much lower in the Pliocene sediments. The agglutinated faunas may reflect conditions in which seasonal mixing on the Alpha Ridge extended to at least 1,370 m, probably signifying more open-water conditions than at present. Seasonal mixing would also account for the absence of calcareous foraminifera in assemblage H, but bottom-water temperatures must have remained low for the CCD to have been this shallow. Dolomitic gravel also suggests the continued influx of IRD from icebergs, starting just below the base of unit C (220 cm), which has an age of 2.2 m.y. in core 14.

Low numbers of calcareous foraminifera (assemblage D) occur from 220–250 cm at the top of unit AB. This fauna has a B:P ratio of 1:1, and it may indicate an early period of continuous ice cover; this is also suggested by the relatively heavy oxygen isotope value for planktonic foraminifera (+2.5), which is about the same as isotope stage 6 in the CESAR cores. The base of this interval lies just below the Matuyama-Gauss boundary (2.48 Ma), and the top occurs just below the Reunion magnetochron (2.08 Ma). This late Pliocene cold interval corresponds closely to the earliest interval (2.4 Ma) of ice rafting and glacial conditions in the North Atlantic DSDP site 552A (Shackleton and others, 1984). The remainder of core 14 contains only the agglutinated assemblage H, with rare occurrence of gravel-sized igneous rock possibly indicating intervals of icebergs at about 3.5 and 4.0 Ma (Fig. 4).

O'Neill (1981) suggested that the first appearance of calcareous faunas (*Stetsonia-Bolivina*) is a result of deepening of the Fram Strait channel which allowed greater inflow of North Atlantic deep water. The *Stetsonia-Bolivina* fauna, however, appears to be endemic to the Arctic Ocean and hence need not have entered from the North Atlantic. The first North Atlantic species do not appear in numbers more than 1% until the middle to late Pleistocene at the CESAR sites, and it is unlikely that they occurred in deep parts of the western and central Arctic before they occurred at the Alpha Ridge. O'Neill (1981) had first appearances of North Atlantic species in the late Pliocene but provided no abundance data.

Stable-Isotope Stratigraphy

We have outlined an oxygen isotope stratigraphy for the three cores in this study, and we are confident of the gross time scale (that is, the position of the Brunhes-Matuyama and Pliocene-Pleistocene boundaries). Specific isotopic stages, however, are difficult to delimit when represented by only about 1 cm of core (for example, stages 1–3). The benthonic data are the first isotopic data to provide a reliable bottom-water signal, but they extend only as far as the lowest occurrence of North Atlantic species in our isotopic stage 8.

The problem of low resolution is compounded by gaps in the planktonic foraminiferal record at critical intervals: that is, most of unit L, parts of units J and I in core 14, and most of the late Pliocene. Despite these problems, however, there is a close similarity between isotopic events for all the CESAR cores, which strongly implies that the signal recorded is a regional one.

Comparison of the Arctic planktonic and benthonic records with records from the Norwegian Sea and the North Atlantic reveals some fundamental differences. Arctic Ocean planktonic $^{18}O/^{16}O$ ratios are lighter (1.0‰ to 3.5‰) than those in the Norwegian Sea (Streeter and others, 1982) and Labrador Sea (Scott and others, 1988), although the amplitude of glacial/interglacial change is the same. The Arctic benthonic ^{18}O values are not lighter than the North Atlantic values, but the glacial/interglacial difference is reduced (1.0‰ in the Norwegian Sea versus 0.6‰ in the Arctic). For the same species (*O. umbonatus*) in the equatorial Pacific, the glacial/interglacial change is more than 2.0‰ at the stage 1/stage 2 boundary (Vincent and others, 1981).

The Arctic Ocean might be expected to reflect at least the amplitude of oxygen isotope change in benthonic foraminifera that is thought to be the ice volume contribution to the global signal (that is, about 1.5‰ heavier in glacials; Chappell and Shackleton, 1986), but it does not. There are a few ways this might be explained. First, bioturbation in the slow-sedimentation Alpha Ridge area may easily mix the record and reduce the contrast (for example, Shackleton and others, 1984). Second, the Arctic Ocean is so isolated from the global ocean that regional bottom-water production may override the global signal, producing more uniformly heavy oxygen isotope values in benthonic foraminifera throughout the late Quaternary. Supporting evidence for the latter is that the amplitude of the glacial/interglacial changes decreases with increasing latitude (that is, from >2‰ in the tropics to 1.0‰ in the Norwegian Sea); furthermore, all the values in the Arctic are heavier than interglacial values from the Pacific, as would be expected if the signal was partially derived from locally produced cold, high-salinity shelf water in the Arctic.

Intuitively, it might be expected that planktonic $^{18}O/^{16}O$ ratios should be heavier in the central Arctic, where cold, high-salinity water is generated at the ocean surface. The CESAR data, however, show Arctic planktonic values averaging 1.0‰ less than those in the North Atlantic and 2.0‰ less at some intervals. This may be because the cold brines formed at the basin margins sink rapidly and do not contribute significantly to the surface water layer in the central Arctic Ocean, which has a low salinity (29‰–30.5‰) throughout the Arctic Ocean.

The $^{13}C/^{12}C$ ratios are more difficult to interpret, because the carbon cycle is more variable and less understood and because few data exist for carbon isotopes in the Arctic Ocean. The carbon isotopes in the CESAR cores essentially track the oxygen isotopes, especially in the planktonic record. The planktonic carbon isotope values are mostly positive, unlike the record from the North Atlantic at 45°N (for example, Scott and others, 1986a) but similar to that from the Labrador Sea (Scott and others, 1986b). Few carbon isotope data have been reported for benthonic species from high latitudes. It is presently not clear if the heavier values (0‰ to −1.5‰) for *O. umbonatus* in the CESAR cores compared to values of about −1‰ to −2.5‰ for this species in the Norwegian Sea (Jansen and Erlenkeuser, 1985) indicate that the Arctic bottom water is better ventilated (compare with Shackleton and others, 1984) or merely less productive.

Comparison with Other Central Arctic Ocean Stratigraphies

Two benthonic foraminiferal stratigraphic records have previously been reported for the central Arctic Ocean (O'Neill, 1981; Herman, 1974). Both of these studies looked at the size fraction greater than 63 μm. O'Neill (1981) used samples of 10–12 cm^3 volume, which is comparable to the CESAR core samples. Herman (1974) used samples of "equal volume weighing 8 to 14 g" but gives no volume. The weight of 8–14 g probably corresponds to about 10 cm^3.

Herman (1974) studied five cores from the southern Mendeleyev Ridge north of the Chukchi Plain (Fig. 1). Discontinuous paleomagnetic data suggest similar sedimentation rates to those found in the CESAR cores, but sample spacing was much coarser (5–15 cm). Herman (1974) recorded low numbers (<100/sample) for most assemblages, which have faunal compositions similar to those in the Pleistocene sediments of the CESAR cores, but with the first appearances of North Atlantic species occurring at greater core depths. The low numbers in Herman's cores suggest that sedimentation rates are higher than in the CESAR cores, which would account for the apparently earlier occurrences of marker species.

O'Neill (1981) studied cores from water depths of 1,800 to 3,500 m on the western Alpha Ridge and Canada Basin. Core lengths varied from 270 to 550 cm, and sample spacing appeared to be about 10 cm, although no sampling depths were given. Extremely low numbers of foraminifera (in most instances less than 50/sample) were obtained, which suggests that sedimentation rates in this region are higher than on the southeastern Alpha Ridge.

As mentioned previously, O'Neill (1981) did not provide quantitative data comparable to ours. He observed, however, three biofacies in his cores: an early Pliocene textulariid biofacies, a transitional biofacies (mixed calcareous and arenaceous) in the late Pliocene to early Pleistocene interval, and a calcareous biofacies in the early Pleistocene to Recent interval. O'Neill's longest core (FL224) from 3,500 m of water has a foraminiferal biostratigraphy similar to CESAR core 14. The difference in water depths, however, precludes direct comparison because the chronology of the lysocline position at these two sites may be different; that is, the top of the agglutinated fauna at FL224 does not necessarily approximate the Pliocene-Pleistocene boundary as it does at the CESAR sites. Core FL393 from the Alpha Ridge at 1,400 m, however, is directly comparable to the CESAR material. Core FL393 has a completely agglutinated fauna throughout, suggesting that the Pleistocene section is missing at that site.

Comparison with the Eurasian Basin

The only stratigraphic study of benthonic foraminifera in the Eurasian Basin is by Markussen and others (1985), who studied 2 short (53–90 cm) gravity cores (FRAM 1/4 and FRAM 1/7). Their qualitative results on benthonic foraminifera are based on the >150 μm fraction, which means that they did not recover the dominant species, *Stetsonia horvathi*. The size-fraction problem is discussed in more detail on a world-wide basis in separate papers (Schroeder and others, 1987; Sen Gupta and others, 1987). The large species, *Oridorsalis umbonatus*, however, was found throughout their cores. This is consistent with the late Pleistocene age assigned to the FRAM cores based on the $^{18}O/^{16}O$ isotope record, which extends to stage 3 (ca. 34 ka), and it supports the interpretation (Markussen and others, 1985) that sedimentation rates in the Eurasian Basin are similar to those of the northeast Atlantic Ocean.

Comparison with the Norwegian Sea

Stetsonia horvathi has not been reported from the deep parts of the Norwegian Sea (for example, Belanger and Streeter, 1980; Streeter and others, 1982; Jansen and others, 1983), but this may be the result of the larger sieve sizes used (that is, >150 μm). This species, however, has been observed in several core sites from Leg 104 of ODP in the Norwegian Sea (L. Osterman, 1986, personal commun.). The diversity of the modern Norwegian Sea fauna, even excluding the smaller size fraction, however, is far greater than that of the Arctic Ocean and similar to other North Atlantic deep-sea faunas. Some of the "barren" zones observed in the cores studied by Streeter and others (1982), however, may be due to the processing method rather than paleoceanography.

There are some clear differences between faunal trends in the Norwegian Sea and the western Arctic Ocean. The most obvious trend is that total foraminiferal populations are reduced during glacials in the Norwegian Sea, probably diluted by ice-rafted debris (Streeter and others, 1982), whereas they are concentrated on Alpha Ridge because of reduced detrital sediment influx during glacial intervals. The Norwegian Sea records also show large glacial-interglacial changes in the faunal assemblages, which cannot be distinguished in the Alpha Ridge cores.

SUMMARY

The data presented herein are the first high-resolution benthonic foraminiferal assemblage data from the Arctic Ocean that cover the entire Quaternary. Although the data are restricted to the CESAR area, it is unlikely that events occurring here took place in isolation from the rest of the Arctic Ocean. Timing in different parts of the Arctic Ocean may have been slightly different but not the over-all picture.

Combined data from the CESAR cores indicate that the present quasi-stable, perennial Arctic Ocean ice cover became established only in the late Pleistocene after a long early Pleistocene history of periodically continuous ice cover. The first evidence of perennial ice cover appears to be marked by a brief interval of calcareous foraminiferal production in the late Pliocene (ca. 2.15–2.48 Ma). The permanent occurrence of perennial sea-ice formation commences just above the Pliocene-Pleistocene boundary. This event is clearly marked by an abrupt increase in the occurrence of calcareous assemblages, which completely replace the agglutinated benthonic forms that mark most of the Pliocene interval and are presently associated with seasonal mixing at the sea-ice margin in Fram Strait.

In the late Pleistocene (isotope stages 8 to present), there is a succession of bottom-water events marked by the first significant occurrences of various North Atlantic deep-sea benthonics. These events can be traced throughout the CESAR cores, and there is evidence that they occur in some western Arctic sequences (Herman, 1974).

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