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36. PALEOGENE BENTHIC FORAMINIFER BIOSTRATIGRAPHY AND PALEOECOLOGY AT SITE 647, SOUTHERN LABRADOR SEA[1]

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ABSTRACT

Benthic foraminifers were examined from the Paleogene of Ocean Drilling Program (ODP) Site 647 and Deep Sea Drilling Program (DSDP) Site 112 in the southern Labrador Sea. The Paleogene sequence of the deep Labrador Sea can be subdivided into seven assemblages, based on the ranges and relative abundance of characteristic taxa. The first occurrences (FOs) and last occurrences (LOs) of important benthic taxa are calibrated to a standard biochronology, by interpolating from our age model for Site 647. The biostratigraphy of Site 647 is used to improve the age estimates of Site 112 cores. Fifteen microfossil events in Site 647 also are found in the sedimentary wedge along the Labrador Margin. A comparison of the probabilistic microfossil sequence from the Labrador Margin with that at Site 647 yields four isochronous benthic foraminifer LOs. Two new species are described from Sites 647 and 112: *Hyperammina kenmilleri*, Kaminski n.sp., and *Ammodiscus nagyi* Kaminski n.sp.

Significant faunal turnovers are observed at the Ypresian/Lutetian and Eocene/Oligocene boundaries. The Ypresian/Lutetian boundary is characterized by a *Glomospira*-facies and is attributed to a rise in the CCD (carbonate compensation depth) associated with the NP14 lowstand in sea level. The Eocene/Oligocene boundary is delimited by the LO of *Spiroplectammina spectabilis* and *Reticulophragmium amplectens*. The change from an Eocene agglutinated assemblage to a predominantly calcareous assemblage in the early Oligocene took place gradually, over a period of about 4 Ma, but the rate of change accelerated near the boundary. This faunal turnover is attributed to changes in the preservation of agglutinated foraminifers, as delicate species disappeared first. Increasingly poorer preservation of agglutinated foraminifers in the late Eocene to earliest Oligocene reflects the first appearance of cool, nutrient-poor deep water in the southern Labrador Sea. The approximately coeval disappearance of agglutinated assemblages along the Labrador Margin was caused by a regional trend from slope to shelf environments, accentuated by the "mid"-Oligocene lowstand in sea level.

INTRODUCTION

The Labrador Sea played an important role in the early history of the North Atlantic, because it has served as a corridor for the exchange of surface water between the North Atlantic and Arctic oceans, possibly since the Late Cretaceous (Gradstein and Srivastava, 1980). Bipolar climatic cooling and the opening of deep marine connections with the Arctic Ocean through the Norwegian-Greenland Sea has been proposed as a causal mechanism resulting in vigorous deep circulation in the North Atlantic near the Eocene/Oligocene boundary (Miller and Tucholke, 1983). As a consequence of increased oceanic circulation, the Eocene/Oligocene boundary is usually represented by a hiatus in western North Atlantic and Rockall Margin sites; thus, limited data exist on the response of benthic foraminifers to climatic and oceanographic changes at this time. However, results from DSDP Leg 12 in the southern Labrador Sea indicated that a continuous Eocene-Oligocene section is present at the Gloria Drift (Fig. 1). The Gloria Drift lies in the pathway of northern-source deep water, relatively near its presumed source in the Faeroe-Shetland Channel. The stratigraphic record of the Labrador Sea thus provides an opportunity to study the early Cenozoic paleoceanographic history of the North Atlantic and its possible connections with the Arctic Ocean.

Paleogene deep-water benthic foraminifer assemblages in high latitudes are composed of predominantly agglutinated taxa, whereas temperate and low-latitude bathyal and abyssal faunas in the Atlantic are mostly calcareous. Drilling during DSDP Leg 12 recovered a mixture of calcareous and agglutinated assemblages at Site 112 (Berggren, 1972; Miller at al., 1982). Therefore, the sediments of the deep Labrador Sea provide a link between low- and high-latitude faunal provinces. Unfortunately, Site 112 was discontinuously cored and sediments spanning major stage boundaries or seismic reflectors were not recovered. Consequently, the geochronology of microfossil events in the Labrador Sea was not firmly established. Earlier studies indicated that a major faunal turnover was associated with the Eocene/Oligocene boundary in the Labrador Sea (Miller et al., 1982), but the timing and rate of change of the microfaunal assemblage was not known.

The primary scientific objectives of Leg 105 benthic foraminifer studies in the Labrador Sea were as follows:

1. To establish the geochronology of benthic foraminifers, to identify and date characteristic assemblages, and to correlate ODP Site 647 with DSDP Site 112 and the Labrador Margin zonation of Gradstein et al. (1985).
2. To examine the benthic foraminifera record and to infer changes in deep-water conditions near major stage boundaries and the development of psychrospheric conditions in the early Oligocene.
3. To determine the relationship of faunal changes to regional seismic horizons.

Here, we develop a high-latitude Paleogene biochronology, compare the stratigraphy of Site 647 with the sequence of microfossil events on the Labrador Margin, identify isochronous

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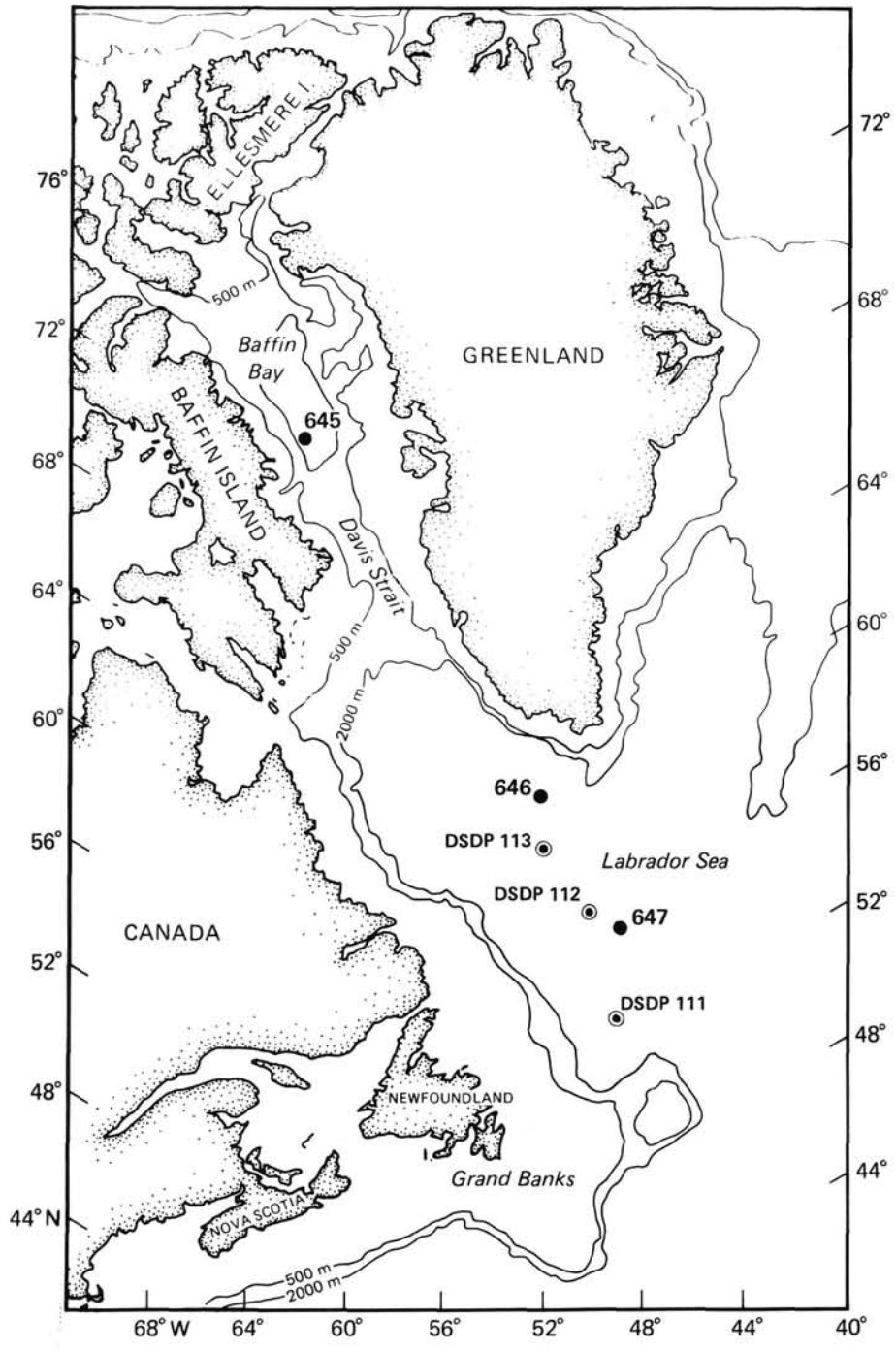

Figure 1. Location of DSDP and ODP sites in the Labrador Sea and exploration wells on the Labrador Margin.

microfossil events, and examine the distribution of benthic foraminifers along a paleobathymetric gradient from the margin to abyssal depths. In addition to the previously mentioned objectives, we compare faunas from Site 647 with those recovered from exploration wells along the Labrador Margin and northern Grand Banks and from DSDP sites in the North Atlantic and Norwegian-Greenland Sea to delineate first-order patterns in benthic foraminifer paleobiogeography. Studies of faunal similarity and migrations of taxa between basins are essential for understanding the history of arctic vs. antarctic sources for deep-water masses in the early Cenozoic.

SAMPLE LOCALITY

Site 647 was drilled at a water depth of 3861.8 m in the southern Labrador Sea (53°19.8′N, 46°15.7′W) on oceanic crust of Chron C24 age. The site is located approximately 90 km southeast of Site 112 (Fig. 1) on the southeast flank of the Gloria Drift, a depositional feature formed by bottom currents that

originate in the Norwegian-Greenland Sea. Two holes were drilled at Site 647. Hole 647A penetrated 580 m of Paleogene sediments, which were subdivided into four lithologic units (Fig. 2). Only Neogene sediments were recovered from Hole 647B, and these are not examined here.

Four major seismic reflectors are evident in multichannel seismic lines and in downhole logging records from Hole 647A (see "Site 647," Srivastava, Arthur, et al., 1987). The R2 reflector corresponds to a hiatus between upper Miocene nannofossil clay and lower Miocene siliceous silty clays. The prominent regional seismic reflector R3-R4 corresponds to lithologic changes bracketing a unit of porous siliceous nannofossil clays and clayey diatomite between 212 and 241 meters below seafloor (mbsf). There is no evidence of a hiatus at either of these reflectors. The R4 reflector corresponds to the previous identification of this reflector at Site 112 and seems to have no relationship to changes in bottom-water circulation.

Two intra-Eocene reflectors are visible near the base of the sediment sequence at Site 647. The first reflector, at approximately 525 mbsf, appears to correspond in depth with the base of lithologic Unit IIIC (Fig. 2). The second, at a calculated depth of 618 mbsf, occurs near a sudden change in carbonate content corresponding to a condensed interval and/or a hiatus separating the middle and lower Eocene.

METHODS

Shipboard core-catcher samples from Hole 647A were processed according to standard laboratory techniques. The 20-cm^3 samples from Hole 647A and samples from Site 112 were processed onshore following a procedure developed by M. A. Kaminski, M. J. Head, and D. B. Lazarus to separate foraminifers from other microfossils. First, samples were dried overnight at 60°C and then weighed to provide data on absolute abundance. Samples containing siliceous microfossils were partitioned into two parts. One-half the sample was disaggregated in a solution of 1% Calgon and sieved over a 38-μm sieve. The residue of this half of the sample was dried, dry-sieved over a 125-μm screen, and foraminifers were selected from the >125-μm fraction. The remaining >125-μm residue was combined with the 38- to 125-μm fraction and was used for radiolarian analyses.

The remaining one-half of the original 20-cm^3 sample was processed for foraminifers and palynomorphs. Distilled water was used at all times to minimize contamination. The sample was disaggregated in a 1% Calgon solution and sieved through a 63-μm sieve that was placed over a 1000-mL Nalgene beaker to save the washthrough. A wash-bottle was used to rinse the sample carefully until all clay and silt was washed through the sieve. The >63-μm fraction was rinsed into a drying pan and examined for palynomorphs. If these were present, distilled water was added to the residue, agitated, and decanted into a 1000-mL washthrough beaker until all light organic particles were decanted.

The beaker was covered with plastic wrap and allowed to settle one week, after which the decantate was siphoned off. The remaining sediment was transferred into Nalgene sample jars and sent to Martin Head at the University of Toronto for further processing for dinoflagellates. The >63-μm fraction was dried, dry-sieved using a 125-μm sieve, and benthic foraminifers were selected from the >125-μm fraction. These benthic foraminifers were combined with the specimens already selected from the radiolarian preparations, and specimens were mounted on cardboard slides for quantitative analysis.

For this study, a total of 124 samples from Hole 647A were quantitatively picked for benthic foraminifers; the faunal census is given in the Appendix. Faunal data (raw counts and percentage abundance) also are available from M. Kaminski in Lotus 123 (.WK1) format on 360k MS-DOS floppy disks. Each sample's age was interpolated from the sedimentation-rate curve (see "Site 647," Srivastava, Arthur, et al., 1987). From intervals having full recovery, we examined three samples per core, which yields a sample resolution of approximately one sample per 100 k.y. This level of resolution was achieved across the Eocene/Oligocene boundary and throughout most of the upper and upper-middle Eocene.

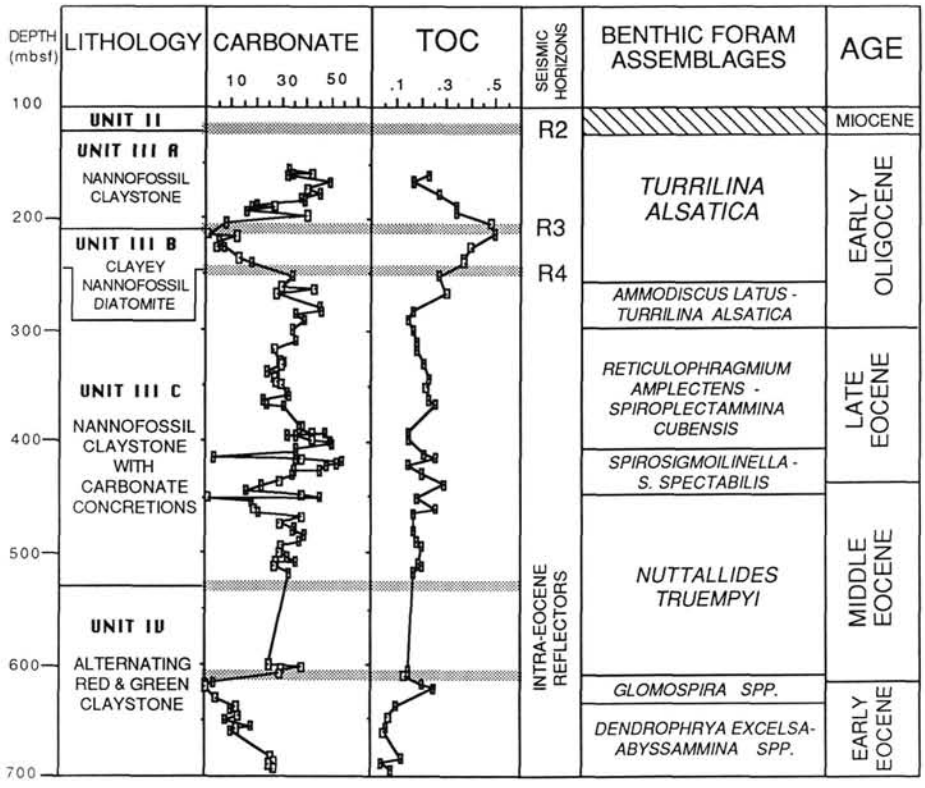

Figure 2. Comparison of lithostratigraphy, midsediment seismic reflectors, percentage of carbonate and total organic carbon content with benthic foraminifer biochronology in the Paleogene of Site 647. Depth to reflectors and lithologic data are taken from the "Site 647" chapter (Srivastava, Arthur, et al., 1987).

RESULTS

Biostratigraphy

The biochronology of Hole 647A is constrained by calcareous nannofossils, planktonic foraminifers, diatoms, radiolarians, and palynomorphs. In addition, the identification of anomaly 15 correlative magnetic reversals allows us to calibrate the age-depth curve to a standard geochronology (Berggren et al., 1985), and determine the chronology of benthic foraminifer FO and LO events (Table 1). A list of microfossil datums used to establish the chronology of Hole 647A can be found in the "Sedimentation Rates" section of "Site 647" (Srivastava, Arthur, et al., 1987). This chronology has been refined by Firth (this volume), and we use his biochronology across the early/middle Eocene boundary. By interpolation from the sedimentation-rate curve, the Eocene/Oligocene boundary was placed at 290 mbsf and the middle/late Eocene boundary at 410 mbsf. A hiatus, or condensed section, separating sediments of early Eocene and middle Eocene age is present between 610 and 640 mbsf. This hiatus, or condensed interval, corresponds approximately to the position of the lowermost intra-Eocene seismic reflector apparent in multichannel seismic records across the Gloria Drift (Fig. 2; "Site 647," Srivastava, Arthur, et al., 1987). Core recovery between the intra-Eocene seismic reflectors was incomplete, and only core-catcher samples from Cores 105-647A-55R to -61R were available for study.

Table 1. Estimated chronologic ages of benthic microfossil events in Site 647, based on the age model used for the sedimentation-rate curve (Srivastava, Arthur, et al., 1987).

Taxon	Depth (mbsf)	Age (Ma)
LO *Turrilina alsatica*	155.9	31
LO *Bathysiphon* sp.	251.2	35.5
LO *Glomospira charoides*	251.1	35.5
LO *Ammodiscus latus*	251.1	35.5
LO *Nuttallides umbonifera*	262.7	35.8
LO *Ammodiscus cretaceous*	280.5	36.3
LO *Osangularia mexicana*	280.5	36.3
LO *Gavelinella micra*	280.5	36.3
LO *Bolivina huneri*	281.4	36.4
LO *GIomospira irregularis*	285.0	36.5
LO *Recurvoides* spp.	290.3	36.6
LO *Reticulophragmium amplectens*	290.3	36.6
LO *Spiroplectammina spectabilis*	290.3	36.6
LO *Ammolagena clavata*	290.3	36.6
LO *Trochammina deformis*	290.3	36.6
LO *Ammobaculites* aff. *polythalamus*	290.3	36.6
LO *Subreophax scalaria*	290.3	36.6
LO *Saccammina complanata*	290.8	36.6
LO *Glomospira serpens*	290.8	36.6
LO *Trochamminoides irregularis*	290.8	36.6
LO *Rhizammina* spp.	300.3	36.9
LO *Haplophragmoides walteri*	300.3	36.9
LO *Reophax pilulifer*	318.0	37.4
LO *Gavelinella capitata*	318.0	37.4
LO *Cibicidoides grimsdalei*	328.4	37.6
LO *Hyperammina kenmilleri* n.sp.	329.9	37.7
LO *Bulimina macilenta*	329.9	37.7
LO *Karreriella coniformis*	331.4	37.7
LO *Bigenerina* sp.	331.4	37.7
LO *Reophax guttifer*	339.2	38 0
LO *Ammosphaeroidina* sp.	340.7	38.0
LO *Reticulophragmium placenta*	350.6	38.3
LO *Hormosina distans*	360.3	38.6
LO *Glomospira gordialis*	360.3	38.6
LO *Nuttallides truempyi*	386.0	39.2
LO *Karreriella conversa*	405.8	39.8
FO *Spiroplectammina cubensis*	408.8	39.9
FO *Spirosigmoilinella compressa*	425.8	40.4
LO *Spiroplectammina spectabilis perplexa*	434.4	40.6
LO *Spiroplectammina navarroana*	460.3	41.3
FO *Ammodiscus nagyi* n.sp.	498.3	42.4
LO *Aragonia* spp.	540.0	43.5
LO *Cibicidoides subspiratus*	569.1	44.3
FO *Ammodiscus latus*	578.8	44.6
LO *Verneuilinoides polystrophus*	578:8	44.6
LO *Dendrophrya* ex gr. *excelsa*	620.7	48.8–52.6
LO *Hormosina ovulum*	627.2	48.8–52.6
LO *Abyssammina* spp.	638.6	52.6–53.6
LO *Quadrimorphina profunda*	657.5	54.2

The lower Eocene to lower Oligocene of Hole 647A can be subdivided into seven assemblages, based on the partial ranges of characteristic benthic taxa. The assemblages were chosen to reflect a subdivision of the sedimentary section at a stage level and are named after taxa that are cosmopolitan and have correlative value in the North Atlantic. These assemblages are shown in Figure 2 and are discussed next, in order from oldest to youngest. The relative proportions of important taxa in the Paleogene section are shown in Figure 3.

1. *Dendrophrya* ex gr. *excelsa—Abyssammina* Assemblage (Samples 105-647A-71R-2, 42–45 cm, to -66R-2, 24–27 cm), lower Eocene:

This assemblage is characterized by the presence of the nominate taxa and contains a mixture of agglutinated and calcareous benthics in a *Subbotina patagonica* planktonic ooze typical of Zones P8 to P9 (Berggren and Schnitker, 1983). Calcareous foraminifers are silicified to some degree. The sediments overlying basement were deposited in a water depth of 1700 to 2000 m, based on estimates using the backtracking method of Sclater et al. (1985). The benthic assemblage displays evidence of a lower bathyal setting; for example, the relative proportion of *Lenticulina* spp. and *Bulimina* spp. is higher than in any of the overlying assemblages. The *Abyssammina—Dendrophrya* assemblage corresponds to nannofossil Zones NP11–NP13 (Firth, this volume).

The nominate taxa are common to abundant in some samples (Fig. 3). *Abyssammina* makes up 10% of the assemblage in Sample 105-647A-68R-1, 129–132 cm, and *Dendrophrya* ex gr. *excelsa* makes up 37% of the assemblage in Sample 105-647A-67-1, 40–43 cm. *Abyssammina* spp., *Quadrimorphina profunda, Bulimina trinitatensis*, and *Bulimina* cf. *semicostata* of Tjalsma and Lohmann (1983) are restricted to this assemblage. The latter species is transitional between *Bulimina semicostata* and *Bulimina glomarchallengeri*. An interesting agglutinated species tentatively identified as *Hormosina ovulum* was found in Samples 105-647A-70R, CC and -64R, CC. This occurrence was unexpected in that *H. ovulum* is not known to occur above the Paleocene in bathyal assemblages, and there is no other evidence for reworking.

2. *Glomospira* Assemblage (Samples 105-647A-65R-2, 31–34 cm, to -63R, CC), lower to middle Eocene:

Samples from a 20-m interval represented by Cores 105-647A-64R and -65R are barren of calcareous microfossils, and the benthic foraminifers are present in a "*Glomospira* facies." The most common species in this interval are *Glomospira irregularis, Glomospira charoides, Ammodiscus cretaceous, Karreriella coniformis, Trochamminoides* spp., and *Haplophragmoides walteri*. Depending upon where the base of the *Glomospira* Assemblage lies in Zone NPl3, the assemblage may be as old as 53.6 to 52.8 Ma. A *Glomospira* facies also occurs in "lower Eocene" sediments in the Carpathian Mountain Belt and is usually interpreted as reflecting a pelagic environment at bathyal to abyssal paleodepths. At Site 647 the presence of a *Glomospira* facies probably results from a rise in the CCD above 2500 m.

3. *Nuttallides truempyi* Assemblage (Samples 105-647A-63R-1, 139–142 cm, to -47R-4, 74–77 cm), middle Eocene:

This is the interval in Hole 647A between the LO of the carbonate-free claystones containing abundant *Glomospira* and the FO of *Spirosigmoilinella*. This assemblage is characterized by the common occurrence of the nominate taxon (Fig. 3). The lower portion of the assemblage corresponds to an interval of poor recovery between Samples 105-647A-54R, CC and -61R, CC. This interval was placed in the middle of Zone NP15 (Zones CPl3b–CP13C of Okada and Bukry, 1980) by Firth (this volume), which corresponds to an age between 48.7 and 47.0 Ma. The *N. truempyi* Assemblage therefore overlies a condensed section and/or a hiatus encompassing the uppermost lower Eocene and the lower-middle Eocene. The species *Cibicidoides subspiratus* (Nuttall) was found in Samples 105-647A-61R, CC, -60R, CC and -59R, CC. This is a distinctive taxon in the Atlantic, owing to its restricted stratigraphic range (Zones P9–P13; Van Morkhoven et al., 1986). The LO of *Aragonia* spp. occurs between Samples 105-647A-55R, CC and -56R, CC. This event was placed at the top of Zone P14 by Tjalsma and Lohmann (1983), but it apparently occured earlier in the Labrador Sea. Above Core 105-647A-55R, recovery was more or less continuous, and *Nuttallides treumpyi* decreases in relative abundance. Core 105-647A-54R was placed in nannofossil Zone NP16 by Firth (this volume), and interpolation from the sedimentation-rate curve yields an age of 45.5 Ma.

The agglutinated component composes approximately 80% of the benthic assemblage between Cores 105-647A-55R and -46R. Tubular species are dominant, but *Reticulophragmium amplectens* and *Recurvoides* spp. attain their maximum relative abundance in this interval. A number of important stratigraphic events also occur (Fig. 4). These are the FO of *Ammodiscus latus* in Sample 105-647A-52R-2, 45–48 cm; the LO of *Ammodiscus nagyi* n.sp. in Sample 105-647A-52R-5, 54–57 cm, and the LO of *Spiroplectammina navarroana* in Sample 105-647A-49R-6, 117–120 cm. In the North Sea, the LO of *S. navarroana* usually occured earlier, in the lower Eocene (Gradstein et al., 1988).

4. *Spiroplectammina spectabilis—Spirosigmoilinella* Assemblage (Samples 105-647A-46R-5, 60–63 cm, to -43R-5, 97–100 cm), middle-upper Eocene:

This interval in Hole 647A is defined by the partial range of *Spirosigmoilinella*, from its FO to the FO of *Spiroplectammina cubensis*. The assemblage is characterized by the acme of the *Spiroplectammina spectabilis* plexus (Fig. 3). This interval corresponds to the uppermost part of middle Eocene nannofossil zone NP17, and the lowermost upper Eocene. The exact position of the middle/late Eocene boundary, however has not been determined. Nannofossil stratigraphy (Firth, this volume) places the boundary within Core 105-647A-46R, but interpolation from the sedimentation rate curve places the boundary in Core 105-647A-43R. Our age model yields an age for this assemblage between 40.4 and 39.9 Ma.

Two important stratigraphic events are associated with the *S. spectabilis—Spirosigmoilinella* Assemblage (Fig. 4). The LO of the small, compressed variety of *Spiroplectammina spectabilis* (*S. spectabilis perplexa* of Kaminski, 1984) occurs in Sample 105-647A-46R-1, 60–63 cm. The last common occurrence (LCO) of *S. spectabilis spectabilis* occurs in Sample 105-647A-43R-3, 104–107 cm. This event occurs approximately 1 m above the middle/late Eocene boundary, as determined from the sedimentation-rate curve. Above this level, the abundance of *S. spectabilis* in our samples never exceeds 10%.

5. *Reticulophragmium amplectens—Spiroplectammina cubensis* Assemblage (Sample 105-647A-43R-3, 104–107 cm, to -31R-1, 132–135 cm), upper Eocene:

Within the accuracy of our microfossil and magnetic chronology, the interval represented by this assemblage encompasses the entire upper Eocene. The assemblage is defined by the concurrent range of *R. amplectens* and *S. cubensis*. The FO of *S. cubensis* (in Sample 105-647A-43R-3, 104–107 cm) occurs at about the same level as the LCO of *S. spectabilis*, so the latter event can also be used to determine the base of the interval. The LO of *R. amplectens* in Sample 105-647A-31R-1, 132–135 cm, occurs within 1 m of the Eocene/Oligocene boundary, which was placed at 290 mbsf according to our age-depth model.

Within this interval, there is a gradual transition from an agglutinated assemblage to a predominantly calcareous assemblage in the Oligocene. A number of typical Eocene taxa, such as *Nuttallides truempyi, Cibicidoides grimsdalei*, and many of the "flysch-type" agglutinated taxa, have their LOs in this assemblage. This is particularly apparent in Cores 105-647A-32R and -31R, which contain the LOs of 10 agglutinated taxa (Fig. 4). The interval can be further subdivided into a lower and upper portion, based on the extinction of *Ammosphaeroidina, Bulimina macilenta, C. grimsdalei*, and *Karreriella coniformis* between Cores 105-647A-35R and -37R. The LO of *N. truempyi* in Sample 105-647A-41R-1, 58–61 cm, is another important extinction event, which corresponds to an approximate age of 39 Ma.

Throughout the interval, the assemblage is still numerically dominated by tubular agglutinated species. In the upper portion of the assemblage, the rectilinear calcareous group (*Stilostomella, Dentalina*, nodosariids), *Pullenia* spp., and the "2nd Principal Component" of Tjalsma and Lohmann (*Cibicidoides, Oridorsalis, Gyroidinoides*, and *Globocassidulina*) become more important.

6. *Ammodiscus latus—Turrilina alsatica* Assemblage (Samples 105-647A-31R-1, 132–135 cm, to -27R-1, 78–83 cm:), basal Oligocene:

This interval is defined by the concurrent range of the nominate taxa. The FO of *Turrilina alsatica* coincides with the LO of *R. amplectens* in Sample 105-647A-31R-1, 132–135 cm. The LO of *Ammodiscus latus* was observed in Sample 105-647A-27-1, 78–83 cm, but its true LO may be as much as 14 m higher. Only drilling slurry was recovered in Core 105-647A-26R, which was not sampled for benthic foraminifers. This assemblage corresponds to the basal Oligocene and represents the time interval between 36.6 ± 0.05 and 35.3 ± 0.2 Ma.

The species *Ammodiscus latus* attains its maximum relative abundance in the basal Oligocene (Fig. 3), and *Turrilina alsatica* is also a common species in many samples. A "flood" of *Nuttallides umbonifera* was observed in Sample 105-647A-30R-5, 10–13 cm (36.5 ± 0.05 Ma), where it makes up 56% of the total assemblage. The increased abundance of *N. umbonifera* has also been observed in the basal Oligocene of the southern Pacific Site 277 (Corliss, 1979) and eastern Atlantic Site 119 (Miller, 1983), which suggests that this event may be useful for interbasinal correlation. Within this interval, the agglutinated foraminifers display a noticable reduction in size, and most of the remaining flysch-type taxa (*Glomospira charoides, Bathysiphon* sp., *Reophax* spp., *Ammodiscus cretaceous*, and *Glomospira irregularis*) have their LOs. Throughout much of the interval, the benthic assemblage is numerically dominated by rectilinear calcareous taxa, the "2nd Principal Component" taxa, and *Pulle-*

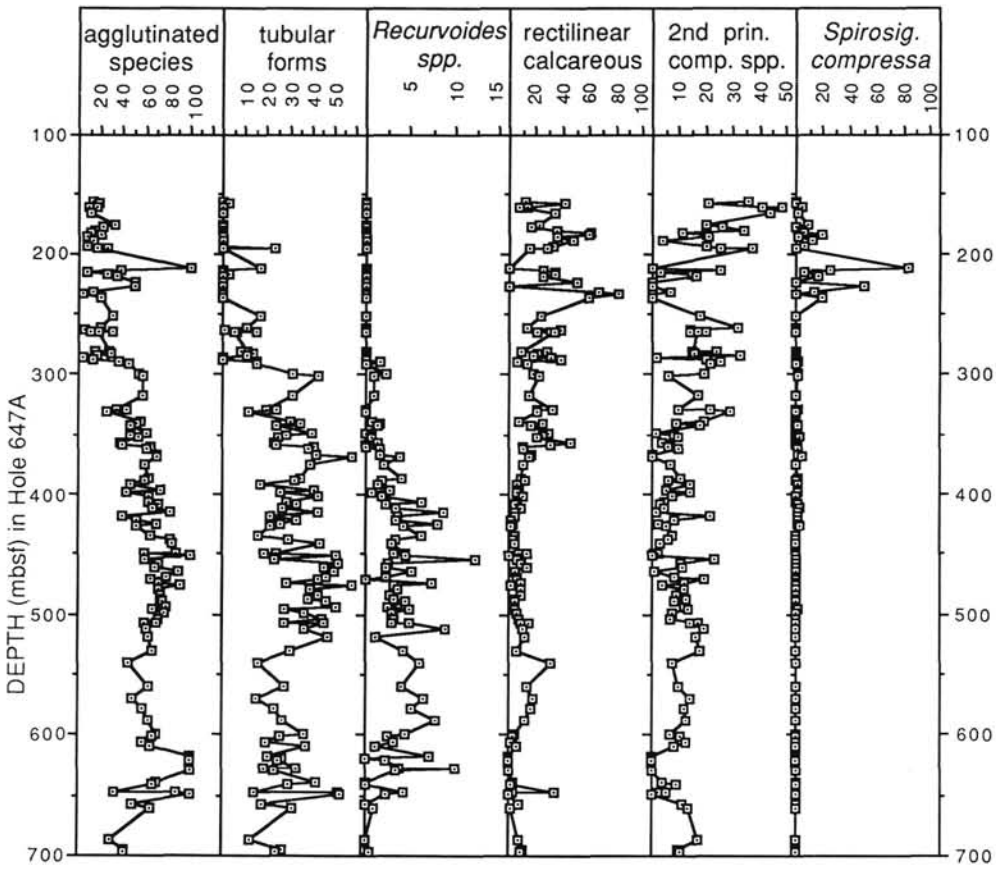

Figure 3. A. Relative abundance of important benthic foraminifer species. B. Species groups in Site 647.

nia spp. This assemblage corresponds to the "*Stilostomella* Assemblage" of Miller et al. (1982) at Site 112.

7. *Turrillina alsatica* Assemblage (Sample 105-647A-25R-4, 107–110 cm, to -17R-1, 107–110 cm), lower Oligocene:

This is the interval between the LO of *Ammodiscus latus* and the top of the Paleogene section in Hole 647A. The upper limit of the *Turrillina alsatica* Assemblage is truncated by a barren interval and one or more hiatuses above Core 105-647A-17R. In exploration wells drilled on the Labrador Margin, the LO of *T. alsatica* is used to identify the Paleogene/Neogene boundary, but a hiatus encompassing much of the late Oligocene is also present in the area (Gradstein, 1987).

Throughout the interval, the abundance and diversity of benthic taxa is low, and washed residues contain mainly siliceous debris. Many samples in lithologic Unit IIIB contain only rectilinear and unilocular calcareous species, *Karreriella*, and *Spirosigmoilinella*. The most characteristic taxa is *Spirosigmoilinella compressa*, which displays its greatest relative abundance in this relatively depauperate assemblage. However, its absolute abundance in the early Oligocene does not differ noticably from its abundance in the late Eocene. *Uvigerina* are common in samples from Core 105-647A-20R. This occurrence corresponds to a peak in the total organic carbon (TOC) content of the sediment (Fig. 2), which along with an increase in the flux of biogenic opal possibly indicates high paleoproductivity. Among flysch-type agglutinated taxa, only *Cribrostomoides subglobosus* and *Rhabdammina* persist into this assemblage.

DISCUSSION

Eocene Benthic Foraminifer Paleobiogeography

The Eocene deep-water benthic foraminifer assemblages of the North Atlantic and adjacent seas can be divided into two end-members, based on the presence or absence of calcareous or agglutinated foraminifers (Fig. 5). Calcareous assemblages are found in low to middle latitudes in DSDP sites and exploration wells along continental margins and in ridge-crest environments. Below or near the oceanic CCD in the equatorial Atlantic, Eocene sediments are barren of foraminifers. The availability of carbonate appears to be a factor controlling the distribution of agglutinated assemblages (Gradstein and Berggren, 1981). Predominantly "flysch-type" assemblages are well developed in high latitudes and in areas where the rapid deposition of clastic sediments creates a benthic environment unfavorable for the preservation of carbonate tests. These assemblages have been found in active margin settings in the Alpine regions and in slope basins in Trinidad (Kaminski et al., 1988), the Labrador Margin and North Sea (Gradstein and Berggren, 1981), as well as in DSDP Sites in the Norwegian-Greenland Sea (Verdenius and van Hinte, 1983). Hole 647A is unique among North Atlantic DSDP and ODP sites, because it is the only hole with a complete record of calcareous and agglutinated benthic foraminifers from the middle Eocene through the early Oligocene.

Comparison of Site 647 Assemblages with Regional Zonations

Agglutinated foraminifers have been used to define regional zonations for the early Tertiary in the North Sea, Norwegian-

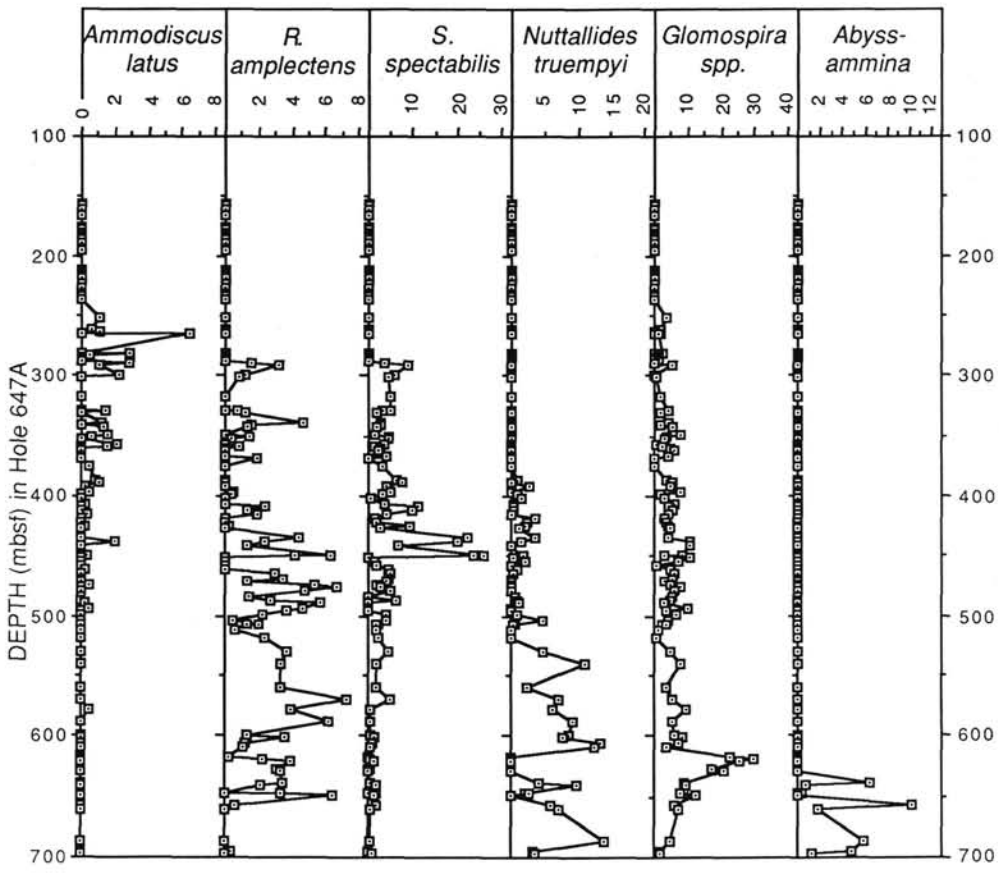

Figure 3 (continued).

Greenland Sea, on the Labrador Margin, as well as in the Polish Flysch Carpathians (Verdenius and van Hinte, 1983; Gradstein and Agterberg, 1982; Geroch and Nowak, 1984; Gradstein et al., 1988). A summary of these zonal schemes is shown in Figure 6. However, in all the regions mentioned above, the task of correlating these zonations to a standard geochronology has been a problem owing to the paucity of calcareous microfossils and lack of magnetic reversal information. Therefore, the biochronology of Hole 647A may serve as a key for correlating the benthic foraminifer stratigraphy of the Labrador Margin to the Norwegian-Greenland and North seas.

The Paleogene Norwegian-Greenland Sea zonation of Verdenius and van Hinte (1983) was based upon DSDP samples collected during Leg 38. The Eocene/Oligocene boundary in the Leg 38 sites was recognized using the LOs of *Spiroplectammina spectabilis* and/or *Reticulophragmium amplectens*. The use of these taxa as Eocene marker species was based on analogies with the Polish Carpathians (Grzybowski, 1898) and the Eocene of Belgium (Kaaschieter, 1961). However, in the Leg 38 samples, calibration of ranges of these taxa to a standard planktonic microfossil chronology was tentative. In Hole 647A, the LO of both taxa was found at 290.3 mbsf, in Sample 105-647A-31R-1, 132–135 cm. This sample is just 30 cm below the position of the Eocene/Oligocene boundary assigned by the paleontologists on Leg 105 (Srivastava, Arthur, et al., 1987).

Both the North Sea and Labrador Margin zonations are made up of RASC (ranking and scaling) interval "zones" based on clusters of LOs of taxa in exploration wells. The RASC biozones are named after characteristic species which most likely have their LOs in the interval, but not necessarily at the top of that interval. Therefore, RASC "zones" reflect the average ranges of taxa, and may differ conceptually from traditional zonations, based on maximum ranges of taxa in a given interval. When a RASC optimum sequence is scaled in linear time by the identification of microfossil datum events, "missing intervals" of time become apparent. In the Paleogene Labrador Margin and North Sea zonations, the missing intervals correspond to hiatuses caused by basinward shifts in shoreline (Gradstein, 1987). Reviews of the methodology used in constructing and interpreting RASC zonations can be found in Gradstein et al. (1985), D'Iorio (1986), Gradstein (1987), and Williamson (1987).

The species *Reticulophragmium amplectens* is perhaps the most distinctive Eocene species in North Atlantic and Tethyan flysch-type assemblages, and it is used as a stratigraphic marker species in every zonal scheme (Fig. 6). Its total range is given as lower to upper Eocene in the Outer Carpathians (Olszewska and Smagowicz, 1977; Morgiel and Olszewska, 1981). Its partial range and optimum occurrence characterizes the middle Eocene *Cyclammina amplectens* Zone of Geroch and Nowak (1984). In the North Sea, Gradstein et al. (1988) defined a middle to late Eocene *R. amplectens* RASC interval zone based on the partial range of this species. In this region, it was reported to range from the lower Eocene to the Eocene/Oligocene boundary, with possible occurrences in the lower Oligocene. On the Labrador Margin, Gradstein (1985) defined a late Eocene *Turborotalia pomeroli—R. amplectens* RASC interval zone. The total range of this species was given as lower to upper Eocene by Miller et al. (1982).

The relative abundance record of *R. amplectens* in Hole 647A is shown in Figure 3. The FO of this taxon was found in Sample 105-647A-70R, CC. This sample has been dated biostratigraphically in the upper part of Zone NP11. The FO of *R. amplectens* in Hole 647A is somewhat older than its FO reported in the Subsilesian Unit of the Outer Carpathians in

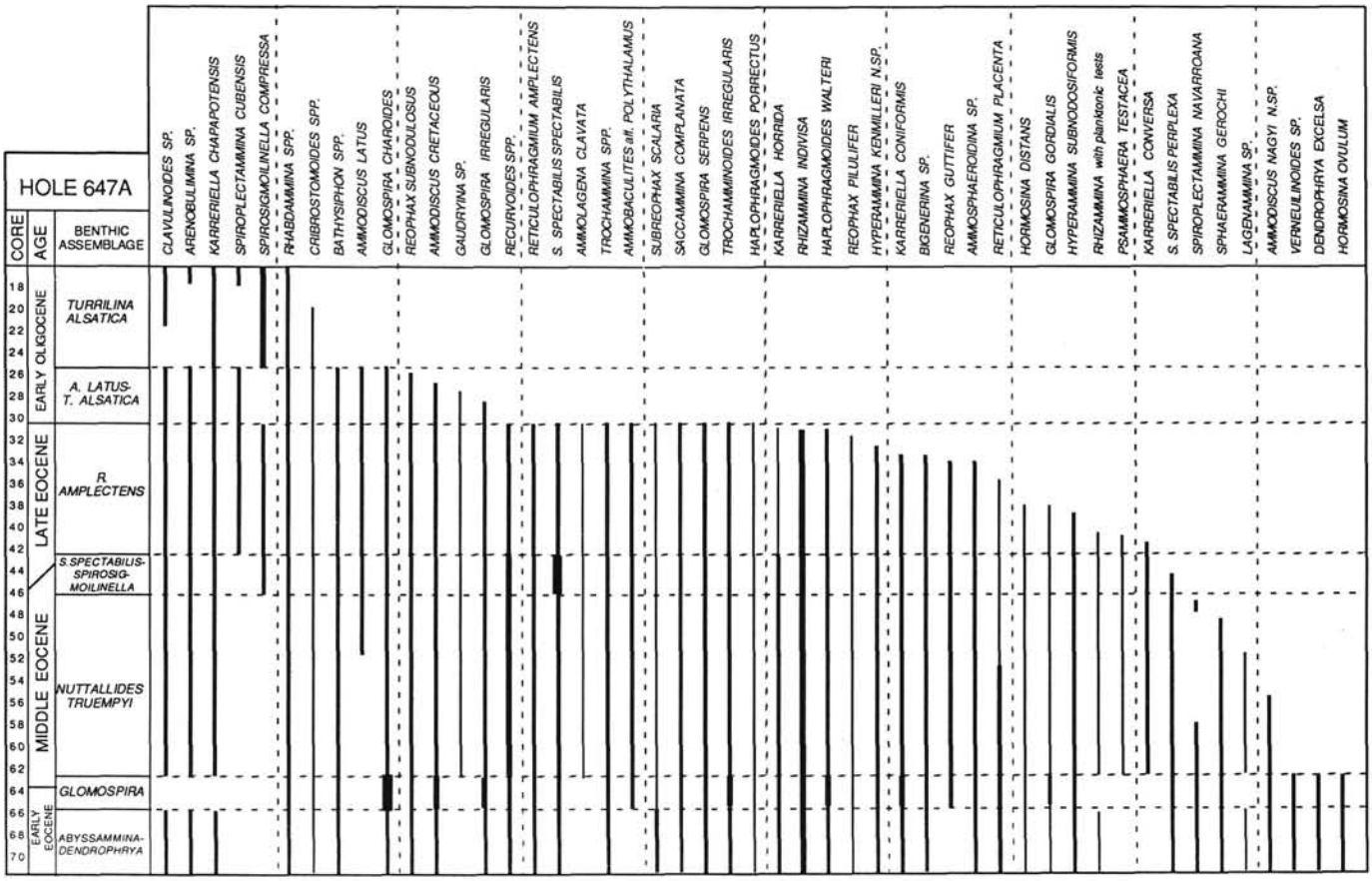

Figure 4. Stratigraphic occurrence of common agglutinated calcareous species in Site 647.

Moravia (Hanzlikova, 1983), where it was first found in the upper part of the *M. aragonensis* Zone (P8). The greatest abundance of *R. amplectens* in Hole 647A occurs in the middle Eocene. In this respect, its occurrence displays similarities with the Carpathian assemblages. The extinction of this species at 36.6 Ma indicates that it is a reliable indicator of the Eocene/Oligocene boundary in the deep Labrador Sea.

The utility of *Spiroplectammina spectabilis* as an indicator of the Eocene/Oligocene boundary is probably restricted to abyssal assemblages. In the North Sea and Labrador Margin, the Eocene sequences display a series of LOs of flysch-type taxa that mainly reflect the shallowing of the basins as sediment supply exceeded tectonic subsidence. *Spiroplectammina spectabilis* disappears from the Labrador Margin in the lower Eocene, but persisted at Site 647 and the deep Norwegian-Greenland Sea until the Eocene/Oligocene boundary. Interestingly enough, in the North Sea, *S. spectabilis* has a diachronous LO in wells aligned from south to north along the axis of the basin (Gradstein et al., 1988).

Upper Eocene assemblages in the North Sea, Poland, and on the Labrador Margin contain the species *Ammodiscus latus* and *Cyclammina rotundidorsata*. In the Carpathians, the partial range of the former and the total range of the latter are used to define a late Eocene zone (Fig. 6). However, neither of these species is present in the deep Norwegian-Greenland Sea. *Cyclammina rotundidorsata* was reported by Verdenius and van Hinte (1983) from the Oligocene of Site 345 and the Miocene of Site 348, but the specimen illustrated by them is not typical of the species, and may have been misidentified. *Ammodiscus latus* (*sensu lato*) occurs in both bathyal and abyssal assemblages in the Labrador Sea. The abyssal variety is noticeably smaller than the bathyal variety, and because of this Miller et al. (1982) recorded its occurrence at Site 112 as *Ammodiscus rugosus* Schijfsma, following Krasheninnikov and Pflaumann (1977). However, *A. rugosus* is an Upper Cretaceous species known from the epicontinental deposits of Europe (Schijfsma, 1946), and possibly from Site 367 off Morocco (Krasheninnikov and Pflaumann, 1977). Because of the restricted stratigraphic occurrence of the "rugose" *Ammodiscus* in Hole 647A, we believe that this species is a deep-water ecophenotype of *A. latus*. Finding the LO of *A. latus* above the extinction of *R. amplectens* in Hole 647A agrees with the relative position of these taxa on the Labrador and northern Grand Banks margins (Fig. 7).

The Oligocene sediments of Norwegian-Greenland Sea sites also contain *Spirosigmoilinella*, which was used by Verdenius and van Hinte (1983) as a zonal indicator. At Site 338 on the Vøring Plateau, *Spirosigmoilinella* was not observed below the LO of *S. spectabilis*, or below the LO of *R. amplectens* at Site 345 in the Lofoten Basin. These species were used to determine the Eocene/Oligocene boundary in the Leg 38 Norwegian-Greenland Sea sites (Verdenius and van Hinte, 1983), and both species range to the top of the Eocene in Site 647.

Correlation of Holes 647A and 112

Site 112 is located approximately 90 km northwest of Site 647, and until now, constituted the only abyssal Paleogene reference section in the Labrador Sea. A total of six cores containing Paleogene sediments were recovered from this site, and preliminary stratigraphic analysis was conducted by Berggren (1972), Perch-Nielsen (1972), and Bukry (1972). Unfortunately, the Eocene/Oligocene boundary and the position of subsurface seismic reflectors at this site are represented by coring gaps. The

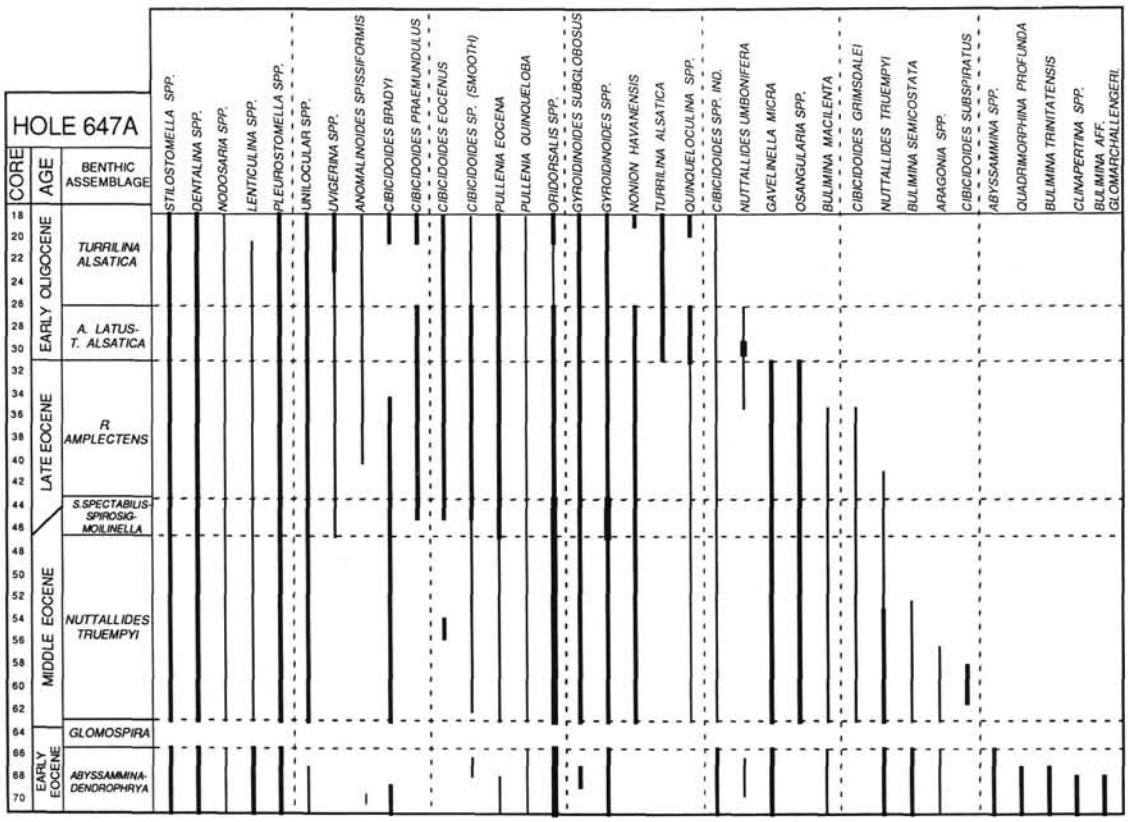

Figure 4 (continued).

foraminifer and nannofossil stratigraphy of Hole 112 was restudied by Miller, Gradstein, Berggren, and Aubry (in Miller et al., 1982), who were able to correlate Cores 12-112-12R to -15R with standard planktonic microfossil zonations (Table 2).

For this study, we examined benthic foraminifer assemblages from Hole 112 to correlate the position of individual cores from this site with Hole 647A (Fig. 6). Our foraminifer abundance data from Hole 112 are given in the Appendix.

Core 12-112-11R contains a calcareous benthic assemblage belonging to the *Turrilina alsatica* Assemblage in Hole 647A. The diverse nature of the fauna and good preservation present in Sample 12-112-11R-2, 102–106 cm, is comparable only to the assemblages above the siliceous sediments of lithologic Unit IIIB in Hole 647A. The composition of the assemblage compares best with assemblages from Core 105-647A-17R.

Sample 12-112-12R-1, 44–46 cm, contains a planktonic assemblage with *Chiloguembelina, Pseudohastigerina*, and *Bolboforma irregularis*. In Hole 647A, the LO of *Chiloguembelina* and *B. irregularis* were found in Sample 105-647A-27R-1, 78–85 cm. However, the only flysch-type agglutinated species present in Sample 12-112-12R-1, 44–46 cm is *Rhabdammina* sp. The lack of *Ammodiscus latus* and *Glomospira charoides* in this sample indicates that it belongs in the *Turrilina alsatica* Assemblage. The assemblage in this sample probably correlates with the unsampled interval between Cores 105-647A-25R and -27R.

Two samples from Core 12-112-13R were examined for benthic foraminifers (Samples 12-112-13R-3, 118–122 cm, and -13R-5, 120–124 cm). Both samples contain *Ammosphaeroidina* and *Karreriella coniformis*, which suggests that Core 12-112-13R correlates with the lower one-half of our *R. amplectens* Assemblage. The position of the assemblage with regard to Hole 647A can be further constrained by the absence of *N. truempyi*, and the low abundance of *Spiroplectammina spectabilis*. This assemblage compares well with assemblages from Cores 105-647A-36R through -40R.

Cores 12-112-14R and -15R correlate with our *Nuttallides truempyi* Assemblage. We did not find any specimens of *Spirosigmoilinella compressa* in the two samples from Core 12-112-14R examined for this study (Samples 12-112-14R-2, 100–104 cm, and 12-112-14R-3, 112–114 cm) but its presence was reported by Miller et al. (1982) from a single sample. In the *Spirosigmoilinella—S. spectabilis* Assemblage of Hole 647A, however, the occurrence of *Spirosigmoilinella* is continuous (see Appendix). The assemblage from Core 12-112-14R contains *S. spectabilis perplexa, Reticulophragmium* sp. (evolute), and abundant *N. truempyi*. In addition, the abundance of *S. spectabilis sensu lato* in our samples from Core 12-112-14R does not exceed 6%. This suggests a better correlation with our *N. truempyi* Assemblage. Although Miller et al. (1982) referred the agglutinated component of this core to a "*Spiroplectammina spectabilis* assemblage," this assemblage does not correlate with our *Spirosigmoilinella—S. spectabilis* Assemblage (Fig. 6). Core 12-112-15R belongs in nannofossil Zone NP14 (Miller et al., 1982) and contains poorly preserved calcareous benthic foraminifers that are overgrown with pyrite in a manner analogous to assemblages from Samples 105-647A-56R, CC and -58R, CC. The assemblage in Core 12-112-15R contains *Ammodiscus nagyi* n.sp., but none of the other species typical of the lower Eocene of Hole 647A (see Fig. 4).

The basal core of Hole 112 was cut approximately 10 m above basement, which at this site was formed near the boundary between the reversed and normal interval of Chron 26. The indurated red claystones overlying basement are barren of calcareous microfossils. On the Labrador Margin, the Paleocene/Eocene boundary is determined by the LOs of *Gavelinella beccariiformis, Rzehakina epigona*, and rare *Planorotalides chap-*

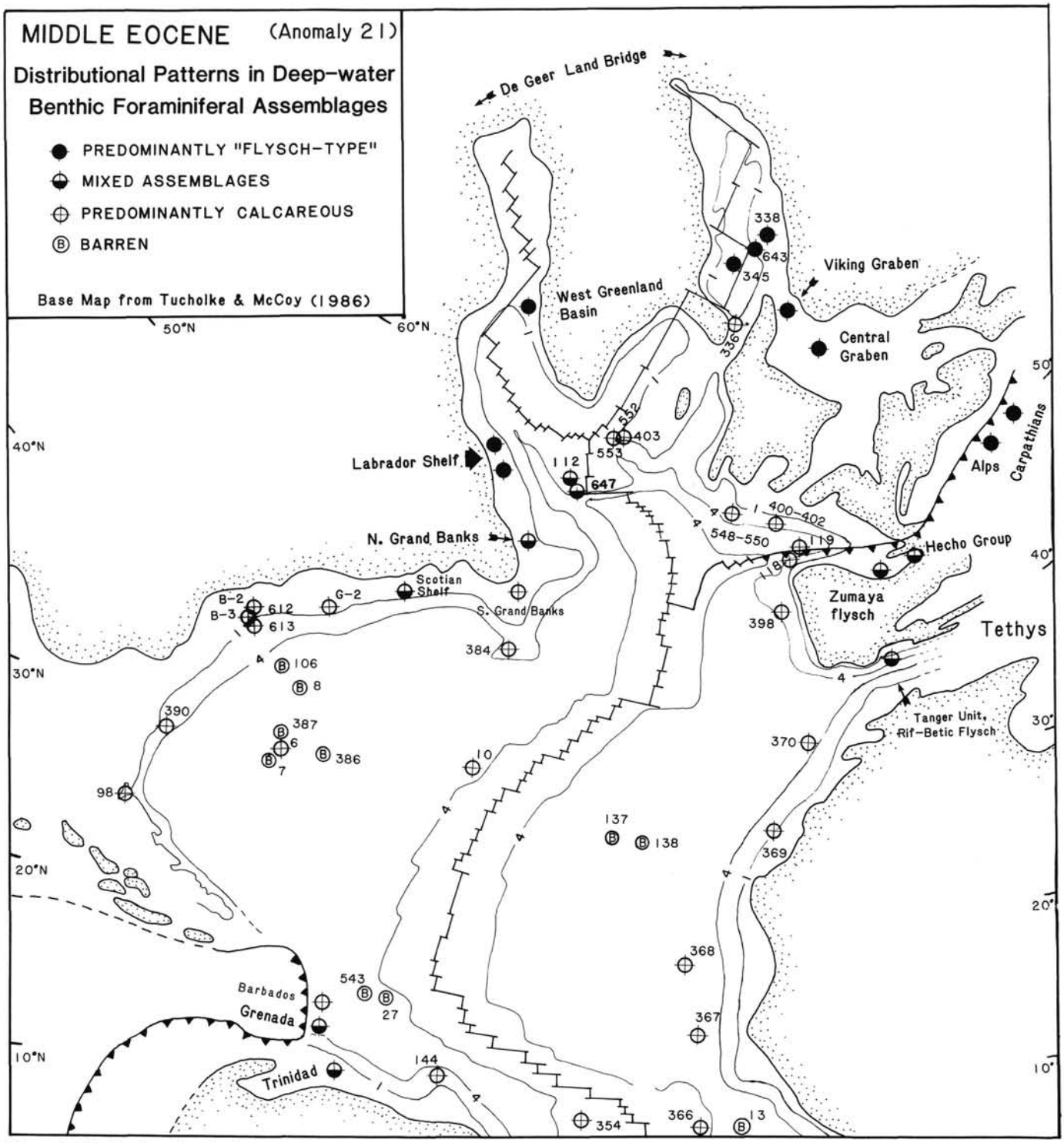

Figure 5. Distribution of agglutinated, calcareous, and mixed benthic foraminifer assemblages in the North Atlantic in the late early to middle Eocene. Data are compiled from site reports, personal observations, and personal communication with J.P. Beckmann, S. Gofas, W. Kuhnt, R. M. Leckie, H. P. Luterbacher, K. G. Miller, L. E. Ostermann, C. W. Poag, A. von Hillebrandt, and M. A. Williamson. Sites that are barren of foraminifers are also shown.

mani. However, the latter species may persist into the lower Eocene in the abyssal western North Atlantic (Tjalsma and Lohmann, 1983). Other species restricted to the Paleocene on the Labrador Margin are *Hormosina ovulum, Hormosina excelsa, Saccammina placenta, Tappanina selmensis*, and rare Danian planktonics (*Subbotina pseudobulloides, S. triloculinoides, Planorotalites compressus*).

In Sample 12-112-16R-1, 85–87 cm, we found specimens of *Hormosina*, but these persist into the lower Eocene of Hole 647A. This sample also contains *R. epigona, Labrospira pacifica*, and *S. placenta*, species that do not occur in Hole 647A. In Trinidad and in the North Sea, *Labrospira* does not occur above the Paleocene. Therefore, we favor a Paleocene age assignment for Core 12-112-16R.

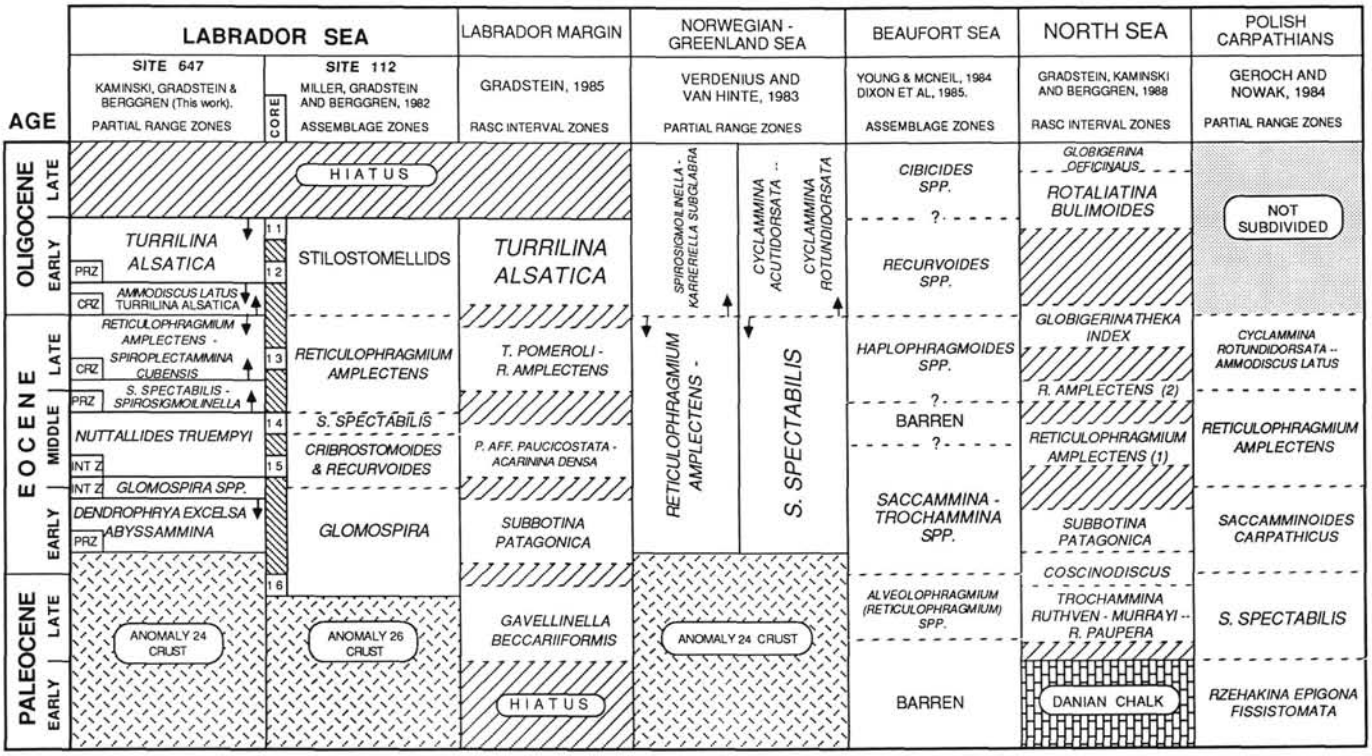

Figure 6. Comparison of Paleogene zonal classifications in areas containing flysch-type assemblages. Correlation of Sites 112 and 647 is from this study. Zonal boundaries that have not been tied to a standard geochronology (Berggren et al., 1985) are indicated by dashed lines. The Labrador Margin and North Sea RASC zonations have been scaled vs. linear time (after Gradstein, 1987) to show the position of stratigraphic breaks.

Correlation of Hole 647A with the Labrador Margin

The benthic foraminifer assemblages from Hole 647A and the Labrador Margin display differences related to paleobathymetry and depositional setting. The Eocene-Oligocene Labrador Margin sequences were deposited in an outer neritic to upper bathyal clastic environment, and abyssal taxa are absent from the benthic foraminifer assemblages. Faunal diversity in samples from exploration wells on the Labrador Margin is noticeably lower than at Site 647, but a number of important benthic foraminifers occur in both regions, including *Turrilina alsatica, Rhabdammina* spp., *Ammodiscus latus, A. cretaceus, Reticulophragmium amplectens, R. placenta, Haplophragmoides walteri, Ammosphaeroidina* sp., *Reophax pilulifer, Karreriella conversa, K. horrida, Spiroplectammina spectabilis, S. navarroana, Ammobaculites* aff. *polythalamus, Glomospira charoides, Trochamminoides* spp., and *Hormosina ovulum*. Few species of calcareous foraminifers are present in the Labrador Margin assemblages, and these are represented mainly by neritic to upper bathyal species of *Nodosaria, Lenticulina, Plectofrondicularia, Cibicidoides*, and uvigerinids. With the exception of *T. alsatica*, none of the middle Eocene-Oligocene calcareous species typical of the Labrador Margin were found in Hole 647A. A few of the more offshore wells contain deep-water calcareous species in the lower Eocene, including *Nuttallides truempyi*.

Figure 7 presents Paleogene RASC benthic foraminifer zones and important benthic taxa in seven wells aligned from south (Adolphus D-50) to north (Karlsefni A-13) on the Labrador Margin. In these wells, several benthic foraminifers possess the same order of LO events. The LOs of *T. alsatica, H. walteri, Ammosphaeroidina*, and *S. navarroana* do not cross over one another. The LO of *Ammodiscus latus*, however, appears to be variable with respect to *T. alsatica*. In the Bonavista C-99 and South Labrador N-79 wells, *A. latus* was found above *T. alsatica*, but this may be an artifact of sampling. *T. alsatica* is often a rare species on the Labrador Margin. *Reticulophragmium amplectens* displays a high crossover frequency with respect to *H. walteri* and *Ammosphaeroidina*, which suggests a small interfossil distance between them. However, this species appears to intergrade with *R. placenta* in the younger portion of its stratigraphic range, so determining its true LO is sometimes subjective. The LOs of *S. spectabilis* and *Glomospira* extend to youngest levels in the southern Adolphus D-50 and Blue H-28 wells, but this may be due to the deeper paleobathymetry of these wells. These species are present at younger levels in deeper assemblages.

The probabilistic optimum sequence of microfossil LOs on the Labrador Margin and northern Grand Banks is shown in Figure 8. This is an ordering based on the average position of extinction events occurring in at least seven of the 23 wells studied. Of the 35 Paleogene extinction events recorded on the Labrador Margin, 15 also were present in Hole 647A. These extinction events are listed across the top of Figure 8, in a manner analogous to a bivariate scatter plot. The probabilistic LO of *Turrilina alsatica* is used to identify the top of the Paleogene sequence on the Labrador Margin. However, the true upper range limit of this event in Hole 647A is most likely truncated by the barren interval and hiatus above Core 105-647A-17R. Microfossil events that extend to younger stratigraphic levels in Hole 647A than on the Labrador Margin, plot below a best-fit line between the points.

The most noticeable difference between the Labrador Margin and deep Labrador Sea extinction events is the stratigraphic range of *Glomospira charoides* (number 56 in Fig. 8). This is a long-ranging taxon that is present in the modern North Atlantic. Its local LO is usually associated with the Paleocene/Eocene boundary on the Labrador Margin and in the southern North Sea, but the taxon extends to the top of the *Ammodiscus latus—Turrilina alsatica* Assemblage (early Oligocene) in Hole 647A.

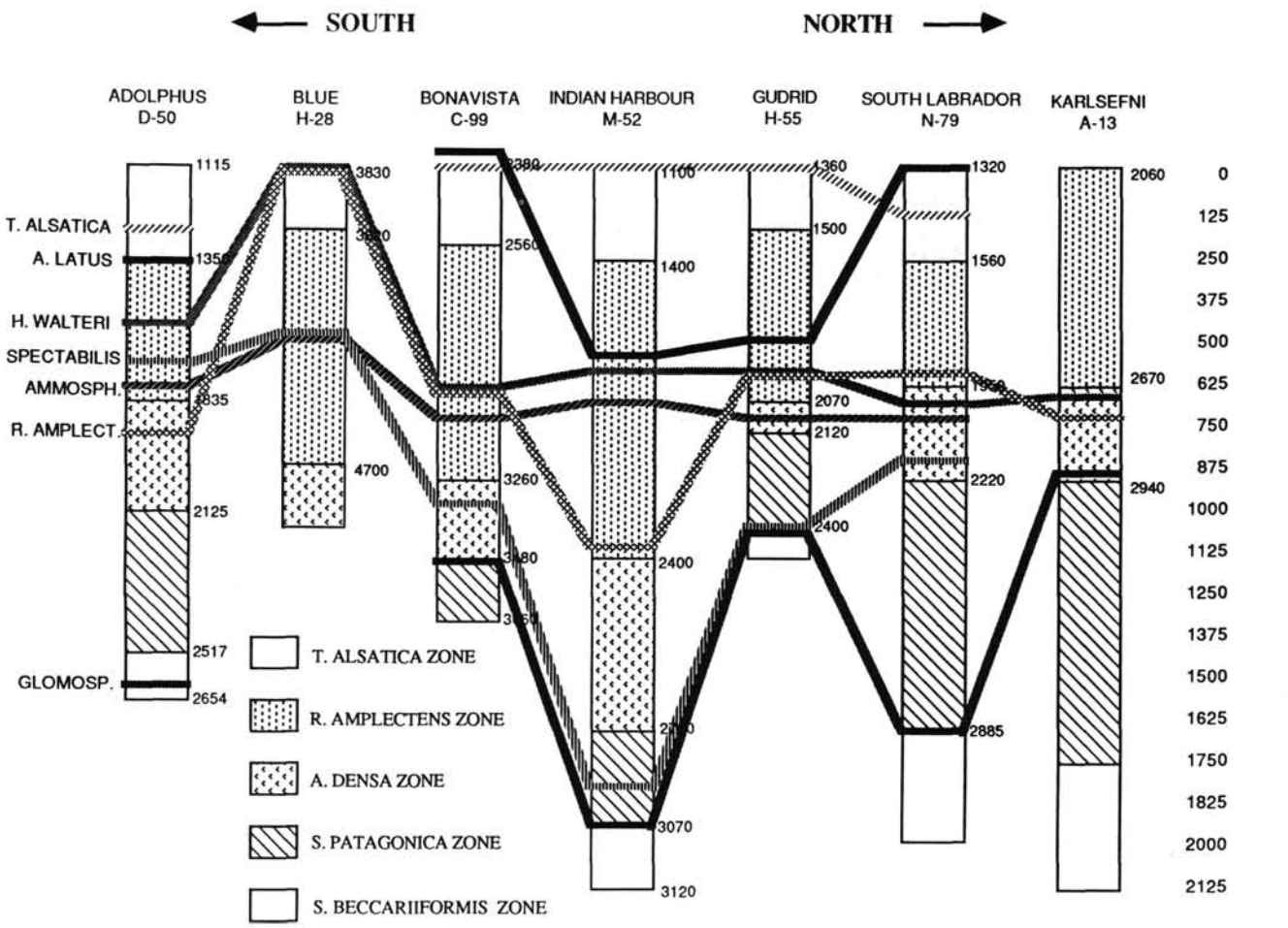

Figure 7. Important benthic foraminifer extinction levels in seven exploration wells on the Labrador Margin. Depth scale on right is thickness of Paleogene sediments (in meters).

Table 2. Paleogene cores from Hole 112.

Hole 112 Core	Age[a]	
	Nannofossil zone	Planktonic zone
12R	NP22	Not diagnostic
13R	NP19	P15–P16
14R	NP17	Not older than P14
15R	NP14	P10
16R	Barren	Barren

[a] (from Miller et al., 1982).

Spiroplectammina spectabilis has its LO earlier on the Labrador Margin than in Hole 647A, as mentioned above. The planktonic species *Pseudohastigerina micra* also extends to younger levels in Hole 647A, but this may be a function of poorer preservation of calcareous microfossils or the larger sieve used to process samples from exploration wells. The LO of *P. micra*, nevertheless occurs about 2 m.y. earlier in the Labrador Sea than in low-latitude sites, and thus cannot be used as a reliable planktonic datum event in high latitudes.

Of the benthic microfossil extinction events in Figure 8, only *A. latus, Ammobaculites* aff. *polythalamus, Ammosphaeroidina* sp. 1, and *Karreriella conversa* plot near a best-fit line. This suggests that these taxa are isobathyal and that their extinction events can be used for correlation at different paleodepths.

PALEOECOLOGY AND PALEOCEANOGRAPHY

Benthic Foraminifers and the Burial History of the Labrador Shelf and Sea

The burial history of the sedimentary wedge along the Labrador Margin and in the deep Labrador Sea is strongly influenced by the tectonic history of the region. The geologic record on the margin shows three phases of sedimentation:

1. A rifting phase before Anomaly 34 of mid-Cretaceous age (Fig. 9, North Leif I-05 well).
2. A seafloor spreading phase between Chrons C34 and C13 (Campanian-Maestrichtian to earliest Oligocene age).
3. A late Paleogene to Neogene Neotectonic phase.

Gradstein and Srivastava (1980) were the first to draw attention to this relatively simple subsidence and sedimentation pattern as illustrated by the depositional histories in several exploration wells. As reported by Gradstein and Berggren (1981), the temporal distribution of flysch-type agglutinated foraminifers on the Labrador Margin is essentially confined to the seafloor-spreading phase, Maestrichtian to Eocene. This is the time when the sedimentary wedge along the margin experienced bathyal conditions, particularly along the modern shelf edge.

The occurrence of flysch-type agglutinated assemblages in selected Labrador Sea wells is shown in Figures 9 and 10. These

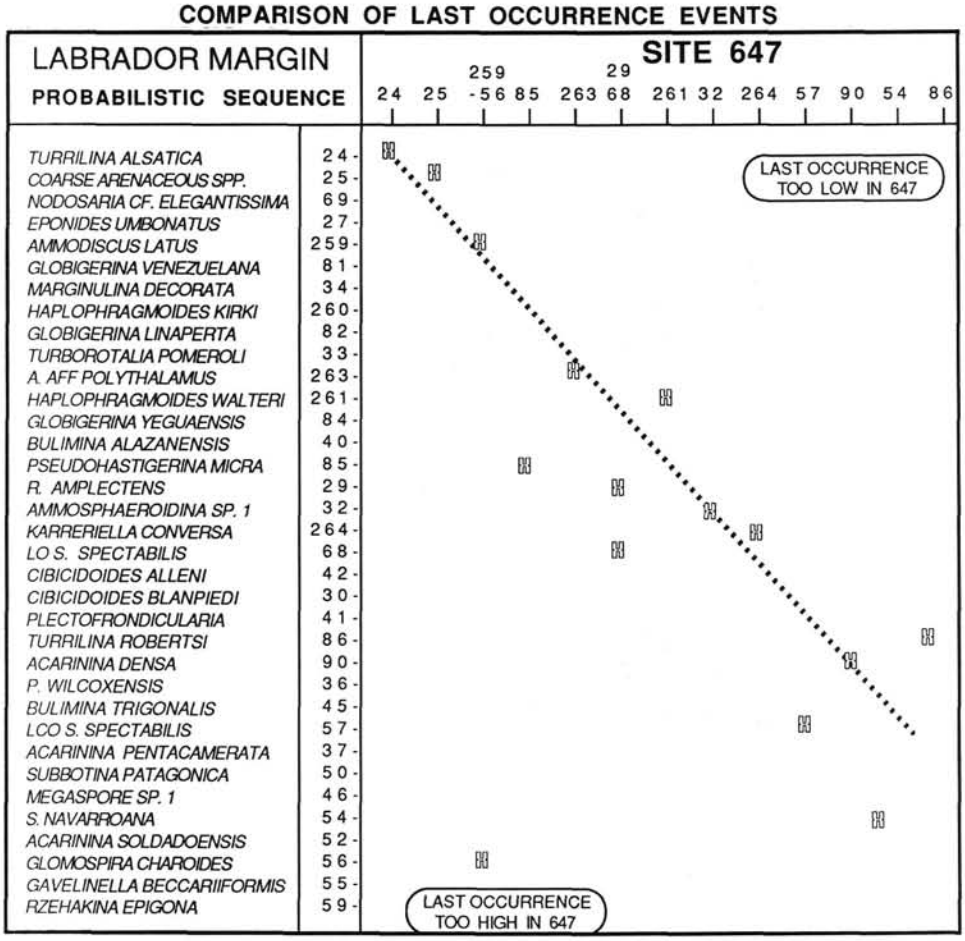

Figure 8. Comparison of microfossil extinction events in common between the probabilistic Labrador Margin sequence and that at Site 647. Numbers across the top of the scatterplot are dictionary numbers assigned to each taxon.

figures display the restored sedimentation rates and burial histories in Hole 647A and in three Labrador Margin wells (Indian Harbour M-52, North Leif I-05, and Karlsefni H-13). Restored sedimentation rate and burial calculations follow Stam et al. (1987). The interval of less diversified agglutinated assemblages coincides with the development of the late Paleocene to early Eocene Gudrid Sands, which created less favorable substrate conditions for the development and preservation of foraminifer assemblages. The disappearance of agglutinated assemblages along the Labrador Margin after the Eocene was caused by a regional trend from slope to shelf environments, accentuated by the "mid"-Oligocene lowstand in sea level.

The *Glomospira* Facies and the NP14 Sea-Level Event

An assemblage of exclusively agglutinated foraminifers dominated by *Glomospira* spp. occurs over a 20-m interval of noncalcareous claystones, and is coincident with an increase in TOC (Fig. 2). This carbonate-free interval is evidence of a rise in the CCD in the Labrador Sea to a level above 2500 m. The age of this assemblage is constrained by nannofossils occurring above and below, as NP13 to the lower part of Zone NP15 (CP13b) (Firth, this volume). The lithologic change from the carbonate-free interval with *Glomospira* (below) to calcareous sediments above also corresponds to a mid-sediment seismic reflector identified at 618 mbsf. An assemblage containing common *Glomospira* also occurs at the top of the lower Eocene in the Bonavista C-99 well on the Labrador Margin (Fig. 7).

In the modern Gulf of Mexico, *Glomospira* assemblages are present in areas of low sedimentation rates, such as on submarine highs (Poag, 1981). The *Glomospira* facies in Hole 647A also represents a period of lowered sedimentation rate (~5 m/m.y., assuming continuous sedimentation, compared with 37 m/m.y. in the middle-late Eocene). Similar *Glomospira* facies are also found in the Carpathian basins in Poland (e.g., Geroch et al., 1967; Morgiel and Olszewska, 1981), and in the Tangier Unit of the Moroccan Rif Zone (Morgiel and Olszewska, 1982). In the Dulka Unit of the Polish Carpathians, the age of the *Glomospira* facies is constrained by nannofossil-bearing sediments above and below, as from NP12 to NP14 (Olszewska and Smagowicz, 1977). In both Poland and Morocco, the *Glomospira* facies is associated with reddish or variegated (red and green) shales, such as those in Hole 647A. Morgiel and Olszewska (1982) noted the remarkable similarity in species composition of this assemblage on both the northern and southern margins of the Mediterranean Tethys. The temporal coincidence of *Glomospira* facies in both the Atlantic and Tethys suggests a common ecological cause.

A number of important oceanographic events occur near the early/middle Eocene boundary (Fig. 11). The basal middle Eocene (Zone NP14) is a time of lowered eustatic sea level (Haq et al., 1987) and inferred increased paleoproductivity, as suggested by the presence of biosiliceous sediments in the equatorial Atlantic. Berggren and Hollister (1974) cited volcanism in the Caribean and Norwegian-Greenland Sea as a possible source of nutrients to the North Atlantic. However, carbon-isotopic evidence suggests that changes in the carbon reservoirs through influx of nutrients from the shelves are also important (Broecker, 1982). Planktonic and benthic carbon-isotope ratios display de-

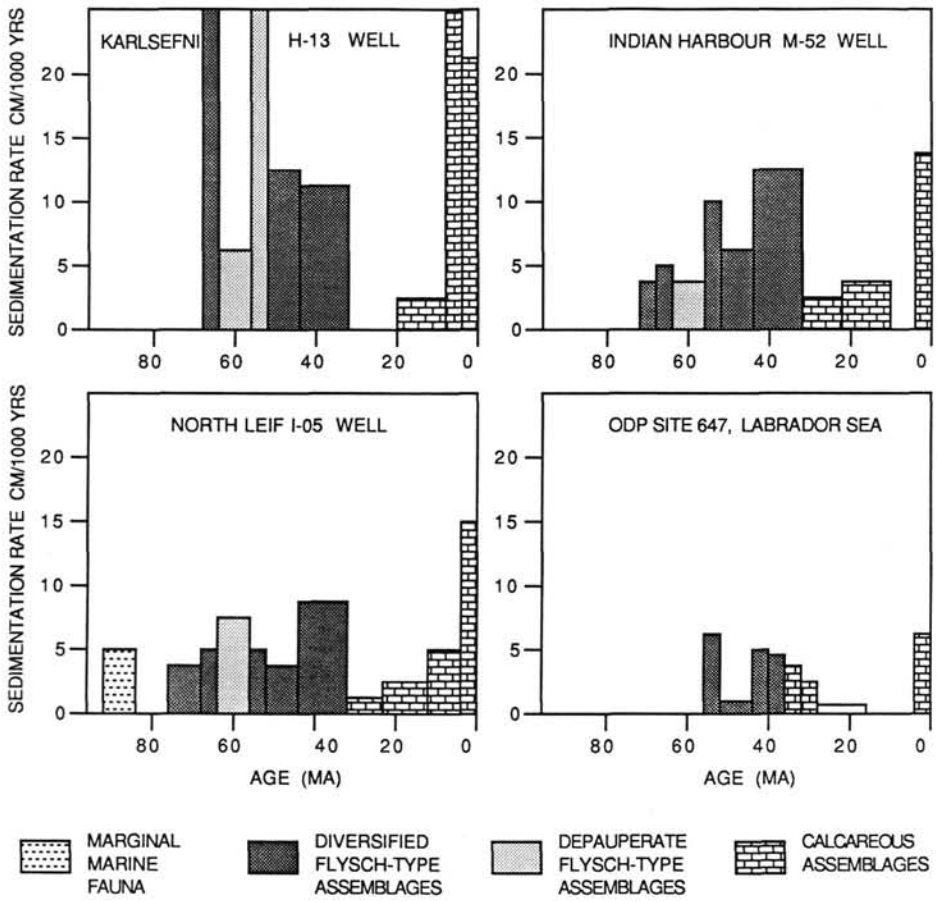

Figure 9. Benthic foraminifer assemblages and restored sedimentation rates in three Labrador Margin wells and in Hole 647A, following calculations by Stam et al. (1987).

creasing surface to bottom gradients from the early Eocene to the late Eocene (Boersma). The somewhat higher carbon isotope gradients might suggest higher nutrient contents and paleoproductivity in the early to middle Eocene. Increased TOC contents, despite lower sedimentation rates in the *Glomospira* facies at Site 647, increased nutrients and (presumably) decreased oxygenation of bottom water. The synecology of the assemblage is consistent with the idea of high productivity. *Glomospira* and *Ammodiscus* are regarded as epifaunal detritus feeders (Jones and Charnock, 1985), and presumably are well-adapted to take advantage of an increased amount of food particles derived from the surface layer of the ocean.

Climatic and paleoceanographic changes were coincident with the eustatic lowering of sea level in the basal Lutetian. In the Atlantic, surface waters cooled approximately 1°C and deep water cooled about 2°C across the early/middle Eocene boundary (Boersma et al., 1987). At the same time, the proto-Gulf Stream flow intensified, possibly due to restriction of the circum-global current in the Carribean (Tucholke and Mountain, 1986), and an east-west gradient was established among planktonic foraminifer faunas (Boersma et al., 1987), indicating intensification of the Atlantic subtropical gyres. The increased circulation that accompanied eustatic decrease in sea level is a likely cause of numerous hiatuses encompassing the early/middle Eocene boundary at DSDP Sites in the western North Atlantic (Poag, 1987) and at bathyal depths on the Goban Spur (Poag et al., 1985), Rockall Margin (Tucholke and Mountain, 1986), and Labrador Margin—Northern Grand Banks (Gradstein, 1987; Fig. 6). Among benthic foraminifers, there appears to be a reduction in numbers of *Bulimina* and an increase in *Nuttallides truempyi* across the Ypresian/Lutetian Boundary in the western North Atlantic (Poag and Low, 1987) as well as in the Labrador Sea. Miller et al. (1987) ascribed the eustatic fluctuations in sea level in the pre-late Eocene to global tectonic and seafloor-spreading rate changes. For example, in the North Atlantic, seafloor-spreading rate changed from ~21 mm/yr to ~9 mm/yr between anomaly 21 and 22 (Srivastava, 1978), and in the Labrador Sea a decrease in spreading rate from 7.5 mm/yr to ~2 mm/yr occurred between anomaly 20 and 21 (S. Srivastava, pers. comm. to MAK, 1987).

Carbon-isotopic evidence at Walvis Ridge Site 357 (Boersma et al., 1987), points to some nutrient-poor deep-water production in the early middle Eocene. Benthic foraminifers record $\delta^{13}C$ ratios of ~0.5‰ in Zone P10, compared with values of about −0.1‰ in the early Eocene (Boersma et al., 1987). The source of the deep water, however, is still a matter of debate. During the basal Lutetian lowstand in sea level, marine connections between the Atlantic and the Norwegian-Greenland Sea were temporarily interrupted, allowing the trans-Atlantic migration of terrestrial faunas (McKenna, 1983). Berggren and Olsson (1986) noted that the opening of surface connections between the Arctic Ocean and the Norwegian-Greenland Sea in the early middle Eocene may have been a source of proto-NADW. However, the presence of warm-temperate early Eocene floras and faunas in northern high latitudes (Schweitzer, 1980; Wolfe, 1980; Estes and Hutchison, 1980) would argue against outflow from the Norwegian-Greenland Sea being very cold. Annual mean early Eocene temperature in Spitsbergen has been estimated as between 15° and 18°C (Schweitzer, 1980). Winter temperatures must have been mild, since the fossil flora con-

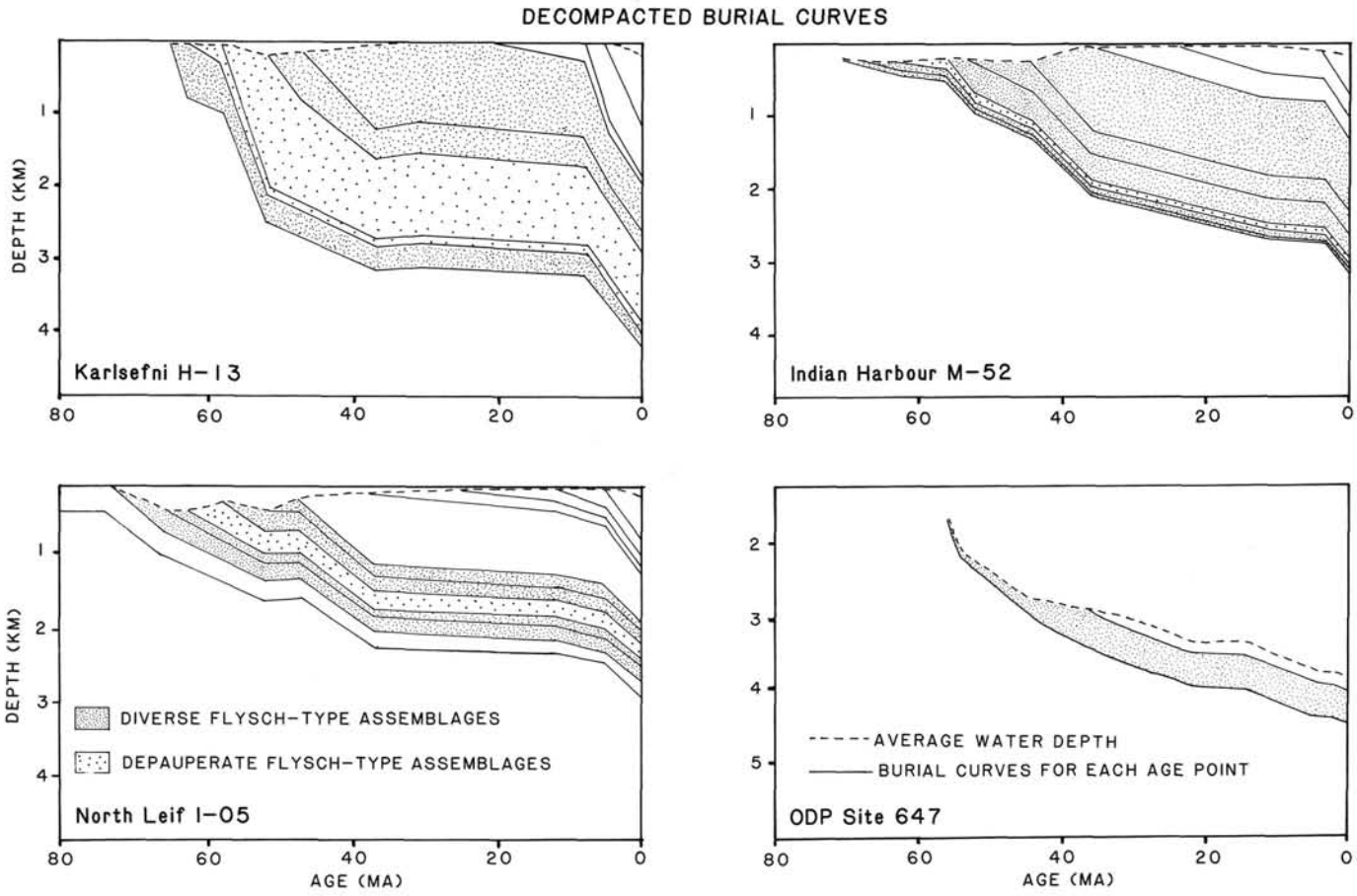

Figure 10. Burial history of the sedimentary wedge in three Labrador Margin wells and at Site 647, following calculations by Stam et al. (1987).

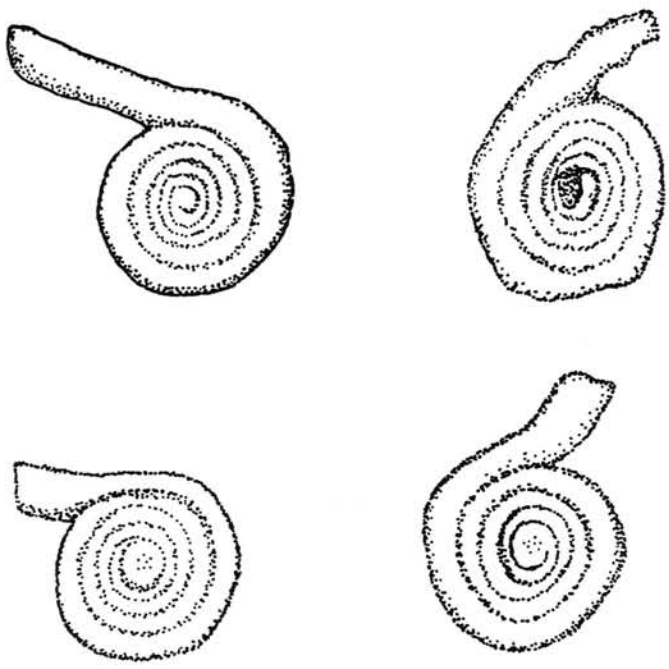

Figure 11. Paratypes of *Ammodiscus nagyi* n.sp. from Sample 105-647A-66R-3, 57-60 cm. Camera lucida drawings, X225.

tains species that do not tolerate frosts (Schweitzer, 1980; M.J. Head, unpubl. data).

Berggren and Schnitker (1983) postulated a northward flow of cool water from the South Atlantic, based on a comparison of oxygen-isotopic evidence. Carbon-isotopic evidence from Hole 647A lends support to the idea of a southern source of nutrient-depleted deep water. Benthic $\delta^{13}C$ ratios at Site 647A average about $-0.5‰$ (Arthur et al., this volume). These values are about 1‰ lighter than the age-equivalent values recorded at Site 367 but may reflect diagenetic overprints. Poag (1987) places the onset of significant thermohaline circulation in the North Atlantic as early as the Paleocene/Eocene boundary, before the opening of the Norwegian-Greenland Sea. However, recent oxygen-isotopic evidence indicates that cooling near Antarctica may have resulted in deep-water production as early as the Late Cretaceous (Barrera et al., 1987).

Agglutinated Foraminifers and the Eocene/Oligocene Boundary

Site 647 is unique because no other DSDP site in the North Atlantic contains assemblages of flysch-type agglutinated foraminifers in an Eocene-Oligocene section. Agglutinated foraminifers from middle Eocene to early Oligocene sediments in Hole 647A display a reduction in abundance, a reduction in size, and a decrease in diversity as the flysch-type taxa underwent a series of extinctions and local pseudoextinctions over a period of 5 m.y.. There is a cluster of LO events near the Eocene/Oligocene boundary, when about 10 species disappeared within a span of about 0.5 m.y. With the exception of two species, the flysch-type taxa disappeared from the deep Labrador Sea by the end of

Zone NP21. The disappearance of flysch-type taxa was essentially completed below the increase in biogenic silica concentrations and the position of the R4 seismic reflector at 240 mbsf.

Unlike at other DSDP sites in the North Atlantic, the Eocene/Oligocene boundary at Site 647 is not delineated by a hiatus or any obvious lithologic change. The abundance of biosiliceous components and TOC increases from late Eocene to the early Oligocene; therefore there is no evidence of oligotrophic conditions observed in other areas of the North Atlantic. The basal Oligocene acme of *Nuttallides umbonifera*, however, displays similarities with coeval assemblages from the Bay of Biscay (Miller, 1983) and the equatorial Pacific (Corliss, 1979).

The sequence of LOs of taxa is shown in Figure 4. Among agglutinated foraminifers, LOs began at an increased rate near the boundary between the middle and late Eocene. The first group of species to disappear are agglutinated taxa with walls composed of small planktonic foraminifer tests, such as *Psammosphaera testacea* and a species of *Rhizammina*. Small elongate forms, such as *Karreriella conversa, Bigenerina* sp., *Reophax guttifer*, and *Karreriella coniformis*, and the delicate species, such as *Hormosina distans, Hyperammina subnodosiformis*, and *Hyperammina kenmilleri* n.sp. were also among the first forms to disappear in the late Eocene. However, some of these LOs are local extinctions, since *K. conversa, P. testacea*, and *R. guttifer*, and *H. distans* are all found in the modern North Atlantic. Near the Eocene/Oligocene boundary, the species that disappeared were mainly lituolids and species that presumably share an epifaunal habitat, such as *Glomospira serpens, Trochammina*, and *Saccammina*.

About 10 species of flysch-type taxa survived the Eocene/Oligocene boundary. These are either robust forms, such as *Rhabdammina, Ammodiscus latus*, and *Cribrostomoides*, or species with smooth, well-cemented tests, such as *Ammodiscus cretaceous, Bathysiphon*, or *Glomospira charoides*. Interestingly, more than one-half the surviving species are ammodiscids or similarly coiled forms (*Spirosigmoilinella*). Such species are epibenthic detritus feeders, according to Jones and Charnock (1985), but the community still contains a mix of infaunal species (*Reophax subnodulosus*) and suspension feeders (*Rhabdammina* and *Bathysiphon*). Therefore, there is no obvious change in the synecologic structure of the assemblage, as observed in the Miocene drift sediments at Site 646 (Kaminski et al., this volume).

The disappearance of agglutinated taxa near the Eocene/Oligocene boundary in Hole 647A suggests a change in water mass properties as a primary cause. Delicate species disappeared first, indicating that the faunal turnover may be at least partly attributed to preservational factors. Therefore, this observation is consistent with the "old bottom-water model" of Gradstein and Berggren (1981). Although carbon $\delta^{13}C$ values in Hole 647A show no consistent trend with depth, the Eocene *Cibicidoides* values are light (mean = −0.55‰), which may suggest the presence of comparatively "old," nutrient-rich bottom water (Arthur et al., this volume). Although there is no benthic isotopic data for the Oligocene of Hole 647A, data from Sites 558 and 563 (Miller and Fairbanks, 1985) indicate the presence of "young," nutrient-poor water in the eastern North Atlantic between 36 and 33 Ma. Thus, we suspect that increased oxygenation of deep water resulted in increasingly poorer preservation of agglutinated foraminifers observed in Hole 647A.

Paleoceanographic Significance of Flysch-Type Assemblages

The disappearance of agglutinated foraminifers in the deep Labrador Sea near the Eocene/Oligocene boundary has been attributed to changes in water mass properties associated with the onset of vigorous thermohaline circulation in the North Atlantic (Miller et al., 1982). Typical bottom-water temperatures cooled from about 6°–10°C in the late Eocene to temperatures similar to modern bottom water in the earliest Oligocene (Miller et al., 1987). At the same time, the Atlantic carbon-isotope values begin to diverge from mean ocean water near the Eocene/Oligocene boundary. A comparison of Atlantic benthic carbon-isotope records with those of the Pacific indicates a maximum supply of nutrient-depleted bottom water between 36 and 34 Ma (Miller and Fairbanks, 1985; Miller and Katz, 1987a). The source of the cool, nutrient-depleted deep water in the early Oligocene was reported by Miller and Tucholke (1983) as Iceland-Scotland Ridge Overflow Water, analogous to the modern North Atlantic. Therefore, we need to look to the Norwegian-Greenland Sea for the ultimate cause of the Eocene-Oligocene faunal turnover at Site 647.

Berggren and Schnitker (1983) noted that the opening of a deep channel through the Fram Strait between Greenland and Spitsbergen during Chronozone 13 probably allowed cold water from the Arctic to enter the Norwegian-Greenland Sea, and from there, to enter the North Atlantic. However, this arctic water was most likely not as dense as the deep water already present in the deep Norwegian-Greenland Sea. Deep sites in the Lofoten Basin and at the base of the Vøring Plateau contain agglutinated foraminifer assemblages throughout the Oligocene, indicating a stable, stratified water column. Shallow sites on the Vøring Plateau, however, display a faunal turnover from agglutinated assemblages in the Eocene to predominantly calcareous assemblages in the Oligocene. Agglutinated foraminifers also disappear near the Eocene/Oligocene boundary in exploration wells from the Beaufort Sea (Young and McNiel, 1983). Thus, if arctic water was the cause of this faunal turnover, the water mass may have been analogous to present-day polar water, which is present in the Norwegian-Greenland Sea to a depth of 150 m (Johannessen, 1986). Since there most likely was no connection with the Atlantic through the Denmark Straits until the mid-Miocene (Thiede and Eldholm, 1983), polar water flowing south along the east coast of Greenland would have turned east at the Greenland-Scotland Ridge to recirculate through the Norwegian-Greenland Sea.

An alternative scenario exists that may account for the disappearance of agglutinated foraminifers in the shallow Norwegian-Greenland Sea. Agglutinated foraminifers also disappear near the Eocene/Oligocene boundary in exploration wells from the Viking Graben (Kaminski and Gradstein, 1987). The outflow of water through the Faeroe-Shetland Channel must be volumetrically balanced by the inflow of eastern Atlantic surface water, as it is today (Worthington, 1970). Return flow to the Norwegian-Greenland Sea would have existed through the Faeroe-Shetland Channel and through the North Sea via the English Channel. Therefore, Atlantic water may have been present over the Vøring Plateau in the early Oligocene. This Atlantic water would have circulated along the eastern margin of the basin through the Greenland-Spitsbergen Channel and into the Arctic Ocean. The first possible evidence for the advection of Atlantic water into the Norwegian-Greenland Sea was Müller's finding (1976) of an abundant and diverse "mid"-Oligocene nannoflora on the Vøring Plateau. Unfortunately, microfossil data near the Eocene/Oligocene boundary still lack sufficient documentation. There is evidence of migration of the benthic taxon *Spirosigmiolinella* from the North Atlantic into the Norwegian-Greenland Sea around this time. This migration may be related to water mass changes. *Spirosigmoilinella* first appears near the middle/late Eocene boundary at Site 647, as well as at Site 612 in the North Atlantic (Miller and Katz, 1987b). In the North Sea, this taxon can be seen first in the late Eocene (Gradstein et al., 1988), but in the Norwegian-Greenland Sea sites, its FO is in the early Oligocene. The addition of warm saline water into the Arctic realm

may have affected the density structure of the surface layer, thereby causing faunal changes at neritic to upper bathyal depths. However, the Atlantic vs. polar water models of faunal change remain to be tested micropaleontologically using benthic and planktonic microfossils at the Vøring Plateau and in the Beaufort Sea.

At first glance, the disappearance of flysch-type taxa near the Eocene/Oligocene boundary in the Labrador Sea and in shallow Vøring Plateau sites suggests an oceanographic link between the regions. Miller et al. (1982), Berggren and Schnitker (1983), and Tucholke and Mountain (1986) favored the production of northern-source deep water as the cause of the faunal turnover in the deep Labrador Sea. However, northern-source deep water may not have been the universal cause of the disappearance of the flysch-type faunas in the Northern Hemisphere. The paleogeographic distribution of flysch-type assemblages in the North Atlantic suggests that a southern source of deep water may have contributed to the disappearance of the North Atlantic assemblages in the early Paleogene (Kaminski and Gradstein, 1987). In the North Atlantic the LCO of flysch-type assemblages displays a diachronous pattern with latitude and depth. In the western basin, agglutinated foraminifers first disappeared from deep, equatorial sites in the late Maestrichtian, but continued into the Paleocene on the margins and in the eastern basin. Flysch-type assemblages disappeared from Site 647 and the Carpathian flysch basins near the Eocene/Oligocene boundary, but persisted at bathyal depths on the Labrador Margin and in the central North Sea into the Oligocene.

The approximately coeval disappearance of flysch-type assemblages in the North Atlantic and Carpathian flysch basins cannot be attributed to northern-source deep water in the latter region. The basal Oligocene lowstand in sea level interrupted connections between the North Sea and the northern Tethys through the Polish-Danish trough, allowing the immigration of Asian vertebrate faunas into western Europe (Cavelier et al., 1981). Deep water in the eastern Tethys may have been derived from a southern source, judging from the distribution of hiatuses along the western margin of the Indian Ocean (Kennett, 1977; Davies and Kidd, 1977). Shackleton and Kennett (1975) attributed the Eocene/Oligocene cooling of deep waters and increased deep circulation throughout the southern oceans to sea-ice formation near Antarctica. The increasing production of well-oxygenated, northern and southern sources of deep waters at the end of the Eocene, and the basal Oligocene lowering of sea level, resulted in a deepening of the oceanic lysocline throughout most of the world ocean, including the Tethyan flysch basins (Van Couvering et al., 1981). These events may have led to the extinction of flysch-type assemblages in the North Atlantic and Tethys. However, the shallow Greenland-Scotland Ridge prevented the exchange of deep Arctic and Atlantic water below sill depth in the Norwegian-Greenland Sea, and this area served as a refuge for flysch-type faunas until the late Neogene. This scenario for the disappearance of flysch-type faunas at the Eocene/Oligocene boundary still remains to be tested with microfossil paleobiogeographic data.

CONCLUSIONS

The recovery of a continuous section of early Eocene to early Oligocene sediments at Site 647 and the establishment of a multiple planktonic microfossil biochronology allowed us to correlate the benthic foraminifer stratigraphy of the deep Labrador Sea to a standard time scale. The Paleogene foraminifers from Site 647 were subdivided into seven assemblages, based on the stratigraphic ranges of important taxa. This subdivision of benthic foraminifer assemblages can also be recognized at DSDP Site 112 and allows us to correlate the two sites precisely. Four of the assemblages (*Abyssammina—Dendrophrya, Nuttallides truempyi, Reticulophragmium amplectens*, and *Turrilina alsatica*) correlate with standard stages (early, middle, and late Eocene and early Oligocene). Periods of increased faunal turnover and opportunistic increases in dominance of individual taxa correlate with stage boundaries, and accordingly, the remaining three assemblages (*Glomospira, Spirosigmoilinella—S. spectabilis*, and *Ammodiscus latus—T. alsatica*) are of shorter duration. The Ypresian/Lutetian boundary is present within a 20-m interval of noncalcareous claystones containing a *Glomospira* facies made up of only agglutinated taxa. The middle/late Eocene boundary is characterized by an acme of *Spiroplectammina spectabilis* and the FO of *S. cubensis* and *Spirosigmoilinella*. The largest cluster of LOs occurs near the Eocene/Oligocene boundary, which is delineated by the disappearance of about 12 species of flysch-type taxa and an acme of *Nuttallides umbonifera*. However, the faunal change from an Eocene agglutinated assemblage to an Oligocene calcareous assemblage is by no means abrupt and takes place over a period of about 4 m.y.

Two of the four prominent mid-sediment seismic horizons recognized at Site 647 correspond to benthic assemblage boundaries. The boundary between the *Glomospira* facies and the overlying calcareous claystones with a *Nuttallides truempyi* Assemblage corresponds to an intra-Eocene seismic horizon and correlates approximately with the basal Lutetian. The presence of the *Glomospira* facies at Site 647 is ascribed to paleoceanographic changes caused by the basal Lutetian lowstand in sea level. The regional seismic reflector R4 occurs approximately 50 m above the Eocene/Oligocene boundary and corresponds to a lithologic change from calcareous claystones to porous siliceous diatomite above. This reflector correlates approximately with the boundary between the *Ammodiscus latus—Turrilina* Assemblage and the *T. alsatica* Assemblage and the LCO of flysch-type taxa.

Comparison of benthic foraminifer extinction events from Site 647 with the Labrador Margin reveals a number of similarities. The LOs of *Turrilina alsatica, Ammodiscus latus, Haplophragmoides walteri, Ammosphaeroidina* sp., and *Spiroplectammina navarroana* occur in the same order on the Labrador Margin and in the deep Labrador Sea, which confirms the utility of these taxa for regional stratigraphy. However, some forms display diachronous LOs with depth. *Glomospira* disappeared in the early Eocene in most Labrador Margin wells, but continued into the early Oligocene at Site 647. The species *R. amplectens* and *S. spectabilis* disappeared at the Eocene/Oligocene boundary at Site 647, but their LOs are earlier on the Labrador Margin.

The transition from a predominantly agglutinated assemblage in the Eocene to a calcareous assemblage in the Oligocene is attributed to the increasingly poorer preservation of agglutinated taxa. The temporal coincidence of this faunal turnover in Site 647, the shallow Vøring Plateau, the Viking Graben, and the Beaufort Sea suggests a common oceanographic link among the regions. At Site 647, the turnover is attributed to the increasing influence of cool, nutrient-poor, deep waters associated with the onset of thermohaline circulation. However, the possible oceanographic causes of this faunal change in the high-latitude basins and Carpathian flysch troughs remain to be investigated.

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APPENDIX

Taxonomy and Description of New Species

Genus HYPERAMMINA Brady, 1878

Hyperammina kenmilleri Kaminski n.sp.
(Pl. 1, Figs. 6, 7)

Bathysiphon sp., Miller et al., 1982. Pl. 1, Fig. 1.

Description. Test-free, delicate, elongate, cylindrical, consisting of a bulbous proloculus and long, rectilinear, tubular second chamber somewhat smaller in diameter than the proloculus. Wall agglutinated, thin, composed mainly of cement. Test is often flattened.

Remarks. This species differs from other species of *Hyperammina* in its minute size and thin wall possessing no visible agglutinated grains. The proloculus is often missing. Specimens often show signs of compaction.

Occurrences. Eocene of Sites 647 and 112, southern Labrador Sea.

Size. Diameter of tubular chamber does not exceed 0.1 mm.

Type locality. Sample 105-647A-49R-1, 118–121 cm.

Holotype. USNM 181877. Pl. 1, Fig. 6.

Paratypes. USNM 181878 and 181879. Pl. 1, Fig. 7. Additional unfigured metatypes have been deposited in the micropaleontological collections of Dalhousie University (DAL-232-F), the Naturhistorische Museum Wien, and at the Smithsonian Institution.

Genus AMMODISCUS Reuss, 1862

Ammodiscus nagyi Kaminski n.sp.
(Pl. 2, Figs. 2,3; Text Fig. 11)

Description. Test-free, discoidal, with a proloculus followed by an undivided, planispirally, enrolled tubular chamber. Test is thin, flat, delicate, and has a characteristic tendency to uncoil tangentially: Coiled

chamber increases in size very slowly. Coiling may be somewhat irregular. Megalospheric forms are made up of four to five whorls and have a large, bulbous proloculus, which may protrude above the flat surface of the coiled part. Microspheric forms are somewhat larger in diameter than megalospheric forms and are composed of six to eight whorls. Wall finely agglutinated, made up mainly of cement. Aperture at open end of tube.

Remarks. This species is characterized by its minute size and its tendency to uncoil (especially megalosphaeric forms). Uncoiling behavior is unusual for post-Paleozoic species of *Ammodiscus*. It differs from *Ammodiscus planus* Loeblich in uncoiling tendency and in possessing a coiled chamber that increases very slowly in size. Thin, minute specimens of *Ammodiscus* are often mistakenly referred to *A. glabratus* Cushman and Jarvis (see Kaminski et al., 1988). However, *A. glabratus* possesses a coiled chamber that increases in thickness very rapidly, so the test is biconcave in edge view. *Ammodiscus tenuissimus* Grzybowski differs in its larger size and in possessing more whorls. *Ammodiscus nagyi* n.sp. is perfectly flat and no doubt is one of the smallest Cenozoic species of *Ammodiscus*.

Occurrences. Lower Eocene to lower middle Eocene of Sites 647 and 112.

Size. Maximum diameter of paratypes: 144–182 μm. Diameter of tubular chamber (uncoiled part): 35–40 μm. Maximum diameter of chamber on coiled part: 22–31 μm.

Type Locality. Sample 105-647A-66R-3, 57–60 cm.

Holotype. USNM 181880. Pl. 2, Fig. 3.

Paratypes. USNM 181881 and 181882. Pl. 2, Fig. 2. Additional unfigured metatypes have been deposited in the micropaleontological collections of Dalhousie University (DAL-231-F), the Naturhistorische Museum Wien, the Jagiellonian University, Cracow (Grzybowski Collection), and at the Smithsonian Institution.

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Addendum 1 (End of "Methods" Section, p. 707)

Although sample and/or event ages are given to the nearest 100 k.y. as interpolated from the linear sedimentation rate curves, the error in these determinations varies significantly. In parts of the sequence, such as for the lower to middle Eocene sediment interval at Site 647, our interpolated ages may be in error by as much as 1 m.y. The Site 647 age-depth curve used in this study (Srivastava, Arthur et al., 1987) also differs somewhat from the final plot illustrated in Baldauf et al. (this volume). We did not adjust our ages on the basis of the Baldauf et al. compilation. The reader should bear in mind that the slope of the Paleogene portion of the curve is based mainly on three Eocene magnetic events and is not well constrained in the upper Oligocene. The age-error estimates given in parentheses after most absolute ages reflects only the possible error in assigning a depth to a given event because of sample spacing.

Addendum 2 ("*Glomospira* Facies" Section, p. 717)

However, the accumulation rate of TOC is low, and the sediments are red and highly oxidized in the low sedimentation rate interval near the early/middle Eocene boundary at Site 647. Biogenic silica accumulation rates are also low (Bohrmann and Stein, this volume). Thus, it is still equivocal as to whether paleoproductivity was higher in association with the *Glomospira* facies. Lower fluxes of TOC to the seafloor would also favor epifaunal benthic foraminifers, rather than infaunal taxa.

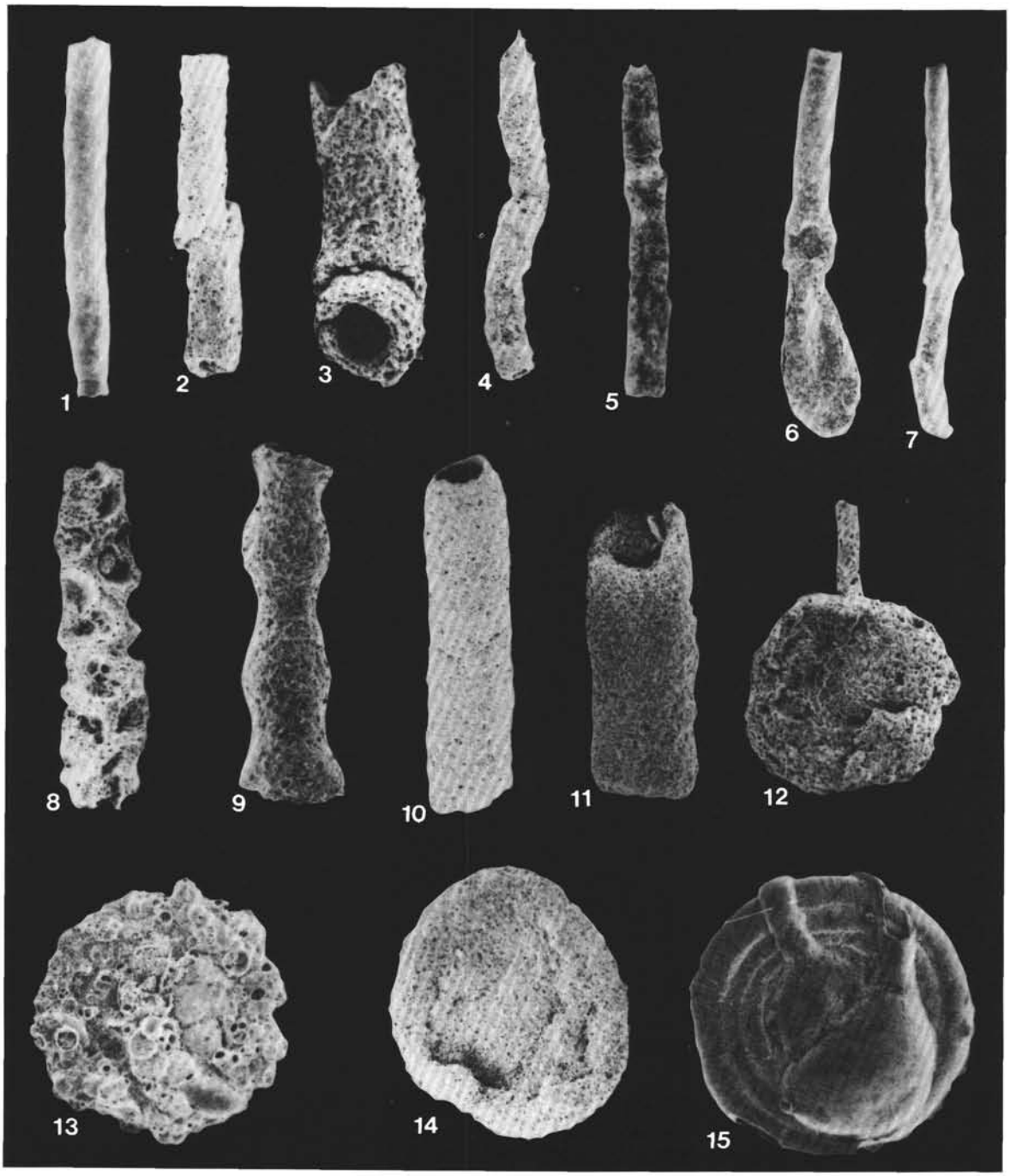

Plate 1. **1.** *Bathysiphon* sp. (105-647A-47R-4, 74–77 cm) X50. **2.** *Rhabdammina* sp. (105-647A-49R-1, 118–121 cm), X50. **3.** *Rhizammina* sp. (105-647A-37R-4, 90–93 cm), X44. **4.** *Rhizammina* sp. (105-647A-49R-I, 118–121 cm), X50. **6,7.** *Hyperammina kenmilleri* n. sp. (105-647A-49R-1, 118–121 cm); 6, X150; 7, X50. **8.** *Rhizammina* sp. (with planktonic tests;105-647A-49R-1, 118–121 cm), X120. **9.** *Hyperammina* ex gr. *subnodosiformis* (Grzybowski) (105-467A-41R-5, 58–61 cm), X83. **10,11.** *Dendrophrya* ex gr. *excelsa* Grzybowski; 10, 105-647A-66R-2, 24–27 cm, X50; 11, 105-647A-67R-1, 40–43 cm, X120. **12.** *Saccammina complanata* (Franke) (105-647A-66R-3, 57–60 cm), X137. **13.** *Psammosphaera testacea* Flint (105-647A-68R-1, 129–132 cm), X96. **14.** *Aschemonella* sp. (105-647A-49R-1, 118–121 cm), X60. **15.** *Ammolagena clavata* (Jones and Parker) on a specimen of *Ammodiscus cretaceous* (Reuss) (105-647A-47R-4, 79–77 cm), X38.

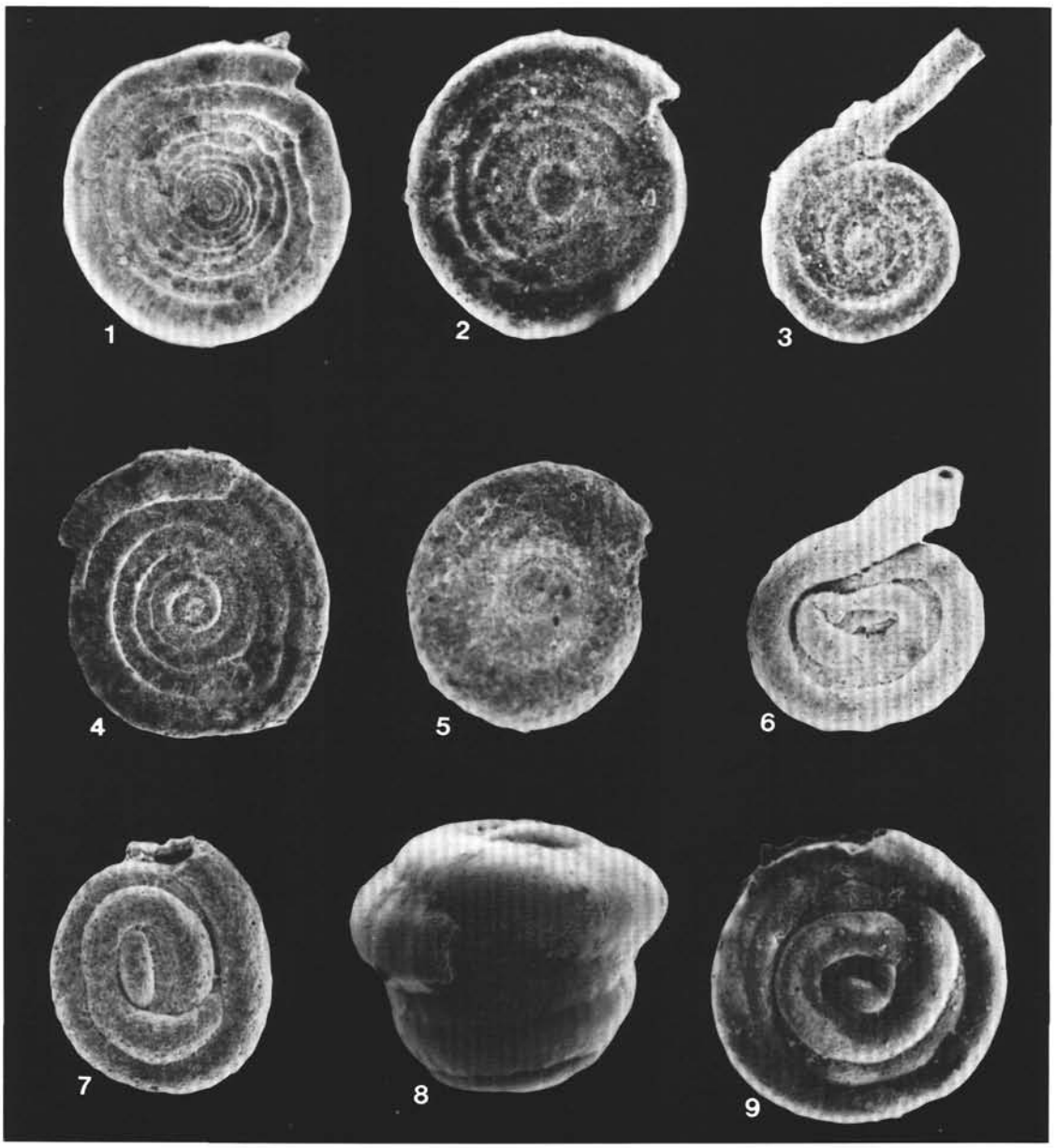

Plate 2. **1.** *Ammodiscus cretaceous* (Reuss) (105-647A-46R-3, 60–63 cm), X38. **2,3.** *Ammodiscus nagyi* n.sp.; 2, 105-647A-63R-3, 74–77 cm, X125; 3, 105-647A-66R-3, 57–60 cm, X150. **4,5.** *Ammodiscus latus* Grzybowski; 4, 105-647A-51R-5, 94–97 cm; X35; 5, 105-647A-41R-1, 58–61 cm. **6.** *Glomospirella* sp. (105-647A-67R-1, 40–43 cm), X83. **7.** *Glomospira irregularis* (Grzybowski) (105-647A-68R-3, 74–77 cm), X110. **8.** *Glomospira charoides* (Jones and Parker) (105-647A-47R-4, 74–77 cm, X110. **9.** *Glomospira diffundens* (Cushman and Renz) (105-647A-65R-2, 31–34 cm,) X150.

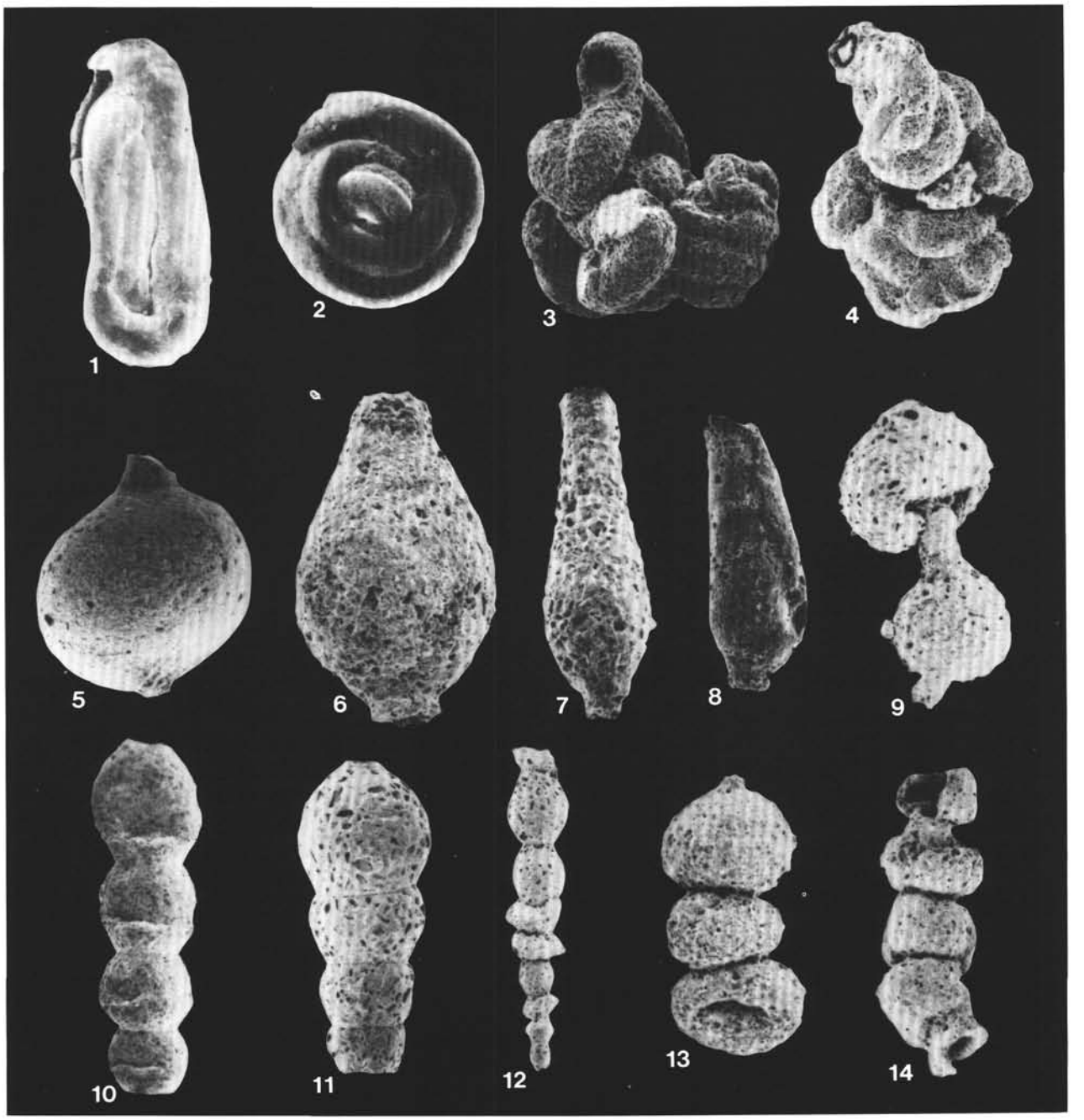

Plate 3. **1.** *Glomospira serpens* (Grzybowski) (105-647A-42R-1, 98–102 cm), X83. **2.** *Glomospira gordialis* (Jones and Parker) (105-647A-65R-2, 31–34 cm), X150. **3,4.** *Ammovertella* sp. (105-647A-65R-1, 31–34 cm) X125. **5.** *Hormosina ovulum ovulum* (Grzybowski) (105-647A-70R-2, 55–58 cm) X15Q. **6.** *Hormosina* sp. 4 (of Miller et al., 1982) (105-647A-47R-6, 52–55 cm. **7,8.** *Hormosina* sp. aff. *H. excelsa* (Dylazanka); 7, 105-647A-62R-1, 112–115 cm, X137; 8, 105-647A-61R, CC, X110. **9.** *Hormosina distans* (Brady) (105-647A-62R-1, 112–115 cm) X137. **10.** ?*Nodellum velascoensis* (Cushman) (105-647A-33R, CC) X33. **11.** *Reophax subnodulosus* Grzybowski (105-647A-45R-1, 14-18 cm) X66. **12.** *Reophax* sp. (105-647A-66R-3, 57–60 cm) X44. **13.** *Reophax pilulifer* Brady (105-647A-47R-6, 52–55 cm) X96. **14.** *Subreophax scalaria* (Grzybowski) (105-647A-49R-1, 118–121 cm) X70.

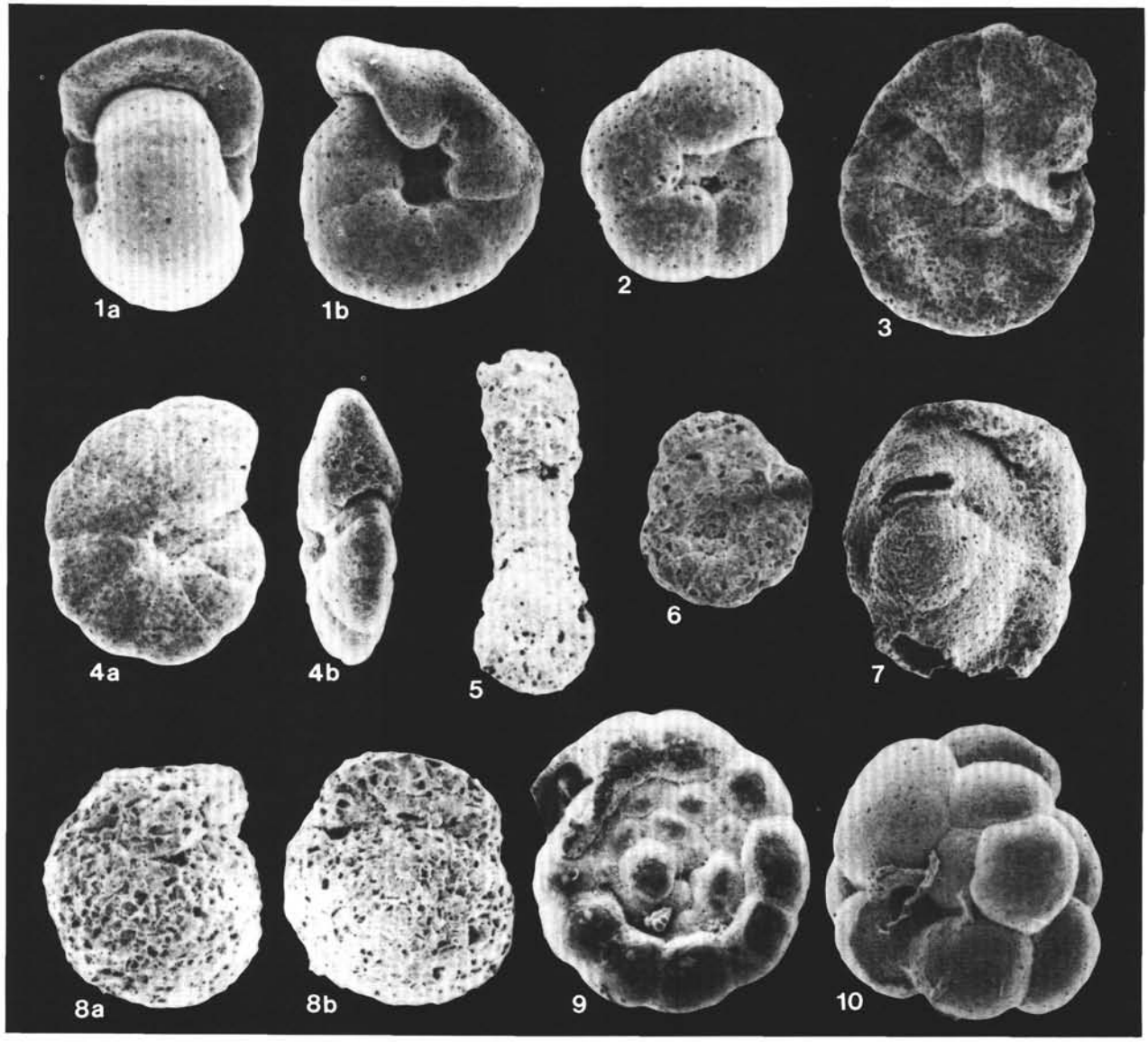

Plate 4. **1a,1b.** *Cribrostomoides* sp. (105-647A-44R-3, 42–45 cm) X55. **2.** *Haplophragmoides porrectus* Maslakova (105-647A-67R-3, 36–39 cm) X150: **3,4a,4b.** *Haplophragmoides walteri* (Grzybowski); 3, 105-647A-46R-3, 60–63 cm, X96; 4a,4b, uncompressed specimen (105-647AS-47R-4, 74–77 cm) X96. **5,6.** *Ammobaculites* aff. *polythalamus* (of Gradstein and Berggren, 1981); 5, 105-647A-42R-1, 98–101 cm, X110; 6, 105-647A-43R-1, 95–98 cm, XllO. **7.** *Sphaerammina gerochi* Hanzlikova (105-647A-65R-1, 31–34 cm) X137. **8a,8b.** *Recurvoides* sp. (105-647A-49R-1, 118–121 cm) X100. **9.** *Trochamminoides proteus* (Karrer) (105-647A-41R-5, 58–61 cm) X38. **10.** *Trochamminoides irregularis* White (105-647A-67R-1, 40–43 cm) X70.

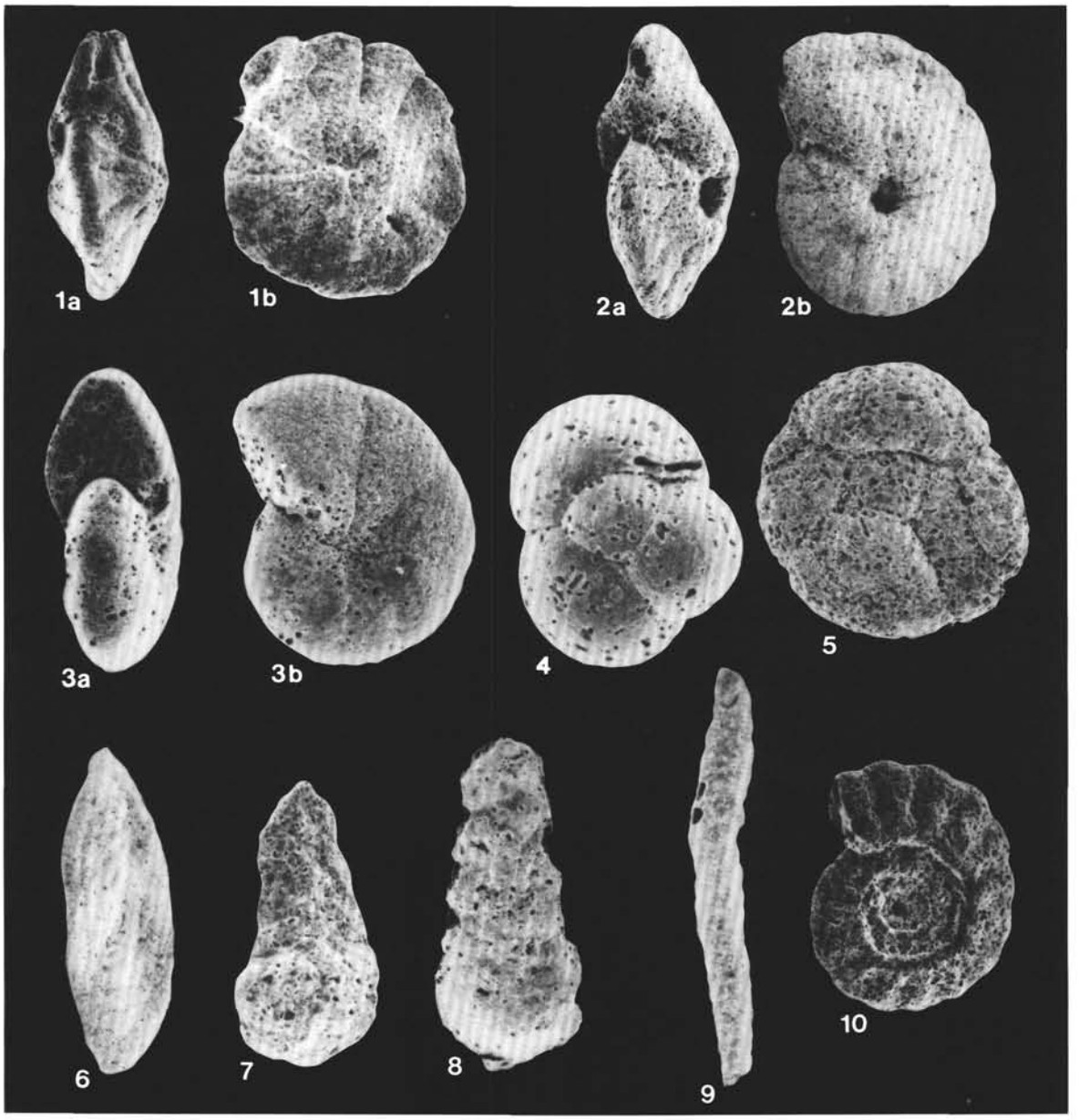

Plate 5. **1a–2b.** *Reticulophragmium amplectens* (Grzybowski); la,1b, late Eocene morphotype, 105-647A-47R-4, 74–77 cm, X96;. **2a,2b,** early Eocene morphotype, Sample 105-647A-61R, CC, X110. **3a,3b.** *Reticulophragmium placenta* (Reuss) (105-647A-70R, CC) X83. **4.** *Ammosphaeroidina* sp. (105-647A-47R-4, 74–77 cm) X135. **5.** *Trochammina deformis* Grzybowski (105-647A-49R-5, 117–120 cm) X98. **6.** *Spirosigmoilinella compressa* Matsunaga (105-647A-3R-3, 104–107 cm) X96. **7–10.** *Spiroplectammina cubensis* (Cushman and Bermudez); 7, macrospheric specimen, 105-647A-30R-2, 25–27 cm, X137; 8, macrospheric specimen, 105-647A-27R-1, 78–83 cm, X83; 9, microspheric specimen, 105-647A-33R, CC, X50; 10, microspheric specimen, 105-647A-27R-1, 78–83 cm, X137.

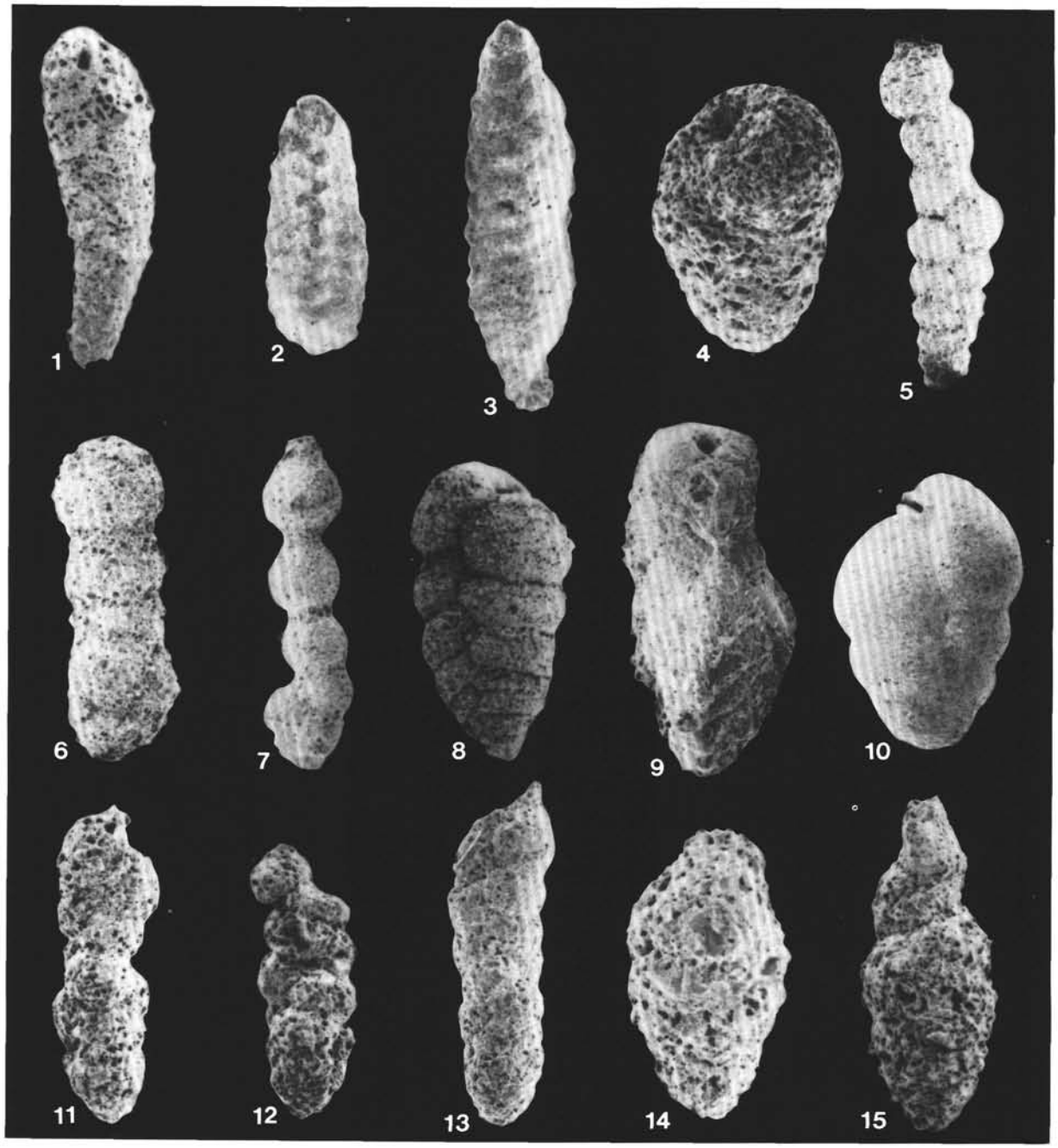

Plate 6. **1.** *Spiroplectammina navarroana* (Cushman) (105-647A-67R-1, 40–43 cm) X96. **2,3.** *Spiroplectammina spectabilis* (Grzybowski) (105-647A-46R-1, 60–64 cm); 2, macrospheric specimen, X80; 3, microspheric specimen, X80. **4.** *Arenobulimina* sp., (105-647A-46R-3, 60–63 cm) XllO. **5.** *Bigenerina* sp. (105-647A-49R-5, 117–120 cm) XllO. **6,7.** *Clavulinoides* sp.; 6, 105-647A-43R-3, 104–107 cm, X83; 7, 105-647A-68R-3, 74-77 cm, X83. **8.** *Gaudryina* sp. A (105-647A-30R-3, 110–113 cm) X33. **9.** *Gaudryina* sp. B (105-647A-44R-3, 42–45 cm) X40. **10.** *Karreriella chapapotensis* (Cole) (105-647A-43R-3, 104–107 cm) X83. **11–13.** *Karreriella conversa* (Grzybowski); 11,12, 105-647A-62R-6, 22–25 cm, XllO; 13, 105-647A-62R-3, 60–63 cm, X83. **14.** *Karreriella coniformis* (Grzybowski) (105-647A-47R-4, 74–77 cm) X98. 15. *Karreriella horrida* Mjatliuk (105-647A-62R-6, 22–25 cm) X96.