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1. FORAMINIFERAL BIOSTRATIGRAPHY OF PLIOCENE DEPOSITS AT SITE 986, SVALBARD MARGIN[1]

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ABSTRACT

The upper Pliocene interval from 647.72 through 955.32 meters below seafloor in Ocean Drilling Program Hole 986D (77°20.408′N, 9°04.654′E) can be subdivided into one planktonic foraminiferal zone: nominate species, *Neogloboquadrina atlantica* (sinistral); one calcareous benthic foraminiferal zone: nominate species, *Melonis zaandamae–Cassidulina teretis*; and four agglutinated foraminifer assemblages: AFA1 through AFA4. The whole interval was deposited between 2.6 and 2.4 Ma during a climatic regime comprising episodic ingressions of warm to transitional surface-water masses into a generally cold ocean. Broken calcareous benthic foraminifers and silicified deformed agglutinated foraminifers indicate considerable reworking. The planktonic and calcareous benthic assemblages are similar to faunas in Hole 910C on the Yermak Plateau (80°15.896′N, 6°35.430′E), Hole 643A on the Vøring Plateau (67°42.9′N, 01°02.0′E), and the exploration Wells 7117/9-1 and 7316/5-1 on the Senja Ridge (71°22′51.05″N, 17°56′5.76″E) and in the Vestbakken Volcanic Province (73°31′12.78″N, 16°25′55.87″E), respectively. The lowermost 55 m of the interval was probably deposited below the local carbonate compensation depth and contains only agglutinated foraminifers.

INTRODUCTION

Along the margins of the Norwegian-Greenland Sea, three main glaciation areas produced extensive ice sheets in Pliocene–Pleistocene times: Greenland, Scandinavia, and the Svalbard-Barents Sea. Site 986 was drilled on the Svalbard Margin (Fig. 1) to establish the history of the Svalbard-Barents Sea Ice Sheet, including the timing of the onset of glaciation, the shift of glaciation style from mountain to ice-sheet type, and the extension of marine-based ice sheets to the outer shelf. Four holes were drilled at Site 986, with a maximum penetration of 964.6 meters below seafloor (mbsf) in Hole 986D. The drilled section penetrates all the main regional reflectors (R1–R7) of the Svalbard-Barents Sea Margin, and there are strong ties between the reflectors and main seismic sequences shown by core physical property measurements and wireline logging (Jansen, Raymo, Blum, et al., 1996). The samples analyzed for foraminifers in this study are from the upper Pliocene interval 162-986D-28R-1, 30–36 cm (647.72 mbsf), through 60R-1, 29–36 cm (955.32 mbsf; 77°20.408′N, 9°04.654′E) (Fig. 2). The seafloor lies at 2063 meters below rig floor.

In the foraminiferal assemblages, an in situ and a redeposited component are distinguished, mainly based on the state of preservation. The in situ component includes both planktonic and benthic taxa, which are used for stratigraphic dating and correlation combined with magnetostratigraphic data. All absolute ages are based on Berggren et al. (1995).

In late Cenozoic time, the western margin of the Barents Shelf was an area of intensive sediment influx from a drainage area of more than 1 million km^2 covering most of the Svalbard-Barents Sea platform. As a result of this influx, extensive Pliocene–Pleistocene sediment wedges were deposited along the continental margin. Site 986 is located on the lower continental slope, on the northern extension of the sediment wedge developed in front (west) of the Storfjorden Trough. In the analyzed interval, the distribution pattern of the three main components of foraminiferal assemblages (the agglutinated, calcareous benthic, and planktonic groups) and the occurrence of the lower taxa (genera and species) support the interpretation of mass-wasting and redeposition processes acting on the continental slope of this region.

METHODS

The stratigraphy of the upper Pliocene succession at Site 986 was established by the investigation of planktonic, calcareous benthic, and agglutinated benthic foraminifers from 131 samples. Approximately one 30-cm^3 sample per section of core was used. The samples were disaggregated with water without dispersant. Samples were soaked in water overnight and then mechanically agitated before washing over a 63-µm sieve. The residue was then dried overnight in an oven at <60°C. The fossil identifications were carried out in the 106- to 500-µm fraction. In some samples, the fractions <106 µm and >500 µm were also investigated. Whenever possible, 300 individuals were picked from each sample. In order to better identify the microfossil assemblages, a number of samples rich in mineral grains were also gravity separated in tetrachloroethylene.

LITHOSTRATIGRAPHY

The investigated interval from Sample 162-986D-28R-1, 30–36 cm (647.72 mbsf), through 45R-7, 29–36 cm (820.02 mbsf), belongs to lithologic Unit III (Figs. 3–6). This unit is characterized by a relatively high sand content and the absence of dropstones. The primary lithologies are very dark gray to dark greenish gray silty clay with sand, clayey silt with sand, silty clay, and sandy silty clay. Biogenic calcareous sediment is present in trace to minor amounts throughout the unit. The biocarbonate consists largely of calcareous nannofossils in amounts up to 20% (by volume) and shows a slight increase downcore. Authigenic iron sulfides, primarily in the form of disseminated pyrite, are commonly present in minor amounts (Jansen, Raymo, Blum, et al., 1996).

The section from Sample 162-986D-46R-1, 29–36 cm (820.59 mbsf), to the base (60R-1, 29–36 cm, 955.32 mbsf) belongs to lithologic Unit IV (Figs. 3–6). The transition from Unit III to Unit IV is

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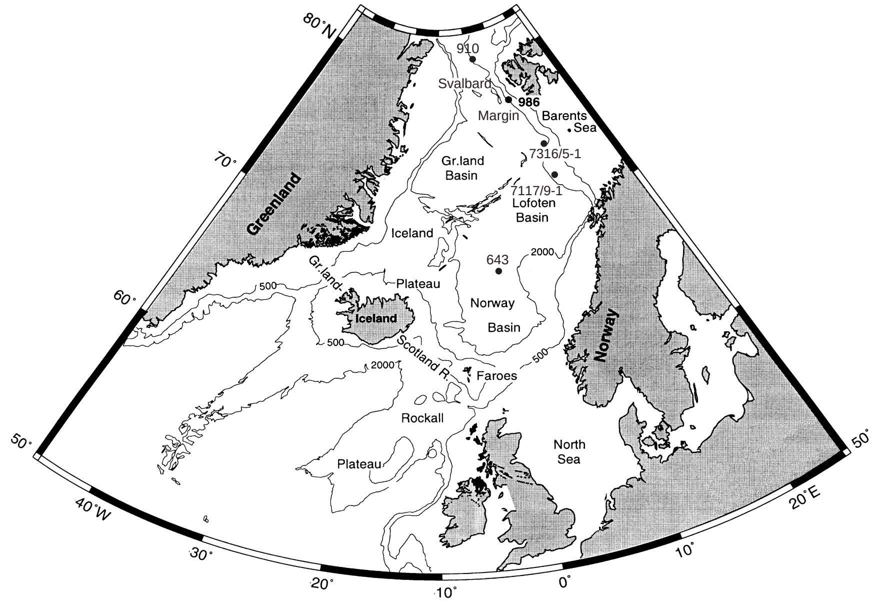


Figure 1. Map of the North Atlantic showing position in the Norwegian-Greenland Sea of sections discussed.

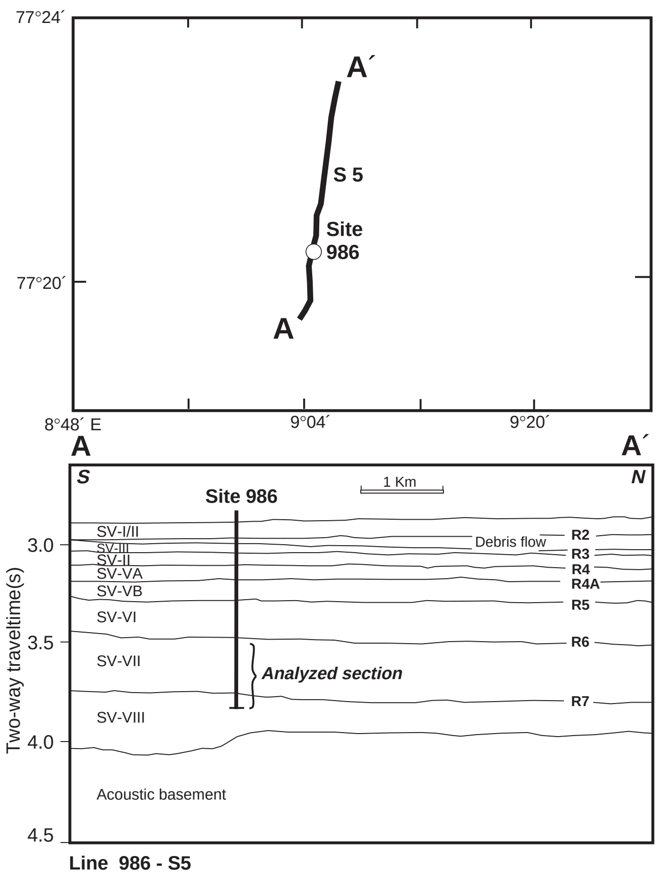


Figure 2. Position of the borehole interval analyzed geographically and in relation to reflectors in a seismic section (A–A′). After Jansen, Raymo, Blum, et al. (1996).

marked by a decrease in sand- and silt-sized components. Subunit IVA (820.0–895.42 mbsf) is distinguished from the underlying sediments by increased magnetic susceptibility values and higher sand content. The sediments are predominantly composed of dark gray to black silty clay, with minor amounts of dark gray to black silty sand. Biocarbonate is present in minor amounts within this subunit (average 2.8%). Subunit IVB (897.62–955.32 mbsf) is distinguished from the overlying sediments by very low magnetic susceptibility values, a further decrease in sand content, and by the absence of biocarbonates. Subunit IVB is entirely composed of very dark to black silty clay. Silt- and sand-sized mineral components are less abundant than in Subunit IVA (Jansen, Raymo, Blum, et al., 1996).

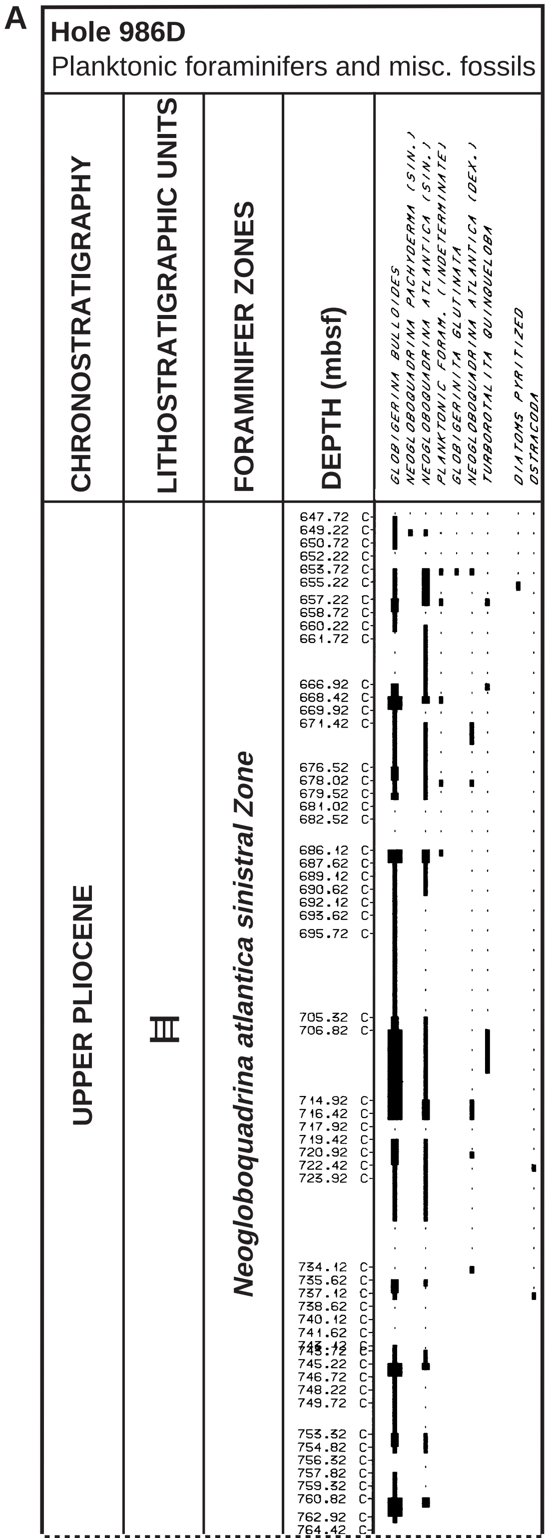
PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY

The high-latitude planktonic foraminiferal associations are low-diversity faunas composed of long-ranging species. In general, it is not possible to apply the standard zonations established for low latitudes (Blow, 1969, 1979; Bolli and Saunders, 1985) or for northern temperate regions (Berggren, 1972; Poore and Berggren, 1975; Poore, 1979; Weaver and Clement, 1986) because the index fossils used for these zonal definitions are often absent in high-latitude assemblages. Studies of Ocean Drilling Program (ODP) Leg 104 sites on the Vøring Plateau in the Norwegian Sea have produced a local high-latitude Neogene zonation (Spiegler and Jansen, 1989; Spiegler, 1996) that is useful for comparison with Site 986. Data from ODP Leg 151 sites from the Fram Strait and the Yermak Plateau are also applicable (Spiegler, 1996).

Planktonic foraminifers are found in 80% of the samples in the interval from Sample 162-986D-28R-1, 30–36 cm (647.72 mbsf), through 54R-1, 29–36 cm (897.62 mbsf). The interval from 897.62 mbsf to the base of the drilled succession (Sample 162-986D-60R-1, 29–36 cm, 955.32 mbsf) is barren of planktonic foraminifers. In the 250-m-thick interval containing planktonic foraminifers, the assemblage exhibits highly variable abundance, fluctuating from rich faunas to intervals that are poor in or barren of planktonic foraminifers. Except in a few samples, most specimens are well preserved and show no signs of reworking.

The assemblage consists mainly of *Neogloboquadrina atlantica* (sinistral) and *Globigerina bulloides*. *N. atlantica* (dextral) occurs sporadically, mainly in the upper part of the section. *Neogloboquadrina pachyderma* (sin., mainly unencrusted form), *N. pachyderma* (dex.), *Turborotalita quinqueloba,* and *Globigerinita glutinata* occur in small numbers in some intervals throughout the succession (Fig. 3).

In the high-latitude Neogene, *N. atlantica* (sin.) is indicative of the *Neogloboquadrina atlantica* (sin.) Zone, spanning Pliocene to latest Miocene age (Spiegler and Jansen, 1989). The entire carbonate-



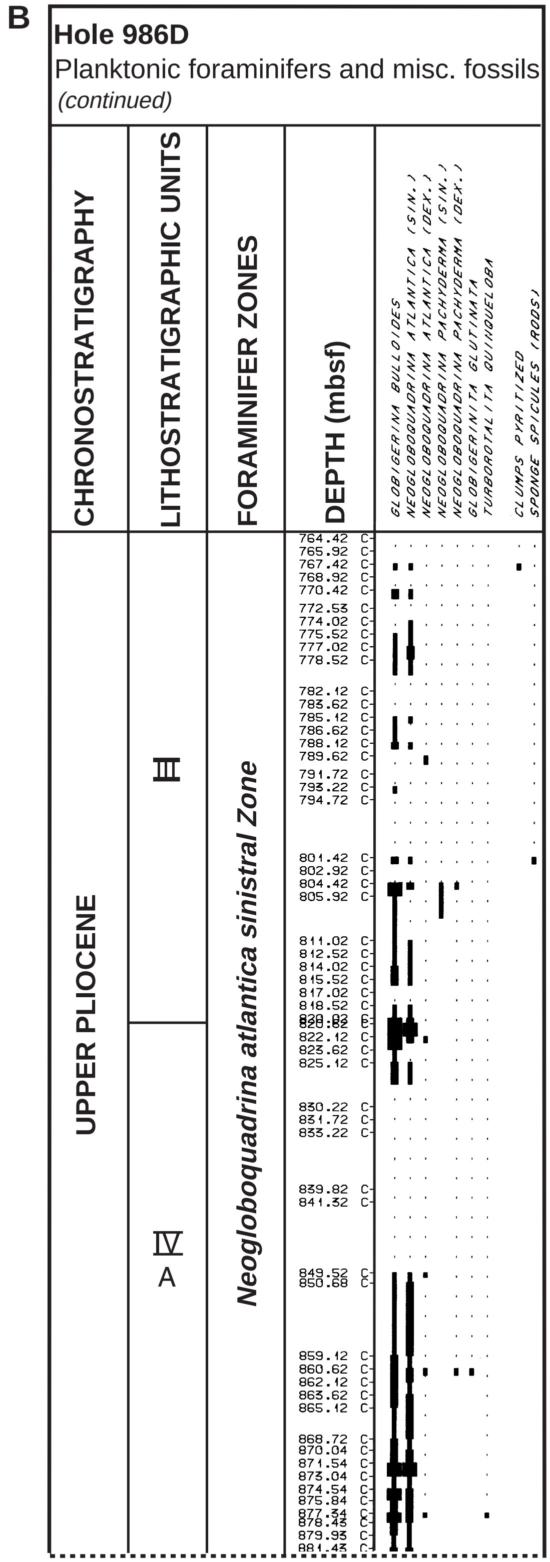


Figure 3. **A.** Range chart of upper Pliocene planktonic foraminifers and miscellaneous fossils in Hole 986D (upper part of investigated section). In the bar chart, a thin bar = <10 specimens, a medium bar = 10 to 30 specimens, and a thick bar = >30 specimens. C = core sample. **B.** Range chart of upper Pliocene planktonic foraminifers and miscellaneous fossils in Hole 986D (middle part of investigated section). (Continued on next page.)

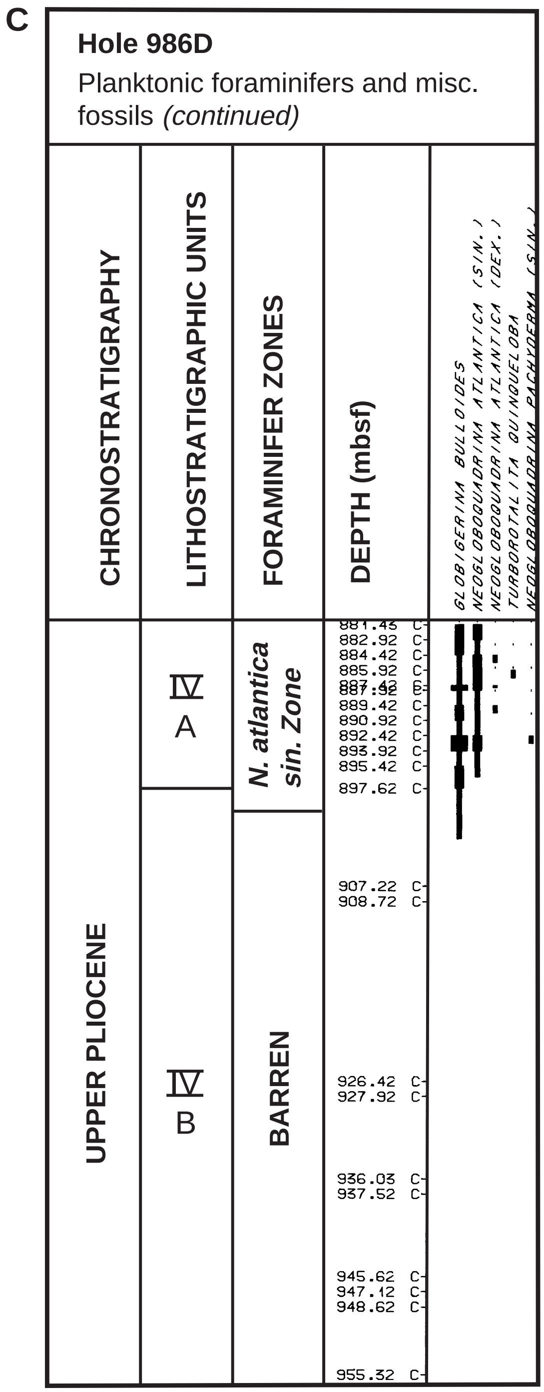


Figure 3 (continued). **C.** Range chart of upper Pliocene planktonic foraminifers and miscellaneous fossils in Hole 986D (lower part of investigated section).

bearing sequence is assigned to the *N. atlantica* (sin.) Zone. This zone is also rich in *G. bulloides.* On the Vøring Plateau and in the North Atlantic, the last occurrence (LO) of *N. atlantica* (sin.) is no younger than 2.4 Ma (Weaver and Clement, 1986; Spiegler and Jansen, 1989; Channell and Lehman, Chap. 8, this volume). The LO of *N. atlantica* (dex.) is close to the Pleistocene/Pliocene boundary (Weaver and Clement, 1986; Spiegler and Jansen, 1989). This species occurs sporadically in the *N. atlantica* (sin.) Zone of Spiegler and Jansen (1989).

Paleomagnetic data in Hole 986D show that the base of the core is in the Matuyama Chron, which implies an age of <2.6 Ma (Channell et al., Chap. 10, this volume). The calcareous benthic foraminifer *Cibicides grossus* occurs down to 877.34 mbsf. This also indicates a late Pliocene age for this interval.

The climatic regime in this area during the late Pliocene may be interpreted to comprise episodic ingressions of warm and transitional surface-water masses into a generally cold ocean. The occurrence of *N. pachyderma* (dex.), *T. quinqueloba,* and *G. glutinata* indicates several short, warm to transitional surface-water events. The cold conditions are documented by *N. atlantica* (sin.) and *N. pachyderma* (sin.) (Spiegler, 1996). The highly variable abundance of planktonic foraminifers seems also to be typical of alternating glacial and interglacial conditions. At high northern latitudes, planktonic foraminifers are generally less common as a result of low water temperatures and/or dissolution of the calcareous microfossils. Another reducing factor is dilution by large amounts of detrital material and ice-rafted debris (Spiegler, 1996).

CALCAREOUS BENTHIC FORAMINIFERAL BIOSTRATIGRAPHY

Upper Pliocene calcareous benthic foraminifers are described from open-ocean high-latitude areas at ODP Sites 642, 643, and 644 on the Vøring Plateau (Leg 104; Osterman and Qvale, 1989) and Site 910 on the Yermak Plateau (Leg 151; Osterman, 1996). Paleomagnetic records from these boreholes provide good age control for the fossil zones. Upper Pliocene calcareous benthic foraminiferal assemblages are described from outer-shelf sites in exploration wells on the Senja Ridge (Eidvin et al., 1993a) and in the Vestbakken Volcanic Province (Eidvin et al., 1998b) in the western Barents Sea (Fig. 1). In the Vestbakken Volcanic Province (Well 7316/5-1), the upper Pliocene section is sampled with sidewall cores. In Wells 7117/9-1 and 7117/9-2 on the Senja Ridge, only ditch cuttings were available. The upper Pliocene deposits in Wells 7316/5-1, 7117/9-1, and 7117/9-2 lack any definitive age control, and dating is based solely on planktonic and benthic foraminifers, supported by lithostratigraphic correlation and strontium isotope stratigraphy. Numerous terrestrial outcrops of shallow-water Pliocene marine deposits occur throughout the Arctic (e.g., Brouwers et al., 1991; Brigham-Grette and Carter, 1992; Feyling-Hanssen, 1976, 1980, 1990; Feyling-Hanssen et al., 1982; Funder et al., 1985; Todd, 1957; Vincent et al., 1984). These outcrop sections also lack definitive age control. They are normally correlated either by means of amino-acid racemization values or by macro- or microfaunal fossil assemblages. Most of these localities represent isolated sections of the Pliocene, which may or may not be correlative (Osterman, 1996).

At Hole 986D, calcareous benthic foraminifers are found in 82% of the samples in the interval between Sample 162-986D-28R-1, 30–36 cm (647.72 mbsf), and 54R-1, 29–36 cm (897.62 mbsf). The interval from 897.62 mbsf to the bottom of the hole (Sample 162-986D-60R-1, 29–36 cm, 955.32 mbsf) is barren. Calcareous benthic foraminifers are found at most of the same levels as planktonic foraminifers, and additionally at a few other levels. As with the planktonic foraminifers, the benthic assemblage in this 250-m-thick interval exhibits highly variable abundance, fluctuating frequently from abundant to rare or barren. Contrary to the planktonic foraminifers, the tests of certain species are broken, worn, or corroded. However, most species that constitute the assemblage occur uniformly throughout the section. Consequently, only one assemblage zone is defined; namely the *Melonis zaandamae–Cassidulina teretis* Zone.

Tests of the nominate species occur quite frequently throughout the succession. Other important taxa are *Pullenia subcarinata*, *Cassidulina reniforme*, *Epistominella exigua*, *Epistominella* spp., *Pullenia bulloides,* and *Cibicides lobatulus* (Fig. 4). Other characteristic forms that occur more sporadically include *Buccella tenerrima, Elphidium excavatum, Elphidium* spp., *Elphidium albiumbilicatum*, *Angulogerina angulosa*, *Quinqueloculina seminulum*, *Buccella frigida*, *Virgulina loeblichi*, *Triloculina* sp., *Angulogerina fluens*, *Cibi-*

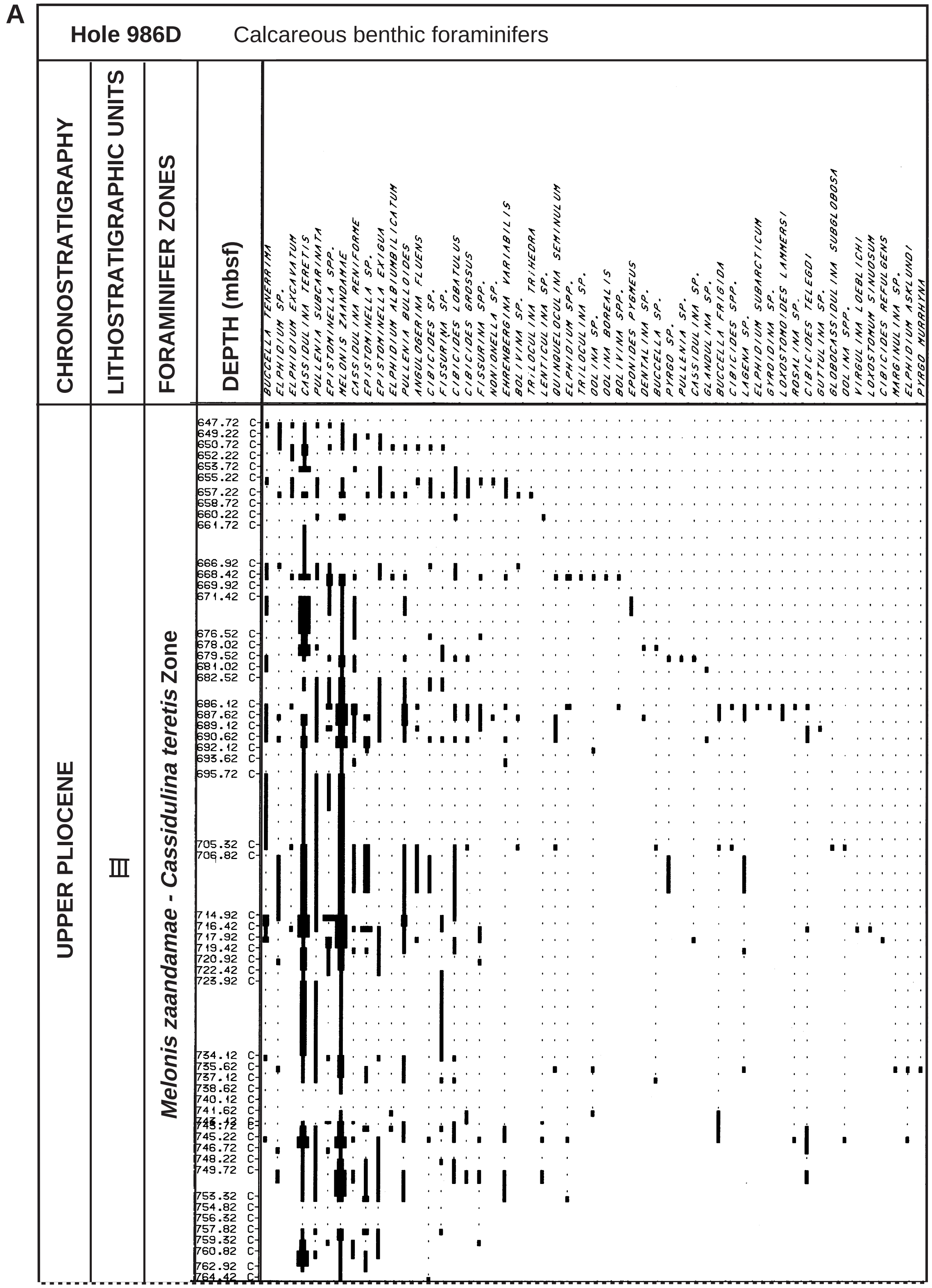


Figure 4. **A.** Range chart of upper Pliocene calcareous benthic foraminifers in Hole 986D (upper part of investigated section). See Figure 3 for explanation of symbols. (Continued on next page.)

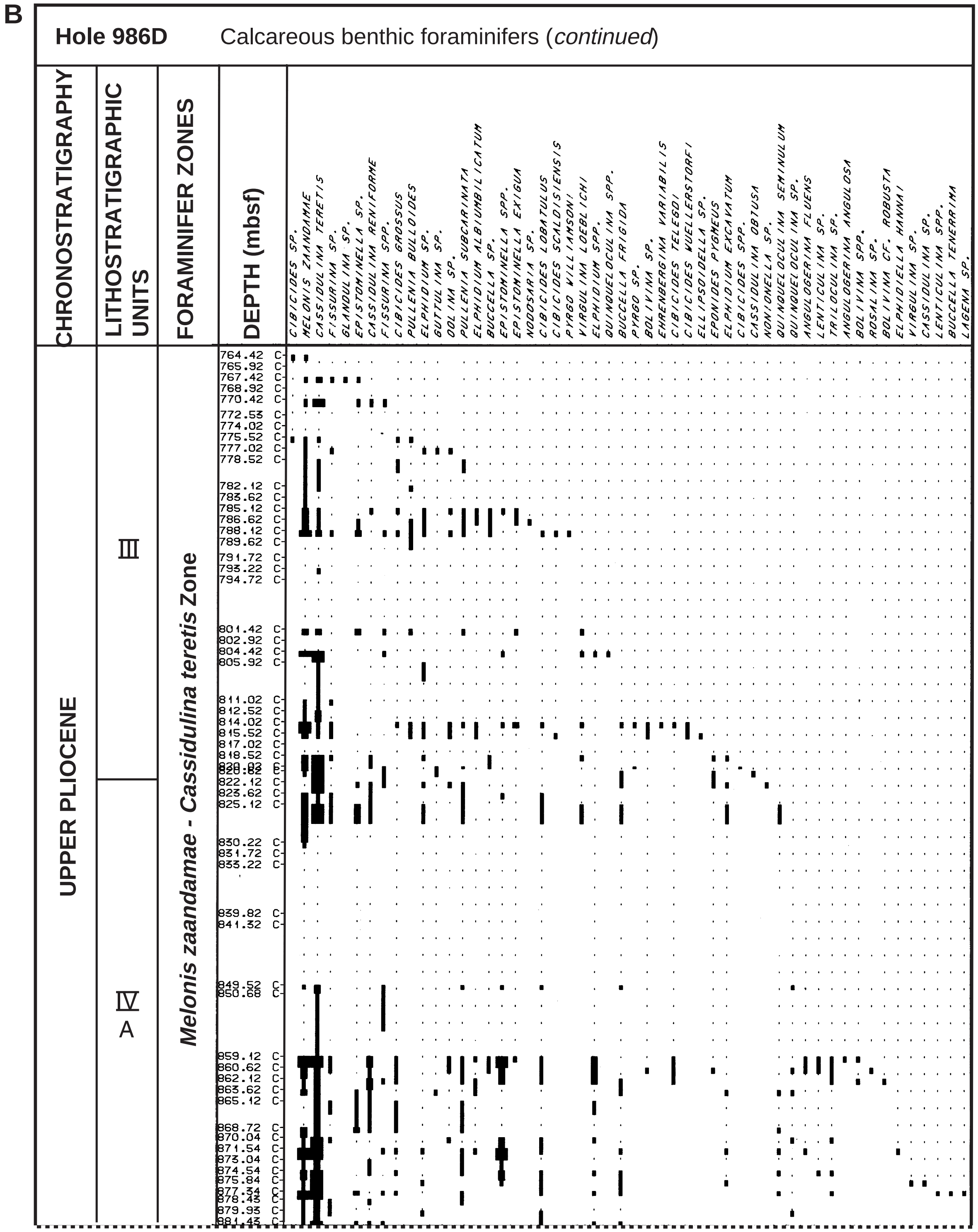


Figure 4 (continued). **B.** Range chart of upper Pliocene calcareous benthic foraminifers in Hole 986D (middle part of investigated section).

cides grossus, *Elphidiella hannai* (one specimen at 871.54 mbsf), *Ehrenbergina variabilis*, *Cibicides telegdi*, and *Eponides pygmeus*.

With the exception of *C. grossus*, *E. hannai*, *E. variabilis*, *C. telegdi*, and *E. pygmeus*, all the calcareous benthic foraminifers are extant species. *E. variabilis*, *C. telegdi*, and *E. pygmeus* are probably reworked from Oligocene or Miocene deposits (Ulleberg, 1974; Stratlab, 1988; Gradstein and Bäckström, 1996; Eidvin et al., 1998a). *C. grossus* and *E. hannai* are known from upper Pliocene deposits in the western Barents Sea (Eidvin et al., 1993a, 1998b), from the Norwegian Sea continental shelf (Eidvin and Riis, 1991; Eidvin et al., 1998a; Poole and Vorren, 1993; Stratlab, 1988), and in the North Sea (King, 1989; Knudsen and Asbjörndottir, 1991; Eidvin and Riis, 1992; Eidvin et al., 1993b; Pedersen, 1995). *C. grossus* is, however, recorded in deposits as old as the late Miocene in the Netherlands. *E.*

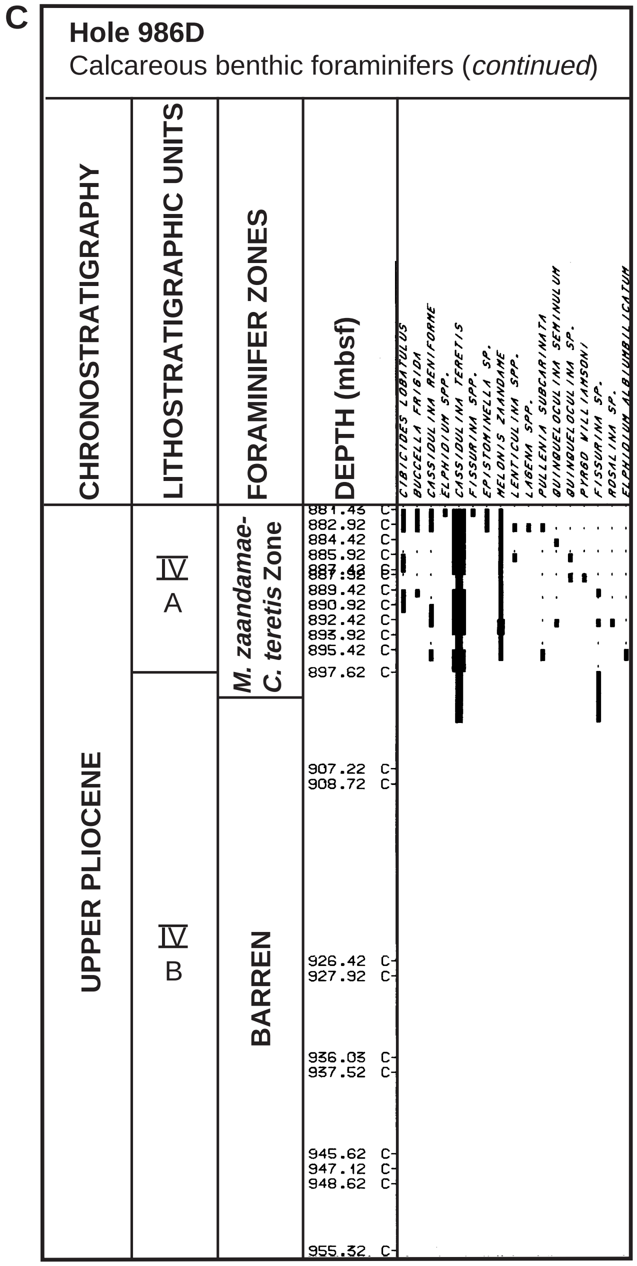


Figure 4 (continued). **C.** Range chart of upper Pliocene calcareous benthic foraminifers in Hole 986D (lower part of investigated section).

hannai is known from upper Pliocene deposits in the same area (Doppert, 1980). The single recorded specimen of *E. hannai* may represent contamination.

Species of *Elphidium* are typically restricted to shallow water and often occur in proximal glaciomarine environments. Therefore, it is possible that most of the *Elphidium* specimens have been ice rafted into these water depths (Osterman, 1984, 1996) or transported by sedimentary mass-flow processes. *A. angulosa*, *E. hannai*, *C. lobatulus*, *A. fluens*, *V. loeblichi*, and *C. grossus* are also probably reworked from shallower water environments (Mackensen et al., 1985; Skarbø and Verdenius, 1986). The origin of some other specimens is not as clear. Many specimens of *C. teretis* and some tests of *N. affine* are worn or broken. Both of these species have a wide water-depth range. Many of these specimens are probably in situ, but some of the broken

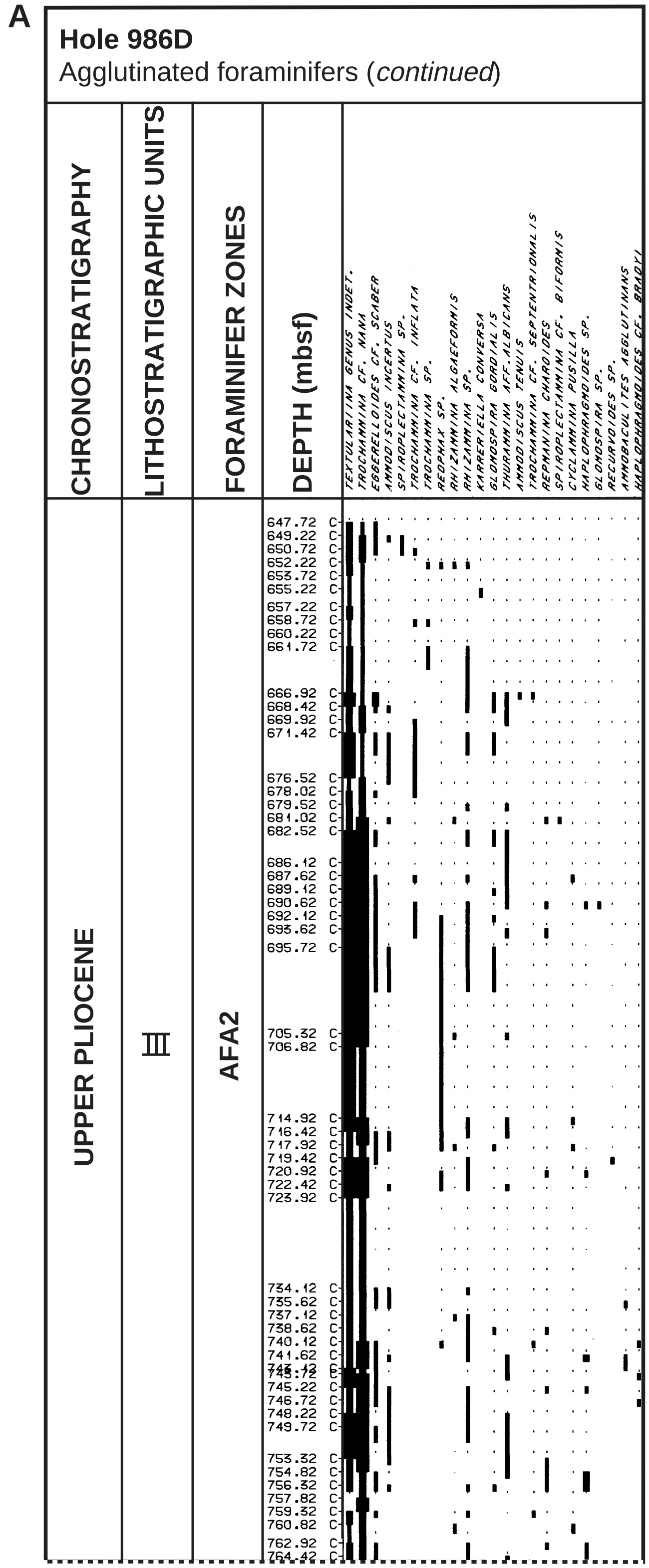


Figure 5. **A.** Range chart of upper Pliocene agglutinated foraminifers in Hole 986D (upper part of investigated section). See Figure 3 for explanation of symbols. (Continued on next page.)

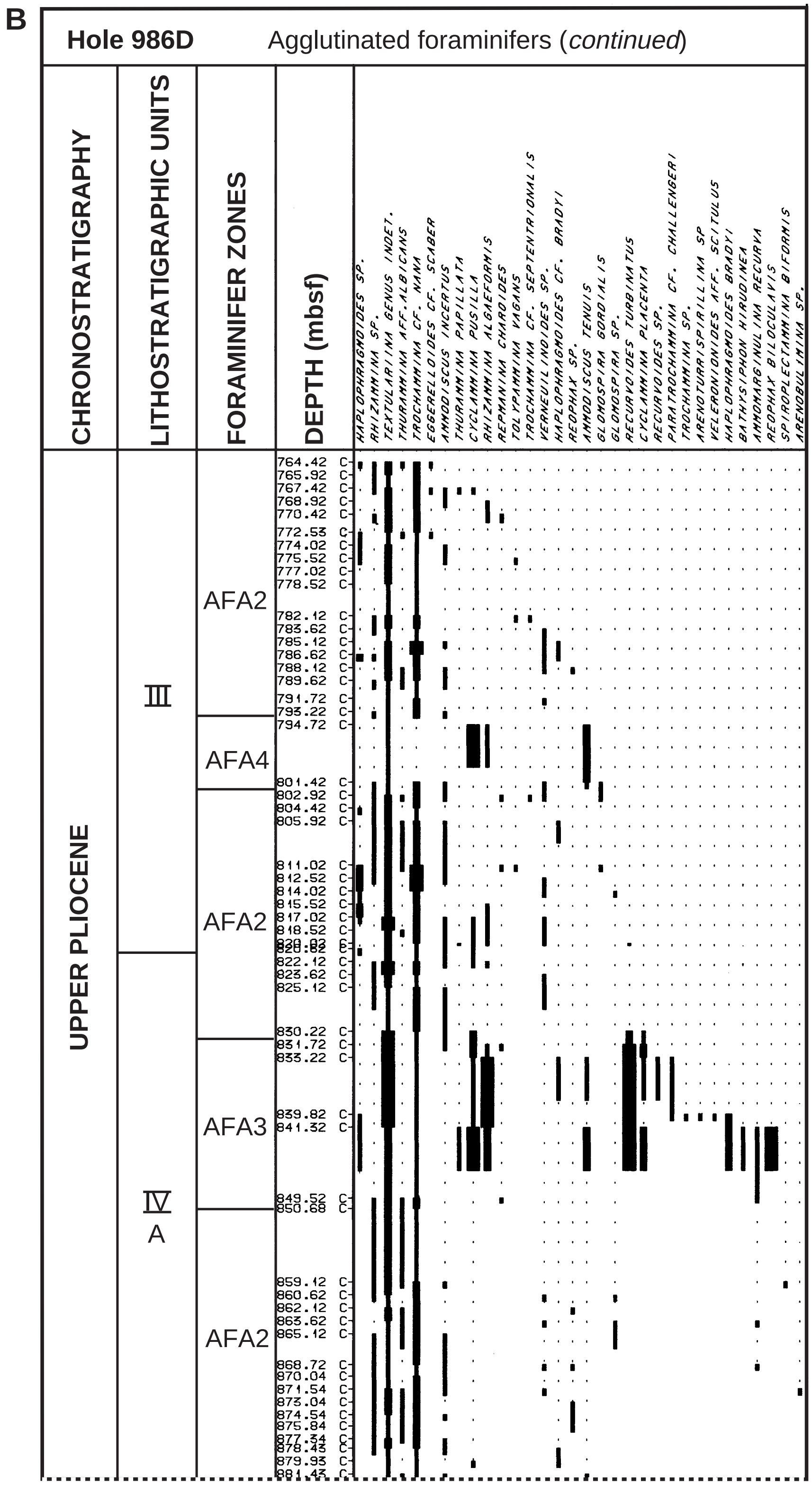


Figure 5 (continued). **B.** Range chart of upper Pliocene agglutinated foraminifers in Hole 986D (middle part of investigated section).

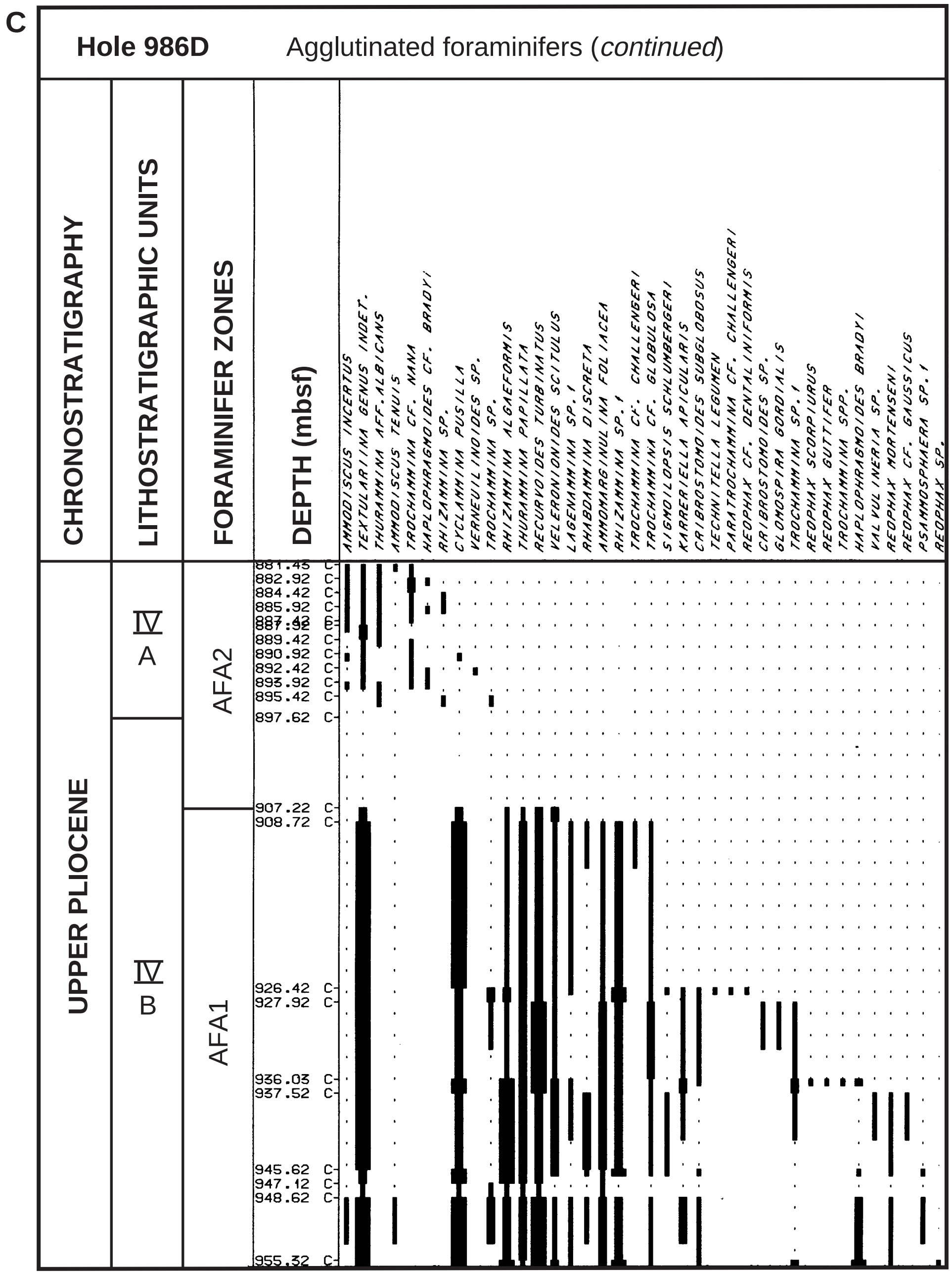


Figure 5 (continued). **C.** Range chart of upper Pliocene agglutinated foraminifers in Hole 986D (lower part of investigated section).

tests might have been reworked from shallower water-depth environments (Mackensen et al., 1985). *E. exigua*, *P. bulloides*, *P. subcarinata*, *Triloculina trihedra*, *Pyrgo murrhina*, and *Cibicides wuellerstorfi* are all deep-water forms (Sejrup et al., 1981; Mackensen et al., 1985; Skarbø and Verdenius, 1986).

In samples containing calcareous benthic foraminifers, the number of species ranges from one to 25 and the number of specimens (per cubic centimeter sediment) from one to 20. An overall low number of species and specimens in this succession indicates a generally cold oceanic climatic regime. Samples that are barren or have low diversities of calcareous foraminifers probably represent episodes of severe glaciation. Samples containing faunas with comparatively high diversities suggest warmer episodes (Osterman, 1996). This interpretation is consistent with the varying contents of Arctic species such as *E. excavatum* f. *clavata*, *C. reniforme*, *V. loeblichi*, *Elphidium subarcticum*, and *Elphidium asklundi* as well as with changing amounts of boreal species, including *A. angulosa*, *C. teretis*, *Bolivina* cf. *robusta*, *E. exigua*, and *E. albiumbilicatum* (Feyling-Hanssen, 1983). However, the presence of reworked forms introduces some uncertainties into this interpretation.

AGGLUTINATED FORAMINIFERAL BIOSTRATIGRAPHY

Main Faunal Features

Agglutinated foraminifers occur in varying amounts in all the analyzed samples from 162-986D-28R-1, 30–36 cm (647.72 mbsf), through 60R-1, 29–36 cm (955.32 mbsf), as shown in Figure 5. Within this interval, four agglutinated foraminiferal assemblages (AFA) are distinguished. The preservation of the assemblages varies from dominantly porous noncompressed through mixed to dominantly

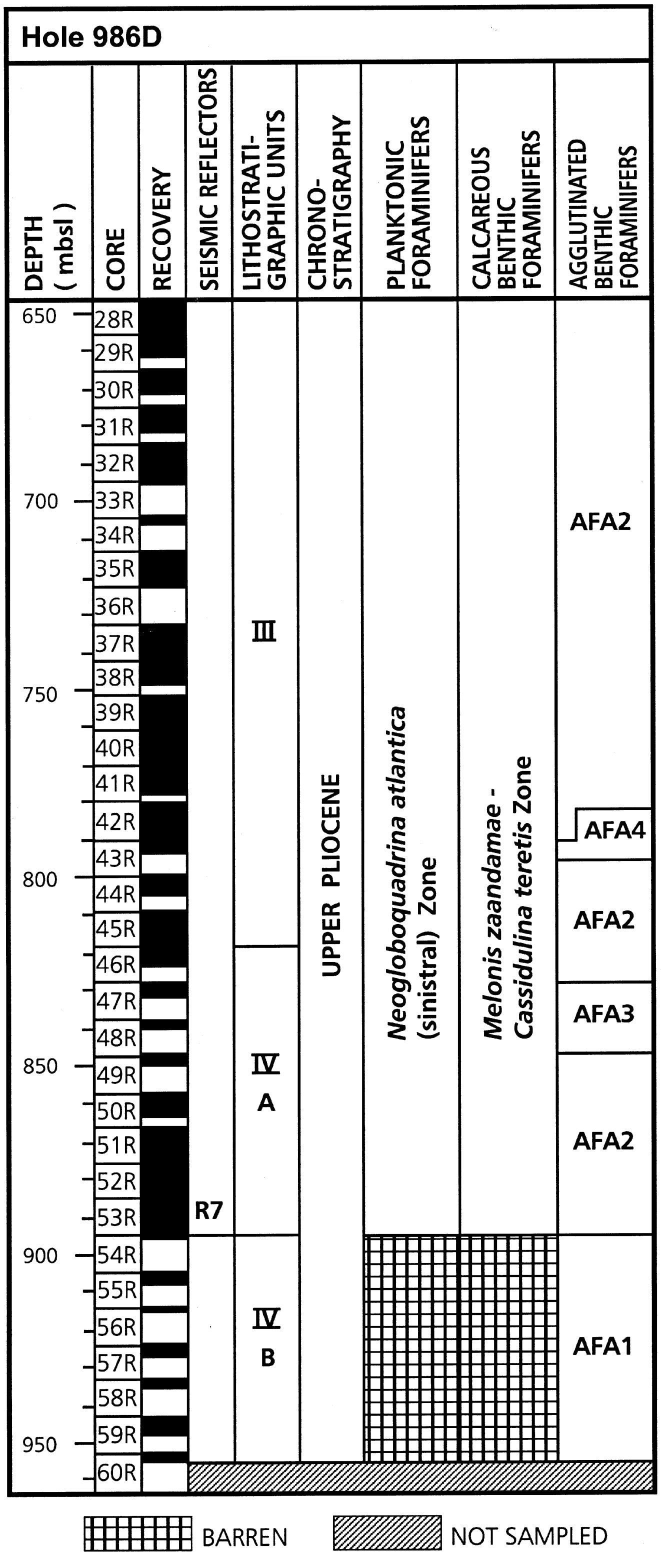


Figure 6. Zonal scheme of the analyzed upper Pliocene section in Hole 986D based on the three main foraminifer groups (AFA = agglutinated foraminiferal assemblage).

silicified compressed. These preservational types occur in repeated units of changing thicknesses throughout the analyzed succession. Based on this distribution pattern, 14 preservational units (PU) are distinguished (Fig. 7).

The porous noncompressed faunal component is composed of specimens showing the original shape of the chambers (which usually are empty) and the slightly porous texture of unaltered agglutinated tests. In the silicified compressed component, the tests are flattened to disappearance of the chamber cavities. Owing to diagenetic silicification, the silt grains forming the walls are no longer discernible.

Agglutinated Assemblages

AFA1, **Cyclammina pusilla** *assemblage*

This fauna describes the lowermost part of the cored section from Sample 162-986D-60R-1, 29–36 (955.32 mbsf), through 55R-1, 24–31 cm (907.22 mbsf). It is dominated by *Cyclammina pusilla*, *Recurvoides turbinatus*, *Rhizammina* sp., and *Thurammina papillata*. Characteristic species include *Rhizammina algaeformis*, *Verneuilinoides scitulus*, *Ammomarginulina foliacea*, *Karreriella apicularis,* and *Reophax mortenseni.* Owing to the poor state of preservation, a large number of specimens could not be identified at the generic level and are designated as *Textulariina* genus indeterminate on the range chart (Fig. 5). Based on its composition and preservational features, the assemblage is interpreted to represent a bathyal in situ fauna. It is identical to the porous noncompressed interval PU1 (Fig. 7).

AFA2, **Trochammina** *cf.* **nana** *assemblage*

This assemblage comprises three intervals characterized by silicified compressed taxa or mixed faunas. It is subdivided into a lower, middle, and thick upper segment by two intervening porous noncompressed assemblages (Fig. 5). *Trochammina* cf. *nana is* dominant through each of the three segments. The undifferentiated group, *Textulariina* genus indeterminate, is also quantitatively important. The assemblage is interpreted to consist mainly of redeposited specimens.

The lower *T.* cf. *nana* assemblage extends from Sample 162-986D-54R-1, 29–36 cm (897.62 mbsf), through 49R-1, 29–36 cm (849.52 mbsf). Characteristic species include *Ammodiscus incertus*, *Rhizammina* sp., and *Thurammina* aff. *albicans* in addition to more sporadic occurrences of *Glomospirella* sp., *Haplophragmoides* cf. *bradyi*, and *Verneuilinoides* sp. This assemblage segment corresponds to the silicified compressed interval PU2.

The middle segment characterized by this assemblage extends from Sample 162-986D-46R-4, 29–36 cm (825.12 mbsf), to 44R-1, 29–36 cm (801.42 mbsf). Besides the dominant forms, significant taxa include *A. incertus, Rhizammina* sp. *T.* aff. *albicans, Haplopragmoides* sp., and *Verneuilinoides* sp. This segment contains the silicified compressed intervals PU4 and PU6 as well as the mixed interval PU5.

The upper part of the *T.* cf. *nana* assemblage extends from Sample 162-986D-43R-2, 29–36 cm (793.22 mbsf), through 28R-1, 30–36 cm (647.72 mbsf). Thus, it makes up almost half of the upper Pliocene part of the cored section. Characteristic, but quantitatively subordinate, species include *Eggerelloides* cf. *scaber*, *A. incertus*, *Rhizammina* sp., and *T.* cf. *albicans*. Many taxa, such as *Glomospira gordialis*, *Repmanina charoides*, *C. pusilla*, and *Haplophragmoides* sp., occur in low numbers restricted to scattered samples. Within this segment, seven preservational units are distinguished. Four of these are of the silicified compressed type (PU8, PU10, PU12, and PU14), whereas three are of mixed nature (PU9, PU11, and PU13).

AFA3, **Recurvoides turbinatus** *assemblage*

This assemblage is developed from Sample 162-986D-48R-2, 29–36 cm (841.32 mbsf), through 47R-1, 29–36 cm (830.22 mbsf).

AGGLUTINATED FORAMINIFER ASSEMBLAGES		AGGLUTINATED FORAMINIFER PRESERVATIONAL UNITS		SILICIFIED COM - PRESSED TESTS %		
				0 - 25	25-75	75-100
AFA2	*Trochammina* cf. *nana*	PU 14	162-986D-28R-01(647.72 mbsf) Silicified compressed 162-986D-28R-04(652.22 mbsf)			
		PU 13	162-986D-28R-05(653.72 mbsf) Mixed 162-986D-29R-02(658.22 mbsf)			
		PU 12	162-986D-29R-03(660.22 mbsf) Silicified compressed 162-986D-34R-02(706.82 mbsf)			
		PU 11	162-986D-35R-01(714.92 mbsf) Mixed			
		PU 10	162-986D-35R-02(716.42 mbsf) Silicified compressed 162-986D-40R-03(765.92 mbsf)			
		PU9	162-986D-40R-04(767.42 mbsf) Mixed 162-986D-40R-06(770.42 mbsf)			
		PU8	162-986D-41R-01(772.53 mbsf) Silicified compressed 162-986D-43R-02(793.22 mbsf)			
AFA4	*Ammodiscus tenuis*	PU7	162-986D-43R-03(794.72 mbsf) Porous non-compressed			
AFA2	*Trochammina* cf. *nana*	PU6	162-986D-44R-01(801.42 mbsf) Silicified compressed 162-986D-45R-05(817.02 mbsf)			
		PU5	162-986D-45R-06(818.52 mbsf) Mixed 162-986D-46R-02(822.12 mbsf)			
		PU4	162-986D-46R-03(823.52 mbsf) Silicified compressed 162-986D-46R-04(825.12 mbsf)			
AFA3	*Recurvoides turbinatus*	PU3	162-986D-47R-01(830.22 mbsf) Porous noncompressed 162-986D-48R-02(841.32 mbsf)			
AFA2	*Trochammina* cf. *nana*	PU2	162-986D-49R-01(849.22 mbsf) Silicified compressed 162-986D-54R-01(897.62 mbsf)			
AFA1	*Cyclammina pusilla*	PU1	162-986D-55R-01(907.22 mbsf) Porous noncompressed 162-986D-60R-01(955.32 mbsf)			

RLN 9707010

Figure 7. Agglutinated foraminiferal assemblages and preservational units in the upper Pliocene succession in Hole 986D (AFA = agglutinated foraminiferal assemblage, PU = preservational units).

In addition to the nominate species, the unit is dominated by *R. algaeformis* and *C. pusilla*. *Textulariina* genus indet. is quantitatively important, whereas the frequency of *C.* cf. *nana* is strongly reduced. Characteristic species are *Cyclammina trullissata*, *Paratrochammina* cf. *challengeri*, *Haplophragmoides bradyi*, *Bathysiphon hirudinea*, and *Reophax bilocularis*. The assemblage is a porous noncompressed type, corresponding to the interval PU3.

AFA4, Ammodiscus tenuis *assemblage*

This is recognized only in Sample 162-986D-43R-3, 29–36 cm (794.72 mbsf), strongly dominated by *C. pusilla* and characterized by *A. tenuis* and *R. algaeformis*. The fauna is of porous noncompressed preservation designated as PU7.

DEPOSITIONAL SIGNIFICANCE OF PRESERVATIONAL UNITS

Porous Noncompressed Faunal Units

In the samples referred to in these preservational units, 75%–100% of the specimens are classified as porous noncompressed. Both small and large specimens are present, although large tubular forms commonly dominate. The porous wall texture indicates that no significant diagenetic cementation of the agglutinated material has taken place. The tests retain their original shape with no, or only very weak, compressional deformation. In most species the color is white or yellowish, but some are reddish or light brown.

The generally well-preserved nature of the assemblages suggests that they have not been significantly affected by post-mortem transport and resedimentation processes. In accordance with this, the taxonomic composition of the faunas indicates bathyal to abyssal conditions and is consistent with a late Pliocene age.

Tubular taxa are abundant in the *Cyclammina pusilla* assemblage, common in the *Recurvoides turbinatus* assemblage, and are present in low numbers in the *Ammodiscus tenuis* assemblage. The group is generally regarded to be characteristic of deep-water, mainly bathyal environments (Gradstein and Berggren, 1981; Miller et al., 1982; Jones, 1988; Gradstein and Bäckström, 1996). In the *C. pusilla* assemblage, the tubular group is represented by *Rhizammina algaeformis*, *Rhabdammina discreta*, and *Rhizammina* sp., whereas in the *R. turbinatus* assemblage, *R. algaeformis* is dominant. As shown by Schröder (1986), *R. algaeformis* is abundant in modern bathyal to abyssal faunas of the northwestern Atlantic Ocean (Nova Scotia Rise, Bermuda Rise, and Nares Abyssal Plain). On the Nova Scotia Rise, *R. discreta* occurs mainly in the depth interval 2750–3550 m.

According to information published by Schröder (1986), Charnock and Jones (1990), and Jones (1994), the following species of the porous noncompressed assemblages are generally confined to bathyal and greater depths in the present-day North Atlantic Ocean: *Ammodiscus tenuis*, *Cyclammina pusilla*, *Thurammina papillata*, *Recurvoides turbinatus*, *Haplophragmoides bradyi*, *Ammomarginulina foliacea*, *Karreriella apicularis*, *Cribrostomoides subglobosus*, *Technitella legumen*, *Reophax guttifer*, *Ammonarginulina recurva*, *Cyclammina trullissata*, and *Reophax bilocularis*.

Silicified Compressed Faunal Units

In the samples belonging to these faunal units, 75%–100% of the foraminifers show the silicified compressed type of preservation. The specimens are small in size, markedly deformed by compression, and are strongly silicified by diagenetic processes. Their color is usually gray or brownish. The poor preservation and small size of the tests made taxonomic determinations difficult, which explains the extensive use of open nomenclature.

The preservational features of this fauna suggest reworking from pre-existing strata, with subsequent transport and resedimentation in the upper Pliocene lower slope environment. The small and relatively uniform size of the tests (usually 130–200 µm) suggests sorting by a hydrodynamic process.

The redeposited faunal component is dominated by *Textulariina* genus indet. and *T.* cf. *nana*. In addition to the redeposited forms, many samples contain scattered, well-preserved tests of more or less in situ origin belonging to species such as *R. algaeformis*, *C. pusilla*, and *Repmanina charoides*.

Mixed Faunal Units

The samples grouped in the mixed units contain 25%–75% porous noncompressed specimens, whereas the rest is silicified compressed. These fauna are developed in four thin intervals between silicified compressed units (Fig. 7). The increased frequency of the in situ faunal component in the mixed assemblages suggests periods with reduced influx of material from extrabasinal sources, or increased benthic productivity within the depositional area.

DISCUSSION

There are marked similarities between the Pliocene section in Hole 986D and some of the other Pliocene-aged deposits mentioned above, in particular the *Geodia* sp.–*Globigerina bulloides* Zone (D) in Well 7117/9-1 on the Senja Ridge (Eidvin et al., 1993a) and the *Globigerina bulloides–Cassidulina teretis* Zone (BB-FB) in Well 7316/5-1 in the Vestbakken Volcanic Province (Eidvin et al., 1998b; Fig. 8). Although the foraminifer assemblages in Wells 7117/9-1 and 7316/5-1 differ somewhat from those of Hole 986D in their generally lower diversity and poorer preservation, many of the recorded species are the same. In all sections, *C. teretis* and *M. zaandamae* dominate the calcareous benthic assemblages, whereas *G. bulloides* dominates the planktonic faunas. In addition, all sections contain many reworked calcareous and agglutinated specimens from Miocene to Eocene deposits. However, the analyzed section in Hole 986D contains more benthic species of deep-water affinity.

A maximum age of 2.7 Ma is assigned to the sections in Wells 7117/9-1 and 7316/5-1, and these sections probably represent sediments deposited after the great increase in the supply of ice-dropped material at the Leg 104 sites at the Vøring Plateau (Jansen and Sjøholm, 1991; Eidvin et al., 1993a, 1998b). A minimum age of 2.4 Ma is based on the fact that *G. bulloides* is common in Pliocene sediments older than 2.4 Ma at the Vøring Plateau sites (Spiegler and Jansen, 1989). However, *G. bulloides* is also found in the warmest interglacials of the last 1 Ma (Kellogg, 1977).

The assemblages in Hole 986D also have a strong affinity with the faunas recorded from the section between 151.27 and 502.97 mbsf in Hole 910C (Leg 141). This section also has a benthic assemblage with *C. grossus* (Osterman, 1996) and common *C. teretis*, *M. zaandamae*, and *Epistominella* associated with rare *E. albiumbilicatum.* The planktonic assemblage is dominated by *N. atlantica* (sin.) and *G. bulloides*. Paleomagnetic and fossil evidence date this section to the late Pliocene. A maximum age of 2.7 Ma is assigned to the base of the section (Spiegler, 1996; Fig. 8).

The interval in between Sample 104-643A-7H-2, 74–78 cm, and 7H-5, 74–78 cm, on the Vøring Plateau also contains common *C. teretis*, *M. zaandamae*, *N. atlantica* (sin.), and *G. bulloides*. Paleomagnetic records date this section from latest early Pliocene to earliest late Pliocene (Spiegler and Jansen, 1989; Osterman and Qvale, 1989; Fig. 8).

According to Channell et al. (Chap. 10, this volume), the uppermost 150 m at Site 986 appears to record the Brunhes/Matuyama boundary and the Jaramillo Subchron. The base of the drilled section (at ~950 mbsf) is interpreted to lie within the Matuyama Chron (age <2.58 Ma) with the normal polarity interval (interpreted as the Olduvai Subchron) occurring from ~730 to 750 mbsf. The age of the Olduvai Subchron is 1.76–1.98 Ma according to Cande and Kent (1992). This implies that the LO of *N. atlantica* (sin.) and the last common occurrence of *G. bulloides* are <1.7 Ma. In other words, this results in an apparent discrepancy of 0.7 m.y. at Site 986 compared to other ODP/Deep Sea Drilling Project Sites in the Norwegian Sea or the North Atlantic. This discrepancy is especially unlikely for the transitional dwelling *G. bulloides*. Extensive reworking of planktonic foraminifers at Site 986 could explain this problem, but few of the tests show any sign of wear. Less than 200 k.y. is an extremely short time to deposit the analyzed section. However, such extreme accumulation rates, in the 2.7–2.4 Ma time interval, are recorded from the western margin of the Barents Shelf (Eidvin et al., 1993a, 1998b), the Norwegian Sea continental shelf (Eidvin et al., 1998a), and the northern North Sea (Eidvin and Riis, 1992). For the time being, we are unable to find a solution on the mentioned discrepancy between the paleomagnetic and biostratigraphic data.

The porous noncompressed assemblages observed between 907.22 and 955.32 mbsf, between 830.22 and 841.32 mbsf, and at 794.72 mbsf consist exclusively of agglutinated taxa. The absence of calcareous benthic and planktonic foraminifers from these intervals indicates that the deposition of the assemblages has taken place most likely below the local carbonate compensation depth, although diagenetic dissolution of carbonate cannot be totally excluded.

The four silicified compressed assemblages and the seven mixed agglutinated assemblages are associated with a calcareous faunal component consisting of relatively few benthic specimens and more

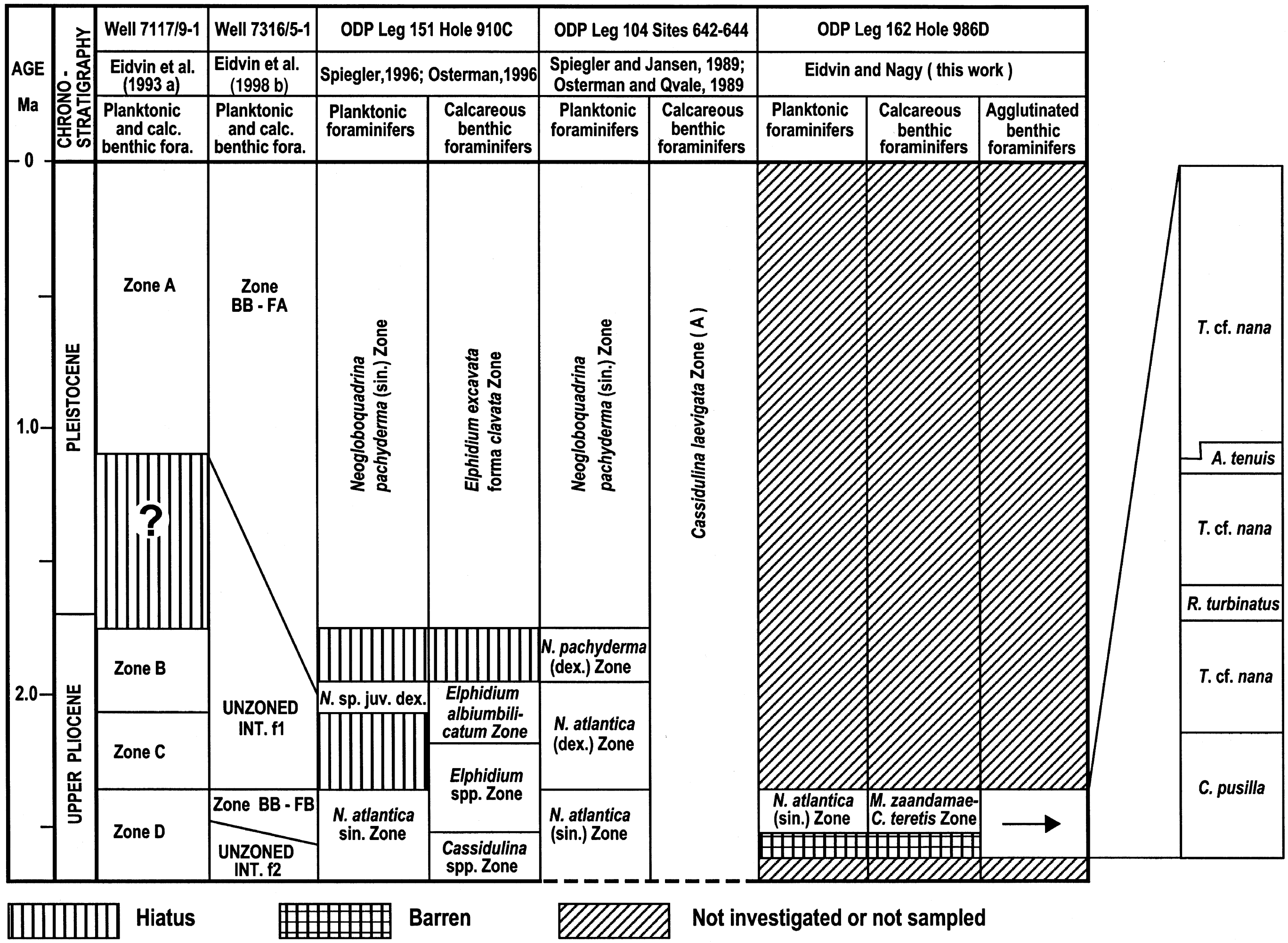


Figure 8. Correlation chart of upper Pliocene and Pleistocene foraminifer stratigraphic units in sections located in the Norwegian-Greenland Sea and the Barents Sea.

common planktonic taxa. It seems also likely that the calcareous benthic component is at least partly reworked, as suggested by the common occurrences of broken specimens.

SUMMARY

The studied interval from 647.72 to 955.32 mbsf in Hole 986D contains the following stratigraphic units based on foraminifers: the planktonic *Neogloboquadrina atlantica* (sinistral) Zone, the benthic *Melonis zaandamae–Cassidulina teretis* Zone, and four agglutinated assemblages designated as AFA1 through AFA4. The lowermost 55 m of the interval are barren of planktonic and calcareous benthic foraminifers but contain varying amounts of agglutinated taxa (Fig. 6).

Paleomagnetic data show that the bottom of the hole is in the Matuyama Chron, which implies an age of <2.6 Ma (Channell et al., Chap. 10, this volume). The occurrence of *N. atlantica* (sin.) implies an age not younger than 2.4 Ma for the top of the interval. The paleomagnetic data indicate a maximum age of ~1.7 Ma for the top of the interval (Channell et al., Chap. 10, this volume) and show a discrepancy between the paleomagnetic and the biostratigraphic data in this part of the hole.

A strongly variable abundance of planktonic and calcareous benthic foraminifers indicates alternating glacial and interglacial conditions. The planktonic fauna suggests a generally cold ocean with short warm to transitional surface-water ingressions and is consistent with the changing content of calcareous benthic Arctic and boreal species. Most of the planktonic specimens are well preserved and show no sign of having been reworked. Many of the calcareous benthic specimens, however, are broken, indicating considerable reworking.

The planktonic and calcareous benthic assemblages are correlated with similar faunas in Hole 910C on the Yermak Plateau, Hole 643A on the Vøring Plateau, the exploration Well 7117/9-1 on the Senja Ridge, and the exploration Well 7316/5-1 in the Vestbakken Volcanic Province.

The agglutinated assemblages represent alternating porous noncompressed bathyal in situ faunas and silicified compressed redeposited taxa as well as mixed faunas of in situ and redeposited specimens (see Fig. 7). The exclusively agglutinated assemblages occurring in three segments of Hole 966D indicate that the deposition has taken place below the local carbonate compensation depth.

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REFERENCES

Berggren, W.A., 1972. Cenozoic biostratigraphy and paleobiogeography of the North Atlantic. *In* Laughton, A.S., Berggren, W.A., et al., *Init. Repts. DSDP,* 12: Washington (U.S. Govt. Printing Office), 965–1002.

Berggren, W.A., Kent, D.V., Swisher, C.C., III, and Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. *In* Berggren, W.A., Kent, D.V., Aubry, M.-P., and Hardenbol, J. (Eds.), *Geochronology, Time Scales and Global Stratigraphic Correlation.* Spec. Publ.—Soc. Econ. Paleontol. Mineral. (Soc. Sediment. Geol.), 54:129–212.

Blow, W.H., 1969. Late middle Eocene to Recent planktonic foraminiferal biostratigraphy. *In* Brönnimann, P., and Renz, H.H. (Eds.), *Proc. First Int. Conf. Planktonic Microfossils, Geneva, 1967:* Leiden (E.J. Brill), 1:199–422.

————, 1979. *The Cainozoic Globigerinida:* Leiden (E.J. Brill).

Bolli, H.M., and Saunders, J.B., 1985. Oligocene to Holocene low latitude planktic foraminifera. *In* Bolli, H.M., Saunders, J.B., and Perch-Nielsen, K. (Eds.), *Plankton Stratigraphy:* Cambridge (Cambridge Univ. Press), 155–262.

Brigham-Grette, J., and Carter, L.D., 1992. Pliocene marine transgressions of northern Alaska: circumarctic correlations and paleoclimate interpretations. *Arctic,* 45:74–89.

Brouwers, E.M., Jørgensen, N.O., and Cronin, T.M., 1991. Climatic significance of the ostracode fauna from the Pliocene Kap København Formation, north Greenland. *Micropaleontology,* 37:245–267.

Cande, S.C., and Kent, D.V., 1992. A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. *J. Geophys. Res.,* 97:13917–13951.

Charnock, M.A., and Jones, R.W., 1990. Agglutinated foraminifera from the Paleogene of the North Sea. *In* Hemlebet et al. (Eds.), *Proc. 3rd Int. Workshop on Agglutinated Foraminifera,* 139–244.

Doppert, J.W.C., 1980. Lithostratigraphy and biostratigraphy of marine neogene deposits in the Netherlands. *Meded. Rijks Geol. Dienst,* 32-16:257–311.

Eidvin, T., Brekke, H., Riis, F., and Renshaw, D.K., 1998a. Cenozoic stratigraphy of the Norwegian Sea continental shelf, 64°N–68°N. *Nor. Geol. Tidsskr.,* 78:125–151.

Eidvin, T., Goll, R.M., Grogan, P., Smelror, M., and Ulleberg, K., 1998b. The Pleistocene to middle Eocene stratigraphy and geological evolution of the western Barents Sea continental margin at well site 7316/5-1 (Bjørnøya West area). *Nor. Geol. Tidsskr.,* 78:99–123.

Eidvin, T., Jansen, E., and Riis, F., 1993a. Chronology of Tertiary fan deposits off the western Barents Sea: implications for the uplift and erosion history of the Barents shelf. *Mar. Geol.,* 112:109–131.

Eidvin, T., and Riis, F., 1991. En biostratigrafisk analyse av tertiære sedimenter på kontinentalmarginen av Midt-Norge, med hovedvekt på øvre pliocene vifteavsetninger. *NPD-Contrib.,* 29.

————, 1992. En biostratigrafisk og seismostratigrafisk analyse av tertiære sedimenter i nordlige deler av Norskerenna, med hovedvekt på øvre pliocene vifteavsetninger. *NPD-Contrib.,* 32.

Eidvin, T., Riis, F., Beyer, C., and Rundberg, Y., 1993b. Et multidisiplinært, stratigrafisk studie av neogene sedimenter i sentrale deler av Nordsjøen (Ekofiskfeltet). *NPD-Contrib.,* 34.

Feyling-Hanssen, R.W., 1976. The Clyde Foreland formation: a micropaleontological study of Quaternary stratigraphy. *1st. Int. Symp. on Benthonic Foraminifera of Continental Margins* (Pt. B): *Paleoecology and Biostratigraphy.* Marit. Sed., Spec. Publ., 1:315–377.

————, 1980. Microbiostratigraphy of young Cenozoic marine deposits of the Qivituq Peninsula, Baffin Island. *Mar. Micropaleontol.,* 5:153–183.

————, 1983. Quantitative methods in micropalaeontology. *In* Costa, L.I. (Ed.), *Laboratories, Equipment and Methods.* NPD Bull., 2:109–151.

————, 1990. Foraminiferal stratigraphy in the Plio-Pleistocene Kap København Formation, North Greenland. *Medd. Groenl., Geosci.,* 24:1–32.

Feyling-Hanssen, R.W., Funder, S., and Petersen, K.S., 1982. The Lodin Elv formation: a Plio-Pleistocene occurrence in Greenland. *Bull. Geol. Soc. Den.,* 31:81–106.

Funder, S., Abrahamsen, N., Bennike, O., and Feyling-Hanssen, R.W., 1985. Forested Arctic: evidence from North Greenland. *Geology,* 13:542–546.

Gradstein, F., and Bäckström, S., 1996. Cainozoic Biostratigraphy and Paleobathymetry, northern North Sea and Haltenbanken. *Nor. Geol. Tidsskr.,* 76:3–32.

Gradstein, F.M., and Berggren, W.A., 1981. Flysch-type agglutinated foraminifera and the Maestrichtian to Paleogene history of the Labrador and North seas. *Mar. Micropaleontol.,* 6:211–269.

Jansen, E., Raymo, M.E., Blum, P., et al., 1996. *Proc. ODP, Init. Repts.,* 162: College Station, TX (Ocean Drilling Program).

Jansen, E., and Sjøholm, J., 1991. Reconstruction of glaciation over the past 6 Myr from ice-borne deposits in the Norwegian Sea. *Nature,* 349:600–603.

Jones, G.D., 1988. A palaeoecological model of late Palaeocene flysch type agglutinated foraminifera using the palaeoslope transect approach, Viking Graben, North Sea. *In* Rögl, F., and Gradstein, F.M. (Eds.), Proc. 2nd Workshop on Agglutinated Foraminifera, Vienna 1986. *Abh. Geol. Bundesanst.,* 4:143–153.

Jones, R.W., 1994. *The Challenger Foraminifera:* New York (Oxford).

Kellogg, T.B., 1977. Paleoclimatology and paleoceanography of the Norwegian and Greenland Seas: the last 450,000 years. *Mar. Micropaleontol.,* 2:235–249.

King, C., 1989. Cenozoic of the North Sea. *In* Jenkins, D., and Murray, J.W. (Eds.), *Stratigraphical Atlas of Fossil Foraminifera:* Chichester (Ellis Horwood Ltd.), 418–489.

Knudsen, K.L., and Asbjörnsdottir, L., 1991. Plio-Pleistocene foraminiferal stratigraphy and correlation in the Central North Sea. *Mar. Geol.,* 101:113–124.

Mackensen, A., Sejrup, H., and Jansen, E., 1985. The distribution of living and dead benthic foraminifera on the continental slope and rise off southwest Norway. *Mar. Micropaleontol.,* 9:275–306.

Miller, K.G., Gradstein, F.M., and Berggren, W.A., 1982. Late Cretaceous to early Tertiary agglutinated benthic foraminifera in the Labrador Sea. *Micropaleontology,* 28:1–30.

Osterman, L.E., 1984. Benthic foraminiferal zonation of a glacial-interglacial transition from Frobisher Bay, Baffin Island, N.W.T., Canada. *In* Oertli, H.J. (Ed.), *Benthos '83,* 471–476.

————, 1996. Pliocene and Quaternary benthic foraminifers from Site 910, Yermak Plateau. *In* Thiede, J., Myhre, A.M., Firth, J.V., Johnson, G.L., and Ruddiman, W.F. (Eds.), *Proc. ODP, Sci. Results,* 151: College Station, TX (Ocean Drilling Program), 187–195.

Osterman, L.E., and Qvale, G., 1989. Benthic foraminifers from the Vøring Plateau (ODP Leg 104). *In* Eldholm, O., Thiede, J., Taylor, E., et al., *Proc. ODP, Sci. Results,* 104: College Station, TX (Ocean Drilling Program), 745–768.

Pedersen, A.M., 1995. The lower Pleistocene in the North Sea. *Min. Envir. Ener., Ser. C,* 13.

Poole, D.A.R., and Vorren, T.O., 1993. Miocene to Quaternary paleoenvironments and uplift history on the mid Norwegian shelf. *Mar. Geol.,* 115:173–205.

Poore, R.Z., 1979. Oligocene through Quaternary planktonic foraminiferal biostratigraphy of the North Atlantic: DSDP Leg 49. *In* Luyendyk, B.P., Cann, J.R., et al., *Init. Repts. DSDP,* 49: Washington (U.S. Govt. Printing Office), 447–517.

Poore, R.Z., and Berggren, W.A., 1975. Late Cenozoic planktonic foraminifera biostratigraphy and paleoclimatology of Hatton-Rockall Basin: DSDP Site 116. *J. Foraminiferal Res.,* 5:270–293.

Schröder, C.J., 1986. Deep-water arenaceous foraminifera in the northwest Atlantic Ocean. *Can. Tech. Rept. Hydrogr. Ocean Sci.,* 71:1–191.

Sejrup, H.P., Fjæran, T., Hald, M., Beck, L., Hagen, J., Miljeteig, I., Morvik, I., and Norvik, O., 1981. Benthonic foraminifera in surface samples from the Norwegian Continental Margin between 62EN and 65°EN. *J. Foraminiferal Res.,* 11:277–295.

Skarbø, O., and Verdenius, J.G., 1986. Catalogue of microfossils: Quaternary-Tertiary. *IKU Publ.,* 113.

Spiegler, D., 1996. Planktonic foraminifer Cenozoic biostratigraphy of the Arctic Ocean, Fram Strait (Sites 908–909), Yermak Plateau (Sites 910–912), and East Greenland Margin (Site 913). *In* Thiede, J., Myhre, A.M., Firth, J.V., Johnson, G.L., and Ruddiman, W.F. (Eds.), *Proc. ODP, Sci. Results,* 151: College Station, TX (Ocean Drilling Program), 153–167.

Spiegler, D., and Jansen, E., 1989. Planktonic foraminifer biostratigraphy of Norwegian Sea sediments: ODP Leg 104. *In* Eldholm, O., Thiede, J., Taylor, E., et al., *Proc. ODP, Sci. Results,* 104: College Station, TX (Ocean Drilling Program), 681–696.

Stratlab, 1988. Mid-Norway offshore Biozonation, Tertiary to Triassic: fossil atlas (Vols. 1 and 2). *Stratlab a.s.* (non-proprietary report).

Todd, R., 1957. Foraminifera from Carter Creek Northeastern Alaska. *Geol.Surv. Prof. Pap. U.S.,* 294-F:260–277.

Ulleberg, K., 1974. Foraminifera and stratigraphy of the Viborg Formation in Sofienlund, Denmark. *Bull. Geol. Soc. Den.*, 23:269–292.

Vincent, J.S., Morris, W.A., and Occheitti, S., 1984. Glacial and nonglacial sediments of Matuyama paleomagnetic age on Banks Island, Canadian Arctic Archipelago. *Geology,* 12:139–142.

Weaver, P.P.E., and Clement, B.M., 1986. Synchroneity of Pliocene planktonic foraminiferal datums in the North Atlantic. *Mar. Micropaleontol.,* 10:295–307.

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