

34. PALEOCEANOGRAPHIC CHANGES IN THE DYNAMICS OF SUBTROPICAL ATLANTIC SURFACE CONDITIONS AT HOLE 997A¹

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ABSTRACT

Hole 997A was drilled during Leg 164 of the Ocean Drilling Program at a depth of 2770 m on the topographic crest of the Blake Ridge in the western Atlantic Ocean. We report here an analysis of the faunal assemblages of planktonic foraminifers in a total of 91 samples (0.39–91.89 mbsf interval) spanning the last 2.15 m.y., latest Pliocene to Holocene. The abundant species, *Globigerinoides ruber*, *Globigerinoides sacculifer*, *Neoglobobulimina dutertrei*, *Globobulimina inflata*, and *Globigerinita glutinata* together exceed over ~70% of the total fauna. Each species exhibits fluctuations with amplitudes of 10%–20% or more. Despite their generally low abundance, the distinct presence/absence behavior of the *Globobulimina menardii* group is almost synchronous with glacial-interglacial climate cycles during the upper part of Brunhes Chron.

The quantitative study and factor analysis of planktonic foraminiferal assemblages shows that the planktonic foraminiferal fauna in Hole 997A consists of four groups: warm water, subtropical gyre (mixed-layer species), gyre margin (thermocline/upwelling species), and subpolar assemblages. The subtropical gyre assemblage dominates throughout the studied section, whereas the abundance of gyre margin taxa strongly control the overall variability in faunal abundance at Site 997. In sediments older than the Olduvai Subchron, the planktonic foraminiferal faunas are characterized by fluctuations in both the subtropical gyre and gyre margin assemblages, similar to those in the Brunhes Chron. The upwelling/gyre margin fauna increased in abundance just before the Jaramillo Subchron and was dominant between 0.7 and 1.07 Ma. The transition from this gyre margin-dominated assemblage to an increase in abundance of the subtropical gyre and gyre margin species occurred around 0.7 Ma, near the Brunhes/Matuyama boundary. The presence of low-oxygen-tolerant benthic foraminifers, pyrite tubes, and abundant diatoms below the Brunhes/Matuyama boundary suggests decreased oxygenation of intermediate waters and more upwelling over the Blake-Bahama Outer Ridge, perhaps because of weaker Upper North Atlantic Deep Water ventilation.

The changes in the relative composition of foraminifer assemblages took place at least twice, around 700 and 1000 ka, close to the ~930-ka switch from obliquity-forced climate variation to the 100-k.y. eccentricity cycle. The climate shift at 700 ka suggests a transition from relatively warmer conditions in the early Pleistocene to warm-cool oscillations in the Brunhes Chron.

INTRODUCTION

The change in the climatic system from an earlier 41-k.y. dominant oscillation to the stronger 100-k.y. oscillation of the late Pleistocene has been recognized based on the spectral analysis of paleoceanographic indicators such as $\delta^{18}\text{O}$, carbonate content, the nannofossil *Florisphaera profunda*, and others. This event, called the “Mid-Pleistocene Revolution” (Berger et al., 1993; Berger and Loutre, 1994), occurred around 0.9 Ma in the interval corresponding to isotopic Stages 25 and 22 and is related to the first severe northern hemisphere glaciation (Pisias and Moore, 1981; Ruddiman et al., 1989; Raymo et al., 1990; Berger et al., 1993). However, it is not yet clear whether the development of the 100-k.y. oscillation was caused by a rapid and global change in the climatic system (Pisias and Moore, 1981; Berger et al., 1993) or was more progressive, taking place approximately in the interval from 1.0–1.2 to 0.6 Ma (Ruddiman et al., 1987, 1989).

In western equatorial Atlantic sites drilled during Leg 154 at Ceara Rise, the “Mid-Pleistocene Revolution” appears to be associated with an important change in Atlantic surface current dynamics as shown by a drastic change in the phase relationships between $\delta^{18}\text{O}$ and the *F. profunda* 41-k.y. oscillation (Bassiot et al., 1997). This

abrupt change occurred over a short period of time centered roughly on 930 ka (isotope Stage 24) and appears to have resulted from modification of the circulation in the subtropical gyre during the growth of the Laurentide ice sheet.

However, Cullen and Curry (1997) did not find a step-like change in foraminifer proxies at ~930 ka, in contrast to the work of Bassiot et al. (1997).

Hole 997A (2770 m in water depth) is located on the crest of the Blake Ridge, in the mid-latitude western Atlantic Ocean (Fig. 1). We expected this site to be sensitive to variations in tropical-subtropical and temperate water masses in the Pleistocene given its location near the frontal boundary between the gyre and the Gulf Stream. Our primary goals were to (1) reconstruct hydrographic conditions of the overlying surface-water mass based on faunal variability of the planktonic species, and (2) document the timing of changes in surface circulation patterns at this temperate site in the western Atlantic as a monitor of Pliocene–Pleistocene changes in Gulf Stream intensity.

METHODS

The samples in the studied interval of Hole 997A come from two lithological units (Shipboard Scientific Party, 1996). Unit I (Samples 164-997A-1H-1, 0 cm, to 2H-3, 30 cm; 0–6.2 mbsf) is composed of foraminifer-bearing nannofossil-rich clay, which is light greenish gray to light gray in color, interbedded with dark gray to greenish gray bands. The uppermost 19 cm of this unit (Subunit IA) consist of grayish brown, bioturbated, foraminifer-bearing, nannofossil-rich clay. The lower boundary of Subunit IA is marked by a sharp color change to the light greenish gray sediments of Subunit IB. Unit II (Samples 164-997A-2H-3, 30 cm, to 13H-7, 35 cm; 6.2–107.83

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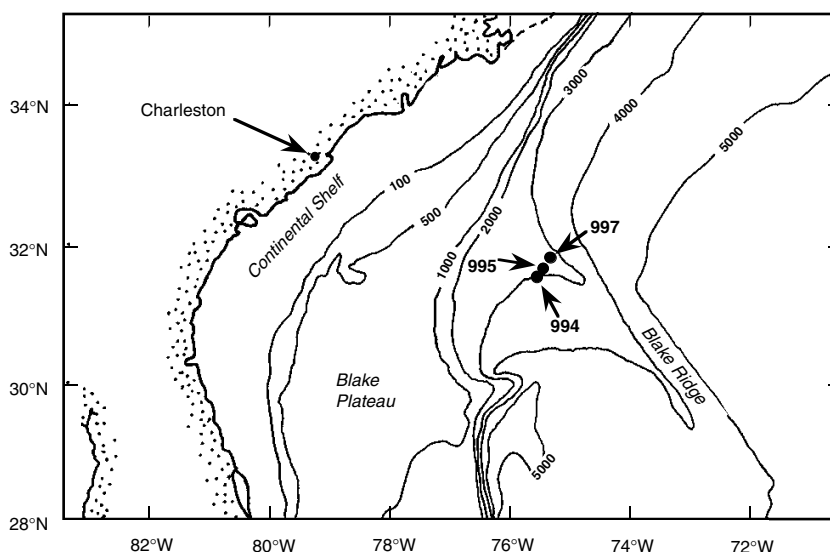


Figure 1. Map location for Leg 164 drilling, including the location of Site 997. The contour shows the bathymetry in meters below sea level.

mbsf) consists of the same lithology, but they are more intensely bioturbated.

We analyzed a total of 91 samples from Samples 164-997A-1H-1, 39–41 cm (0.39 mbsf), to 12H-2, 49–51 cm (91.89 mbsf) for our study of the faunal assemblages of planktonic foraminifers. Samples (10 cm³ in size) were washed through a 63- μ m sieve using water. Population counts of planktonic foraminifers were based on aliquot samples containing 200 or more specimens in the size fraction larger than 177 μ m. In this study, we used the *Globorotalia menardii* group as an index marker of warm climate. However, the abundance of this species is generally rare to few throughout core samples. We checked the abundance of this species in different mesh size and concluded that *G. menardii* is most reliably found in size fractions larger than 177 μ m. We used the >177- μ m fraction in this study, because we hoped to be able to use the abundance of *G. menardii* as a paleoclimate proxy. All specimens of each aliquot were picked and listed in Table 1, and the total abundance of specimens was calculated.

RESULTS

Biostratigraphy in Hole 997A

A total of 15 genera and 50 species of planktonic foraminifers were identified at this site (Table 1). Our uppermost sample (Sample 164-997A-1H-1, 39–41 cm, 0.39 mbsf) contains pink specimens of *Globigerinoides ruber*, *Globorotalia fimbriata*, *Globorotalia unguata*, and *Bolliella calida calida*, and is late Pleistocene to Holocene in age. Although the extinction of pink *G. ruber* is dated at 120 ka in the Pacific Ocean (Thompson et al., 1979), this datum is not useful in the Atlantic Ocean. Bé and Hamlin (1967) and Bé and Tolderlund (1971) reported the common occurrence of living pink *G. ruber* in modern plankton tows from the North Atlantic Ocean. No reliable markers of late Pleistocene such as *Globorotalia menardii flexuosa* and *Pulleniatina finalis* are present in the core top sample. However, the dominant occurrence of *Emiliania huxleyi* in Samples 164-997A-1H-1, 0–1 cm, and 1H-CC indicates latest Pleistocene or Holocene age (<85 ka; Shipboard Scientific Party, 1996). The Leg 164 Shipboard Scientific Party also reported the existence of a significant coring gap or a hiatus between Cores 164-997A-1H and 2H because *E. huxleyi* decreases in abundance in Sample 164-997A-2H-1, 0–1 cm (2.90 mbsf). The first occurrence of *E. huxleyi* is placed at Sample 164-997A-2H-3, 39 cm (6.29 mbsf), and the lower part of Core 164-997A-2H is assigned to upper Pleistocene Subzone CN14b.

In sediments older than late Pleistocene, the following five datums of planktonic foraminifers are recognized at this site (Fig. 2); the first occurrence (FO) of *Globorotalia hirsuta* (0.45 Ma), the last occurrence (LO) of *Globorotalia tosaensis* (0.65 Ma), the LO of *Globigerinoides obliquus* (1.77 Ma), the FO of *Globorotalia truncatulinoides* (2.0 Ma) and the LO of *Globorotalia exilis* (2.15 Ma) in descending order. The age of these datums are based on Berggren et al. (1995a, 1995b). The lowest sample in this study contains no specimens of *Globorotalia miocenica* and is assigned to the PL6 zone of Berggren et al. (1995b). Therefore, the section studied here ranges from latest Pliocene to Holocene in age (0–2.15 Ma).

The lower boundary of the Jaramillo normal chron is placed at 52 mbsf, and the Pleistocene/Pliocene boundary (the upper boundary of the Olduvai normal chron) is at 72 mbsf. The Brunhes/Matuyama boundary and top of Jaramillo normal chron are tentatively defined at 36 and 41 mbsf, respectively (Shipboard Scientific Party, 1996). Hence, three nannofossil datums ([1] extinction of large *Gephyrocapsa*, [2] reappearance of medium-size *Gephyrocapsa*, and [3] extinction of *Discoaster brouweri*) do not match the magnetostratigraphy (Fig. 2). *Globigerinoides obliquus* was also found to be unreliable as a marker of the Pleistocene/Pliocene boundary at this site because this species disappeared at 70.94 mbsf, about 1.06 m from the top of the Olduvai Subchron. The discrepancies between magnetostratigraphy and biostratigraphy of calcareous fossils may indicate redeposition of marker species or an unreliable magnetostratigraphy. The Shipboard Science Party identified a short hiatus in the CN13b subzone, around Core 164-997A-7H, just below the lower boundary of Jaramillo Subchron. Although the magnetostratigraphic study demonstrated that the base of Jaramillo Subchron is well defined, the biostratigraphic ages of Samples 164-997A-7H-1, 39–41 cm, to 8H-2, 54.89 cm (52–55.97 mbsf; 1.07- to 1.46-Ma interval) are not clearly defined in this study.

Climatic Curve

The presence/absence behavior of the *G. menardii* complex in Pleistocene sediments from the tropical Atlantic has been well documented in many previous studies (Ericson and Wollin, 1956, 1968; Ruddiman, 1971). The abundance peaks and barren zones of this group correspond, to some extent, with warm isotopic stages (odd numbered) and cooling isotopic stages (even numbered). Hays et al. (1969) correlated the *G. menardii* “Y,” “W,” and “U” zones proposed by Ericson and Wollin (1956, 1968) with isotope Stages 2–4, 6, and 15 of Emiliani (1966).

Table 1. Percent relative abundance of planktonic foraminifers in Hole 997A.

Core, section, interval (cm)	Depth (mbsf)	Aliquot	<i>Beella digitata</i>	<i>Bolliella calida</i>	<i>Candeina nitida</i>	<i>Globigerina bulloides</i>	<i>Globigerina decorapeta</i>	<i>Globigerina jalcensis</i>	<i>Globigerina cf. joliana</i>	<i>Globigerina quinqueloba</i>	<i>Globigerina rubescens</i>	<i>Globigerina umbilicata</i>	<i>Globigerinella aequilateralis</i>	<i>Globigerinita glutinata</i>	<i>Globigerinoides conglobatus</i>	<i>Globigerinoides extremus</i>	<i>Globigerinoides obliquus</i>	<i>Globigerinoides quarilobatus</i>	<i>Globigerinoides ruber</i>	<i>Globigerinoides sacculifer</i>	<i>Globigerinoides tenellus</i>	<i>Globobulimina bermudezi</i>	<i>Globobulimina aff. cavernula</i>	<i>Globobulimina crassaformis</i>	<i>Globobulimina crassula</i>	<i>Globobulimina exilis</i>	<i>Globobulimina jimbriata</i>	<i>Globobulimina hessi</i>	<i>Globobulimina hisuta</i>	
164-997A-																														
1H-1, 39-41	0.39	16	0.3	2.1	0.0	1.4	0.0	2.8	0.0	0.0	1.0	0.0	12.5	5.6	0.3	0.0	0.0	0.0	32.1	14.6	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	2.1	
1H-1, 114-116	1.14	4	0.0	0.0	0.0	2.7	0.0	3.4	0.0	0.0	0.0	0.0	4.0	3.4	1.3	0.0	0.0	0.0	40.6	9.4	0.0	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0	
1H-2, 39-41	1.89	4	0.0	1.1	0.0	4.1	0.0	2.2	0.0	0.0	0.0	0.0	4.5	6.4	0.0	0.0	0.0	0.0	31.8	9.7	0.0	0.0	0.0	3.4	0.0	0.0	0.0	0.0	0.0	
1H-2, 114-116	2.64	4	0.2	1.9	0.0	3.2	0.0	6.3	0.0	0.0	0.7	0.0	6.6	15.5	0.5	0.0	0.0	0.0	23.8	4.1	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	
2H-1, 39-41	3.29	8	0.0	0.6	0.0	1.1	0.0	4.7	0.0	1.7	0.6	0.0	2.5	8.9	0.0	0.0	0.0	0.0	32.7	12.6	1.4	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	
2H-1, 114-116	4.04	4	0.0	0.3	0.0	1.0	0.0	0.6	0.0	0.0	0.3	0.0	8.7	2.6	1.0	0.0	0.0	0.0	22.9	5.5	0.0	0.0	0.0	4.8	1.3	0.0	0.0	0.0	0.0	
2H-2, 39-41	4.79	2	0.0	1.4	0.0	1.4	0.0	6.3	0.0	0.0	1.7	0.0	4.2	10.8	1.0	0.0	0.0	0.0	39.0	7.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	
2H-2, 114-116	5.54	8	0.0	0.5	0.0	1.9	0.0	0.8	0.0	0.0	0.8	0.0	6.6	2.7	1.1	0.0	0.0	0.0	26.1	11.7	0.5	0.3	0.0	3.2	0.0	0.0	0.0	0.0	0.3	
2H-3, 39-41	6.29	1	0.2	0.0	0.0	0.7	0.0	3.8	0.0	0.0	0.7	0.0	7.7	5.5	1.0	0.0	0.0	0.0	33.2	8.9	0.2	0.0	0.0	0.5	0.0	0.0	0.0	0.0	8.4	
2H-3, 114-116	7.04	1	0.0	0.6	0.0	0.0	0.3	2.9	0.0	0.0	0.6	0.0	5.1	11.9	0.3	0.0	0.0	0.0	21.8	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.2	
2H-4, 39-41	7.79	1	0.0	0.0	0.0	3.1	2.2	1.3	0.0	0.0	0.0	0.0	4.0	4.4	0.9	0.0	0.0	0.0	19.9	7.5	1.3	0.0	0.0	3.5	0.0	0.0	0.0	0.0	9.3	
2H-4, 114-116	8.54	2	0.0	0.7	0.0	0.0	0.0	5.8	0.0	0.0	0.4	0.0	6.1	3.2	0.0	0.0	0.0	0.0	38.6	7.9	0.4	0.0	0.0	0.0	1.8	0.0	0.0	0.0	7.2	
2H-5, 39-41	9.29	1	0.0	0.0	0.5	0.0	0.0	5.2	0.0	0.0	0.9	0.0	2.8	13.6	1.4	0.0	0.5	0.0	36.2	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	
2H-5, 114-116	10.04	4	0.0	0.9	0.0	2.8	0.0	0.5	0.0	0.0	0.9	0.0	9.6	6.0	1.4	0.0	0.0	0.0	33.9	10.1	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	6.0	
2H-6, 39-41	10.79	2	0.0	0.9	0.6	0.9	0.0	5.5	0.0	0.0	0.0	0.0	4.9	10.7	0.0	0.0	0.0	0.0	33.6	8.6	0.3	0.0	0.0	1.2	0.0	0.0	0.0	0.0	6.4	
2H-6, 114-116	11.54	2	0.0	0.4	0.0	0.4	0.0	7.7	0.0	0.0	0.0	0.0	12.4	9.3	0.0	0.0	0.0	0.0	27.4	6.2	1.2	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	
3H-1, 39-41	12.79	4	0.0	1.1	0.0	3.1	0.0	5.4	0.0	0.0	0.0	0.0	8.2	12.4	0.8	0.0	0.0	0.0	24.9	9.6	1.4	0.0	0.0	4.8	0.0	0.0	0.0	0.0	0.0	
3H-1, 114-116	13.54	2	0.0	0.0	0.0	1.4	0.0	1.8	0.0	0.0	0.0	0.0	7.2	9.4	1.2	0.0	0.2	0.0	38.8	8.2	0.0	0.0	0.0	3.5	0.0	0.0	0.0	0.0	0.0	
3H-2, 39-41	14.29	4	0.0	0.0	0.0	2.8	0.0	4.4	0.0	0.0	0.0	0.0	7.5	11.2	0.0	0.0	0.0	0.0	43.9	8.4	0.3	0.0	0.0	2.5	0.0	0.0	0.0	0.0	0.0	
3H-2, 114-116	15.04	2	0.0	0.0	0.0	1.7	0.6	2.0	0.0	0.0	0.0	0.0	9.8	9.5	0.8	0.0	0.0	0.0	37.4	8.9	0.0	0.0	0.0	2.8	0.0	0.0	0.0	0.0	0.0	
3H-3, 39-41	15.79	4	0.0	0.0	0.0	2.2	0.0	5.6	0.0	0.7	0.0	0.0	4.4	11.7	0.7	0.0	0.0	0.0	44.4	4.9	0.0	0.2	0.0	1.5	0.0	0.0	0.0	0.0	0.0	
3H-3, 114-116	16.54	8	0.0	0.0	0.0	3.0	0.5	4.9	0.0	0.0	0.0	0.0	7.9	6.6	0.5	0.0	0.0	0.0	17.8	10.1	0.3	0.0	0.0	6.3	0.0	0.0	0.0	0.0	0.0	
3H-4, 39-41	17.29	2	0.0	0.0	0.0	2.1	0.0	6.9	0.0	0.0	0.0	0.0	6.7	7.2	1.5	0.0	0.0	0.0	16.9	14.1	3.6	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	
3H-4, 114-116	18.04	4	0.0	0.0	0.5	1.3	1.8	4.2	0.0	0.0	0.0	0.0	10.7	8.1	1.3	0.0	0.0	0.0	32.3	1.8	0.0	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0	
3H-5, 39-41	18.79	4	0.0	0.0	0.0	2.7	0.0	7.0	0.0	0.0	0.0	0.0	10.0	10.2	1.6	0.0	0.0	0.0	30.2	16.1	1.6	0.0	0.0	2.9	0.0	0.0	0.0	0.0	0.0	
3H-5, 114-116	19.54	8	0.0	0.0	0.0	1.1	0.8	4.5	0.0	0.0	0.0	0.0	5.9	5.1	3.7	0.0	0.0	0.0	35.4	15.7	0.3	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	
3H-6, 39-41	20.29	32	0.0	0.0	0.0	2.4	0.2	3.3	0.0	0.0	0.2	0.0	3.8	2.4	2.9	0.0	0.0	0.0	34.3	12.2	0.2	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	
3H-6, 114-116	21.04	8	0.0	0.0	0.0	2.6	0.0	4.1	0.0	0.0	0.0	0.0	13.1	5.7	1.7	0.0	0.0	0.0	32.3	9.0	0.7	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	
3H-7, 39-41	21.79	4	0.0	0.0	0.0	1.8	0.0	5.7	0.0	0.0	0.3	0.0	9.7	2.5	1.0	0.0	0.0	0.2	26.4	14.1	0.0	0.0	0.0	2.6	0.0	0.0	0.0	0.0	0.0	
4H-1, 39-41	22.29	2	0.0	0.0	0.0	3.7	0.0	0.7	0.0	0.0	0.4	0.0	5.8	15.6	0.0	0.0	0.0	0.0	33.7	11.9	0.0	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	
4H-1, 114-116	23.04	4	0.4	0.0	0.0	0.4	0.0	2.9	0.0	0.0	0.4	0.0	9.0	10.1	0.4	0.0	0.0	0.0	37.4	15.1	0.0	0.0	0.0	3.2	0.0	0.0	0.0	0.0	0.0	
4H-2, 39-41	23.79	2	0.4	0.0	0.0	0.4	0.0	3.4	0.0	0.0	0.9	0.0	2.3	8.7	3.8	0.0	0.0	0.0	36.1	5.7	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	
4H-3, 39-41	25.29	8	0.0	0.0	0.0	1.4	0.0	3.1	0.0	0.0	0.0	0.0	3.4	2.0	0.3	0.0	0.0	0.0	36.9	7.5	0.0	0.3	0.0	9.2	0.0	0.0	0.0	0.0	0.0	
4H-3, 114-116	26.04	2	0.0	0.0	0.0	0.8	1.6	2.8	0.0	0.0	0.0	0.0	2.0	5.9	3.5	0.0	0.0	0.0	51.6	5.9	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	
4H-4, 39-41	26.79	1	0.0	0.0	0.0	2.1	0.0	1.8	0.0	0.0	0.9	0.0	3.0	2.1	2.7	0.0	0.0	0.0	57.9	0.0	0.3	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	
4H-5, 39-41	28.29	2	0.0	0.0	0.0	0.5	0.0	4.1	0.0	0.0	2.5	0.0	1.9	6.0	1.6	0.0	0.0	0.0	28.3	8.2	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	
4H-6, 114-116	30.54	4	0.0	0.0	0.0	2.4	0.0	1.9	0.0	0.0	0.0	0.0	4.9	1.5	0.0	0.0	0.0	0.0	35.9	7.3	0.0	0.0	0.0	6.3	0.0	0.0	0.0	0.0	0.0	
4H-7, 39-41	31.29	2	0.0	0.0	0.0	4.2	0.0	4.6	0.0	0.0	0.8	0.0	8.8	2.9	0.4	0.0	0.0	0.0	23.9	2.9	0.0	0.0	0.0	7.6	0.0	0.0	0.0	0.0	0.0	
5H-1, 39-41	31.79	4	0.0	0.0	0.0	1.0	0.0	13.1	0.0	0.3	0.0	0.0	6.4	1.7	0.3	0.0	0.0	0.0	36.0	4.7	0.0	0.0	0.0	5.4	0.0	0.0	0.0	0.0	0.0	
5H-1, 114-116	32.54	4	0.0	0.0	0.1	0.6	0.1	3.8	0.0	0.0	0.3	0.0	6.6	0.4	1.3	0.0	0.0	0.0	24.8	7.9	0.0	0.0	0.0	7.9	0.0	0.0	0.0	0.0	0.0	
5H-2, 39-41	33.29	1	0.0	0.0	0.0	1.3	0.0	4.4	0.0	0.0	0.0	0.0	2.2	0.4	0.0	0.0	0.0	0.0	24.1	15.4	0.0	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	
5H-2, 114-116	34.04	8	0.0	0.0	0.0	0.3	0.3	2.1	0.0	0.0	0.0	0.0	9.0	2.1	0.6	0.0	0.0	0.0	32.5	20.3	0.0	0.0	0.0	4.8	0.0	0.0	0.0	0.0	0.0	
5H-3, 39-41	34.79	1	0.3	0.0	0.3	0.6	0.0	1.9	0.0	0.0	0.6	0.0	3.8	3.5	1.6	0.0	0.0	0.0	22.8	19.3	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	
5H-3, 114-116	35.54	4	0.0	0.0	0.3	1.5	1.5	1.2	0.0	0.0	0.0	0.0	3.6	2.7	0.9	0.0	0.0	0.0	24.2	19.7	0.0	0.0	0.0	3.6	0.0	0.0	0.0	0.0	0.0	
5H-4, 39-41	36.29	2	0.0	0.0	0.0	4.2	0.0	3.2	0.0	0.0	0.7	0.0	4.2	1.7	0.0	0.0	0.0	0.0	15.1	23.1	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	
5H-4, 114-116	37.04	2	0.0	0.0	0.0	1.6	0.0	1.2	0.0	0.0	0.0	0.8	2.8	2.4	0.8	0.0	0.0	0.0												

[illegible]

Table 1 (continued).

Core, section, interval (cm)	Depth (mbsf)	Aliquot	<i>Beella digitata</i>	<i>Bolliella calida</i>	<i>Candaina nitida</i>	<i>Globigerina bulloides</i>	<i>Globigerina decoraperta</i>	<i>Globigerina falconensis</i>	<i>Globigerina cf. foliata</i>	<i>Globigerina quinqueloba</i>	<i>Globigerina rubescens</i>	<i>Globigerina umbilicata</i>	<i>Globigerinella aequilateralis</i>	<i>Globigerinita glutinata</i>	<i>Globigerinoides conglobatus</i>	<i>Globigerinoides extremus</i>	<i>Globigerinoides obliquus</i>	<i>Globigerinoides quadrilobatus</i>	<i>Globigerinoides ruber</i>	<i>Globigerinoides sacculifer</i>	<i>Globigerinoides tenellus</i>	<i>Globorotalia bermudezi</i>	<i>Globorotalia aff. cavemula</i>	<i>Globorotalia crassaformis</i>	<i>Globorotalia crassula</i>	<i>Globorotalia exilis</i>	<i>Globorotalia fimbriata</i>	<i>Globorotalia hessi</i>	<i>Globorotalia hirsuta</i>	
6H-2, 39-41	42.79	1	0.0	0.0	0.0	3.6	0.0	5.4	0.0	0.0	0.0	0.0	9.0	1.8	6.3	0.0	0.0	0.0	12.6	28.8	0.0	0.0	0.0	0.0	3.6	0.0	0.0	0.0	0.0	0.0
6H-3, 39-41	44.29	2	0.0	0.0	0.0	0.0	0.0	3.1	0.0	0.0	0.0	0.0	9.3	4.6	1.2	0.0	0.0	0.0	23.1	14.8	0.0	0.0	0.0	0.0	9.9	0.0	0.0	0.0	0.0	0.0
6H-3, 114-116	45.04	2	0.3	0.0	0.3	2.0	0.0	3.6	0.0	0.0	0.0	0.0	4.6	4.3	0.7	0.0	0.0	0.0	19.9	10.9	0.0	0.0	0.0	0.0	5.3	0.0	0.0	0.0	0.0	0.0
6H-4, 39-41	45.79	1	0.0	0.0	0.0	0.9	0.0	3.0	0.0	0.0	0.9	0.0	2.7	7.1	0.9	0.0	0.0	0.0	49.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0	0.0	0.0
6H-4, 114-116	46.54	8	0.0	0.0	0.0	4.3	0.0	3.5	0.0	0.0	0.0	0.0	4.6	2.0	1.3	0.0	0.0	0.0	40.0	10.1	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0
6H-5, 39-41	47.29	8	0.0	0.0	0.3	3.9	0.0	2.4	0.0	0.0	0.5	0.0	7.9	3.9	0.3	0.0	0.0	0.3	21.3	0.3	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
6H-6, 39-41	48.79	1	0.0	0.0	0.0	1.9	0.0	1.4	0.0	0.0	0.7	0.0	3.7	7.5	4.7	0.0	0.0	0.0	26.6	16.6	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0
6H-7, 39-41	50.29	1	0.0	0.0	0.0	0.8	0.6	1.7	0.0	0.0	0.0	0.0	3.1	6.8	2.0	0.0	0.0	0.0	16.9	7.9	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
7H-1, 39-41	50.77	1	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	6.4	8.9	0.3	0.0	0.0	0.0	36.4	15.3	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0
7H-2, 37-39	52.27	2	0.4	0.0	0.4	0.0	0.4	2.5	0.0	0.0	0.0	0.0	8.8	9.5	0.4	0.0	0.0	0.0	21.8	19.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8H-1, 49-51	53.39	2	0.0	0.0	0.0	0.5	0.0	1.0	0.0	0.0	1.0	0.0	4.4	8.0	0.0	0.0	0.0	0.0	42.7	8.5	0.0	0.0	0.0	0.0	5.6	0.0	0.0	0.0	0.0	0.0
8H-2, 49-51	54.89	2	0.0	0.0	0.0	1.7	0.2	2.9	0.0	0.0	0.2	0.0	5.0	3.4	0.2	0.0	0.0	0.0	29.7	34.1	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0	0.0
8H-3, 49-51	56.39	4	0.0	0.0	0.0	2.5	0.0	1.7	0.0	0.0	0.0	0.0	0.8	9.1	1.7	0.0	0.0	0.0	32.6	29.3	0.0	0.0	0.0	0.0	7.0	0.0	0.0	0.0	0.0	0.0
8H-4, 49-51	57.94	8	0.0	0.0	0.0	0.2	0.0	3.5	0.0	0.0	0.0	0.0	1.2	3.1	1.2	0.0	0.0	0.0	36.3	34.7	0.0	0.0	0.0	0.0	4.8	0.0	0.0	0.0	0.0	0.0
8H-5, 49-51	59.44	4	0.2	0.0	0.0	1.1	0.2	1.7	0.0	0.0	0.0	0.0	1.9	3.9	0.9	0.0	0.0	0.0	38.1	28.5	0.0	0.0	0.0	0.0	6.5	0.0	0.0	0.0	0.0	0.0
9H-1, 49-51	61.89	1	0.0	0.0	0.0	0.6	0.3	1.6	0.0	0.0	0.0	0.0	5.7	11.1	1.0	0.0	0.0	0.0	37.3	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9H-2, 49-51	63.39	1	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.7	0.0	5.0	6.5	0.0	0.0	0.0	0.0	33.8	22.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9H-3, 49-51	64.89	1	0.9	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	2.6	7.0	2.6	0.0	0.0	0.0	49.1	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9H-4, 49-51	66.39	1	0.0	0.0	0.0	0.7	0.0	1.1	0.0	0.0	0.0	0.0	4.0	8.8	0.4	0.0	0.0	0.0	37.9	12.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9H-5, 49-51	67.89	2	0.4	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	3.3	2.5	2.0	0.0	0.0	0.0	35.7	13.1	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0
9H-6, 49-51	69.39	8	0.0	0.0	0.0	0.2	0.0	1.4	0.0	0.0	0.0	0.0	4.7	12.6	0.9	0.0	0.0	0.0	43.4	4.9	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.2
9H-7, 49-51	70.94	4	0.3	0.0	0.0	1.3	0.3	0.3	0.0	0.0	0.0	0.0	2.3	9.8	2.0	0.0	0.3	0.0	30.9	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10H-1, 49-51	71.39	2	0.3	0.0	0.0	0.8	0.0	7.1	0.5	0.0	0.8	0.0	4.3	4.8	0.0	0.0	0.0	0.0	44.3	5.1	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
10H-2, 49-51	72.79	2	0.2	0.0	0.5	0.5	0.5	1.6	0.0	0.0	0.0	0.0	3.4	4.4	0.3	0.0	0.0	0.0	37.8	16.6	0.0	0.0	0.0	0.0	6.5	0.0	0.0	0.0	0.0	0.0
10H-3, 49-51	74.29	2	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	3.8	9.6	3.4	0.0	0.0	0.0	13.3	23.2	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
10H-4, 49-51	75.74	4	0.7	0.0	0.7	0.0	2.0	3.0	0.0	0.0	0.0	0.0	1.3	14.1	1.3	0.0	0.0	0.0	41.3	2.6	0.0	0.3	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
10H-5, 49-51	77.24	4	0.0	0.0	0.0	1.8	0.4	0.4	0.0	0.0	0.0	0.0	4.7	5.7	1.4	0.0	0.0	0.0	39.1	9.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7
10H-6, 49-51	78.74	2	0.0	0.0	0.0	2.7	1.7	4.7	0.0	0.7	0.0	0.0	1.7	6.7	3.0	0.0	0.0	0.0	17.7	5.7	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10H-7, 49-51	80.24	2	0.0	0.0	0.0	1.1	0.0	1.8	0.0	0.0	0.0	0.0	4.0	1.8	0.4	0.0	0.0	0.0	47.2	12.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
11H-1, 49-51	80.89	2	0.3	0.0	0.3	0.0	0.5	2.8	0.0	0.0	0.0	0.0	3.4	5.4	1.8	0.0	0.0	0.0	39.0	6.7	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	11.1
11H-2, 49-51	82.39	1	0.2	0.0	0.0	0.9	0.4	4.9	0.0	0.0	0.0	0.0	3.3	7.8	1.1	0.0	0.0	0.0	17.5	20.6	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0
11H-3, 49-51	83.89	2	0.0	0.0	0.0	0.5	0.5	1.0	0.0	0.0	0.0	0.0	2.6	6.2	0.5	0.3	0.0	0.0	29.9	10.9	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	5.7
11H-4, 49-51	85.39	4	0.0	0.0	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	5.6	4.1	2.2	0.0	0.0	0.0	27.0	20.4	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	11.1
11H-5, 49-51	86.89	4	0.0	0.0	0.0	4.0	1.7	2.3	0.0	0.0	0.0	0.0	3.6	4.3	0.3	0.3	0.0	0.0	22.2	11.6	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.3
11H-6, 49-51	88.39	4	0.0	0.0	0.2	3.1	2.1	0.0	0.0	0.0	0.0	0.0	6.6	5.9	0.0	1.2	0.0	0.0	19.0	28.2	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
11H-7, 49-51	89.89	2	0.0	0.0	0.0	3.3	1.1	5.7	0.0	0.0	0.0	0.0	2.7	8.7	1.1	0.3	0.5	0.0	35.8	12.7	0.0	0.0	0.0	0.0	8.1	0.0	0.0	0.0	0.0	0.0
12H-1, 49-51	90.39	2	0.0	0.0	0.0	1.0	0.0	1.3	0.0	0.0	0.0	0.0	1.6	2.6	1.0	0.0	0.0	0.0	26.1	2.9	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0
12H-2, 49-51	91.89	2	0.0	0.0	0.0	1.7	0.6	5.6	0.0	0.0	0.0	0.2	5.4	6.0	0.6	0.0	0.0	0.0	43.9	15.4	0.0	0.0	0.0	0.0	3.0	0.0	2.6	0.0	0.0	0.0

Table 1 (continued).

Core, section, interval (cm)	Depth (mbsf)	Aliquot	<i>Globorotalia</i>					<i>Globorotalia</i>					<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia</i>				<i>Globorotalia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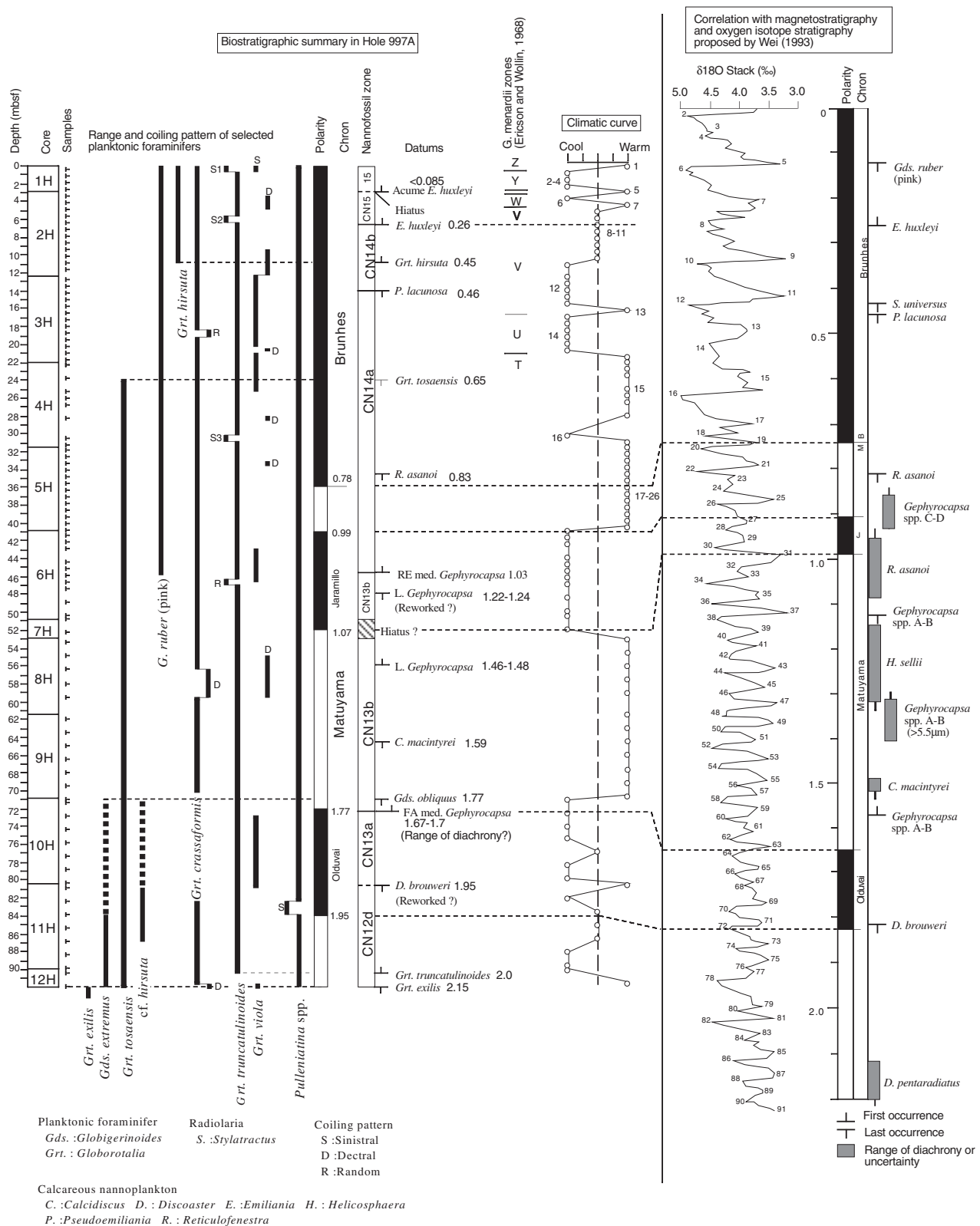


Figure 2. Biostratigraphic summary of planktonic foraminifers and magnetostratigraphy during the last 2.15 m.y. in Hole 997A based on this study and the Leg 164 science party. Age of magnetostratigraphic scales and nannofossil datums are adopted from Berggren et al. (1995a, 1995b). The climatic curve is based on the occurrence of the *Globorotalia menardii* group and its correlation with the standard oxygen isotope stratigraphy and the *G. menardii* zones of Ericson and Wollin (1968). Wei (1993) proposed the correlation adopted here of nannofossil datums with magnetostratigraphy and oxygen isotope stratigraphy. Because he did not use the timescale of Berggren et al. (1995a, 1995b), we apply only the stratigraphic relationship among nannofossil datums, magnetostratigraphic boundaries, and isotope stages to our climatic curve. The climatic curve at this site is shown in Figures 2 through 12 and is tentatively used as a biostratigraphic indicator, although no oxygen isotope stratigraphy exists in Hole 997A.

We used the abundance of the *Globorotalia menardii* complex (*menardii*, *tumida*, *ungulata*, and *exilis*) as time stratigraphic markers and climatic indices during the Brunhes instead of isotope stages, because detailed isotopic records are not yet available for Site 997. We regard the occurrence of *G. menardii* as an indicator of warm interglacial conditions, whereas barren zones represent cold, glacial stages. Furthermore, we recognized a temperate assemblage that is characterized by the occurrence of *G. hirsuta*, associated with a few to common *G. truncatulinoides*, *G. crassaformis*, and *Globigerinita glutinata*. This group is considered to reflect transitional conditions, because *G. truncatulinoides* and *G. hirsuta* are particularly abundant in the central gyre of the temperate North Atlantic (Kipp, 1976; Bé, 1977). The climatic curve in Hole 997A and its correlation with a standard oxygen isotope curve are shown in Figure 2. In the upper part of the Brunhes (0–0.26 Ma), the presence/absence cycle of *G. menardii* is repeated in a pattern similar to that of the *G. menardii* zones of Ericson and Wollin (1956, 1968; Fig. 2). However, the fluctuations in *G. menardii* abundance in Hole 997A do not correlate with the standard oxygen isotope curve and Ericson and Wollin's *G. menardii* zones below the lower part of Brunhes (Fig. 2). Prior to the Brunhes, fluctuations in *G. menardii* abundance may be controlled by other aspects of the ocean surface conditions, rather than just surface temperature in Hole 997A.

Coiling Change of Planktonic Foraminifers

Coiling changes in *Pulleniatina* are excellent biostratigraphic markers in the Indo-Pacific Ocean during the Pleistocene to late Pliocene. There are eight coiling-shift events numbered L1 to L8 in the Pacific Ocean, whereas the coiling patterns in the Atlantic Ocean are relatively constant, and only two events (AL1 and AL2) are recognized (Saito, 1976). In Hole 997A, the left-coiling form of *Pulleniatina* was observed in the interval between 82.39 and 83.89 mbsf (Samples 164-997A-11H-2, 39–41 cm, and 164-997A-11H-3, 39–41 cm), close to the bottom of the Olduvai Subchron (Fig. 2). This interval is identical with the AL2 event of Saito (1976). Thus, AL1 is probably missing.

On the other hand, most Pleistocene globorotaliid species display preferred coiling patterns and sometimes change their coiling mode quickly. For example, *G. crassaformis* is usually sinistral, but there are two intervals of random coiling at 18.79 mbsf (Sample 164-997A-3H-5, 39–41 cm) and dextral coiling from 56.39 to 59.44 mbsf (Samples 164-997A-8H-3, 49–51 cm, to 8H-5, 49–51 cm; Fig. 2). *Globorotalia viola* switched its coiling pattern several times during the Pleistocene. However, a systematic coiling trend in this species cannot be clearly identified because of its discontinuous occurrence throughout Hole 997A.

Two coiling populations of the temperate species *Globorotalia truncatulinoides* exist in the surface sediments of the North and South Atlantic. In the North Atlantic, right-coiling provinces appear to be separated from each other by a left-coiling province in the middle of the subtropical gyre (Bé and Tolderlund, 1971). The left-coiling specimens are dominant in the modern northwestern Sargasso Sea, comprising 5%–98% of the total in the surface waters, whereas right-coiling forms are abundant in the tropical Atlantic and northeast Atlantic (Ericson et al., 1954; Bé and Hamlin, 1967; Bé and Tolderlund, 1971; Kipp, 1976). The two coiling variants of *G. truncatulinoides* have been utilized as stratigraphic markers in equatorial Pleistocene sediments of the Atlantic Ocean (Ericson and Wollin, 1956, 1968; Ruddiman, 1971). Two abundance peaks of left-coiling *G. truncatulinoides* are known during the Brunhes Epoch, within the “X” and “U” zones of Ericson and Wollin's zones. During the Jaramillo event, an additional left-coiling spike is present in the lowermost “T” zone.

In Hole 997A, dextral specimens of *G. truncatulinoides* are dominant in many samples, but sinistral specimens are found in Sample

164-997A-1H-1, 39–41 cm (0.39 mbsf, S1), 2H-3, 39–41 cm (6.29 mbsf, S2), and 4H-6, 114–116 cm (30.54 mbsf, S3), and random-coiled populations are present in Sample 6H-4, 114–116 cm (46.54 mbsf, R; Fig. 2). The stratigraphic levels of sinistral *G. truncatulinoides* probably correlate with the “Z,” “V,” and “T” zones of Ericson and Wollin (1956, 1968). We suggest that the coiling shift from dextral to sinistral in *G. truncatulinoides* is not useful as a stratigraphic marker in the temperate region in Hole 997A. The coiling shift may be related with water mass change between tropical Atlantic water (or western boundary current water) and the North Atlantic subtropical gyre over the Blake Ridge.

Analysis of Planktonic Foraminiferal Assemblages

Faunal Abundance

The total abundance (per 10-cm³ sample) of planktonic foraminifers shows extremely large fluctuations, ranging from 62 (Sample 164-997A-6H-1, 39–41 cm, 41.29 mbsf) to about 14,370 specimens (Sample 164-997A-3H-6, 39–41 cm, 20.29 mbsf). There are 11 abundance peaks of over 2000 specimens/sample within the Brunhes Chron and five in the Matuyama (Fig. 3). Species of *Globigerinoides* are dominant throughout the Pliocene–Pleistocene and fluctuate in abundance between 35% and 55% (Fig. 4). The genus *Globorotalia* comprises 10%–20% of the planktonic foraminifer assemblage, but decreases to less than 10% in the interval between the base of the Jaramillo and the top of the Olduvai Subchron (Sections 164-997A-6H-5 through 9H-5). Species of *Neoglobobulimina* also occur abundantly (10%–20%), and increase rapidly to over 40% of the assemblage within the Jaramillo Subchron (Core 164-997A-6H). The globular forms of *Globigerina*, *Globigerinita*, and *Globigerinella* are common (5%–10%), sometimes reaching 13%–15% within the Brunhes Chron. *Pulleniatina* (*obliquiloculata* and *primalis*) and *Orbulina* (*universa* and *bilobata*) are generally few (<5%), except during the Jaramillo when both genera exhibited high abundance (9%–10%; Fig. 4). *Orbulina* and *Pulleniatina* tend to display similar patterns of abundance to each other. *Sphaeroidinella dehiscens* is present in trace amounts or absent in sediments younger than the Jaramillo, but is a common part of foraminiferal faunas below this chron, reaching a maximum abundance of 7% within the Olduvai Subchron.

Globigerinoides ruber is the most abundant species and fluctuates between 20% and 40% of the total foraminifer assemblage (Fig. 5). The other dominant species are *Globigerinoides sacculifer* and *Neoglobobulimina dutertrei* whose abundance are generally 5%–15%, but frequently exceed 20% (Figs. 5, 6). Other common members of the foraminiferal faunas are *Globorotalia inflata* and *Globigerinita glutinata*, which constitute 5%–10% of the total assemblage. *Globorotalia inflata* displays two high-abundance intervals (15%–20%) within Cores 164-997A-1H through 2H (CN15) and Core 164-997A-5H (between the lower Brunhes and top of the Jaramillo; Fig. 7), whereas larger specimens (>177 µm) of *Globigerinita glutinata* decrease to 5% in this interval (Fig. 6). *Globorotalia truncatulinoides* and *G. crassaformis* occur consistently (<5%–10%) above the Jaramillo (Cores 164-997A-1H through 7H), but are absent or rare in sediments below this chron (Fig. 7). Despite their generally low abundance, species in the *Globorotalia menardii* complex (*menardii*, *tumida*, *ungulata*, and *exilis*) are characterized by several significant abundance peaks, which suggest warm or interglacial periods (Fig. 8). Forms of *G. hirsuta* (*G. hirsuta* and *G. cf. hirsuta*) occurred abundantly in the restricted intervals of Cores 164-997A-2H (*G. hirsuta*) and 11H (*G. cf. hirsuta*; Fig. 7). The species *Globigerina bulloides*, *G. falconensis*, and *Globigerinella aequilalateralis* exhibit a constant, but low abundance with small amplitude and short-term fluctuations (Figs. 5, 6).

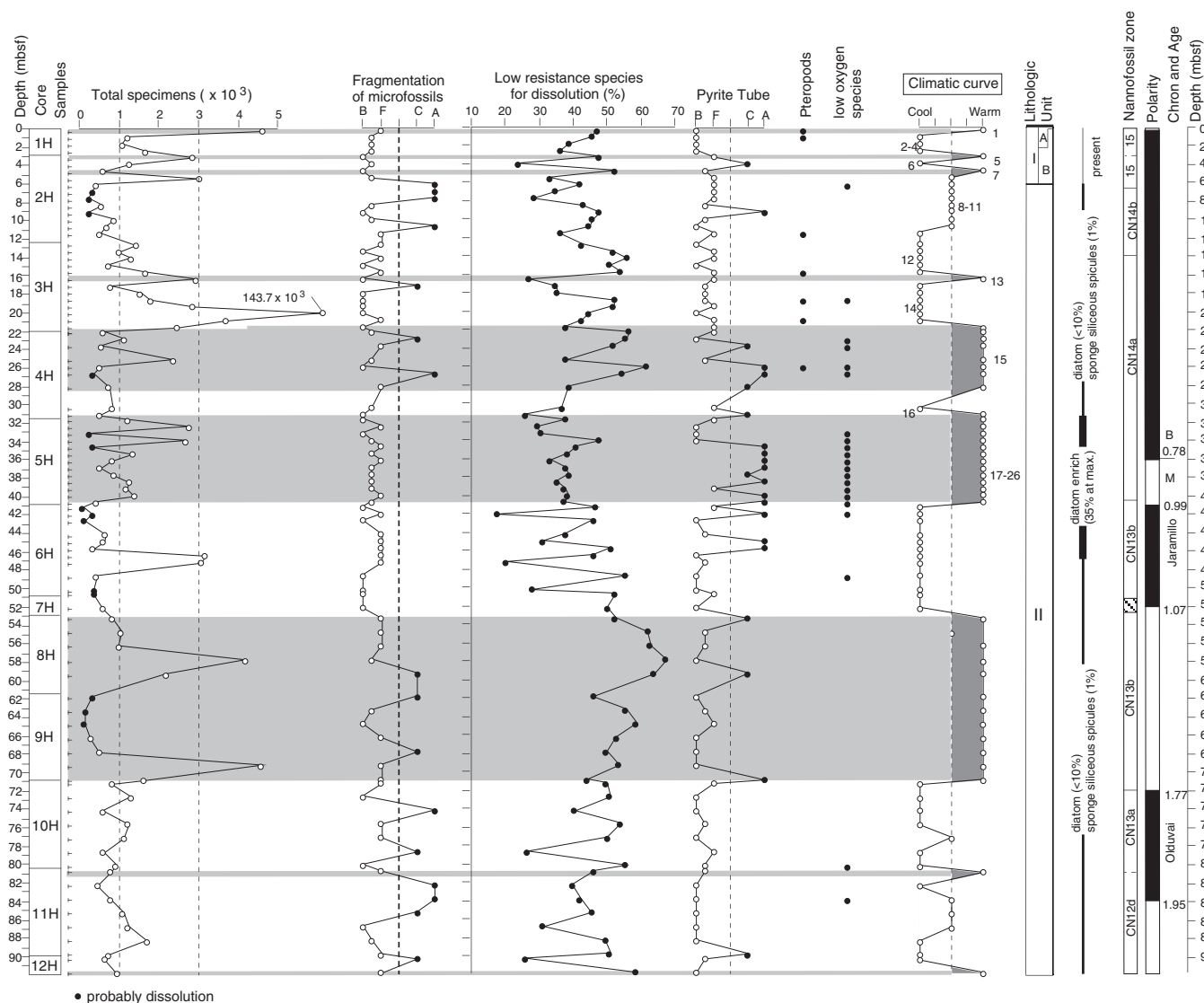


Figure 3. Downcore variations in abundance and fragmentation of planktonic foraminifers, dissolution susceptible species, and occurrences of other microfossils and pyrite tubes. On the right is a summary of lithostratigraphy, biostratigraphy, and magnetostratigraphy. For fragmentation in planktonic foraminifers, the following scale is used: B = barren (0 on tray), F = few (0–10 tests), C = common (10–20), and A = abundant (more than 20). For estimates of pyrite tube abundance, the following scale is used: B = barren (0 on tray), F = few (1–3 specimens), C = common (3–5), and A = abundant (more than 5).

Preservation and Dissolution

Planktonic foraminifers are moderate to well preserved in many samples, whereas broken tests are common to abundant in several samples of two intervals of Cores 164-997A-2H through 4H, and below Core 164-997A-8H (Fig. 3). Decreases in the abundance of foraminifer shells was not always synchronous with that of fragments of tests or with decreasing abundance of dissolution-susceptible species such as the members of the genus *Globigerinoides* (Figs. 3, 4).

Species Diversity

For each sample, species richness, Shannon/Weaver diversity, and equitability were calculated (Fig. 9; Buzas and Gibson, 1969). Species richness is the number of species in each sample, whereas the Shannon/Weaver information index describes diversity, taking into account the relative population of each species within a sample ($H =$

$-\sum P_i \ln P_i$; where P_i is the proportion of each species). Equitability is a measure of the evenness of the species distribution within a sample ($E = e^{H/S}$ in which S = number of species in a sample). Equitability equals one if all species are present in the same population and approaches zero when one species dominates the fauna.

The richness of planktonic foraminifers in Hole 997A is nearly constant (21–31 species) throughout the studied cores. Shannon/Weaver diversity exceeds 2.0 in many samples, except for lower values between 0.65 and 0.75 Ma (the lower Brunhes, the middle part of Core 164-997A-4H) and between 1.0 and 1.6 Ma (the Jaramillo to top of the Olduvai Subchrons, Cores 164-997A-6H through 8H). Equitability is nearly synchronous with Shannon/Weaver diversity such that intervals of low equitability (0.55–0.65) coincide with the low intervals of Shannon/Weaver diversity (Fig. 9). The general trends of these diversity indices suggest that Shannon/Weaver diversity is controlled more by equitability fluctuations than by species richness.

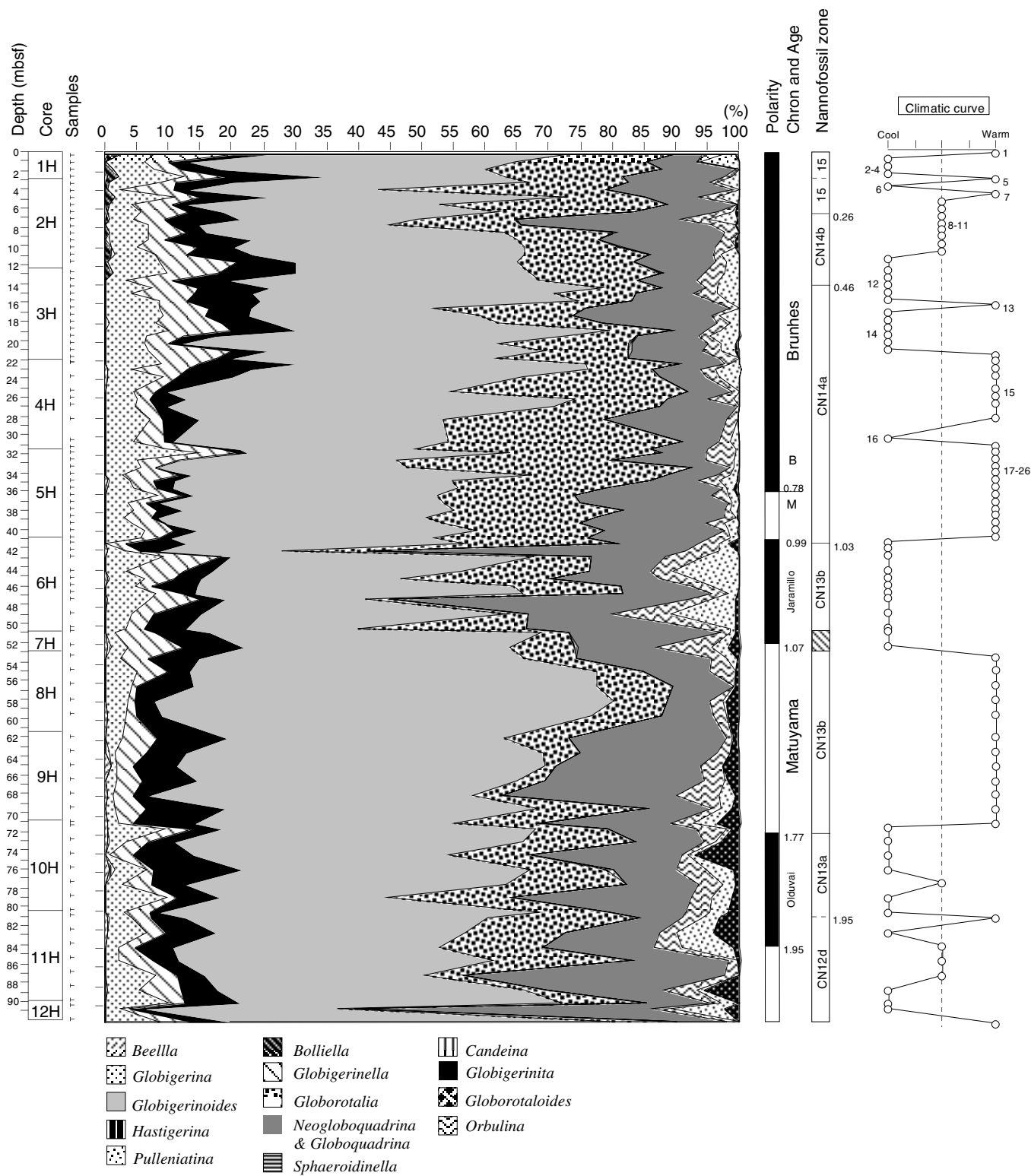


Figure 4. Downcore variations in the percent relative abundance of planktonic foraminifer genera.

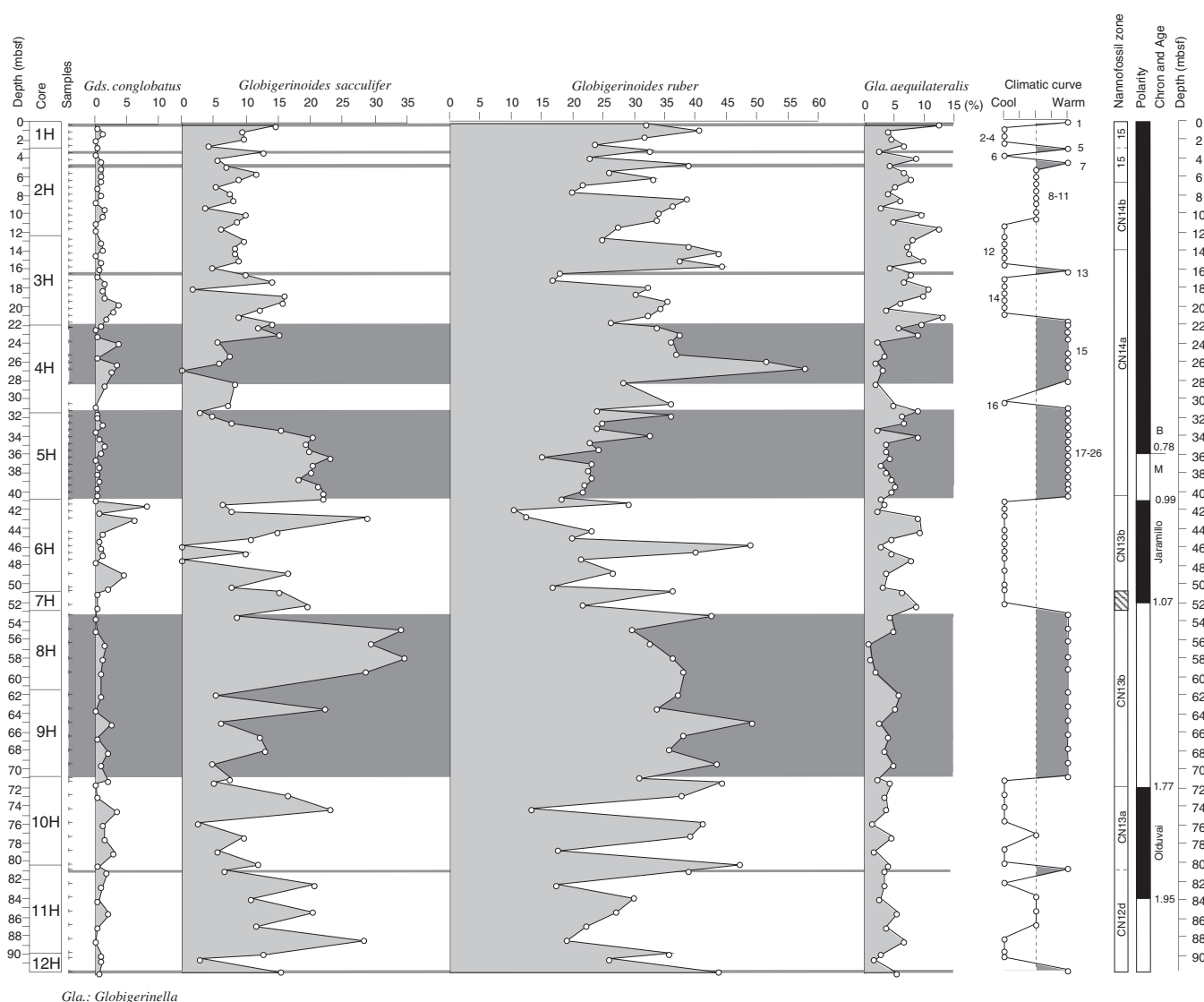


Figure 5. Downcore variations in the percent relative abundance of selected species of planktonic foraminifers of the genera *Globigerinoides* and *Globigerinella*.

Ottens (1991) examined species diversity of planktonic foraminifers in four different surface-water masses in the eastern North Atlantic Basin. The boundary between these water masses corresponds approximately with the boundary of faunal assemblages in planktonic foraminifers. The highest Shannon/Weaver diversity (over 2.0) and highest equitability (close to 0.6–0.7) are recorded around frontal zones between major surface water masses, in agreement with work in the Indian Ocean (Ottens, 1991).

The high-diversity and high-equitability assemblages in Hole 997A, therefore, suggest proximity to the frontal zones between two different water masses, probably the subtropical gyre and Gulf Stream. Low values of both indices during the intervals of 0.65–0.75 Ma and 1.0–1.6 Ma suggest that Site 997 was intermittently under the edge of the subtropical gyre (Fig. 9).

Recognition of Faunal Assemblages

Principal Component Analysis

Hole 997A is located at 31°51'N and 75°3'W and is within the subtropical bioprovince of Holocene planktonic foraminifers (Bé, 1977). Hence, it is not surprising that the most abundant to common

taxa are members of the genus *Globigerinoides* (*G. ruber* and *G. sacculifer*) during the Pliocene–Pleistocene. We used Q-mode factor analysis with varimax rotation to identify foraminifer assemblages in our downhole abundance data (Tables 2, 3). Principal component analysis of Hole 997A data identifies at least three factor assemblages in this subtropical fauna (Table 2). The calculated eigenvalues for the first three components explain 38.5%, 22.8%, and 16.3% of the total variance, respectively.

The first assemblage is dominated by mixed-layer species (*G. ruber* and *G. glutinata*), with rare *G. inflata* and *N. dutertrei* (Table 2), and represents a warm-water mass with a stable, deep mixed layer. *Globigerinoides ruber* dominates assemblages in the central Sargasso Sea and *G. sacculifer* (which negatively loads on the first principal component) is abundant in the southern Caribbean Sea and equatorial Atlantic in the surface sediments (Bé and Tolderlung, 1971; Kipp, 1976; Bé, 1977). Therefore, the first component describes assemblages from the central subtropical gyre (Sargasso Sea). Principal component one describes our “subtropical gyre assemblage.”

The second principal component is dominated by *N. dutertrei*, and contains common *G. hirsuta* and *O. universa*, and few *G. glutinata* with rare specimens of *G. sacculifer*, *G. crassaformis*, *G. truncatuli-*

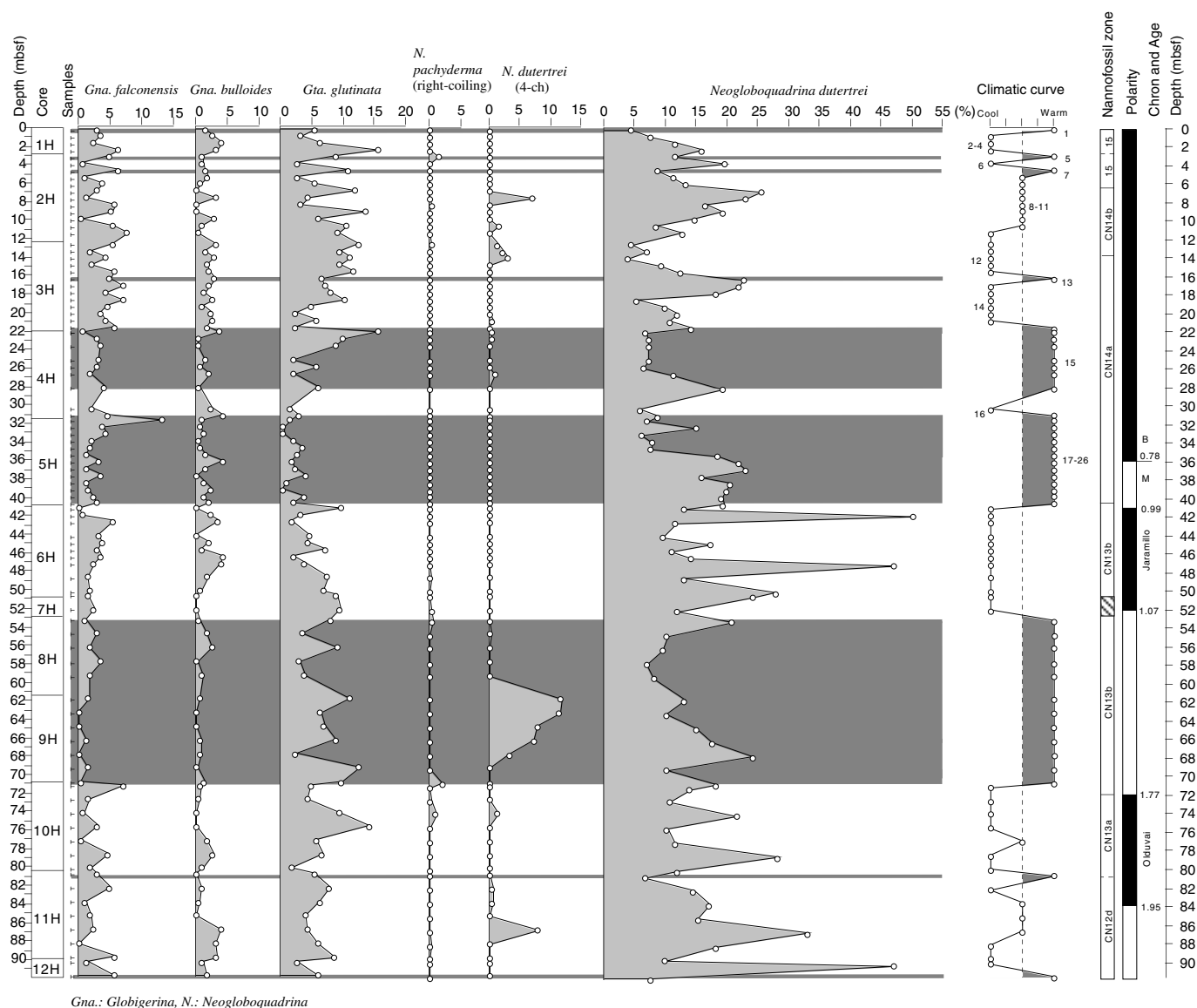


Figure 6. Downcore variations in percent relative abundance of selected species of the genera *Globigerina*, *Globigerinita*, and *Neogloboquadrina*.

noides, *G. inflata*, and *G. ruber* (Table 2). *Neogloboquadrina pachyderma* (right-coiling) is also present in this group. According to Bé (1977), *N. dutertrei* is a tropical to subtropical species that occurs abundantly in active current systems along the continental margin and upwelling regions. Kipp (1976) also showed that *N. dutertrei* is very abundant along the western boundary of the subtropical gyre.

Globorotalia hirsuta is a subtropical species, occurring abundantly in subsurface depths of the central water masses during the winter or spring seasons. Although the generally low abundance of this species makes its difficult to define its distribution limits in the modern oceans, it is rare or absent poleward of the Northern and Southern Transition Zones. The maximum abundance of *G. hirsuta* in the North Atlantic is in the northwestern Sargasso Sea (Bé and Tolderlund, 1971; Kipp, 1976). High concentrations in the western North Atlantic are observed in February/March when the seasonal thermocline breaks down (Bé, 1960; Bé and Tolderlund, 1971). The water here is well mixed, with salinity of almost 36.5‰ and temperature of 18.5–20.1°C. Below 400 m, a permanent thermocline exists and water temperature decreases to 10°C at about 800 m (Morris et al., 1977). *Globorotalia hirsuta* is also found to be normally more abun-

dant in deep tows (0–300 m) than in surface hauls (0–10 m; Bé and Tolderlund, 1971). *Globorotalia hirsuta* thrives in deep mixing conditions and is a deep-living planktonic foraminifer in the gyres (Lohmann, 1992). We consider *G. hirsuta* to be an index of seasonal breakdown of surface-water stratification. Hence, the second principal component suggests thermocline waters with upwelling or deep mixing as in the northern subtropical gyre. We call the fauna characterized by the second principal component a “gyre margin assemblage.”

The third principal component is dominated by *G. inflata* and *G. truncatulinoides* with lesser abundance of *N. dutertrei*, *G. aequilateralis*, *G. ruber*, and very rare *G. sacculifer* (Table 3). *Globorotalia inflata* is only abundant in the transition zone between the subpolar and subtropical provinces (Kipp, 1976). The highest frequencies are recorded between 35°N and 45°N in the North Atlantic (Bé, 1977). Fairbanks et al. (1980) found that living *G. inflata* are abundant within slope waters, and rare or absent within Gulf Stream cold core rings and the Sargasso Sea in November.

Globorotalia truncatulinoides is a mid-latitude species, and living populations show a distinct preference for winter conditions, pre-

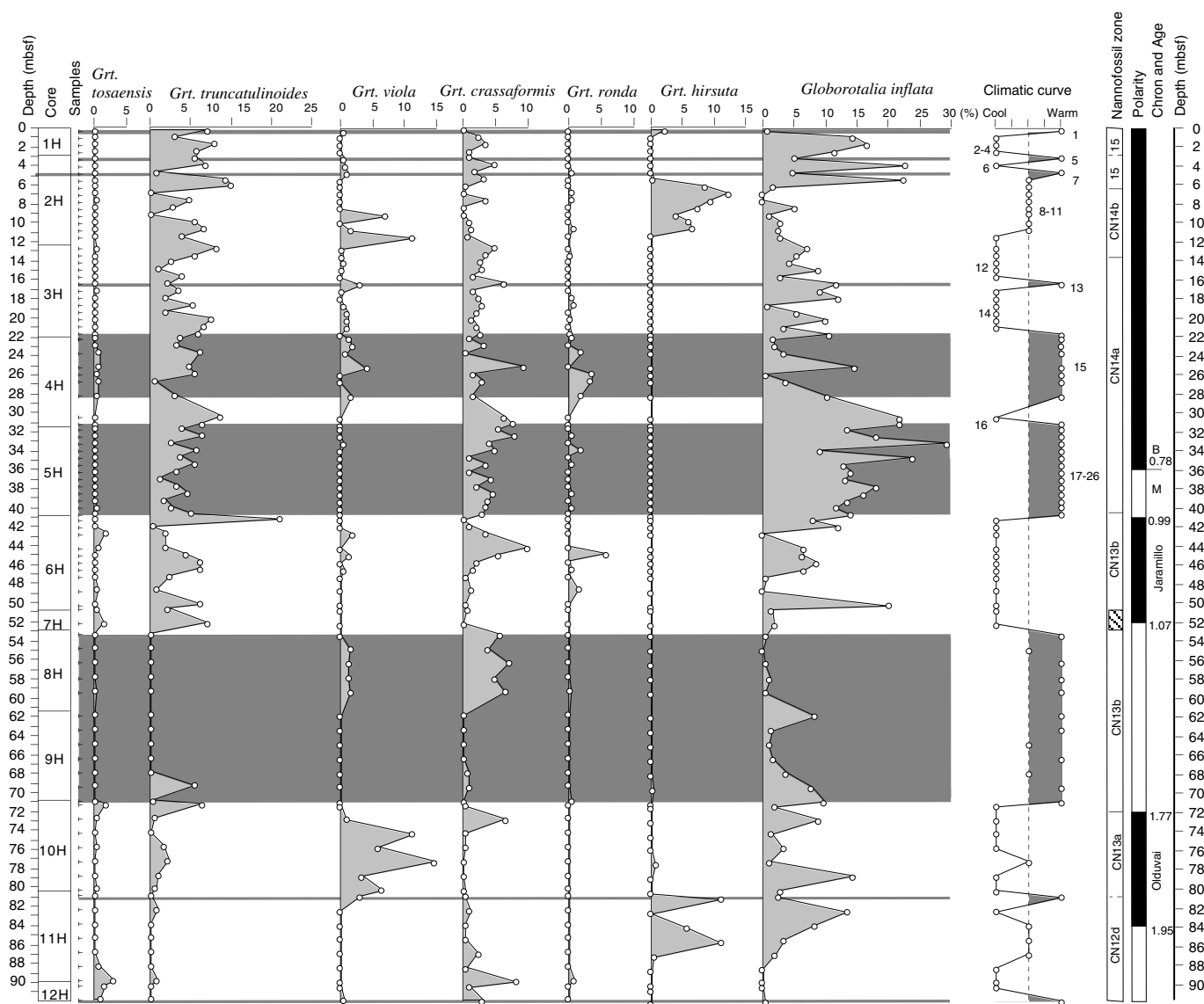


Figure 7. Downcore variations in the percent relative abundance of selected species of the genus *Globorotalia*.

dominantly between December and April (Bé, 1977). In the Sargasso Sea off Bermuda, the abundance peak of this species is in January before *G. hirsuta* and *G. inflata* become locally abundant in March and April (Bé, 1960; Bé and Tolderlund, 1971). Today, *G. truncatulinoides* is found in the western Mediterranean where there is seasonal deep mixing down to 600 m, but not in the eastern Mediterranean where deep mixing conditions do not develop (Lohmann, 1992). Moreover, the distribution of left-coiling and right-coiling varieties of this species are related to deep mixing of water masses because the abundance of right-coiling specimens increases towards the tropics, paralleling the decrease in vertical mixing (Bé and Tolderlund, 1971; Bé, 1977; Lohmann, 1992). Therefore we interpret the third principal component as a "slope-water assemblage," indicating cooler conditions or weaker seasonal deep-mixing conditions than the second factor assemblage.

Our statistically identified assemblages resemble some of the faunal groups recognized by Imbrie and Kipp (1971) and Kipp (1976). These authors analyzed the core top assemblage of planktonic foraminifers in the Atlantic Ocean using factor analysis, and classified them into five assemblages:

1. The tropical is dominated by *G. ruber* and *G. sacculifer*, followed in decreasing order by *G. aequilateralis*, *G. menardii* and *P. obliquiloculata*.
2. The five species of *N. dutertrei*, *G. menardii*, *G. tumida*, *P. obliquiloculata*, and *G. sacculifer* are characteristic of the gyre margin assemblage, associated with *G. inflata*, and a rarity of *G. tenellus* and *G. ruber* (In a transect from gyre margin to gyre center, the abundance of *G. ruber* and *G. menardii* are inverted).
3. The subtropical assemblage (our slope-water fauna) includes *G. falconensis*, *G. bulloides*, *G. truncatulinoides*, and *G. hirsuta*.
4. The subpolar assemblage is composed predominantly of right-coiled *N. pachyderma*, *G. bulloides*, and *G. glutinata*.
5. The dominant species in the polar assemblage is the left-coiling form of *N. pachyderma*.

Based on comparisons of our data with the distributional and ecological studies of planktonic foraminiferal faunas in the modern

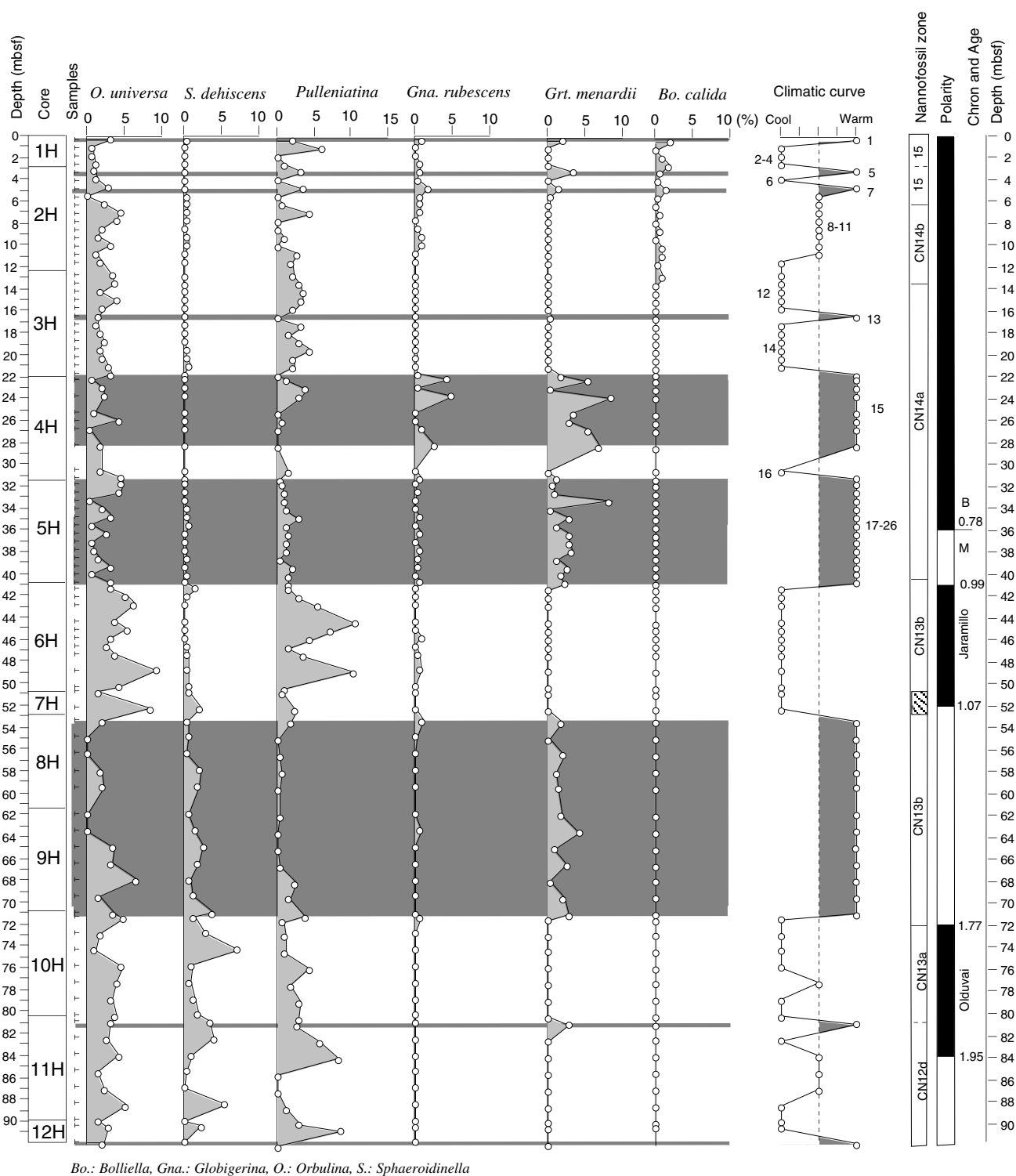


Figure 8. Downcore variations in the percent relative abundance of selected species of the genera *Orbulina*, *Sphaeroidinella*, *Pulleniatina*, *Globigerina*, *Globorotalia*, and *Bolliella*.

oceans, the following five assemblages representing different hydrographic conditions are recognized at Site 997.

Warm-Water (Gulf Stream) Assemblage

The tropical fauna is characterized by the occurrence of the *G. menardii* complex (*menardii*, *tumida*, *ungulata*, and *exilis*), suggesting the influx of warm-water species from the Gulf Stream that advanced

out of the Gulf of Mexico and Caribbean regions. Other warm or tropical indices consist of *Sphaeroidinella dehiscens*, *G. tenellus*, and *Globigerina rubescens*, which are also distributed abundantly in the tropical Gulf of Mexico and Caribbean regions. The abundance of *G. sacculifer* is difficult to understand, but may also represent a warm-water index, because *G. sacculifer* is the most prolific tropical species, whose peak abundance occurs throughout the tropics and warm

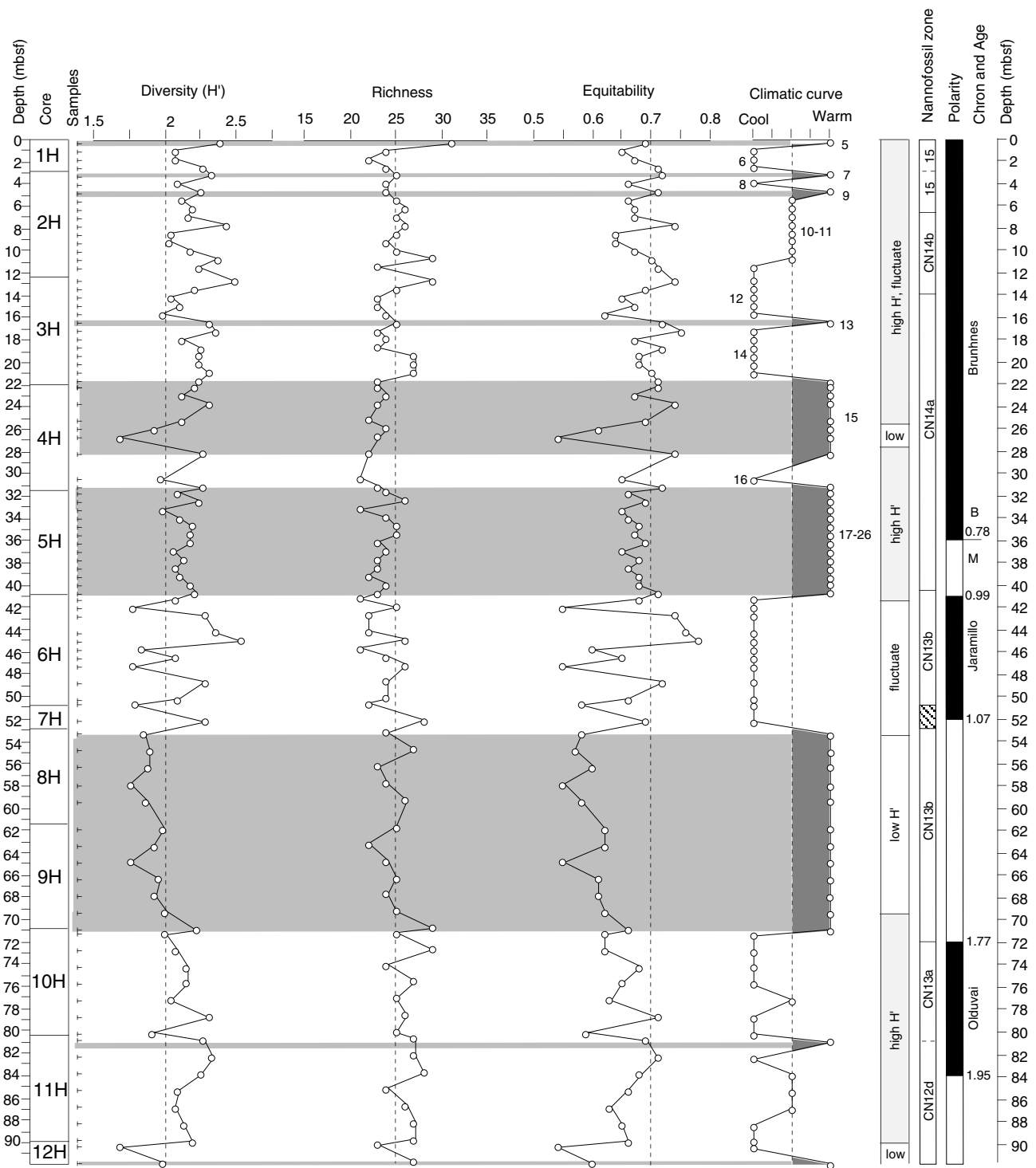


Figure 9. Shannon/Wiener diversity, species richness (species numbers), and equitability index calculated for the studied interval.

subtropics between 20°N and 20°S in the modern ocean (Kipp, 1976; Bé, 1977).

Gyre Margin/Slope-Water Assemblage

The gyre margin assemblage lives along the frontal zone between the subtropical gyre and Gulf Stream and has the highest diversity and equitability of any assemblage recognized in this study. One group of this assemblage contains abundant temperate or cooler

globorotaliids composed of *G. hirsuta*, *G. crassaformis*, *G. truncatulinoides*, and *G. inflata*. They are considered to be dwellers within very deep mixing conditions, suggesting no thermocline or a seasonal breakdown of surface-water stratification. In particular, the abundant occurrences of *G. hirsuta* or *G. inflata* suggest times when the surface-water stratification decreased and the gyre edge or slope water moved over the Blake-Bahama Outer Ridge, perhaps because of decreases in Gulf Stream flow. The other group associated with this

Table 2. Varimax factor score matrix showing the contribution of planktonic foraminifers to each score.

Species	1st factor	2nd factor	3rd factor
<i>Globigerina bulloides</i>	-0.290	-0.105	0.093
<i>Globigerina falconensis</i>	0.190	-0.553	0.287
<i>Globigerina rubescens</i>	0.106	-0.375	0.055
<i>Globigerina quinqueloba</i>	0.009	0.001	0.013
<i>Globigerinella aequilateralis</i>	-0.120	-0.479	0.060
<i>Globigerinita glutinata</i>	1.381	0.609	-0.110
<i>Globigerinoides conglobatus</i>	0.048	0.002	-0.095
<i>Globigerinoides ruber</i>	9.225	-0.916	0.414
<i>Globigerinoides sacculifer</i>	-3.181	-2.053	-3.352
<i>Globorotalia crassaformis</i>	-0.355	-1.038	-0.013
<i>Globigerinoides tenellus</i>	-0.052	-0.007	-0.004
<i>Globorotalia crassula</i>	-0.002	-0.001	0.034
<i>Globorotalia hirsuta</i>	0.230	-0.514	-0.116
<i>Globorotalia inflata</i>	-3.578	-3.492	4.207
<i>Globorotalia menardii</i>	0.047	-0.397	0.090
<i>Globorotalia ronda</i>	0.139	-0.018	0.024
<i>Globorotalia scitula</i>	0.001	0.008	-0.015
<i>Globorotalia truncatulinoides</i>	-0.101	-1.252	1.230
<i>Globorotalia tumida</i>	0.054	-0.033	-0.011
<i>Globorotalia viola</i>	0.290	0.141	-0.314
<i>Neoglobobulimina dutertrei</i>	-4.060	7.866	1.610
<i>Neoglobobulimina pachyderma</i>	-0.006	0.018	-0.021
<i>Orbulina universa</i>	-0.103	0.339	-0.208
<i>Pulleniatina obliquiloculata</i>	-0.023	0.102	0.055
Eigenvalue:	134.646	79.963	58.109
Proportion:	38.550	22.890	16.630
Cumulative proportion:	38.550	61.450	78.080

assemblage consists of typical thermocline/upwelling species, including *N. dutertrei*, *Pulleniatina (primalis and obliquiloculata)*, *Orbulina (universa and bilobata)*, and *Globigerinoides conglobatus*.

Subtropical Gyre and Subpolar Assemblages

The subtropical gyre assemblage consists of such abundant mixed-layer species as *G. ruber*, *G. glutinata*, and *G. falconensis*, suggesting oligotrophic, seasonal conditions with stable deep-mixed layers. The cool-or high-latitude indices in the subpolar assemblage are characterized by the occurrence of *Neoglobobulimina pachyderma* (dextral coiling) and *Globigerina bulloides*.

Changes in Water Mass Assemblages During the Past 2000 k.y.

During the Brunhes Chron, the warm-water (Gulf Stream) assemblage was extremely rare (<2%), except during two interglacial times (presumably Stages 1 and 5). The assemblage reached higher average abundance (generally 3%) in the lower Brunhes, where distinct abundance maxima occurred during the interval between 0.6 and 0.78 Ma (Fig. 10). This group was very rare or absent in the Jaramillo Subchron, and fluctuated between 0% and 7% before 1.55 Ma.

The gyre margin/slope-water assemblage is one of the dominant groups of planktonic foraminifer faunas in Hole 997A. During the middle to late Pleistocene (0.2–0.3 Ma), the relative abundance of this assemblage increased during glacial/cooler times and decreased during interglacial/warmer times (Fig. 10). This pattern, however, is difficult to recognize in the lower Pleistocene and Pliocene. The relative abundance of this assemblage dropped to 10%–15% in the intervals between 0.5–0.7 Ma and 1.3–1.5 Ma, but increased to as much as 40%–45% in other intervals (Fig. 10). Within the gyre margin assemblages, the abundance of the slope-water globorotaliid group (*G. inflata*, *G. hirsuta*, and *G. truncatulinoides*) increased in the two intervals of 1.6–1.9 Ma and <1.0 Ma, whereas the other gyre margin assemblage dominated by *N. dutertrei* occurred consistently throughout the Pliocene–Pleistocene (Figs. 3, 11). The increase in the globorotaliid group between these intervals may suggest cooling in the frontal zone between the gyre and Gulf Stream because *G. inflata* characterizes a transitional assemblage between subpolar and subtropical waters in the modern ocean.

The subtropical gyre assemblage is the dominant group with high-amplitude fluctuations of 25%–60% (Fig. 10). During the late Pleis-

Table 3. Varimax factor loading matrix for core samples in Hole 997A.

Core, section, interval (cm)	Depth (mbsf)	1st factor	2nd factor	3rd factor
164-997A-				
1H-1, 39-41	0.39	8.08	7.1	-3.58
1H-1, 114-116	1.14	10.81	2.64	7.84
1H-2, 39-41	1.89	1.74	3.38	10.19
1H-2, 114-116	2.64	-4.06	-3.18	8.41
2H-1, 39-41	3.29	4.42	1.61	-0.91
2H-1, 114-116	4.04	-10.43	-0.08	16.65
2H-2, 39-41	4.79	11.97	-2.28	0.94
2H-2, 114-116	5.54	-4.09	8.37	14.57
2H-3, 39-41	6.29	4.89	-2.58	-0.92
2H-3, 114-116	7.04	-9.85	-11.82	-4.54
2H-4, 39-41	7.79	-14.92	-11.42	-4.42
2H-4, 114-116	8.54	6.27	-6.31	-0.15
2H-5, 39-41	9.29	5.43	-12.24	-2.88
2H-5, 114-116	10.04	3.89	-2.9	-2.13
2H-6, 39-41	10.79	7.89	-0.68	-0.48
2H-6, 114-116	11.54	1.52	-2.15	0.61
3H-1, 39-41	12.79	2.28	6.61	4.58
3H-1, 114-116	13.54	11.03	-1.09	1.56
3H-2, 39-41	14.29	18.45	0.57	0.41
3H-2, 114-116	15.04	9.09	0.35	2.89
3H-3, 39-41	15.79	14.87	-8.03	-0.01
3H-3, 114-116	16.54	-14.55	-0.78	4.64
3H-4, 39-41	17.29	-14.87	1.4	0.68
3H-4, 114-116	18.04	0.71	-7.53	8.81
3H-5, 39-41	18.79	6.26	7.78	-4.74
3H-5, 114-116	19.54	6.34	4.31	-2.9
3H-6, 39-41	20.29	3.87	2.5	3.55
3H-6, 114-116	21.04	4.97	0.09	0.57
3H-7, 39-41	21.79	-3.87	5.12	3.18
4H-1, 39-41	22.29	9.11	2.47	-3.25
4H-1, 114-116	23.04	10.44	3.77	-5.05
4H-2, 39-41	23.79	11.16	-1.22	2.27
4H-3, 39-41	25.29	8.69	3.96	10.29
4H-3, 114-116	26.04	23.64	-5.37	-1.41
4H-4, 39-41	26.79	25.72	-12.85	2.61
4H-5, 39-41	28.29	-3.77	-3.51	4.14
4H-6, 114-116	30.54	7.27	6.62	16.9
4H-7, 39-41	31.29	-2.76	5.39	19.55
5H-1, 39-41	31.79	8.87	2.12	11.36
5H-1, 114-116	32.54	-5.93	3.42	12.7
5H-2, 39-41	33.29	-4.86	16.38	17.95
5H-2, 114-116	34.04	3.6	11.14	-0.93
5H-3, 39-41	34.79	-6.25	16.06	10.73
5H-3, 114-116	35.54	-9.54	6.5	0.78
5H-4, 39-41	36.29	-19.48	9.16	-0.27
5H-4, 114-116	37.04	-13.38	4.15	-0.99
5H-5, 39-41	37.79	-10.31	9.81	4.66
5H-5, 114-116	38.54	-12.07	5.6	3.86
5H-6, 39-41	39.29	-12.82	7.5	-0.23
5H-6, 114-116	40.04	-11.95	7.8	-1.82
5H-7, 39-41	40.79	-15.46	9.28	0.82
6H-1, 39-41	41.29	1.51	-1.25	6.52
6H-1, 114-116	42.04	-36.24	-19.21	1
6H-2, 39-41	42.79	-14.01	17	-12.52
6H-3, 39-41	44.29	-3.09	8.58	0.06
6H-3, 114-116	45.04	-9.16	1.37	1.12
6H-4, 39-41	45.79	18.58	-9.52	7.7
6H-4, 114-116	46.54	7.86	-2.67	1.12
6H-5, 39-41	47.29	-22.64	-27.11	-3.17
6H-6, 39-41	48.79	-1.47	3.23	-8.28
6H-7, 39-41	50.29	-19.43	-4.15	11.44
7H-1, 39-41	50.77	-0.1	-7.25	-8.63
7H-2, 37-39	52.27	-4.98	7.89	-6.66
8H-1, 49-51	53.39	7.9	-10.88	-5.58
8H-2, 49-51	54.89	-0.98	15.99	-17.35
8H-3, 49-51	56.39	3.07	12.48	-14.63
8H-4, 49-51	57.94	5.78	17.1	-16.69
8H-5, 49-51	59.44	7.73	11.78	-14.18
9H-1, 49-51	61.89	0.91	-12.86	1.42
9H-2, 49-51	63.39	-2.16	-0.32	-12.24
9H-3, 49-51	64.89	11.91	-15.96	-5.34
9H-4, 49-51	66.39	1.09	-10.4	-7.62
9H-5, 49-51	67.89	-2.21	-8.42	-6.2
9H-6, 49-51	69.39	14.47	-5.24	4.25
9H-7, 49-51	70.94	-1.11	-5.1	2.85
10H-1, 49-51	71.39	13.53	-8.38	-0.12
10H-2, 49-51	72.79	6.74	4.83	-1.3
10H-3, 49-51	74.29	-18.32	4.6	-12.24
10H-4, 49-51	75.74	14.21	-7.82	0.9
10H-5, 49-51	77.24	10.22	-3.29	-4.54
10H-6, 49-51	78.74	-17.64	-7.73	7.12
10H-7, 49-51	80.24	14.93	-3.59	-4.9
11H-1, 49-51	80.89	13.04	-2	-1.04
11H-2, 49-51	82.39	-12.59	10.32	0.44
11H-3, 49-51	83.89	-2.18	-2.61	-0.06
11H-4, 49-51	85.39	-3.89	4.75	-8.4
11H-5, 49-51	86.89	-20.71	-16.14	-7.85
11H-6, 49-51	88.39	-12.63	9.43	-14.94
11H-7, 49-51	89.89	8.36	1.05	-5.37
12H-1, 49-51	90.39	-19.42	-27.29	-5.99
12H-2, 49-51	91.89	15.07	1.86	-7.13

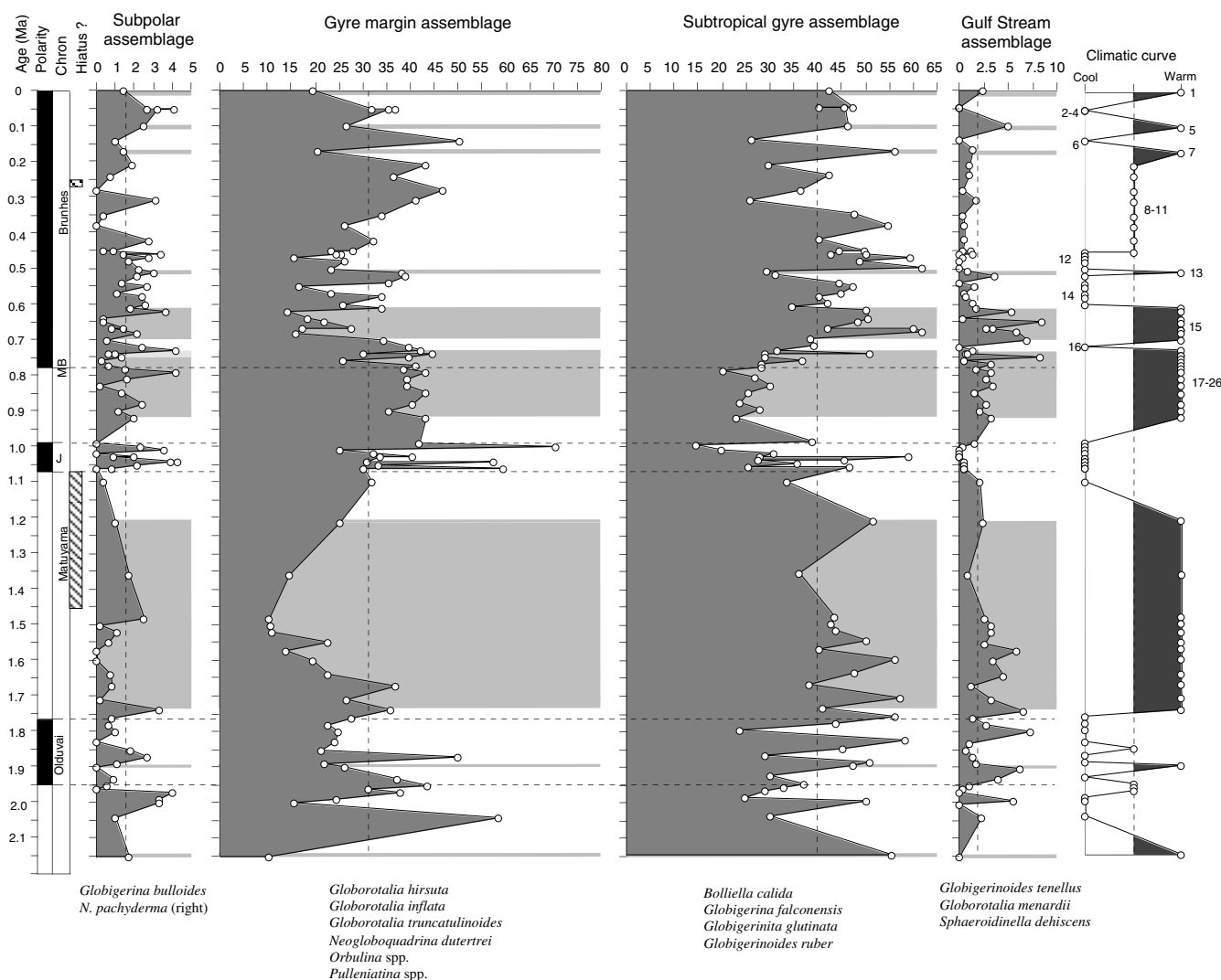


Figure 10. Time series of downcore variations in percent relative abundance of warm-water, subtropical gyre, gyre margin, and subpolar assemblages. Each assemblage is the cumulative total abundance of the species listed below each column.

toocene, the abundance peaks of this assemblage coincided with warm/interglacial times, representing a trend opposite to gyre margin species. The correspondence between the abundance peaks and warm-cool cycles, however, is not clear in the Pliocene and early Pleistocene. The subtropical gyre assemblage became relatively rare (<20%) in the interval between 0.78 and 1.0 Ma (from the Brunhes/Matuyama boundary to the top of the Jaramillo Subchron). This assemblage also exhibited abundance fluctuations before 1.5 Ma similar to the abundance histories of the gyre margin assemblage in this interval (Fig. 10).

The subpolar assemblage is a minor element (generally <5%) and displays high-frequency fluctuations with an amplitude of 1%–5% throughout the studied section (Fig. 10).

Temporal trends in these assemblages are summarized as follows (Fig. 12):

1. The subtropical gyre and gyre margin species are dominant through Quaternary time in Hole 997A.
2. Below top of the Olduvai Subchron, the planktonic foraminiferal faunas are characterized by high-amplitude fluctuations of both the gyre and gyre margin assemblages and contain few, if any, Gulf Stream indices.
3. The gyre margin assemblage displays a gradual decrease between about 2.0 and 1.5 Ma, and the subtropical gyre assemblage, associated with small amounts of a Gulf Stream warm fauna, is dominant between 1.3 and 1.7 Ma.

4. The gyre margin assemblage increased in abundance between the top of the Jaramillo Subchron and the bottom of the Brunhes Chron (0.7–1.07 Ma). The abundance of thermocline/upwelling species such as *N. dutertrei* suggests less stratified conditions or more marginal conditions in the subtropical gyre. These changes may reflect the expansion of a frontal zone between the western boundary current and the gyre, producing upwelling along the margin.
5. The transition from a gyre margin assemblage to the alternation in abundance of the gyre and gyre margin species occurred around 0.7 Ma, very close to the Brunhes/Matuyama boundary. Gyre species are characteristic of warm times and gyre margin taxa dominate cooler intervals. This pattern, however, is not clear in the samples older than the lower Brunhes Chron.

DISCUSSION

Early Matuyama Ocean (2.0–1.07 Ma)

Beginning ~2.0 Ma, foraminifer assemblages are dominated by northern gyre margin taxa such as *G. inflata* and include rare warm

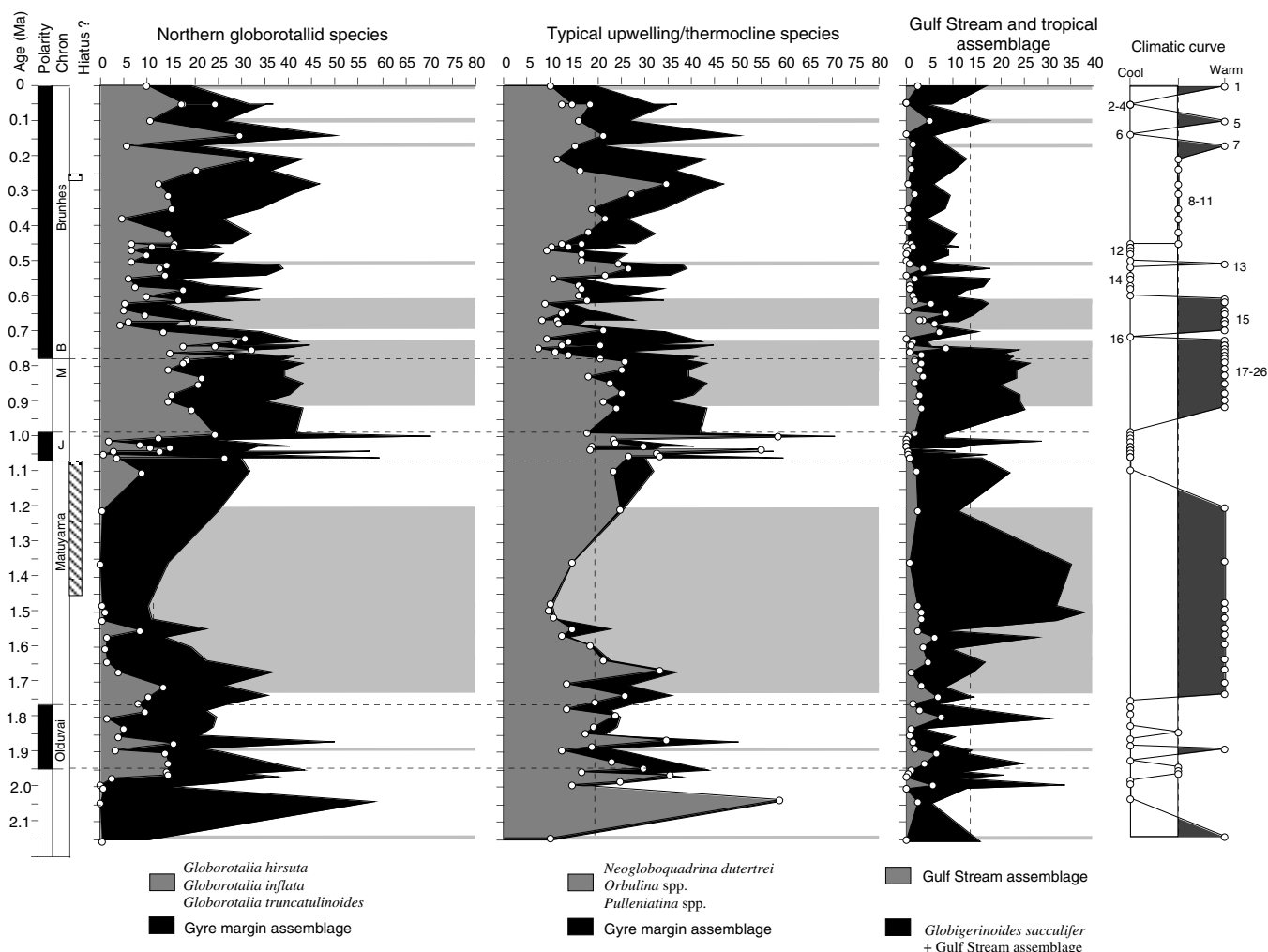


Figure 11. Time series of downcore variations in percent relative abundance of northern globorotaliid species and upwelling/thermocline species in the gyre margin assemblage, and possible warm-water species (a Gulf Stream assemblage and *G. sacculifer*). Each species group consists of the cumulative total abundance of the taxa listed below each column.

species, suggesting cold conditions near the base of the Olduvai Subchron (Fig. 12). We suggest that weakening of the western boundary current caused less warm water to flow into the western boundary of the subtropical gyre and result in a shallower thermocline and generally cooler conditions. In the early Matuyama, the warm subtropical gyre assemblage became dominant, presumably because of the general warming and northward movement of the warm part of the subtropical gyre system (Fig. 12). This warming could have been produced by intensification of the gyre circulation due to a stronger trade-wind system (Fig. 13; warm time).

Jaramillo Upwelling Event (1.07–0.78 Ma)

In the early Jaramillo Subchron, the subtropical gyre assemblage gave way to a gyre margin assemblage at Site 997 (Figs. 10, 12), suggesting expansion of the mixing zone between the Gulf Stream to the west and the subtropical gyre to the east. Bassinot et al. (1997) have hypothesized that the switch from 41-k.y. to 100-k.y. cyclicity during the “Mid-Pleistocene Revolution” (~930 ka) was associated with a southward shift of the Intertropical Convergence Zone (ITCZ) or a southward shift in the North Equatorial Counter Current. Their data suggest that this change in tropical hydrography produced a shallower thermocline at Ceara Rise Site 927 in the tropical Atlantic Ocean. Other work at Ceara Rise has demonstrated that thermocline taxa

dominated in glacial stages and mixed-layer taxa dominated in interglacials during the mid-Pleistocene between 1000 and 500 ka (Cullen and Curry, 1997). These authors did not observe major changes in assemblages at the 930 k.y. onset of the 100-k.y. cycle, but they did observe a general decrease in mixed-layer species during the Jaramillo and the early Brunhes as in our data from Hole 997A. These observations suggest that the southern part of the subtropical gyre became less well stratified than it had been in the lower Matuyama Chron. The rapid change in Hole 997A from the warm subtropical gyre (mixed layer) assemblage to the cooler gyre margin/slope-water assemblages at the top of the Jaramillo Subchron suggests that the “Mid-Pleistocene Revolution” was accompanied by an expansion of the frontal zone between the western boundary current and the subtropical gyre, along with greater upwelling along this frontal boundary.

Latest Matuyama Low-Oxygen Event

During the late Jaramillo and upper Matuyama, benthic foraminifers characteristic of low oxygen conditions became common (samples between 33.29 and 40.79 mbsf; Samples 164-997A-5H-2, 39–41 cm, to 5H-7, 39–41 cm) and sediments also contain abundant dark-gray to black colored, cylindrical pyrite tubes that are 1–2 mm in length and 100–200 µm in diameter (Figs. 3, 12). In addition, diatoms

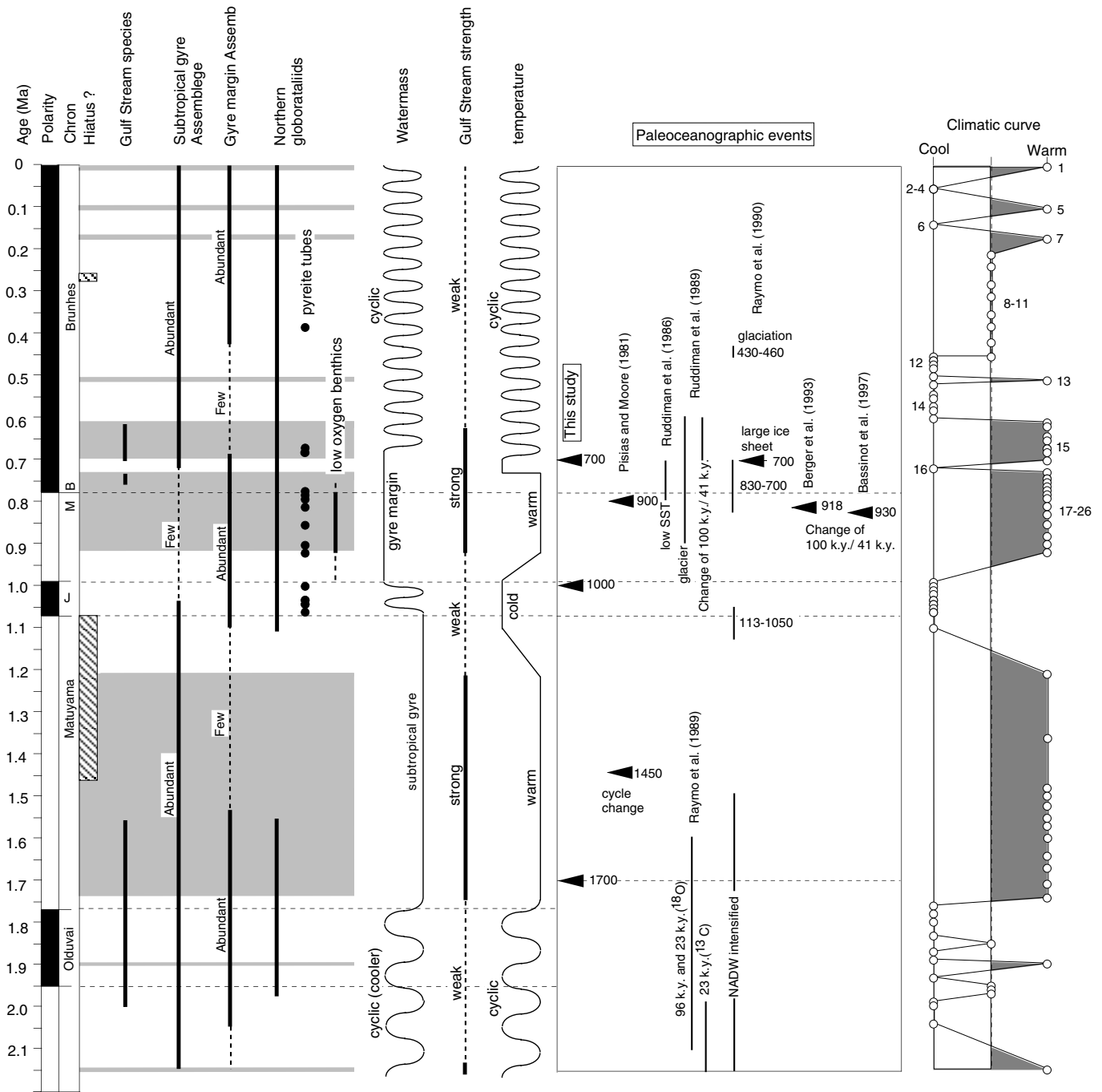


Figure 12. The summary of abundance in different planktonic foraminiferal assemblages (Gulf Stream, subtropical gyre, gyre margin, and northern globorotaliid species) with the occurrence of low-oxygen benthic foraminifera and pyrite tubes plotted as a time series. The second column shows inferred hydrographic conditions of water masses, Gulf Stream strength, and sea-surface temperature derived from the changes of these planktonic assemblages. The third column summarizes the paleoceanographic events in Hole 997A and at other sites in the North Atlantic Ocean.

became abundant (up to 35% of the fossil assemblage), whereas they are usually below 10% of the sediments throughout the remainder of the studied interval (Fig. 3; Shipboard Scientific Party, 1996). All these features suggest lower oxygen contents of intermediate waters and more upwelling over the Blake-Bahama Outer Ridge. Our observations are consistent with weak upper North Atlantic Deep Water ventilation during the late Jaramillo Subchron and the upper Matuyama Chron.

The combination of weak intermediate water ventilation, evidence for an increase in Gulf Stream species, and the re-establish-

ment of the gyre margin assemblage suggests that the waters over Site 997 marked a dynamic frontal system where faunas converged from the Gulf Stream, as well as warm and cold core rings spun off the Gulf Stream and both gyre margin water and the gyre water (Fig. 13, Transition time). The increase of both diatoms and the gyre margin faunas indicate high surface productivity, associated with stronger surface overturning. The "Mid-Pleistocene Revolution," therefore, marked a transition from warmer subtropical gyre conditions to strong warm-cold oscillations at the location of Site 997 between 1.0 and 0.7 Ma (Fig. 12).

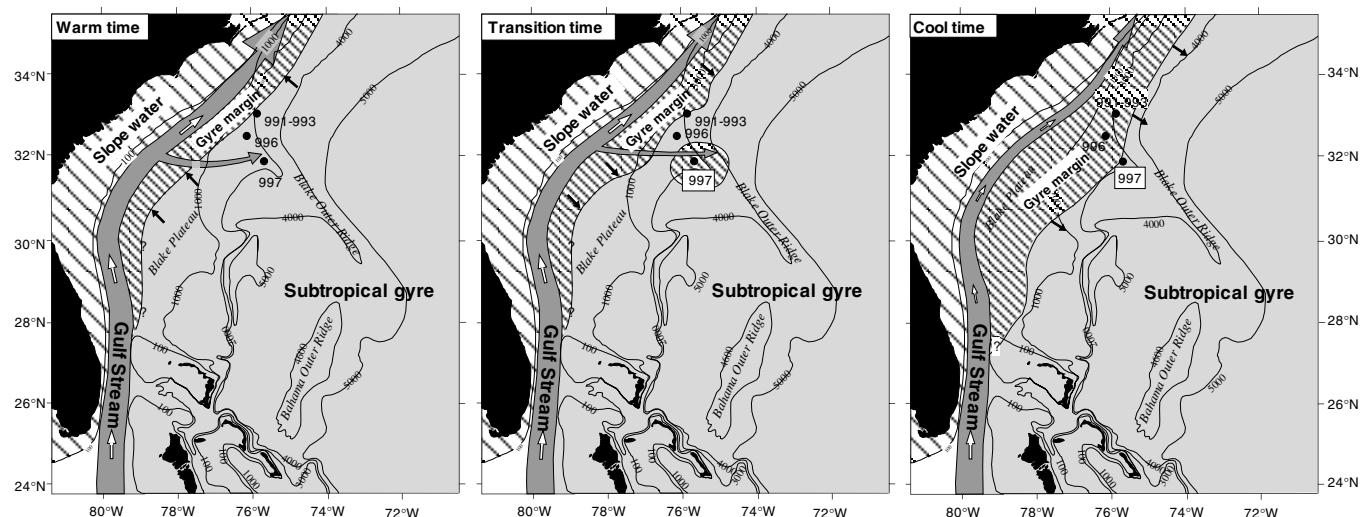


Figure 13. Inferred changes of Pleistocene surface-water circulation patterns during warm, cool, and transitional times. The subtropical gyre group is characteristic of interglacial and warm periods, whereas the upwelling/gyre margin group is typical of cooler intervals and an expanded frontal hydrographic system over the Blake Bahama Outer Ridge. The faunas in the transition time (latest Matuyama interval) are dominated by the gyre margin group, but include a minor component of warm-water species such as *G. menardii*. The transitional period is associated with an expansion of low oxygen conditions over the Blake-Bahama Outer Ridge that may be related to increasing upwelling or decreased upper North Atlantic Deep Water ventilation.

Brunhes Cyclic Intervals (780–0 ka)

The gyre margin assemblage in Hole 997A remained an important part of the planktonic foraminiferal faunas through the Brunhes Chron, although the warm subtropical gyre assemblage made a partial reappearance with higher abundance of *G. ruber* and *G. sacculifer* in the early Brunhes. Based on our data, the modern ecotone between the Gulf Stream and the subtropical gyre had developed close to 0.7 Ma and just above the Brunhes/Matuyama boundary. The warm foraminiferal component, presumably from the Gulf Stream or southern Sargasso Sea, became less important later in the Brunhes because *G. sacculifer* decreases in abundance above 32 mbsf. A gyre assemblage with *G. hirsuta* appeared between 5 and 10 mbsf, suggesting that the climate system favored a more northern subtropical gyre assemblage in the middle Brunhes. Finally, the gyre margin group re-emerged as a dominant component in the last glacial cycle above 5 mbsf (Fig. 12).

CONCLUSIONS

Upper Pliocene to Holocene planktonic foraminifer assemblages at Site 997 are classified into four groups based on quantitative and principal component analyses: (1) warm water (Gulf Stream) (2) subtropical gyre (mixed-layer species), (3) gyre margin (thermocline/upwelling species), and (4) subpolar faunas. The subtropical gyre and gyre margin assemblages are dominant at Site 997, associated with small amounts of Gulf Stream species such as *G. menardii*.

Planktonic foraminifer assemblages display major changes in dominance between 0.7 and 1.0 Ma. In sediments older than the Olduvai Subchron and younger than the Matuyama, the planktonic foraminiferal faunas are characterized by alternations in the relative abundance of gyre and gyre margin assemblages, whereas assemblages from ~0.7 to 1.0 Ma are dominated by gyre margin taxa, particularly species characteristic of modern slope-water settings. Low-oxygen conditions expanded over the Blake-Bahama Outer Ridge at Site 997A during this change in planktonic foraminifer assemblages perhaps because of weaker upper North Atlantic Deep Water ventilation.

No distinct changes have been recognized at about 900 ka at Blake Ridge during the switch from 41- to 100-k.y. cyclicity in the well known "Mid-Pleistocene Revolution." Instead, we observed at least two intervals of faunal turnover around 700 and 1000 ka, just above and below the "Mid-Pleistocene Revolution." (Fig. 12). We conclude that the "Mid-Pleistocene Revolution" was not an "event" per se, but involved a gradual refrigeration and speeding-up of gyral circulation that helped expand the frontal zone over the Blake Ridge and establish the slope-water foraminifer assemblage over the Blake Bahama Outer Ridge throughout the late Pleistocene. Our data also indicate that changes in both Gulf Stream intensity and southward movements of northern cooler water masses containing transitional groups are responsible for variations in planktonic foraminifer assemblages over Blake Ridge. We suggest that an increase in trade-wind velocity connected with sea-surface temperature or insolation changes can explain the time-progressive changes of thermocline depths and foraminifer assemblages.

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