

A comparison between smaller (>63 µm) and larger (>150 µm) planktonic foraminiferal faunas from the Pleistocene of ODP Site 1073 (Leg 174A), New Jersey margin, NW Atlantic Ocean

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ABSTRACT – Planktonic foraminiferal faunas have been studied from the Pleistocene of ODP Site 1073 (Leg 174A), New Jersey margin, NW Atlantic Ocean and their abundances have been compared in the >63 µm and >150 µm size-fractions from the same samples. Trends in the relative abundance of many species are similar in the two size-fractions, although the general level varies considerably. The mean abundance and ranges of *Neogloboquadrina pachyderma* (sinistral), *N. pachyderma* (dextral), *Globorotalia inflata* and *Globigerina bulloides* are greater in the >150 µm size-fraction compared with the >63 µm size-fraction. *Turborotalita quinqueloba*, *Globigerinita uvula*, *G. glutinata*, *G. clarkei*, and juvenile species are more abundant in the >63 µm size-fraction than the >150 µm size-fraction. Peaks (c. 60%) in abundance of *G. uvula* occur in the >63 µm size-fraction only, although the causes of these patterns are unclear. The data suggest that, in general, consistent palaeoclimatic/palaeoceanographic information is achieved by studying planktonic foraminiferal faunas from either size-fraction. However, because particular smaller species are either under-represented or even absent from the larger (>150 µm) size-fraction, the smaller (>63 µm) size-fraction must be included in studies of planktonic foraminifera. Furthermore, studies that involve planktonic foraminifera in the >63 µm size-fraction could provide different transfer function estimates for sea surface temperatures in areas where workers have only used larger (>125 µm and >150 µm) size-fractions. *J. Micropalaeontol.* 21(2): 137–147, December 2002.

INTRODUCTION

Planktonic foraminiferal faunas have been used extensively in reconstructing past oceanographic and climatic conditions. In the modern ocean, their distribution shows a distinct global latitudinal pattern, forming five major biogeographical provinces, which is closely related to the hydrographic features of oceanic water masses (e.g. Bé & Tolderlund, 1971; Bé, 1977; Bé & Hutson, 1977). The geographical and vertical distribution of planktonic foraminifera is principally related to their preferences for specific temperatures and food requirements (e.g. Bé & Tolderlund, 1971; Kipp, 1976; Bé, 1977). This relationship has been applied to fossil faunas to understand past distribution and abundance patterns.

The use of particular size-fractions in foraminiferal analysis has important implications for the interpretation of modern and past environments. Various authors have suggested the use of specific size-fractions for the study of foraminifera, including >63 µm, >125 µm, >150 µm and even >250 µm. The CLIMAP (Climate, Long-Range Investigation, Mapping and Prediction) Project members (McIntyre *et al.*, 1976; CLIMAP, 1981, 1984) recommended the use of the >149 µm size-fraction as a standard in palaeoceanographic and palaeoecological studies. This is because the smaller-sized planktonic foraminifera which are difficult to identify and time consuming to count are eliminated from the sample (Imbrie & Kipp, 1971). However, in benthic foraminiferal studies, it has been argued (e.g. Schröder *et al.*, 1987; Sen Gupta *et al.*, 1987) that in order to include the large number of smaller-sized and ecologically significant species in the analysis, the >63 µm size-fraction must be used. Following the recommendations of the CLIMAP project, many authors have employed the >149/150 µm size-fraction in planktonic foraminiferal studies. Kellogg (1984) argued in favour of using the >149 µm sieve size to avoid taxonomic problems with

juvenile specimens and to reduce the effect of dissolution encountered with fine (>62 µm) size-fractions. Lu & Keller (1995) recommended using the >106 µm fraction, whilst Martin & Liddell (1989) proposed a 'sieve method' whereby multiple size-fractions are analysed for each sample. However, whatever size-fraction is used, in order to achieve reliable comparisons between foraminiferal faunas of different workers only the same size-fraction should be considered.

The aim of this paper is to compare the distribution and palaeoecological significance of Pleistocene planktonic foraminiferal faunas in the >63 µm and the >150 µm size-fractions from one site (ODP Site 1073, Leg 174A) in the northwest Atlantic Ocean. A detailed study of the palaeoclimatic and palaeoceanographic history of the Pleistocene of Site 1073 based on planktonic foraminifera in the >150 µm size-fraction is dealt with in a separate paper (Olson & Smart, *in press*).

MATERIAL AND METHODS

Site 1073

Site 1073 (Hole 1073A) was drilled as part of the New Jersey Mid-Atlantic Sea-Level Transect in order to evaluate the effects of 'Icehouse' glacial-eustatic change at a passive continental margin characterized by predominantly siliciclastic sedimentation (Austin *et al.*, 1998). Site 1073 (39°13.5214'N, 72°16.5461'W; 639 m water depth) is located on the continental slope offshore New Jersey (Fig. 1). A single hole (Hole 1073A) was drilled to a depth of 663.6 mbsf (metres below seafloor). Core recovery at this site was excellent (99.9%) and a thick (519.8 m) Pleistocene sequence (<1.77 Ma) dominated by clays, silty clays, sandy muds and muddy sands was recovered (Austin

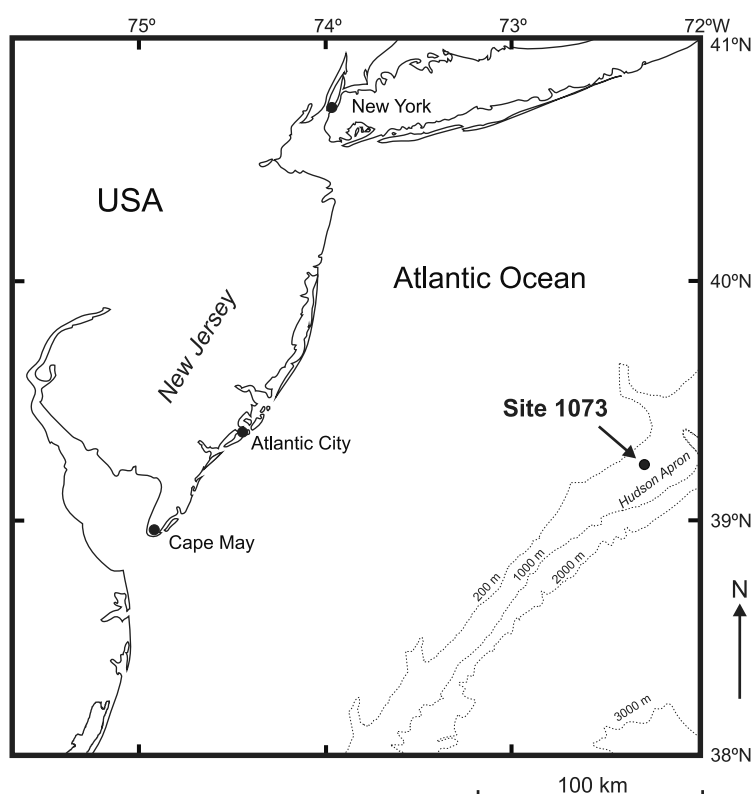


Fig. 1. Location map of Site 1073. Bathymetric contours (in metres) are shown as dotted lines.

et al., 1998). The thick Pleistocene sequence recovered from Site 1073, where planktonic foraminifera are common, provides a unique opportunity to study climatic change in detail in an upper slope setting.

The stratigraphy of the Pleistocene succession of Site 1073 is summarized in Figure 2. Age control is provided by nannofossil biostratigraphy (Wei, 2001) and oxygen isotope stratigraphy (McHugh & Olson, 2002). A radiocarbon age of $14,400 \pm 55$ years was recorded at 0.40 mbsf suggesting that the Holocene is either very thin or missing (McHugh & Olson, 2002). The section from *c.* 0–30 mbsf is represented by a sandy debris flow (McHugh & Olson, 2002).

Investigations of multichannel seismic data on the slope and adjacent continental shelf of the NW Atlantic Ocean indicate the presence of four Pleistocene sequence boundaries labelled pp1, pp2, pp3 and pp4 (Mountain *et al.*, 1994; Austin *et al.*, 1998). The positions of sequence boundaries pp1, pp2 and pp3 are shown in Figure 2. The base of the Pleistocene section is marked by a surface of discontinuity (pp4) at 520 mbsf which is just below the section sampled for isotopic analysis (McHugh & Olson, 2002). These boundaries are inferred to reflect phases of rapid sea-level rise, drowning of the shelf, and subsequent sediment starvation on the slope. Predominantly off-lapping reflectors beneath the slope reflect enhanced offshore sediment transport and margin progradation during periods of falling sea-level (Savrdá *et al.*, 2001).

The percentages of calcium carbonate (B. Balsam & J. Damuth, unpublished data) and opal (McHugh & Olson, 2002) reveal an inverse correlation that is especially evident from

0 mbsf to 120 mbsf. Peaks in calcium carbonate are generally correlated with interglacial stages and opal to glacial stages (McHugh & Olson, 2002).

Sediment accumulation rates for the Pleistocene at Site 1073 vary from 25 cm ka^{-1} (OIS 4) to 270 cm ka^{-1} with the highest values occurring during glacial periods OIS 2 and 10 (McHugh & Olson, 2002). The high sedimentation rates recorded at Site 1073 are because of its close proximity (*c.* 20 km) to the Hudson Canyon Shelf Valley System.

Sample preparation and data collection

Sediment samples were examined for planktonic foraminifera at intervals varying from *c.* 1–5 m above *c.* 100 mbsf and at less frequent intervals from *c.* 100 mbsf to 434.47 mbsf. Each of the 20 cm^3 samples were split into two sub-samples of 10 cm^3 . Each sub-sample was dried, weighed, disaggregated using a 10% sodium hexametaphosphate solution, and then washed over a $63 \mu\text{m}$ sieve. The washed sub-samples were dried and re-weighed to calculate the percentage of coarse fraction (percentage of sediment $>63 \mu\text{m}$). For each interval, one of the sub-samples was studied for foraminifera in the $>63 \mu\text{m}$ size-fraction, whilst the other was analysed for foraminifera in the $>150 \mu\text{m}$ size-fraction. For analysis of the $>150 \mu\text{m}$ size-fraction, the $>63 \mu\text{m}$ portion was dry-sieved using a $150 \mu\text{m}$ sieve. For each of the sub-samples, the fractions were subdivided using a modified Otto microsplitter until aliquots of approximately 300 planktonic foraminiferal specimens were attained for foraminiferal analysis. Specimens were picked and mounted on gummed slides for identification and the proportions of the various species were

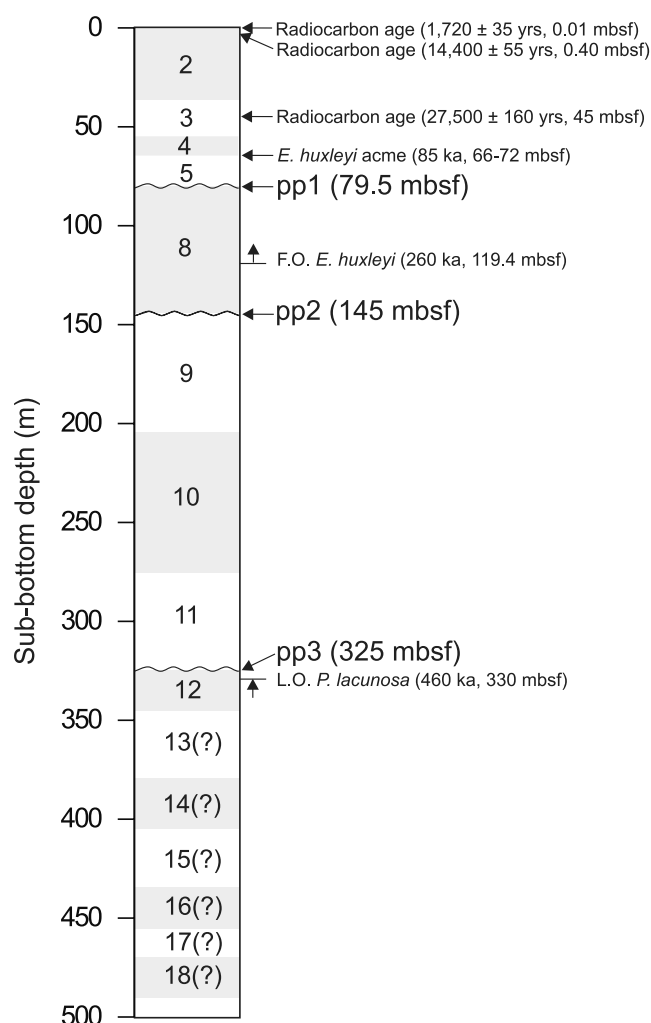


Fig. 2. The stratigraphy of Site 1073 based on nannofossil biostratigraphy (Wei, 2001), radiocarbon ages and oxygen stable isotope stratigraphy (McHugh & Olson, 2002). Numbers refer to Oxygen Isotope Stages (OIS) with the glacials shaded. The positions of sequence boundaries pp1, pp2 and pp3 (Austin *et al.*, 1998) are shown with wavy lines. Note *E. huxleyi*=*Emiliania huxleyi*, *P. lacunosa*=*Pseudoemiliania lacunosa*, F.O., first occurrence; L.O., last occurrence; mbsf, metres below seafloor.

calculated. The association between relative abundances was measured using correlation coefficients. Differences between relative abundances of different size-fractions were tested for significance using the Wilcoxon Test for paired data.

For a number of samples, the weight of the picked portion was determined in order to calculate the number of foraminifera per gram of dry sediment. The Planktonic Fragmentation Index (PFI) was recorded in the >150 µm size-fraction and was calculated as the percentage of test fragments relative to whole planktonic foraminifera+test fragments. Species diversity was recorded in terms of the alpha index (Fisher *et al.*, 1943) using the graph in Murray (1991).

Taxonomy

For the most part, planktonic foraminifera were identified following the suggestions of Saito *et al.* (1981) and Kennett &

Srinivasan (1983). A faunal reference list is given in the Appendix. A number of specific taxonomic concepts have been incorporated into this study and details of these are given below.

***Neogloboquadrina pachyderma* and *N. dutertrei*.** Both dextral (d) and sinistral (s) forms of *N. pachyderma* were recognized and their proportions were calculated. Transitional forms (P-D intergrade of Kipp, 1976) between *N. pachyderma* (d) and *Neogloboquadrina dutertrei* could not be consistently distinguished and were thus combined with *N. pachyderma* (d). Forms considered to be *N. dutertrei* were typically relatively large in size, comprised at least five chambers in the final whorl, had a wide umbilicus and a high spire (e.g. Giraudeau, 1993). Forms with four or four-and-a-half chambers and a small umbilicus, with an aperture often bordered by a lip, were assigned to *N. pachyderma*.

***Turborotalita quinqueloba*.** In this study, *Turborotalita quinqueloba* includes *Turborotalita quinqueloba* (*sensu stricto*), *Globigerina exumbilicata* and *Globigerinita clarkei*. *Globigerina exumbilicata* could not be consistently distinguished from *T. quinqueloba* in the samples studied, although it was considered to be rare. It also proved difficult to separate consistently the occasionally reasonably abundant (up to 10%) *G. clarkei* from *T. quinqueloba* in the samples studied particularly where preservation was poor. It was, therefore, decided to include *G. clarkei* within the *T. quinqueloba* group. However, preliminary work carried out by the author has shown that it is possible to distinguish these taxa with reasonable consistency using the SEM. *Globigerinita clarkei* is consistently smaller than *T. quinqueloba*, its test is more compressed, chambers are less inflated, intercameral sutures are less incised, pores are larger and it has a thicker wall (Rögl & Bolli, 1973; Boltovskoy, 1977, 1991). According to Boltovskoy (1977), *G. clarkei* should be placed in the genus *Globigerinita* and this is followed here.

***Globigerinita glutinata*.** *Globigerinita glutinata* mainly includes specimens similar to that illustrated in Kennett & Srinivasan (1983, fig. 3, plate 56). Some specimens have a bulla and some specimens have chambers that increase more rapidly in size with the ultimate chamber being much larger than the penultimate chamber. *Globigerinita glutinata* was distinguished from *Globigerina bulloides* mainly by the wall structure. *Globigerinita glutinata* has a smooth to finely hispid and non-spinose test surface with fine pores whereas *G. bulloides* shows a hispid, densely perforate surface and usually has a more sugary appearance. Some specimens of *G. bulloides* have a very small aperture but are consistent with the surface texture of *G. bulloides*.

***Globigerina bulloides*.** In this study, *G. bulloides* includes a few specimens which could be considered in the *Globigerina falconensis* and *G. umbilicata* group, although a clear distinction was not apparent in the samples analysed from Site 1073.

***Globorotalia* spp. (other).** The *Globorotalia* spp. (other) includes specimens which could not be clearly identified because many were juveniles.

RESULTS

A total of 53 sediment samples was studied for planktonic foraminifera from ODP Site 1073. Only 31 samples yielded sufficient specimens in both size-fractions (>63 µm and >150 µm) for analysis and interpretation. A number of samples were found to contain too few specimens or were barren of foraminifera. Table 1 lists the number of samples studied together with their sub-bottom depths.

Seven species dominate the planktonic foraminiferal assemblage in the >63 µm size-fraction in the studied interval of Site 1073: *T. quinqueloba* (mean 55.1%), *G. uvula* (14.5%), *N. pachyderma* (d) (9.1%), *N. pachyderma* (s) (8.1%), *G. glutinata* (6.0%), *G. inflata* (2.2%) and *G. bulloides* (2.1%). In the >150 µm size-fraction, apart from *G. uvula* which is rare/absent (0.1%), these species are also significant components of the assemblage, although their mean abundances differ: *N. pachyderma* (d) (34.1%), *T. quinqueloba* (19.9%), *N. pachyderma* (s) (18.7%), *G. bulloides* (11.3%), *G. inflata* (7.7%), and *G. glutinata* (4.0%).

Graphs showing abundance fluctuations of the seven most abundant species are shown in Figures 3 and 4. These are species that exceed 10% in two or more samples in either size-fractions. On the whole, the trends in the relative abundances of many species are similar in the two size-fractions, although the general level varies considerably between the two size-fractions.

Correlation coefficients and significance of differences (Wilcoxon Test) of species between the two size-fractions are given in Table 2. There is overwhelming evidence of differences ($p=0.000$) between the two size-fractions in the abundances of *N. pachyderma* (s), *N. pachyderma* (d), *G. bulloides*, *T. quinqueloba*, *G. uvula* and *G. inflata*, and strong evidence of a difference ($p=0.009$) in the abundance of *G. glutinata*. *Neoglobobulimina pachyderma* (s), *N. pachyderma* (d), *G. bulloides* and *G. inflata* are more abundant in the >150 µm compared with the >63 µm size-fraction whereas, *T. quinqueloba*, *G. uvula* and *G. glutinata* are more abundant in the >63 µm compared with the >150 µm size-fraction (see Figs 3 and 4). A comparison of species abundances between the two size-fractions show that there is strong positive correlation of variations in *N. pachyderma* (s) ($r=0.889$, $p=0.000$), *G. bulloides* ($r=0.801$, $p=0.000$) and *N. pachyderma* (d) ($r=0.705$, $p=0.000$) (Table 2). Weaker positive correlations are also evident in *T. quinqueloba* ($r=0.506$, $p=0.004$), *G. uvula* ($r=0.431$, $p=0.016$) and *G. glutinata* ($r=0.385$, $p=0.032$). There is little/no correlation in the abundance of *G. inflata* ($r=0.104$, $p=0.579$) between the two size-fractions. The results of the correlation coefficients and significance of differences for the other planktonic foraminifera are less clear due mainly to the fact that these taxa occur rarely (<5%) in the samples studied.

Large fluctuations occur in the relative abundance of *T. quinqueloba* and *N. pachyderma* (d) throughout the studied interval in both size-fractions (Fig. 3). The abundance of *N. pachyderma* (s) shows moderate variation in both size-fractions (Fig. 3). Peaks in abundance of *N. pachyderma* (s) in the >63 µm size-fraction are consistent with peaks in abundance in the >150 µm size-fraction and occur during Oxygen Isotope Stages (OIS) 2, 4, 12, and 16(?).

Fluctuations in the abundance of *G. inflata* are evident particularly in the >150 µm size-fraction, although, for the most

| Samples (>63 µm) | Sub-bottom depth (m) | Samples (>150 µm) | Comments |
|---------------------|-------------------------|----------------------|----------|
| 1H-1, 55-57 | 0.55 | x | |
| 1H-3, 56-58 | 3.56 | x | |
| 1H-5, 14-16 | 6.14 | | barren |
| 2H-3, 55-57 | 10.15 | | barren |
| 2H-5, 55-57 | 13.15 | | barren |
| 3H-3, 55-57 | 19.45 | | barren |
| 4H-3, 55-57 | 29.01 | | barren |
| 4H-5, 55-57 | 31.95 | | barren |
| 5H-2, 49-51 | 37.09 | x | |
| 5H-3, 116-118 | 39.26 | x | |
| 5H-4, 56-58 | 40.16 | x | |
| 6H-3, 56-58 | 47.39 | x | |
| 6H-4, 55-57 | 48.88 | x | |
| 6H-5, 55-57 | 50.38 | x | |
| 6H-6, 48-50 | 51.81 | x | |
| 7H-1, 55-57 | 54.65 | x | |
| 7H-3, 56-58 | 57.66 | x | |
| 7H-5, 48-50 | 60.58 | x | |
| 8H-1, 55-57 | 64.15 | x | |
| 8H-2, 53-55 | 65.63 | x | |
| 8H-3, 56-58 | 67.16 | x | |
| 8H-4, 54-56 | 68.64 | x | |
| 10H-1, 55-57 | 83.15 | | v. rare |
| 10H-2, 55-57 | 84.65 | | v. rare |
| 10H-3, 55-57 | 86.15 | | v. rare |
| 10H-7, 55-57 | 92.15 | | v. rare |
| 11H-5, 55-57 | 98.65 | | v. rare |
| 12H-2, 55-57 | 103.65 | | v. rare |
| 12H-3, 55-57 | 105.15 | | v. rare |
| 13H-2, 55-57 | 113.15 | | v. rare |
| 14H-3, 56-58 | 124.16 | x | |
| 15H-3, 55-57 | 133.65 | x | |
| 16H-3, 55-57 | 143.15 | x | |
| 17H-3, 55-57 | 152.65 | x | |
| 18H-3, 55-57 | 162.15 | | v. rare |
| 19H-3, 55-57 | 171.55 | x | |
| 20H-3, 56-58 | 181.02 | x | |
| 21H-3, 56-58 | 188.54 | x | |
| 22H-3, 56-58 | 198.16 | x | |
| 23H-3, 56-58 | 206.36 | x | |
| 24H-1, 56-58 | 212.36 | | v. rare |
| 24H-3, 56-58 | 215.32 | | v. rare |
| 25X-3, 56-58 | 219.26 | | v. rare |
| 26X-3, 56-58 | 227.96 | | v. rare |
| 26X-4, 56-58 | 229.46 | | v. rare |
| 28X-3, 56-58 | 247.06 | x | |
| 32X-3, 55-57 | 284.89 | | v. rare |
| 34X-3, 64-66 | 303.74 | | v. rare |
| 36X-3, 56-58 | 321.96 | x | |
| 38X-3, 55-57 | 340.75 | x | |
| 40X-3, 55-57 | 359.55 | x | |
| 46X-3, 56-58 | 414.86 | x | |
| 48X-3, 57-59 | 434.47 | x | |

Samples represented by crosses ('x') contained sufficient numbers of foraminifera and the data are presented in this study.

Table 1. Samples studied from ODP Site 1073 (Hole 1073A)

part, values rarely exceed 15% (Fig. 4). Higher abundances of *G. bulloides* are recorded in both size-fractions from the interval 37.09–65.63 mbsf, with peaks occurring in OIS 3 and 4 (Fig. 4). *Globigerinita glutinata* typically has low abundances (<10%) in both size-fractions throughout the studied interval (Fig. 4). A number of peaks in abundance (up to 63.7%) of *G. uvula* occur

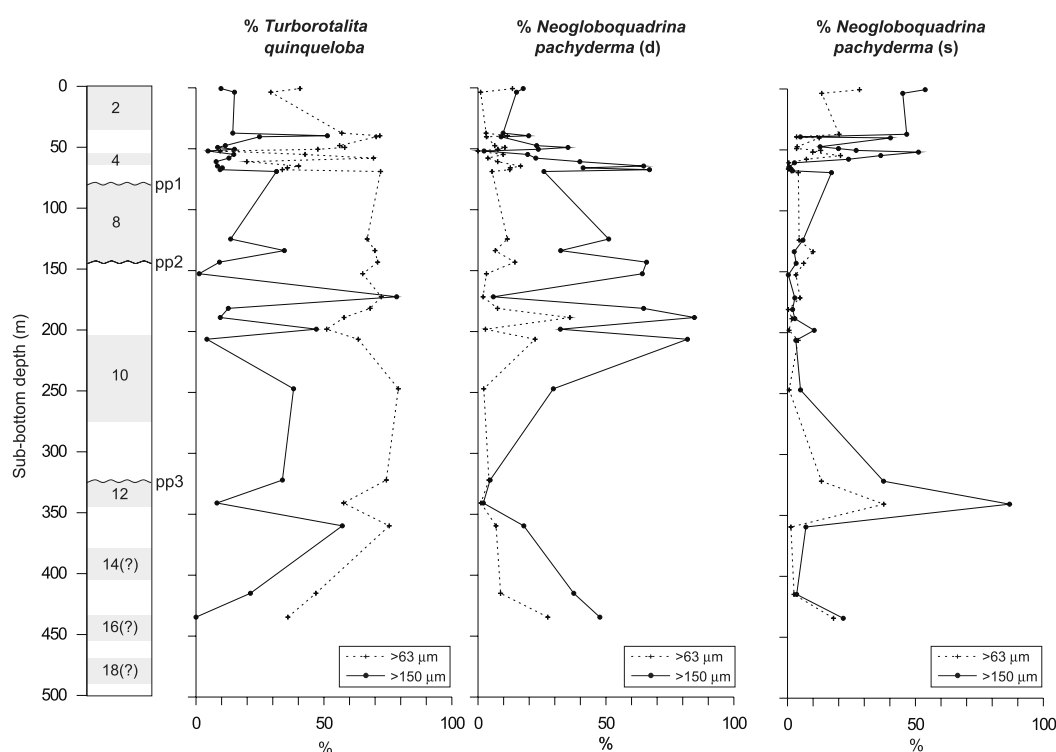


Fig. 3. Relative abundance variations of *Turborotalita quinqueloba*, *Neogloboquadrina pachyderma* (d), and *Neogloboquadrina pachyderma* (s) in the $>63\ \mu\text{m}$ size-fraction (dashed lines) and $>150\ \mu\text{m}$ size-fraction (solid lines) plotted versus sub-bottom depth (m) at Site 1073. Also shown is the stratigraphy with glacial OIS numbered and shaded (McHugh & Olson, 2002), together with the positions of sequence boundaries pp1, pp2 and pp3 (Austin *et al.*, 1998).

in the $>63\ \mu\text{m}$ size-fraction, although this species is rare/absent in the $>150\ \mu\text{m}$ size-fraction (Fig. 4). Peaks are recorded during OIS 2, 3, 4, 5, 9, and 15(?).

Fluctuations in the alpha index are shown in Figure 5. Although the means and ranges of the alpha index are the same in both size-fractions (2.1 and 1.0–3.5 respectively, $>63\ \mu\text{m}$ $n=31$, $>150\ \mu\text{m}$ $n=28$), there is little in the way of correlation between the trends ($r=0.204$, $p=0.297$) and there is no evidence of a difference in the values ($p=0.952$).

The concentration (number per gram of sediment) of planktonic foraminifera is shown in Figure 5. Although data were not calculated for all the studied samples (particularly the $>150\ \mu\text{m}$ size-fraction), there is strong evidence ($p=0.001$) that the number of planktonic foraminifera per gram is higher in the $>63\ \mu\text{m}$ compared with the $>150\ \mu\text{m}$ size-fraction. In the $>63\ \mu\text{m}$ size-fraction, the mean number per gram is 360, with a range of 18–3422 ($n=30$), compared with the $>150\ \mu\text{m}$ size-fraction where the mean is 30 and range is 2–80 ($n=13$). There is a good correlation of peaks in the number of planktonic foraminifera per gram between the two size-fractions ($r=0.775$, $p=0.002$).

The planktonic fragmentation index (PFI) was calculated for the $>150\ \mu\text{m}$ size-fraction and the results are shown in Figure 5. Peaks in the percentage of fragments occur during OIS 2, 9, and 10. The peak in fragments (42.2%) at 152.65 mbsf correlates with the large peak in the total number of planktonic foraminifera ($>63\ \mu\text{m}$) per gram ($3422\ \text{g}^{-1}$). In general, increases in % fragments are associated with decreases in the abundance of *T. quinqueloba* and low % fragments correlate with high

abundances of *T. quinqueloba* ($>63\ \mu\text{m}$: $r=-0.338$, $p=0.063$; $>150\ \mu\text{m}$: $r=-0.362$, $p=0.045$).

DISCUSSION

Since the work of the CLIMAP project (McIntyre *et al.*, 1976; CLIMAP, 1981, 1984), the $>149/150\ \mu\text{m}$ size-fraction has commonly been taken as a standard in studies of planktonic foraminifera. Most workers are in agreement that the use of the coarser size-fraction avoids taxonomic problems encountered with smaller-sized specimens. However, it has been argued (e.g. Schröder *et al.*, 1987) that in order to include the large number of smaller-sized specimens which may be ecologically important, only the $>63\ \mu\text{m}$ size-fraction should be used in the analysis. The use of including smaller planktonic foraminifera ($63\text{--}150\ \mu\text{m}$) in palaeoceanographic studies has clearly been shown by a number of workers including Marquard & Clark (1987) and Bauch (1994). In a recent study of the glacial–interglacial palaeoceanography of the polar North Atlantic, Kandiano & Bauch (2002) clearly demonstrated the advantage of studying planktonic foraminifera in smaller size-fractions ($80\text{--}150\ \mu\text{m}$). Carstens *et al.* (1997) have demonstrated the value of studying smaller living forms ($>63\ \mu\text{m}$) in net tow samples from the Fram Strait, Arctic Ocean. Their study revealed that significant differences exist in the species composition and abundances between the $63\ \mu\text{m}$ mesh and previous studies from the same area which used meshes of $150\ \mu\text{m}$ and $200\ \mu\text{m}$. They calculated that only 10–30% of the assemblage was recovered in studies using the larger (i.e. $>150\ \mu\text{m}$ and $>200\ \mu\text{m}$) mesh sizes compared with the smaller ($>63\ \mu\text{m}$) mesh size.

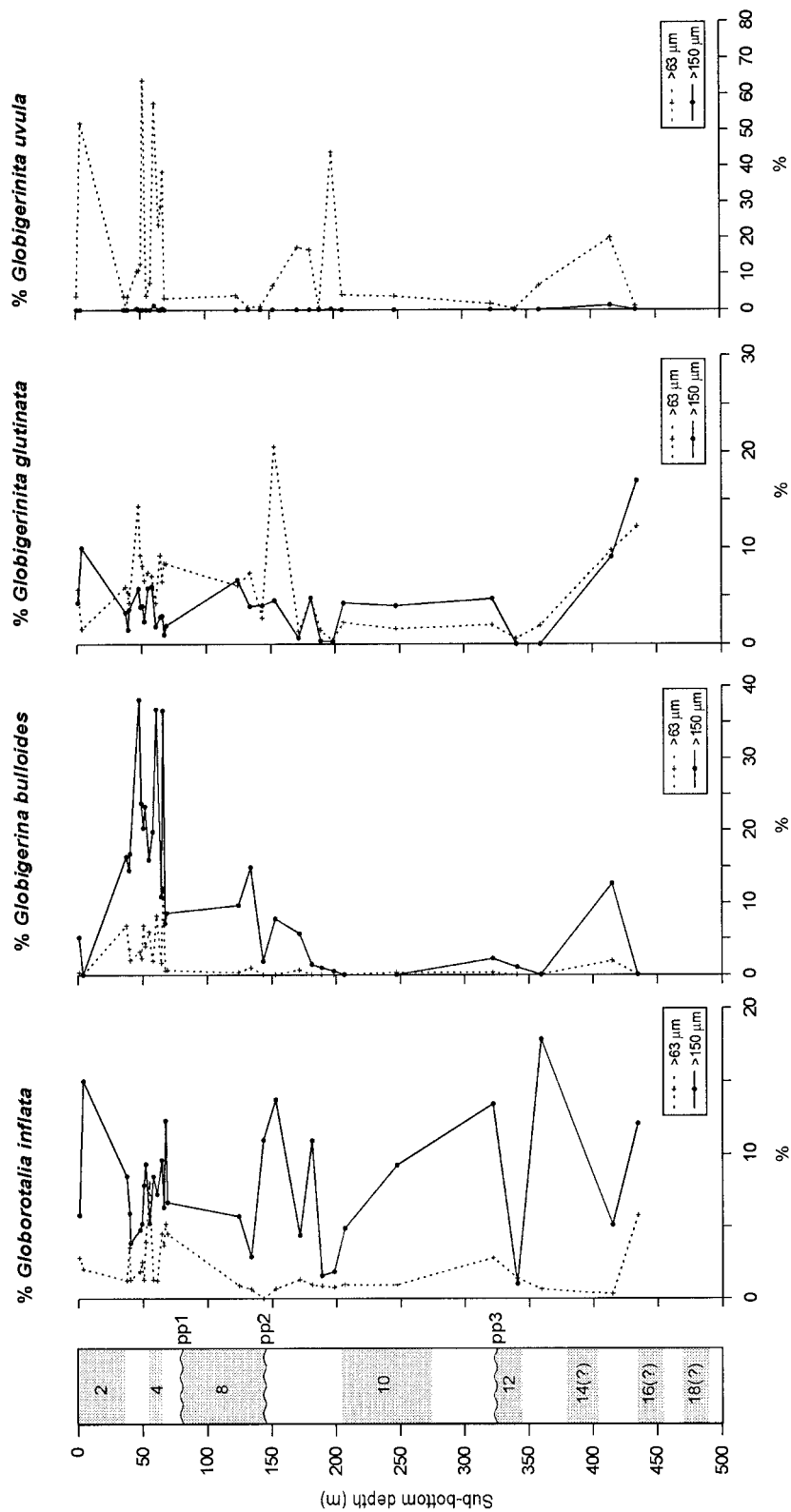


Fig. 4. Relative abundance variations of *Globorotalia inflata*, *Globigerina bulloides*, *Globigerinita glutinata*, and *Globigerinita uvula* in the >63 μm size-fraction (dashed lines) and >150 μm size-fraction (solid lines) plotted versus sub-bottom depth (m) at Site 1073. Also shown is the stratigraphy with glacial OIS numbered and shaded (McHugh & Olson, 2002), together with the positions of sequence boundaries pp1, pp2 and pp3 (Austin *et al.*, 1998).

| | Correlation coefficient between size-fractions (<i>r</i>) | Significance (<i>p</i>) | Wilcoxon Test of paired differences (<i>p</i>) | Number (<i>n</i>) |
|----------------------------------|---|------------------------------|--|------------------------|
| <i>N. pachyderma</i> (s) | 0.889 | 0.000 | 0.000 | 31 |
| <i>G. bulloides</i> | 0.801 | 0.000 | 0.000 | 31 |
| <i>N. pachyderma</i> (d) | 0.705 | 0.000 | 0.000 | 31 |
| <i>G. puncticulata</i> | 0.681 | 0.000 | 0.026 | 31 |
| <i>G. scitula</i> | 0.605 | 0.000 | 0.123 | 31 |
| <i>T. quinqueloba</i> | 0.506 | 0.004 | 0.000 | 31 |
| <i>G. ruber</i> | 0.494 | 0.005 | 0.024 | 31 |
| <i>G. uvula</i> | 0.431 | 0.016 | 0.000 | 31 |
| <i>G. glutinata</i> | 0.385 | 0.032 | 0.009 | 31 |
| <i>O. universa</i> | 0.175 | 0.346 | 0.063 | 31 |
| <i>G. inflata</i> | 0.104 | 0.579 | 0.000 | 31 |
| <i>G. pyramidalis</i> | 0.053 | 0.779 | 0.262 | 31 |
| <i>Globorotalia</i> spp. (other) | −0.002 | 0.990 | 0.374 | 31 |
| <i>G. truncatulinoides</i> | −0.091 | 0.627 | 0.013 | 31 |
| <i>G. sacculifer</i> | −0.107 | 0.566 | 0.314 | 31 |
| <i>G. cyclostomus</i> | −0.145 | 0.436 | 0.004 | 31 |
| <i>N. dutertrei</i> | −0.159 | 0.394 | 0.001 | 31 |
| <i>G. hirsuta</i> | — | — | 0.109 | 31 |
| <i>G. menardii</i> | — | — | 0.317 | 31 |

Globigerina bulloides includes *G. bulloides*, *G. falconensis* and *G. umbilicata*. *Turborotalita quinqueloba* includes *T. quinqueloba*, *G. exumbilicata* and *G. clarkei*.

Table 2. Correlation coefficients and significance of differences (Wilcoxon Test) of relative abundances of planktonic foraminifera between the two size-fractions (>63 μm and >150 μm) at Site 1073

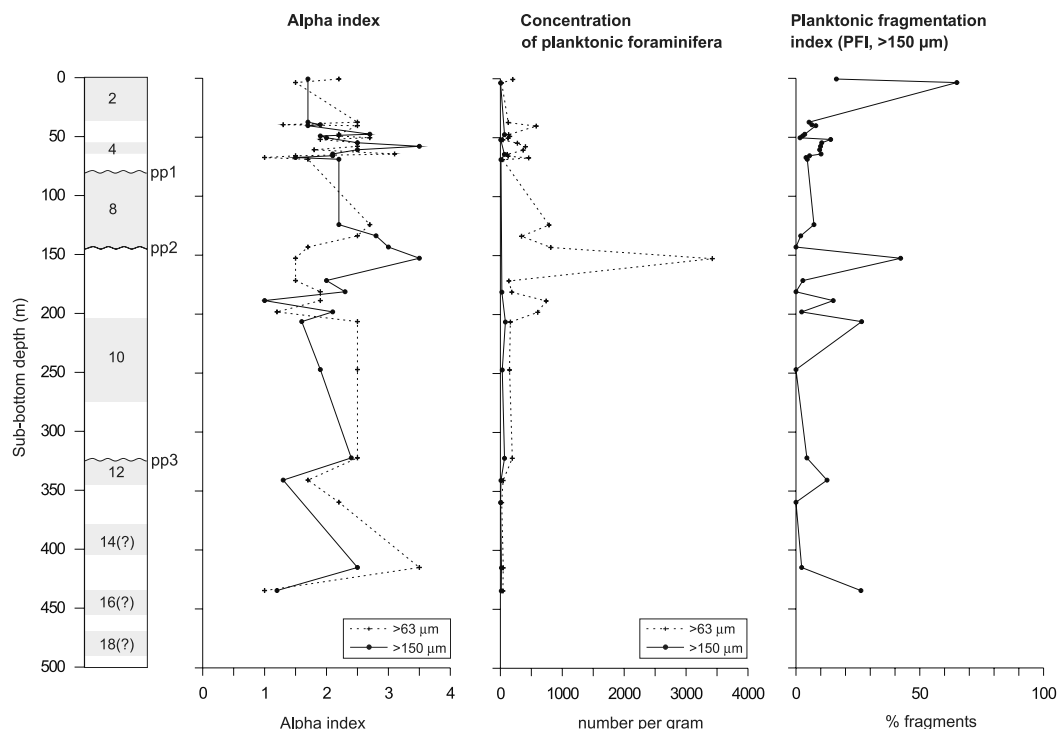


Fig. 5. Variations in the alpha index and concentration (number per gram of sediment) of planktonic foraminifera in the >63 μm size-fraction (dashed lines) and >150 μm size-fraction (solid lines), and planktonic fragmentation index (PFI) of the >150 μm size-fraction, all plotted versus sub-bottom depth (m) at Site 1073. Also shown is the stratigraphy with glacial OIS numbered and shaded (McHugh & Olson, 2002), together with the positions of sequence boundaries pp1, pp2 and pp3 (Austin *et al.*, 1998).

In a recent study of size distributions of planktonic foraminifera from the Arabian Sea, Peeters *et al.* (1999) recommend the use of the >150 μm size-fraction for standard faunal analysis

because most species have reached their adult stage of ontogeny in this size-fraction. However, they also suggest that the >125 μm and >250 μm have to be used as well so that a reliable

estimate of the small and large species respectively can be determined.

In this study, particular species are either under-represented or even absent from the larger size-fraction ($>150\text{ }\mu\text{m}$) whilst they may have high abundances in the smaller size-fraction ($>63\text{ }\mu\text{m}$). In addition, higher proportions of juvenile species occur in the smaller size-fraction. The most significant species which occurs almost entirely in the $>63\text{ }\mu\text{m}$ size-fraction is *G. uvula*. At certain intervals it comprises up to c. 60% of the total planktonic foraminiferal assemblage in the $>63\text{ }\mu\text{m}$ size-fraction. In the $>150\text{ }\mu\text{m}$ size-fraction, it has very low abundances and is commonly absent. *Globigerinita uvula* is a small species which is generally considered to be associated with colder/subpolar waters (e.g. Bé & Tolderlund, 1971; Bé & Hutson, 1977) and, together with *T. quinqueloba*, is relatively more susceptible to dissolution than *N. pachyderma* (s), *G. inflata*, *G. truncatulinoides*, *G. bulloides*, *G. glutinata* and *N. pachyderma* (d) (Malmgren, 1983). Although Niebler & Gersonde (1998) noted low numbers of *G. uvula* in the $>125\text{ }\mu\text{m}$ size-fraction from all areas of the Antarctic Circumpolar Front, southern South Atlantic Ocean, they found a distinct maximum in abundance at c. $7\text{ }^{\circ}\text{C}$ representing the average summer surface water temperature at the Subantarctic Front. Recently, Boltovskoy *et al.* (2000) reported high abundances of the typically 'cold water' forms, *G. bulloides*, *T. quinqueloba* and *G. uvula*, from the southwestern Atlantic occurring in water temperatures as high as $20\text{--}24\text{ }^{\circ}\text{C}$. Boltovskoy *et al.* (2000) suggest that this casts doubt on the use of these species as indicators of cool waters. The causes of the abundance peaks of *G. uvula* at Site 1073 are not clear as there appears to be no consistent correlation with the abundances of other taxa, the oxygen stable isotope record, and dissolution reflected in the PFI.

As might be expected, the mean percentages and percentage ranges of the larger species *N. pachyderma* (sinistral and dextral), *G. bulloides* and *G. inflata* are greater in the $>150\text{ }\mu\text{m}$ size-fraction than in the $>63\text{ }\mu\text{m}$ size-fraction. *Neogloboquadrina pachyderma* is known to be a cool-water species which is resistant to dissolution (Martinez *et al.*, 1998). *Neogloboquadrina pachyderma* (s) is a polar species which peaks in colder water temperatures of between 0° and 9°C (Bé & Tolderlund, 1971). *Neogloboquadrina pachyderma* (d) is a subpolar species which peaks in waters of between 10° and 14°C , but can calcify at temperatures lower than $7\text{--}8^{\circ}\text{C}$ (Bé & Tolderlund, 1971; Reynolds & Thunell, 1985; Wu & Hillaire-Marcel, 1994). At Site 1073, peaks in the abundance of *N. pachyderma* (s and d) are consistent in both the $>63\text{ }\mu\text{m}$ and the $>150\text{ }\mu\text{m}$ size-fractions. Peaks in *N. pachyderma* (s) are associated with $\delta^{18}\text{O}$ increases and reflect cooler/glacial conditions.

Globigerina bulloides is a transitional to polar species and occurs mainly in subpolar areas and upwelling regions (e.g. Thiede, 1975; Hemleben *et al.*, 1989). *Globigerina bulloides* occurs in water temperatures of between 0°C and 23.3°C , although the optimum temperature for this species is $9\text{--}11^{\circ}\text{C}$ (Bé & Tolderlund, 1971). Recently, Schmidt & Mulitza (2002) suggested a temperature range of $3\text{--}19^{\circ}\text{C}$ and optimum of $10\text{--}12^{\circ}\text{C}$ for *G. bulloides* in the North Atlantic. Reynolds & Thunell (1985) suggest that the distribution and abundance of *G. bulloides* may be related to food availability rather than to particular temperature ranges. The peaks in abundance of

G. bulloides at Site 1073 during OIS 3 and 4 possibly indicates that increased upwelling and nutrient levels occurred during both interglacial and glacial stages.

Turborotalita quinqueloba is significantly more abundant in the $>63\text{ }\mu\text{m}$ size-fraction than in the $>150\text{ }\mu\text{m}$ size-fraction. This is not surprising since it is well known to be a small species which commonly dominates in size-fractions of $<150\text{ }\mu\text{m}$ (Kellogg, 1984; Bauch, 1994; Peeters *et al.*, 1999; Kandiano & Bauch, 2002). In a study of size variations in *T. quinqueloba* from the LGM of the Norwegian–Greenland Sea, Bauch (1994) noted the palaeoceanographic significance of *T. quinqueloba* and found that the main abundances occur in the $<149\text{ }\mu\text{m}$ size-fraction. At Site 1073, there is a relationship between PFI values (% fragments) and relative abundances of *T. quinqueloba*; i.e. increases in PFI are associated with decreases in % *T. quinqueloba* and decreases in PFI are associated with increases in % *T. quinqueloba*. It has been suggested by a number of workers (e.g. Thunell, 1975; Le & Shackleton, 1992) that the PFI is a reliable indicator of carbonate dissolution and *T. quinqueloba* is susceptible to dissolution (e.g. Malmgren, 1983). Thus, the abundance of *T. quinqueloba* at Site 1073 can be explained, at least in part, by changes in the amount of carbonate dissolution (reflected in the PFI).

In this study, *G. clarkei* is included in the *T. quinqueloba* group. Although readily distinguished under the SEM, these two species proved difficult to consistently separate under a light microscope and were, therefore, grouped together. For the most part, *G. clarkei* has only been reported rarely in the literature. However, as pointed out by Boltovskoy (1977, 1990, 1991) this is because most foraminiferal workers use coarse size-fractions ($>125\text{ }\mu\text{m}$ and $>150\text{ }\mu\text{m}$) and because of its very small size (maximum diameter, $100\text{--}150\text{ }\mu\text{m}$; height $60\text{--}80\text{ }\mu\text{m}$) it will be missed. Furthermore, Boltovskoy (1991) reported extremely high abundances (mean c. 20%, and up to 50%) of *G. clarkei* from the $>63\text{ }\mu\text{m}$ size-fraction of Quaternary sediments recovered from Atlantic, Indian and Pacific Ocean DSDP Sites. Although abundances of *G. clarkei* are not as high from the Pleistocene of ODP Site 1073 (up to 10%), their presence in the $>63\text{ }\mu\text{m}$ size-fraction only and not the $>150\text{ }\mu\text{m}$ size-fraction is significant.

Boltovskoy (1977) concluded that *G. clarkei* is a eurythermic species found from the subantarctic to equatorial zone and, because of its thick wall, is the most resistant species to dissolution among Recent planktonic foraminifera. In this study, no consistent correlation between abundances of *G. clarkei* and dissolution indices (e.g. PFI) was found. Clearly, further, more detailed work would be required to investigate the causes of abundance and distribution of *G. clarkei* in the world's ocean.

There does not appear to be a consistent relationship between species diversity (reflected by alpha index values) and the relative abundance fluctuations of the planktonic foraminiferal taxa in either size-fraction. However, as might be expected, lowered diversity values correlate with major increases in individual species. A good example of this are the peaks in *G. uvula* which generally correlate with decreases in alpha index values in the $>63\text{ }\mu\text{m}$ size-fraction.

The study of different size-fractions has important implications for establishing planktonic foraminiferal transfer

functions. For example, Niebler & Gersonde (1998) concluded that in the southern South Atlantic Ocean, their analysis of planktonic foraminifera in the >125 µm size-fraction, instead of the >150 µm size-fraction, increased the temperature signal stored in the preserved faunal record. Apart from *N. pachyderma* (s), Niebler & Gersonde (1998) found that their study of the >125 µm size-fraction resulted in species such as *T. quinqueloba*, *G. uvula*, *G. bulloides*, *N. pachyderma* (d) and *G. inflata* contributing considerably to the colder water assemblages deposited in the Polar Front Zone and the Subantarctic Zone of the Antarctic Circumpolar Front. They noted that previous high-latitude investigations restricted to the >150 µm size-fraction have overlooked this relationship. At Site 1073, the smaller species, *T. quinqueloba*, *G. clarkei* and *G. uvula*, are more significant components in the >63 µm size-fraction compared with the >150 µm size-fraction. Thus planktonic foraminiferal studies involving the >63 µm size-fraction could potentially produce different transfer function estimates for sea surface temperatures in a given study area compared with studies that utilize the >150 µm size-fraction and even the >125 µm size-fraction.

CONCLUSIONS

A comparison of the planktonic foraminiferal faunas between the >63 µm and >150 µm size-fractions from the same samples from the Pleistocene of ODP Site 1073 (Leg 174A), New Jersey margin, NW Atlantic Ocean reveal important differences. Although the trends in the relative abundances of many species are similar in the two size-fractions, the general level varies considerably between the two size-fractions.

Higher proportions of juvenile species occur in the smaller size-fraction and the mean percentages and abundance ranges of larger species, e.g. *N. pachyderma* (s), *N. pachyderma* (d), *G. inflata* and *G. bulloides* are higher in the >150 µm size-fraction compared with the >63 µm size-fraction. The smaller species, *T. quinqueloba*, *G. uvula*, *G. glutinata* and *G. clarkei* are more abundant in the >63 µm size-fraction compared with the >150 µm size-fraction.

A comparison of the dominant species abundances between the two size-fractions reveals strong positive correlations of variations in *N. pachyderma* (s) ($r=0.889$, $p=0.000$), *G. bulloides* ($r=0.801$, $p=0.000$) and *N. pachyderma* (d) ($r=0.705$, $p=0.000$), and weaker positive correlations in *T. quinqueloba* ($r=0.506$, $p=0.004$), *G. uvula* ($r=0.431$, $p=0.016$) and *G. glutinata* ($r=0.385$, $p=0.032$). There is little/no correlation in the abundance of *G. inflata* ($r=0.104$, $p=0.579$) between the two size-fractions. Correlation coefficients and significance of differences for other species are less clear because they occur rarely (<5%) at Site 1073.

For the most part, consistent palaeoclimatic/palaeoceanographic interpretations are achieved from the planktonic foraminiferal abundance fluctuations from the two size-fractions. Peaks in abundance of *N. pachyderma* (s) are associated with $\delta^{18}\text{O}$ increases and reflect cooler/glacial conditions. The peaks in abundance of *G. bulloides* during OIS 3 and 4 may reflect increases in upwelling and nutrients. The inverse relationship between the abundance of *Turborotalita quinqueloba* and PFI (% fragments) suggests that variations in carbonate dis-

solution have an important influence on the abundance of this dissolution-susceptible species.

The most significant species which occurs almost exclusively in the >63 µm size-fraction is *G. uvula* (mean abundance 14.5%). At particular intervals, peaks of up to 60% are recorded in its abundance in the >63 µm size-fraction only. In the >150 µm size-fraction *G. uvula* is rare/absent (mean abundance 0.1%). The small species *G. clarkei*, which in this study is grouped in *T. quinqueloba*, occurs in moderate abundance (up to 10%) in the >63 µm size-fraction but is absent from the >150 µm size-fraction. The palaeoenvironmental significance of the observed trends in *G. uvula* and *G. clarkei* is not fully understood and, therefore, further detailed studies from other areas are required.

The results of this study indicate that since particular species are either under-represented or even absent from the >150 µm size-fraction and may have high abundances in the >63 µm size-fraction, it is recommended that the >63 µm size-fraction cannot be ignored in studies of high-latitude planktonic foraminifera. Furthermore, the study of different size-fractions has important implications for establishing planktonic foraminiferal transfer functions. Studies involving smaller (>63 µm) planktonic foraminifera could generate different transfer function estimates for sea surface temperatures in a given study area compared with studies that only use larger (>150 µm and >125 µm) planktonic foraminifera.

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APPENDIX: Faunal reference list

Globigerina bulloides d'Orbigny, 1826
Globigerina exumbilicata Herman, 1974
Globigerina falconensis Blow, 1959
Globigerina umbilicata Orr & Zaitzeff, 1971
Globigerinita clarkei (Rögl & Bolli)=*Globigerina clarkei* Rögl & Bolli, 1973
Globigerinita glutinata (Egger)=*Globigerina glutinata* Egger, 1895
Globigerinita uvula (Ehrenberg)=*Pylodexia uvula* Ehrenberg, 1861
Globigerinoides cyclostomus (Galloway & Wissler)=*Globigerina cyclostoma* Galloway & Wissler, 1927
Globigerinoides pyramidalis (van den Broeck)=*Globigerina bulloides* d'Orbigny var. *rubra* d'Orbigny subvar. *pyramidalis* van den Broeck, 1876

Globigerinoides ruber (d'Orbigny)=*Globigerina rubra* d'Orbigny, 1839
Globigerinoides sacculifer (Brady)=*Globigerina sacculifer* Brady, 1877
Globorotalia hirsuta (d'Orbigny)=*Rotalina hirsuta* d'Orbigny, 1839
Globorotalia inflata (d'Orbigny)=*Globigerina inflata* d'Orbigny, 1839
Globorotalia menardii (Parker, Jones & Brady)=*Rotalia menardii* Parker, Jones & Brady, 1865
Globorotalia puncticulata (Deshayes)=*Globigerina puncticulata* d'Orbigny, 1826 nomen nudum
Globorotalia scitula (Brady)=*Pulvinulina scitula* Brady, 1882
Globorotalia truncatulinoides (d'Orbigny)=*Rotalia truncatulinoides* d'Orbigny, 1839
Neogloboquadrina dutertrei (d'Orbigny)=*Globigerina dutertrei* d'Orbigny, 1839
Neogloboquadrina pachyderma (Ehrenberg)=*Aristospira pachyderma* Ehrenberg, 1861
Orbulina universa d'Orbigny, 1839
Turborotalita quinqueloba (Natland)=*Globigerina quinqueloba* Natland, 1938

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