



## Response of planktonic foraminifera to glacial cycles: Mid-Pleistocene change in the southern South China Sea

Jian Xu\*, Pinxian Wang, Baoqi Huang, Qianyu Li, Zhimin Jian

Laboratory of Marine Geology, Tongji University, Shanghai 200092, China

Received 5 November 2002; received in revised form 15 March 2003

### Abstract

A high-resolution study (~2 ka) of planktonic foraminifers in 997 samples from ODP Site 1143 (9°21.72' N, 113°17.11' E, water depth 2772 m) in the southern South China Sea (SCS) reveals faunal response to glacial cycles in the last 2.1 Ma. Most distinctive is the contrasting variations in the abundance of two tropical–subtropical species that exhibit similar resistance to dissolution in modern oceans. The relative and absolute abundances of *Globorotalia menardii* are high in interglacials and low in glacial and covary with  $\delta^{18}\text{O}$  fluctuations over the studied interval. *Pulleniatina obliquiloculata*, however, follow oxygen isotopes only before the Mid-Pleistocene Revolution (MPR), showing high abundances during glacial and low during interglacials after ~850 ka. Three abundance maxima of *P. obliquiloculata* are observed, corresponding to three major glacial episodes, Marine Isotope Stages (MIS) 2, 12, and 16, respectively. This change in abundance patterns of *P. obliquiloculata* appears to be unique to the southern SCS, as in late Pleistocene records from other western Pacific regions, including the Okinawa Trough and the northern SCS, all show co-varying patterns with  $\delta^{18}\text{O}$  as *G. menardii* does.

Cross-spectral analyses performed between percentages of *Globorotalia menardii* and  $\delta^{18}\text{O}$  records show high coherency at 41 ka obliquity and then at 100 ka eccentricity bands. We suggest that the high abundances of *G. menardii* during interglacials in the past 2.1 Ma reflect warmer temperatures. Percentages of *Pulleniatina obliquiloculata* vs. oxygen isotope records show quite large phase difference at 41 ka obliquity band before the MPR. As a contrast, there are negligible phase differences in the vicinity of 100 and 41 ka after the MPR, which means reverse trend between percentages of *P. obliquiloculata* and  $\delta^{18}\text{O}$  fluctuations. The differences of *P. obliquiloculata* from *G. menardii* in abundance and orbital forcings are interpreted as resulting from a profound change in the regional upper ocean structure during the MPR time, probably relating to a final glacial cut-off of the southern SCS from the Indian water at ~850 ka and to higher salinity during glacial times after 850 ka. We speculate that this change is related to the decreased connection between the Pacific and Indian Ocean.

© 2004 Elsevier B.V. All rights reserved.

**Keywords:** Quaternary; planktonic foraminifers; ODP Site 1143; orbital forcing; Mid-Pleistocene Revolution; South China Sea

\* Corresponding author. Fax: +86 21 65988808.

E-mail address: [kenne\\_hsu@263.net](mailto:kenne_hsu@263.net) (J. Xu).

## 1. Introduction

The distribution patterns of planktonic foraminifer were closely associated with the environmental conditions they inhabited (Bé, 1977). While several species datum levels remain biostratigraphically significant, abundance variations of many species continue to serve as proxies of temperature, productivity, thermocline and other paleoceanographic issues in a paleoclimatic and stratigraphic framework (e.g. Le et al., 1995; Chen and Farrell, 1991; Jian et al., 2000c; Li et al., 1997; Ujiie and Ujiie, 1999). Most of the species usually show consistent relationships relative to glacial/interglacial cycles, as expressed by  $\delta^{18}\text{O}$  curve, throughout the time series, though the variations of different species are not identical to each other. For example, Late Quaternary *Globorigerinoides ruber*, *Globorotalia menardii* and *Globorinoides sacculifer* show positive and *Globigerina bulloides* negative correlation with the oxygen isotopic records in the eastern equatorial Pacific Ocean (Le et al., 1995).

Despite of the patterns above, there are also the documents that downcore variations in abundances of species do not seem to have a simple relationship with glacial/interglacial cycles (e.g. Cullen and Drozler, 1990; Le et al., 1995). In our work, we found *Pulleniatina obliquiloculata* shows completely reverse relationship to glacial/interglacial cycles taking the MPR as the transition in our work.

In this paper, we will discuss the downcore variations of *Pulleniatina obliquiloculata* and *Globorotalia menardii* at ODP Site 1143 to trace the unsteady relationships between glacial/interglacial cycles and the fluctuations of the abundance of these planktonic foraminifera species, and further to discuss the possible reasons.

## 2. Material and methods

ODP Site 1143 is within a basin on the southern continental margin of the SCS and located at

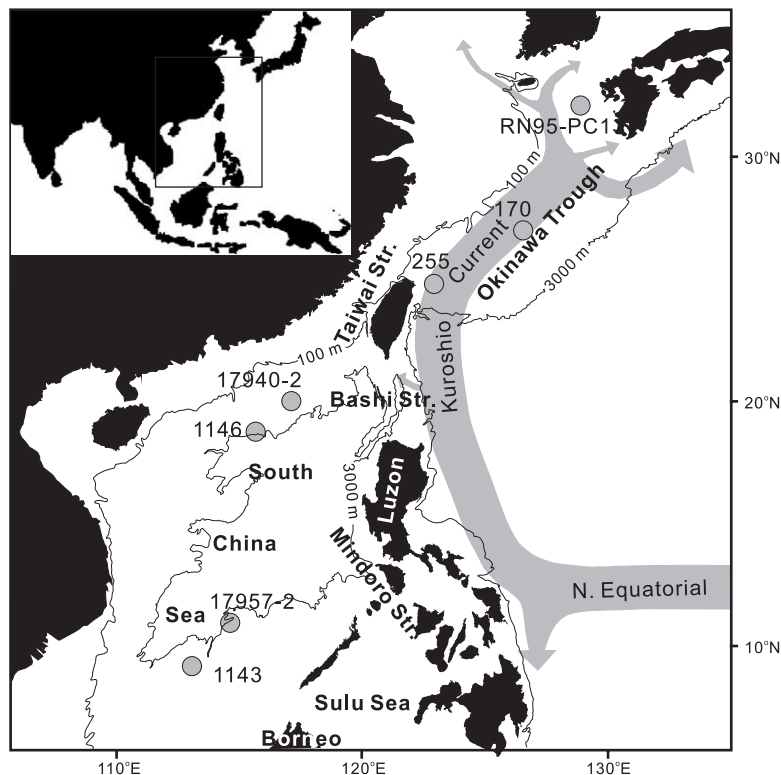


Fig. 1. Location map showing core sites and major oceanographic features.

9°21.72' N, 113°17.11' E, at a water depth of 2772 m (Wang et al., 2000) (Fig. 1, Table 1). The water depth of this site is situated between the modern lysocline (2500–3000 m) and the calcite compensation depth (CCD) [3000–3500 m (Tu, 1984) or 3800 m (Miao et al., 1994)]. The upper section at this site was triple cored, and the cores were combined to represent a complete section on a continuous composite depth scale, or meters composite depth (mcd, abbreviated 'm' in this paper) by splicing high resolution records (2 cm spacing) of magnetic susceptibility and other physical properties between 0 and 190.77 mcd from the advanced piston coring interval (Wang et al., 2000). The material used in the present study covers the upper 99.4 m, representing a continuous record over the last 2.1 Ma (Wang et al., 2001; Tian et al., 2002).

The core was sampled at 10-cm intervals corresponding to a time resolution of approximately 2 ka. A total of 997 samples were examined. All samples were dried in an oven under 60 °C, disaggregated by soaking in tap water, and wet sieved over a 63- $\mu$ m screen, and then dried again in an oven under the same temperature. Planktonic foraminifers were picked, identified and counted only from the size fraction >154  $\mu$ m. When planktonic foraminifers were abundant, the sample was split into an aliquot containing 250 or more specimens. A consistent measure was taken in calculating species abundances, resulting in the omission of 79 samples due to insufficient number of specimens (<100). In addition, the number of fragments also was counted for the calculation of fragmentation index with the method of Le and Shackleton (1992). Our taxonomy follows that of Bé (1977) and Saito et al. (1981). The age model is based on an astronomically tuned benthic  $\delta^{18}\text{O}$  record together with nannofossil and planktonic foraminifer biostratigraphy (Tian et al., 2002), and it is advantageous that both the isotopic and faunal

analyses were based upon the same set of planktonic foraminifers of samples.

A Macintosh program of Crospec in ARAND package developed by Howell (2001) was executed in order to unambiguously demonstrate relationships of percentages of *Globorotalia menardii* and *Pulleniatina obliquiloculata* to oxygen isotopic records in two time slices: 0–850 and 850–2102 ka.

All data discussed in this paper are available upon request from the first author (kenne\_hsu@263.net) or via internet at <http://www.elsevier.com/locate/marmicro>.

### 3. Oceanographic settings

The South China Sea is the largest semi-enclosed marginal sea of the West Pacific Ocean, with several pathways to the surrounding oceans and seas. In the northeastern part, the SCS has a fairly broad connection to the western Pacific via the Bashi Strait (with a sill depth of 2600 m) between Luzon and Taiwan, and also exchanges waters with the East China Sea (ECS) though the shallow Taiwan Strait between Taiwan and the Chinese mainland (Fig. 1). The southern Sunda Shelf is open to the Java Sea to the south and is connected to the northern Indian Ocean through the elongate, NW–SE stretching Strait of Malacca. To the Sulu Sea, the only deep channel is the narrow, 420-m-deep Mindoro Strait at the southern tip of Luzon.

The water circulation in the SCS is strongly controlled by the semiannual reverse of East Asian monsoonal winds (Shaw and Chao, 1994; Huang et al., 1994). In winter, the northeast monsoon driven water circulation is counterclockwise (Fig. 2a). Warm water derived from the western Pacific through the Bashi Strait and some cold water from the ECS via the

Table 1  
Information on the cores used in this paper

Core	Latitude (N)	Longitude (E)	Water depth (m)	Core length analyzed (m)	References
1143	9°21.72'	113°17.11'	2 772	99.4	This paper
1146	19°27.4'	116°16.37'	2 092	197.8	Huang, 2002; Clemens and Prell, 2003
17957-2	10°53.9'	115°18.3'	2 195	13.84	Jian et al., 2000a
17940	20°07.0'	117°23.0'	1 727	13.30	Pflaumann and Jian, 1999
255	25°12'	123°06'	1 575	6.55	Li et al., 1997
170	26°38'	125°48'	1 470	3.60	Li et al., 1997
RN95-PC1	32°04.8'	128°59.7'	676	4.70	Ujiié and Ujiié, 1999

Taiwan Strait flow westward along the continental slope south of China. Water leaves into the Java Sea at the southern tip of the SCS. The inflow water through the Bashi Strait is practically the only salinity source for surface waters in the basin (Shaw and Chao, 1994). During the southwest monsoon prevailing in summer, water enters from the Java Sea and a northeastward current is established along the coast

of Vietnam. In the southern SCS, the currents trend north and northeast approximately parallel to the coast of Borneo and the Philippines. This less saline SCS water then flows through the Bashi Strait into the Pacific (Fig. 2b).

The East Asian monsoons also control the upper water structure such as the thermocline depth. In winter, the mixed layer is greatly thickened and

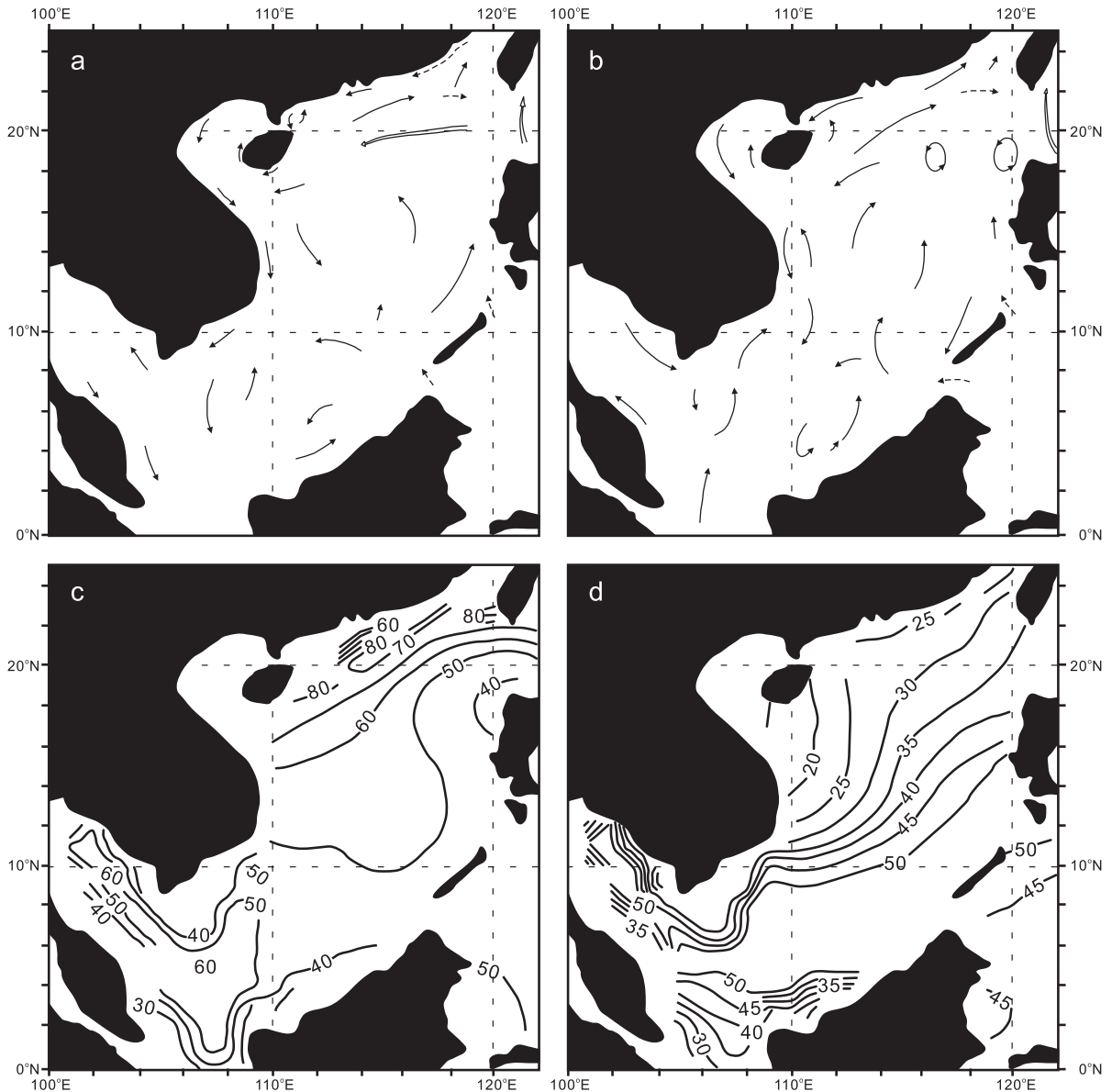


Fig. 2. Surface current patterns (a, b) and thermocline depths in meters (c, d) of the South China Sea. (a, c) Winter; (b, d) summer (modified from Huang et al., 1994; Shi et al., 2001).

increases the thermocline depth as much as to 80 m in the northern SCS, decreasing to the South (Fig. 2c); in summer, the maximal thermocline depth moves to the South due to the Southwest summer monsoon (Fig. 2d) (Shi et al., 2001).

#### 4. Results

A total of 27 species of planktonic foraminifers were identified and counted. The present study focuses on two species: *Globorotalia menardii* and *Pulleniatina obliquiloculata*, both being warm-water dissolution-resistant forms (Bé, 1977).

##### 4.1. Downcore variations

Downcore variations in the absolute and relative abundances of *Pulleniatina obliquiloculata* and *Globorotalia menardii* are shown in Figs. 3 and 4, together with the benthic  $\delta^{18}\text{O}$  record for comparison. In order to filter out the noise and details, a 6-point running average was run on the original data.

These results show *Globorotalia menardii* abundance covary with  $\delta^{18}\text{O}$  over the entire studied section (Figs. 3 and 4). The abundance of *G. menardii* increases in interglacials and decreases in glacials, with a maximal abundance of 62.7% from near the core top (MIS 1). High percentages of *G. menardii* (>20%) at interglacial stages are: MIS 5 (37.5%), MIS 7 (24.8%), MIS 9 (21.2%), and MIS 11 (30.6%) (Fig. 4). Its maximal abundance during interglacial stages is also observed in the Pacific Ocean (Le et al., 1995; Mckenna et al., 1995).

The distribution pattern of *Pulleniatina obliquiloculata* is more complicated. Its absolute abundance fluctuation is reverse to that of benthic foraminiferal isotope in the upper 45 m (Fig. 3). In the section below 45 m, however, there is covariation between the absolute abundance of *P. obliquiloculata* and  $\delta^{18}\text{O}$ . Similar appearance is better expressed in Fig. 4, where an age of 850 ka equals to 45 m level. Reverse trends between the fluctuations of  $\delta^{18}\text{O}$  and %*P. obliquiloculata* is observed in the past ~850 ky. High abundances of *P. obliquiloculata* are seen in peaking at MIS 2 (44.3%), MIS 12 (55.7%), and MIS 16 (52.6%). Before ~850 ka, the percentages of *P. obliquiloculata* are lower (7.7% in average, compare

to 18.4% after 850 ka), and covary with  $\delta^{18}\text{O}$ , with higher values during interglacials and lower during glacials (Fig. 4). The turning point from covariations to reverse oscillations between *P. obliquiloculata* and  $\delta^{18}\text{O}$  occurred at MIS 21, shortly after the Middle Pleistocene Revolution (MPR, ~0.9 Ma; Pisias and Moore, 1981; Maasch, 1988), which is marked by a minimal abundance of *P. obliquiloculata* (Fig. 4).

##### 4.2. Cross-spectral analysis

Fig. 5 presents the results of cross-spectral analyses between percentages of *Globorotalia menardii* and *Pulleniatina obliquiloculata* and oxygen isotope records. Percentage of *G. menardii* is highly coherent with oxygen isotopic records in eccentricity, obliquity and precession of orbital cyclicities in 0–850 ka, with coherencies of 0.90, 0.79 and 0.75, respectively (Table 2). In addition, *G. menardii* display undoubtedly highest peak at eccentricity band. Result of cross phase analysis demonstrates *G. menardii* has quite large phase differences (near by  $\pm 180^\circ$ ) from oxygen isotopic records over the entire spectrum in the past 850 ky (Table 2; Fig. 5a). In 850–2102 ka, there are highest coherency and also quite large phase difference between frequencies of *G. menardii* and  $\delta^{18}\text{O}$  at 41 ka obliquity band (Table 2; Fig. 5b). Taking the reversed order of oxygen isotopic values in generally used  $\delta^{18}\text{O}$ -drawings into account, large phase differences close to  $\pm 180^\circ$  between original %*G. menardii* and  $\delta^{18}\text{O}$  data should indicate they are coherent with each other in curves.

In contrast to *Globorotalia menardii*, *Pulleniatina obliquiloculata* displays very small phase differences from oxygen isotopic records over the entire spectrum, though there are high values of coherencies at 100, 41 and 23 ka bands in the past 850 ky (Table 2; Fig. 5c). Similarly, the small phase differences close to zero should imply reverse profile of %*P. obliquiloculata* to that of  $\delta^{18}\text{O}$ . Before 850 ka, *P. obliquiloculata* has high coherencies to oxygen isotopic records in the vicinity of orbital cyclicities of 41 ka (0.85) and 23 ka (0.67), and further quite large phase difference at these two bands (Table 2; Fig. 5d). Moreover, *P. obliquiloculata* itself also displays a complex configuration of frequencies: ~200 and 43 ka cyclicities dominating the past 850 ky (Fig. 5c) and overwhelming ~400 ka cyclicity before 850 ka (Fig. 5d).

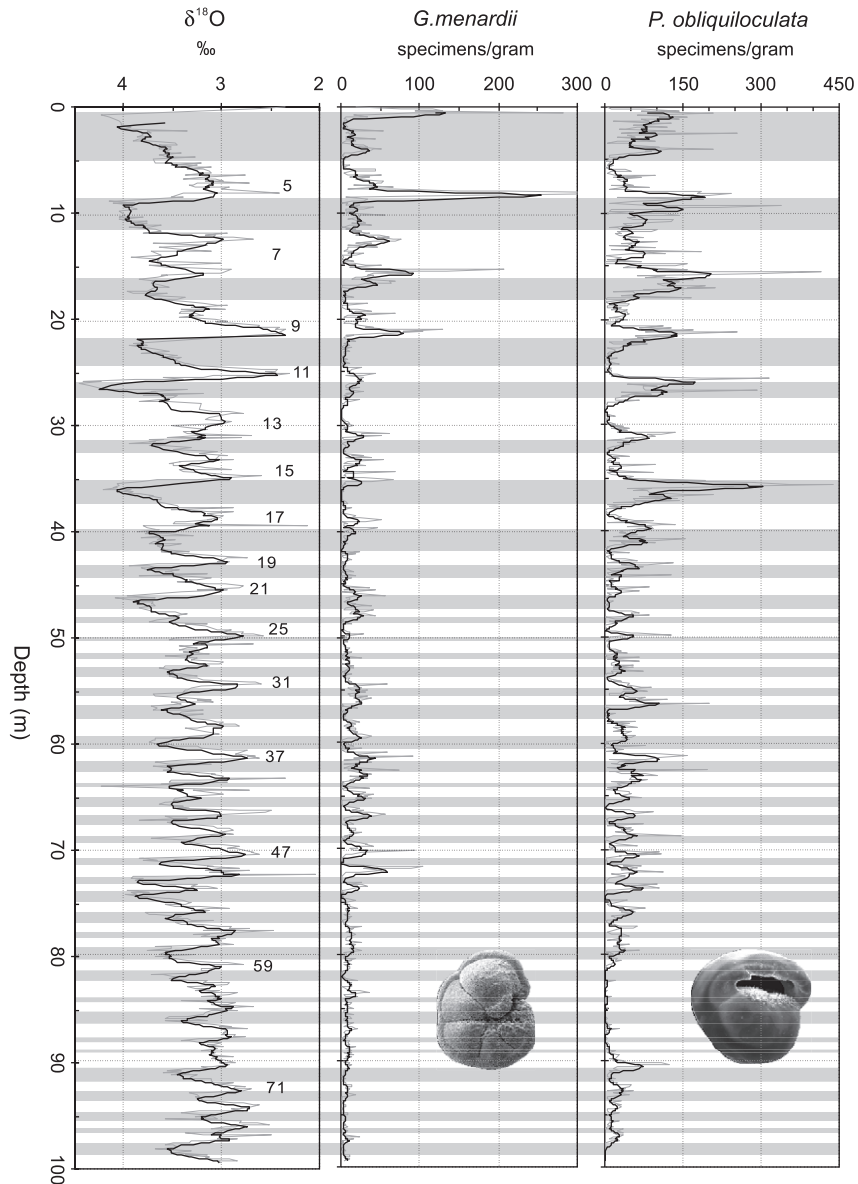


Fig. 3. Downcore records of the benthic foraminifer  $\delta^{18}\text{O}$  (‰ PDB, from Tian et al., 2002), and the absolute abundances of *Globorotalia menardii* and *Pulleniatina obliquiloculata* in the Quaternary section of Site 1143. Bold curves indicate the 6-point running average. Gray bars mark glacial intervals, and numbers are marine oxygen isotope stages (MIS).

Therefore, these results suggest there is a high coherence between profiles of %*Globorotalia menardii* and benthic  $\delta^{18}\text{O}$  over the entire interval. At the Site 1143, the MPR not only marks the 41 ka to 100 ka transition in orbital forcing but also separates the two stages between which the responses of *Pulleniatina obliquiloculata* to glacial cycles were different.

### 5. South China Sea comparisons

A similar reverse fluctuations between %*Pulleniatina obliquiloculata* and benthic  $\delta^{18}\text{O}$  after the MPR has been observed also at other localities in SCS, such as SONNE Core 17957-2 ( $10^{\circ}53.9' \text{ N}$ ,  $115^{\circ}18.3' \text{ E}$ , water depth: 2 195 m; Jian et al., 2000a) (Fig. 6), and



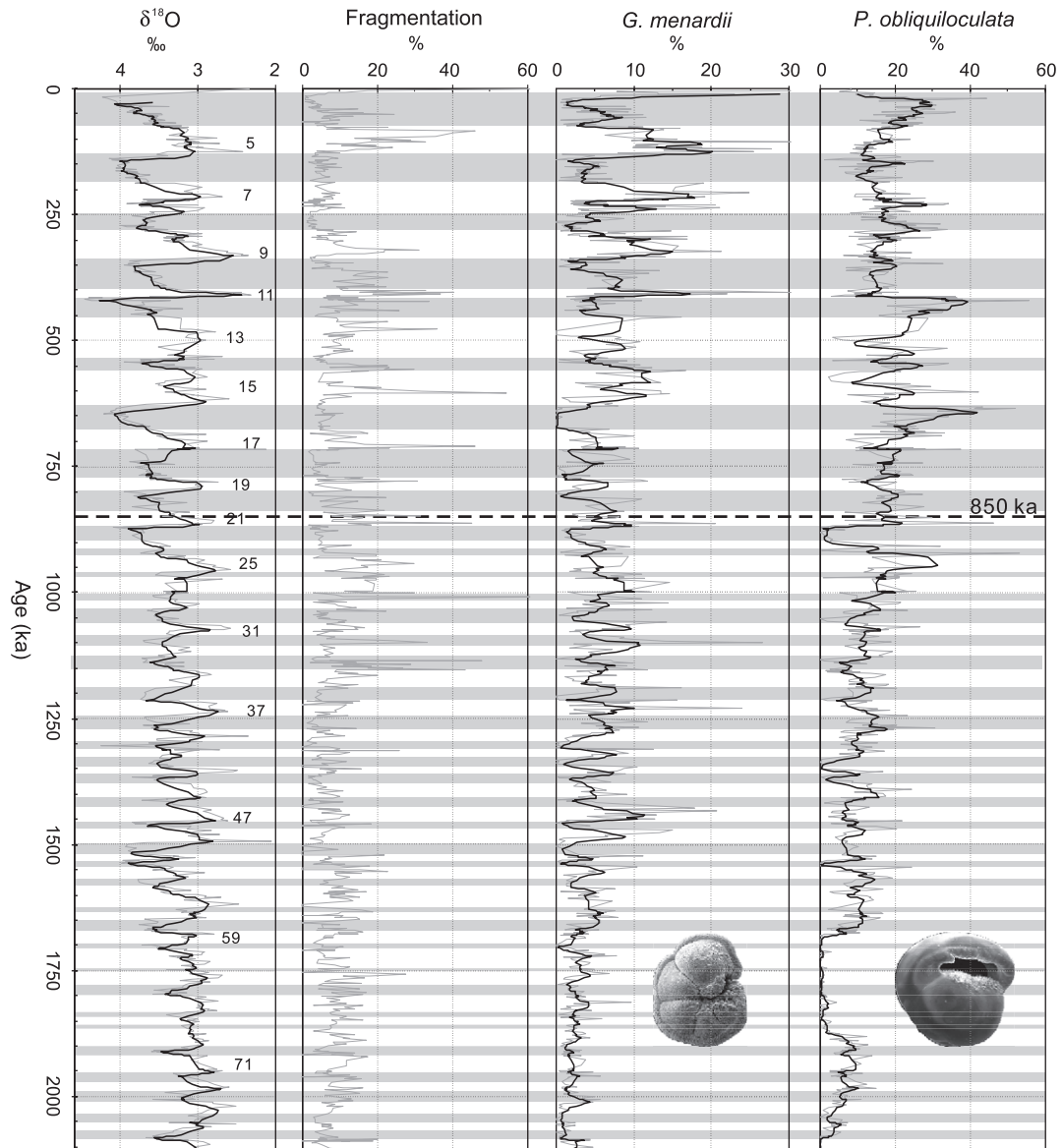


Fig. 4. The last 2 Ma records of the benthic  $\delta^{18}\text{O}$ , %fragmentation, %*Pulleniatina obliquiloculata* and %*Globorotalia menardii*. Bold curves indicate the 6-point running average. Horizontal dashed line displays the age of 850 ka. Gray bars mark glacial intervals, and numbers are marine oxygen isotope stages (MIS).

Core 17962 (7°11' N, 112°5' E, water depth: 1968 m; Fang, 1997). At all these southern SCS sites, *P. obliquiloculata* increases its abundance during glacial periods starting from the MPR, in opposition to the relationship between %*Globorotalia menardii* and  $\delta^{18}\text{O}$ . This appears to be a phenomenon unique to the southern SCS because similar patterns from

neighboring regions in the western Pacific are absent. In contrast, in the northern SCS, %*P. obliquiloculata* always shows coherence with  $\delta^{18}\text{O}$  fluctuation, such as at SONNE Core 17940 (20°07.0' N, 117°23.0' E, water depth: 1727 m; Pflaumann and Jian, 1999) and ODP Site 1146 (19°27.4' N, 116°16.37' E, water depth: 2092 m; Huang, 2002) (Fig. 6). To the further

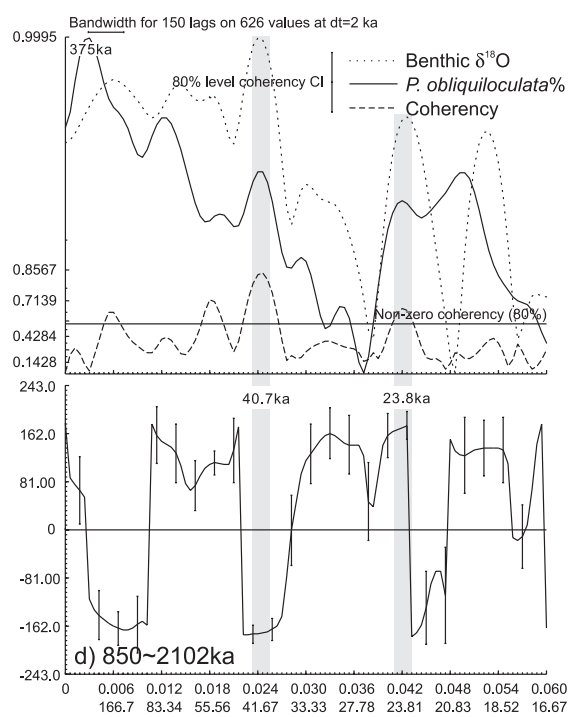
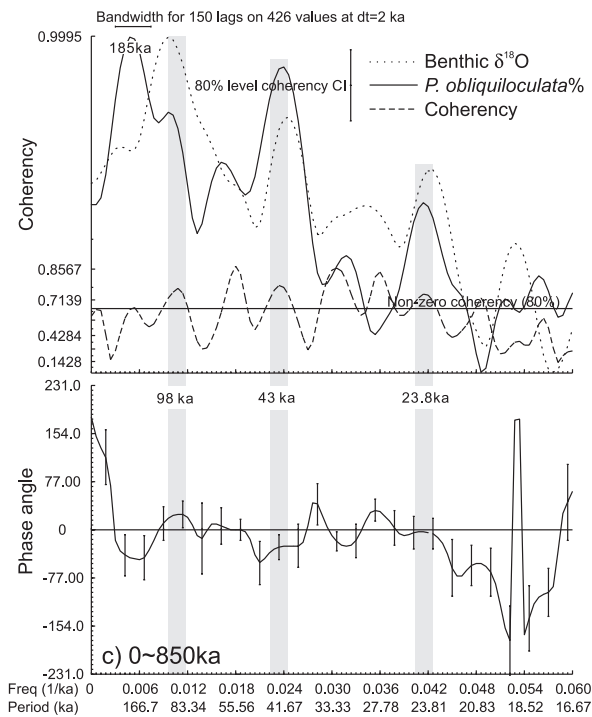
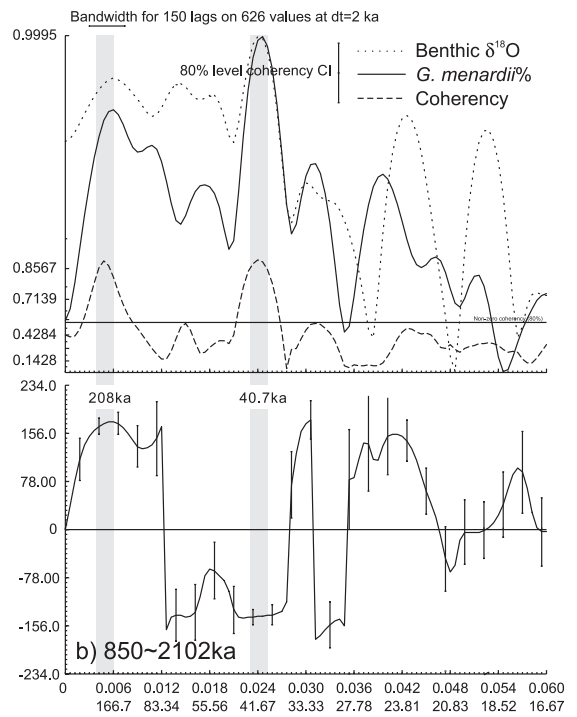
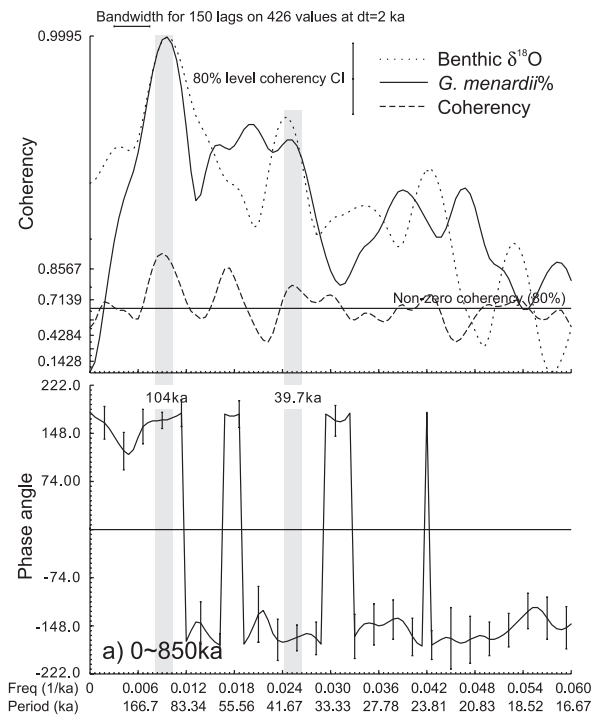




Table 2

Cross-spectral coherencies and phase relationships of %*Globorotalia menardii* and %*Pulleniatina obliquiloculata* vs. benthic  $\delta^{18}\text{O}$  (‰) in the vicinity of 100 ka eccentricity, 41 ka obliquity and 23 ka precession cyclicities at ODP Site 1143

	0–850 ka						850–2102 ka			
	Eccentricity		Obliquity		Precession (23 ka)		Obliquity		Precession (23 ka)	
	C	PS	C	PS	C	PS	C	PS	C	PS
G	0.90	168.1±12.7	0.79	-169.3±19.7	0.75	179.9±22.6	0.88	-140.3±11.9	#	#
P	0.78	22.8±21.6	0.79	-27.7±19.7	0.75	-3.9±22.6	0.85	-173.0±13.6	0.67	172.0±23.2

G—%*Globorotalia menardii*; P—%*Pulleniatina obliquiloculata*; C—coherency; PS—phase; “#”—coherency smaller than 0.66.

Test statistic for non-zero coherency at 80% level equals to 0.66 for 0–850 ka and 0.55 for 850–2102 ka.

north in the Okinawa Trough, co-variation of %*P. obliquiloculata* with  $\delta^{18}\text{O}$ , similar to the northern SCS record, has been reported at RN95-PC1 (Ujiié and Ujiié, 1999) and Cores 170 and 255 (Li et al., 1997). Therefore, this unique southern SCS phenomenon raises several questions: Why only in the southern SCS did *P. obliquiloculata* respond to the mid-Pleistocene event differently? What was the main mechanism causing this change? Was this change an ecologic modification of the species' adaptive strategy, or is it an evidence of upper water reconfiguration at the MPR, or both?

## 6. Discussions

### 6.1. Modern distribution of *Pulleniatina obliquiloculata* and *Globorotalia menardii*

The highest abundance of *Pulleniatina obliquiloculata* in the global ocean surface sediments is restricted to a relatively narrow belt between  $\sim 10^\circ\text{N}$  and  $10^\circ\text{S}$ , broadly coinciding with the equatorial current systems in the Atlantic, Indian and Pacific oceans. This species displays higher percentages in the Pacific than in the Atlantic or Indian Oceans (Bé, 1977), and its high percentages are also related to carbonate dissolution (Bé, 1977; Thompson, 1981; Cullen and Prell, 1984; Fang, 1997; Jian et al., 1999). Seasonally, its peak abundance occurs in November

off Bermuda (Bé, 1977), and also in winter in the northern (Zheng in Li et al., 1997) and central SCS (Chen et al., 2000) according to sediment trap data.

Also inhabiting the tropical–subtropical upper water is *Globorotalia menardii*, which is, however, much less abundant in the Pacific (Bé, 1977). It occurs abundantly between  $20^\circ\text{N}$  and  $10^\circ\text{S}$  in the Atlantic Ocean, north of the equator in the Indian Ocean, and in isolated areas of the eastern tropical Pacific Ocean (Bé, 1977; Cullen and Prell, 1984). In the Pacific, maximum abundance of *G. menardii* often occurs in places where SSTs are between 26 and  $28^\circ\text{C}$  (Le et al., 1995).

Both *Pulleniatina obliquiloculata* and *Globorotalia menardii* grow in greatest abundance along the seasonal thermocline in association with maximum chlorophyll concentration, indicating that they proliferate when the seasonal thermocline is in the photic zone (Ravelo and Fairbanks, 1990; Ravelo et al., 1992). Therefore, these two species can be categorized as subsurface species, and their abundance can be used as proxies indicating shallow thermocline (Ravelo and Fairbanks, 1990; Jian et al., 2000a, 2001; Huang, 2002).

The different distribution patterns of *Pulleniatina obliquiloculata* and *Globorotalia menardii* in the modern ocean indicate that the physiochemical requirements of these two warm-water dwellers are different (Cullen and Prell, 1984). Both preying on phytoplankton (chrysophytes and diatoms), *G. menar-*

Fig. 5. Cross spectral and phase analyses of %*Globorotalia menardii* (a and b) and %*Pulleniatina obliquiloculata* (c and d) vs.  $\delta^{18}\text{O}$  (‰) in two time slices of 0–850 and 850–2102 ka at ODP Site 1143. Spectral densities are plotted on normalized log scales. Dotted lines denote benthic  $\delta^{18}\text{O}$  (‰). Solid lines show %*G. menardii* or %*P. obliquiloculata*. The coherence spectrums (dashed lines) are plotted on a hyperbolic arctangent scale. The solid horizontal line on the upper graph of a couple indicates test statistic for non-zero coherency at the 80% level. Vertical gray bars mark frequencies in the vicinity of 100 ka eccentricity, 41 ka obliquity and 23 ka precession cyclicities. Solid curve with a bunch of vertical error bars on the bottom graph of a couple indicates phase angle.

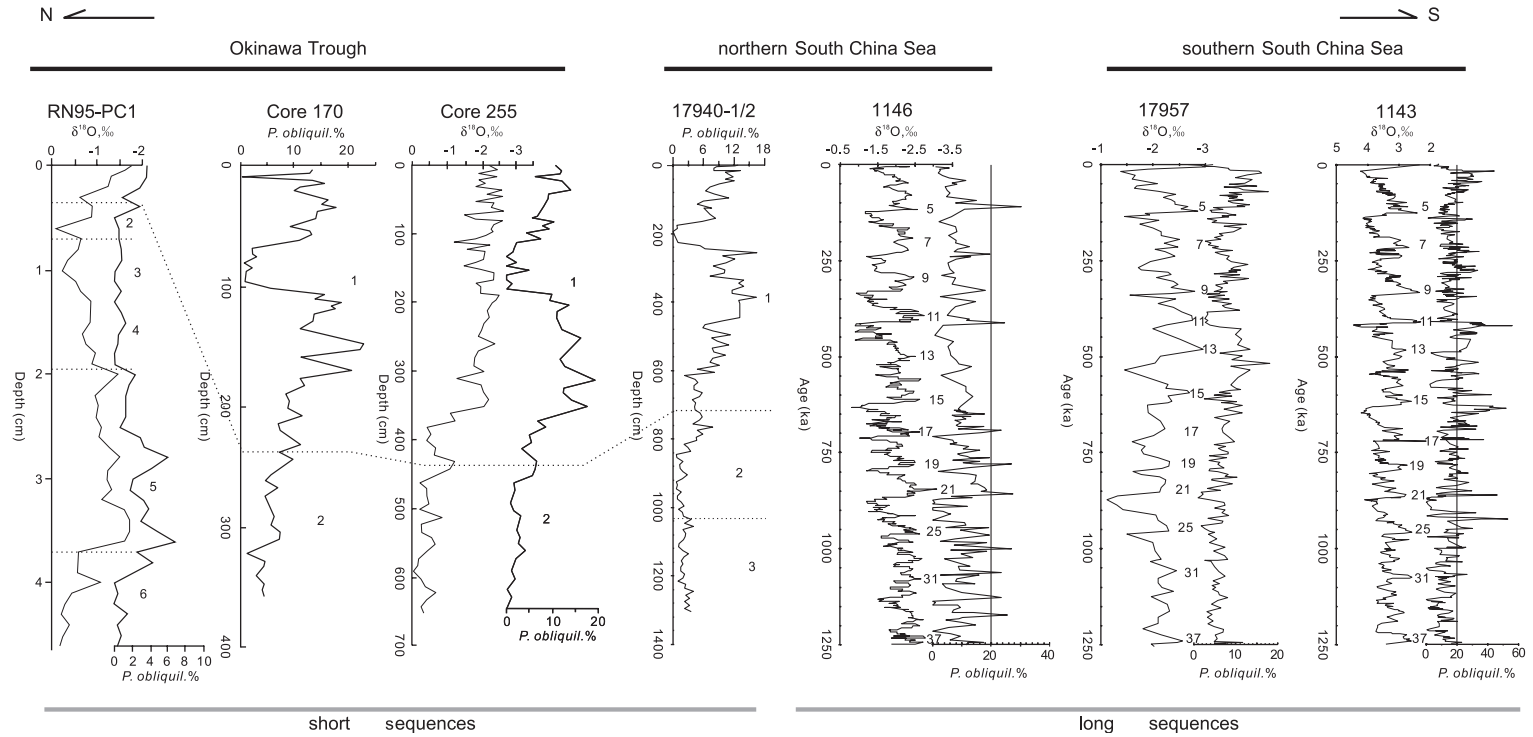


Fig. 6. Variations of  $\%Pulleniatina obliquiloculata$  in cores from the Okinawa Trough and the South China Sea compared to  $\delta^{18}\text{O}$ . RN95-PC1 from Ujiie and Ujiie (1999); Cores 170 and 255 from Li et al. (1997); 17940-1/2 from Pflaumann and Jian (1999); ODP 1146 from Huang (2002) and Clemens and Prell (2003); 17957 from Jian et al. (2000a); and ODP 1143 from this paper.

*dii* seems to be omnivorous, but *P. obliquiloculata* could be mainly herbivorous if its pre-adult stage is indeed a herbivorous *Neogloboquadrina* (Hemleben et al., 1989). *Globorotalia menardii* appears to be a stenohaline species while the euryhaline *P. obliquiloculata* could sustain a wider range of salinity and temperature. In the equatorial Atlantic, high abundance of *P. obliquiloculata* is closely associated with high-salinity undercurrent (25 °C and 35.9–36.1‰S), indicating the importance of salinity in controlling its distribution (Jones, 1967). Similarly, in the western Pacific, the close tie of *P. obliquiloculata* to the Kuroshio makes it a reliable marker of this high salinity current (Wang et al., 1985; Li et al., 1997; Ujiie and Ujiie, 1999; Jian et al., 2000b).

In the northern SCS, the inflow of western Pacific water is indicated by a distinct northeasterly tongue of salinity >33.5‰ in winter, producing a steep gradient in the Bashi Strait (Pflaumann and Jian, 1999), and is practically the only salt source for surface waters in the basin (Shaw and Chao, 1994). This saline water, when moving southward, is gradually diluted by the input of fresh water from rivers and precipitations. The distribution of *P. obliquiloculata* in the SCS surface sediments displays well this scenario. In the northern SCS, the planktonic foraminifer assemblage is similar to the western tropical Pacific in having abundant *P. obliquiloculata*. Its >20% abundance contour produces a ‘tongue’ in the northeastern SCS representing the intrusion of the saline western tropical Pacific water as a branch the Kuroshio Current (Xu et al., 2001). The abundance of *P. obliquiloculata* decreases southwestward and southward off the Bashi Strait to 10% or less in most parts of the southern SCS (Pflaumann and Jian, 1999; Xu et al., 2001) (Fig. 7c). Clearly, the lower abundance of *P. obliquiloculata* in the southern SCS results from a weaker influence of the western tropical Pacific water (Fig. 7b).

### 6.2. Occurrence patterns in the Atlantic and Caribbean during the late Quaternary

In the equatorial Atlantic and Caribbean, *Globorotalia menardii* is abundant in late Quaternary interglacials but is rare or even absent in glacials. The relative abundance of *Pulleniatina obliquiloculata* shows a similar pattern but it often has wider

distribution by appearing earlier and disappearing later than *G. menardii*, indicating a wider salinity tolerance in *P. obliquiloculata* (Fig. 8a). Since the disappearance of *P. obliquiloculata* is time transgressive from approximately 60 ka in the Gulf of Mexico, to 50 ka in the western Caribbean and to 35 ka in the equatorial Atlantic, Prell and Damuth (1978) attributed its cause to progressive increases in salinity in the surface water, that resulting in a reduction of the distribution zone of *P. obliquiloculata*.

Flower and Kennett (1990) also found that both *Pulleniatina obliquiloculata* and *Globorotalia menardii* were absent from glacial intervals in cores EN32-PC4 and EN32-PC6 in Gulf of Mexico. However, *P. obliquiloculata* reappeared and increased earlier than *G. menardii*, indicating that *P. obliquiloculata* had a wider adaptive zone.

### 6.3. Late Quaternary occurrences in western Pacific marginal seas

In the Okinawa Trough and the northern South China Sea, abundant *Globorotalia menardii* and *Pulleniatina obliquiloculata* occur in interglacial intervals and they are rare in glacials (Fig. 6), resulting from the waning and waxing of the Kuroshio Current (Ujiie and Ujiie, 1999; Li et al., 1997; Pflaumann and Jian, 1999; Jian et al., 2000b; Huang, 2002). Unlike other parts of the western Pacific, the southern SCS preserves a unique record in which *P. obliquiloculata* became abundant in glacial intervals after the MPR, as revealed in this study. Could this shift in *P. obliquiloculata*’s response to glacial–interglacial cyclicity be merely an artifact caused by differential dissolution?

Fragmentation of planktonic foraminiferal shells is a reliable indicator of dissolution level that a foraminiferal assemblage has experienced (Le et al., 1995). The fragmentation curve of Site 1143 indicates strong dissolution during interglacials (Fig. 4). It compares well with %*Globorotalia menardii* variations but its correlation with %*Pulleniatina obliquiloculata* is poor. The covariations between fragmentation and *G. menardii* and  $\delta^{18}\text{O}$  fluctuations at Site 1143 are similar to records from the equatorial Pacific (Le et al., 1995). Both species are dissolution-resistant, although *P. obliquiloculata* may sustain more corrosive water (Bé, 1977). If stronger dissolu-

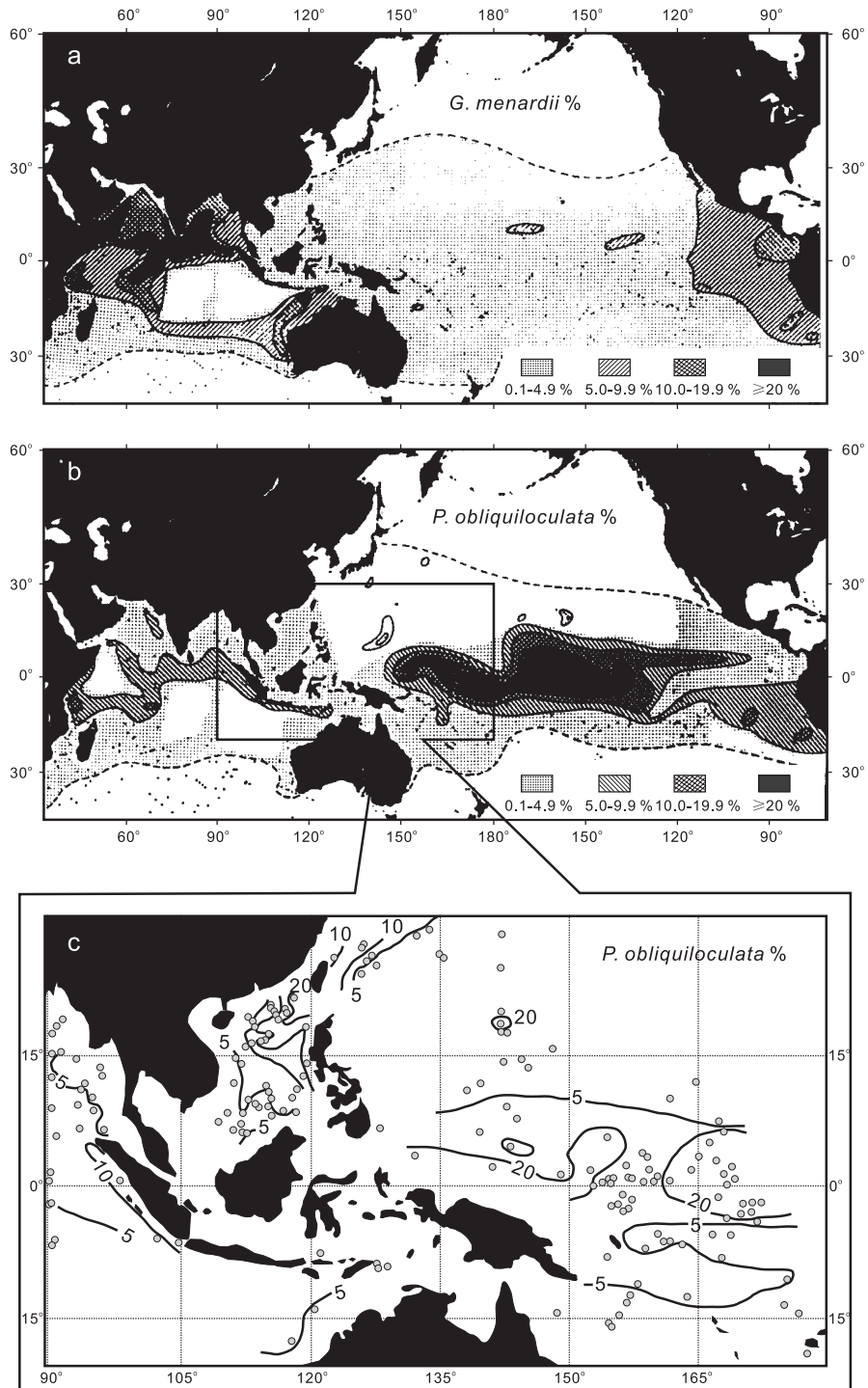


Fig. 7. Distributions of (a) %*Globorotalia menardii* and (b) %*Pulleniatina obliquiloculata* in surface sediments of the Indian Ocean and the Pacific (modified from Bé, 1977), and (c) %*Pulleniatina obliquiloculata* in the South China Sea (modified from Pflaumann and Jian, 1999).

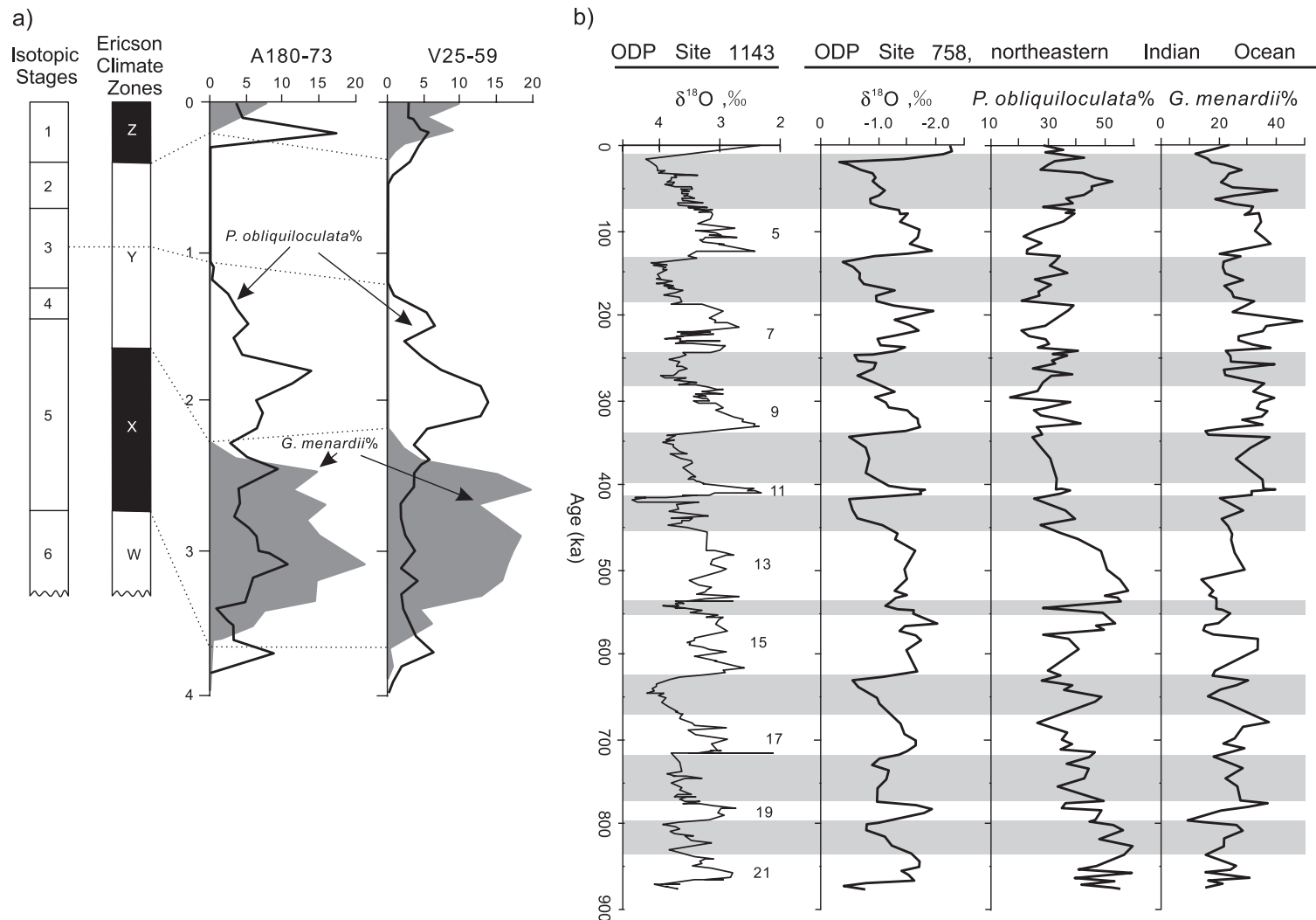


Fig. 8. (a) Downcore variations of the percentages of *Globorotalia menardii* and *Pulleniatina obliquiloculata* in Cores A180-73 and V25-59 from the equatorial Atlantic (modified from [Prel and Damuth, 1978](#)). Note different appearances and disappearances of *G. menardii* and *P. obliquiloculata* with the isotopic record at ODP Site 758, northeastern Indian Ocean (modified from [Chen and Farrell, 1991](#)). Benthic foraminifer  $\delta^{18}\text{O}$  of ODP Site 1143 ([Tian et al., 2002](#)) alongside is for calibrating the age. Gray bars mark glacial intervals, and numbers are marine isotope stages (MIS).

tion during interglacials did not cause a significant reduction of the abundance of *G. menardii*, then the decrease of *P. obliquiloculata* in the same interglacial intervals after the MPR could not have been attributed to dissolution alone. Changes of temperature in glacial–interglacial cycles surely caused fluctuations in  $\delta^{18}\text{O}$  and species abundance, but neither temperature nor dissolution changes can explain why more *P. obliquiloculata* accumulated during glacials after the MPR in the southern SCS.

#### 6.4. Variations in the Indian Ocean

Similar to the Site 1143 records, high percentages of *Pulleniatina obliquiloculata* accompanied by rare *Globorotalia menardii* also occur during glacial MIS 4, 12, and MIS 3/2 transition in the equatorial Indian Ocean ODP Site 716 (Maldive Ridge, 4°56' N, 73°17' E, water depth 533 m) (Cullen and Droxler, 1990). The upper 18.4 m section at this site, representing the last 700 ka, is high in carbonate content, averaging >80%. These authors suggested that the abundances of foraminifer species were more likely related to changes in salinity and nutrient levels rather than SST.

In the northeastern Indian Ocean, Chen and Farrell (1991) documented a negative correlation between %*Pulleniatina obliquiloculata* and *Globorotalia menardii* after recalculating their relative abundance at ODP Site 758 (5°23' N, 90°22' E, water depth 2924 m) (Fig. 8b). An analog was made between the assemblages in coretop samples from the Pacific and in the late Quaternary samples they studied. They suggested that the surface water conditions in the northeastern Indian Ocean during the late Quaternary were similar to the modern western tropical Pacific surface water. They attributed the extremely high abundances of *P. obliquiloculata* during interglacials (such as MIS 13) in the northeastern Indian Ocean to an increase of the advection of warm surface waters through the Indonesian Archipelago into the northeastern Indian Ocean.

#### 6.5. Possible cause of *Pulleniatina obliquiloculata* change in the southern SCS

Characterized by more *Pulleniatina obliquiloculata* in glacial than in interglacial periods since the

MPR, a negative correlation between %*P. obliquiloculata* and  $\delta^{18}\text{O}$  exists in the southern SCS. The causes to this *P. obliquiloculata* shift probably lie either in regional salinity change or Indo-Pacific connection, or both. Increase in regional salinity during glacials in the last 850 ka could have favored the proliferation of the euryhaline *P. obliquiloculata*. Or, on the other hand, periodical exchange between Indian Ocean and southern SCS water in interglacial times might have played a critical role in controlling *P. obliquiloculata* distribution in these two regions.

The average downcore percentages of *Pulleniatina obliquiloculata* in the southern SCS are higher than that in the Okinawa Trough and northern SCS (Fig. 6), and its high percentages during glacials finds no analog in the modern southern SCS (Fig. 7c). Paralleled to the argument made by Chen and Farrell (1991) that the surface water conditions during glacials since 850 ka were similar to those in the modern western tropical Pacific. Similarly, lower abundance of *P. obliquiloculata* during interglacials after the MPR may have been influenced by surface water from the Indian Ocean, which at present is characterized by low abundance of *P. obliquiloculata* (Fig. 7b) (Bé, 1977; Cullen and Prell, 1984).

Probably only after the MPR did the lowered sea level during glacials transform the SCS into a semi-enclosed basin with the Bashi Strait (2600 m deep) in the northeast acting as its only passageway to the open ocean (Wang and Wang, 1990; Wang, 1990). Connection between the SCS and Indian Ocean was then interrupted, consequently causing salinity to rise and allowing *Pulleniatina obliquiloculata* to be advantageous over *Globorotalia menardii*. During interglacials, sea level rose, and the Indian Ocean would, as it is today, freely exchanges surface water with the southern SCS. The influx of the low salinity Indian water likely reduced the dominance of *P. obliquiloculata*. Such situation probably becomes more obvious during summer monsoons. Such periodic recharges of Indian waters during interglacials probably resulted in distinct different water conditions in the southern SCS from the northern SCS. Before the MPR, however, the SCS was likely able to exchange water freely with both the Indian and Pacific Oceans during interglacial as well as glacial periods. This assumption, however, remains speculative pending further studies on the



changing configurations of gateways as resulted from tectonic modification and/or increased amplitudes of sea level change after the MPR.

When the SCS was transformed into a semi-enclosed basin during glacials, the polar front in the North Pacific also shifted southward, and temperate waters, now at 25–35°N, would have reached as far south as 20°N, where the Bashi Strait is located (Wang and Wang, 1990; Wang and Sun, 1994). This could have enhanced the contrast in the upper water structure between the northern and southern SCS, while the SST in the southern SCS (Site 1143) would change little due to its tropical position. Seawater salinity, however, would increase progressively due to the expansion of continental glaciers and low precipitation, although winter monsoon was probably still strong in the region (Wang and Wang, 1990; Jian et al., 1999). The nutricline deepened in the upper water column as indicated by abundant nannoplankton *Florisphaera profunda* (Liu, 2002; personal communication). As a result, it is interpreted that the glacial subsurface water conditions in the southern SCS were similar to the modern western tropical Pacific in favoring the abundant growth of *Pulleniatina obliquiloculata*.

## 7. Conclusions

- (1) Variations of planktonic foraminiferal species in the upper 99.4 m of ODP Site 1143 provide evidence of paleoceanographic changes for the past 2.1 Ma in the southern SCS. Two warm-water dissolution-resistant species, *Pulleniatina obliquiloculata* and *Globorotalia menardii*, display opposite fluctuation patterns in their abundances since the MPR.
- (2) *Globorotalia menardii* was more abundant in interglacial intervals, displaying statistically peaking coherence with the benthic  $\delta^{18}\text{O}$  fluctuation throughout the section. Also related was dissolution as indicated by quantitative changes in fragmentation of planktonic foraminiferal tests. We conclude that %*G. menardii* reflects warmer temperatures and stronger dissolution during interglacials.
- (3) A peak-to-peak coherence between *Pulleniatina obliquiloculata* and  $\delta^{18}\text{O}$  existed before the

MPR, but reversed to peak-to-valley coherence since 850 ka with more *P. obliquiloculata* in glacial than in interglacial intervals. This is accompanied by its frequency changes from 400 to 41 ka and 185 ka cyclicities. This shift appears to have occurred only in the southern SCS as records from the northern SCS and other NW Pacific localities continue to show that *P. obliquiloculata* remained abundant in interglacial periods.

- (4) In many parts of modern western Pacific, *Pulleniatina obliquiloculata* is frequent to abundant, but is very rare in the modern northern Indian Ocean. Such a contrast may imply that the low %*P. obliquiloculata* in the interglacial southern SCS was associated with periodic influence by currents from the Indian Ocean when surface waters were able to exchange between these two basins, as they are today. Similarly, the high %*P. obliquiloculata* in the glacial southern SCS may indicate water conditions similar to modern western Pacific: warm and saline. The shift of *P. obliquiloculata* abundance after the MPR was probably a direct response to a complete closure of the gateways between the Indian Ocean and southern SCS at the MPR low sea-level time. Before the MPR, the connection between these two basins was likely opened throughout all glacial–interglacial cycles.
- (5) Low sea level during glacials since 850 ka transformed the southern SCS into a semi-enclosed basin, leading to fundamental changes in the upper water structure. These may include salinity increase due to low precipitation and upwelling of more saline bottom water caused by stronger winter monsoons, a shoaled thermocline. These conditions favored such euryhaline, deep planktonic dwellers as *Pulleniatina obliquiloculata*. Their unique distribution pattern during the late Quaternary illustrates the characters of the southern SCS responding to regional paleoceanographic changes since the MPR.

## Acknowledgements

Prof. Wolfgang Kuhnt and Prof. Kuo-Yen Wei are genuinely thanked for their reviews on our manu-

script, constructive suggestions and improving the English as well. We would like to thank Prof. Dr. Christoph Hemleben for his greatly helpful communications. Cross-spectral analyses were performed using the ARAND package supplied generously by Philip Howell of Brown University. Thanks are also extended to the Ocean Drilling Program (ODP) for the Site 1143 material and the late Dr. L. Wang for taking most samples used in this study. ODP is sponsored by the U.S. National Science Foundation (NSF) and participating countries under management of Joint Oceanographic Institutions (JOI). This study is supported by the NNSFC (Grant 49999560) and NKBRFS (Grant G2000078500).

## References

- Bé, A.W.H., 1977. An ecological, zoogeographical and taxonomic review of recent planktonic foraminifera. In: Ramsay, A.T.S. (Ed.), *Oceanic Micropaleontology* vol. 1. Academic Press, London, pp. 1–100.
- Chen, M., Farrell, J., 1991. Planktonic foraminifer faunal variations in the northeastern Indian Ocean: a high-resolution record of the past 800,000 years from site 758. *Proc. Ocean Drill. Prog., Sci. Results* 121, 125–140.
- Chen, R., Jian, Z., Zheng, Y., Chen, J., 2000. Seasonal variations of the planktonic foraminiferal flux in the Central South China Sea. *J. Tongji Univ.* 28 (1), 73–77. (in Chinese, with English abstract).
- Clemens, S.C., Prell, W.L., 2003. Data report: oxygen and carbon isotopes from Site 1146, northern South China Sea. In: Prell, W.L., Wang, P., Blum, P., Rea, D.K., Clemens, S.C. (Eds.), *Proc. Ocean Drill. Prog., Sci. Results*, vol. 184. pp. 1–8. Online.
- Cullen, J.L., Drozler, A.W., 1990. Late quaternary variations in planktonic foraminifer faunas and pteropod preservation in the equatorial Indian Ocean. *Proc. Ocean Drill. Prog., Sci. Results* 115, 579–588.
- Cullen, J.L., Prell, W.L., 1984. Planktonic foraminifera of the northern Indian Ocean: distribution and preservation in surface sediments. *Mar. Micropaleontol.* 9, 1–52.
- Fang, D., 1997. Sedimentological and paleoceanographic changes in the southern South China Sea since the Last Glacial Stage-taking core 17962 as an example. MS thesis. Tongji University (in Chinese, with English abstract).
- Flower, B.P., Kennett, J.P., 1990. The Younger Dryas cool episode in the Gulf of Mexico. *Paleoceanography* 5 (6), 949–961.
- Hemleben, C., Spindler, M., Anderson, O., 1989. *Modern Planktonic Foraminifera*. Springer-Verlag, pp. 8–32.
- Howell, P., 2001. ARAND time series and spectral analysis package for the Macintosh, Brown University. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series #2001-044. NOAA/NGDC Paleoclimatology Program, Boulder, CO, USA.
- Huang, B., 2002. Late Plio-Pleistocene evolution of the East Asian monsoon recorded by foraminiferal fauna in the northern South China Sea. PhD Thesis, Tongji University (in Chinese with English abstract).
- Huang, Q., Wang, W., Li, Y., Li, C., 1994. Current characteristics of the South China Sea. In: Zhou, Di, et al. (Eds.), *Oceanology of China Seas* vol. 1. Kluwer Academic Publishers, pp. 39–47.
- Jian, Z., Wang, L., Kienast, M., Sarnthein, M., Kuhnt, W., Lin, H., Wang, P., 1999. Benthic foraminiferal paleoceanography of the South China Sea over the last 40,000 years. *Mar. Geol.* 156, 159–186.
- Jian, Z., Wang, P., Chen, M., Li, B., Zhao, Q., Bühring, C., Laj, C., Lin, H., Pflaumann, U., Bian, Y., Wang, R., Cheng, X., 2000a. Foraminiferal responses to major Pleistocene paleoceanographic changes in the southern South China Sea. *Paleoceanography* 15 (2), 229–243.
- Jian, Z., Wang, P., Saito, Y., Wang, J., Pflaumann, U., Oba, T., Cheng, X., 2000b. Holocene variability of the Kuroshio Current in the Okinawa Trough, northwestern Pacific Ocean. *Earth Planet. Sci. Lett.* 184, 305–319.
- Jian, Z., Li, B., Huang, B., Wang, J., 2000c. *Globorotalia truncatulinoides* as indicator of upper-ocean thermal structure during the Quaternary: evidence from the South China Sea and Okinawa Trough. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 162, 287–298.
- Jian, Z., Huang, B., Kuhnt, W., Lin, H., 2001. Late Quaternary upwelling intensity and East Asian Monsoon forcing in the South China Sea. *Quat. Res.* 55, 363–370.
- Jones, J.I., 1967. Significance of distribution of planktonic foraminifera in the Equatorial Atlantic Undercurrent. *Micro-paleontology* 13 (4), 489–501.
- Le, J., Shackleton, N.J., 1992. Carbonate dissolution fluctuations in the western equatorial Pacific during the late Quaternary. *Paleoceanography* 7, 21–42.
- Le, J., Mix, A.C., Shackleton, N.J., 1995. Late Quaternary paleoceanography in the eastern equatorial Pacific Ocean from planktonic foraminifera: a high-resolution record from Site 846. *Proc. Ocean Drill. Program Sci. Results* 138, 675–693.
- Li, B., Jian, Z., Wang, P., 1997. *Pulleniatina obliquiloculata* as a paleoceanographic indicator in the southern Okinawa Trough during the last 20,000 years. *Mar. Micropaleontol.* 32, 59–69.
- Maasch, K.A., 1988. Statistical detection of the mid-Pleistocene transition. *Clim. Dyn.* 2, 133–143.
- Mckenna, V.S., Farrell, J.W., Murray, D.W., Clemens, S.C., 1995. The foraminifer record at Site 847: paleoceanographic response to late Pleistocene climate variability. *Proc. Ocean Drill. Program Sci. Results* 138, 695–714.
- Miao, Q., Thunell, R.C., Anderson, D.M., 1994. Glacial–Holocene carbonate dissolution and sea surface temperatures in the South China and Sulu seas. *Paleoceanography* 9 (2), 269–290.
- Pflaumann, U., Jian, Z., 1999. Modern distribution patterns of planktonic foraminifera in the South China Sea and western Pacific: a new transfer technique to estimate regional sea-surface temperatures. *Mar. Geol.* 156, 41–83.
- Pisias, N.G., Moore Jr., T.C., 1981. The evolution of Pleistocene climate: a time series approach. *Earth Planet. Sci. Lett.* 52, 450–458.

- Prell, W.L., Damuth, J.E., 1978. The climate-related diachronous disappearance of *Pulleniatina obliquiloculata* in late Quaternary sediments of the Atlantic and Caribbean. *Mar. Micropaleontol.* 3, 267–277.
- Ravelo, A.C., Fairbanks, R.G., 1990. Reconstruction tropical Atlantic hydrography using planktonic foraminifera and an ocean model. *Paleoceanography* 5 (3), 409–431.
- Ravelo, A.C., Fairbanks, R.G., Philander, S.G.H., 1992. Oxygen isotopic composition of multiple species of planktonic foraminifera: recorders of the modern photic zone temperature gradient. *Paleoceanography* 7 (6), 815–831.
- Saito, T., Thompson, P.R., Breger, D., 1981. *Systematic Index of Recent and Pleistocene Planktonic Foraminifera*. University of Tokyo Press. 190 pp.
- Shaw, P., Chao, S., 1994. Surface circulation in the South China Sea. *Deep-Sea Res., I. Oceanogr. Res. Pap.* 41 (11/12), 1663–1683.
- Shi, P., Du, Y., Wang, D., Gan, Z., 2001. Annual cycle of mixed layer in South China Sea. *J. Trop. Oceanogr.* 20 (1), 10–17. (in Chinese with English abstract).
- Thompson, P.R., 1981. Planktonic foraminifera in the western north Pacific during the past 150 000 years: comparison of modern and fossil assemblages. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 35, 241–279.
- Tian, J., Wang, P., Cheng, X., Li, Q., 2002. Astronomically tuned Plio-Pleistocene benthic  $\delta^{18}\text{O}$  record from South China Sea and Atlantic–Pacific comparison. *Earth Planet. Sci. Lett.* 203, 1015–1029.
- Tu, X., 1984. Dissolution of planktonic foraminifera in the central waters of the South China Sea—A preliminary study on carbonate dissolution. *J. Trop. Oceanogr.* 3 (4), 18–23 (in Chinese, with English abstract).
- Ujiié, H., Ujiié, Y., 1999. Late Quaternary course changes of the Kuroshio Current in the Ryukyu Arc region, northwestern Pacific Ocean. *Mar. Micropaleontol.* 37, 23–40.
- Wang, P., 1990. The ice-age China sea—status and problems. *Quat. Sci.* 2, 111–124. (in Chinese with English abstract).
- Wang, P., Sun, X., 1994. Last glacial maximum in China: comparison between land and sea. *Catena* 23, 341–353.
- Wang, L., Wang, P., 1990. Late Quaternary paleoceanography of the South China Sea: glacial–interglacial contrasts in an enclosed basin. *Paleoceanography* 5 (1), 77–90.
- Wang, P., Zhang, J., Min, Q., 1985. Distribution of foraminifera in surface sediments of the East China Sea. In: Wang et al. (Eds.), *Marine Micropaleontology of China*. China Ocean Press and Springer Verlag, Beijing, pp. 34–69.
- Wang, P., Prell, W.L., Blum, P., et al., 2000. Proceedings of the Ocean Drilling Program. Initial Reports vol. 184. Ocean Drilling Program, College Station, TX.
- Wang, P., Tian, J., Cheng, X., 2001. Transition of Quaternary glacial cyclicity in deep-sea records at Nansha, the South China Sea. *Sci. China, D* 44 (10), 926–933.
- Xu, J., Huang, B., Chen, R., Zhang, F., 2001. Distribution of foraminifera in surface sediments of northeastern South China Sea and its environmental implications. *J. Trop. Oceanogr.* 20 (4), 6–13 (in Chinese with English abstract).