



# Paleoceanography of the South China Sea since the middle Miocene: evidence from planktonic foraminifera

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## Abstract

Late middle Miocene to Pleistocene planktonic foraminifera (PF) in fairly continuous hemipelagic sediments recovered at Ocean Drilling Program (ODP) Site 1143 from the southern South China Sea (SCS) were studied with sampling intervals of 10 to 150 cm. A total of 16 PF events are revised for the 516-m long section, providing an age model for the last 12 Ma at this site. On the basis of benthic foraminiferal  $\delta^{18}\text{O}$  stratigraphy and the smoothed planktonic age model, new ages are assigned to three PF events (last occurrence [LO] *Globorotalia multicamerata* sensu lato [s.l.] at 2.18 Ma, first occurrence [FO] *Sphaeroidinella dehiscens* sensu stricto [s.s.] at 3.6 Ma, and FO *Globigerinoides conglobatus* at 6.6 Ma) in the South China Sea.

Distinct PF faunal transition from *Globorotalia siakensis*–*G. mayeri* group to mixed-layer species occurred during the early late Miocene (~9.6 Ma). The transition reflects a deepened upper water thermocline, possibly corresponding to the closure of the Indonesian seaway and intensification of equatorial Pacific warm currents. Abundance variations of *Neogloboquadrina* spp. indicate a marked shoaling of the thermocline in the northern South China Sea after 3–2.5 Ma affected possibly by a strengthened Asian winter monsoon, while a deeper thermocline existed in the southern South China Sea since the late Miocene, characterizing the west Pacific “warm pool” (WPWP).

A deepening thermocline influenced by consistently warm surface water since the late Miocene in the southern South China Sea is also evidenced by a two-stepwise increase of *Pulleniatina* group, by a gradually decreasing *Sphaeroidinella*–*Sphaeroidinellopsis* spp. and abundant *Globorotalia menardii* and related species. The FO *Globigerinoides ruber* (pink) at approximately 1 Ma and an abrupt increase in the pink-to-all ratio of *G. ruber* at 0.4 Ma at Site 1143 provide two additional PF events for deciphering Pleistocene biostratigraphy and paleoceanography.

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**Keywords:** late Cenozoic; planktonic foraminifera; stratigraphy; paleoceanography; ODP Site 1143; South China Sea

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## 1. Introduction

As the largest marginal sea between the largest continent (Eurasia) and largest ocean (the Pacific),

the South China Sea (SCS) is attracting more and more intensive paleoceanographic studies. Most work has been focused on late Quaternary climate and environmental changes, such as glacial and interglacial contrasts and abrupt climate variations on the millennial scale (Rottman, 1979; Wang et al., 1986; Wang and Wang, 1989, 1990; Thunell et al., 1992; Wang et al., 1995, 1999; Pelejero et al., 1999; Jian et al., 2001). Although extensive petroleum explorations have been carried out on the northern shelf of the SCS and around coral reef regions during the last two decades, very few academic researches have benefited from industrial drilling (Wang et al., 1991; Zhao et al., 1992; Jiang et al., 1994; Wu, 1994; Huang, 1997), and detailed paleoceanographic studies were limited only to the sediment record of the last 1.5 Ma (Wang et al., 2000; Jian et al., 2000). For longer term records, especially those of marginal marine deposits, a poor stratigraphic control makes it difficult to correlate the poorly recovered local sediment sections with the standard stratigraphy from world oceans.

Using the technique of advanced hydraulic piston corer (APC) and extended core barrel (XCB), Ocean Drilling Program (ODP) Leg 184 recovered fairly continuous late Miocene (~10 Ma) to Holocene hemipelagic sections of fine-grained terrigenous material and pelagic carbonate at Site 1143, the only ODP site in the southern SCS (Shipboard Scientific Party, 2000). Shipboard biostratigraphy for Site 1143 was mainly based on the analysis of core catcher samples, providing only a coarse stratigraphic resolution with considerable uncertainties in planktonic foraminifer datum levels. Therefore, a more accurate chronobiostratigraphy for Site 1143 is needed to set up for stratigraphic correlation between the southern and northern SCS, as well as for paleoenvironmental comparisons between the SCS and world oceans.

This paper aims to revise the occurrence data of planktonic foraminifera (PF) and to discuss the evolutionary characteristics of selected species and their paleoceanographic significance over the last 12 Ma in the southern SCS. Based on the orbital-tuned  $\delta^{18}\text{O}$  stratigraphy from Site 1143, more accurate ages for the local data of several species were given. All this will benefit future palaeoceanographic and stratigraphic studies in the region.

## 2. Material and methods

Site 1143 (Fig. 1) is the only site drilled in the southern SCS during Leg 184, to provide a Neogene paleoceanographic record within the west Pacific “warm pool” (WPWP; Yan et al., 1992). It is located at  $9^{\circ}21.72' \text{ N}$  and  $113^{\circ}17.11' \text{ E}$  at a water depth of 2772 m. The site lies above the modern lysocline (water depth ~2900 m), above which relatively well-preserved carbonate sediments can be expected (Li, 1989). The upper part of the recovered succession, between 0 and 160 mcd (meter of composite depth, abbreviated as “m”), consists of olive-gray, light grayish green and greenish gray clayey nannofossil-mixed sediment, clay with nannofossils and clay. The lower part between 160 and 516 m is made up of higher carbonate, lighter clayey nannofossil-mixed sediment, as well as nannofossil clay and nannofossil ooze with clay. Evidence of bedding, slumping and turbidites has also been observed in the lower part of the section (Shipboard Scientific Party, 2000).

Samples were taken at intervals between 10 and 150 cm in a volume of 10–15 ml each from cores without obvious slumps or turbidites. Samples were oven-dried at  $80^{\circ}\text{C}$  for 1 or 2 days and soaked in water for about 1 week. Diluted  $\text{H}_2\text{O}_2$  was added into the water for disaggregating those consolidated samples. The soaked samples were then wet-washed through a 63- $\mu\text{m}$  screen and oven dried. The >63- $\mu\text{m}$  residue was weighted and dry sieved through a 154- $\mu\text{m}$  screen.

All planktonic foraminifera (PF) in the >154- $\mu\text{m}$  fractions were checked, and their first occurrence (FO) and last occurrence (LO) were recorded. Quantitative counting was proceeded after subdividing the coarse fraction (>154  $\mu\text{m}$ ) into a proportion containing 300 or more specimens. Planktonic foraminifer taxonomy of Kennett and Srinivasan (1983) and Bolli and Saunders (1985) is used in this study. The chronology of planktonic foraminiferal data follows those of Thompson et al. (1979), Berggren et al. (1995a), Chaisson and Pearson (1997) and Li et al. (2001). Benthic foraminifera (BF) and PF fragments were also counted to calculate the carbonate dissolution index using the method of Le and Shackleton (1992).

Two benthic taxa, *Cibicidoides wuellerstorfi* Schwager (two to eight specimens, test size 300–900  $\mu\text{m}$ ) or *Uvigerina* spp. (three to six specimens, 400–900  $\mu\text{m}$  in length), were picked up for stable

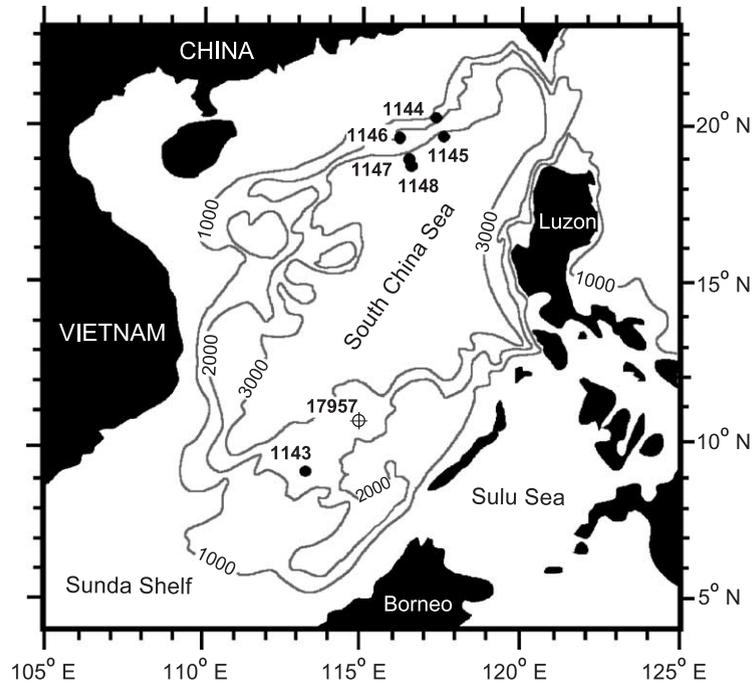


Fig. 1. Location of ODP Leg 184 sites and Core 17957 mentioned in this study. Site 1143 is the only ODP site from the southern South China Sea during the Leg 184. Core 17957 is from the “Sonne” cruise 95 (Sarnthein et al., 1994).

oxygen isotope analysis. The isotope analysis was conducted using a Finnigan-MAT 252 mass spectrometer equipped with an automated carbonate preparation device at the Laboratory of Marine Geology, Tongji University. The analytical precision for  $\delta^{18}\text{O}$  is  $\pm 0.06\text{‰}$  (PDB). Oxygen isotopes of *Uvigerina* spp. are adjusted to those of *C. wuellerstorfi* with a systematic subduction of  $0.64\text{‰}$  (Cheng et al., 2004). Isotopic stages at Site 1143 are subdivided by correlation to those of Site 677 (Shackleton et al., 1990) and Site 659 (Tiedemann et al., 1994), as well as PF biostratigraphy. Age-control points for the last 2.5 Ma are modulated by an astronomical calibration of  $\delta^{18}\text{O}$  (Tian et al., 2002).

### 3. Results and discussion

#### 3.1. Revised planktonic foraminiferal data and stratigraphy at Site 1143

Fig. 2 shows the revised 16 PF bio-events at Site 1143 with errors ranging from  $\pm 5$  to  $\pm 75$  cm. Most

ages are after Berggren et al. (1995a) and Chaisson and Pearson (1997), except where specific descriptions are given, as detailed below.

#### 3.1.1. LO pink-pigmented *Globigerinoides ruber* (*d'Orbigny*)

Pink *Globigerinoides ruber* last appears at a core depth of 8.37 m (1143C-1H-4W, 67–69 cm, 5.17 mbsf), adjusted to 8.12 m on a sampling error of 0.25 m, which is corresponding to an age of 0.12 Ma in the Indo-Pacific regions (Thompson et al., 1979).

#### 3.1.2. FO pink *Globigerinoides ruber acme*

The pink-pigmented *Globigerinoides ruber* acme begins at 24.78 m (1143B-3H-5W, 116–118 cm, 22.06 mbsf), subsequently calculated to be 25.03 m. Compared to the age data from an adjacent core (17957; Li et al., 2001), this datum corresponds to 0.40 Ma.

#### 3.1.3. LO *Globigerinoides fistulosus* (Schubert)

*Globigerinoides fistulosus* last occurs at 83.66 m (1143B-9H-4W, 68–70 cm, 77.08 mbsf), recalculated to be 83.66 m.

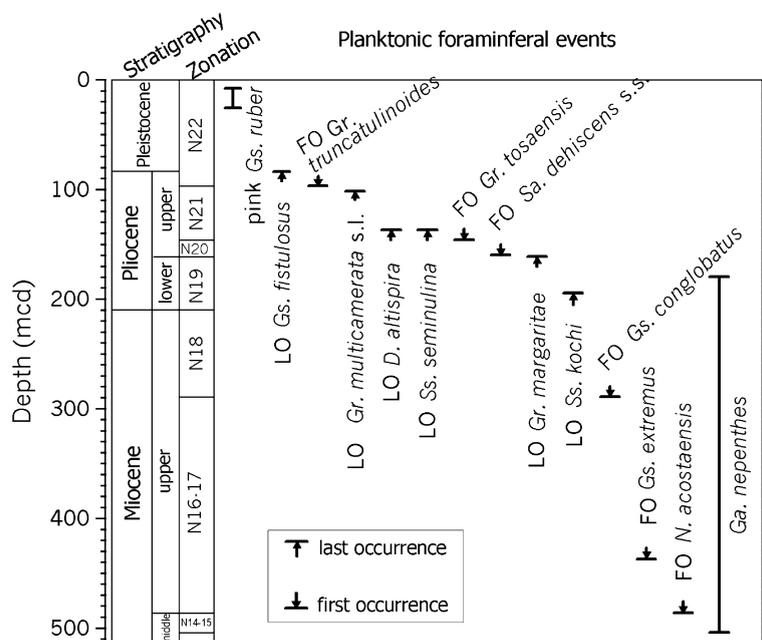


Fig. 2. Planktonic foraminiferal occurrences in Site 1143. Zonation is after Kennett and Srinivasan (1983). Range of pink-pigmented *Globigerinoides ruber* begins from its first abundance acme.

lated to be 83.40 m. According to the latest International Stratigraphic Chart (Remane et al., 2000), the LO *G. fistulosus* bears an age of 1.77 Ma (base of Zone N22), marking the Pleistocene/Pliocene boundary.

### 3.1.4. FO *Globorotalia truncatulinoides* (d'Orbigny)

*Globorotalia truncatulinoides* first appears at 95.94 m (1143C-10H-5W, 2–4 cm, 88.42 mbsf), adjusted to 96.09 m. This recalculated datum represents an age of 2.00 Ma (top of Zone N21).

### 3.1.5. LO *Globorotalia multicamerata* Cushman and Jarvis

The last appearance of *Globorotalia multicamerata* sensu lato (s.l.) in Site 1143 is recorded at 101.92 m (1143B-11H-3W, 92–94 cm, 94.82 mbsf), recalculated to 101.77 m (late Zone N21). Inasmuch as various ages (from 2.0 to 3.09 Ma) have been estimated for this datum due probably to different definitions of the species *G. multicamerata* (Heath and McGrowran, 1984; Wang et al., 1991; Berggren et al., 1995a), more detailed discussion on this datum level is given in Section 3.2 on the basis of the fairly continuous section from Site 1143.

### 3.1.6. LOs *Dentoglobigerina altispira* Cushman and Jarvis and *Sphaeroidinellopsis seminulina* Schwager

These two last appearance data occur together at 139.73 m (1143A-15H-5W, 45–50 cm, 132.85 mbsf), adjusted to 138.98 m. An age of 3.09–3.12 Ma (lower Zone N21) is calculated for them at Site 1143.

### 3.1.7. FO *Globorotalia tosaensis* Takayangi and Saito

*Globorotalia tosaensis* first appears at 144.34 m (1143C-15H-5W, 10–12 cm, 136 mbsf), recalculated to 144.39 m, with an age of 3.35 Ma (lower Zone N21).

### 3.1.8. FO *Sphaeroidinella dehiscens* (Park and Jones)

*Sphaeroidinella dehiscens* sensu stricto (s.s., with encircling girdle) first appears at 158.32 m (1143B-17H-2W, 2–10 cm, 149.5 mbsf), recalculated to 158.37 m. This datum has been assigned with an age of 3.25 Ma by Berggren et al. (1995a) and 5.54 Ma by Chaisson and Pearson (1997; see discussion below).

### 3.1.9. LO *Globorotalia margaritae* Bolli and Bermúdez

The LO *Globorotalia margaritae* occurs at 162.87 m (1143A-18H-1W, 45–50 cm, 155.35 mbsf), recal-

culated to 161.58 m, which corresponds to an age of 3.58 Ma (top of Zone N20).

#### 3.1.10. LO *Sphaeroidinellopsis kochi* Caudi

*Sphaeroidinellopsis kochi* disappears above 195.52 m (1143A-21H-2W, 50–52 cm, 185.4 mbsf), recalculated to 195.5 m. This datum corresponds to an age of 4.53 Ma (Zone N19).

#### 3.1.11. FO *Globigerinoides conglobatus* (Brady)

*Globigerinoides conglobatus* first appears at 287.29 m (1143A-31X-6W, 47–50 cm, 277.17 mbsf). This datum has been widely used to mark the top of Zone N17b at 6.2 Ma. Accordingly, its calculated depth at 288.39 m is assigned to represent the top of Zone N17b at Site 1143.

#### 3.1.12. FO *Globigerinoides extremus* Bolli

This datum occurs at 434.65 m (1143C-46X-2W, 45–50 cm, 422.25 mbsf), recalculated to 435.40 m which corresponds to 8.58 Ma (middle Zone N16).

#### 3.1.13. FO *Neogloboquadrina acostaensis* (Blow)

*Neogloboquadrina acostaensis* first appears at 484.35 m (1143C-51X-3W, 45–50 cm, 471.95 mbsf). It has been assigned to an age of 9.82 Ma (base of Zone N16). Thus, its calculated datum level at 484.50 m marks the base of Zone N16 for this site.

#### 3.1.14. LO and FO *Globigerina nepenthes* Todd

*Globigerina nepenthes* is present from 179.77 m (1143B-19H-3W, 80–82 cm, 170.7 mbsf) to 502.55 m (1143C-53X-2W, 43–445 cm, 489.83 mbsf). The calculated depths for these two data are at 179.72 and 502.99 m, corresponding to 4.20 Ma (Zone N19-20) and 11.19 Ma (base of Zone N14), respectively. The FO *G. nepenthes* is the oldest bio-event recorded at Site 1143.

A microtektite layer was found in Section 1143B-5H-4W, 17–19 cm, 38.56–38.58 mbsf (42.81–42.83 m), coinciding with the Brunhes–Matuyama paleomagnetic boundary (42.5–43.8 m, Shipboard Scientific Party, 2000). This event has been given with an age of 0.78 Ma (Zhao et al., 1999). Microtektites, at 42.82 m in Site 1143, are highly concentrated only at this thin level and disappeared almost completely either from immediately below or above in the same section (38.5–38.52 mbsf or 42.74–42.76 m; 38.6–

38.62 mbsf or 38.84–38.86 m). Abundant volcanic ash, however, was observed between 38.5–38.52 mbsf (42.74–.76 m) above the microtektite layer at Site 1143. The distribution of microtektite in Site 1143 not only provides a chronological datum but also implies that bioturbation was weak at least for the late Pleistocene in the southern SCS.

Together with the calcareous nannofossil data reported in the initial report, the above detailed planktonic foraminiferal and microtektite events provide a reliable chronologic framework for Site 1143 (Fig. 3). Several thin layers of volcanic ashes and turbidites, as described by the Shipboard Scientific Party (2000, Tables T5 and T6), are likely to have accumulated in such short periods of time that their influence on sedimentation at the site was minimal. Sedimentation rates at Site 1143 can then be recalculated by subtracting these disturbed intervals. The revised sedimentation rates for the Pleistocene (0–1.77 Ma) and Pliocene (1.77–5.3 Ma) are 4.54 and 3.56 cm/kyr, respectively. The late Miocene, between 5.3–8.6 Ma, has a relatively high sedimentation rate of 6.28 cm/kyr, which is in contrast to the average rate of only 2.37 cm/kyr, for the late middle to early late Miocene (8.6–12 Ma), the lowest sedimentation rate recorded in the southern SCS.

### 3.2. Ages of some problematic planktonic foraminiferal data

Three datum levels, LO *Globorotalia multicamerata* s.l., FO *Sphaeroidinella dehiscens* and FO *Globigerinoides conglobatus*, appear to have different ages from those conveyed previously at other oceanic settings. As no evidence for turbidite has been found associated with these events at Site 1143, their occurrence levels can be assumed to be in situ. On the age model presented in Fig. 3, we suggest preliminary new ages for these data pending further studies in the region.

#### 3.2.1. LO *Globorotalia multicamerata* s.l.

*Globorotalia multicamerata* disappeared at 3.09 Ma from the Atlantic Ocean (Berggren et al., 1995a), but in the western equatorial Pacific (Site 289), it disappeared much later, at ~2 Ma (Heath and McGrowran, 1984). On the northern shelf of the South China Sea, the LO *G. multicamerata* s.l.

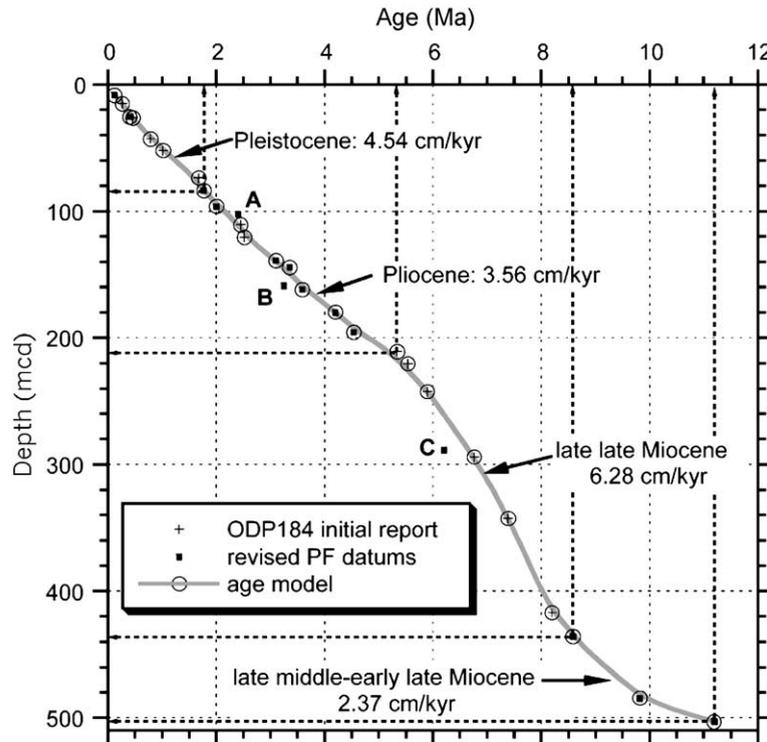


Fig. 3. Site 1143 chronologic framework based on planktonic foraminifera. The solid line shows the smooth fit of the age model versus core depth. Sedimentation rates are shown for different periods. Three out-of-curve bio-events were subsequently adjusted (see text): (A) LO *Globorotalia multicamerata* s.l.; (B) FO *Sphaeroidinella dehiscens* s.s. and (C) FO *Globigerinoides conglobatus*.

(including *G. pertenuis*) has been found coeval with a depositional hiatus of 2.0–2.5 Ma, an age previously used for this bio-event in the SCS region (Wang et al., 1991).

Based on the average sedimentation rate of 3.54 cm/kyr for the latest Pliocene at Site 1143 (Fig. 3), the LO *Globorotalia multicamerata* s.l. at 101.92 m should fall at 2.18 Ma. According to the orbitally tuned BF  $\delta^{18}\text{O}$  stratigraphy (Fig. 4b,d), this datum lies at marine isotopic stage (MIS) 82 at 2.17 Ma.

### 3.2.2. FO *Sphaeroidinella dehiscens* s.s.

Berggren et al. (1995a) dated the FO *Sphaeroidinella dehiscens* s.s. in the Mediterranean Sea at about 3.25 Ma; Heath and McGrowran (1984) proposed a slightly earlier age of 3.56 Ma for this datum from the Ontong Java Plateau of the west Pacific. Chaisson and Pearson (1997) reported a much earlier appearance of this taxon (at 5.54 Ma) at Site 925 from the western tropical Atlantic. Apparently, the

older age given by Chaisson and Pearson is because these authors included sphaeroidinellid forms with a minute secondary aperture in their concept of *S. dehiscens* s.l., while other researchers referred tests with pronounced secondary aperture on the spiral side to *S. dehiscens* s.s. In this study, the species concept of *S. dehiscens* s.s. is followed, and its FO datum level is recorded at 158.32 m. This datum would then bear an age of 3.55 Ma based on the biostratigraphic age model (Fig. 3) or 3.72 Ma on the BF  $\delta^{18}\text{O}$  stratigraphy, within MIS Gi6 (Fig. 4c,e; Tiedemann et al., 1994). Therefore, the first appearance of *S. dehiscens* s.s. in the South China Sea was ca. 3.6 Ma, similar to its record from the Ontong Java Plateau.

### 3.2.3. FO *Globigerinoides conglobatus*

This datum has been given with an age of ~6.2 Ma by Berggren et al. (1995b). It occurs at 287.29 m of Site 1143 and appears to secure an age of at least 6.6

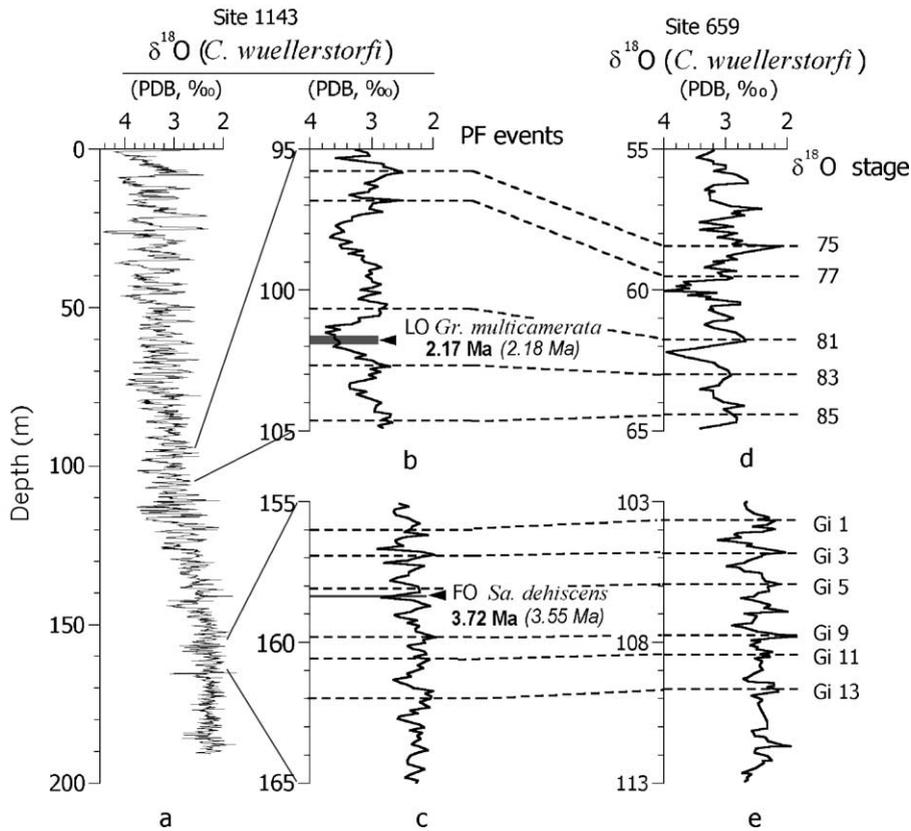


Fig. 4. Long-term and short-term benthic  $\delta^{18}\text{O}$  variations, marine isotope stages and planktonic foraminiferal bio-events. Site 1143  $\delta^{18}\text{O}$  stratigraphy after Tian et al. (2002). Site 659  $\delta^{18}\text{O}$  stratigraphy (Tiedemann et al., 1994) is also shown for comparison ([d] and [e]). Ages for the bio-events are based on  $\delta^{18}\text{O}$  data (bold) and the smoothed age model of Fig. 3 (italic, in brackets).

Ma based on the age model (Fig. 3). This new age takes into account likely distortion by turbidites, which are frequent in the lower part of Site 1143 succession. Because calibrated  $\delta^{18}\text{O}$  age is lacking, we temporarily place this datum at 6.6 Ma, and further work is required to verify its validity for the SCS–west Pacific region.

### 3.3. Planktonic foraminifer evidence of paleoceanographic changes

#### 3.3.1. *Globorotalia siakensis*–*G. mayeri* bioseries

As shown in Fig. 5, the early late Miocene is marked by distinct transition between the intermediate-layer (or deep dwelling) and the mixed-layer (or shallow dwelling) PF species, represented respectively by *Globorotalia siakensis*–*G. mayeri* and *Dentoglobigerina altispira*–*G. trilobus* (paleoecology

based on Kennett et al., 1985; Stephen Nathan, 2001, personal communication). Before 9.6 Ma, *G. siakensis*–*G. mayeri* are abundant but subsequently become extinct, and from 9.6 to 9.3 Ma, they are replaced by abundant mixed layer species including *D. altispira* and *G. trilobus*. This transition from deep-dwelling to shallow-dwelling species around 9–10 Ma likely responded to a deepening thermocline caused by the closure of Indonesian seaway and intensification of equatorial Pacific warm currents (Kennett et al., 1985).

#### 3.3.2. *Neogloboquadrina* spp.

After the extinction of *Globorotalia siakensis*–*G. mayeri* group, the deep-dwelling *Neogloboquadrina* group first appeared at ~9.3 Ma at least at the Site 1143 locality. Large specimens of *Neogloboquadrina* have also been found around 8–9 Ma in the Indian

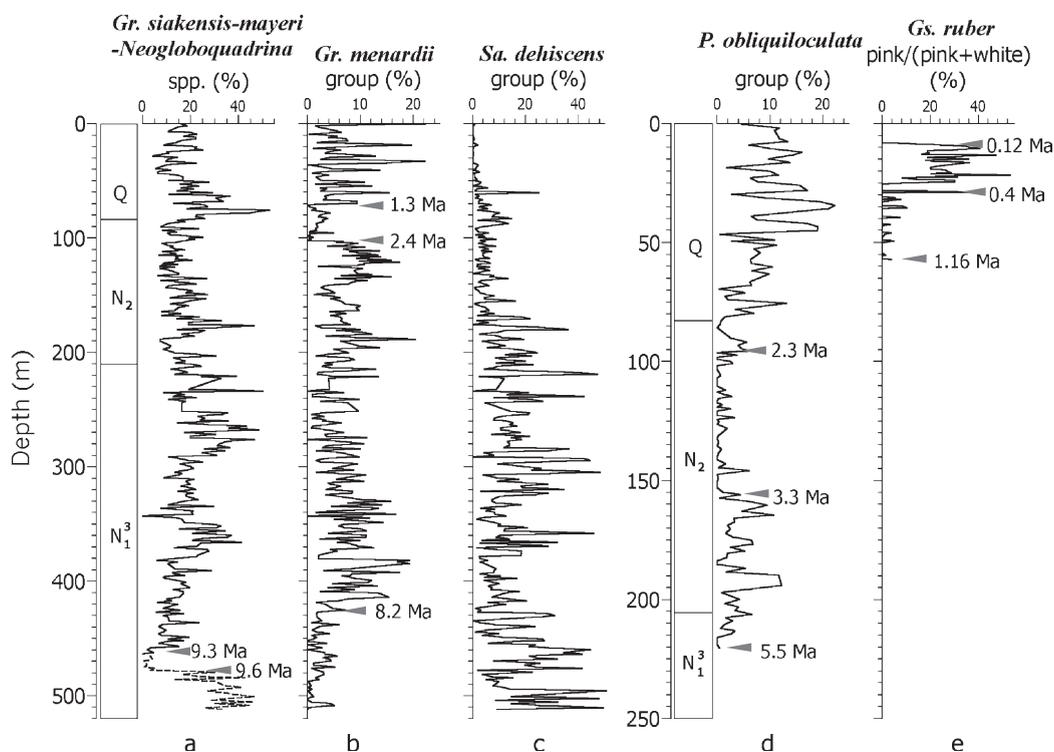


Fig. 5. Down-core variations of some planktonic foraminifera (in percentage) in Site 1143. Ages are calculated according to the smoothed age model in Fig. 3. The dashed and solid lines in column a refer to *Globorotalia siakensis*–*G. mayeri* (below 460 m) and *Neogloboquadrina* (above 460 m). Note the different scale for panels (d) and (e).

Ocean (Dick Kroon, 2001, personal communication). Their average abundance since the late Miocene at Site 1143 attains 18%, without obvious trend in fluctuations. This group becomes dominant (~40%) in the eastern equatorial Pacific where thermocline has been consistently shallow since late Miocene time (Site 847, Fig. 6a), while it has a relatively lower abundance in the western equatorial Pacific (Site 806, Fig. 6b). Therefore, the similarly low abundance of *Neogloboquadrina* spp. in the southern SCS (Site 1143) and in the western equatorial Pacific should be considered as the characteristic of a deeper thermocline in these two regions.

The abundance variation of *Neogloboquadrina* spp. at Site 1143 is in great contrast to the northern SCS record, in which *Neogloboquadrina* increased markedly from <10% to >20% in average, after ca. 3 Ma at Site 1146 (Wang, 2001, Fig. 4-15b). Their sudden increase at ~3 Ma in the northern SCS reflects a shoaling thermocline, possibly resulted from the

strengthening of Asian winter monsoon (Liu and Ding, 1993; An et al., 2001).

Site 1143 lies within the modern WPWP, where the thermocline depth is between 175–300 m and much deeper than that of the eastern equatorial Pacific. This different thermocline structure in the upper water column exerts strong impacts on PF diversity and abundance of deep-dwelling species between the west and east Pacific (Kennett et al., 1985; Chaisson, 1995). Site 1146 is located just outside of the present WPWP, and the characteristic increase of *Neogloboquadrina* abundance, together with a gradual decrease in sea surface temperature after 3.1 Ma (Huang, 2002), indicates a winter monsoon enhancement; while the abundance variation of *Neogloboquadrina* at Site 1143 more likely indicates thermocline depth changes influenced by different evolutionary stages of the WPWP rather than the influence of monsoon, although the evolution of these climatoceanographic phenomena could have closely connected.

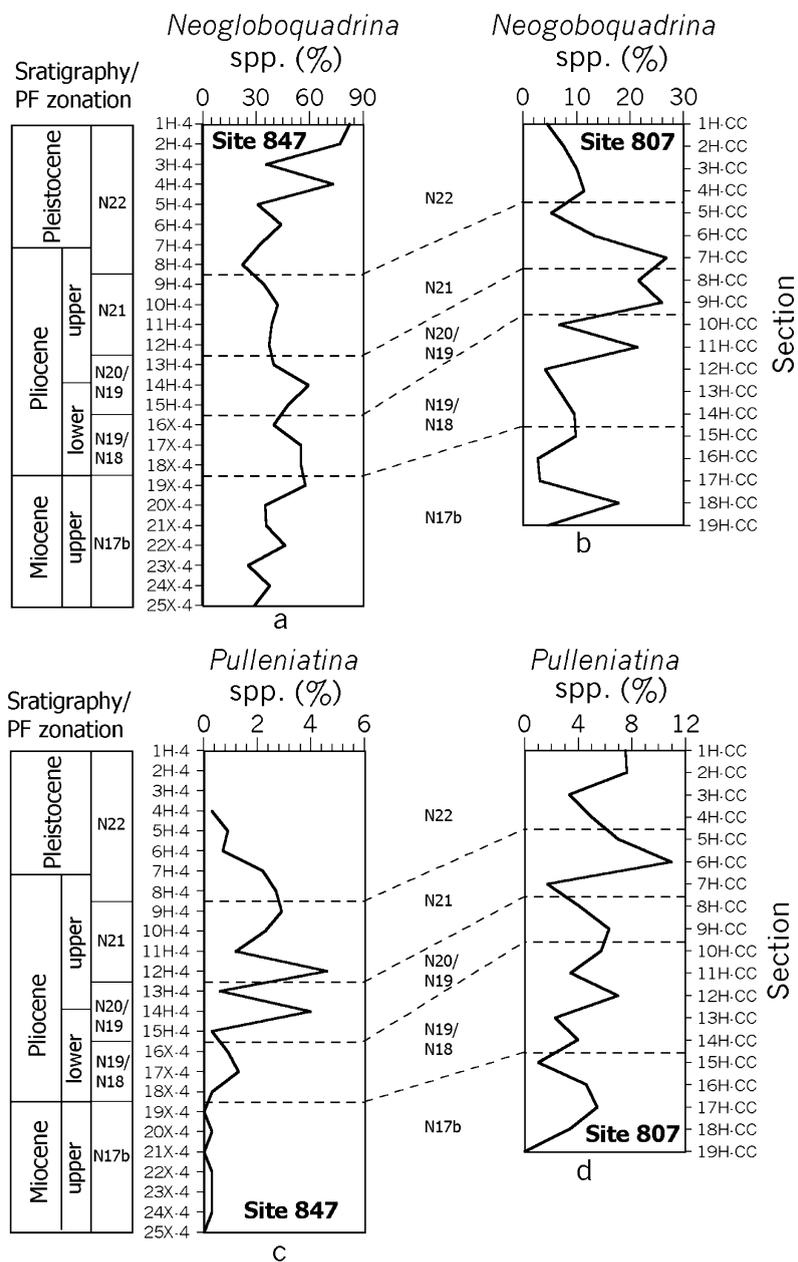


Fig. 6. Comparison of *Neogloboquadrina* spp. and *Pulleniatina* spp. between the east and western equatorial Pacific. *Neogloboquadrina* is more abundant in the eastern Pacific Site 847, while *Pulleniatina* is proportionally higher in the west Pacific Site 806 (modified after Chaisson (1995) with data from <http://iodp.tamu.edu/download/paleontology/>).

### 3.3.3. *Pulleniatina* group

The *Pulleniatina* group (including *Pulleniatina obliquiloculata*, *Pulleniatina primalis*, *Pulleniatina praecursor* and *Pulleniatina finalis*) first appeared at

Site 1143 about 5.5 Ma (1143A-24X-6W, 45–50 cm, 209.95 mbsf), almost 1 Ma younger than its record of 6.4 Ma in the west Pacific (Berggren et al., 1995b). They were rare during the middle to late Pliocene

(3.4–2.3 Ma), between 156–101 m at Site 1143, gradually increased in the Pleistocene and reached the highest abundance of >20% in the mid-Pleistocene at 34.22 m.

The low abundance of *Pulleniatina* during 3.4–2.3 Ma in the southern South China Sea can be correlated with its local disappearance at 3.45 Ma and reappearance at 2.3 Ma in the Atlantic (Berggren et al., 1995a). Thus, these patterns imply a three-period evolution of the *Pulleniatina* lineage in world oceans.

The higher abundance of *Pulleniatina* during the Pleistocene at Site 1143 in the South China Sea is comparative with its higher content in the Ontong Java Plateau (Site 806, western equatorial Pacific, Fig. 6d), which reflect a warm surface environment in the west Pacific region, in contrary to the lower *Pulleniatina* content in the east Pacific (Site 847, Fig. 6c), displaying a longitude increase of sea surface temperature toward the west influenced by the WPWP.

### 3.3.4. *Sphaeroidinella*–*Sphaeroidinellopsis*

*Sphaeroidinella dehiscens* and *Sphaeroidinellopsis* spp. (including *Sphaeroidinellopsis paenedehiscens*, *Sphaeroidinellopsis seminulina* and *Sphaeroidinellopsis kochi*) are abundant in the lower part of Site 1143, with the highest percentage of >50% in the late middle Miocene (Fig. 5c). Their total abundance fluctuated strongly throughout the late Miocene and early Pliocene and decreased substantially towards younger horizons or even became totally absent from some Pleistocene samples.

Although both are highly solution resistant, their high abundance in the lower part of Site 1143 appears to be unrelated to dissolution because carbonate dissolution indexes indicate that dissolution was weak during this period (see further discussion below). On the contrary, these typical deepwater dwellers (Kennett et al., 1985; Chaisson and Ravelo, 1997) likely reflect a deepened thermocline towards the Pleistocene in the southern SCS.

### 3.3.5. *Globorotalia menardii* group

Since ~8 Ma, the average relative abundance of the warm-water *Globorotalia menardii* group (including *G. menardii* complex, *Globorotalia limbata*, *Globorotalia multicamerata*, *Globorotalia plesiotumida* and *Globorotalia tumida*) remained at 8% in Site 1143

(Fig. 5b). Their abundance, however, decreased to 2.3% in average during the latest Pliocene–early Pleistocene (2.4–1.3 Ma).

As distinct tropical to warm subtropical dwellers, *Globorotalia menardii* and related species have been widely used as a semiquantitative indicator of warm climate and warm water masses (Ericson, 1968; Bé, 1977; Kennett and Srinivasan, 1983; Nishi et al., 2000). The relatively high percentage of *G. menardii* group after 8.2 Ma implies a warm water environment, while their low abundance between 2.4–1.3 Ma possibly marks cool water or climate conditions in the southern South China Sea.

### 3.3.6. Pink-pigmented *Globigerinoides ruber*

The first appearance of pink *Globigerinoides ruber* at 57.02 m (1143C-6H-5W, 116–118 cm, 51.6 mbsf) indicates an age of 1.16 Ma. The ratio of pink to all *G. ruber* [ $p/(p+w)$ ] increased markedly after 0.4 Ma to a maximum of 53% at 0.35 Ma (Fig. 5e), averaging to 26% between 0.4–0.12 Ma. The pink form disappeared abruptly at 0.12 Ma in Site 1143, as marked by a sudden decrease in the  $p/(p+w)$  ratio. Similar patterns also exist in Core 17957 which is located ~280 km northeast of Site 1143 (Fig. 1; Li et al., 2001).

The pink-pigmented *Globigerinoides ruber* first appeared at 1.04 Ma in the west Atlantic (Site 997; Nishi et al., 2000) and at ~0.8 Ma in the east Atlantic with consistently high abundance after 450 kyr (Core 13519; Pflaumann, 1986). Therefore, its FO datum in the southern SCS appears to be only slightly earlier than its record from the west Atlantic. The pink variety is still living in the modern Atlantic Ocean and the Mediterranean Sea, although it disappeared from the Indo–Pacific region after 0.12 Ma (Thompson et al., 1979).

### 3.4. Dissolution patterns and early Pliocene circulation

Although overall preservation of planktonic foraminifera in Site 1143 is good, evidence exists from PF fragmentation and BF abundance that major foraminiferal (carbonate) dissolution has intensified since the late Pliocene over the last 12 Ma history studied. The average PF fragments quickly multiply from 5% to 25% after 4.5 Ma above a core depth of 195 m, while

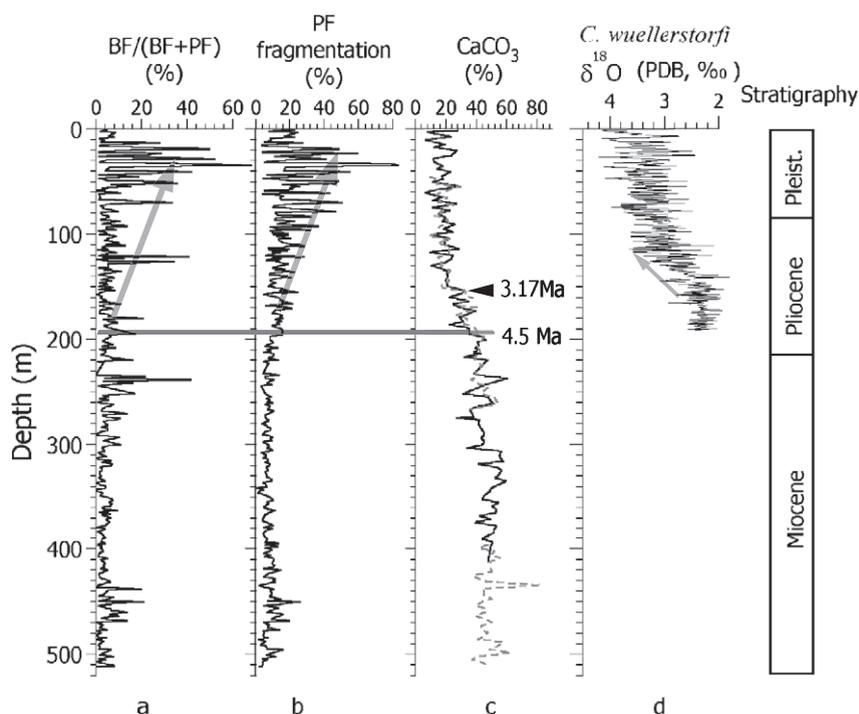


Fig. 7. Down-core variations of BF/(BF+PF), PF fragmentation,  $\text{CaCO}_3$  content and *Cibicidoides wuellerstorfi*  $\delta^{18}\text{O}$  in Site 1143. These metrics show enhanced carbonate dissolution after 4.5 and 3.17 Ma. The  $\text{CaCO}_3$  curve is from Shipboard Scientific Party (2000): solid line (Hole 1143A), dashed line (Holes 1143B and 1143C). The benthic  $\delta^{18}\text{O}$  is from Tian et al. (2002).

the BF abundance increases especially toward the upper part of the section and up to 40–70% at three Pleistocene levels (Fig. 7a,b). Together with the down core  $\text{CaCO}_3$  variations (Fig. 7c), these dissolution indices suggest an intensified carbonate dissolution that caused the gradual decrease in  $\text{CaCO}_3$  towards the upper part of the section, i.e., since the late Pliocene.

Modeling of ocean passage changes by Heinze and Crowley (1997) and Huag and Tiedemann (1998) suggests that the end of a free exchange of lower salinity water between the north Pacific and North Atlantic after the closure of the Central American isthmus at ~3 Ma could have caused a reorganization of ocean circulation systems and the intensification of the North Atlantic Deep Water (NADW). Consequently, carbonate dissolution became stronger, and the lysocline rose by about 1–2 km in the Pacific Ocean; while in the Atlantic Ocean, the pattern was reversed. Such reorganization probably began in the late Miocene but remained weak until 4.6 Ma in the early Pliocene when a major stage of current

reorganization occurred (Huag and Tiedemann, 1998). The intensified carbonate dissolution after 4.5 Ma (especially after 3.17 Ma), as recorded in various carbonate dissolution indices in Site 1143, is likely related to a shoaled lysocline in the Pacific. From the southern part of the largest marginal sea in the west Pacific, the Site 1143 record may have amplified this paleoceanographic event.

The major reorganization of ocean circulation systems around 3 Ma is also indicated by BF  $\delta^{18}\text{O}$  at Site 1143 (Fig. 7d). A marked increase in oxygen isotopic values occurred just above 146 m (at 3.2 Ma), reflecting a sudden decrease in deep-water temperature due to major northern hemisphere glaciation and reorganization of ocean circulation.

#### 4. Conclusions

Sixteen planktonic foraminiferal events recognized from Site 1143 provide a biostratigraphic framework on which an age model is established

for refining the stratigraphy in the southern SCS. The local ages for three bio-events are dated on the basis of the age model and benthic  $\delta^{18}\text{O}$  stratigraphy: LO *Globorotalia multicamerata* s.l. at 2.18 Ma, FO *Sphaeroidinella dehiscens* s.s. at ~3.6 Ma and FO *Globigerinoides conglobatus* at 6.6 Ma. The earliest PF event, FO *Globigerina nepenthes* at 11.18 Ma from a core depth of 502.99 m, indicates that the 516-m long sediment core recovered at Site 1143 records the last 12 Ma sedimentary and paleoceanographic history. Sedimentation rates increased from 2.37 cm/kyr during the late middle–early late Miocene to 6.28 cm/kyr in the later part of the late Miocene and decreased to 3.56 and 4.54 cm/kyr in the Pliocene and Pleistocene, respectively.

A distinct faunal transition from the deep-dwelling *Globorotalia siakensis*–*G. mayeri* group to mixed-layer species around 9.6 Ma in the early late Miocene indicates the deepening of the upper water thermocline, possibly corresponding to the closure of the Indonesian seaway and intensification of equatorial warm currents. The development of a deep thermocline appears to have persisted since the late Miocene in the southern SCS, but it was interrupted by a marked shoaling event after 3–2.5 Ma in the northern SCS, as indicated by variations of *Neogloboquadrina* spp. between these two regions. This difference implies that a strengthened Asian winter monsoon after 3–2.5 Ma was affecting the surface water in the north, while the west Pacific “warm pool” constantly influenced the water property in the south of the SCS.

The influence of warm climate, a tropical–subtropical water and a deepening thermocline in the southern SCS since late Miocene is also recorded, in other deep-dwelling species, by a two-stepwise increase in *Pulleniatina*, a gradual decrease in *Sphaeroidinella*–*Sphaeroidinellopsis* and abundance of *Globorotalia menardii* group. The pink *Globigerinoides ruber* first evolved almost simultaneously at ~1 Ma in both the SCS (west Pacific) and in the Atlantic, and an abrupt increase in its abundance at 0.4 Ma (indicated by the pink-to-all ratio of *G. ruber* in Site 1143) appears to be also synchronous in these areas, providing a potential useful tool for the mid-Pleistocene biostratigraphy.

Stronger carbonate dissolution during the late Pliocene and Pleistocene is marked by increase in planktonic fragments and benthic abundance and by a

decreased  $\text{CaCO}_3$  content after 4.5 Ma (especially after 3.17 Ma) at Site 1143. Considering a gradual increase of  $\delta^{18}\text{O}$  values after ~3.2 Ma, we suggest that the intensified carbonate dissolution may have been caused by the closure of the Central American isthmus and the subsequent reorganization of ocean circulation systems. This reorganization may have resulted in the intensification of the NADW and the enlargement of the Northern Hemisphere glaciation.

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