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Development of the East Asian monsoon and Northern Hemisphere glaciation: oxygen isotope records from the South China Sea

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Abstract

Oxygen isotope records of the surface-dwelling foraminifer *Globigerinoides ruber* from ODP Site 1143 in the southern South China Sea (SCS) are presented for the last 5 Ma. The *G. ruber* $\delta^{18}O$ of Site 1143 for the past 500 ka is lighter by 0.5–1.0‰ in interglacial, and by 0.1–0.5‰ in glacial periods, than the Site 806B record from the Ontong Java Plateau. We infer the light glacial/interglacial *G. ruber* $\delta^{18}O$ at Site 1143, compared with the open western Pacific, to have been caused by stronger monsoon-induced precipitation over the SCS. While glacial/interglacial planktonic $\delta^{18}O$ values remained stable over the 3.3–2.5 Ma period, the benthic *Cibicidoides wuellerstorfi* $\delta^{18}O$ gradually became positive, leading to an obvious slope in their $\delta^{18}O$ difference ($\Delta\delta^{18}O_{b-p}$). The stable glacial/interglacial *G. ruber* $\delta^{18}O$ over this period is probably caused by the decrease of sea surface salinity, which counteracted the effects of global ice volume and sea surface temperature on the *G. ruber* $\delta^{18}O$. We interpret that the intensification of the East Asian monsoon winds coupled with the northern hemisphere glaciation 3.3–2.5 Ma ago likely brought frequent and strong precipitation over the SCS and/or caused large-scale intrusions of Borneo alongshore low-salinity waters to the southern SCS, which greatly freshened the SCS and decreased its salinity. After 2.5 Ma, especially in the Quaternary period, the planktonic and benthic $\delta^{18}O$ show similar variations over glacial/interglacial cycles in responding to the waxing and waning of the northern hemisphere continental ice sheet, and their relatively stable $\delta^{18}O$ difference ($\Delta\delta^{18}O_{b-p}$) indicates a period of steady fluctuations of the East Asian monsoon winds. The more positive values of $\Delta\delta^{18}O_{b-p}$ probably suggest stronger East Asian winter monsoon during Quaternary glacials whereas the more negative values of $\Delta\delta^{18}O_{b-p}$ may imply stronger East Asian summer monsoon during Quaternary interglacials.

1. Introduction

The past fluctuations of the East Asian summer and winter monsoons have been studied from the loess-paleosol sequences in the Chinese loess plateau, with magnetic susceptibility and Rr/Sr ratio as the summer monsoon proxies, and grain size and Al fluxes as the winter monsoon proxies (Ding et al., 1992, 1994; Porter et al., 1992; Vandenberghe et al., 1997; An et al., 2001; Guo et al., 2002). The dust flux in the deep sea sediments of the North Pacific, transported from the arid inner Asia, also records changes in the strength of the monsoon (Rea et al., 1994, 1998). The seasonal reversal East Asian summer and winter monsoons characterize the local climate over the South China Sea (SCS), and monsoon-induced precipitation affects sea surface salinity (SSS) and nutrient content of the upper ocean as well as the isotopic composition of water masses. Previously, due to the constraint of drilling equipment and technology onboard, only short cores were obtained from the SONNE cruise 95 and from IMAGES cruises in the SCS (Sarnthein et al., 1994), which limited the monsoon research to the late Quaternary. ODP Leg 184 recovered undisturbed Oligocene to Holocene sediments from the northern and southern slopes of the SCS (Wang P. et al., 2000), providing long monsoonal records comparable with the loess-paleosol sequence. Here we present new $\delta^{18}O$ time series over the past 5 Ma for the surface-dwelling foraminifer *Globigerinoides ruber* at Site 1143 from the southern SCS (Fig. 1). The $\delta^{18}O$ differences between planktonic and benthic foraminifers reveal the coupled variations of the East Asian monsoon winds with the northern hemisphere glaciation

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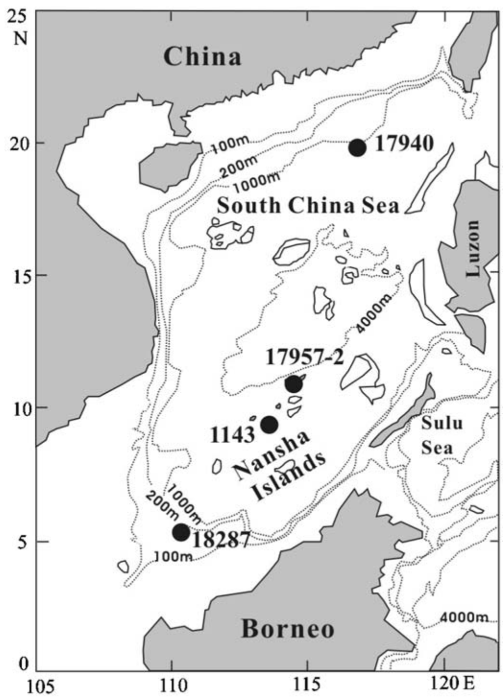

Fig. 1. Location map of Site 1143 and 1148 as well as other cores.

since the late Pliocene, especially the intensified East Asian monsoon winds in the late Pliocene and the relatively stable period of the monsoon fluctuations during the Quaternary.

2. Modern oceanographic setting

The SCS, with its total area of $3.50 \times 10^6\,km^2$ and total volume of $4.24 \times 10^6\,km^3$, is open to the western Pacific through the Bashi Strait with a sill depth of 2.6 km (Wang P. et al., 1995). The seasonal reversal of winter and summer monsoons and the monsoon-induced precipitation characterize the local climate over the SCS (Wiesner et al., 1996). During these monsoon seasons, many bio-productivity indices such as opal flux, organic carbon flux, diatom flux and radiolarian flux are much higher than that in the normal seasons (Fig. 2, Chen et al., 1998; Wang R.J. et al., 2000). Annually in the southern SCS, a clockwise surface circulation driven by the southwest monsoon winds is formed in summer from June to August, and an anti-clockwise surface circulation driven by the northeast monsoon winds exists in winter from October to February (Fig. 3, Zhao, 1996). The long-term observations in the southern SCS show that the mean annual sea surface temperature (SST) is close to 30°C, and the seasonal SSS within a year varies from 30.0‰ to 34.0‰, with the lowest value in winter and the highest value in spring (Li et al., 1988). Due to fluvial runoff, the offshore SSS is generally higher than the SSS along shore. ODP Site 1143 (9°21.72′N, 113°17.11′E, 2772 m) is located in the central part of the southern SCS, with little influence from the along shore fresh water or the Kuroshio intrusion. However, in the case of strong precipitation or the intrusion of Borneo alongshore low-salinity water, the SSS in the southern SCS will decrease to its minimum, less than 31‰. The SSS will reach a maximum of 34.3‰ or higher when the high-salinity subsurface water upwells or a strong mixing of the surface ocean by storms prevails (Zhao, 1996). Compared to the southern SCS, the SSS in the open western Pacific is much higher, reaching as much as 35–35.5‰ throughout the upper 560 m of the water column (Shipboard Scientific Party of ODP Leg 130, 1990).

3. Materials and methods

The upper 200 m of Site 1143 was triply cored using the advanced piston corer (APC) system during drilling, which ensures that the recovered deep sea sediments are complete, continuous and undisturbed. Samples were taken continuously at 10 cm apart from Holes A, B and C according to the composite depth, approximately at a time resolution of 2 ka. A total of 1992 samples of planktonic foraminifers from upper 190.77 mcd (meter composite depth) was measured for stable isotopes. The preparation of the samples and stable isotope analyses were performed in the Laboratory of Marine Geology, Tongji University, Shanghai. Well preserved specimens (clean, intact, with no signs of dissolution) of planktonic foraminifers *G. ruber* (white, 0.3–0.36 mm in diameter, 8 specimens, from upper 0–160.22 mcd) or *Globigerinoides obliquus* (from 160.22–190.77 mcd, 0.3–0.36 mm in diameter, 8 specimens) were chosen, then washed by ethanol (⩾99.7%) in ultrasonic bath with 40 KHz frequency for three times, each time lasting for 5 to 10 s, dried at 60°C in an oven for 5 h, moved to the sample vial in a Finnigan automatic carbonate device (Kiel III), reacted with ortho-phosphoric acid at 70°C to generate CO_2, then transferred to and measured in a Finnigan MAT252 mass spectrometer. Precision was regularly checked with a Chinese national carbonate standard (GBW04405) and international standard NBS19; the standard deviation was 0.07‰ for $\delta^{18}O$ and 0.04‰ for $\delta^{13}C$ during the year 2000. Conversion to the international Pee Dee Belemnite (PDB) scale was performed using NBS19 and NBS18 standards. *G. obliquus* is an extinct species, and accordingly no ecological information is available, but presumably it had a similar paleoecology as *G. ruber*. Therefore, we made no adjustment on the isotope values of *G. obliquus*, assuming that its value is in equilibrium to that of *G. ruber*.

Oxygen and carbon isotopes were also measured for the benthic *Cibicidoides wuellerstorfi* from the same

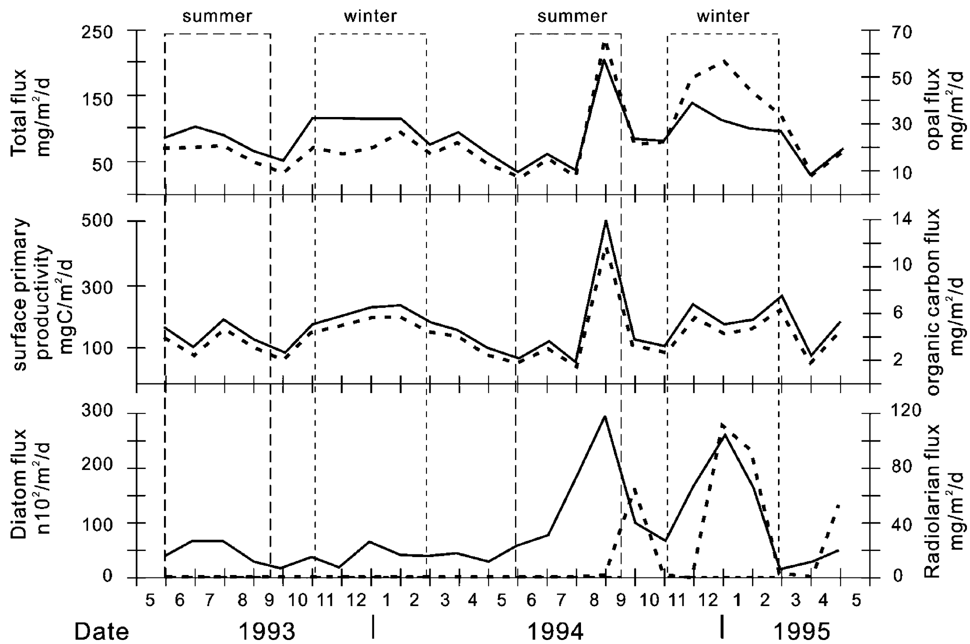

Fig. 2. Sediment trap fluxes during 1993–1995 in the central part of the South China Sea. The dashed quadrangles denote the East Asian summer or winter monsoon seasons (Chen et al., 1998; Wang R.J. et al., 2000).

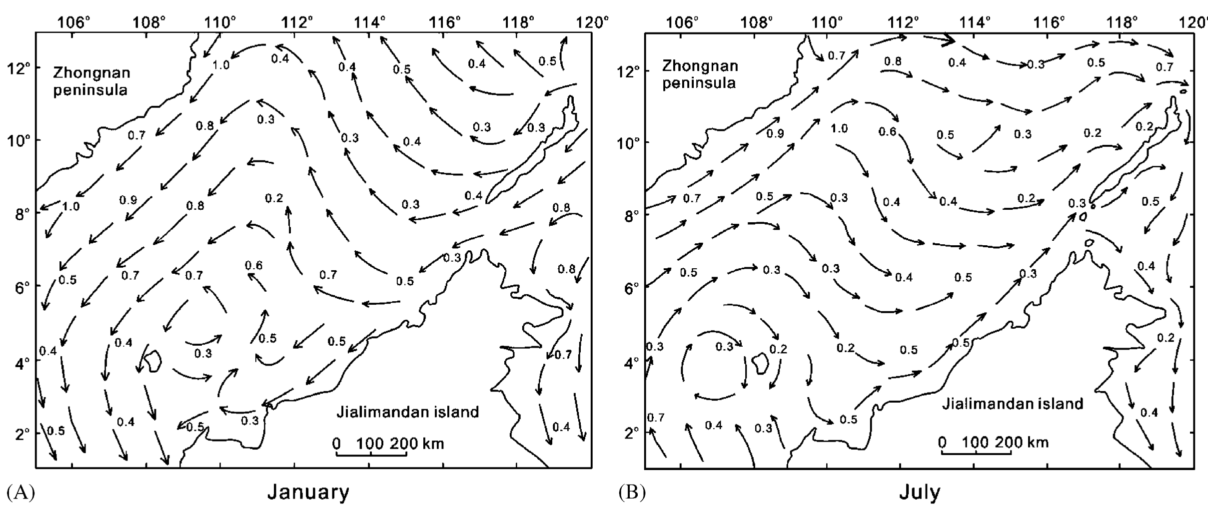

Fig. 3. The surface water circulation in the southern SCS in (A) July and (B) January. Note that an anti-clockwise surface water current forms in January and a clockwise surface water current forms in July (Zhao, 1996). The centers of both currents are close to the Natuna Island.

samples, as reported in Tian et al. (2002). The age model for Site 1143 was developed on the basis of the benthic isotopic record, magnetostratigraphy and biostratigraphy (Tian et al., 2002). Tuning the benthic isotopic record directly to the Earth's orbit helped create an astronomical timescale that bears greater chronological precision. The obliquity and precession of the astronomical solution of Laskar (1990) were used as the tuning targets. An 8-ka lag for the obliquity and a 5-ka lag for the precession were adopted for calculating the phase relationship between the benthic $\delta^{18}O$ and the orbit forcing.

4. Results

4.1. Comparison of *G. ruber* $\delta^{18}O$ between the SCS and the open western Pacific

Fig. 4A displays the *G. ruber* $\delta^{18}O$ of Site 1143 from the southern SCS and Site 806B (Lea et al., 2000) from the open western Pacific for the past 500 ka. The size of the foraminifer *G. ruber* for the isotope analysis at both sites is within the range from 0.25 to 0.35 mm. The laboratories at Tongji and Carrara marble had similar standard deviations, 0.07‰ for Site 1143 and 0.06‰ for

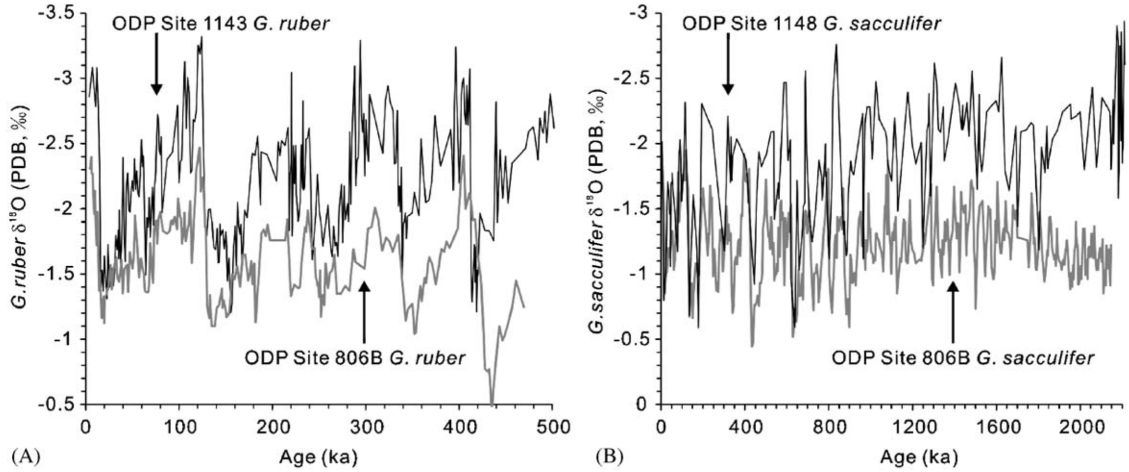

Fig. 4. Comparison of planktonic foraminiferal $\delta^{18}O$ records between the SCS and Ontong Java plateau, open western Pacific. (A) *G. ruber* $\delta^{18}O$ of Site 1143 and Site 806B; (B) *G. sacculifer* $\delta^{18}O$ of Site 1148 and Site 806B.

Site 806B. For the past 500 ka, Site 1143 *G. ruber* $\delta^{18}O$ has been light compared to Site 806B values by as much as 0.5–1.0‰ in interglacial periods and 0.1–0.5‰ in glacial periods. The average $\delta^{18}O$ amplitude of the last two glacial/interglacial cycles is ~1.65‰ at Site 1143, but is only ~1.2‰ at Site 806B. However, this value is ~1.7‰ at core TR163-19 from the eastern equatorial Pacific (Lea et al., 2000), very similar to the Site 1143 average. The primary factors affecting the planktonic foraminiferal $\delta^{18}O$ include SST, SSS and global ice volume change (Shackleton, 1974; Lear et al., 2000). The last glacial maximum (LGM) cooling relative to the Holocene was ~3°C in the tropical western Pacific including the SCS and the Ontong Java plateau (Lea et al., 2000; Kienast et al., 2001). The average glacial/interglacial temperature contrast for the past 470 ka on the Ontong Java Plateau was ~3–4°C based on Mg/Ca ratios (Lea et al., 2000). Although no Mg/Ca or alkenone $U^{k'}_{37}$ SST records before the LGM can be obtained from the SCS, the transfer function based on planktonic foraminiferal faunal analysis at core 17957-2 from the southern SCS indicates that the average glacial/interglacial winter and summer SST contrasts are ~3°C and less than ~1°C, respectively, for the past 1.5 Ma (Jian et al., 2000). These faunal SST estimates may characterize the overall temperature change in the ocean mixed layer, but they should not differ too much from the SST values from Mg/Ca or alkenone $U^{k'}_{37}$ methods. Assuming the glacial/interglacial SST changes were similar and the influence of the global ice volume change was equal between the two localities, the lighter *G. ruber* $\delta^{18}O$ of Site 1143 compared to that of Site 806B should be ascribed to low SSS in the southern SCS. This inference is consistent with modern observations that show a negligible mean annual SST difference of less than 0.5°C between the southern SCS and the open western Pacific but a lower mean annual SSS in the southern SCS by as much as 1‰ (Levitus et al., 1994). Modern observations also reveal that the SSS of the southern SCS will reach its minimum by decreasing 3‰ when strong winter and summer monsoons prevail (Zhao, 1996). Therefore, high precipitation during monsoon seasons often contributes to sea surface freshening and a lower SSS in the SCS compared to the normal seasons. During El-Niño years, when the precipitation center moves from the western Pacific to the central Pacific, precipitation increases over the SCS but decreases over other areas of the western Pacific (Wang B. et al., 2000). More negative planktonic $\delta^{18}O$ values than those from the open western Pacific are not only observed from the southern but also from the northern SCS, at Site 1148 where the *Globigerinoides sacculifer* $\delta^{18}O$ (Jian et al., 2003) is much lighter compared to the Site 806B record (Berger et al., 1993) (Fig. 4B). The stable isotope analyses of Sites 1148 and 1143 were all performed in the Laboratory of Marine Geology, Tongji University, which has similar standard deviation as the University of Bremen laboratory which measured the isotopes for Site 806B, with standard deviation of 0.07‰ for $\delta^{18}O$ and 0.05‰ for $\delta^{13}C$ during the year 1990 (Berger et al., 1993). The *G. sacculifer* $\delta^{18}O$ at Site 1148 is lighter than that at Site 806B by 0.5–1.0‰ in interglacial periods and by 0.1–0.7‰ in glacial periods for the past 2.2 Ma. In sum, the light planktonic foraminiferal $\delta^{18}O$ at Site 1143 and Site 1148 highlights the profound influence of the monsoon-induced precipitation on the hydrography of the SCS.

4.2. Comparison of the planktonic and benthic $\delta^{18}O$ at site 1143

For the past 5 Ma, especially during the Quaternary period, the benthic and planktonic $\delta^{18}O$ at Site 1143 display similar glacial/interglacial cycles and similar variations in their amplitude (Fig. 5). Some minor differences associated with amplitude variations exist in the time interval 4.1–5.0 Ma, and some significant differences associated not only with the amplitude but also with the glacial/interglacial pattern exist in the time interval 3.3–2.5 Ma. Thus, the Site 1143 $\Delta\delta^{18}O_{b-p}$ (benthic minus planktonic) for the past 5 Ma can be visually divided into three time intervals, namely, 5.0–3.3, 3.3–2.5 and 2.5–0 Ma.

The most significant change of the Site 1143 $\Delta\delta^{18}O_{b-p}$ is its gradual increase from 3.3 to 2.5 Ma (Fig. 5), apparently caused by more positive changes of the benthic $\delta^{18}O$ relative to the planktonic $\delta^{18}O$ over glacial/interglacial cycles. The time from 3.3 to 2.5 Ma was a period of the Northern Hemisphere ice-sheet building and amplifying, as documented clearly in many benthic $\delta^{18}O$ records such the tropical Atlantic ODP Site 659 (Tiedemann et al., 1994) and the east equatorial Pacific ODP Site 846 (Mix et al., 1995; Shackleton et al., 1995). The first and minor occurrence of ice-rafted detritus was found in Arctic and North Atlantic sediments with an age of ~2.75 Ma, indicating the initial Northern Hemisphere glaciation (Haug and Tiedemann, 1998). This global cooling and the final formation of the Northern Hemisphere glaciation are recorded in the glacial benthic $\delta^{18}O$ increase at Site 1143 from ~2.55‰ at 3.3 Ma to ~3.75‰ at 2.5 Ma, a positive shift of ~1.2‰. During the same period, however, the interglacial benthic $\delta^{18}O$ only increased by ~0.6‰ (Fig. 5). Although some benthic $\delta^{18}O$ changes may be due to deep water temperature and salinity variations, more than two-thirds of the benthic $\delta^{18}O$ increase over the past 4 Ma can be attributed to the accumulation of continental ice (Lear et al., 2000). Any change in the global ice volume may have an equal impact on the planktonic and benthic $\delta^{18}O$, and a growing global ice volume should have driven the planktonic $\delta^{18}O$ as well as the benthic $\delta^{18}O$ to become more positive. Therefore, the relatively stable glacial/interglacial planktonic $\delta^{18}O$ from 3.3 to 2.5 Ma at Site 1143 should be attributed to local SST and SSS changes in the southern SCS that made the planktonic $\delta^{18}O$ more negative so as to offset the positive impact from an increasing ice volume. Several cases should be considered under the premise that 2.334‰ SSS increase may lead to 1‰ $\delta^{18}O_{water}$ increase while 1°C SST increase may lead to 0.22‰ $\delta^{18}O_{water}$ decrease (Wang L. et al., 1995). Assuming there was no SSS changes 3.3–2.5 Ma ago, the glacial southern SCS as indicated by the planktonic $\delta^{18}O$ would have warmed by at least 5.5°C to constrain the effects of the gradually growing global ice volume on the planktonic isotopic composition. An increase of over 5°C may be unrealistic because the global cooling during this period was worldwide (Lear et al., 2000). The *G. ruber* $U^{k'}_{37}$-SST records from piston core 17 940 in the northern SCS imply a cooling of ~3°C during the LGM relative to the Holocene (Wang L. et al., 1999a). In the southern SCS, the *G. ruber* $U^{k'}_{37}$-SST records from core 18287-3 also imply a cooling of ~3°C at the LGM (Kienast et al., 2001). The *G. ruber* Mg/Ca-SST records from the open western Pacific suggest that the tropical equatorial Pacific SST was lower during the LGM than in the Holocene by at least 3°C or even 5°C (Lea et al., 2000; Visser et al., 2003). Therefore, an increase of more than 5.5°C SST in the southern SCS 3.3–2.5 Ma ago was impossible. By using planktonic foraminiferal faunal data from eight DSDP (deep sea drilling project) sites in the western Pacific and an improved transfer function particularly developed for tropical and subtropical areas, Wang L. (1994) found paleo-SST from 3.1 to 2.7 Ma decreased in the western sub-tropical Pacific but increased slightly or remained relatively stable in the western tropical and equatorial Pacific. If a decreased or stable SST existed in the southern SCS during this time period to counter the global ice volume impacts on the planktonic isotopic composition, the mean glacial SSS should be required to decrease by at least 2.8‰. An average glacial or interglacial SST change of 2°C in the region then seems to be reasonable. The SST estimates using planktonic foraminiferal transfer function from Site 1143 support a change of 2–3°C for the time period of 2.75–2.5 Ma (Xu Jian, Li Baohua, personal communication). An increase by ~2.5°C in the glacial or interglacial winter SST and a relative stable summer SST from 2.75 to 2.5 Ma shown in these results may suggest a decrease by ~0.794‰ of the local SSS in the southern SCS. Therefore, much of the planktonic $\delta^{18}O$ variations 3.3–2.5 Ma ago at Site 1143 most likely resulted from the local SSS decrease.

Unlike the great changes during 3.3–2.5 Ma, the glacial/interglacial $\delta^{18}O_{b-p}$ at Site 1143 was relatively stable after 2.5 Ma, especially in the Quaternary period. If the inference that the increased glacial or interglacial $\delta^{18}O_{b-p}$ indicates the local SSS decrease is correct, the relatively stable $\delta^{18}O_{b-p}$ during the Quaternary should correspond to relatively stable local SSS change although its amplitude within a glacial or interglacial cycle may be prominent. Generally, the Quaternary $\delta^{18}O_{b-p}$ is more positive in glacial periods and more negative in interglacial periods (Fig. 5). The benthic–planktonic $\delta^{18}O$ difference ($\delta^{18}O_{b-p}$) removes the global ice volume effects and mainly reserves the temperature and salinity effects of bottom and surface waters. Compared to the sea surface water, the modern SCS bottom water below 2000 m has rather stable temperature (2.5°C) and salinity (34.6–34.7‰) (Zhao, 1996). For the past 5 Ma, the average bottom water temperature of the global ocean had decreased for about 4°C, with a glacial/interglacial difference of less than 2°C during the Quaternary (Billups and Schrag, 2002), which is much smaller than SST fluctuations. Therefore, the primary part of the glacial/interglacial $\delta^{18}O_{b-p}$ fluctuations at

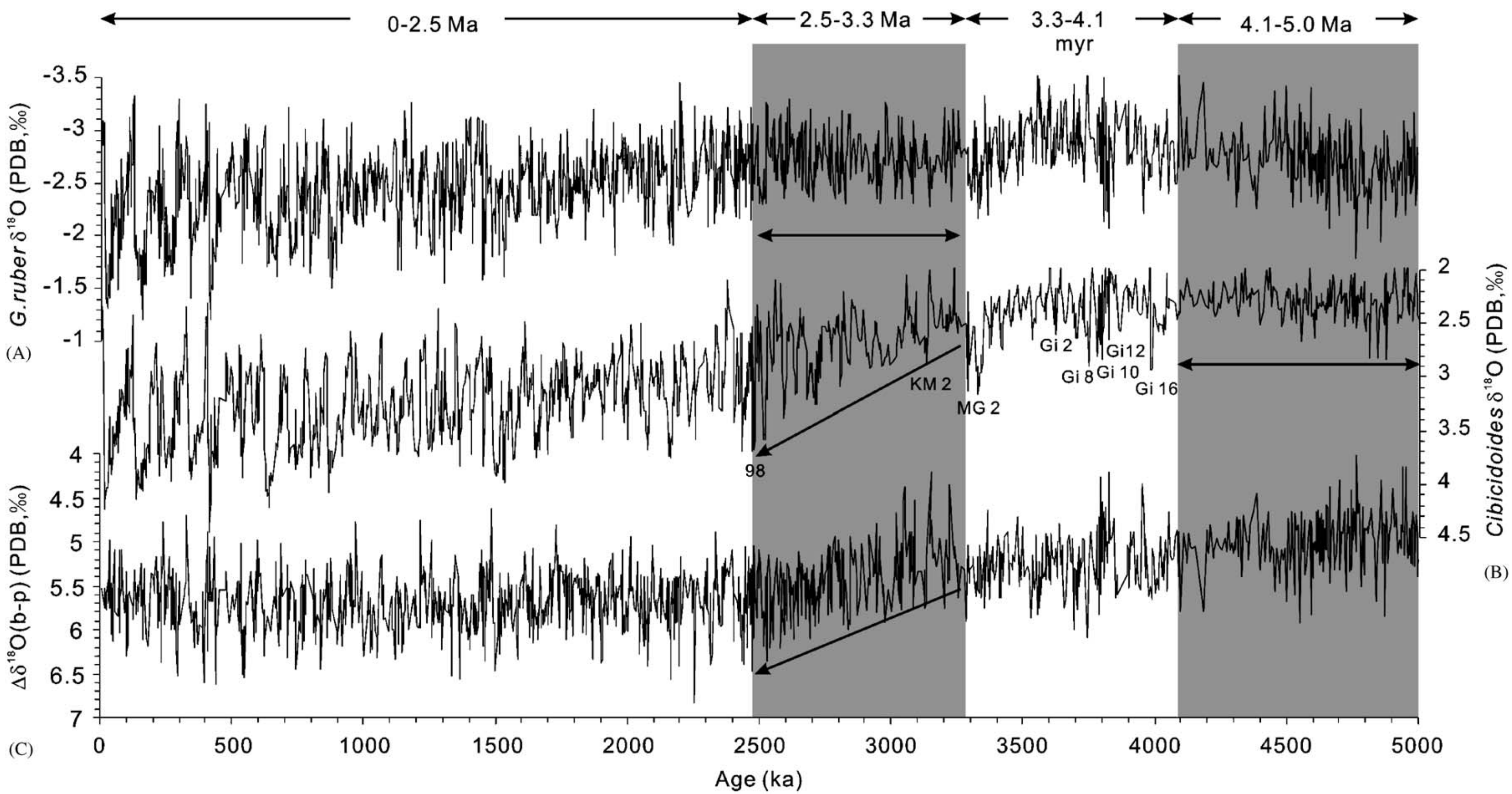

Fig. 5. Benthic and planktonic foraminiferal $\delta^{18}O$ records for the last 5 Ma from Site 1143. (A) *Cibicidoides* $\delta^{18}O$; (B) *G. ruber* $\delta^{18}O$; (C) $\Delta\delta^{18}O_{b-p}$. Numbers besides curve B denote some selected Marine Isotope Stages (MIS). $\Delta\delta^{18}O_{b-p}$ denotes the difference between the benthic and planktonic $\delta^{18}O$. Arrows denote the variational trend.

Site 1143 should be ascribed to SST and SSS variations. Because the planktonic and benthic δ^{18}O curves have identical glacial/interglacial cycles and similar amplitude variations (Fig. 5), implying the global ice volume change, the total effects of the SST and SSS on the planktonic foraminiferal isotopic composition in the southern SCS are believed to have been small relative to the continental ice volume effects.

5. Discussion

We interpret that intensified East Asian monsoon winds 3.3–2.5 Ma ago brought about frequent and strong precipitation and likely also the intrusion by Borneo alongshore low-salinity waters into the southern SCS, and ultimately led to the great decrease in the local SSS. Increased runoff in the same period may also be significant, especially for the northern SCS because of its proximity to the Asian continent although the runoff impacts are presently limited to the along shore areas, within a range of tens of kilometers (Sarnthein et al., 1994). The SSS time series deduced from the planktonic foraminiferal δ^{18}O and $U^{k'}_{37}$-SST records in core 17940 has indicated the East Asian monsoon variations from the LGM to present in the southern SCS (Wang L. et al., 1999a). ODP Site 1143 is more distant from the surrounding continents and islands than core 17940. Even during the LGM, the two main runoff sources of the southern SCS, the paleo-Mekong river and Molengraaff river mouths on the Sunda shelf, were still far away from the Site 1143 locality (Molengraaff, 1921; Tjia, 1980). Therefore, we exclude the runoff effects on the major local SSS change 3.3–2.5 Ma ago and ascribe this change to intensified East Asian monsoon winds that caused frequent and strong precipitation in the southern SCS.

Abundant evidence exists from the loess deposition in the central China and marine sediments in the north Pacific and Arabian Sea to support the inference of intensified Asian monsoon winds 3.3–2.5 Ma ago (Fig. 6). The magnetic susceptibility and Rb/Sr ratio, as the summer monsoon proxies, and grain size (>19 μm) variations and Al flux, as the winter monsoon proxies at Bajiazui section from the eastern loess plateau show gradual increasing trends 3.6–2.5 Ma ago, indicating the intensified East Asian summer and winter monsoon winds (An et al., 2001). The constructed record of eolian dust accumulation from the central North Pacific reveals the increase of dust deposition by an order of magnitude quite rapidly at 3.6 Ma that persisted until 2.5 Ma ago (Rea et al., 1998), implying the increased continental aridity over the central Asia and intensified Asian winter monsoon winds. The intensified Asian monsoon winds 3.6–2.5 Ma ago have been related to the uplift of the Himalaya–Tibetan Plateau at least along its northern and eastern margins, as demonstrated by the depositional facies transition from distal alluvial plains to

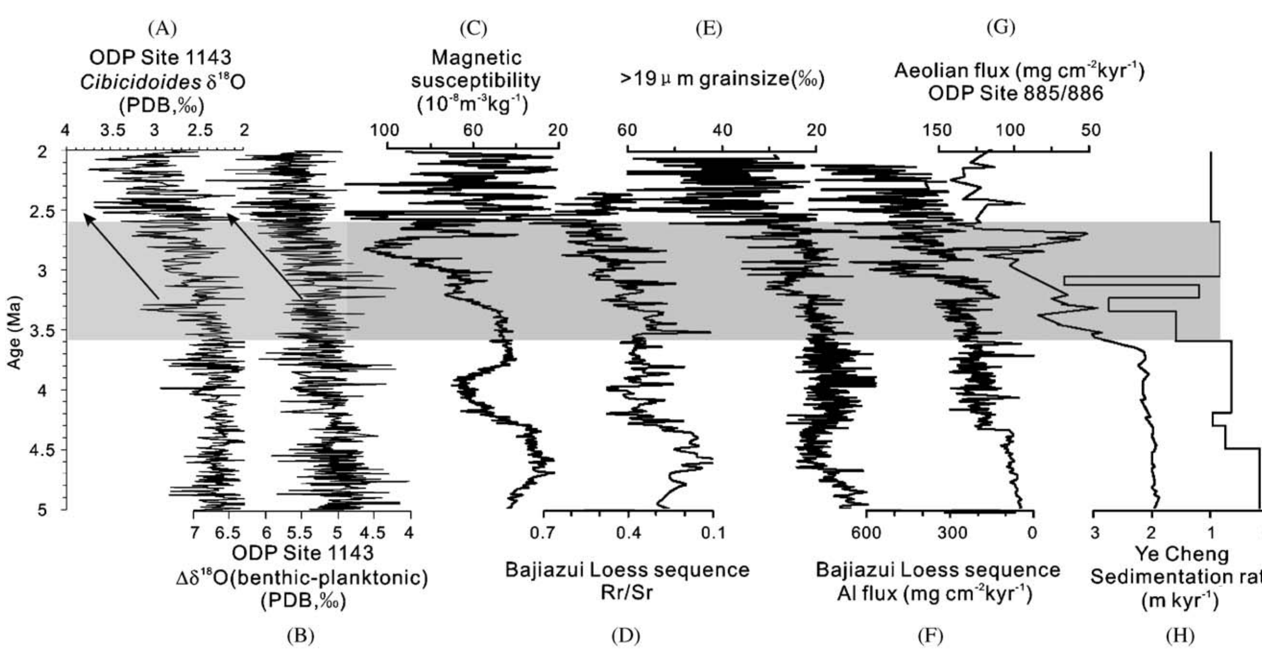

Fig. 6. Last 5–2 Ma monsoon proxy records from marine and terrestrial sediments. (A) *Cibicidoides* δ^{18}O of Site 1143; (B) $\Delta\delta^{18}O_{b-p}$ of Site 1143; (C) Magnetic susceptibility of Bajiazui section; (D) Rb/Sr ratio of Bajiazui section; (E) > 19 μm grain-size of Bajiazui section; (F) Al flux of Bajiazui section; (G) Aeolian flux of the north Pacific; (H) sedimentation rate at Yecheng. Note that the Bajiazui section is in the eastern loess plateau (An et al., 2001) and Yecheng is in the western Kunlun Mountains (Zheng et al., 2000). The arrows in A and B indicate the heavy trend of the δ^{18}O and $\Delta\delta^{18}O_{b-p}$ 3.3–2.5 Ma ago, which lag the abrupt changes of the aeolian flux in the north Pacific, the sedimentation rate of western Kunlun Mountains and the climate proxy records of the loess/paleosol sequences in the eastern loess plateau for about 300 ka.

proximal alluvial fans 4.5–3.5 Ma ago in the western Kunlun Mountain, and by the accompanying increase of sedimentation rate from an average ~ 0.15 mm/yr between the earliest Oligocene and the earliest Pliocene to ~ 1.4 mm/yr 3.6–2.6 Ma ago (Zheng et al., 2000). The average sedimentation rate also increases abruptly from ~ 39.5 m/Ma before 2.9 Ma to ~ 65.4 m/Ma after 2.9 Ma at Site 1143 (Tian et al., 2002). Numerical climate-modelling supports the coupled relationship between the Asian monsoon evolution and the Himalayan–Tibetan Plateau uplift (Prell and Kutzbach, 1992; An et al., 2001). Other proxies from SCS marine sediments also reveal the monsoon-related changes 3.3–2.5 Ma ago. For example, the total percentage of the warm water planktonic foraminiferal assemblage at Site 1143 gradually increased from $\sim 30\%$ to $\sim 70\%$ in this time period. The ratio between the mixed-layer species and thermocline species at Site 1143 indicates that the thermocline depth in the southern SCS abruptly shoaled 3.3 Ma ago (Li J. R., personal communication), and similar thermocline shoaling has also been recorded at Site 1146 in the northern SCS (Huang B. Q., personal communication). The opal flux is an indicator of the silica productivity, and at Site 1143 it also increases gradually over this time period (Li et al., 2002). Both the thermocline and opal flux changes at Site 1143 reflect the upper ocean structure changes in the southern SCS caused by the intensified East Asian monsoon winds.

The relatively stable glacial/interglacial $\Delta\delta^{18}O_{b-p}$ at Site 1143 after 2.5 Ma, especially in the Quaternary Period, implies a relatively steady stage of the East Asian monsoons both in the strength and in the frequency. Several evolutionary stages of Asian monsoons can be identified in the loess-paleosol sequence from the loess plateau of China and in marine sections from the Indian and North Pacific oceans (An et al., 2001). As revealed in those records, the East Asian summer monsoon weakened whereas the winter monsoon strengthened continuously from the late Pliocene to the Quaternary. Compared to the stage 3.6–2.6 Ma ago, however, the difference of the summer or winter monsoon strength between different glacials or interglacials since the late Pliocene was relatively small (An et al., 2001). This late Pliocene-Quaternary stage is characterized by relatively stable glacial or interglacial values of the $\Delta\delta^{18}O_{b-p}$ from Site 1143. The northern hemisphere ice sheet developed to the full scale in the late Quaternary, and its periodical waxing and waning not only modulate the two states of the global climate, the glacial and interglacial, but also strongly influence other regional climate activities such as the monsoon (Prell and Kutzbach, 1992). At Site 1143, the $\Delta\delta^{18}O_{b-p}$ is generally more positive during glacials but more negative during interglacials, indicating two different states of the East Asian monsoon alternating between these periods. Previous studies by Wang L. et al. (1999b) concluded that the late Quaternary East Asian winter monsoon was strong in glacials but weak in interglacials whereas the summer monsoon was strong in interglacials but weak in glacials. As indicated by the foraminiferal transfer-function-SST records at core 17957-2 in the southern SCS, the amplitude of the winter SST change across successive Quaternary glacial/interglacial cycles is 3–4°C, but less than 1°C for the summer SST (Jian et al., 2000). Although the SST–SSS relationship is complicated and may not always be linear, strong winter monsoon during glacials could bring the cold subsurface water to the surface and cause a mixing in the upper ocean. Therefore, we interpret the more positive values of $\Delta\delta^{18}O_{b-p}$ during Quaternary glacials reflect stronger East Asian winter monsoon but weaker summer monsoon and their more negative values during interglacials likely correspond to stronger East Asian summer monsoon but weaker winter monsoon.

The Site 1143 $\Delta\delta^{18}O_{b-p}$ record indicates two main stages of the East Asian monsoon in the last 5 Ma: the intensification of the monsoon 3.3–2.5 Ma ago followed by a relatively steady stage of the monsoon variability in the Quaternary period. Detailed SST reconstruction based on Mg/Ca ratios or alkenone thermometry $U_{37}^{k'}$ and global ice volume reconstruction since the Pliocene may provide a key to the understanding of the evolution of the monsoon as well as the mechanism as to how the monsoon influences the foraminiferal isotopic composition.

6. Conclusions

1. The glacial–interglacial planktonic $\delta^{18}O$ was relatively stable compared to the gradually increasing benthic $\delta^{18}O$ 3.3–2.5 Ma ago from Site 1143 in the southern South China Sea, at the time of Northern Hemisphere glaciation. We infer the increasing benthic-planktonic $\delta^{18}O$ difference ($\Delta\delta^{18}O_{b-p}$) during this time period to be caused primarily by the local SSS changes, which counteracted the effects of SST and global ice volume. The intensified East Asian monsoon winds 3.3–2.5 Ma ago brought about much more frequent and intense precipitation over the SCS and likely enhanced the intrusions of Borneo alongshore low-salinity water to the southern SCS, leading to the dramatic decrease of the local SSS and the observed large $\Delta\delta^{18}O_{b-p}$ difference.
2. During the Quaternary, the relatively stable $\Delta\delta^{18}O_{b-p}$ over glacial–interglacial intervals at Site 1143 implies a steady stage in the evolution of the East Asian monsoon modulated by glacial–interglacial cycles. The more positive values of the glacial $\Delta\delta^{18}O_{b-p}$ probably indicate stronger East Asian winter monsoon at cooler times, and the more

negative values of the interglacial $\Delta\delta^{18}O_{b-p}$ likely correspond to stronger East Asian summer monsoon at warmer times.

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References

An, Z.S., Kutzbach, J.E., Prell, W.L., Porter, S.C., 2001. Evolution of Asian monsoons and phased uplift of the Himalaya–Tibetan plateau since Late Miocene times. Nature 411, 62–66.

Berger, W.H., Bickert, T., Schmidt, H., Welfer, G., 1993. Quaternary oxygen isotope records of pelagic foraminifers: Site 806, Ontong Java Plateau. In: Berger, W.H., Mayer, L.W., et al. (Eds.), Proceeding of ODP Scientific Results, Vol. 130, pp. 381–395.

Billups, K., Schrag, D.P., 2002. Paleotemperatures and ice volume of the past 27 Myr revisited with paired Mg/Ca and 18O/16O measurements on benthic foraminifera. Paleoceanography 17 (3–1), 3–11.

Chen, J.F., Zheng, L.F., Wiesner, M.G., Chen, R., Zheng, Y., Wong, H.K., 1998. Estimations of primary production and export production in the South China Sea on sediment trap experiments. Chinese Science Bulletin 43 (7), 583–586.

Ding, Z.L., Rutter, N.W., Han, J.T., Liu, T.S., 1992. A coupled environmental system formed at about 2.5 Ma over East Asia. Palaeogeography, Palaeoclimatology, Palaeoecology 94, 223–242.

Ding, Z.L., Yu, Z.W., Rutter, N.W., Liu, T.S., 1994. Towards an orbital time scale for Chinese loess deposits. Quaternary Science Reviews 13, 39–70.

Guo, Z.T., Ruddiman, W.F., Hao, Q.Z., Wu, H.B., Qiao, Y.S., Zhu, R.X., Peng, S.Z., Wei, J.J., Yuan, B.Y., Liu, T.S., 2002. Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China. Nature 416, 159–163.

Haug, G.H., Tiedemann, R., 1998. Effect of the Formation of the Isthmus of Panama on Atlantic Ocean Thermohaline Circulation. Nature 393, 673–676.

Jian, Z.M., Wang, P.X., Chen, M.P., Li, B.H., Zhao, Q.H., Burhring, C., Lin, H.L., Laj, C., Pflaumann, U., Bian, Y.H., Wang, R.J., Cheng, X.R., 2000. Foraminiferal responses to major Pleistocene paleoceanographic changes in the southern South China Sea. Paleoceanography 15, 229–243.

Jian, Z.M., Zhao, Q.H., Cheng, X.R., Wang, J.L., Wang, P.X., Su, X., 2003. Pliocene–Pleistocene stable isotope and paleoceanographic changes in the northern South China Sea. Palaeogeography, Palaeoclimatology, Palaeoecology 193, 425–442.

Kienast, M., Steinke, S., Stattegger, K., Calvert, S.E., 2001. Synchronous tropical South China Sea SST change and Greenland warming during deglaciation. Science 291, 2132–2134.

Laskar, J., 1990. The chaotic motion of the solar system: a numerical estimate of the size of the chaotic zones. Icarus 88, 266–291.

Lea, D.W., Pak, D.K., Spero, H.J., 2000. Climate impact of Late Quaternary equatorial Pacific sea surface temperature variation. Science 289, 1719–1724.

Lear, C.H., Elderfield, H., Wilson, P.A., 2000. Cenozoic deep-sea temperatures and global ice volumes from Mg/Ca in benthic foraminiferal calcite. Science 287, 269–272.

Levitus, S., Burgett, R., Boyer, T.P., 1994. World Ocean Atlas, Salinity, Vol. 3, US Department of Commerce, Washington DC, p. 99.

Li, C.Z., Huang, Z.Z., Chen, R.X., et al., 1988. Integrated Environmental and Resources Investigation Reports in the Middle South China Sea. China Ocean Press, Beijing, p. 45.

Li, J.R., Wang, R.J., Li, B.H., 2002. Variations of opal accumulation rates and paleoproductivity over the past 12 Ma at ODP Site 1143 southern South China Sea. Chinese Science Bulletin 47 (07), 596–598.

Mix, A.C., Pisias, N.G., Rugh, W., Wilson, T., Morey, A., Hagelberg, T.K., 1995. Benthic foraminifer stable isotope record from site 849 (0–5 Ma): local and global climate changes. In: Pisias, N.G., Mayer, L.A., Janecek, T.R., et al. (Eds.), Proceedings of the ODP Science Results, Vol. 138, pp. 371–412.

Molengraaff, G.A.F., 1921. Modern deep-sea research in the East Indian Archipelago. Geography Journal 57, 95–121.

Porter, S.C., An, Z.S., Zheng, H.B., 1992. Cyclic Quaternary alleviation and terracing in a nonglaciated drainage basin on the north flank of Qingling Shan, central China. Quaternary Research 38, 157–169.

Prell, W.L., Kutzbach, J.E., 1992. Sensitivity of the Indian monsoon to forcing parameters and implications for its evolution. Nature 360, 647–652.

Rea, D.K., 1994. The paleoclimatic record provided by eolian deposition in the deep sea: the geologic history of wind. Reviews of Geophysics 32, 159–195.

Rea, D.K., Snoeckx, H., Joseph, L.H., 1998. Late Cenozoic eolian deposition in the North Pacifc: Asia drying, Tibetan Uplift, and cooling of the Northern Hemisphere. Paleoceanography 13, 215–224.

Sarnthein, M., Pflaumann, U., Wang, P.X., Wong, H.K. (Eds.), 1994. Preliminary Report on SONNE-95 Cruise 'Monitor Monsoon' to the South China Sea. Berichte-Reports, Geol.-Palaeontol. Inst. Univ. Kiel, Vol. 48, p. 225.

Shackleton, N.J., 1974. Attainment of isotopic equilibrium between ocean water and the benthonic foraminifera genus *Uvigerina*: isotopic changes in the ocean during the last glacial. Les Meth. Quant. d'etude Var. Clim. an Cours du Pleist., Coll. Int. CNRS 219, 203–209.

Shackleton, N.J., Hall, N.J., Pate, D., 1995. Pliocene stable isotope stratigraphy of site 846. In: Pisias, N.G., Mayer L.A., Janecek, T.R., et al. (Eds.), Proceedings of the ODP Science Results, Vol. 138, pp. 337–355.

Shipboard scientific party of ODP Leg 130, 1990. Initial Reports 130. Ocean Drilling Program College Station, TX, pp. 320.

Tian, J., Wang, P.X., Chen, X.R., Li, Q.Y., 2002. Astronomically tuned Plio-Pleistocene benthic $\delta^{18}O$ records from South China Sea and Atlantic-Pacific comparison. Earth and Planetary Science Letters 203, 1015–1029.

Tiedemann, R., Sarnthein, M., Shackleton, N.J., 1994. Astronomic timescale for the Pliocene Atlantic $\delta^{18}O$ and dust flux records from Ocean Drilling Program Site 659. Paleoceanography 9, 619–638.

Tjia, H.D., 1980. The Sunda Shelf, southeast Asia. Z. Geomorphology 24, 405–427.

Vandenberghe, J., An, Z.S., Nugteren, G., Lu, H.Y., Huissteden, K.V., 1997. New absolute time scale for the Quaternary climate in the Chinese loess region by grain size analysis. Geology 25, 35–38.

Visser, K., Thunell, R., Stott, L., 2003. Magnitude and timing of temperature change in the Indo-Pacific warm pool during deglaciation. Nature 421, 152–155.

Wang, B., Wu, R., Fu, X., 2000. Pacific-East Asian Teleconnection: how does ENSO affect east Asian climate. Journal of Climate 3, 1517–1536.

Wang, L., 1994. Sea surface temperature history of the low latitude western Pacific during the last 5.3 million years. Palaeogeography, Palaeoclimatology, Palaeoecology 108, 379–436.

Wang, L., Sarnthein, M., Duplessy, J.-C., Erlenkeuser, H., Jung, S., Pflaumann, U., 1995. Paleo sea surface salinities in the low-latitude Atlantic: the $\delta^{18}O$ record of Globigerinoides ruber (white). Paleoceanography 10, 749–761.

Wang, L., Sarnthein, M., Erlenkeuser, H., Grimalt, J., Grootes, P., Grimalt, J., Pelejero, C., Linck, G., 1999a. Holocene variations in Asian monsoon moisture: a bidecadal sediment record from the South China Sea. Geophysical Research Letters 26, 2889–2892.

Wang, L., Sarnthein, M., Erlenkeuser, H., Grimalt, J., Grootes, P., Heilig, S., Ivanova, E., Kienast, M., Pelejero, C., Pflaumann, U., 1999b. East Asian monsoon climate during the late Pleistocene: high-resolution sediment records from the South China Sea. Marine Geology 156, 245–284.

Wang, P., Wang, L., Bian, Y., Jian, Z., 1995. Late Quaternary paleoceanography of the South China Sea: surface circulation and carbonate cycles. Marine Geology 127, 145–165.

Wang, P., Prell, W.L., Blum, P., 2000. Proceedings of the Ocean Drilling Program, Initial Reports 184, Ocean Drilling Program College Station, TX.

Wang, R.J., Lin, J., Zheng, L.F., Chen, R.H., Chen, J.F., 2000. Siliceous microplankton fluxes and seasonal variations in the central South China Sea during 1993–1995: monsoon climate and El Niño responses. Chinese Science Bulletin 45 (23), 2168–2172.

Wiesner, M.G., Zheng, L., Wong, H.K., Wang, Y.B., Chen, W.B., 1996. Fluxes of particulate matter in the South China Sea. In: Ittekkot, V., Schäfer, P., Honjo, S., Depetris, P.J. (Eds.), Particle Flux in the Ocean. Wiley, New York, pp. 293–312.

Zhao, H.T., 1996. Natural Geography of Nansha Islands. Science Press of China, Beijing, pp. 186–201 (in Chinese).

Zheng, H.B., Powell, C., An, Z., Zhou, J., Dong, G., 2000. Pliocene uplift of the northern Tibetan Plateau. Geology 28, 715–718.