Phased evolution of the south–north hydrographic gradient in the South China Sea since the middle Miocene

Zhimin Jian a,*, Yongqiang Yu b, Baohua Li c, Jiliang Wang d, Xuehong Zhang b, Zuyi Zhou c

a State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China
b State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Chinese Academy of Sciences, Beijing 100029, China
c Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China
d Shanghai Science and Technology Museum, Shanghai 200127, China

Received 22 October 2004; received in revised form 22 July 2005; accepted 29 July 2005

Abstract

The hydrography of the South China Sea (SCS) is characterized by a south–north (S–N) thermocline gradient in the upper water column from the northern margin of the western Pacific warm Pool (WPWP) to the sea area largely controlled by the East Asian monsoon. Here we examine the records of planktonic foraminifers from Ocean Drilling Program (ODP) Sites 1143 and 1146 in the southern and northern parts of the SCS, respectively, that identify three stages of evolution of the S–N hydrographic gradient in the SCS since the middle Miocene: first, the S–N thermocline gradient possibly occurred in the SCS for the first time during the period 11.5~10.6 Ma, reflected by an opposite change in the relative abundance of deep-dwelling planktonic foraminiferal species in the south and north; next, the S–N thermocline gradient weakened or even disappeared during the period 10.6~4.0 Ma, indicated by similar changes in the relative abundance of deep-dwelling species in the south and north; last, the S–N thermocline gradient substantially increased from about 4.0~3.2 Ma, marked by a major increase in abundance of deep-dwelling species in the northern SCS and a decrease in the southern SCS. Based on the results of oceanic and coupled ocean–atmosphere model experiments and previous studies on planktonic foraminifers in the Pacific Ocean, it is inferred that the initial WPWP was probably formed during the period of 11.5~10.6 Ma in response to the closure of the Indonesian seaway; The WPWP then weakened or became extremely unstable, before developing its present expression about 4.0~3.2 Ma, induced by the emergence of the Isthmus of Panama. Our observations and model experiments support the argument that the stages in evolution of the WPWP are linked to tectonic changes in ocean gateways.

Keywords: Planktonic foraminifera; Upper water structure; South China Sea; Western Pacific warm pool; Numerical modeling; Miocene–Pliocene

* Corresponding author. Tel.: +86 21 65984819; fax: +86 21 65988808.
E-mail address: zjiank@online.sh.cn (Z. Jian).

0031-0182/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
1. Introduction

The climate in the South China Sea (SCS) region is largely controlled by the East Asian monsoonal wind system which is characterized by its pronounced seasonality. Since the Sonne-95 cruise in 1994, the SCS has been intensively studied for reconstruction of the evolution and variability of the East Asian monsoon (Sarnthein et al., 1994; Wang et al., 1999; Jian et al., 2001). The Ocean Drilling Program (ODP) Leg 184 to the SCS in 1999 and associated post-cruise researches have resulted in many publications on this topic (see Wang et al., 2000; Clemens et al., 2003; Jia et al., 2003; Jian et al., 2003).

The SCS strides the northern margin of the western Pacific warm Pool (WPWP) which is bounded approximately by the 28 °C surface isotherm (Yan et al., 1992), and hence its hydrography is strongly influenced by the tropical climate (Wang, 1998; Wang et al., 2003). From the WPWP to extra-WPWP regions, there are distinct thermocline gradients in the upper water column. For instance, the equatorial Pacific is characterized by a west–east (W–E) thermocline gradient from the WPWP to the

Fig. 1. Locations of ODP Sites 1143 and 1146 and geographic features. The dashed lines indicate the multi-annual surface isotherms, with a heavy line for the 28 °C surface isotherm which is approximately regarded as the northern boundary of the present WPWP, while the black arrows indicate generalized wind directions of the winter monsoon.
eastern equatorial Pacific (Kennett et al., 1985; Cannariato and Ravelo, 1997; Chen and Prell, 1998; Chaisson and Ravelo, 2000; Ravelo et al., 2004). Likewise, there is a distinct south–north (S–N) thermocline gradient in the modern SCS (Wyrtki, 1961; Levitus and Boyer, 1994; Chen et al., 1998), that is, from the northern WPWP to extra-WPWP regions.

In this study, we selected ODP Sites 1143 (9°21.72′N, 113°17.11′E; 2772 m water depth) and 1146 (19°27.4′N, 116°16.4′E; 2092 m water depth) from the southern and northern parts of the SCS, respectively for planktonic foraminiferal analysis to estimate the changes in the depth of thermocline (DOT) since the early Miocene at Site 1146 and the middle Miocene at Site 1143 (Wang et al., 2000). Site 1143 is located within the northern margin of the WPWP and has kept its position since the cessation of seafloor spreading of the SCS basin around 17 Ma (Taylor and Hayes, 1980). Its hydrography is greatly influenced by the tropical climate and should be sensitive to the evolution of the WPWP (Wang, 1998; Wang et al., 2003; Li et al., 2004). Conversely, Site 1146 is outside the present WPWP, and its hydrography is largely controlled by the East Asian monsoon (Fig. 1). The annual DOT in the SCS rises from ~175 m in the south to ~125 m in the north (Levitus and Boyer, 1994; Chen et al., 1998) due to the different climatic regime. This results in the S–N thermocline gradient from the WPWP to extra-WPWP regions between the two sites. It is believed that the S–N thermocline gradient strengthens along with the increase in the influence of the WPWP on the southern SCS through the piling of warm surface water.

In order to improve our understanding of the hydrographic history of the tropical ocean in the Pacific, we examine planktonic foraminifera from two ODP sites to evaluate the changes of the S–N thermocline gradient in the upper water column since middle Miocene in the SCS, and then to reconstruct the evolution of the WPWP, which is furthermore verified by numerical simulations.

2. Materials and methods

Sediments at the two ODP sites are mainly composed of carbonate-rich grey clay with good preservation. We sampled Site 1143 every 50–150 cm and Site 1146 every 100–150 cm, obtaining 497 and 538 samples, respectively, equivalent to an average time resolution of ~25 ka for Site 1143 and ~35 ka for Site 1146 according to the revised biostratigraphy and magnetostratigraphy of Wang et al. (2000) and Li et al. (2004). All the samples were processed using standard micropaleontological techniques. At least 300 specimens of planktonic foraminifers were picked from the size fraction ≥150 µm in each sample, and then identified and counted.

Planktonic foraminifers live in the upper water column with distinct depth habitats. The shallow-dwelling species in the mixed-layer are often characterized by a spinose wall, while most deep-dwelling species within and/or below the thermocline have a non-spinose, pitted to smooth or postulate test surface (Bé, 1977; Fairbanks et al., 1982; Hemleben et al., 1989). Previous studies have demonstrated that the deep-dwelling species increase in abundance when the thermocline becomes shallow and vice versa (Ravelo et al., 1990). Based on the depth habitats of recent planktonic foraminiferal species (Fairbanks et al., 1982; Ravelo et al., 1990) and the paleoecology of extinct species estimated by evidence for morphological evolution and oxygen isotopes (Kennett and Srinivasan, 1983; Gasperi and Kennett, 1993; Chaisson, 1995; Chen and Prell, 1998), the following species: Globorotalia crassaformis, Globorotalia fohsi, Globorotalia margaritae, Globorotalia menardii s.l., Globorotalia inflata, Globorotalia periphreroacuta, Globorotalia puncticulata, Globorotalia scitula, Globorotalia tosaensis, Globoquadrina truncatulinoides, Globoquadrina venezuelana, Globoquadrina dehiscentis, Neogloboquadrina spp., Peneroplis spp., Sphaeroidinella spp. and Globigerina nepenth is adopted as deep-dwelling species in this study.

In order to examine the effect of the closure of the Indonesian and Central American seaways on the evolution of the WPWP, we have performed oceanic and coupled ocean–atmosphere model experiments. All the experiments were forced with the modern surface conditions except topography. The oceanic model L30T63 is the third-generation global Oceanic General Circulation Model (OGCM) developed at the Institute of Atmospheric Physics by Jin et al. (1999). Its horizontal grid is just the same as that of a T63 spectral atmospheric general circulation model (AGCM) with the grid size of about 1.875° × 1.875°. There are 30
layers in the vertical, of which 12 equal depth layers were placed in the upper 300 m for better depiction of the equatorial DOT. Based on the plate tectonic evolution of Southeast Asia and the Southwest Pacific (Hall, 2002) and the OGCM’s horizontal resolution, three model topographies, i.e. modern, 6.0 Ma (with the Indonesian seaway largely closed) and 14.0 Ma (with an open Indonesia seaway) were produced (Fig. 2; Yu et al., 2004) for sensitivity experiments, named as O0, O6 and O14, respectively, to test the sensitivity of the DOT of the WPWP to the changing topography at different times. The OGCM was integrated 1160 years before reaching the equilibrium state (Jin et al., 1999), and then integrated another 500 years for all three experiments before reaching the equilibrium state. In the study, the annual mean results of O0, O6 and O14 experiments in the 1660th model year are compared. In addition to the sensitivity experiments for the individual OGCM as above, we carried out four coupled ocean–atmosphere model experiments with the grid size of approximately $2.8^\circ \times 2.8^\circ$ for the atmosphere model, using the primary version of a Flexible General Circulation Model for the climate system (referred to as FGCM-0) (Yu et al., 2002), based on the model topography of modern (Control), 6 Ma (EXP-1), 14 Ma (EXP-2), and 14 Ma but with an open Central American seaway (EXP-3), respectively. The FGCM-0 is formulated based on the NCAR CSM-1 (Boville and Gent, 1998), by replacing the CSM-1’s ocean component with the L30T63 in virtue of the CSM’s flux coupler. The atmosphere component of FGCM-0 is the CCM3 (Kiehl et al., 1998). To diminish the initial shock in the coupling process, a spin-up procedure was adopted before running the FGCM-0, which has been integrated for 60 years successfully. Although the flux correction was not employed in the coupled model FGCM-0, the model does not show obvious

Fig. 2. The horizontal currents averaged in the upper 300 m from the individual OGCM with contemporary climatological forcing. The modern (a), 6 Ma (b) and 14 Ma (c) topographies are adopted in the model, in which arrows indicate currents while black areas show land distribution.
climate drift. This is because all component models, the NCAR CCM3, the land model, the sea ice model, as well as the OGCM, show good ability to depict dynamical and physical processes in the climate system. Initial values of the four coupled experiments come from the equilibrium state of the sensitivity experiments with the OGCM only and they are integrated for 20 years. Then, five-year mean results of Control, EXP-1, EXP-2 and EXP-3 were compared during the last 5 model years, which are sufficient knowing that ENSO has only a ~2 year periodicity in this coupled model (Yu et al., 2002). Although, the resolutions of the oceanic and coupled ocean–atmosphere models are too low to adequately depict the thermocline changes of the SCS with complicated topography, these sensitive experiments do show significant adjustments in the DOT across the Pacific that are relevant to the SCS data, and could provide helpful information on the role of tectonic changes of various ocean gateways in the evolution of the WPWP.

3. Results

The changes in relative abundance of planktonic foraminiferal deep-dwelling species are displayed in Fig. 3, which can be used to qualitatively indicate the DOT changes (Ravelo et al., 1990; Chen and Prell, 1998) in this study. Overall, prior to ~11.5 Ma the changes in relative abundance of deep-dwelling species displays a similar trend at the two sites (Fig. 3c), indicating that the DOT was almost the same in the southern and northern parts of the SCS. This implies that the S–N thermocline gradient did not exist in the SCS at that time. However, during the period of 11.5–

![Fig. 3. Changes of proxies indicating the south–north thermocline gradient in the SCS and the west–east thermocline gradient in the equatorial Pacific. The shaded zones at 11.5–10.6 and 4.0–3.2 Ma indicate the times of the WPWP evolution detailed in the text. a) The relative abundance (%) of the planktonic foraminiferal deep-dwelling species at ODP Site 1146 in the northern SCS. Higher abundance indicates shallower DOT. b) The relative abundance (%) of the deep-dwelling species at ODP Site 1143 in the southern SCS. c) Five-points moving average of curves a and b after interpolation every 35 ka. The relative abundance of planktonic foraminiferal deep-dwelling species displays an opposite trend in the northern and southern SCS, with high values in the north and low ones in the south during the period 11.5–10.6 Ma and since 4.0–3.2 Ma, indicating that the DOT shoaled in the northern SCS while it deepened in the southern SCS during the two time intervals. d) The δ¹⁸O difference between *N. dutertrei* and *G. sacculifer* (Δδ¹⁸O_{dut–sac}) at ODP Sites 847 and 806 from the eastern and western equatorial Pacific, respectively, which represents the thermal gradient between the thermocline habitat of the former species and surface habitat of the latter. The shaded zone is the interval in which a significant increase in Δδ¹⁸O_{dut–sac} occurs in the eastern equatorial Pacific.}
10.6 Ma, the relative abundance of deep-dwelling species displays an opposite trend in the south and north, with low values (minimum 3.5%) in the south and high ones in the north (maximum 82.0%), showing that the DOT was deep in the southern SCS while shallow in the northern SCS. This could reflect the first occurrence of the S–N thermocline gradient in the SCS.

Afterwards, the relative abundance of deep-dwelling species displayed parallel changes again at the two sites and the values at the two sites were very close during the period of 10.6~4.0 Ma (Fig. 3c), implying the DOT was not distinctly different and it consistently changed in the south and north. It is inferred that the S–N thermocline gradient became very weak and unstable or even disappeared in the SCS during this time interval.

The most conspicuous change in the relative abundance of deep-dwelling species took place about 4.0~3.2 Ma. When the deep-dwelling species conspicuously increased in abundance from ~30% to 60% in the northern SCS and decreased in the southern SCS with minimum value lower than 10% (Fig. 3). This indicates that the DOT shoaled in the northern SCS and deepened in the southern SCS and thus the S–N thermocline gradient increased substantially. In the northern SCS, the most abundant deep-dwelling species was *Neoglobaquadrina dutertrei* (with an average value of 22.6% for the last 3.2 Ma), a typical East Asian winter monsoon indicator. Its remarkable increase in the northern SCS has previously been ascribed to the nutrient-rich surface water and the shoaled DOT induced by the strengthened East Asian winter monsoon (Huang et al., 2003; Jian et al., 2003). However, in the southern SCS, this species did not show the same pattern of change. Most of the deep-dwelling species except *Pulleniatina obliquiloculata* (with an average value of 14.3% for the last 1.5 Ma) decreased in abundance in the southern SCS during the last 3.2 Ma. *P. obliquiloculata* is a typical...

![Fig. 4. Changes of proxies indicating carbonate preservation and productivity in the SCS during the last 18 Ma.](image-url)

<table>
<thead>
<tr>
<th>MAR carbonate (g/cm²/ka)</th>
<th>MAR opal (g/cm²/ka)</th>
<th>Fragmentation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1146</td>
<td>Site 1143</td>
<td>Site 1146</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>0.6</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>0.8</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>12</td>
<td>1.2</td>
<td>12</td>
</tr>
<tr>
<td>14</td>
<td>1.4</td>
<td>14</td>
</tr>
<tr>
<td>16</td>
<td>1.6</td>
<td>16</td>
</tr>
<tr>
<td>18</td>
<td>1.8</td>
<td>18</td>
</tr>
</tbody>
</table>

Fig. 4. Changes of proxies indicating carbonate preservation and productivity in the SCS during the last 18 Ma. a) The mass accumulation rate (MAR) of carbonate at ODP Site 1146 in the northern SCS. MAR (g/cm²/ka)=content (%) × sedimentation rate (cm/ka) × dry bulk density (g/cm³). Higher values indicate increased productivity. b) The MAR of opal at ODP Site 1143 in the southern SCS (Li et al., 2002). Higher values indicate increased productivity. c) The planktonic foraminiferal fragmentation at ODP Site 1146 in the northern SCS. Fragmentation=(F/8)/(F/8+W)%, where F is the number of fragments and W is that of well-preserved planktonic foraminifera in the sample. d) The planktonic foraminiferal fragmentation at ODP Site 1143 in the southern SCS.
tropical species, which is very abundant in the western equatorial Pacific with a deep thermocline (Bé, 1977; Chaisson, 1995). Therefore, since about 4.0–3.2 Ma, the northern and southern SCS have belonged to different climate regimes, in which the climate in the northern SCS is dominated by the East Asian monsoon while that in the southern SCS is strongly influenced by the tropical climate, resulting in a distinct and stable S–N thermocline gradient in the SCS.

In order to evaluate how robust the relative abundance values of deep-dwelling species are to hydrographic changes, other factors such as carbonate preservation and productivity also have been examined in this study. Planktonic foraminiferal fragmentation is used to indicate carbonate preservation, while mass accumulation rate (MAR) of carbonate at Site 1146 and of opal at Site 1143 (Li et al., 2002) are adopted to indicate changes of productivity (Fig. 4). During the period 11.5–10.6 Ma, both fragmentation and MAR of carbonate or opal changed little at both sites, indicating that foraminiferal changes in the SCS during this period were not caused by the carbonate preservation and productivity. However, during the period of 5.0–2.0 Ma, although productivity indicated by the MAR of carbonate or opal did not show any significant changes at both sites, carbonate preservation indicated by fragmentation displayed substantially increased dissolution from ~3.0 Ma B.P. at both sites and the carbonate dissolution was stronger in the south than in the north. Because strong carbonate dissolution tends to preserve more deep-dwelling dissolution-resistant planktonic foraminiferal tests, the decrease in deep-dwelling species abundance and associated deepened DOT in the southern SCS since 4.0–3.2 Ma (Fig. 3) was not controlled by the degree of carbonate preservation.

Therefore, based on the changes in the relative abundance of deep-dwelling planktonic foraminiferal species, three stages of evolution of the S–N hydrographic gradient have been identified in the SCS since the middle Miocene: first, the S–N thermocline gradient probably occurred in the SCS for the first time during the period of 11.5–10.6 Ma; next, the S–N thermocline gradient was weakened or even disappeared during the period of 10.6–4.0 Ma; finally, the S–N thermocline gradient increased conspicuously since about 4.0–3.2 Ma in the SCS.

4. Discussion

Present day climates are affected significantly by the WPWP through the El Niño–Southern Oscillation (ENSO) phenomenon. The hydrography of the equatorial Pacific is characterized by a zonal seesaw of the thermocline in the upper water column with deeper DOT in the west and shallower DOT in the east (Chen and Prell, 1998). The changes disturbing this W–E thermocline gradient are so-called El Niño or La Niña events. The DOT deepens in the east and shoals in the west during El Niños, and vice versa during La Niñas (Le Borgne et al., 2002), which are thought to be responsible for interannual to decadal climate variability observed in extratropical regions (Cane, 1998; Hoerling et al., 2001). Recent studies suggest that the WPWP also plays an important role in global climate changes on millennial and orbital timescales through a system similar to the way ENSO regulates the poleward flux of heat and water vapour (Lea et al., 2000; De Deckker et al., 2002; Visser et al., 2003; Stott et al., 2004). However, the evolution of the WPWP on long-term timescale remains unclear.

Many researchers have tried to determine when and how the W–E thermocline gradient resulting in the occurrence of the WPWP was formed. It had been suggested that the WPWP and associated W–E thermocline gradient were likely formed right after the closure of the Indonesian seaway during the late Miocene based on planktonic foraminiferal paleogeography (Kennett et al., 1985; Gasperi and Kennett, 1993). However, recent studies of ODP Sites 847 (0°N, 95°W; eastern Pacific) and 806 (0°N, 165°E; western Pacific) have proposed that the W–E thermocline gradient was finally formed at 4.5–4.0 Ma, possibly responding to the emergence of the Isthmus of Panama (Chaisson and Ravelo, 2000). This interpretation is supported by numerical simulations that a closed Central American seaway at ~4.0 Ma may have resulted in the DOT deepening in the WPWP (Maier-Reimer et al., 1990; Mikolajewicz and Crowley, 1997; Murdock et al., 1997).

As previously mentioned, the S–N thermocline gradient in the SCS could be regarded as some kind of hydrographic gradient from the northern margin of the WPWP (southern SCS) to the extra-WPWP northern SCS region which is largely controlled by the East Asian monsoon. We have used changes in this gradi-
ent to indicate the evolution of the WPWP, in contrast to previous studies that adopted the W–E thermocline gradient of the equatorial Pacific for this purpose (Chaisson, 1995; Cannariato and Ravelo, 1997; Chaisson and Ravelo, 2000).

4.1. Possible initial development and stability of the WPWP

Based on the changes in relative abundance of planktonic foraminiferal deep-dwelling species, the S–N thermocline gradient probably developed for the first time in the SCS during the period of 11.5–10.6 Ma (Fig. 3). This indicates that the WPWP did not take shape prior to 11.5 Ma B.P. and the first occurrence of the S–N thermocline gradient in the SCS should represent the beginning of the WPWP in the latest middle Miocene. It should be noted that the data from Site 1143 are limited to the last 12.2 Ma. The evolution of the S–N hydrographic gradient and the WPWP prior to 12 Ma needs to be further testified using even longer records from the SCS and also from the Pacific Ocean.

The most remarkable paleoenvironmental changes in the studied area during the late Cenozoic are the phased evolution of the East Asian Monsoon induced by the uplift of the Tibetan Plateau. However, its main changes since the Oligocene took place at ~22.0 Ma (Guo et al., 2002), ~9.0–8.0 Ma and 3.6–2.6 Ma (An et al., 2001), instead of during the time period of 11.5–10.6 Ma. Interestingly, the first occurrence of the S–N thermocline gradient in the SCS and associated the initial WPWP during the period of 11.5–10.6 Ma was coincident with the significantly narrowing or partial closure of the Indonesian seaway between the Pacific and Indian Oceans (Hall, 2002), though the time of the closure of the Indonesian seaway is still a point of vigorous discussion (Cane and Molnar, 2001). It was inferred that the major or step-wise closure of the Indonesian seaway since about 12–10 Ma (Hall, 2002) played a critical role in the formation of the WPWP (Kennett et al., 1985), by enhancing the piling of warm surface water in the west equatorial Pacific driven by the easterly trade winds (Hirst and Godfrey, 1993).

Both the oceanic and coupled model experiments show similar circulation patterns induced by the closure of Indonesian seaway. The results from the oceanic and coupled model simulations are shown in Fig. 5. Although all the experiments give similar zonal gradients in the DOT of the equatorial Pacific (i.e., each has a WPWP in Fig. 5), they really show us the difference in the amplitude of DOT change and then tell us how the WPWP responds to the closure of Indonesian seaway around 12–10 Ma. The progressive closure of the Indonesian seaway since 12–10 Ma (Hall, 2002) resulted in an obvious deepening of the DOT in the western Pacific with little change in the DOT of the eastern Pacific. The maximum DOT change in the western Pacific could have reached ~30 m based on the oceanic model. The DOT difference was greater between experiments O14 and O6 than between experiments O6 and O0 (Fig. 5a,b), indicating that the effect of the closure of the Indonesian seaway on the ocean circulation took place mainly between 14 and 6 Ma, not after 6 Ma. It is noticeable that the closure of Indonesian seaway resulted in subsurface warming in the Pacific and cooling in the Indian Ocean (Fig. 5c); and furthermore, the Indonesian Through Flow (ITF) mainly originated from the southern Pacific at 14 Ma in contrast to its origination mainly from the northern Pacific at present (Fig. 2, Hirst and Godfrey, 1993; Rodgers et al., 2000). Therefore, the numerical simulations also support that the progressive closure of the Indonesian Seaway since the middle Miocene could be a reasonable explanation for the causes of the initial WPWP.

After the initial WPWP was formed, the S–N thermocline gradient in the SCS was weak or even disappeared during most of the period 10.6–4.0 Ma, indicated by similar changes in relative abundance of deep-dwelling species in the south and north. This implies that the WPWP, even if it existed, could have weakened and shrunk so as to exclude Site 1143 or been extremely unstable at that time. During the short period around 6–7 Ma, the two curves diverged as they did around 11 Ma (Fig. 3c). This could indicate a similar event to that at 11 Ma but of lower intensity, or simply reflects the consequence of the sea level change during the Messinian event (Haq et al., 1987). It is likely that the status of the WPWP during the period of 10.6–4.0 Ma will remain a mystery for some time, and the questions regarding its nature, particularly the complex links between tectonic, climate, and paleoceanography during this period,
require further work using many different signals at higher time resolution. Furthermore, since the evolution of the WPWP during the Miocene–middle Pliocene are mostly based on data from the SCS rather than from the Pacific itself, it is crucial to produce longer records from the eastern and western equatorial Pacific in the future for testing the proposed evolution of the WPWP during this period.

4.2. Final formation of the WPWP

Since about 4.0–3.2 Ma, the S–N thermocline gradient conspicuously increased, reflected by the substantial increase in abundance of deep-dwelling species in the northern SCS and the decrease in the southern SCS (Fig. 3). It is interesting that the W–E thermocline gradient across the equatorial Pacific was

Fig. 5. Simulated DOT averages from 2°S–2°N as a function of longitude (X axis) and depth (Y axis, unit: meter) in the equatorial Pacific. The DOT is estimated by the depth of the 18°C isotherm. a) Based on the oceanic model experiments using the modern (O0), 6 Ma (O6) and 14 Ma (O14) topographies. b) Based on the coupled ocean–atmosphere model experiments using the modern (control), 6 Ma (EXP-1), 14 Ma (EXP-2), and 14 Ma with an open Central American seaway (EXP-3) topographies. c) The difference of sea subsurface temperature at a depth of 187.5 m between experiments O0 and O14. Notice the subsurface warming in the Pacific and cooling in the Indian Ocean.
finally formed almost at the same time, judging from the $\delta^{18}$O difference between Neogloboquadrina dutertrei and Globigerinoides sacculifer ($\Delta\delta^{18}$O$_{dut-sac}$) at ODP Sites 847 and 806 from the eastern and western equatorial Pacific, respectively (Chaisson and Ravelo, 2000) (Fig. 3d). Because $\Delta\delta^{18}$O$_{dut-sac}$ represents the thermal gradient between the thermocline habitat of N. dutertrei and surface habitat of Gs. sacculifer, its significant increase in the eastern equatorial Pacific indicates the shoaling of the DOT and the intensification of the W–E thermocline gradient in the equatorial Pacific at about 4.0 Ma (Chaisson and Ravelo, 2000). Therefore, the modern WPWP is inferred to have finally formed during the period 4.0–3.2 Ma based on the significant increases in the S–N thermocline gradient of the SCS and the W–E thermocline gradient of the equatorial Pacific. This is also supported by the evidence for an increase in the sea area with warm ($>27$ °C) winter sea surface temperatures, estimated by planktonic foraminifer target transfer function, in the North Pacific at about 3.2 Ma (Wang, 1994).

Though tremendous climate and environmental changes took place around 4.0–3.2 Ma, e.g. the rapid uplift of the Tibetan Plateau, strongly intensification of the East Asian winter monsoon on land (An et al., 2001) and sea (Jian et al., 2003), onset of the Northern Hemisphere Glaciation, and final closing of the Indonesian seaway at 4–5 Ma (Cane and Molnar, 2001), only the progressive closure of the Central American seaway at 3.8–3.2 Ma (Keigwin, 1982; Huag and Tiedemann, 1998) has been often linked with the W–E thermocline gradient of the equatorial Pacific by marine records and modeling experiments (Maier-Reimer et al., 1990; Mikolajewicz and Crowley, 1997; Chaisson and Ravelo, 2000; Rodgers et al., 2000). Because the onset of the Northern Hemisphere Glaciation is around 3.2–2.5 Ma (Shackleton et al., 1984; Maslin et al., 1995), it is believed not to be the cause of the significant increase of the S–N thermocline gradient of the SCS and the W–E thermocline gradient of the equatorial Pacific at 4.0–3.2. In a recent paper (Huang et al., 2003), the increase of deep-dwelling species since 3.2 Ma at the northern Site 1146 was ascribed to the strengthened East Asian winter monsoon. Based on the changes in the relative abundance of N. dutertrei and the $\delta^{13}$C of planktonic foraminifer Globigerinoides ruber, the East Asian monsoon strengthened at 7.6–6.4 Ma and 3.2–2.2 Ma (Jian et al., in preparation). Although the strengthened East Asian monsoon since 3.2 Ma could have caused the DOT shoaling in the northern SCS and hence enhance the S–N thermocline gradient of the SCS, it is hard to explain the DOT deepening of the southern SCS since 4.0 Ma indicated by the decrease of deep-dwelling species at Site 1143. It seems that the increased S–N thermocline gradient in the SCS should be related to not only the strengthened East Asian winter monsoon (Huang et al., 2003; Jian et al., in preparation), but also the change in the tropical climate, i.e. the evolution of the WPWP.

The comparison of the coupled ocean–atmosphere model experiments EXP-2 (with the Central American seaway closed) and EXP-3 (with an open Central American seaway) has convincingly demonstrated that the closing of the Isthmus of Panama in the experiment EXP-2 caused strong upwelling and DOT uplift in the eastern equatorial Pacific and DOT decrease in the western Pacific (Fig. 5b). Of course, further work is needed to test the difference between sensitive experiments based on the topography with and without the Panama isthmus around 4 Ma (Keigwin, 1982; Huag and Tiedemann, 1998). Actually, this tectonic event isolated heat exchange between Pacific and Atlantic Oceans, and eventually resulted in cooling of sea surface temperature and DOT uplift in the eastern Pacific (Huag and Tiedemann, 1998; Chaisson and Ravelo, 2000) and hence increased the contrast of heat content between the western and eastern Pacific. The amplitude of DOT change is much greater in the experiment EXP-3 than in the experiment EXP-2, indicating that the emergence of the Isthmus of Panama played a much more important role in the evolution of the WPWP. Based on the numerical simulations, it is inferred that the closure of the Indonesian seaway could have resulted in the initial WPWP, but the final formation of the WPWP should be attributed to the emergence of the Isthmus of Panama.

5. Conclusion

Based on the changes in the relative abundance of deep-dwelling planktonic foraminiferous species from
ODP Sites 1143 and 1146, three stages of evolution of the S–N hydrographic gradient have been identified in the SCS since the middle Miocene. First, the S–N thermocline gradient probably occurred in the SCS for the first time briefly during the period of 11.5–10.6 Ma, representing the initial WPWP possibly in response to the major closure of the Indonesian seaway. Secondly, the S–N thermocline gradient of the SCS conspicuously increased since about 4.0–3.2 Ma, possibly indicating the final formation of the WPWP induced by the emergence of the Isthmus of Panama. Despite the debate over what caused the final formation of the WPWP, our observations on the marine sediments from the SCS and previous studies on planktonic foraminifers in the Pacific Ocean (Chaisson and Ravelo, 2000) have demonstrated that the evolution of the WPWP clearly displayed three major phases since the middle Miocene. These conclusions are supported by results from oceanic and coupled ocean–atmosphere model simulations that take into account changes in ocean gateways (mainly the Indonesian seaway and the Isthmus of Panama). These inferences support and extend earlier conclusions (Kennett et al., 1985; Wang, 1994; Chaisson and Ravelo, 2000) concerning the timing of the multi-stage evolution of the WPWP in the equatorial Pacific and possible links with tectonic changes in ocean gateways.

Acknowledgements

This work was supported by the Ministry of Science and Technology of China (grants G2000078502 and 2001DIA50041), the National Natural Science Foundation of China (grants 40125015, 4031002 and 40321603) and the China Ocean Mineral Resources Research and Development Association (grant DY105-01-04-09). We sincerely thank two anonymous reviewers for their critical reviewing the manuscript. This research used samples and data provided by the ODP, which is sponsored by the U.S. National Science Foundation and participating countries under management of Joint Oceanographic Institutions Inc.

References

Lea, D., Pak, D., Soper, H., 2000. Climate impact of late Quaternary

Le Borgne, R., Barber, R., Delcroix, T., Inoue, H., Mackey, D., Rodier, M., 2002. Pacific warm pool and divergence —


