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行政院國家科學委員會補助專題研究計畫成果報告

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Reconstruction of Hydrological Structures of Upper Ocean Using Oxygen and Carbon Isotopes of Multiple Planktic Foraminifera (II): Case Studies of the South China Sea and Southern Okinawa Trough

Abstract

We measured the oxygen and carbon isotopic ratios of several foraminiferal species to reconstruct the hydrological structures of surface-waters during (1) the Marine Isotope Stages (MIS) 10-12 of the South China Sea and made a comparison with the record of MIS 1-6, and (2) the Holocene of Southern Okinawa Trough. In addition, organic carbon content and major elements in bulk sediment of the MIS 10-12 of two cores from the South China Sea were analyzed to examine the surface-water productivity and bottom water conditions.

The fluctuation amplitudes of oxygen and carbon isotopic ratios of two studied species and the isotopic offsets between them are both smaller during the MIS 12-10 compared to that in MIS 1-6. It appears that the lower amplitude of solar insolation during MIS 10-12 is responsible for the smaller isotopic fluctuation. The offsets in $\delta^{18}O$ and $\delta^{13}C$ between the surface dwelling species (*Globigerinoides ruber*) and the thermohaline species (*Neogloboquadrina dutertrei*) during the MIS 10-12 become smaller compared to that in the MIS 1-6, signifying a less stratified surface-water column. The bottom waters are more oxygenated and probably also better ventilated during the interglacials as evidenced by lower content of total organic carbon and the elevated MnO/Al_2O_3 and P_2O_5/ Al_2O_3 ratios.

The $\delta^{18}O$ values of four foraminiferal species (*Globigerinoides ruber*, *Neogloboquadrina dutertrei, Globorotalia menardii* and *Pulleniatina obliquiloculata*) all display a decreasing trend during the past 8 kyrs while the offsets among them remain to be relatively constant. No sensible excursion can be identified to explain the drastic reduction of *Pulleniatina obliquiloculata*, a Kuroshio characteristic species, during 4.5 – 3.0 Ka. This result leaves the occurrence of the *Pulleniatina obliquiloculata* Minimum Event (PME) to be an unsolved paleoecologic enigma. A major shift to heavier $\delta^{13}C$ values occurred at ~8 ka as manifested by all four species in the Southern Okinawa Trough. The offset in $\delta^{13}C$ between *G. ruber* and *P. obliquiloculata* increased after 8 ka compared to the earliest Holocene. Integrating the various lines of evidence, we interpret that a stable hydrological condition in the Okinawa Trough established at about 8 ka and lasted until 2 ka.

Key words: paleomonsoon, Kuroshio Current, planktic foraminifers, Okinawa Trough, South China Sea, MIS 11, thermocline

1. Introduction

In this study, we measured the oxygen and carbon isotopic ratios of multiple foraminiferal species to reconstruct the thermocline structures in (1) the Marine Isotope Stages (MIS) 10-12 of the South China Sea, and (2) the Holocene of Okinawa Trough. The former allows us to compare the two most significant analogs of global warming: the MIS 5 and MIS 11, while the latter one focuses on a high-resolution record of the Holocene. The unifying theme in this report is that the hydrological structure of the upper-water layers in the two marginal seas holds important clues to differentiate various hypotheses purported to explain the observed paleoceanographic changes. For instance, it has been argued whether the increased upwelling, or, alternatively, the increasing mixing due to strong winter monsoon, is responsible for the observed increased productivity during glacial periods in the South China Sea (e.g., Huang et al., 1997). On the other hand, the low abundances of *Pulleniatina obiquiloculata* (the so-called *Pulleniatina* minimum event, PME) at ca 4 ka in the South China Sea and the Okinawa Trough has been proposed to be either due to the change in surface-water structure or the diversion of Kuroshio. We are aware of the fact that these so-called "alternative" hypotheses are not mutually exclusive, and the differentiation between them is subtle. We hope that a better understanding of the surface-water vertical hydrological structure would shed new lights for these long-lasting problems.

1.1. South China Sea

Increasing lines of evidence suggest that the tropics play an important role in the global climate system through their influence on the global heat and moisture budget (Gupta et al., 2003). Slight variations in sea surface temperature of the tropical oceans can influence the global climate through atmospheric teleconnection as demonstrated by the El Nino-Southern Oscillation (ENSO) phenomenon. Recent studies also suggest that the tropical warming might precede ice volume change during the last deglaciation, indicating the importance of the tropics as a major driver in the global climate system (Lea et al., 2000; Visser et al., 2003).

The modern surface circulation in the South China Sea is strongly influenced by the East Asian monsoon system where the strong northeast (winter) monsoon drives a cyclonic gyre over the whole basin whereas the weaker southwest (summer) monsoon drives a anticyclonic gyre primarily in the southern part of the basin (Wyrtki, 1961; Liang et al., 2000). The fact that the thermocline responds more or less "immediately" to changes in surface wind field allows a test of model predictions of changes in the monsoon system over glacial-interglacial cycles, as variations in the upper water structure are recorded by the isotopic compositions of different foraminiferal species (Ravelo and Fairbanks, 1992). Furthermore, the Asian monsoon controls seasonal winds, precipitation and run-off patterns, character of land vegetation, volume and mineralogy of terrigenous influx into the sea, and flux of aeolian (wind-blown) dust. Thus, the sediments in the South China Sea provide not only exquisite Quaternary paleoceanographic records, but also offer a record of variations in southeast Asian continental climate.

To a better handle of predicting future climate changes, the scientific community for a long time has looked at the last interglacial for an analog. The Eemian (MIS 5e, ~120 ka) is our closest and best-known warm stage. That interglacial lasted about 10 ka so the conclusion was that we were quickly approaching the onset of a new ice age (Berger and Loutre, 2002). However, it appears that the last interglacial was actually quite different from the present one. Of the Quaternary interglacials, MIS 11 probably offers the best analog to the present conditions for its similarities in the orbital configuration which controls the solar insolation (Howard, 1997; Loutre and Berger, 2003). Particularly, the insolation during the MIS 11 and in the near future displays only small difference (Loutre et al., 2003). MIS 11 exhibits some intriguing features of great importance to our understanding of the global climate system. First, there is a very prominent termination at the boundary between the MIS 11 and 12 although it occurs at a time of low orbital eccentricity, resulting in low amplitude of insolation fluctuation. Second, whereas MIS 5, 7, and 9 show short warm periods followed by early returns to glacial conditions, the MIS 11 display a long-lasting interglacial condition. Another important feature of MIS 11 is a sea level of about 20 m higher than the present (Howard, 1997).

The Milankovitch hypothesis explains most of the features observed in the geological record and is widely accepted as a valid explanation for the cyclicity of the glacial fluctuation. However, at ~ 400 ka there is a large discrepancy between the amplitude of insolation and the observed $\delta^{18}O$ values. One of the important questions we wish to address is how there can be one of the largest deglaciations during a minimum in the amplitude of insolation change.

In the study, we expanded the previous our previously studied interval (0 to 160 ka) in core MD972142 to include MIS 10 to 12. Oxygen and carbon isotopes of multiple foraminiferal species were employed to reconstruct the thermocline depth and upper water hydrography of this interval. Preliminary results from this interval (MIS 12-10) using a two-species approach (*Globogerinoides ruber* and *Neogloboquadrina dutertrei*) have shed new light on glacial-interglacial variations of the East Asian monsoon system during MIS 12 to 10. Additional clues are also found through XRF-measurements of major elements in the bulk sediment. New results from this project show a clear glacial-interglacial fluctuation pattern in most measured elements. Partly contradictory data of opal, phosphorus and TOC data further illustrates the need of a better understanding of upper water hydrographic variation.

1.2. Okinawa Trough

The Kuroshio Current, the Western Boundary Current of the northwestern Pacific, originates form the North Equatorial Current and carries warm and saline water northward. Its present main path flows east of Taiwan where it enters into the Okinawa Trough, strongly influencing the regional climate, upper-layer ocean conditions, and the distribution of marine sediments in NW Pacific area. To gain more insight into the ocean/atmospheric circulation dynamics, changes in the Kuroshio Current during the late Quaternary, especially during the Holocene, have been studied by Asian researchers (e.g., Shieh and Chen, 1995; Ujiié and Ujiié, 1999; Jian *et al.*, 2000). As a typical western boundary current controlled by sea-floor bathymetry and wind system, the role of the Kuroshio Current in the Okinawa Trough has also been explained by two different hypotheses: One regards the existence of a land bridge connecting the southern Ryukyu Arc with Taiwan during the last glacial blocking the Kuroshio to enter the trough (Ujiié *et al.*, 1991; Ujiié and Ujiié, 1999), whereas the other considers the East Asian monsoon to be more important in regulating the regional hydrology (Jian *et al.*, 2000). Various interpretations on the occurrence of the Holocene '*Pulleniatina* minimum event' are also in these contexts.

According to previous studies (Li *et al*., 1997), there is a prominent paleoceanographic event at ~4.0-2.0 kyr BP, reflected by the remarkable decrease in the abundance of the planktonic foraminifera *Pulleniatina obliquiloculata*, the characteristic species of the Kuroshio Current (Ujiié and Ujiié, 2000). Also found in the cores of South China Sea (e.g., Huang *et al*., 2002), this '*Pulleniatina* minimum event (PME)' is interpreted as the result of a diverged Kuroshio (Ujiié and Ujiié, 1999) or intensified winter monsoon (Jian *et al.*, 2000). From the ecological point of view, however, this could not explain why *P. obliquiloculata* and *Neogloboquadrina dutertrei*, both of which are thermocline dwellers, usually display opposite trends of abundance during the *Pulleniatina* minimum event as well as in glacial-interglacial cycles (Ujiié *et al*., 2003a; Steinke *et al.*, unpublished data). To better understand the genuine causes of the PME, a detailed, high-resolutin study of the hydrological condition of the surface ocean in the marginal seas and the upper reach area of the Kuroshio is necessary.

In this report, we present the reconstructed thermocline hydrography in the southern Okinawa Trough and western Philippine Sea during the Holocene and evaluate the various interpretations of the PME.

2. Modern upper-layer ocean environments

2.1. South China Sea

The surface water of the South China Sea is characterized by the inflow of saline Western Philippine Water through the Luzon strait that is mixed with fresh river water from the surrounding land areas (Wyrtki, 1961). Using NOAA's atlas data, Ho et al. (1998) made a thorough visualization of the hydrographic conditions of the South China Sea. Their compilation exhibits the depths of mixed-layer, thermocline, halocline, and pycnocline in

January and July. The sea surface density at Site MD972142 becomes less during summer probably due to heavier precipitation brought in by southwestly monsoons. The halocline becomes also shallower in July at a depth of ~40, which is 20 meters shallower than winter's at 70 m depth. Correspondingly, thermocline is shallower in July. The thermocline was estimated to be at a depth of 80-120m. However, this shows a discrepancy with Jian et al. (2000a). We will search for field observation data of the eastern South China Sea to get better handle of the seasonal changes shown by vertical profiles of various hydrographic parameters in this region.

2.2. Okinawa Trough

The North Equatorial Current encounters the western boundary along the Philippine coast and bifurcates into the northward flowing Kuroshio and the southward flowing Mindanao Current (Fig. 3) (Qiu and Lukas, 1996). The Kuroshio, with a mean volume transport of ~15 Sv (1 Sv = 10^6 m^3 s^{-1}) in the study area (Liang *et al.*, 2003), transports warm, saline and oligotrophic water northward along the east coast of Taiwan. After entering the southern Okinawa Trough, this current is blocked by the continental shelf of the East China Sea and turns northeastward along the shelf break. The mainstream of the Kuroshio finally exits the trough and becomes the Kuroshio Extension in the north Pacific.

The cores used in this study were recovered from the southern Okinawa Trough and the upper reach of the Kuroshio (Fig. 1). Here the term 'upper reach' refers to the region between the North Equatorial Current bifurcation point (11º-20º N, see Qiu and Lukas, 1996) and the Ryukyu Ridge. MD98-2188 (123.5°E, 14.8°N, water depth 730 m, MD88 henceforth), taken from the western Philippine Sea, is located at the north margin of the Western Pacific Warm Pool. The annual average sea surface temperature (SST) at this site is 28.5°C, and the seawater temperature falls rapidly from 28°C at 50 m to 19°C at 200 m to form a steep thermocline (Levitus and Boyer, 1994). MD01-2403 (123.2°E, 25.3°N, water depth 1420 m, MD403 henceforth) is beneath the main axis of the Kuroshio in the Southern Okinawa Trough. The annual average SST at MD403 is 24.8°C. The temperature gradient in the thermocline at MD403 is smaller than that at MD88. The annual average sea surface salinity (SSS) at MD88 are ~34.3 p.s.u., 0.1 unit lower than that at MD403 (Levitus and Boyer, 1994).

3. Methods

3.1. Using oxygen and carbon isotopic ratios of multiple foraminiferal species to reconstruct thermocline hydrography

Various studies have demonstrated that stable ratios of oxygen and carbon isotopes in the shell calcite of planktonic foraminifera are related to depth stratification of foraminiferal habitats in the upper water column. Factors such as temperature, light penetration, mixing depth, thermohaline gradient and chlorophyll concentration would determine the niche stratification (e.g., Fairbanks *et al.*, 1982; Curry *et al.*, 1983; Thunell *et al.*, 1983; Watkins *et al.*, 1998; Faul *et al.*, 2000). Ideally, a predictable relationship exists between the isotopic signals of planktonic foraminifera and the physical/chemical properties of the water layer where the foraminifera reside. The major factors determining oxygen isotope geochemistry would be temperature and salinity of seawater, while carbon isotopes would be determined by $\delta^{13}C$ of dissolved inorganic carbon (DIC). As depth increases, the $\delta^{18}O$ of residing foraminifera should increase due to decreasing temperature and/or increasing salinity ($\delta^{18}O_{water}$). Conversely, $\delta^{13}C$ decreases when water depth increases. This is because that in the surface water layer phytoplankton uptakes preferentially ^{12}C during photosynthesis and elevates $\delta^{13}C$ of DIC. In contrast, underneath the nutricline the $\delta^{13}C$ of DIC decreases with increasing depths as the mineralization of organic matter introduces the ^{12}C-enriched CO_2 back to the water via respiration (Kroopnick, 1974). However, these predicted relationships are often offset by other hydrological properties of the water column such as pH and $[CO_3^{2-}]$ (Spero *et al.*, 1997) and 'vital effects' such as foraminiferal respiration and symbiont physiological process (Spero and Williams, 1998; Spero and Lea, 1993; Bemis *et al.*, 2000). Fortunately, the affects of these complicating factors have been well documented, and species-specific corrections (e.g., normalization to values of *G. ruber*) can be done (Spero et al., 2003).

To reconstruct the Holocene thermocline hydrography, we will analyze oxygen and carbon isotope ratios of four planktonic foraminifera species, including two spinose and two non-spinose ones. The two spinose species, *G. ruber* and *G. sacculifer*, are dwellers of the mixed layer and upper thermocline, respectively (Fairbanks *et al.*, 1982; Ravelo and Fairbanks, 1992; Faul *et al.*, 2000). For the two non-spinose species, *G. menardii* dwells within the upper to middle thermocline, whereas *N. dutertrei* resides in the middle to deep thermocline (Fairbanks *et al.*, 1982; Faul *et al.*, 2000). Both species track closely the chlorophyll maximum (Watkins *et al.*, 1998). In addition, to locate the habitat of *P. obliquiloculata* in relation to other species, its isotope ratios in selected intervals were also analyzed.

3.2. X-ray fluorescence method

Major elements measured by X-ray fluorescence have been successfully employed in paleoclimatological studies to investigate phenomenon such as dust input (Porter and An, 1995; Jahn et al., 2003) or variations in the terrigenous source material (Wehausen and Brumsack, 2000). In core MD972142, the aluminum-normalized abundances of manganese, phosphorus and sodium are analyzed to infer sedimentary properties and related sedimentary processes. Phosphorus and Sodium reflect the weathering intensity controlled by summer monsoon, whereas Manganese content is an indicator of bottom water oxygenation condition. Iron, magnesium and titanium show no significant glacial-interglacial fluctuation, which is consistent with the expected results considering the remote distance to the Central Asian source of eolian and the varying petrological compositions of the surrounding islands of the South China Sea.

4. Results and discussions

4.1. Productivity and preservation of organic in the South China Sea: Insights from redox-sensitive elements

Sedimentary records of organic carbon and redox-sensitive element ratios covering approximately the last four glacial-interglacial cycles from two cores from the northern and southeastern South China Sea. Core MD972142 (12°41.33'N, 119°27.90'E) was retrieved at a water depth of 1557 m at the continental slope off Palawan Island during the 1997 IMAGES-III-IPHIS Cruise, and the 1215 cm long piston core GIK17925-3 (119º2.8'E, 19º51.2'N, 2980 m water depth) was taken from the north-eastern South China Sea during the *SONNE 95* cruise in 1994 (Fig. 2). Sedimentary organic carbon (TOC) content shows glacial-interglacial cyclicity with elevated values during glacial periods, as well as higher frequency oscillations corresponding presumably to precession and obliquity changes (Fig. 3).

The amplitude of the variations generally is considerably larger at the southeastern compared to the northeastern site. The $\delta^{13}C$ of organic carbon suggests that increased marine productivity rather than change in the input of terrestrial carbon is responsible for the fluctuation in TOC. Proposed explanations for these increased glacial levels of TOC include enhanced primary productivity due to enhanced upwelling or mixing of surface waters by intensified monsoonal winds, or nutrient trapping caused by decreased exchange with the open ocean during glacial periods of low sea-level. The manganese/aluminum and phosphorus/aluminum ratios suggest decreased bottom water oxygenation during glacial maxima and well-oxygenated conditions during peak interglacial periods (Fig. 3). Again, the southeastern site displays considerably larger amplitude in its fluctuation when compared to the northeastern site. Manganese and phosphorus are both redox-sensitive elements and the increased values during peak interglacial conditions could be a result of higher oxygen contents in the deep waters due to a more vigorous exchange between the South China Sea and neighboring oceans during high sea-level intervals. In contrast, during the low-stands of sea-level when the exchange with the open ocean was restricted, low-oxic conditions developed particularly in the southern part of the basin which was situated the furthest from the only remaining connection at the Luzon Strait. We therefore propose that the TOC reflects short-term productivity variation affected by insolation, while the bottom condition was mainly governed by ventilation of deep waters which in turn were controlled by the openness of the SCS in relation to eustatic fluctuation.

4.2. Insolation controlled variations in the South China Sea surface waters

Stable oxygen and carbon isotopes of the planktic foraminifers *Globigerinoides ruber* and *Neogloboquadrina dutertrei*, a surface and a thermocline dweller, respectively, were measured in two intervals in core MD972142 from the southeastern South China Sea (Fig. 2). The lower interval, encompassing Marine Isotope Stage (MIS) 13 to 9, is characterized by rather small amplitude in insolation variability while the upper interval, covering MIS 6 to 1, is characterized by comparatively strong fluctuations in insolation. This difference in amplitude of the insolation variation between the two intervals allows an assessment of the relative importance of insolation vs. ice volume/sea level changes on the surface water hydrography of the South China Sea.

Because the surface circulation in the South China Sea is strongly influenced by the East Asian monsoon system, changes in the monsoon strength, related to variations in insolation, can be expected to manifest themselves as changes in the surface hydrography. During precessional minima, summer insolation is strong resulting in a stronger summer monsoon, conversely the weak winter insolation causes a strengthened winter monsoon.

The strong summer monsoon increases precipitation leading to larger isotopic differences between the surface dwelling *G. ruber* and the thermocline dwelling *N. dutertrei*. The stronger winter monsoon during precessional minima causes an enhanced biological pumping of organic carbon in the surface waters, resulting in a larger difference between the two species. (Fig. 4). During the lower interval (MIS 13-9), where the amplitude of the insolation variations is smaller, the short-term variations in isotopic gradients ($\Delta\delta^{18}O$ and $\Delta\delta^{13}C$) between the two species are smaller, and consequently show clear lower frequency fluctuation presumably corresponding to the 100ky ice volume cyclicity. In contrast, during the upper interval these long-term variations are effectively superimposed by high amplitudes of the short-term variations. Our data also are consistent with the idea that the exceptionally long duration and warm conditions during the interglacial MIS 11 are attributed to the relatively low amplitude of the precession cycle during this interval.

4.3. Holocene Pulleniatina munimum event

To identify the PME more precisely, we define the PME as a period when the relative abundance of *P. obliquiloculata* is continuously below 5 %. According to the definition, cores MD403 and MD88 both records the PME during about 4.5-3 ka.

From 8 ka to the present, the $\delta^{18}O$ records of *G. ruber*, *P. obliquiloculta* and *N. dutertrei* all display a long-term decreasing trend, with the MD88 record being more prominent than the MD403 record (Fig. 5). As Field (2004) suggested, shared variability in signatures of all species would likely reflect real changes in temperature and/or salinity within the thermocline. Therefore, it appears that water mass in the upper reach of the

Kuroshio has become progressively warmer and/or less saline in the period, but such a signal was somewhat modified by the complex hydrographic processes in the southern Okinawa Trough. The *G. ruber* $\delta^{18}O$ values during the PME period did not display any sensible excursion, being consistent with previous observation of Li *et al.* (2001) and Ujiié *et al.* (2003) that there was no obvious change in plankton $\delta^{18}O$ values in the interval. In the MD88 and MD403 records, the offsets in $\delta^{18}O$ values of *P. obliquiloculata* from the other three species during 8 to 2 ka are relatively constant without showing any anomalous excursions during the PME, implying that thermocline condition did not change abruptly or the relative position of the habiting depths between *P. obliquiloculata* and *N. dutertrei* did not change during this period.

We interpreted the normalized $\delta^{13}C$ variations as changes in $\delta^{13}C_{DIC}$ or vertical migration of planktonic foraminifers within the chemocline. The first remarkable feature in both sequences is the ~0.5 $^{o}/_{oo}$ difference in $\delta^{13}C$ before and after 8 ka (Fig. 5). Such a shift at 8 ka was also observed in the Northern Okinawa Trough (Jian *et al*., 2000; Ijiri *et al*., 2005) and the southern SCS (Stephan Steinke, pers. commun.), but the reason for this post-deglacial $\delta^{13}C$ shift is unclear. The $\delta^{13}C$ values of *P. obliquiloculata* in the MD88 shifted closer to *G. ruber* surface values by ~0.3 $^{o}/_{oo}$. The decreased difference between $\delta^{13}C$ values of *P. obliquiloculata* and surface species was also documented in some cores from the Okinawa Trough (Ujiié *et al*., 2003b), but not in the MD403 record. Although Ujiié *et al*. (2003b) interpreted the decreased $\Delta\delta^{13}C$ between the surface and thermocline dwellers as an evidence of a shoaling thermocline due to a weaker Kuroshio transport under an El Niño-like condition, it is important to recognize that the $\delta^{18}O$ data do not support a habitat transition of *P. obliquiloculata* toward a shallower depth during the PME in MD88. Rather, because the $\delta^{13}C_{DIC}$ transition zone occurs across a narrow depth range situated within the upper pycnocline (Fairbanks *et al*., 1982), the $\delta^{13}C$ shift could be the result of a small change in *P. obliquiloculata* habitat depth within the upper thermocline or merely a shift in depth of the $\delta^{13}C_{DIC}$ chemocline related to some subtle changes in the structure of the pycnocline (Loubere, 2001). Not observed in other sites during the PME, such a slight change at MD88 in subsurface nutrient condition was more possibly a local phenomenon rather than a widespread event that resulted in the drastic reduction of *P. obliquiloculata* populations.

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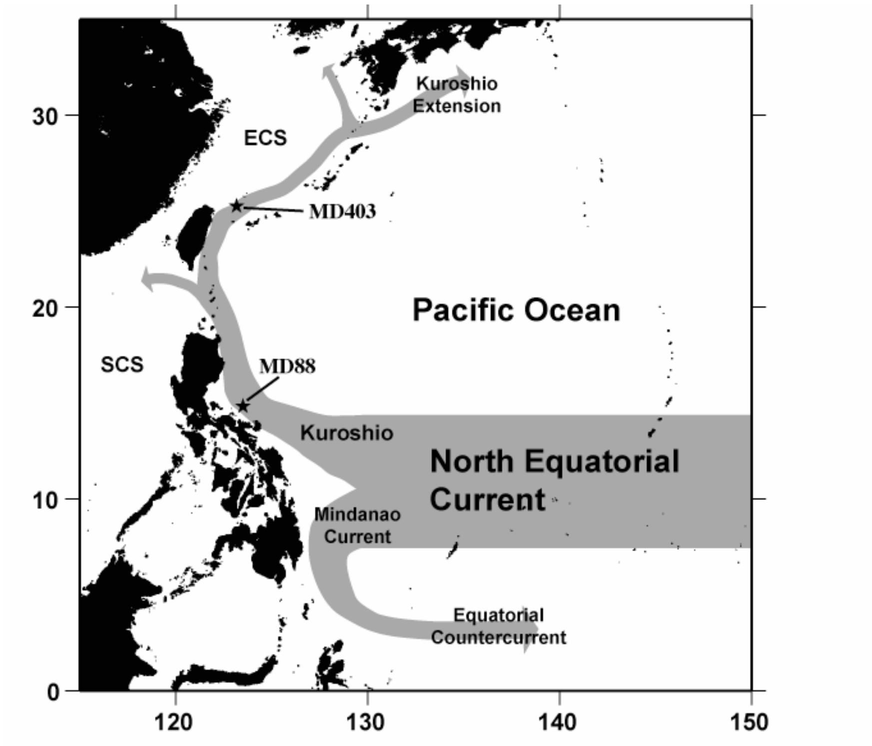

Figure 1. Oceanographic settings of the study area. The North Equatorial Current bifurcates into the Kuroshio and the Mindanao Current. ECS: East China Sea. SCS: South China Sea.

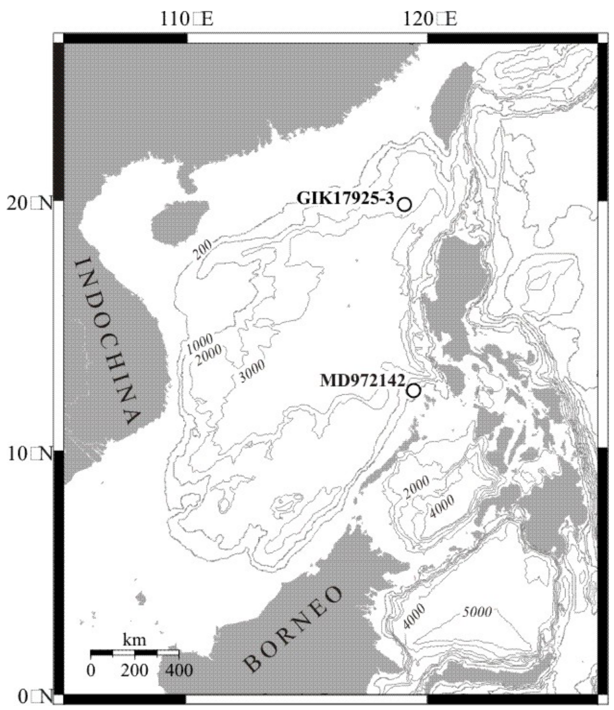

Figure 2. Location map of studied sites in the South China Sea.

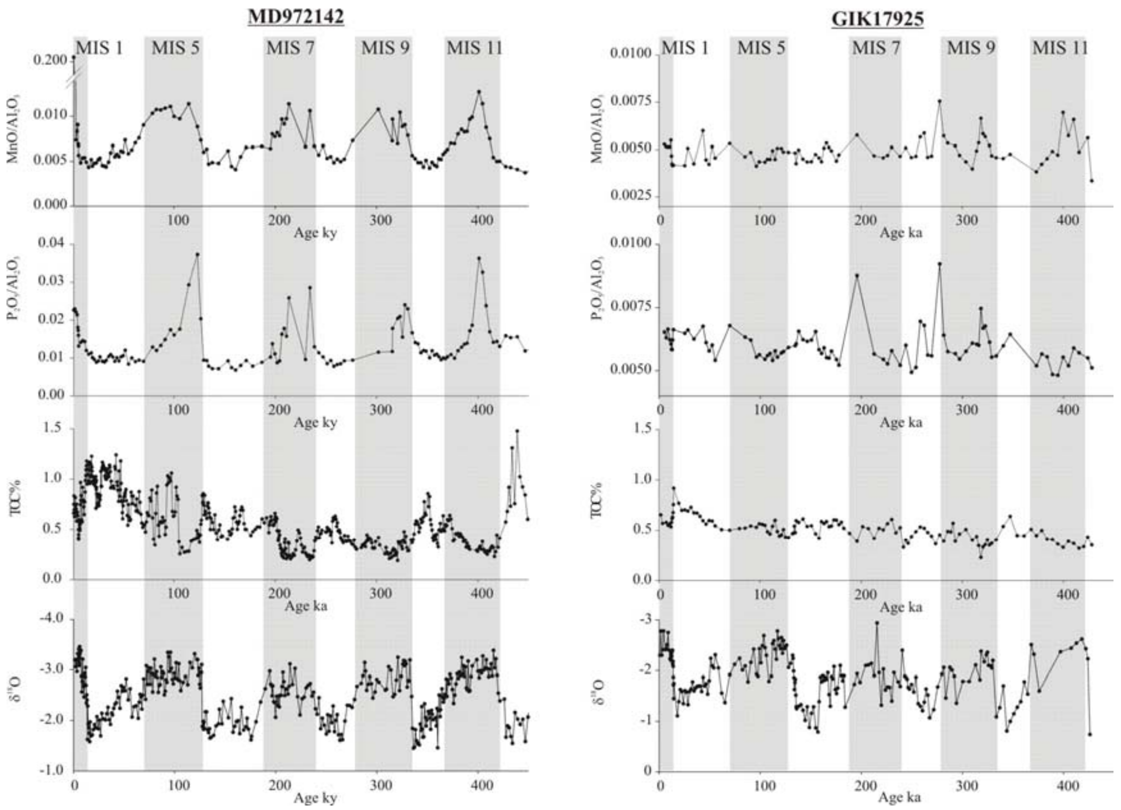

Fig. 3. MnO/Al_2O_3, P_2O_5/ Al_2O_3, total organic carbon content and $\delta^{18}O$ values of planktic foraminifera *Globigerinoides ruber* in Core MD972142 and GIK17925 during the past 450 kyrs (MIS 1-12). The interglacial stages are shaded.

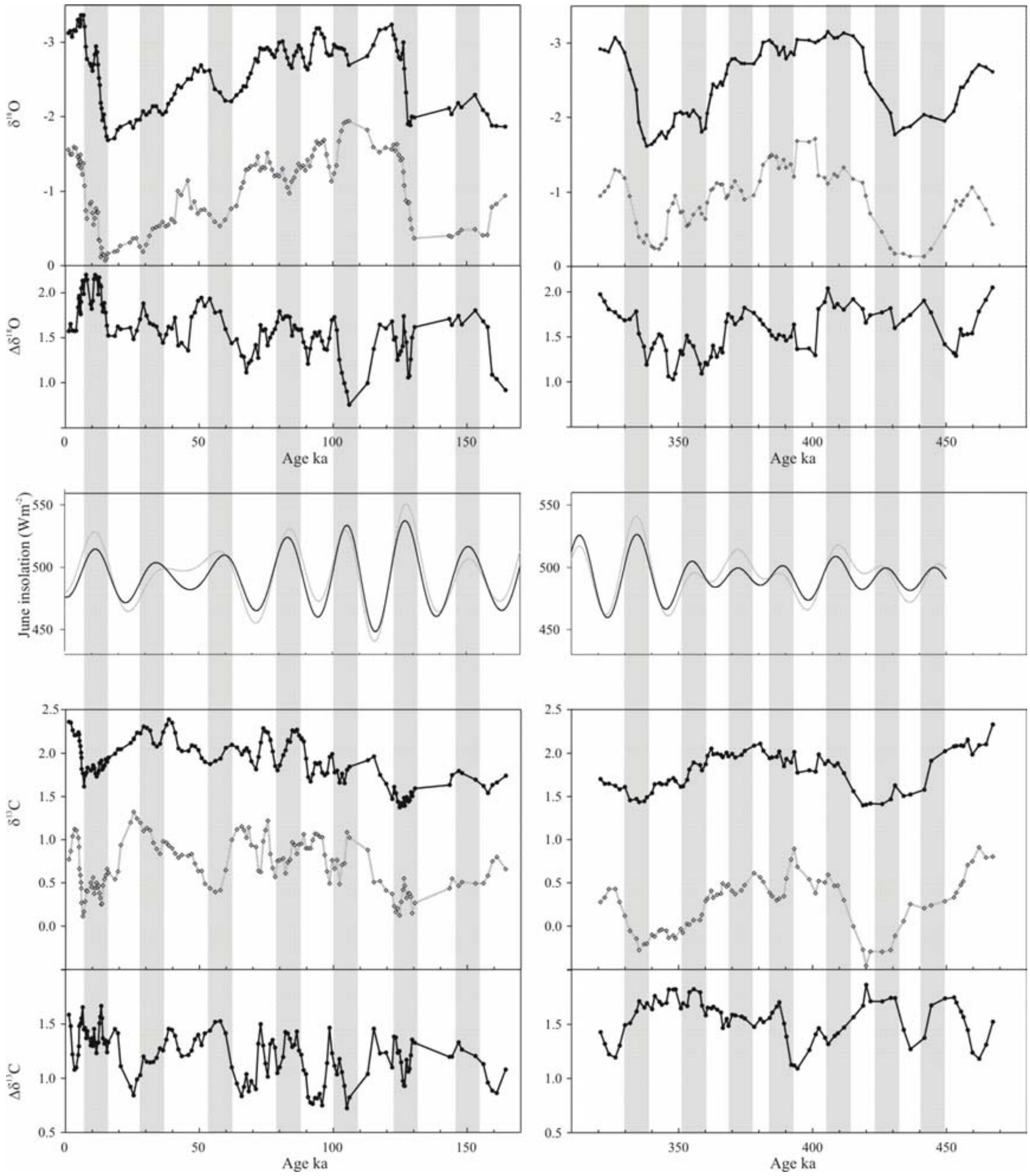

Fig. 4. Comparison between MIS 1-6 (left) and MIS 10-14 (right panel) in MD972142. The precessional insolation maxima are shaded. Note that the amplitudes of fluctuation in isotopic gradients during the last 160 kyrs are generally larger than that during 320-470 ka.

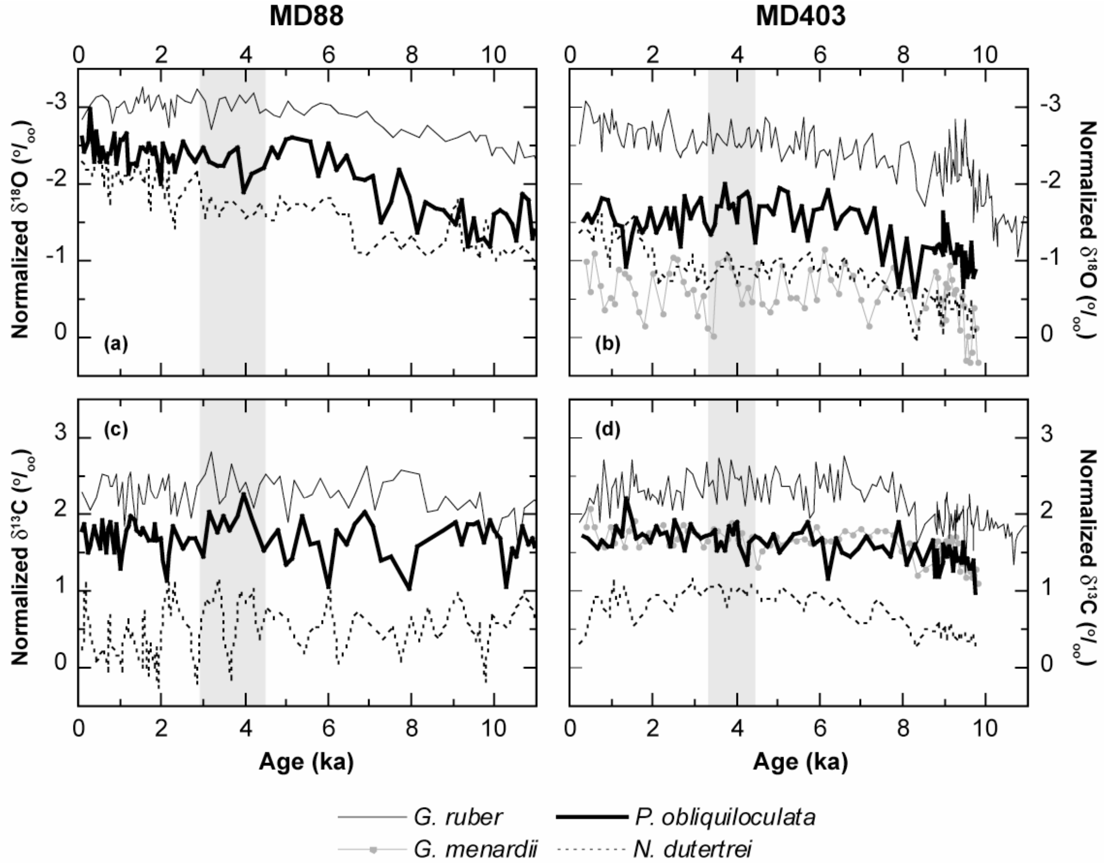

Figure 5. Results of the multispecies isotopic analyses. (a)(b) Oxygen and (c)(d) carbon isotope data for *G. ruber*, *P. obliquiloculata*, *N. dutertrei* and *G. menardii* normalized to $\delta^{18}O_{G. ruber}$ and $d^{13}C_{DIC}$, respectively. The PME period is shaded.