The Holocene *Pulleniatina* Minimum Event revisited: Geochemical and faunal evidence from the Okinawa Trough and upper reaches of the Kuroshio current

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Abstract

The Holocene *Pulleniatina* Minimum Event (PME) is characterized by a very low abundance of the planktonic foraminifer *Pulleniatina obliquiloculata* between ∼4.5 and 3 ka. The PME occurs widely in the Okinawa Trough and the South China Sea, and can be correlated throughout this area; it has been related to variability in the Kuroshio current. To further explore the nature of the PME, we studied cores obtained from the southern Okinawa Trough and the upper reaches of the Kuroshio current. Faunal census data indicate that all cores record the PME between ∼4.5 and ∼3 ka. The relative abundance of *Neogloboquadrina dutertrei* is negatively correlated to that of *P. obliquiloculata* in the southern Okinawa Trough, but not in the sites at the upper reaches. Mg/Ca and $\delta^{18}O$ measurements on *Globigerinoides ruber* shells from the southern Okinawa Trough indicate that there was no change in sea surface temperature or sea surface salinity during the PME. The vertical structure of the water column as reconstructed by multispecies $\delta^{18}O$ and $\delta^{13}C$ profiles shows no consistent anomalies in the southern Okinawa Trough and western Philippine Sea during the PME. These observations suggest that: (1) the PME was not restricted to marginal seas, but widespread in the western North Pacific. (2) The high abundance of *N. dutertrei* during the PME in the Okinawa Trough may be a result of higher food-availability in the absence of *P. obliquiloculata*. (3) No distinctive, consistent anomalies in the paleoceanographic proxies are associated with the PME, implying there were no changes in hydrography and productivity. The absence of a linkage between faunal variation and paleoceanographic proxies indicates that we do not yet understand what causes changes in planktonic foraminiferal assemblages. This lack of understanding implies that we cannot always trust fauna-based paleothermometry at millennial timescales.
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1. Introduction

During the past decade, paleoceanographers have documented an event called the '*Pulleniatina* Minimum Event (PME)', occurring between ∼4.5 and 3 ka in deep-sea cores from the western North Pacific. The PME is characterized by minimum abundance of the planktonic foraminifer *Pulleniatina obliquiloculata*. The event generally lasted for at least 1000 years. The PME was recorded in several high-resolution cores located under the influence of the Kuroshio in the Okinawa Trough (Li et al., 1997; Jian et al., 2000; Ujiié and Ujiié, 1999; Ujiié et al., 2003a; Ijiri et al., 2005), the South China Sea (Jian et al., 1996; Pflaumann and Jian,

1999; Wang et al., 1999; Yu et al., 2000; Huang et al., 2002; Liu, 2004) and off the eastern coast of Taiwan (Shieh, 1993), whereas at least one core to the east of the Ryukyu Islands does not record the event (Fig. 1). The PME can be correlated over a wide area, and its significance has become an important issue in the Holocene paleoceanography of the western North Pacific. Some authors proposed that *P. obliquiloculata*, a species with its highest abundance in the equatorial current system in the Pacific Ocean (Bé, 1977; Pflaumann and Jian, 1999) (Fig. 2), serves as an indicator of the pathway of the Kuroshio. The marked reduction of *P. obliquiloculata* therefore was said to reflect a weakening or diversion of that current (Li et al.,
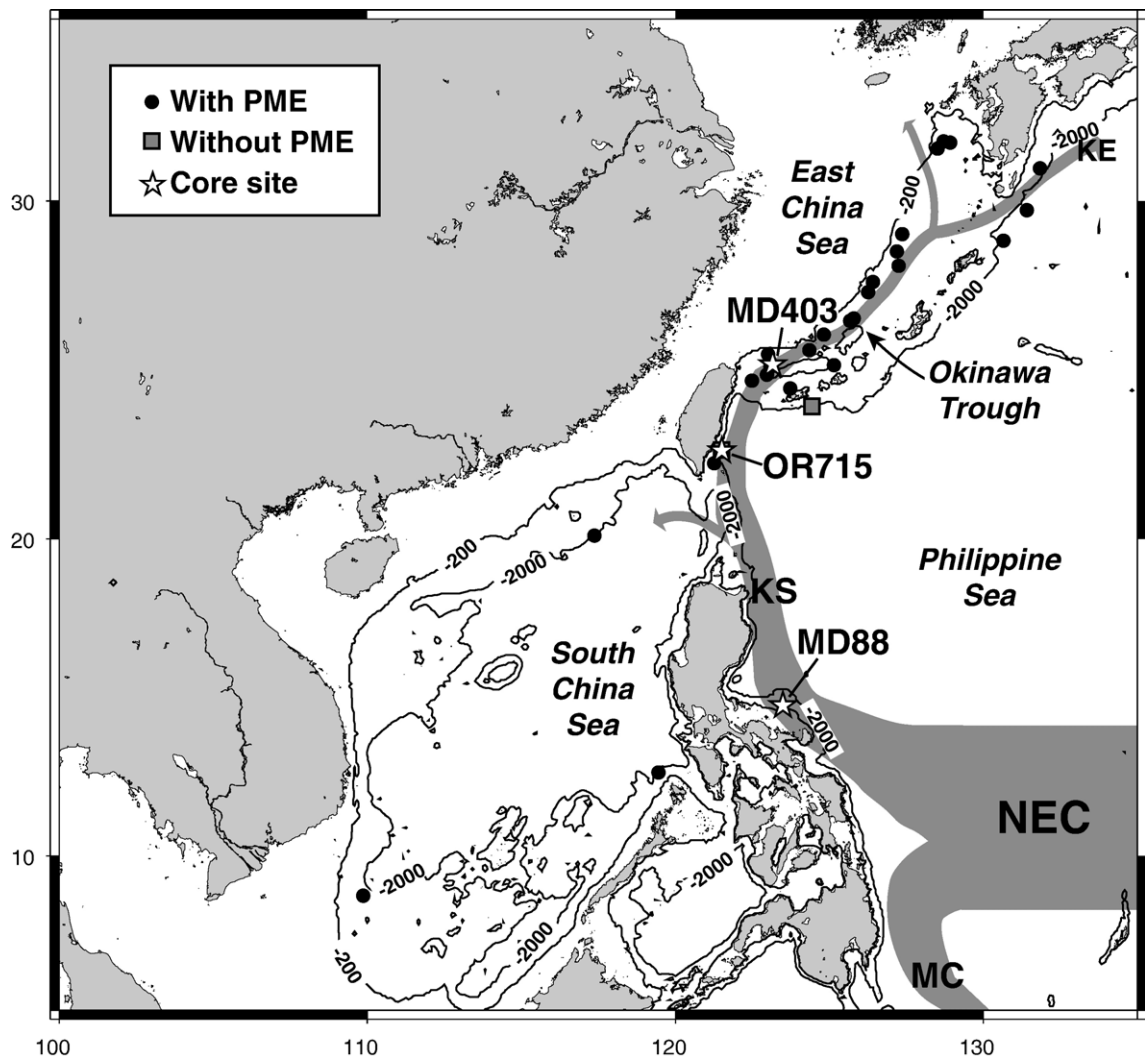

Fig. 1. Occurrence of the PME and the oceanographic settings of the study area. The North Equatorial Current bifurcates into the Kuroshio and the Mindanao Current. Faunal records are from Shieh (1993); Jian et al. (1996, 2000); Li et al. (1997, 2001); Pflaumann and Jian (1999); Ujiié and Ujiié (1999); Yu et al. (2000); Huang et al. (2002); Ujiié et al. (2003a); Liu (2004); Ijiri et al. (2005); Yuan-Pin Chang (personal communication). NEC: North Equatorial Current; KS: Kuroshio; MC: Mindanao Current; KE: Kuroshio Extension.
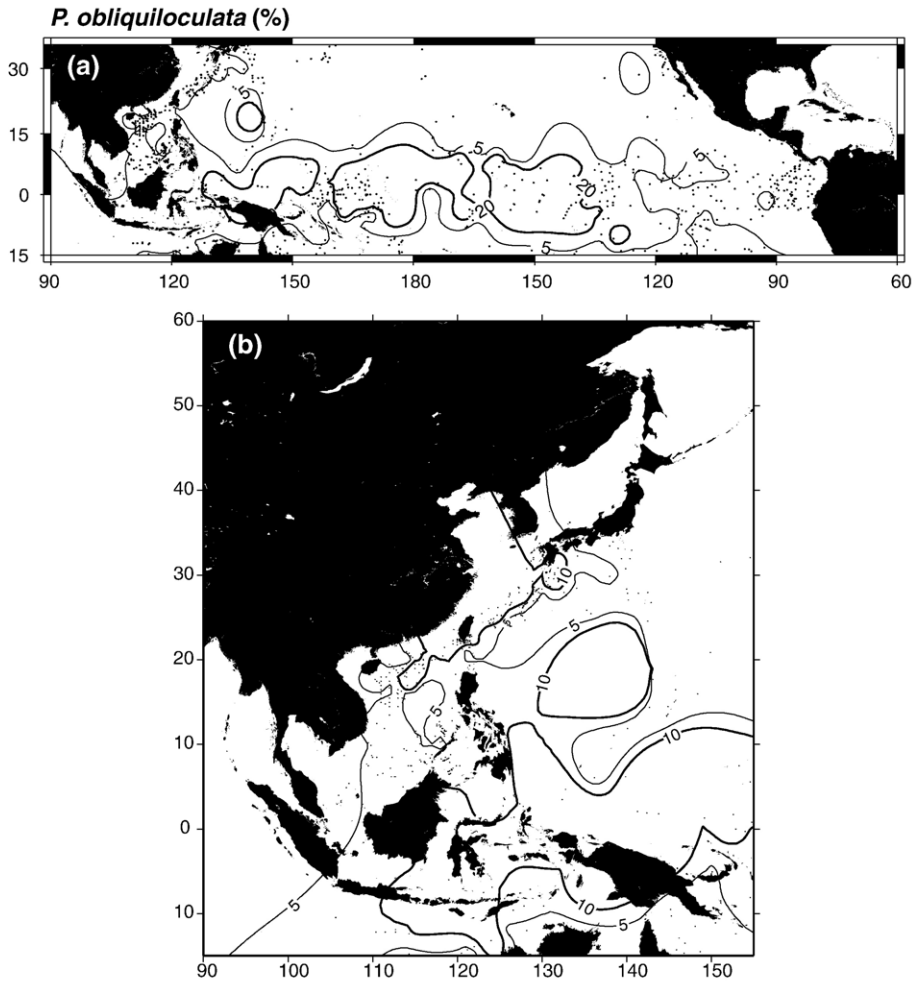
P. obliquiloculata (%)

Fig. 2. Relative abundance of *P. obliquiloculata* in surface sediments in the Equatorial Pacific. (a) The relative abundance of *P. obliquiloculata* is highest in the central Equatorial Pacific. (b) In the western North Pacific, the relative abundance of *P. obliquiloculata* is high in the northern SCS and the Okinawa Trough. Faunal data are from Kucera et al. (2005).

1997; Cheng and Wang, 1998; Ujiié and Ujiié, 1999). Others suggested that an intensification of the winter monsoon and consequently decreased winter sea surface temperatures would have caused the PME (Jian et al., 2000), and that it could be correlated to the Neoglacial cooling in China (Wu and Liu, 2004; Peng et al., 2005). The PME assemblages in the Okinawa Trough are usually marked by a high abundance of *Neogloboquadrina dutertrei*, a species less abundant in nutrient-rich waters than *P. obliquiloculata* in the central Equatorial Pacific (Watkins et al., 1998), and therefore Ujiié et al. (2003a) ascribed the PME to the occurrence of El Niño-like conditions, under which *P. obliquiloculata* decreased in abundance due to diminished upwelling of nutrient-rich water in the central Equatorial Pacific, whereas *N. dutertrei* increased in abundance due to an

enhanced influence of gyre-margin water in the Okinawa Trough. These interpretations need further investigations because of the limited geographic and proxy coverage in previous studies.

In the present study we specifically addressed the question why species decreased suddenly and significantly in abundance at a millennial timescale. The decrease in the abundance of species of planktonic foraminifera is usually attributed to changes in local hydrographic or nutrient conditions associated with major environmental changes, for example, a glacial–interglacial transition. This explanation is based on the correlation between foraminiferal species distribution and hydrographic properties in the modern ocean, and on the correlation between faunal records and records of geochemical and/or isotope proxies. With the recovery

of high sedimentation rate cores and the recognition of climate changes at millennial timescales, questions are being raised about the stability of foraminiferal distributions at such timescales, and their relations to environmental changes. The PME occurred in the late Holocene, at a time when climate history is well documented and for which corresponding records are easy to recover. This event thus is an excellent case for detailed study.

We acquired faunal census data from the upper reaches of the Kuroshio current and the southern Okinawa Trough to examine the distribution of the PME in a wider geographic area. In addition, we measured the Mg/Ca values of *Globigerinoides ruber* and oxygen and carbon isotopic ratios in multiple species of planktonic foraminifera in order to investigate the possible link among faunal changes, sea surface temperature (SST), and thermocline hydrography. The wider geographic coverage enabled us to evaluate explanations for the PME, and provided information on the paleoceanographic relations between the open western North Pacific Ocean and the Okinawa Trough.

2. Oceanographic settings

The North Equatorial Current bifurcates into the northward flowing Kuroshio and the southward flowing Mindanao Current as it approaches the Philippine coasts (Fig. 1) (Qiu and Lukas, 1996). The Kuroshio, with a mean volume transport of ~ 15 Sv (1 Sv $= 10^6$ m^3 s^{-1}) along the east coast of Taiwan and southern Okinawa

Trough (Liang et al., 2003), transports warm, saline and generally oligotrophic water northward. After entering the southern Okinawa Trough, this current is blocked by the continental shelf of the East China Sea, splits, and its eastern extension turns northeastward along the shelf break. The main stream of the Kuroshio exits the trough and becomes the Kuroshio Extension in the north Pacific.

Monsoonal winds and El Niño-Southern Oscillation (ENSO) activity determine the latitude of the North Equatorial Current bifurcation point, which in turn controls the northward volume transport of the Kuroshio (Qu and Lukas, 2003; Kim et al., 2004; Qu et al., 2004). A more southerly position of the bifurcation point during summer favors more transport in the Kuroshio, and vice versa during winter. The Kuroshio transport is weakened during El Niño years and strengthened during La Niña years, but the effect of interannual variability is secondary to the seasonal cycle of volume transport driven by monsoonal winds (Kim et al., 2004).

The three cores used in this study were recovered from the upper reaches of the Kuroshio and the southern Okinawa Trough, respectively (Fig. 1). The term 'upper reaches' refers to the region between the North Equatorial Current bifurcation point (11°–20°N, see Qiu and Lukas, 1996) and the seas off eastern Taiwan. MD98-2188 (123.5°E, 14.8°N, water depth 730 m, MD88 henceforth; Bassinot et al., 1998), taken from the western Philippine Sea, is located at the northern margin of the Western Pacific Warm Pool. The annual sea surface temperature (SST) at this site is 28.5 °C, and the
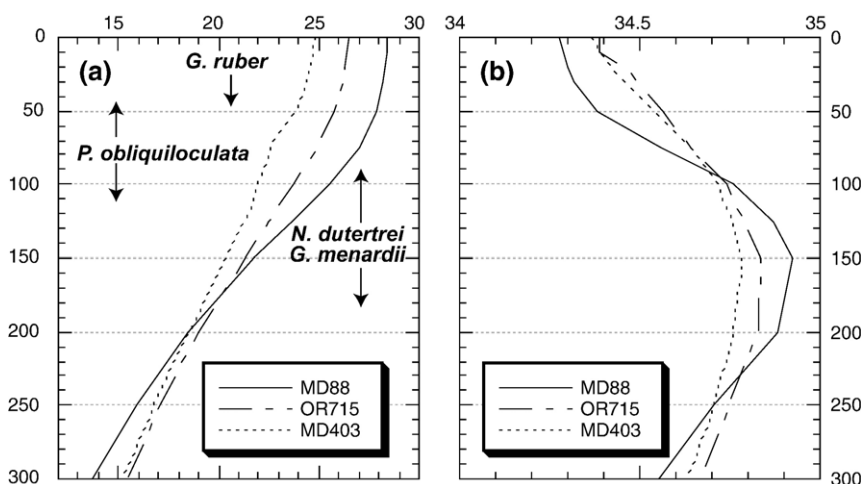

Fig. 3. Vertical hydrographic profiles at the core sites. (a) Temperature profiles at sites MD88, OR715 and MD403. The approximate depth habitats of *G. ruber*, *P. obliquiloculata*, *N. dutertrei* and *G. menardii* are also indicated according to plankton tow or sediment trap data in adjacent seas (Shieh and Chen, 1990; Lin et al., 2004). See text for discussion. (b) Salinity profiles of the three core sites. Temperature and salinity data are from Levitus and Boyer (1994).

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) (Fig. 3a). Both OR715-21 (121.5°E, 22.7°N, water depth 760 m, OR715 henceforth) and MD01-2403 (123.2°E, 25.3°N, water depth 1420 m, MD403 henceforth; Bassinot et al., 2002) are beneath the main axis of the Kuroshio. The annual SSTs at OR715 and MD403 are 26.4 °C and 24.8 °C, respectively. The temperature gradients in the thermocline at OR715 and MD403 are smaller than at MD88. The annual sea surface salinity (SSS) at MD88 is ∼ 34.3 p.s.u., 0.1 unit lower than that at OR715 and MD403 (Levitus and Boyer, 1994) (Fig. 3b). The water depths of the three cores are all above the reported depth interval of the regional lysocline (1500–3000 m) (Pan et al., 1988; Thunell et al., 1992).

3. Materials and methods

Sediments in the three cores consist of gray clay and silt with few thin ash and turbidite layers in the Holocene sections. All sediment samples were washed through a 63-μm screen and divided into aliquots convenient for picking and counting the planktonic foraminifers. To construct the age models, >6 mg of planktonic foraminiferal shells (>250 μm, *Globigerinoides* spp. and *Orbulina universa*) were picked from 16 samples in the three cores and subjected to AMS ^{14}C dating at the Rafter Radiocarbon Laboratory, Institute of Geological and Nuclear Sciences, New Zealand. The raw AMS ^{14}C ages were corrected for a 400-year reservoir effect and then converted to calendar ages using CALIB 5.0 program (Stuiver et al., 2005) with dataset Marine04 (Hughen et al., 2004) (Table 1). The sedimentation rates of core MD88 range from 20 to 60 cm/kyr, equivalent to a temporal resolution of 70–200 years for the 4-cm sampling interval. Core OR715 has uniform sedimentation rates of 20–30 cm/years except in 144–152 cm where a turbidite layer occurs. The average resolution is ∼ 175 years at a 4-cm sampling interval. Core MD403 has sedimentation rates of 50–80 cm/kyr from 8 ka to the present, and our 5-cm sampling interval resulted in a average temporal resolution of ∼ 70 years per sample for the last 8 kyr. Between 8 and 11.5 ka, the sedimentation rates are >100 cm/kyr, as resulted from the increased sediment flux in the southern Okinawa Trough when sea levels rose rapidly (Wei et al., 2005).

3.1. Faunal analysis

Sampling intervals for planktonic foraminiferal faunal analyses in cores MD88, OR715, and MD403

Table 1
AMS ^{14}C ages and calendar ages used in this study

Core	Depth (cm)	AMS ^{14}C age (year BP)	Error (years)	Calendar age (year BP)
MD982188	2.5	474	40	75
	134.5	2668	40	2382
	202.5	4913	35	5192
	278.5	8623	75	9266
	382.5	10991	55	12672
OR715-21	5	407	40	0
	70.5	3491	35	3372
	144	5694	35	6094
	152	5752	35	6135
	164	6229	35	6675
	174	6454	35	6957
MD012403	31.5	1048	45	608
	241.5	3244	45	3068
	371.5	4432	45	4625
	491.5	6164	55	6595
	601.5	8221	50	8761
	951.5	9553	70	10393
	1141.5	10312	45	11300

are approximately 8 cm, 6 cm, and 10 cm, respectively. The planktonic foraminifer faunal census data were made on splits of the >149 μm size fraction containing approximately 300 specimens. The taxonomy of planktonic foraminifers used in this study is primarily based on Parker (1962) and Kipp (1976), and the taxonomic conventions used for late Quaternary Western Pacific faunal records (Chen et al., 1999, 2005). We have combined three conventional taxonomical categories *Neogloboquadrina pachyderma* (right coiling), *pachyderma-dutertrei* intergrade (P-D intergrade), and *N. dutertrei* into a single unit *N. dutertrei*, for the three categories cannot be clearly distinguished. A total of 29 species were identified in this study.

3.2. Multispecies isotopic analyses

3.2.1. Depth habitats of planktonic foraminifers

Geochemical signatures from multiple species of planktonic foraminifers may reflect changes in hydrographic structure (e.g., Spero et al., 2003; Bostock et al., 2004; Rohling et al., 2004), or permit the detection of changes in depth habitat of a given species (Field, 2004). We used carbon and oxygen isotope values from a suite of planktonic foraminiferal species with different life cycles, ecologic preferences and distributions to investigate possible changes in the depth habitat of *P. obliquiloculata* and thermocline hydrography. Plankton tow data or sediment trap data in the study area are limited; only the studies by Shieh and Chen (1990), Yamasaki and Oda (2003) and Xu et al.

(2005) provide some clues for the depth range and seasonality of species. The 300-μm mesh size used in the research of Shieh and Chen (1990) was much larger than the 63-μm mesh size used in recent plankton tow studies (Watkins et al., 1998; Field, 2004; Kuroyanagi and Kawahata, 2004) and therefore the inferred depth habitats from Shieh and Chen (1990) are closer to those of adult planktonic foraminifera. Data collected from sediment traps and plankton tows in other regions thus were used to infer the life habitats for different species.

G. ruber, a spinose photosymbiotic species with dinoflagellates in its protoplasm (Hemleben et al., 1989), is considered to be one of the most reliable indicators of tropical to subtropical sea surface conditions, as its habitat depth is primarily limited to the mixed layer (Ravelo and Fairbanks, 1992). In the middle Okinawa Trough, G. ruber was more abundant in warm months than during the cold seasons (Yamasaki and Oda, 2003; Xu et al., 2005). The depth habitat of G. ruber was estimated to be 2–50 m based on measured shell $\delta^{18}O$ and estimated $\delta^{18}O$ values (Lin et al., 2004).

N. dutertrei and Globorotalia menardii are both non-spinose species and are mainly herbivorous, but some specimens bear symbionts (Hemleben et al., 1989). These two species exhibit distribution over a large vertical extent throughout their life cycles. For example, G. menardii lives in the euphotic zone or mixed layer during juvenile stages, but then descends to the thermocline in late ontogeny (Bé and Huston, 1977; Schweitzer and Lohmann, 1991). Neoglobquadrina dutertrei seems to consist of two populations: one in tropical water masses, and the other in subtropical water masses near ocean margins (Hilbrecht, 1997). Xu et al.

(2005) reported that the seasonal flux of N. dutertrei in the middle Okinawa Trough is mainly controlled by the oscillation of the Kuroshio. When the Kuroshio shifted northwesterly towards the shelf area, the flux of N. dutertrei was lower than when under the direct influence of the Kuroshio. The preferred habitats of G. menardii and N. dutertrei are thought to be closely associated with the chlorophyll maximum (Watkins et al., 1998; Field, 2004; Kuroyanagi and Kawahata, 2004). Although G. menardii is considered to reside within the upper to middle thermocline at depths between 25 and 85 m in the eastern Equatorial Pacific (Spero et al., 2003), Shieh and Chen (1990) reported that off the eastern coast of Taiwan, the abundances of both G. menardii and N. dutertrei increased with depth and they reached their maxima at the depth of 200 m. We therefore regard N. dutertrei and G. menardii as middle-to-deep thermo-cline dwellers.

P. obliquiloculata is also a non-spinose species and a facultative symbiont bearer. It exhibits moderate vertical migration between the mixed layer and the upper thermocline during its life cycle (Hemleben et al., 1989). The preferred habitat of the species seems to be primarily associated with tropical upwelling (Watkins et al., 1996, 1998). Off the eastern coast of Taiwan, an abundance peak was observed in the upper thermocline at the station located under the main path of the Kuroshio (Shieh and Chen, 1990). Similar to N. dutertrei, the seasonal flux of P. obliquiloculata is also closely associated with the oscillation of the Kuroshio, showing higher flux under the direct influence of the Kuroshio (Xu et al., 2005). In agreement with Tian et al. (2005), we propose that P. obliquiloculata resides within the upper to middle thermocline in our study area; its habitat might partially overlap with that of N. dutertrei.

Table 2
Planktonic foraminiferal temperature–$\delta^{18}O$ relationships used in this study

Materials	Size (μm)	$T = a + b(\delta_c - \delta_w)$		δ_w correction (VSMOW to VPDB, ‰)	Reference
		a	b		
G. ruber	250–350	14.9	−4.80	−0.27	Spero et al. (2003), using Bemis et al. (1998) equation for HL conditions
N. dutertrei (plankton tow)	n.d.	10.5	−6.58	−0.22	Bouvier-Soumagnac and Duplessy (1985)
G. menardii (culture)	600–850	14.9	−5.13	−0.27	Spero et al. (2003)
P. oblquiloculata (plankton tow)	>500	16.5	−4.80	−0.27	Russell and Spero (2000), using Bemis et al. (1998) equation for LL conditions

3.2.2. Normalization of multispecies stable isotopic data

We used the multispecies approach of Spero et al. (2003). The basic premise behind this approach is that variations in the isotopic composition of foraminiferal shells are primarily a function of physical properties of the water column such as temperature, salinity and $\delta^{13}C$ of dissolved inorganic carbon ($\delta^{13}C_{DIC}$). Isotopic signatures of multiple planktonic species with different depth preferences can be used to reconstruct thermocline structure and $\delta^{13}C_{DIC}$ gradient. However, the effects of disequilibrium precipitation of calcite by foraminifera on isotopes have to be corrected. The main difference between the traditional constant correction factors (Patrick and Thunell, 1997; Niebler et al., 1999) and the multispecies approach is that the latter includes temperature-dependent normalization corrections to normalize the $\delta^{18}O$ using temperature–$\delta^{18}O$ relationships. For the western Pacific, the foraminiferal temperature–$\delta^{18}O$ correlation has not been established. We used the empirical relations from laboratory culturing and field studies from other regions, assuming that these are applicable in our study area (Table 2). For *G. ruber*, we used the correlation of Spero et al. (2003), because this equation gives a better estimate of the

Table 3
$\delta^{18}O$ and $\delta^{13}C$ normalization corrections to $\delta^{18}O_{G.\ ruber}$ and $\delta^{13}C_{DIC}$ for core MD88

Species	$\delta^{18}O$ normalization (‰)			$\delta^{13}C$ normalization (‰)
	at 28 °C	at 25 °C	at 22 °C	
G. ruber	0			+0.94
P. obliquiloculata		−0.33		+0.94 [a]
N. dutertrei		0.05 [b]		−0.50
G. menardii			n.d.	0

[a] The $\delta^{13}C$ normalization factor of *P. obliquiloculata* is calculated using the equation $\Delta\delta^{13}C_{shell\text{-}DIC} = 2.49 - 0.137\ T$ (Russell and Spero, 2000).
[b] The correction value applied to covert $\delta^{18}O_w$ values from the VSMOW to VPDB scales in Bouvier-Soumagnac and Duplessy (1985) is −0.22‰, which is 0.05‰ higher than the current adopted value of −0.27‰. The 0.05‰ offset is included in our calculation.

surface water $\delta^{18}O$ (see below). Lin et al. (2004) demonstrated that the *G. ruber* $\delta^{18}O$–temperature correlation in the northern SCS is more consistent with the values calculated based on Mulitza et al. (2003), we found that the application of either equation yields similar results in the reconstructed vertical hydrography. We applied the equation of Bouvier-Soumagnac and Duplessy (1985) for *N. dutertrei,* since
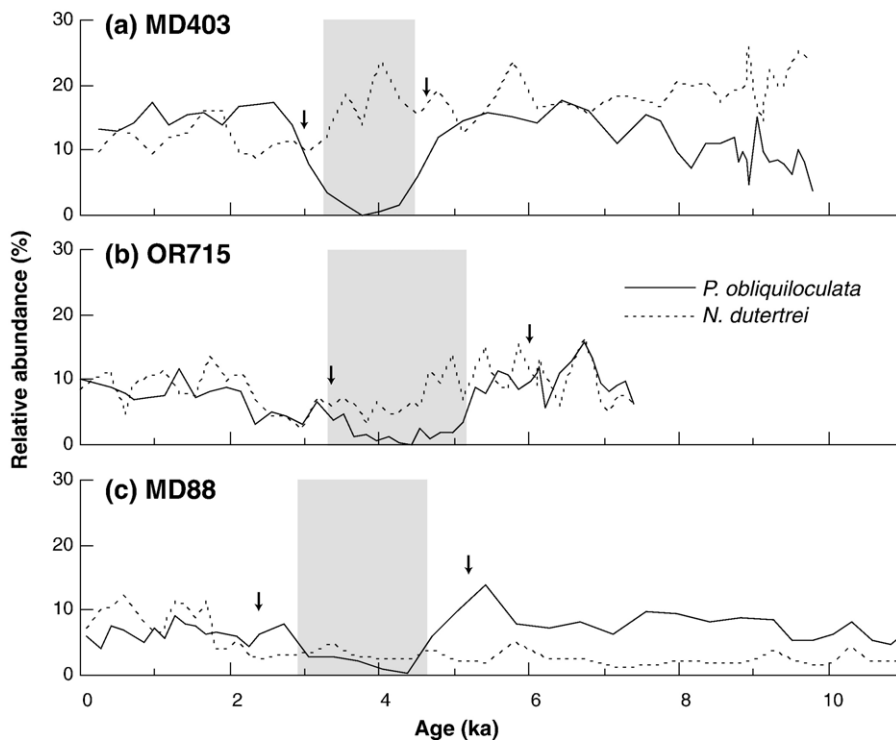

Fig. 4. Relative abundances of *P. obliquiloculata* (solid line) and *N. dutertrei* (dash line) in (a) MD403, (b) OR715 and (c) MD88. The PME period is shaded. Arrows indicate the ^{14}C data bracketing the PME period.

no new equation has been published. We used the equation of Spero et al. (2003) for *G. menardii*, as this experiment-derived relationship is indistinguishable from the plankton tow based relationship (Bouvier-Soumagnac and Duplessy, 1985). Although *P. obliquiloculata* is a species rarely used in isotopic analyses, we followed Russell and Spero (2000), who applied the low-light (LL) temperature–$\delta^{18}O$ relationship of *O. universa* (Bemis et al., 1998) to *P. obliquiloculata* data and found an acceptable correlation between observed and estimated temperatures ($R^2 = 0.77$, $n = 6$). Based on the temperature profiles in Fig. 4a, we estimated the mean temperatures at depth of the mixed layer, the middle thermocline and the deep thermocline at sites MD88 and MD403. The final results of the $\delta^{18}O$ normalization factors to *G. ruber* $\delta^{18}O$ are listed in Tables 3 and 4. The difference in VSMOW to VPDB corrections among the four empirical relationships (Coplen et al., 1983; Hut, 1987) was adjusted.

Foraminiferal $\delta^{13}C$ is controlled by several factors, including the $\delta^{13}C_{DIC}$ (Kroopnick, 1985; Spero, 1992), vital effects (Spero and Williams, 1988), carbonate ion effects (Spero et al., 1997; Russell and Spero, 2000), temperature (Bemis et al., 2000), and dissolution (Berger and Killingley, 1977). For *G. ruber*, *N. dutertrei* and *G. menardii*, we applied the constant normalization factors used in Spero et al. (2003) (Tables 3, 4). The $\Delta\delta^{13}C_{shell-DIC}$ offset of -0.94 ± 0.28‰ for *G. ruber* based on plankton tow data collected from the tropical Atlantic and northern Caribbean is not significantly different from the $\Delta\delta^{13}C_{shell-DIC}$ of -0.84 ± 0.25‰ ($n = 8$) established using sediment trap data from the northern SCS (Lin et al., 1999, 2004). We did not apply any temperature correction to the $\delta^{13}C$ normalization factors for *G. ruber*, *N. dutertrei* and *G. menardii*

because no temperature-$\delta^{13}C$ relationship is available. For *P. obliquiloculata*, Russell and Spero (2000) found that its $\Delta\delta^{13}C_{shell-DIC}$ and $\delta^{13}C_{DIC}$ display a strong negative linear relationship ($\Delta\delta^{13}C_{shell-DIC} = 2.49 - 0.137$ T, $R^2 = 0.82$, $P = 0.01$), implying that isotopically light metabolic carbon is preferentially incorporated under higher temperatures. We therefore applied this equation to calculate the normalization factors for *P. obliquiloculata*.

3.2.3. Downcore analysis

For stable oxygen and carbon isotopic analyses, *G. ruber* was used at every 4-cm interval in cores MD88 and OR715, and every 5 cm in core MD403. The other three species were sampled every 4 cm in MD88 and 10 cm in MD403. *G. ruber* (white) were picked from the 250- to 355-μm size fraction, *N. dutertrei* from the 355- to 425-μm size fraction, and *G. menardii* and *P. obliquiloculata* from the >425 μm size fraction. *G. ruber* is known to have two morphotypes, *G. ruber* sensu stricto (s.s.) and *G. ruber* sensu lato (s.l.). We picked *G. ruber* s.s. because its habitat is closer to sea surface than *G. ruber* s.l. (Wang, 2000; Löwemark et al., 2005; Steinke et al., 2005). *N. dutertrei* and *G. menardii* are reported to add a calcite crust of varying amounts that can shift the isotopic composition toward deeper, colder environments (Hemleben et al., 1989). We visually identified and selected specimens with minimal crustation for analysis. We picked specimens of *P. obliquiloculata* with shiny cortex in order to be consistent with the morphological criterion used in Russell and Spero (2000).

Six to eight shells of *G. ruber* were required to give a total sample weight of 80–100 μg for isotope analysis, while *N. dutertrei*, *G. menardii* and *P. obliquiloculata* samples were made up of 2–5 individuals to achieve the required weight. Samples were immersed in CH_3OH and subjected to ultrasonic vibration for 6 seconds three times to remove clay particles. After removing methanol, they were immersed in NaOCl for 24 hours to remove organic matter. After being cleaned by deionized water five times and dried, specimens from core MD88 were measured using the Finnigan MAT Delta^{plus} mass spectrometer with a Kiel Device at the Department of Geosciences, National Taiwan University, while samples from cores OR715 and MD403 were measured using the Micromass Isoprime isotope ratio mass spectrometer housed at the Department of Earth Sciences, National Taiwan Normal University. All $\delta^{18}O$ and $\delta^{13}C$ values are reported vs. the Pee Dee Belemnite scale. External precision was

Table 4
$\delta^{18}O$ and $\delta^{13}C$ normalization corrections to $\delta^{18}O_{G.\ ruber}$ and $\delta^{18}O_{DIC}$ for core MD403

Species	$\delta^{18}O$ normalization (‰)			$\delta^{13}C$ normalization (‰)
	at 25 °C	at 22 °C	at 20 °C	
G. ruber	0			+0.94
P. obliquiloculata		−0.33		+0.53 [a]
N. dutertrei		+0.22 [b]		−0.50
G. menardii			−0.07	0

[a] The $\delta^{13}C$ normalization factor of *P. obliquiloculata* is calculated using the equation $\Delta\delta^{13}C_{shell-DIC} = 2.49 - 0.137$ T (Russell and Spero, 2000).

[b] The correction value applied to covert $\delta^{18}O_w$ values from the VSMOW to VPDB scales in Bouvier-Soumagnac and Duplessy (1985) is −0.22‰, which is 0.05‰ higher than the current adopted value of −0.27‰. The 0.05‰ offset is included in our calculation.

better than 0.10‰ and 0.06‰ ($\pm 1\sigma$) for $\delta^{18}O$ and $\delta^{13}C$, respectively, based on repeated analyses of the internal laboratory standard. Thirty samples from core MD403 were repicked and rerun for duplication test of $\delta^{18}O$. One standard deviation of the difference of $\delta^{18}O$ between duplicates is ~0.17‰.

3.3. Mg/Ca ratio measurement

To estimate SST using a method independent of the faunal composition, we measured the Mg/Ca values of planktonic foraminifera in core MD403. Approximately 20 individuals of *G. ruber*, 250–355 μm in size, were picked from the 1-cm slice adjacent to the sample slice from which the specimens for isotope analysis had been picked. Although the isotope and Mg/Ca samples were not exact 'paired samples', we assumed that bioturbation had homogenized these two adjacent layers to certain degree, so that the $\delta^{18}O$ and Mg/Ca values can be combined to calculate $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$). The Mg/Ca samples were processed following a cleaning procedure modified from Shen et al. (2001). First, shells were gently crushed using two ethanol-cleaned glass plates, making sure that all chambers were fully opened. Samples were then leached sequentially in an ultrasonic bath using four reagents designed to remove attached fine clays, organics, chemically exchangeable contaminants, and hydrogenous metal oxides, respectively. The sequence of the four reagents was: (1) ethanol, (2) 1% H_2O_2 at pH 8–8.5, (3) 1.0 M NH_4Cl and (4) 0.01 M NH_2OH, which was prepared from hydroxylamine–HCl. After leaching with 0.5×10^{-3} M HNO_3 for 5 min, the samples were dissolved completely in 1% HNO_3. The Mg/Ca ratio was determined on a quadrupole inductively coupled plasma mass spectrometer (Q-ICPMS, Agilent 7500) at the Department of Geosciences, National Taiwan University. Details of the instrumental analysis were described in Shen et al. (2004). Analyses of the Mg/Ca working standard showed that the long-term precision was 0.5% (1σ) for Mg/Ca during our measurement period. Fifteen samples were repicked and rerun. One standard deviation of the difference of these analyses is ~0.22 mmol/mol, or 0.38 °C. We conservatively estimated the total error to be equivalent to ~±0.5 °C (1σ). The *G. ruber* Mg/Ca values were converted to SST using the equation developed from South China Sea core-top sediments: SST=ln(Mg/Ca/0.38)/0.089 (Hastings et al., 2001). Random error in $\delta^{18}O_{sw}$, propagated from errors in $\delta^{18}O$ and Mg/Ca-derived SST, is ~0.19‰.

4. Results and discussion

4.1. Planktonic foraminiferal assemblages

To identify the PME more precisely, we defined the PME as a period in which the relative abundance of *P. obliquiloculata* is continuously lower than 5%. According to the definition, all the three cores record the PME (Fig. 4). The timing of the minimum zone seems to agree well in cores MD88 and MD403 based upon ^{14}C dating, but the starting point is about 500 years earlier in core OR715. The apparent heterochroneity may be the result of lack of age control: ages are not well constrained by ^{14}C data for the 5–4 ka interval in core OR715. Therefore, we followed the previous report that the PME occurred from ~4500 to 3000 year BP (Ujiié et al., 2003a).

The occurrence of the PME at site MD88 in the neighborhood of the North Equatorial Current bifurcation point supports the argument of Ujiié et al. (2003a) that the PME may have originated in the equatorial Pacific and propagated westward and northward through the North Equatorial Current–Kuroshio system. However, their argument that the low abundance of *P. obliquiloculata* in the western North Pacific is linked to ENSO activity in the remote equatorial Pacific (Ujiié et al., 2003a) remains to be tested. These authors assume that *P. obliquiloculata* is mainly transported from the equatorial area to higher latitudes via the Kuroshio, which is not supported by a transit time from central Equatorial Pacific to the southern Okinawa Trough of approximately 6 years as estimated by Lee et al. (2004). Such a transit time would have allowed the population of *P. obliquiloculata* to respond to local hydrography rather than to reflect remote oceanographic conditions.

The negative correlation of the relative abundances of *P. obliquiloculata* and *N. dutertrei* in core MD403 agrees well with previous records (Ujiié et al., 2003a), but is less prominent in core OR715 and absent in core MD88 (Fig. 4). The warm, well-stratified and oligotrophic waters at the MD88 core site may account for the low abundance of *N. dutertrei*, which prefers cooler and more eutrophic waters (Yamasaki and Oda, 2003). *N. dutertrei* is considered characteristic of both Kuroshio water (Ujiié and Ujiié, 2000) and gyre-margin assemblages (Thompson, 1981). Ujiié et al. (2003a) argued that the high abundance of *N. dutertrei* in the Okinawa Trough during the PME implied a weakened Kuroshio under El Niño-like conditions, which in turn led to the thriving of *N. dutertrei* as a gyre-margin water indicator. However, according to Xu et al. (2005), during the period when the Kuroshio axis
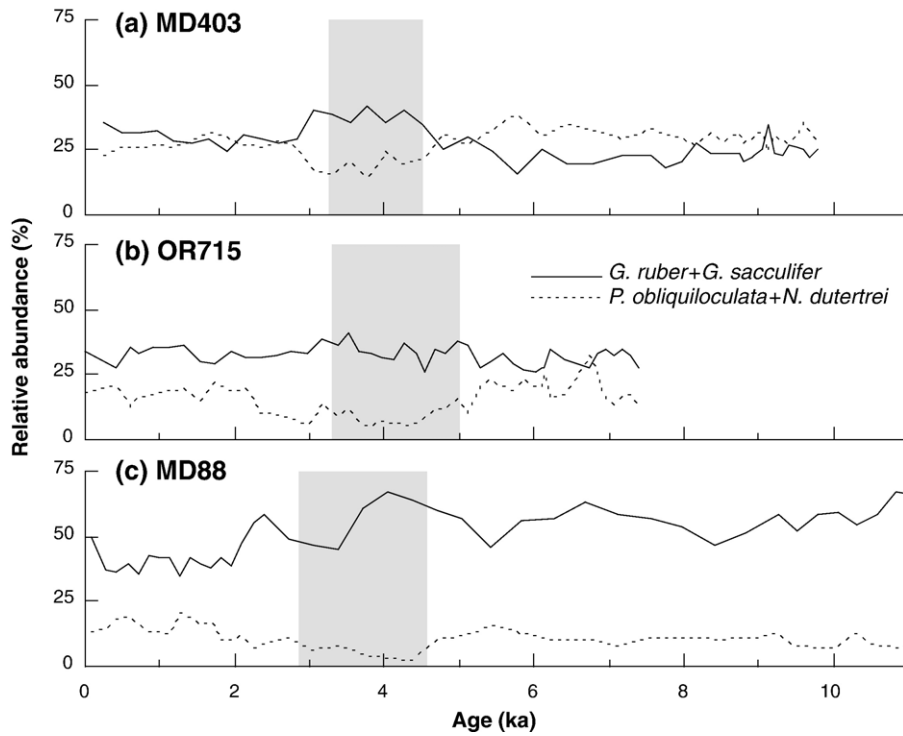
Fig. 5. Relative abundances of *G. ruber+G. sacculifer* (solid line) and *P. obliquiloculata+N. dutertrei* (dash line) during the Holocene. The PME period is shaded.
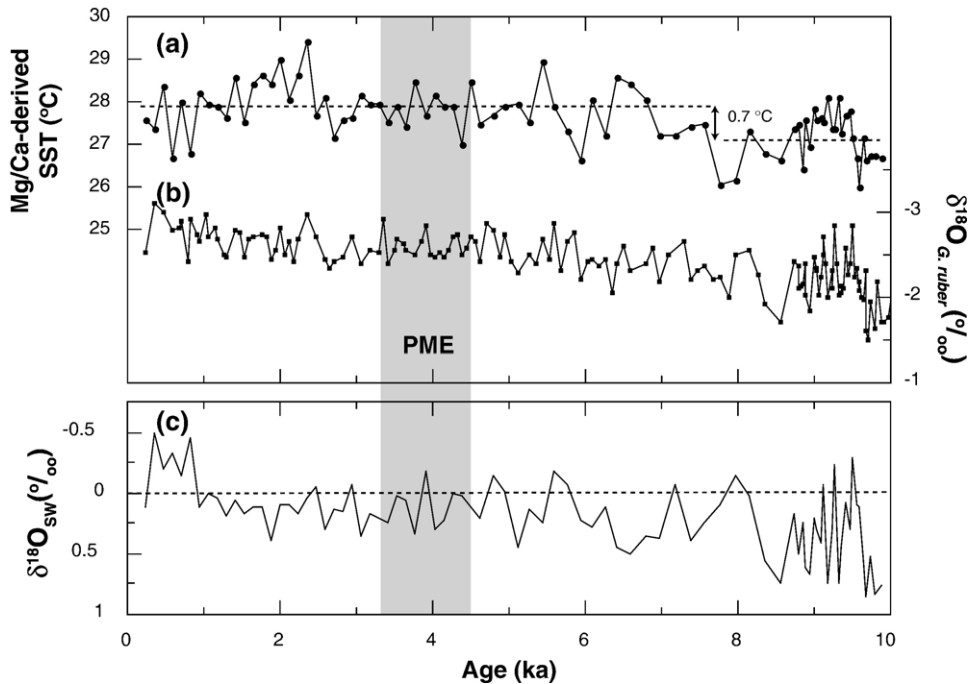

Fig. 6. SST and SSS estimates of MD403. (a) *G. ruber* Mg/Ca-derived SST. (b) *G. ruber* δ^{18}O. (c) The calculated δ^{18}O of seawater.

shifted northwestwards and the middle Okinawa Trough was under higher influence of gyre-margin water, the flux of *N. dutertrei* did not increase but decreased simultaneously with that of *P. obliquiloculata*. The diets of both species consist mainly of diatoms (Hemleben et al., 1989), so it is probable that even without paleoceanographic changes during the PME, *N. dutertrei* could thrive in the Okinawa Trough because it enjoyed a higher food supply in the absence of competition by *P. obliquiloculata*.

These faunal data can also be used to evaluate the paleoceanographic connections between the upper reaches of the Kuroshio and the Okinawa Trough. The time-series of the relative abundances of four species (*G. ruber*, *G. sacculifer*, *P. obliquiloculata*, *N. dutertrei*) in our study area (Fig. 5) show that the difference between the relative abundances of *G. ruber* + *G. sacculifer* and *P. obliquiloculata* + *N. dutertrei* decreases northward. This transition implies that the planktonic foraminiferal assemblage in the Okinawa Trough does not merely reflect the signal of the warm, saline, oligotrophic

Kuroshio water, but records a modified signal modulated by the processes in the Okinawa Trough.

4.2. SST and SSS in the southern Okinawa Trough

The Holocene record of foraminiferal Mg/Ca in the southern Okinawa Trough shows moderate variability (Fig. 6a). The core-top measurement yields a temperature of 27.6 °C, which is close to the present-day average SST during May to October (27.3 °C; Levitus and Boyer, 1994). Accordingly, we consider the *G. ruber* Mg/Ca-derived temperatures to represent the average SST of warm seasons. The mean Mg/Ca-based SST during the early Holocene (10–8 ka) is ~27.1 °C, ~0.7 °C lower than the average SST from 8 ka to present. Details of the Mg/Ca data are discussed elsewhere (Lin, 2005) and here we only focus on the PME period.

We firstly tested the 'cooling hypothesis' proposed by Jian et al. (2000). During the PME period, the average SST is 27.9±0.4 °C, not significantly different
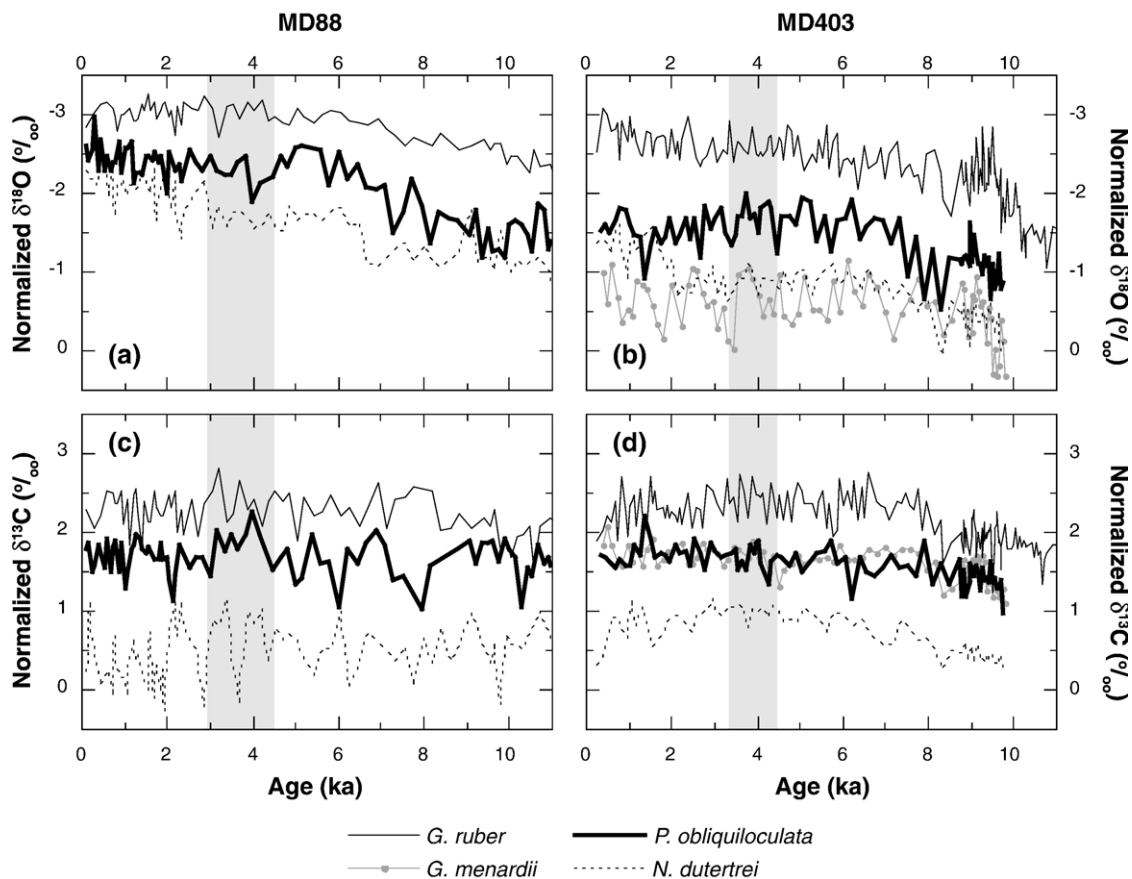

Fig. 7. Results of the multispecies isotopic analyses. (a)(b) Oxygen and (c)(d) carbon isotope data of *G. ruber*, *P. obliquiloculata*, *N. dutertrei* and *G. menardii* normalized to $\delta^{18}O_{G. ruber}$ and $\delta^{13}C_{DIC}$, respectively. The PME period is shaded.

from the average SSTs during 6–4.5 ka (27.7 ± 0.6 °C) and 3–2.5 ka (27.8 ± 0.4 °C). A Mg/Ca-derived SST record from the middle Okinawa Trough also does not display cooling during the PME (Sun et al., 2005). These Mg/Ca-derived SST records thus confirm the arguments of Li et al. (2001) and Ujiié et al. (2003a), who rejected cooling during the PME because they did not observe changes in planktonic δ^{18}O values.

Ujiié et al. (2003a) argued that during the El Niño-like conditions, the weakened Kuroshio transport would result in an increase in relative abundance of *N. dutertrei*, along with other species characteristics of the coastal water assemblage throughout the Okinawa Trough. Such an increase in coastal water assemblage species should be accompanied by lowered SSS. We calculated the δ^{18}O$_{sw}$ by subtracting the temperature effect from the *G. ruber* δ^{18}O values using the temperature–δ^{18}O relationship of Spero et al. (2003). The calculated core-top δ^{18}O$_{sw}$ is 0.11‰ (Fig. 6c), within the range of δ^{18}O$_{sw}$ values (0.18 ± 0.19‰) measured in surface water samples near the core site during summer. The MD403 δ^{18}O$_{sw}$ record displays a long-term decrease in variability. The δ^{18}O$_{sw}$ values during the early Holocene oscillate from 0.7‰ to −0.2‰, but the magnitudes of oscillation decrease to ~0.5‰ in the mid Holocene and ~0.2‰ during 2–1 ka. During the PME, the δ^{18}O$_{sw}$ values did not deviate from the generally decreasing trend in variability. Other than that, our evidence does not support that surface waters became less saline at the location of core MD403 during the PME.

In addition, the PME has been recorded in the southern SCS (Fig. 1) where no SSS front between salty and fresh waters exists. Therefore, it is unlikely that the PME was related to changes in SSS in these two marginal seas.

4.3. Thermocline hydrography

The normalized multispecies δ^{18}O records for cores MD88 and MD403 are shown in Fig. 7a and b. We did not measure the isotopes of *G. menardii* in core MD88 because of its scarcity throughout the Holocene. In both records, these species show a clear and consistent depth ranking in which *G. ruber* registered the lowest δ^{18}O values indicating the shallowest habitat. *P. obliquiloculata* had more negative δ^{18}O values than *N. dutertrei* during the early to middle Holocene, but the δ^{18}O values converged at 2 ka in both sequences. In core MD403, *G. menardii* and *N. dutertrei* have similar δ^{18}O values, but the δ^{18}O record of *G. menardii* displays higher variability, suggesting

either a larger vertical migration depth range, or random errors due to the low number of specimens (2–3 individuals) used in measurements. The δ^{18}O values in core MD88 are generally more negative than those in core MD403, as a reflection of the warmer environment in the western Philippine Sea (Fig. 3).

From 8 ka to the present, the δ^{18}O records of *G. ruber*, *P. obliquiloculata* and *N. dutertrei* all display a long-term decreasing trend, more prominent in the MD88 record than in the MD403 record (Fig. 7). Shared variability in signatures of all species would likely reflect real changes in temperature and/or salinity within the thermocline (Field, 2004). Therefore, it is likely that the waters in the upper reaches of the Kuroshio became progressively warmer and/or less saline in the period, but such a signal was somewhat modified by complex hydrographic processes in the southern Okinawa Trough. Ujiié et al. (2003b) reported more positive δ^{18}O values of *P. obliquiloculata* and *N. dutertrei* in the Okinawa Trough during the PME. In the MD88 and MD403 records, there are consistent differences in δ^{18}O values of *P. obliquiloculata* and the other three species from 8 to 2 ka, but without any excursions during the PME, implying that the thermocline conditions did not change abruptly, or that the relationship between the depth habitats of *P. obliquiloculata* and *N. dutertrei* did not change. After 2 ka, the δ^{18}O values of *N. dutertrei* became more negative by ~0.5‰ in both cores, implying a smaller temperature gradient within the upper to middle thermocline or a change in the depth habitat of *N. dutertrei*.

The subsurface nutrient condition was examined using the δ^{13}C records. The multispecies δ^{13}C values normalized to δ^{13}C$_{DIC}$ show a similar pattern of depth ranking as the normalized δ^{18}O records (Fig. 7c, d). *G. ruber*, the shallowest dwelling species, yields a δ^{13}C of ~2‰ before 8 ka and ~2.5‰ after 8 ka. *P. obliquiloculata* records δ^{13}C values representing either the lower mixed layer or upper thermocline conditions. *N. dutertrei* has the most negative δ^{13}C values, in agreement with its deeper habitat. The *G. menardii* values are close to those of *P. obliquiloculata*, implying similar habitat depths of both species as to nutrient gradient, but, the δ^{18}O records suggest a deeper habitat for *G. menardii* (Fig. 7b). We attribute this inconsistency to either incorrect estimation of habitat depth or the use of an inappropriate normalization factor. Despite this inconsistency in the depth ranking between the δ^{18}O and δ^{13}C records, the isotopic values of *G. menardii* do not show an excursion during the PME, supporting our interpretation that there is no change in thermocline hydrography during the PME.

We interpreted the normalized $\delta^{13}C$ variations as indications of change in $\delta^{13}C_{DIC}$ or vertical migration of planktonic foraminifers within the chemocline. A remarkable feature in both sequences is the $\sim 0.5‰$ difference in $\delta^{13}C$ values before and after 8 ka. Such a shift at 8 ka was also observed in the northern Okinawa Trough (Jian et al., 2000; Ijiri et al., 2005) and southern SCS (Stephan Steinke, personal communication, 2005), 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 $\sim 0.3‰$. 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. Ujiié et al. (2003b) interpreted the decreased $\Delta\delta^{13}C$ between the surface and thermocline dwellers as evidence for a shoaling thermocline due to a weaker Kuroshio transport, but the $\delta^{18}O$ data do not support such a change in habitat of *P. obliquiloculata* toward shallower depth during the PME in core MD88. The $\delta^{13}C_{DIC}$ transition zone occurs within a narrow depth range in the upper pycnocline (Fairbanks et al., 1982), so the $\delta^{13}C$ shift could be the result of a small change in *P.*
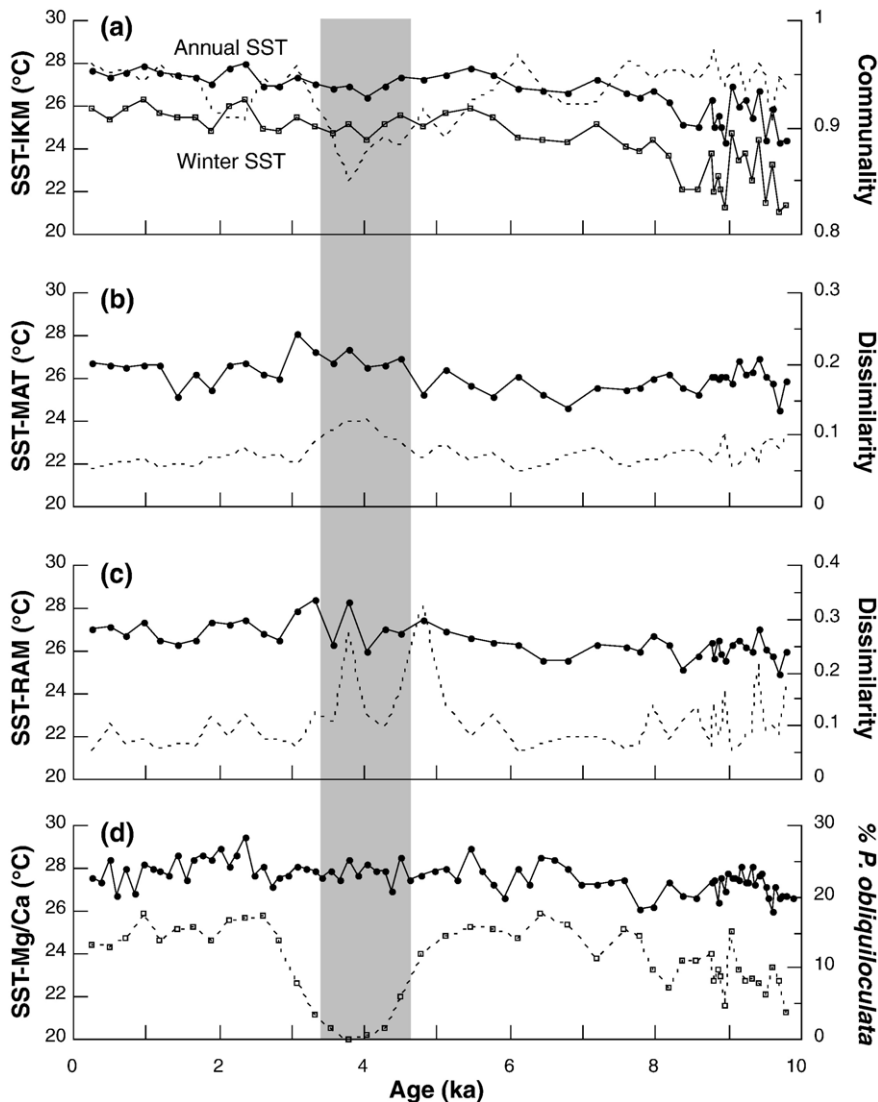

Fig. 8. Comparison of three SST reconstructions based on planktonic foraminifer counts in core MD403. (a) IKM: Imbrie–Kipp method; (b) MAT: modern analog technique; (c) RAM: revised analog method. The dash lines denote the communality or dissimilarity of each SST reconstruction. (d) The *G. ruber* Mg/Ca-derived SST (solid line) and relative abundance of *P. obliquiloculata* (dash line). The PME period is shaded. Data and method for these reconstructions are from Chen et al. (2005).

obliquiloculata habitat depth within the upper thermo-cline or merely a shift in depth of the $\delta^{13}C_{DIC}$ chemocline associated with subtle changes in the structure of the pycnocline (Loubere, 2001). Not observed in other sites during the PME, such a slight change in subsurface nutrient condition at MD88 is more likely to be a local phenomenon rather than a widespread event that would result in the reduction of *P. obliquiloculata* populations.

4.4. On the PME and ENSO

Existing paleoenvironmental hypotheses (Li et al., 1997; Cheng and Wang, 1998; Ujiié and Ujiié, 1999; Jian et al., 2000) were not supported by the evidence in this study. A common feature in these hypotheses is their 'marginal-sea' point of view. In contrast, the Ujiié et al. (2003a) hypothesis pointed out for the first time the possible relationship between the PME and the equatorial Pacific, and their suggestion of the existence of El Niño-like conditions during the PME deserves further discussion.

The long-term variability of Holocene ENSO-like events is debated vigorously among climate modelers and paleoclimatologists. Data from Peruvian archaeo-logical deposits suggest that the eastern equatorial Pacific was relatively warmer during the middle Holocene, indicating El Niño-like conditions (Sand-weiss et al., 1996; Andrus et al., 2002). Various lines of evidence suggest the occurrence of more La Niña-like conditions during the early Holocene (Clement et al., 2000; Koutavas et al., 2002; Moy et al., 2002). It would be consistent with the hypothesis that ENSO conditions became enhanced after the middle Holocene if the PME could be seen as a proxy signal for El Niño (Ujiié et al., 2003a). However, the PME did not persist long enough into the late Holocene, when ENSO became further strengthened after 3 ka (Moy et al., 2002; Rein et al., 2005). Unusual conditions at ~4.2 ka (Hong et al., 2005) were interpreted as a 'super El Niño', with a timing coincident with that of the PME. The record by Hong et al. (2005), however, does not agree with the interpretation of the interval of 3.7–4.5 ka as a 'quiescent' ENSO period (Moy et al., 2002), supported by marine records which display no sign of a strong El Niño during 4.5–3 ka (Rein et al., 2005). As long as there is no agreement on the reconstructions of the strength of El Niño conditions in the past, we cannot interpret the PME in terms of El Niño strength. In summary, the cause of the PME remains enigmatic and requires further study. The factors controlling variability in relative abundance of planktonic foraminiferal species at millennial timescales are not yet understood and may be difficult to gauge with presently available paleoceanographic proxies.

4.5. Implications for fauna-based paleoceanographic reconstructions

The most fundamental assumption of fauna-based paleoceanographic reconstructions is the dominant control of environmental factors on the abundance one single species or on the whole assemblage. In the case of the Holocene PME, the species considered to be a 'Kuroshio indicator' suddenly decreased in abundance, but there are no corresponding anomalies in isotope and trace element proxies. Such a discrepancy has profound implications for the applicability and methodology of the fauna-based techniques. To demonstrate the influ-ence of the PME on the applicability of fauna-based paleothermometers, we present a comparison of three SST reconstructions derived from the Imbrie–Kipp method (IKM), the modern analog technique (MAT), and the revised analog method (RAM) based upon the faunal census data in MD403 (Fig. 8), using techniques and a calibration database as in Chen et al. (2005) and Kucera et al. (2005).

In contrast to a decreased winter SST in the Okinawa Trough as estimated by the FP-12E transfer functions (Jian et al., 2000), we were surprised to see that none of the fauna-based SSTs decreased during the PME period. The discrepancy between the SST reconstructions of FP-12E (Jian et al., 2000) and IKM may be due to the use of the more recent planktonic foraminifer databases. The MAT-derived SSTs increased slightly during about 5–3 ka, but the magnitude of the increase is within the uncertainties of ~1 °C (Chen et al., 2005). The reliability of all three SST estimates decreases for the PME interval, as indicated by the lowered communality values for the IKM and increased dissimilarities for the MAT and RAM (Fig. 8). The locations of the identified analogous faunas in the MAT and RAM during the PME are in the northern SCS and in the western equatorial Pacific, respectively. The selection of these tropical sites as analogs might be due to the increased relative abundance of warm water species, e.g., *G. ruber*, during the PME in MD403 (Fig. 5). The PME, therefore, makes the fauna-based paleothermometers potentially less trustworthy.

The assumption of that one environmental factor (e.g., temperature or nutrients) dominates the life history of planktonic species has been a fundamental basis of fauna-based techniques. This presumption may cause misleading results for paleoceanographic

reconstructions. For example, in the case of the PME, one consequence is the eagerness to attribute the faunal change to an environmental cause, and, in some cases, leading to circular reasoning. None of the previous environmental explanations for the PME were supported by our data: an abrupt change in fauna is not necessarily equivalent to an abrupt environmental change. What we need is to know more about the organisms in the present ocean as well as in the past.

5. Conclusions

We evaluated several explanations for the Holocene *Pulleniatina* Minimum Event (PME) using deep-sea cores with a wide geographic coverage and new paleoceanographic proxies, including Mg/Ca values and multispecies isotopic analyses. Our data indicate that the PME was a widespread paleoecological event in the western North Pacific, but no marked anomalies in conventional paleoceanographic proxies can be identified to account for the catastrophic reduction of *P. obliquiloculata* between 4.5 and 3 ka. The proposed different preferences for ocean fertility, resulting in opposite patterns in relative abundance of *P. obliquiloculata* and *N. dutertrei* during a weaker Kuroshio and an El Nino-like condition, is not supported by our multispecies isotope data. The cause of the PME thus remains enigmatic and requires further study. Our evidence indicates that fauna-based reconstructions of SST are not very reliable, at least during some periods such as the PME, implying that the presumed relations between faunal parameters and physical environmental factors was variable, even during such a short time period as the Holocene.

Acknowledgements

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