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Pulleniatina Minimum Event during the last deglaciation in the southern South China Sea

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The planktonic foraminiferal faunal census of core MD 05-2894 (7°2.25′N, 111°33.11′E, water depth 1982 m), retrieved from the southern South China Sea (SCS) during the "Marco Polo" cruise in 2005, was performed to investigate the abundance changes of a subsurface dweller, *Pulleniatina obliquiloculata*. The results display that the abundance of *P. obliquiloculata* nearly declines to zero during 16.0—14.9 ka, corresponding to the Heinrich 1 (H1) cold interval. The unexpected decrease of *P. obliquiloculata* occurs in the adjacent cores, roughly between 17 and 14.8 ka based on the previous studies. Accordingly, the *Pulleniatina* Minimum Event in the last deglaciation can serve as a good stratigraphical indicator, at least in the southern SCS. To further explore the changes of sea surface temperature (SST) and subsurface seawater temperature (SSST), we made parallel Mg/Ca measurements on surface dweller *Globigerinoides ruber* and subsurface dweller *P. obliquiloculata* tests. Since the last deglaciation, the SSTs show a continuous increasing trend towards the late Holocene, while the warming of the subsurface water is punctuated by a 2℃-cooling interval across the deglacial *Pulleniatina* Minimum Event. Both increased δ^{18}O differences between *G. ruber* and *P. obliquiloculata*, and increased temperature differences between surface and subsurface water suggest a shoaling of the mixed layer during the deglacial *Pulleniatina* Minimum Event. Therefore, we consider that the significant changes in the upper ocean structure are responsible for the *Pulleniatina* Minimum Event during the last deglaciation in the southern SCS.

Pulleniatina Minimum Event, subsurface seawater temperature, upper ocean structure, the last deglaciation, the southern South China Sea

Pulleniatina obliquiloculata, a tropical subsurface dwelling planktonic foraminifer, calcifies most of its test below the mixed layer. In the global ocean, its highest abundance in surface sediments occurs in a relatively narrow belt between about 10°N and 10°S, which coincides generally with the equatorial current systems in the Atlantic, Indian and Pacific Oceans[1]. High concentrations (more than 20%) of the species are found in the western equatorial Pacific and the northern South China Sea (SCS)[1,2]. Previous studies in northwestern Pacific[3] and the northern SCS[2] demonstrate that *P. obliquiloculata* is closely related to warm and saline currents like the Kuroshio Current. Sediment traps from the northern SCS show that *P. obliquiloculata* occurs during the winter monsoon[4]. So it is believed that the abundance of *P. obliquiloculata* is closely related to subsurface seawater temperatures (SSSTs), especially SSSTs in winter, and the depth of thermocline (DOT). Studies on this species have become an important issue in paleoceanography of the western Pacific[5–8].

Paleoceanographers have documented an extremely low abundance of *P. obliquiloculata* between 4.5 and 3.0 cal. ka in deep sea sediment cores in Okinawa Trough[5,6,9–11] and the northern SCS[12], which is defined as "*Pulleniatina* Minimum Event" (PME). It correlates well with the Chinese lake[13] and stalagmite[14] records,

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which show the weakening of East Asian summer monsoon during this period. Previous studies ascribed the Holocene PME to the track and intensity changes of Kuroshio or the decline of winter sea surface temperatures (SSTs)[5,6,9,11]. During the last deglacial warming period, there is another low abundance of *P. obliquiloculata* in the southern SCS similar to the late Holocene PME. In this study, we'll try to understand when, where and why this event happens so as to get a better understanding of the paleoceanographic changes in the southern SCS during the last deglaciation.

1 Materials and methods

MD 05-2894 (lat. 7°2.25′N, long. 111°33.11′E, Figure 1, 1982 m water-depth; MD 94 henceforth), retrieved from the southern SCS during the "Marco Polo" cruise in 2005, is a 10.85 m long CASQ core free of turbidites. 230 samples were sampled in the upper 467 cm with an interval of 2 cm for oxygen, carbon isotopic and Mg/Ca measurements on surface dweller *Globigerinoides ruber* and subsurface dweller *P. obliquiloculata*. All laboratory methods can be referred to ref. [15] and all experiments were completed at State Key Lab of Marine Geology, Tongji University. The >154 μm fraction of each sample (with the sampling interval of 2—4 cm) was split into an aliquot containing 200 to 300 specimens. Main species, such as *G. ruber*, *Globigerinoides sacculifer*, *P. obliqui loculata* and *Neogloboquadrina dutertrei*, were counted. To construct the precise age model, 7 samples (Table 1) consisting of mixed tests of *G. ruber* and *G. sacculifer* (800—1200 specimens, >154 μm) were subjected to AMS ^{14}C dating at Peking University. The results were converted to calendar years based on Fairbanks et al.'s[16] method and CALIB 5.0 software, respectively. Few differences occurred between 12.41 ka BP and the present. From 11.9 to 14 ka, the dataset used by CALIB 5.0 includes predominantly laminated sediments from the Cariaco Basin, along with coral data from numerous investigators of varying sample quality, in contrast, Fairbanks et al.'s[16] dataset uses the 1382-ring floating tree ring data. We use the latter method to construct our age model because it is more accurate and widely cited.

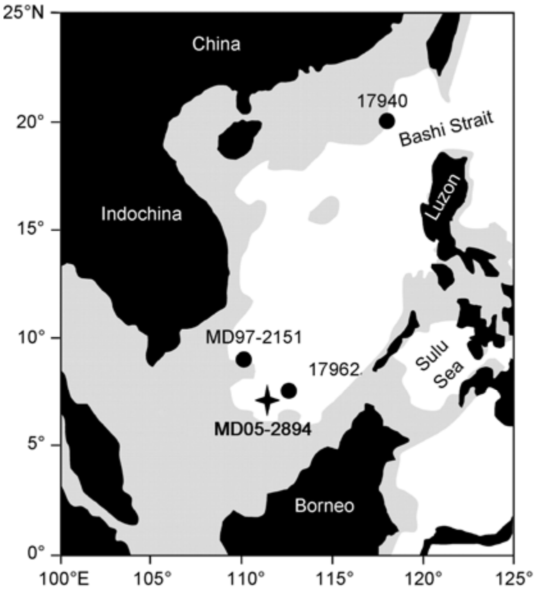

Figure 1 Locations of cores in the southern SCS related to this study.

Table 1 AMS ^{14}C datings of MD 05-2894

Depth (cm)	AMS ^{14}C years (a BP (±1 σ))	Cal. years (a BP)
62.5	5010±35	5337±56
104.5	6765±40	7289±42
140.5	10825±45	12324±105
188.5	13195±50	14909±101
214.5	13285±45	15012±103
284.5	13785±50	15584±121
368.5	14890±65	17117±177

2 Results and discussion

The precise age model is established based on the calendar years converted from the AMS ^{14}C dating results. The studied interval covers about 18.9 cal. ka (All ages discussed henceforth are calendar ages), with an average time resolution of 82 a. The sedimentation rate (SR) varies much among different time intervals. The upper 134.5 cm Holocene samples have a low average SR of 11.7 cm/ka; while the lower part has a relatively high SR of 46.2 cm/ka in average, with its maximum of 252.4 cm/ka (Figure 2(c)). The 8 a/sample-resolution then is the highest temporal resolution till now for the late Quaternary paleoceanographic study in the southern SCS.

The oxygen isotope values of *G. ruber* show an obvious glacial/interglacial cycle, varying between –0.894‰ and –3.492‰ (Figure 2(a)). During the early stage of the deglaciation (15—18.9 ka), the δ^{18}O of *G. ruber* fluctuated around –1.7‰, and then became more negative to –3.0‰ in the Holocene. δ^{18}O of *P. obliquiloculata* vary in a similar trend to that of *G. ruber* (Figure 2(b)), but shows heavier values of –0.1‰ and –1.3‰ in the early deglaciation and the Holocene, respectively. δ^{18}O of *G. ruber* have an average difference of 1.3‰

between the early deglaciation and the Holocene, which is a little larger than that (1.2‰) of *P. obliquiloculata*. Furthermore, both species have clear responds to the Younger Dryas event (13.2—11.5 ka), with reduced oxygen isotopes by ~1.0‰ and ~0.8‰, respectively (Figure 2). Such changes clearly indicate the existence of millennial-scale climate fluctuations like the Younger Dryas event in the southern SCS.

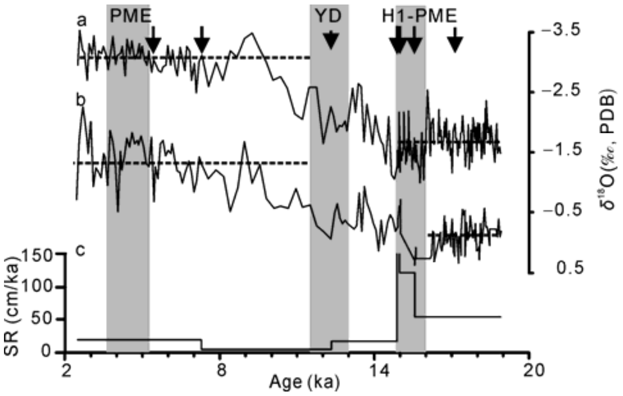

Figure 2 Oxygen isotopic records of planktonic foraminifera and the sedimentation rate in core MD 05-2894. a, *G. ruber*. b, *P. obliquiloculata*; c, sedimentation rate. PME is the Holocene *Pulleniatina* Minimum Event, and YD is Younger Dryas event. H1-PME is the deglacial *Pulleniatina* Minimum Event correlating to H1 event. Average values of various periods are represented by the dotted lines. Arrows show the AMS ^{14}C radiocarbon datings.

It is indicated by the faunal census data that the abundance of *P. obliquiloculata* varies from 0 to 21.6% from the last glacial maximum (LGM) to present, with an average of 5.4%. The abundance of this species shows a decreasing trend since the last deglaciation. Its highest abundance is documented in the early deglaciation (16.2 ka; Figure 3(b)), while its lowest concentrations are recorded during two time-intervals, 3.7—5.2 ka and 14.9—16.0 ka. *P. obliquiloculata* has a very low abundance of 1.9% in average, with its lowest value of 0.4% during 3.7—5.2 ka. This section correlates well with the Holocene PME which is extensively documented in marginal seas of the western Pacific[5,6,9–11]. But after the PME, the abundance is still lower than the early Holocene in the southern SCS, which is different from that in the northern SCS (Figure 3(a)) and Okinawa Trough[12]. What's more, *P. obliquiloculata* shows another dramatically low abundance between 14.9 and 16.0 ka. The average abundance of 1.1% is obviously lower than that of the upper and lower parts of this core (usually greater than 10%). This event lasts for 1.1 ka from 16.0 to 14.9 ka (Figure 3(b)) and correlates well with the Heinrich 1 event, so we define it as H1-PME. Comparing the result with that of the adjacent cores such as 17962[18] and MD97-2151[19], we will see that the H1-PME extensively occurs in the southern SCS, roughly between 17 and 14.8 ka. But no such event exists in the northern SCS (17940[17], Figure 3(a)), so the H1-PME may be a unique event and can be a good stratigraphical indicator in the southern SCS.

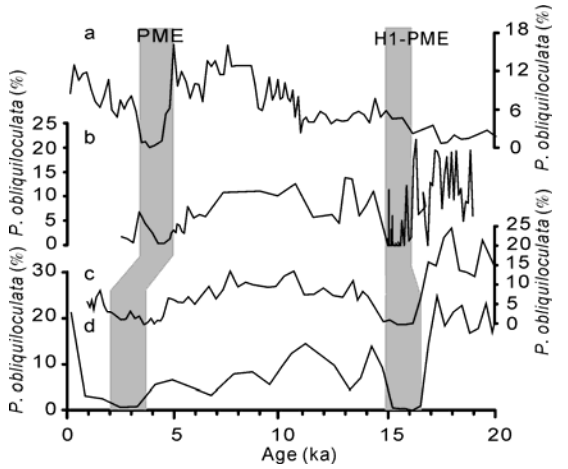

Figure 3 The abundance of *P. obliquiloculata* of various cores in the southern SCS and 17940 in the northern SCS. a, 17940[17]; b, MD 05-2894, this study; c, 17962[18]; d, MD97-2151[19]. PME is the Holocene *Pulleniatina* Minimum Event; H1-PME is the deglacial *Pulleniatina* Minimum Event correlating to H1 event.

Paleoceanographers have thoroughly investigated the Holocene PME. They first ascribed this event to winter SST declines[5,12], further studies concluded that track and intensity changes of Kuroshio Current might also cause the event[5,6,9,11], and also considered ENSO factor[20]. Lin et al.[10] has performed multi-species isotopic analysis and *G. ruber* Mg/Ca SST reconstructions. Based on the data in the western Pacific marginal seas (mainly in Okinawa Trough and SCS), she insisted on that the Holocene PME be independent of any above-mentioned paleoceanographic changes. Till now we indeed can not attribute the Holocene PME in the southern SCS (Figure 3) to variations of Kuroshio Current; we can not expect decreases of Mg/Ca-derived SSTs in Okinawa Trough[10,21] or the southern SCS[22,23], either. According to the numerical simulation study[20], El Niño strengthened after the Holocene PME, which is contradictory to the ENSO hypothesis. Observed only in the southern SCS, H1-PME may have a reason completely different from that occurred in the Holocene, which means Kuroshio can not be the triggering factor. No obvious SST declines are documented in the southern SCS during H1-

PME[20], so SST changes are not the cause. Then we must divert our attention to other influencing factors such as subsurface water temperatures and nutrient supply, etc.

In order to explore the reasons of H1-PME, we ran parallel oxygen, carbon isotopic and Mg/Ca ratio measurements on *G. ruber* and *P. obliquiloculata* tests. Mg/Ca SSTs are derived by the equations of Deckens et al.[25], Lea et al.[26] and Huang et al.[27], respectively. SSTs of coretop samples derived by the equation of Huang et al.[27] (28.0℃, averaged by spring-summer and fall-winter SSTs) are closer to modern annual SST[28] at this site, therefore we adopted Huang et al.'s[27] equation-derived SSTs in this study. Furthermore, we use Anand et al.'s[26] and Huang et al.'s[27] equation to obtain *P. obliquiloculata* Mg/Ca SSSTs, respectively. The difference between the two estimates is about 0.29℃, which may be caused by the differences between Sargasso Sea and SCS. We use Huang et al.'s[27] estimates because the equation come from SCS. Here we specially addressed the two PMEs in the Holocene and the last deglaciation; detailed Mg/Ca-derived paleotemperatures will be discussed elsewhere.

Mg/Ca-derived SSTs vary from 23.7℃ to 29.8℃, with a similar trend to that of δ^{18}O (Figure 4(b)). They rise from an average of 25.5℃ in early deglaciation to 28.8℃ in the Holocene. The~3.3℃ difference is close to those of the adjacent cores such as MD97-2151 (2.9℃[30]) and MD01-2390 (3℃[22]). Mg/Ca-derived SSTs show a gradual increase since H1-PME, with no punctuations during the two PMEs (Figure 4(b)), but SSTs derived by transfer functions have a remarkable decrease during the two periods. For instance, winter SSTs of 17962 drop by as much as about 6℃[31] between 17 and 15 ka. Such differences may be due to the "No-analog" [15,23] problem. That is to say, the low abundance of *P. obliquiloculata* makes the application of transfer functions in the southern SCS problematic. SSTs from nearby cores (MD97-2151[30] and MD01-2390[22]) demonstrate no obvious changes between 17 and 14.8 ka, and then it can be concluded that SST declines are not the reason for the PM-Es.

As shown in Figure 4(a)), SSSTs have a fluctuation from 16.0 to 23.2℃, slightly larger than SSTs. Both of them show a similar trend to δ^{18}O, that is, an increasing trend towards the Holocene. Different from SSTs, SSSTs continuously decrease after reaching its maximum in early to mid-Holocene, which displays a similar trend to that of Timor Sea[8]. The warming process of subsurface water was interrupted in the Holocene PME, H1-PME and YD event. SSSTs decline as much as ~3.1℃, 4.8℃ and 3.1℃ in the three periods, respectively, the most obvious among which is the ~2℃ decrease in average during H1-PME.

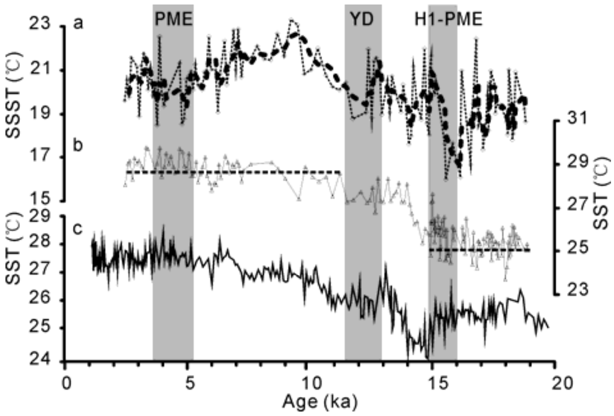

Figure 4 SSTs and SSSTs of MD 05-2894 and SST comparisons between MD 05-2894 and MD97-2151. a, Mg/Ca-derived SSST, 3-point smoothed values are represented by dashed line; b, Mg/Ca-derived SST, averages of various periods are indicated by dotted lines; c, $U_K^{37'}$-derived SST of MD97-2151[30]. PME is the Holocene *Pulleniatina* Minimum Event, and YD is Younger Dryas event. H1-PME is the deglacial *Pulleniatina* Minimum Event correlating to H1 event.

Previous studies demonstrated that the δ^{18}O differences ($\Delta\delta^{18}$O) of planktonic subsurface dweller such as *P. obliquiloculata* and surface dweller such as *G. ruber* can be used to indicate the relative depth of thermocline. Large $\Delta\delta^{18}$O indicate a shallow thermocline, and vice versa[7,32]. So do the temperature gradients (ΔT) between SSTs and SSSTs. Large ΔT indicate a shallow mixed layer, and vice versa. During the deglacial PME, SSTs show no obvious declines while SSSTs have an average decrease of ~2℃, so ΔT becomes larger, which means a shallow thermocline then. The shallow thermocline is also indicated by larger $\Delta\delta^{18}$O values during the PMEs. Besides, both $\Delta\delta^{18}$O and ΔT show a deep thermocline in the early deglaciation and a shallow thermocline in the Holocene. H1-PME occurred exactly during the transition of the two stages. The SSSTs decrease and upper ocean structure changes (Figure 5) influence the habitat of *P. obliquiloculata* and cause the low abundance of this species.

The Holocene PME is widely distributed in marginal seas of the western Pacific, but H1-PME is only documented in the southern SCS, so some unique paleocean-

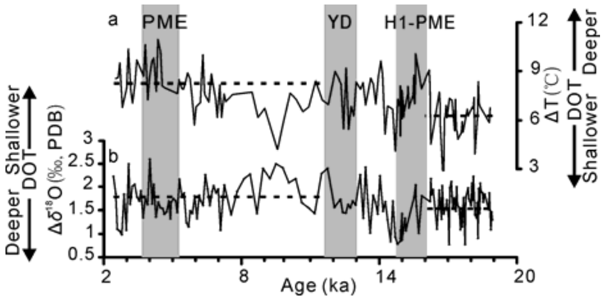

Figure 5 The temperature gradients (ΔT) between SSTs and SSSTs, and the $\delta^{18}O$ differences ($\Delta\delta^{18}O$) between *P. obliquiloculata* and *G. ruber*. a, The temperature gradients (ΔT) between SSTs and SSSTs; b, the $\delta^{18}O$ differences ($\Delta\delta^{18}O$) between *P. obliquiloculata* and *G. ruber*. PME is the Holocene *Pulleniatina* Minimum Event, and YD is Younger Dryas event. H1-PME is the deglacial *Pulleniatina* Minimum Event correlating to H1 event.

ographic changes may exist in the southern SCS during the last deglacial warming period. Koutavas et al.[33] compared SSTs of V21—30 in the eastern Pacific with 18287 in the southern SCS and implied a more El Nino-like condition between 17.0 and 14.8 ka, which is contemporary with H1-PME in the southern SCS. But there is no such event in the western equatorial Pacific[8], so H1-PME cannot be ascribed to the tropical factors like ENSO. Here we present the following hypothesis about the reasons of H1-PME. One is related to that North Atlantic Deep Water (NADW) weakens while North Pacific Deep Water (NPDW) strengthens during H1[34]. Cold NPDW upwells to be subsurface water when blocked in the southern SCS; then SSSTs decrease; the thermocline shoals and the abundance of *P. obliquiloculata* drop. Another hypothesis is that seaways connecting the southern SCS with Indian and Pacific Ocean gradually open during the last deglaciation. The restructured upper ocean makes subsurface dweller *P. obliquiloculata* absent in this region. Furthermore, forced by winter monsoon, the mixed layer in the upper SCS will deepen. When the meridional seawater temperature gradient increases, the thermocline is best ventilated. More surface water from the northern SCS mixed layer is drained into the upper seasonal thermocline; moves southward and becomes subsurface water of the southern SCS[35]. Then the southern SCS SSSTs show an obvious decline; the thermocline shoals; and *P. obliquiloculata* decrease. In order to understand the reasons why SSSTs decline during H1-PME, further studies are still needed to discuss the links between various paleoceanographic changes.

3 Conclusions

Based on a careful planktonic foraminiferal faunal census count, we discovered that *P. obliquiloculata* nearly disappears between 16.0 and 14.9 ka in the southern SCS. This interval correlates well with the Heinrich 1 cooling event. The H1-PME is extensively documented in the southern SCS, thus can be a good stratigraphical indicator in this region. Mg/Ca-derived SSTs gradually increase since the last deglaciation, with little punctuation during the Holocene PME, H1-PME or Younger Dryas event. But SSSTs demonstrate significant decreases during these periods. Both $\delta^{18}O$ and temperature differences become larger during the two PMEs, indicating the shoaling of the thermocline. The restructured upper ocean may be responsible for the SSSTs decline, which results in the remarkable decrease of *P. obliquiloculata* during the deglacial *Pulleniatina* Minimum Event. Such restructuring may be caused by the upwelling of NPDW, gradual opening seaways, or better thermocline ventilation during the last deglaciation. Further studies are still needed to know the exact reasons for these changes.

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