Pulleniatina Minimum Events in the Andaman Sea (NE Indian Ocean): Implications for winter monsoon and thermocline changes

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Abstract

The late Quaternary record of Pulleniatina obliquiloculata was investigated from two well dated sediment cores from the Andaman Sea (NE Indian Ocean) to examine its paleoceanographic significance and the presence of the Pulleniatina Minimum Events (PME) in the western North Pacific. As in the Pacific, our study shows that PMEs exist in the Indian Ocean albeit with a lower intensity. The Holocene PME occurs between 4.5 to 3.0 cal ka BP with a considerable reduction in P. obliquiloculata abundance, and which matches well with the Pacific records influenced by the Kuroshio Current. Additionally, two significant minimum events of P. obliquiloculata are also seen during the Younger Dryas (YD) and late Last Glacial Maximum (LGM, 20-18 cal ka BP). Overall, the PMEs of the Andaman Sea are not current driven events like in the western Pacific margin either by the weakening of the Kuroshio Current or reduced winter SSTs. The PMEs of the Andaman Sea are characterised by lower abundances of thermocline species indicating the increased depth of the thermocline (DOT) and reduced winter SSTs mainly during the minimum events of the YD and late LGM. The high SSTs during the Holocene PME make this event a mystery. However, the presence of PMEs in the Andaman Sea suggests that these events are not confined to areas influenced by the Kuroshio Current but may be responding to a broad scale oceanographic-climatic process or mechanism which needs to be explored with a detailed study.

Keywords: Andaman Sea; Pulleniatina obliquiloculata; thermocline; winter monsoon; late Quaternary; paleoceanography.

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1. Introduction

A *Pulleniatina* minimum event (PME) refers to the sudden decrease in abundance of the planktic foraminifera *Pulleniatina obliquiloculata* in Holocene sediments of the western Pacific Ocean; such as the one recorded between ~4.5 and 3 ka in deep-sea cores from the western North Pacific (Pflaummann and Jian 1999; Ujiié and Ujiié 1999; Yang and Jian 2009; Li et al., 1997; Wang et al., 1999; Jian et al., 2000; Yu et al., 2000; Huang et al., 2002; Ujiié et al., 2003; Lin et al., 2006; Xiang et al., 2009). In the South China Sea (SCS) another minimum event has been reported during Heinrich Event 1 (H1 PME) (Liu 2004; Pflaummann and Jian 1999; Yang and Jian 2009; Wang et al., 1999; Yu et al., 2000; Huang et al., 2002; Xiang et al., 2009). On the other hand, disappearance of *P. obliquiloculata* mainly during the middle of the last glacial period was also reported from the Atlantic Ocean (Prell and Damuth 1978). However, to our knowledge, no such minimum events are known in the Indian Ocean region.

In the modern ocean, *P. obliquiloculata* lives in the subsurface waters below the thermocline (e.g., Ravelo et al., 1990). Therefore, variations in its abundance can be interpreted as a change in the thermocline depth (Li et al., 1997). Currently, there are two views on the cause of PMEs in the western Pacific region. Low abundances of *P. obliquiloculata* are considered to be indicative of the weakening/diversion of the Kuroshio Current (Li et al., 1997; Ujiié and Ujiié 1999). Alternatively, according to plankton tow studies, this warm water, dissolution resistant species is most abundant when winter sea surface temperatures (SST) are relatively high (Bé and Tolderlund 1971; Ravelo and Fairbanks 1992). The Holocene PME has also been attributed to the intensification of the winter monsoon and consequently to decreased SST (Jian et al., 2000) which was correlated to the neoglacial cooling in China (Wu and Liu 2004; Peng et al., 2005). Another characteristic feature associated with the PME of the western Pacific is the high abundance of the thermocline species *N. dutertrei*, which was interpreted as related to the enhanced influence of gyre-margin water in the Okinawa Trough (Ujiié et al., 2003).

The Andaman Sea is a semi enclosed marginal sea which exchanges water with the Bay of Bengal (BOB) in the northern Indian Ocean and marginal seas of western Pacific mainly via shallow channels (Fig. 1a). It is interconnected with the BOB by the Deep Prepares Channel, Ten Degree Channel and the Great Channel. The oceanographic processes in these seas are however comparable only up to a depth of about 1000 m, as the deep water exchange between these two regions (Andaman Sea and BOB) is hampered by several sills which have significant influence on intermediate to deep water circulation in the Andaman Sea. The Sunda Shelf provides a shallow route to the eastern seas and to the Pacific Ocean, which is the southeast extension of the continental
shelf of southeast Asia. As in the Arabian Sea, the Andaman Sea also experiences a seasonal reversal in surface circulation triggered by the Indian monsoon. The Andaman Sea has been well documented as a productive sea owing to the prevailing upwelling during the winter monsoon (Wyrtki, 1973). Biological productivity in the offshore region is ~ 0.8-1.0 mgC/m²/d compared to lesser values (<0.6 mgC/m²/d) observed in the coastal areas (Janekarn and Hylleberg 1989). The Andaman Sea is characterized by a low surface salinity (Fig. 1b) ranging between 31.8 and 33.4 practical salinity units (psu), due to the influence of fresh water discharge from the Ayeyarwady-Salween river system (Sarma and Narvekar 2001). The average surface temperature of the Andaman Sea is 29°C, and is nearly homogenous up to a depth of 50 m leading to stratification, which hinders vertical mixing (Sarma and Narvekar 2001). The temperature decreases down to 13°C at a depth of 200 m and 9°C at a depth of 500-600 m and the total thermocline thickness is about 150 m (Saidova, 2008). Here, we report on the occurrence of more than one PME in the Andaman Sea. In addition, we make an attempt to understand the causes and paleoceanographic significance of \textit{P. obliquiloculata} variability in this marginal sea.

2. Materials and Methods

The sediment cores SK 168/GC-1 (11°42.463′N; 94°29.606′E, water depth: 2064 m, core length: 4.20 m) and AAS 11 GC 1 (9°N; 94°17′E, water depth: 2909 m; core length: 4.28 m) were collected from the Andaman Sea (Fig. 1). SK 168/GC-1 was collected during the 168th cruise of ORV Sagar Kanya from the Alcock Seamount Complex and core AAS 11/GC-1 was collected during the 11th expedition of RV AA Sidorenko. About 10 g of dried samples were soaked in Milli-Q water overnight and washed through a 63 μm mesh sieve. Later the dried filtrate was sieved through a 125 μm mesh sieve. The coarse fraction (>125 μm) was split into several aliquots to reduce the total number of planktic foraminifera to a minimum of 300 individuals which were used for quantitative and qualitative analyses of planktic foraminifera assemblages. Thermocline species are represented by the total percentages of \textit{Globorotalia menardii}, \textit{Neogloboquadrina dutertrei} and \textit{Pulleniatina obliquiloculata}. Resistant species include \textit{G. menardii}, \textit{N. dutertrei}, \textit{P. obliquiloculata}, \textit{Globorotalia tumida}, \textit{G. crassaformis}, \textit{G. truncatulinoides}, \textit{Candeina nitida} and \textit{Sphaerodinella dehiscence}. The taxonomic identification to species level followed that of Kennett and Srinivasan (1983).

Approximately 10 to 16 tests of \textit{Globigerinoides ruber} (white) exhibiting a wide morphologic variation in the size range of 250-315 μm were used for oxygen isotope analysis. Microscopic examination showed that the tests were well preserved with no apparent dissolution. The shells were placed in thimbles and crushed using a thin needle, then a few drops of methanol were added and the
shells were cleaned using an ultrasonic bath for 8-10 seconds. The cleaned tests were analysed for oxygen isotopes using an Isotope Ratio Mass Spectrometer (IRMS). The oxygen isotopic measurements of core SK 168/GC 1 were carried out at the National Institute of Oceanography, Goa, India, while the values presented here for core AAS 11/GC 1 were already published by Ahmad et al. (2000).

The age model for the cores (SK 168/GC-1 and AAS 11/GC-1) was constructed mainly using the Accelerator Mass Spectrometer (AMS) $^{14}$C dates of planktic foraminiferal tests ($G. \ ruber$ and $Globigerinoides \ sacculifer$). In core SK 168 oxygen isotope stratigraphy was also used to produce independent age controlling points for sediments older than 24 ka BP. AMS $^{14}$C ages were determined for 17 horizons (for both cores) (Table 1) and calendar age calibration was based on the CalPal 2007 (Weninger et al., 2007, http://www.calpal.de). The AMS $^{14}$C dates were corrected for a 460 year reservoir age following Butzin et al. (2005) and Cao et al. (2007). Oxygen isotope stratigraphy (core SK 168) was established by correlation of the oxygen isotopic values of $G. \ ruber$ with the standard oxygen isotopic curve of Martinson et al. (1987). The boundary between marine isotope stage (MIS) 3 and MIS 2 (24.11 ka), and sub events of MIS 3 (3.1=25.42 ka and 3.13=43.88 ka) were also used as independent age controlling points (Fig. 2a and Fig. 3a). The low resolution oxygen isotope record in core AAS 11 limits its use for constructing an age model, whereas the faunal records of both cores are comparable for the last 30 ka (see Fig. 4). Older sediments (>30 ka) show a roughly 1 ka shift in the faunal composition between SK 168 and AAS 11, reflecting the upper limit of uncertainty for sections older than 30 ka in core AAS 11. Both cores have a continuous record since ~44 cal ka BP and they show distinct last glacial to interglacial changes. The ages for other horizons were assigned by interpolation/extrapolation of calibrated dates, assuming constant sedimentation rates. The average sedimentation rates are about 7.79 cm/ka and 9.37 cm/ka for cores SK 168 (Fig. 2a) and AAS 11 (Fig. 2b), respectively.

3. Results

The down core variation of the relative abundance of $P. \ obliquiloculata$ in both cores is plotted with the oxygen isotope record of the planktic foraminifer $G. \ ruber$, the SST record of Andaman Sea (Rashid et al., 2007) and total planktic foraminifera tests per gram against calendar age in Fig. 3a-f. The abundance curves of $P. \ obliquiloculata$ of both cores show good stratigraphic correlation mainly during the last 25 cal ka BP (Fig. 3b,c). Overall, a marked change in abundance of $P. \ obliquiloculata$ is seen at 10 cal ka BP (Pleistocene-Holocene boundary) (Fig. 3b,c). The maximum abundances of $P. \ obliquiloculata$ are seen at 33.5 ka and Heinrich Event 1 (H1, 14.5-16 cal ka BP) whereas minimum events occur during the late Last Glacial Maximum (LGM, 20-18 cal ka BP, Younger Dryas (YD,
13-10.5 cal ka BP) and late Holocene (4.5-3 cal ka BP). Northern core SK 168 shows distinctive minimum events and the intensity of variation reduces towards the south. The Holocene PME is a little longer in core SK 168 (4.5 to 2 cal ka BP) than that of AAS 11 (4.5 to 3 cal ka BP). PMEs of YD and LGM are correlatable with heavier oxygen isotope values and lower SST whereas Holocene PME is correlatable with lighter oxygen isotope values and higher SST. Total planktic foraminiferal numbers are characteristically high during the PME suggesting enhanced foraminiferal productivity.

*P. obliquiloculata* variability in relation with other planktic foraminifera, thermocline and resistant species are given in Fig. 4a-j. *G. menardii* shows low abundance during the PMEs and high abundance during the H1 maximum event of *P. obliquiloculata* (Fig. 4e). Like *G. menardii*, *G. sacculifer* shows a characteristic low abundance during PMEs but high abundance during H1 (Fig. 4f). The planktic foraminifera assemblage of PMEs is characterised by the low abundances of *G. menardii*, *G. sacculifer*, total thermocline species, low to moderate abundances of *N. dutertrei* and high abundances of *G. bulloides*.

The resistant species show changes in abundance throughout the cores (Fig. 4i and j). During the PMEs, resistant species are very low in abundance with values as low as 8%. In general, resistant species are low in abundance during PMEs, YD and H1 and high in abundance during the Bolling/Allerød (B/A), and MIS 3/MIS 2 transition. Though the resistant species are very low in abundance during H1, it marks the maximum abundance of *P. obliquiloculata*. The thermocline species show a lower abundance during PMEs. During the last 40 cal ka BP, the lowest abundance of thermocline species is seen during YD (Fig. 4h). *G. sacculifer* is a shallow dwelling species and tolerates a wide range of temperature and prefers to live in the mixed layer condition with low seasonal changes in SST (Bé, 1977; Fairbanks et al., 1982). *G. sacculifer* has a low abundance during PMEs but higher abundance during H1.

**4. Discussion**

*P. obliquiloculata* is thick walled and highly resistant to dissolution (Berger, 1970) hence its relative abundance is usually high when carbonate dissolution is strong. In order to understand the variability of *P. obliquiloculata*, we have compared it with resistant species. The inverse relationship suggests that its variability is not related with carbonate dissolution in the Andaman Sea. If it were due to carbonate dissolution, a positive relationship between *P. obliquiloculata* and resistant species would have been witnessed. We used the oxygen isotope, SST record and other planktic foraminiferal proxies to understand the causes and paleoceanographic changes associated with the three minimum events (Holocene, YD and late LGM PMEs) occurring in the Andaman Sea.
The Holocene PME occurred from 4.5-3.0 cal ka BP (4.5 to 2.0 cal ka BP for core SK 168) and is marked by very low abundances of *P. obliquiloculata* which is in good agreement with western Pacific records (Ujiié et al., 2003; Lin et al., 2006; Xiang et al., 2009). During the Holocene PME in the Andaman Sea, the total planktic foraminifera were moderately high (Fig. 3f) which indicates that general foraminiferal productivity was high during this period. The important feature of the Holocene PME of the Andaman Sea was higher SSTs, whereas other minimum events were marked by lower SSTs (Fig. 3). The Holocene PME of the western Pacific was interpreted as a result of the weakening/diversion of the Kuroshio Current (Li et al., 1997; Ujiié and Ujiié 1999) or an intensification of the winter monsoons and consequently of decreased SSTs (Jian et al., 2000). *P. obliquiloculata* usually proliferates during high winter SST (Jian et al., 2000). Hence lower abundances during higher SSTs (Fig. 3) make this event (Holocene PME) unclear. The Holocene PME of the Andaman Sea might be due to an increase in the depth of the thermocline (DOT) marked by lower abundances of *G. menardii*, *N. dutertrei* and *G. sacculifer*.

The low abundances of *P. obliquiloculata* occur during the YD, which shows pronounced changes in the global atmospheric and oceanic circulation system especially in the north eastern Atlantic (Duplessy et al., 1981) and also in the Indian Ocean characterised by an abrupt weakening of the summer monsoon (Schulz et al., 1998). The oxygen isotope record of both cores shows heavier values during the YD (the average and heaviest YD values are -1.91‰ and -1.7‰) indicating either reduced SSTs or a change in salinity. The abundances of total planktic foraminifera and *G. bulloides* indicate an enhanced summer monsoon during BA and slight weakening during the late YD in the Andaman Sea. Similar low abundances of *P. obliquiloculata* during the YD period are also seen in the Okinawa Trough of the East China Sea (Li et al., 1997). The lowest percentage of thermocline species during the YD suggests a deepening of the DOT and reduced SSTs during an enhanced winter monsoon, which may have caused hostile conditions for *P. obliquiloculata*.

The third minimum event of *P. obliquiloculata* occurred between 20 to 18 cal ka BP and is characterised by relatively heavier oxygen isotope values (average LGM value is ~ -1‰ for both cores) and reduced SSTs (Rashid et al., 2007), marking the coolest period in the glacial Andaman Sea during the last 44 cal ka BP. The oxygen isotope record of *G. ruber* has shown that the LGM to Holocene (∆δ 18O) amplitude is 2.09‰ from which the global ice volume effect would account for 1.2‰ and remaining 0.90‰ would either require an increase in salinity by 3‰ or a decrease in temperature by ~ 4.5°C. In the Andaman Sea, the Mg/Ca records have shown that the LGM temperature is 3°C less than that seen presently or during the Holocene (Rashid et al., 2007). This temperature change would thus account for an enrichment of 0.60‰ and the remaining 0.30‰ (of
LGM to Holocene $\Delta \delta^{18}O$ amplitude) will require an increase in salinity by 1‰ during the LGM. The estimated salinity change of 1‰ is negligible whereas the decrease in temperature by 3°C played a major role in the LGM PME.

The LGM is also characterised by low abundances of warm water species such as *G. menardii* and *G. sacculifer* and moderate abundances of *N. dutertrei*, marking reduced winter SSTs. According to Duplessy (1982) and Sarkar et al. (1990) the winter monsoon was stronger during the LGM. The weakening of the summer monsoon during the LGM is clearly indicated by the lower abundances of *G. bulloides* and total planktic foraminifera. Similar to the YD, the LGM is also characterised by a deepened DOT, which reduced the abundances of *P. obliquiloculata*, a species that usually proliferates when the DOT shoals (Lin and Hsieh 2007). The LGM PME in the Andaman Sea might be related to reduced winter SSTs, a deepened thermocline and low productivity. The PME during the late LGM (20 to 18 cal ka BP) was not recorded in the southern SCS, instead it is present during H1. While the Holocene PME is widely distributed in marginal seas of the western Pacific, the H1 PME has been only documented in the southern SCS (Yang and Jian 2009). The H1 PME in the SCS has been attributed to shoaling of the mixed layer due to changes in surface and subsurface temperatures and resultant changes in water column structure during the last deglacial warming period (Yang and Jian 2009) or due to a drop in winter SSTs due to an intensified winter monsoon (Xiang et al., 2009).

While the above paragraphs describe the minimum events, distinct maxima in the abundances of *P. obliquiloculata* are also seen at 33.5-35.5 cal ka BP and H1. High abundances of *P. obliquiloculata* at H1 are in contrast to a PME noticed in the southern SCS. The H1 *Pulleniatina* maximum in our cores from the Andaman Sea corresponds to lighter oxygen isotope values and moderate to high abundances of *G. sacculifer* and *G. menardii*, suggesting increased surface and subsurface temperatures during the deglacial. The high abundances of *P. obliquiloculata* during the late glacial to H1 marks the driest climatic period in the Andaman Sea (Rashid et al., 2007). The high abundances of *P. obliquiloculata* in the Andaman Sea during the early to middle glacial (cores SK 168, 20-23 and AAS 11 20-21 cal ka BP) and late MIS 3 are correlated with high abundances of thermocline species, suggesting that a shoaling of the thermocline caused the proliferation.

In general the PMEs of the Andaman Sea are characterised by low abundances of thermocline species suggesting a deepening of the DOT. No significant change in relative abundance of *N. dutertrei* was seen in the Andaman Sea, which is unlike that found in the Okinawa Trough where higher abundances were seen during the Holocene PME (Ujiié et al., 2003). The minimum events of the YD and LGM are the result of enhanced winter monsoons with reduced winter SSTs and
deepened DOT whereas the Holocene PME of the Andaman Sea is still a mystery, characterised by higher SSTs and deepened DOT. The presence of PMEs in the Andaman Sea affirms the view of Ujiie et al. (2003) that PMEs may not be local phenomena of the Kuroshio source region but may be responding to a broad scale oceanographic-climatic process or mechanism which needs to be explored with a detailed study.

Conclusions

This study reports on the presence of PMEs in the Indian Ocean. The abundances of *P. obliquiloculata* along with other planktic foraminiferal proxies from two well dated cores from the Andaman Sea show a relationship between PMEs and oceanographic conditions. In the Andaman Sea, the Holocene PME occurred between 4.5 to 3.0 cal ka BP where relative abundances of *P. obliquiloculata* show a considerable reduction which matches well with Pacific records. In addition, we report two other significant minimum events during the YD and the late LGM (20 cal ka to 18 cal ka). The H1 PME of the South China Sea is not seen here, but this period instead is characterised by high abundances of *P. obliquiloculata* which mark the driest climatic period in the Andaman Sea. Overall, the PMEs of the Andaman Sea are not current driven like that in the western Pacific margin. The minimum events of the YD and LGM seem to be controlled by enhanced winter monsoons with reduced SSTs and deepened DOT whereas the Holocene of the Andaman Sea is still a mystery and characterised by higher SSTs and deepened DOT.

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References


Figure captions.

Fig. 1 Location of cores SK 168/GC 1 and AAS 11/GC 1, Andaman Sea, in the eastern Indian Ocean (modified from Sijinkumar et al., 2010): a) bathymetry of Andaman Sea along with core locations; b) salinity (annual salinity at the surface, World Ocean Atlas, 2009, www.nodc.noaa.gov) and monsoon currents in Andaman Sea; black arrow-summer monsoon, yellow arrow-winter monsoon, (modified from Brown, 2007 reference therein).

Fig. 2 Age-depth model with sedimentation rate; a) Core SK 168 (Sijinkumar et al., 2010) (based on 6 age control points to obtain this sedimentation rate. The ages represented by black circles are based on the calibrated AMS $^{14}$C ages, and the open circles based on the oxygen isotope records (refer text for details); b) Core AAS 11 (based on 12 AMS $^{14}$C dates).

Fig. 3 Planktic foraminiferal ($G. \text{ ruber}$) oxygen isotope record of cores SK 168 and AAS 11 in relation with Pulleniatina Minimum Events (PMEs) of Andaman Sea; a) Oxygen isotope record of core SK 168 (Sijinkumar et al., 2010); b) Relative abundance of $P. \text{ obliquiloculata}$ in core SK 168; c) Relative abundance of $P. \text{ obliquiloculata}$ in core AAS 11; d) Oxygen isotope record of core AAS 11 (Ahmad et al., 2000 plotted with $^{14}$C AMS dates); e) SST ($^\circ\text{C}$) of core RC 12-344 (Rashid et al., 2007); f) Total number of planktic foraminiferal tests per gram in core SK 168. Marine Isotope Stage (MIS), Younger Dryas (YD), Bølling–Allerød (B/A), Heinrich Event 1 (H1) last glacial maximum (LGM) are shaded. The long arrow indicates the depth horizon for $^{14}$C AMS dating and small arrow indicates MIS 3/MIS 2 boundary and sub stages of MIS 3 (See text for details).

Fig. 4 Comparison of $P. \text{ obliquiloculata}$ record with other planktic foraminiferal proxies in core SK 168 and AAS 11; a) Relative abundance of $P. \text{ obliquiloculata}$ in core SK 168; b) Relative abundance of $P. \text{ obliquiloculata}$ in core AAS 11; c) and d) Relative abundance of $N. \text{ dutertrei}$ (SK 168 and AAS 11); e) Relative abundance of $G. \text{ menardii}$ (SK 168); f) Relative abundance of $G. \text{ sacculifer}$ (SK 168); g) Relative abundance of $G. \text{ bulloides}$ (SK 168); h) total thermocline species % (SK 168); i) and j) total planktic foraminifera resistant species % (SK 168 and AAS 11)
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Mixed planktic foram (*Globigerinoides ruber* + *Globigerinoides sacculifer*)