

Timing and preservation mechanism of deglacial pteropod spike from the Andaman Sea, north-eastern Indian Ocean

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The aragonite compensation depth (ACD) fluctuated considerably during the last glacial to Holocene with a dominant pteropod preservation spike during deglacial, which is prominently seen in three well dated cores covering the Andaman Sea, north-eastern Indian Ocean. Resolving the precise time period of the preservation spike of pteropods is not known which is crucial for stratigraphic correlation and also for understanding the driving mechanism. Isotopic and foraminiferal proxies were used to decipher the possible mechanism for its preservation in the Andaman Sea. The poor preservation/absence of pteropods during Holocene in the Andaman Sea may have implications on ocean acidification driven by enhanced atmospheric CO₂ concentration. Strengthening of summer monsoon and resultant high biological productivity may also have played a role in poor pteropod preservation. The deglacial pteropod spike is characterized by high abundance/preservation of the pteropods between ~19 and 15 cal. ka BP associated with very low atmospheric CO₂ concentration. Isotope data suggest the prevalence of glacial environment with reduced sea surface temperature, upwelling and enhanced salinity during the pteropod preservation spike. Total planktic foraminifera and *Globigerina bulloides* abundances are low during this period implying weakened summer monsoon and reduced foraminiferal productivity. Based on the preservation record of pteropods, it is inferred that ACD was probably deepest (>2900 m) during 16.5 cal. ka BP. The synchronous regional occurrence of the pteropod preservation spike in the Andaman Sea as well as in the north-western Indian Ocean can possibly be employed as a potential stratigraphic marker.

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Pteropods are marine gastropods made up of aragonitic shells, a metastable polymorph of CaCO_3 which is more susceptible to dissolution than calcite. Preservation and accumulation of pteropods on the seafloor is controlled by the aragonite compensation depth (ACD) and changes in the properties of water masses (e.g. Berger 1978; Klöcker *et al.* 2006). Based on the temporal changes in the abundance of pteropods, pteropod preservation spikes have been identified by various workers (Thiede 1971; Diester-Haass *et al.* 1973; Kudrass 1973; Diester-Haass 1975; Berger 1977; Berger & Killingley 1977; Melkert *et al.* 1992). The deglacial pteropod preservation spike characterized by a very high abundance/preservation of the aragonitic pteropods between ~19 and 13 ka BP was first reported on the continental slopes of Portugal and Morocco (Thiede 1971; Diester-Haass *et al.* 1973; Kudrass 1973; Diester-Haass 1975; Berger 1977) and later widely reported in the Pacific, the Atlantic and the Indian Oceans (Thiede 1971; Diester-Haass *et al.* 1973; Kudrass 1973; Diester-Haass 1975; Berger 1977; Berger & Killingley 1977; Melkert *et al.* 1992; Sijinkumar *et al.* 2010) and can be spatially correlated between different regions. In addition, the deglacial preservation spike was also reported from the Caribbean, the Gulf of Mexico and the Mediterranean Sea (Chen 1968), continental margin off Northwest Africa (Diester-Haass 1975), suggesting that the deglacial preservation spike is a global phenomenon (Berger 1977; Berger & Killingley 1977; Sijinkumar *et al.* 2010).

There are diverse views on the factors relating to better preservation of pteropods during the deglacial periods. Mainly they include, the red tide induced mass mortality (Diester-Haas & Van der Spoel 1978) and the rapid growth of biosphere during deglaciation, leading to the extraction of atmospheric CO_2 and carbonate preservation (Shackleton 1977). Berger (1977) opined that a combination of increased saturation of deep waters, decreased bottom currents and increased sedimentation rates are responsible for the preservation spike. Recent studies from the Indian Ocean reveal that the good preservation is due to the strong winter monsoon, enhanced ventilation, resultant weakening of oxygen minimum zone and deepening of ACD (Klöcker & Henrich 2006; Böning & Bard 2009; Sijinkumar *et al.* 2010).

Occurrence and abundance of aragonitic pteropod during the latest Holocene is a subject of renewed interest owing to the fact that they are the most vulnerable among the major plankton producers of CaCO_3 in the current levels of atmospheric CO_2 resulting from ocean acidification (Feely *et al.* 2004; Wall-Palmer *et al.* 2012). The study by Sabine *et al.* (2002) from the Indian Ocean has revealed the anthropogenic effects on aragonite preservation. The aragonite saturation depth (ASD) during the recent times shoaled significantly by 25-155 m in the Indian Ocean due to the absorption of anthropogenic CO_2 in the subsurface water masses and also due to increased organic matter

decomposition rates (Sabine *et al.* 2002; Sarma *et al.* 2002). The aragonite saturation level of present day in the Indian Ocean is significantly shallower than the pre-industrial time. For example, current ASD in the Arabian Sea and the Bay of Bengal is shallower by 100-200 m than that of pre-industrial times (Sabine *et al.* 2002; Sarma *et al.* 2002).

While there are several reports on the pteropod abundances and preservation from western Indian Ocean (Almogi-Labin 1982; Almogi-Labin *et al.* 1986, 1991, 2000; Reichart *et al.* 1998; von Rad *et al.* 1999; Klöcker & Heinrich 2006; Klöcker *et al.* 2006; Singh *et al.* 2006; Böning & Bard 2009), there is very limited record from the north eastern Indian Ocean. However, the precise timing, latitudinal variability and oceanographic as well as climatic conditions prevalent during the preservation spike in this region are yet to be discerned. The present study attempts to understand the preservation record of aragonitic pteropod shells for the late Quaternary from the three well dated cores in a north-south transect in the Andaman Sea. The study also evaluate the possible mechanisms of pteropod preservation spike by employing isotopic and faunal records, regional comparisons with other Indian Ocean records and its potential use for correlation.

Oceanographic setting

The Andaman Sea (maximum water depth 4400 m) is a semi-enclosed marginal sea in the eastern part of the northern Indian Ocean. Andaman Sea exchanges water masses with the Bay of Bengal in the north Indian Ocean and also with the marginal seas of western Pacific via shallow channels. It is connected with the Bay of Bengal by Deep Prepares Channel, Ten Degree Channel and the Great Channel. The deep water exchange between the Andaman Sea and Bay of Bengal is hampered by several sills which have significant influence on intermediate to deep water circulation in the Andaman Sea (Fig. 1A). Ramesh Babu & Sastry (1976) reported that the depth of these sills is about 1300 m and the surface oceanographic processes in these seas are comparable above the sill depth. As in the northern Indian Ocean, the Andaman Sea also experiences a seasonal reversal in surface circulation, driven by the Indian monsoon. The Andaman Sea is well documented as a productive sea owing to the prevailing upwelling during the winter monsoon (Wyrтки 1973). The Andaman Sea is characterized by a low surface salinity ranging from 31.8 to 33.4 psu due to the influence of fresh water discharge from the Ayeyarwady-Salween river system (Sarma & Narvekar 2001). According to Milliman & Meade (1983), Ayeyarwady River drains ~428 km³ of fresh-water annually from the Ayeyarwady catchment region to the Andaman Sea. The average sea surface temperature of the Andaman Sea is 29°C, which is homogenous up to a depth of 50 m forming stratification, and preventing vertical mixing (Sarma & Narvekar 2001). The temperature falls below 13°C at a depth of 200 m and 9°C at 500-600 m with a total thermocline thickness of about 150 m (Saidova 2008).

Deep Andaman Sea water is consistently warmer than that of Bay of Bengal with an approximate offset of 2°C (Sarma & Narvekar 2001), which can be attributed to the enclosed nature of the Andaman Basin (Sengupta *et al.* 1981) or the transfer of intermediate Bay of Bengal waters into the Andaman deep (Naqvi *et al.* 1994). The high temperature of the deeper water in the Andaman Sea lowers the ACD in the region (Sijinkumar *et al.* 2010). The present day ACD of the Andaman Sea lies around 1200 m water depth (Bhattacharjee & Bandyopadhyay 2002), while the ASD is situated at ~300 m water depth (Fig. 1B) (Sarma & Narvekar 2001).

Materials and methods

The deep-sea sediment cores SK 168/GC 1 (hereafter SK 168) (11°42'N; 94°29'E, water depth: 2064 m, length: 4.20 m), AAS 11/GC 1 (hereafter AAS 11) (9°00'N; 94°17'E, water depth: 2909 m, length: 4.28 m) and RVS 2/GC 3 (hereafter RVS 2) (07°42'N; 93°58'E, water depth: 2301 m, length: 5.64 m) were collected from the Andaman Sea (Fig. 1A). SK 168 was collected during the 168th cruise of ORV *Sagar Kanya* from the Alcock Seamount Complex in the Andaman Sea. The core AAS 11 was collected during the 11th expedition of research vessel *A. A. Sidorenko* and Core RVS 2 was collected onboard German Research vessel *F. S. Sonne*. These cores in the north-south transect provided an ideal opportunity for studying spatial and temporal variability in pteropod preservation in the Andaman Sea. The age model for the cores were constructed mainly based on the dates obtained by Accelerator Mass Spectrometer (AMS) ¹⁴C dates of planktic foraminiferal tests (mixed *Globigerinoides ruber* and *Globigerinoides sacculifer*) (Sijinkumar *et al.* 2011). Calendar age calibration was based on the CalPal 2007 programme (Weninger *et al.* 2007; <http://www.calpal.de>) (Table 1). The age model indicates varying sedimentation rates of 8, 9 and 23 cm ka⁻¹ in the cores SK 168, AAS11 and RVS 2, respectively (Fig. 2).

About 10 g of dried sample was 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 samples were split into several aliquots to obtain a minimum of 300 individuals. The coarse fraction (>125 µm) was used for qualitative and quantitative analysis of pteropod assemblages under a stereo zoom binocular microscope and also for quantifying *Globigerina bulloides*, total planktic and benthic foraminifera. The pteropod species were identified following Van der Spoel (1967), Bè & Gilmer (1977) and Almogi-Labin (1982). Pteropod fragmentation ratios were computed using the expression $n_F / (n_F + n_W)$, where n_F is the number of fragments and n_W is the number of whole tests (Klöcker *et al.* 2006).

The oxygen isotope analysis were carried out by using 10 to 16 tests of well preserved *G. ruber* (white) in the size range of 250-315 µm. Microscopic examination revealed that the tests were well

preserved with no sign of dissolution. The shells were placed in thimbles and crushed using a thin needle, then a few drops of methanol was added and then cleaned using an ultrasonic bath for 8-10 seconds. These cleaned tests were used for oxygen ($\delta^{18}\text{O}$) and carbon ($\delta^{13}\text{C}$) isotopic measurements using the DeltaPlus Advantage Isotope Ratio Mass Spectrometer (IRMS) coupled with a Kiel IV automatic carbonate device. Isotopic compositions are reported in δ notation as per mil deviation from PDB (Pee Dee Belemnite) standard. Analytical precision was 0.10‰ for $\delta^{18}\text{O}$ and 0.05‰ for $\delta^{13}\text{C}$. Replicate measurements were performed to ensure reproducibility.

Results

The study has documented the late Quaternary record of total abundance/preservation of pteropods for all the three cores from the Andaman Sea. A total of 15 pteropod species were identified from the Andaman Sea. The core locations (2000-3000 m) are below the present day ASD (300 m) and ACD (1200 m) (Fig. 1B), believed to have remained stable throughout the Holocene. The downcore variation of the important pteropod species for the cores AAS 11 and RVS 2 are shown in Fig. 3A,B. The species diversity and downcore variation of core SK 168 is already published in Sijinkumar *et al.* 2010. *L. inflata*, is the most abundant species in all the cores and its variation is similar to the total pteropod abundance variation, with maximum abundances observed during deglacial (19 to 16 cal. ka BP) (Fig. 3A,B). Similarly, all other major species showed maximum abundance during deglacial pointing towards a better preservation event (Fig. 3A,B). The abundance of total pteropods and the carbonate/aragonite preservation proxies from the Andaman Sea are shown in Fig. 4. It is observed that all the cores displayed a good preservation during last glacial to deglacial and total absence of pteropods during Holocene. The presence of transparent *L. inflata* species in all the cores during deglacial period suggests better preservation during the pteropod spike. The maximum abundance of pteropods is seen in the shallower core (SK 168) followed by southern core (RVS 2) with the least abundance in a deepest core AAS 11 (Fig. 4). The ratio of planktic to benthic foraminifera shows lower values during late MIS 3 and higher during Younger Dryas (YD), deglacial and Last Glacial Maximum (LGM) (Fig. 4). In all the cores, ratio of planktic to benthic are high during deglacial preservation/abundance spike indicating the prevalence of good carbonate preservation.

The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of planktic foraminifera, *G. ruber* (white) in the past 30 ka are compared with the pteropod preservation spike (Fig. 5A,B). In core SK 168, the $\delta^{18}\text{O}$ value of *G. ruber* ranged between -3.57 and -1.05‰ with the heaviest value coinciding with the last glacial pteropod preservation spike (Fig. 5A). Oxygen isotope record of AAS 11 and SK 168 first published by Sijinkumar *et al.* (2011) is now plotted with RVS 2, carbon isotopes and total pteropods (Fig. 5). In core RVS 2, the $\delta^{18}\text{O}$ value of *G. ruber* ranges between -3.16 and -0.68‰ with the heaviest value

seen at ~21 ka (Fig. 5B). These cores show heavier values during LGM, deglacial and YD which correspond well with good pteropod preservation/abundance. All the cores show distinct last glacial to Holocene variability in $\delta^{13}\text{C}$ values. The $\delta^{13}\text{C}$ values of *G. ruber* for cores SK 168, AAS 11 and RVS 2 vary from 0.8 to 1.2‰, 1.0 to 1.2‰ and 0.5 to 1.3‰, respectively (Fig. 5C). Furthermore, these cores show depleted values during deglacial and enriched values during LGM and late Holocene. In the Andaman Sea, $\delta^{13}\text{C}$ variations are not coherent with $\delta^{18}\text{O}$ record, suggesting a possible role of nutrient generation through winter mixing. The deglacial pteropod spike is characterised by lighter $\delta^{13}\text{C}$ values whereas enriched values are seen during Holocene (Fig. 5C). The deglacial pteropod spike is also characterised by reduced sea surface temperature (Fig. 5D) (Rashid *et al.* 2007).

In order to assess the role of summer and winter monsoon system on pteropods abundance/preservation, we have used *G. bulloides*, total foraminifera (summer monsoon) and *Pulleniatina obliquiloculata* (winter) abundances. The comparison between summer monsoon upwelling proxy *G. bulloides*, total foraminifera (productivity) and *P. obliquiloculata* (winter monsoon) with total pteropod is shown in Fig. 6. The *G. bulloides* is an important upwelling indicator ranging from 1.5 to 22.5% in all the cores (Fig. 6). Its increased abundance is observed in the last glacial-interglacial transition while the minimum abundance is noticed during LGM and deglacial pteropod preservation spike. The total planktic foraminifera significantly increased during the last glacial to interglacial transition and decreased abundance during deglacial pteropod spike (Fig. 6). The increased abundances of *P. obliquiloculata* is seen during deglacial spike and YD. Late Quaternary pteropod preservation records of northern Indian Ocean are compared with CO_2 record from the Vostok Ice Core (Fig. 7A-I). All the available records show good preservation during deglacial (corresponds to Heinrich Event 1), YD and poor preservation during Holocene (Fig. 7). The preservation spike of the Andaman Sea is matching with the record of the Arabian Sea (Table 2,3).

Discussion

Poor pteropod preservation periods in the Andaman Sea

The most prominent poor preservation/absence of pteropods is during Holocene. The poor preservation or absence of pteropods has begun between 10 cal. ka BP (SK 168 and AAS 11) and 9 cal. ka BP (RVS 2). The poor preservation/absence of pteropods from early Holocene is possibly related to the sharp rise in the calcite compensation depth at the glacial-Holocene boundary which was identified on the basis of foraminiferal assemblages in the Pacific (Berger 1977 references

therein). The CO₂ concentration in the surface waters has sharply increased from early Holocene onwards (Barnola *et al.* 2003) which is in close agreement with the absence of pteropods in the sediments (Fig. 7A). The study shows that there is a sharp rise in the ACD from early Holocene to the present and core locations may have remained below the ACD. Increased concentration of atmospheric CO₂ during Holocene resulted in ocean acidification and affected pteropod preservation (Fig. 7A), by reducing the saturation levels of ACD of the oceans (Kleypas *et al.* 1999; Feely *et al.* 2004). The climate change caused by global warming plays a prominent role in dissolution of carbonate.

The second important poor preservation of pteropods is seen during Bølling/Allerød (B/A), where preservation is very low in comparison with preceding deglacial and following YD (Fig. 4). The poor preservation of B/A is coinciding with high fragmentation ratio and low planktic to benthic ratio (Fig. 4). Interestingly, summer monsoon proxies such as the abundances of *G. bulloides* and total planktic foraminifera were increased from early B/A which reflects its impact on pteropod preservation by high biological productivity by increasing concentration of dissolved inorganic carbon, resulting from high input and remineralisation of organic matter, lowering the pH (Millero *et al.* 1998). It is also reported from the Andaman Sea that during B/A and Holocene, summer monsoon was stronger (Rashid *et al.* 2007) whereas winter monsoon weak (Sijinkumar *et al.* 2011).

Timing of the preservation spike in the Indian Ocean

Resolving the precise time period of the preservation spike of pteropods is crucial for stratigraphic correlation and also for understanding the driving mechanism (Berger 1977). The earlier studies from the Pacific revealed that the preservation spike is centered at 13.5 ka BP, whereas in the western equatorial Pacific, it is centered at 14 ka BP (Berger & Killingley 1977). In the Gulf of Mexico, high abundance/preservation of pteropod is encountered at 15 to 12.5 ka BP. But in the Equatorial Atlantic, it is centered between 13.5 and 14 ka BP (Wiseman 1965). Preservation spike during deglacial period was also observed in the coast off Morocco (Diester-Haass *et al.* 1973) and South China Sea (Wang *et al.* 1997).

Pteropod preservation spikes from the Andaman Sea along with other late Quaternary records of the northern Indian Ocean (viz., the eastern and western Arabian Sea and Gulf of Aden) are presented for comparison (Table 2; Fig. 7). It is observed that the event is nearly synchronous in the northern Indian Ocean suggesting that the pteropod preservation during the last deglacial is a regional phenomenon. The timing of the preservation spike in the Indian Ocean is consistent between 19 and 14 cal. ka BP, while the exact timing of Andaman Sea preservation spike is between 19 and 15.5 cal.

ka BP (18.5-15.5 for SK 168, 19-15.5 for AAS 11, 19-15.5 for RVS 2, Table 2). In the Andaman Sea, the spike is centered at 17 cal. ka BP (Fig. 7B-D) whereas in the eastern Arabian Sea, the preservation spike off Goa is reported at 17.8-15 cal. ka BP (Singh *et al.* 2006; Fig. 7E), followed by 17 and 15 cal. ka BP off Pakistan coast (Klöcker & Heinrich 2006; Fig. 7G). Preservation spike is observed between 18.8 and 14 cal. ka BP in Gulf of Aden (Fig. 7F) (Almogi-Labin *et al.* 2000) and between 17 and 13 cal. ka BP off Somalia (Fig. 7H) in the western Arabian Sea (Klöcker *et al.* 2006). The aragonite record from the northern Arabian Sea also shows good preservation between 18 and 14.4 ka BP (Fig. 7I) (Böning & Bard 2009). Overall, in the Indian Ocean, maximum duration of this preservation event is seen in the cores of Arabian Sea taken from intermediate water depths (~1600 m depth) whereas pteropod preservation event based on shallow cores (573, 828 and 840 m) shows shorter duration of this event. In the Andaman Sea cores recovered from deeper water depths (~2000, 2300 and 2900 m) also shows even shorter duration. The Andaman Sea records are apparently representing the deepest records so far of this event. This indicates that the preservation is to a large degree a phenomena of intermediate water depths.

Based on the available data from Pacific and Atlantic, Berger (1977) has suggested that the pteropod spike has its maximum abundance at about 14 cal. ka BP. The observed lag in the occurrence of preservation spike in the Indian, Atlantic and Pacific Oceans may be related to discrepancies in reporting radiocarbon and calibrated calendar ages. The position and fluctuations of the ACD in the geological past is often inferred from the presence/absence of pteropods. Based on the preservation record of pteropods from the Andaman Sea, it is inferred that ACD was probably deepest (>2900 m) during 16.5 cal. ka BP, which then shoaled over a brief period during B/A and later again deepened during YD. According to Berger (1977) the depth of ACD in oceans varied between 1700 and 3600 m during the last deglacial period. The new data from the Andaman Sea and the western Indian Ocean indicates the presence of well resolved preservation spikes with their maxima at 16.5 cal. ka BP (Fig. 7B-I) which in turn act as a useful stratigraphic marker in the Andaman Sea.

What drives the pteropod preservation spike in the Andaman Sea?

Pteropod preservation spike in deglacial period has been attributed to various controlling factors. According to Weyl (1968), preservation spike is the result of deepening of ACD driven by the increase in temperature of deep ocean waters during deglacial period. This is further substantiated by the evidence from the Atlantic Ocean (Streeter 1973; Duplessy *et al.* 1975). While in the Andaman Sea, sea surface temperature was relatively low (26°C) contradicting the view of warming of sea water during deglacial period (Fig. 5D). Diester-Haas & Van der Spoel (1978) are of the opinion that the preservation spike was driven by red tide induced mass mortality, whereas Shackleton (1977)

attributed this to rapid growth of biosphere during deglaciation leading to the increased uptake of atmospheric CO₂ and carbonate preservation. Worthington (1968) opined that a low salinity meltwater during the deglaciation acted as a lid leading to stagnant bottom waters affecting carbonate preservation. This may not be the case in the Andaman Sea, as salinity was higher during deglacial period by a factor of 1 psu than at present (Sijinkumar *et al.* 2010). Berger (1977) proposed a combination of increased saturation of deep waters, decreasing bottom currents and increased sedimentation rates for the better preservation. However, no considerable change in sedimentation rate during deglacial was noticed in the Andaman Sea (Fig. 2). Pteropod preservation spike in the Atlantic Ocean is interpreted as the combined effect of climatically induced non-dissolution and hydrothermally induced preservation (Melkert *et al.* 1992).

G. ruber δ¹³C record in the Andaman Sea showed a rapid change in the chemistry of ocean water corresponding to deglacial preservation spike. *G. ruber* δ¹³C record shows significantly enhanced nutrient generation from deglacial times beginning from 18 cal. ka BP to early Holocene, which corresponds with good pteropod preservation. Older waters that have been long isolated from the atmosphere have lower δ¹³C because of organic matter oxidation. The depleted δ¹³C values during the deglaciation correlate with the increased abundance of pteropods revealing enhanced ventilation and nutrient rich surface water driven by enhanced winter monsoon in the Andaman Sea. During the last glaciations, the supply of ¹²C rich deep water was reduced due to weak upwelling and weakening of summer monsoon, which led to enriched δ¹³C values during the LGM. The changes in intermediate to deep water circulation during the last glacial to early Holocene have significant role in pteropod preservation in the Indian Ocean. In the Andaman Sea, the Antarctic Intermediate Water enters through the shallow sills connected with Bay of Bengal as a mixture of overlying water mass containing Subantarctic Mode Antarctic Intermediate Waters and the high salinity outflows from the Persian Gulf and the Red Sea and the underlying North Atlantic Deep Water (Naqvi *et al.* 1994). These water masses may have profoundly influenced the pteropod preservation during last glacial to deglacial. The good aragonite preservation in the Arabian Sea during glacial was attributed to enhanced ventilation and strengthened influx of intermediate water from Antarctica and weakening of oxygen minimum zone (Böning & Bard 2009). These water masses are sufficiently enriched with the dissolved oxygen affecting oxygen minimum zone and thermocline structure. Poor pteropod preservation during the Holocene and B/A may be attributed to low supply of O₂ combined with elevated O₂ demand controlled by monsoon-related productivity (Böning & Bard 2009).

In addition to circulation and ventilation changes during deglacial period, another possible factor controlling pteropod preservation spike may be the changing intensity of monsoon in the region.

Abundance and good preservation of pteropods during deglacial is associated with lower abundances of *G. bulloides* % and total foraminifera (Fig. 5), suggesting that the pteropod preservation is strongly influenced by the strength of summer monsoon in the Andaman Sea. Upwelling and resulting high biological productivity greatly affects the accumulation of sedimentary carbonates, particularly pteropods owing to their vulnerability to dissolution. The *G. bulloides* and total foraminiferal assemblage from the Andaman Sea show that summer monsoon was stronger during B/A, last glacial to Holocene transition, early Holocene, and it was weaker during late glacial (see also Rashid *et al.* 2007). Whereas, high abundance of *P. obliquiloculata* during LGM and deglacial spike suggest enhanced winter monsoon. In the Andaman Sea, the abundance of this species has varied with changes in winter monsoon and thermocline depth (Sijinkumar *et al.*, 2011). Increased *P. obliquiloculata* abundances also coincide with increased nutrient generation (shown by *G. ruber* $\delta^{13}\text{C}$ record) which in turn corresponds to preservation spike. This increased nutrient generation is not reflected in *G. bulloides* abundances which is an established summer upwelling species. Hence, the abundances of *P. obliquiloculata* are potentially related with winter monsoon changes. Enhanced winter monsoon strength over summer monsoon during LGM to deglacial is reported from the northern Indian Ocean (Duplessy 1982; Sarkar *et al.* 1990). Increased winter monsoon activity during LGM probably caused deeper convective winter mixing; ventilation of oxygen minimum zone, deepening of ACD and reduced atmospheric CO_2 , which in turn has improved the aragonite preservation potential in the region. The present study clearly suggests that the global nature of deglacial pteropod preservation spike has been controlled by different mechanism such as role of intermediate water circulation, changes in monsoon induced sea water chemistry and global lowering of atmospheric CO_2 and resultant more alkaline sea water. As far as Indian Ocean is concerned, the dominant factors are changes in intermediate circulation and chemistry of sea water driven by monsoon climate.

Conclusions

It is inferred from the present study that the pteropod preservation records from the Andaman Sea have shown a significant variation from the last glacial to Holocene with a prominent deglacial preservation spike centering at ~16.5 cal. ka BP. Observations of pteropod preservation/abundance from the Indian Ocean show that the total absence of pteropods during Holocene may be attributed to several reasons, the foremost being core locations that may have continued to remain below the ACD throughout the Holocene or sharp shoaling in the ACD during the early present interglacial. Increased concentration in atmospheric CO_2 during Holocene is also contributed for the poor preservation by acidification of ocean water and resultant reduction in the saturation state of the

oceans with respect to calcium carbonate. The poor preservation during B/A is the result of enhanced upwelling and resulting high biological productivity due to strong summer monsoon. The deglacial pteropod spike is characterized by a very high abundance/preservation of the pteropods between ~19 and 15 cal. ka BP associated with very low atmospheric CO₂ concentration. The time period of the preservation spike in the Indian Ocean is consistent during 19-13 cal. ka BP. Isotope data suggest glacial environment with reduced sea surface temperature, upwelling and enhanced salinity during the pteropod preservation spike. Total foraminifera and *G. bulloides* abundances are very low during this period indicating the prevalence of weaker summer monsoon and reduced foraminiferal productivity in the region. Two possible factors responsible for the deglacial spike are changes in intermediate water circulation and chemistry of sea water driven by monsoon climate. The synchronous regional occurrence of the pteropod preservation spike in the Andaman Sea as well as in the north-western Indian Ocean can possibly be employed as a potential stratigraphic marker.

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Figure captions

Fig. 1. A. Location map of the Andaman Sea showing core locations. B. Depth-wise averaged vertical distribution of aragonite saturation values in the Andaman Sea (ASD is marked at 300 m) (modified from Sarma & Narvekar 2001).

Fig. 2. Age-depth model with sedimentation rate. A. Core SK 168; B. Core AAS 11 (Sijinkumar *et al.* 2011). C. Core RVS 2. The age model based on Accelerator Mass Spectrometer (AMS) ^{14}C dates of planktic foraminiferal tests and their calendar age calibration was based on the CalPal 2007 programme.

Fig. 3. Absolute abundance of total pteropods and major species (*Limacina inflata*; *L. trochiformis*, *Diacria quadridentata*, *Clio convexa*, *Styliola subula* and *Creseis acicula*) in core AAS 11 (A), and that of core RVS 2 (B).

Fig. 4. Proxies for aragonite dissolution (pteropod fragmentation ratio) and carbonate dissolution (ratio of planktic to benthic foraminifera) in all three cores from the Andaman Sea with respect to deglacial spike and climatic events Younger Dryas (YD), Bølling/Allerød (B/A) and Last Glacial Maxima (LGM). The black arrows indicate the depth horizon for ^{14}C AMS dating.

Fig. 5. Comparison of deglacial pteropod spike with oxygen and carbon isotope records from the Andaman Sea. A. Total pteropod records of cores SK 168 (Sijinkumar *et al.* 2010), AAS 11 and RVS 2. B. Oxygen isotope record of 3 cores C. Carbon isotope record of 3 cores. D. Sea surface temperature record of the Andaman Sea (Rashid *et al.* 2007).

Fig. 6. Pteropod spike versus monsoon proxies (summer - *G. bulloides* %; Sijinkumar *et al.* 2010 and total planktic foraminifera) record in cores SK 168, AAS 11 and RVS 2 and *P. obliquiloculata* of core SK 168 (winter - Sijinkumar *et al.* 2011) from the Andaman Sea.

Fig. 7. Ice core CO_2 concentration record versus deglacial pteropod preservation spikes in the Northern Indian Ocean. A. Atmospheric CO_2 concentration (record from the Vostok Ice Core; Barnola *et al.* 2003). B. Total pteropod abundance in SK 168 (Sijinkumar *et al.* 2010). C. Total pteropod abundance in AAS 11 (Sijinkumar *et al.* 2010). D) Total pteropod abundance in RVS 2. E. Total pteropod abundance in SK 17 off Goa (Singh *et al.* 2006). F. Total pteropods in core KL 15 from the Gulf of Aden (Almogi-Labin *et al.* 2000). G. Pteropod % in SO 90/137 KA, off Pakistan (Klöcker & Heinrich 2006). H. Pteropod % in NIOP 905, off Somalia, western Arabian Sea (Klöcker *et al.* 2006). I. Aragonite % in core MD 042876 from the Northern Arabian Sea (Böning & Bard 2009) (modified from Sijinkumar *et al.* 2010 with additional records).

Table 1. AMS ^{14}C dates and calibrated ages of sediment samples for SK 168/GC-1, AAS 11/GC-1 and RVS 2/GC 3.

Depth in core (cm)	Material	Accession No.	Radiocarbon age (^{14}C age in years)	Calendar age (Cal. a BP)
SK 168/GC 1				
SK168/0-2	Mixed planktic foram	OS-64674	1440±30	883±47
SK168/75-77	Mixed planktic foram	OS-64675	9650±30	10 361±76
SK168/95-97	Mixed planktic foram	OS-64676	10 850±50	12 321±178
SK168/215-220	Mixed planktic foram	OS-64677	27 900±220	32 055±215
AAS 11/GC 1				
AAS11/10-12	Mixed planktic foram	—	3085±50	2807±39
AAS11/36-38	Mixed planktic foram	—	4755±35	4923±45
AAS11/66-68	Mixed planktic foram	—	7995±50	8406±30
AAS11/97-99	Mixed planktic foram	—	10 850±70	12 374±185
AAS11/136-138	Mixed planktic foram	—	14 245±100	17 070±207
AAS11/166-168	Mixed planktic foram	—	16 645±120	19 421±334
AAS11/176-178	Mixed planktic foram	—	17 310±150	20 154±314
AAS11/181-183	Mixed planktic foram	—	17 450±130	20 385±387
AAS11/198-200	Mixed planktic foram	—	18 700±155	21 969±341
AAS11/248-250	Mixed planktic foram	—	23 465±260	27 612±480
RVS 2/GC 3				
RVS 2/30-31	Mixed planktic foram	OS-69876	1730±30	1306±14
RVS 2/50-51	Mixed planktic foram	OS-69877	2430±30	2059±44
RVS 2/120-122	Mixed planktic foram	OS-69878	5280±30	5660±38
RVS 2/210-212	Mixed planktic foram	OS-69879	7190±45	7676±42
RVS 2/290-292	Mixed planktic foram	OS-69880	12 100±50	13 634±127
RVS 2/360-362	Mixed planktic foram	OS-69881	14 800±70	17 588±251
RVS 2/456-458	Mixed planktic foram	OS-69718	19 900±90	23 341±340

Mixed planktic foram (*Globigerinoides ruber*+*Globigerinoides sacculifer*)

Table 2. Timing of the preservation spike in the Indian Ocean.

Sl. No.	No. and location of the cores	Time period of the preservation spike (age in cal. ka BP)	Time period of maximum spike in the pteropod preservation (age in cal. ka BP)	References
1	SK 168 Northern Andaman Sea	15.5-18.5	16.5	Sijinkumar <i>et al.</i> (2010)
2	AAS 11 Central Andaman Sea	15.5-19.0	16.5	This paper
3	RVS 2 Southern Andaman Sea	19.0-15.5	16.5	This paper
4	SK 17 Eastern Arabian Sea	19.0-15.0	16.5	Singh <i>et al.</i> (2006)
5	KL 15 Gulf of Aden	19.0-14.0	17.0	Almogi-Labin <i>et al.</i> (2000)
6	SO90 137 KA Off Pakistan	18.0-14.0	16.0	Klöcker & Heinrich (2006)
7	NIOP 905 Western Arabian Sea	19.0-14.0	15.0	Klöcker <i>et al.</i> (2006)
8	MD042876 Northern Arabian Sea	19.0-14.0	16.0	Böning & Bard (2009)

Table 3. Total pteropods number in all the three cores from the Andaman Sea. Age in cal. ka BP. TPt.= Total pteropods; A= absent.

SK 168								AAS 11				RVS 2			
Age	TPt. (# g ⁻¹)	Age	TPt. (# g ⁻¹)	Age	TPt. (# g ⁻¹)	Age	TPt. (# g ⁻¹)	Age	TPt. (# g ⁻¹)	Age	TPt. (# g ⁻¹)	Age	TPt. (# g ⁻¹)	Age	TPt. (# g ⁻¹)
0.88-10.04	A	16.78	8824	24.11	20	41.69	204	0.63-9.62	A	20.77	231	0.02-8.37	A	22.80	444
10.36	235	17.10	6833	24.79	40	42.22	91	10.27	81	21.26	85	9.11	902	23.42	1066
10.61	481	17.42	4854	25.48	319	42.76	118	10.91	83	21.74	81	9.84	449	24.04	284
10.85	674	17.74	4125	26.16	211	43.29	435	11.55	0	22.27	78	10.58	403	24.66	290
11.10	1034	18.06	3889	26.85	77	43.83	196	11.99	0	22.84	187	11.34	3925	25.28	370
11.34	562	18.37	8644	27.95	83	44.36	294	12.61	0	23.40	152	12.07	2188	25.90	205
11.59	870	18.69	7547	29.32	120	44.90	165	12.79	0	23.96	160	12.81	547	26.52	274
11.83	1915	19.01	5413	30.69	275	45.43	299	13.39	93	24.53	0	13.54	516	27.14	75
12.08	704	19.33	5000	32.06	533	45.97	81	13.98	0	25.09	0	14.07	470	27.75	40
12.32	1714	19.65	1264	32.59	303	46.50	326	14.57	83	25.65	0	14.60	1429	28.37	156
12.64	949	19.97	1894	33.13	463	47.04	267	15.17	556	26.22	0	15.12	390	28.99	95
12.96	982	20.29	632	33.66	619	47.57	187	15.76	79	26.78	104	15.65	5867	29.61	156
13.28	1570	20.61	708	34.20	519	48.11	102	16.36	973	27.34	0	16.18	8036		
13.60	385	20.92	652	34.73	174	48.64	83	16.95	2868	27.91	0	16.70	9898		
13.91	714	21.24	125	35.27	164	49.18	154	17.35	2190	28.47	0	17.23	6990		
14.23	395	21.56	290	36.87	222	49.71	100	17.75	1765	29.04	0	17.85	8407		
14.55	154	21.88	208	37.41	374	50.25	125	18.15	1241	29.61	0	18.47	894		
14.87	308	22.20	111	37.94	426	50.78	156	18.55	1000	30.17	0	19.09	833		
15.19	741	22.52	796	39.01	0	51.32	50	18.95	278	30.74	0	19.71	690		
15.51	341	22.84	97	39.55	247	51.85	111	19.35	268	31.30	0	20.33	545		
15.83	1250	23.15	99	40.08	360	52.39	40	19.71	152	31.87	0	20.95	875		
16.14	3261	23.47	156	40.62	300	52.93	40	20.07	168	32.43	83	21.56	508		
16.46	9135	23.79	155	41.15	155	53.46	130	20.29	92	32.99-47.83	A	22.18	323		

Fig. 1

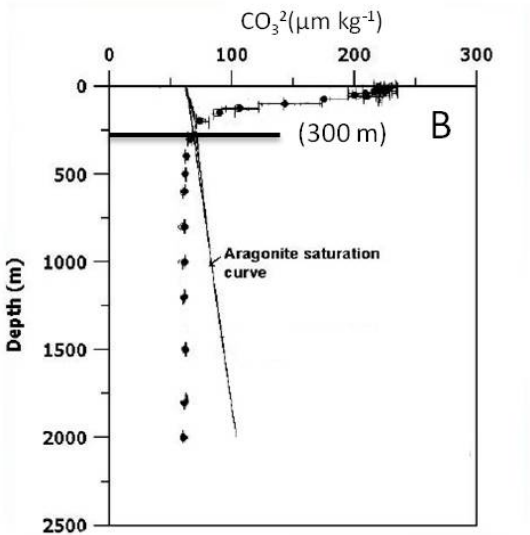
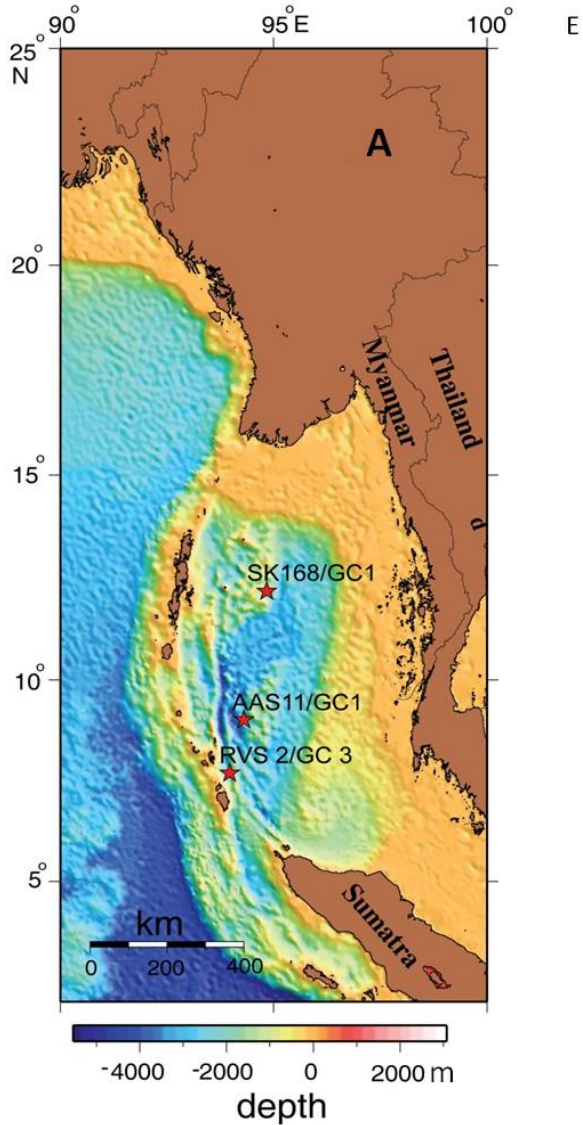


Fig. 2

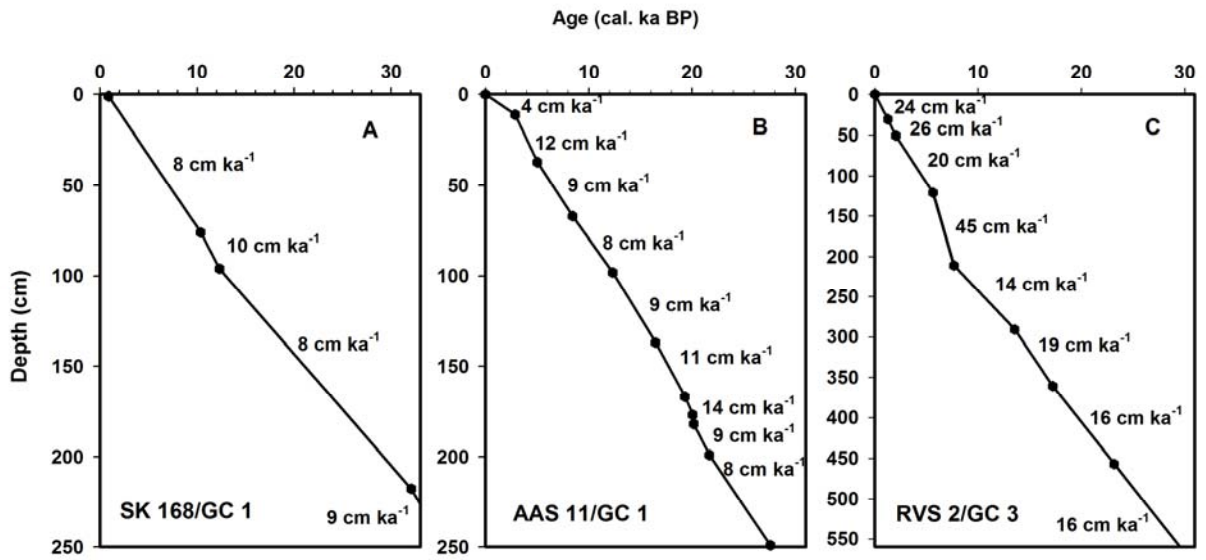


Fig 3

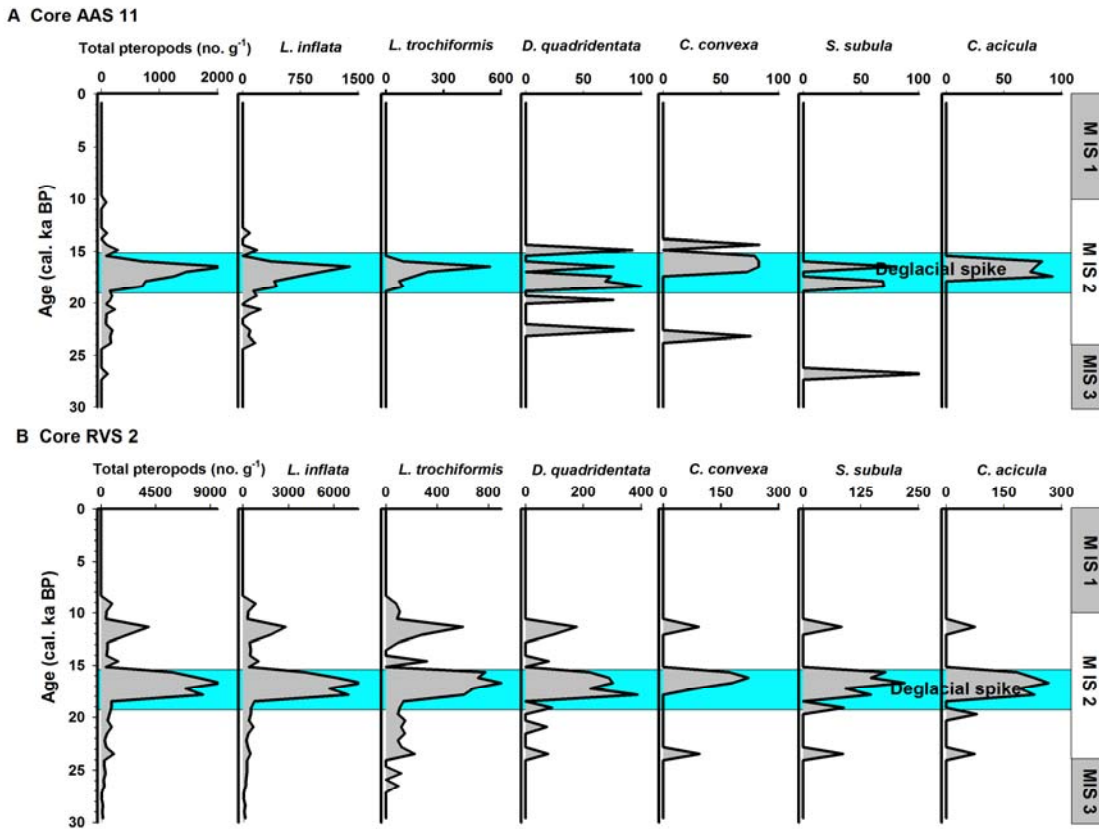


Fig. 4

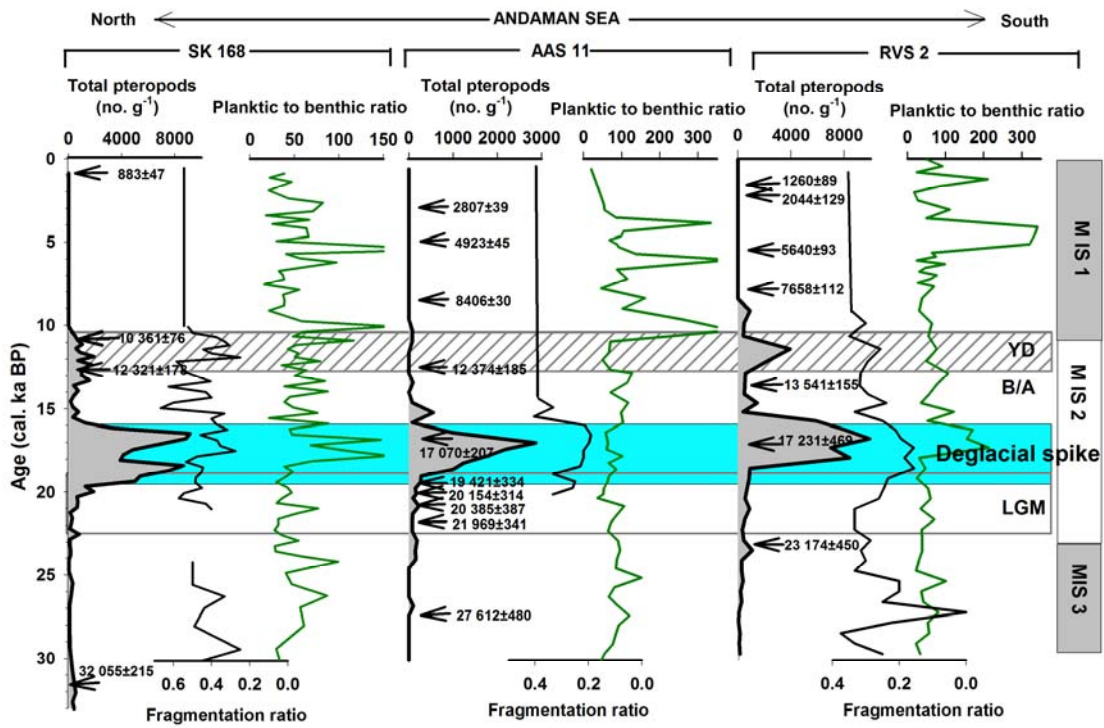


Fig. 5

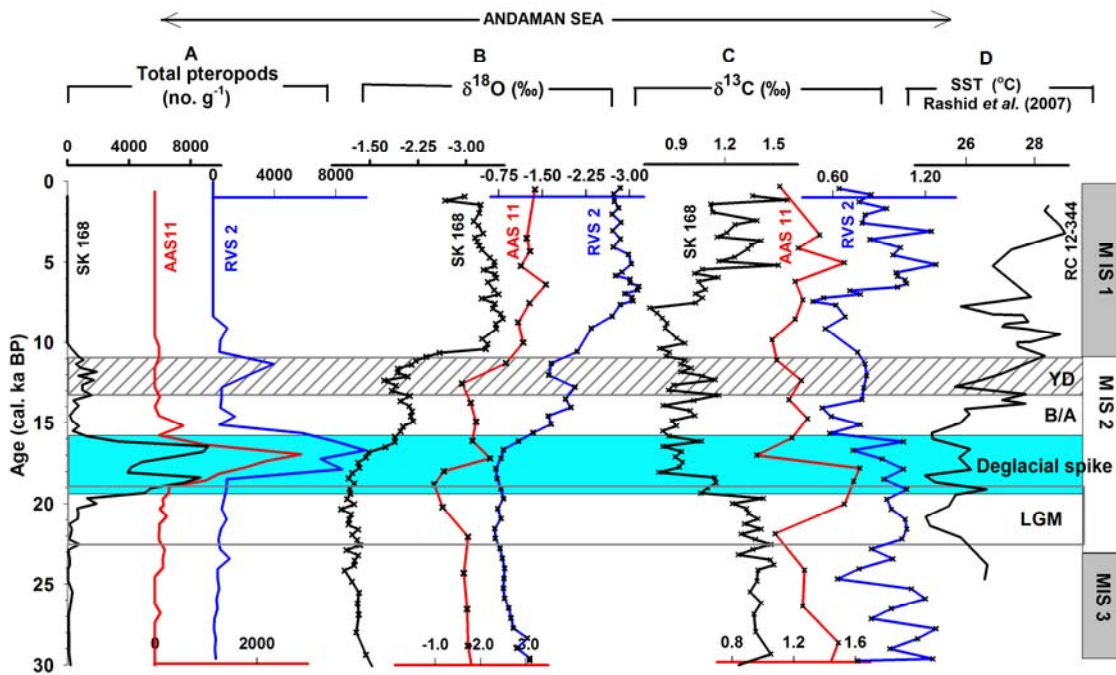


Fig. 6

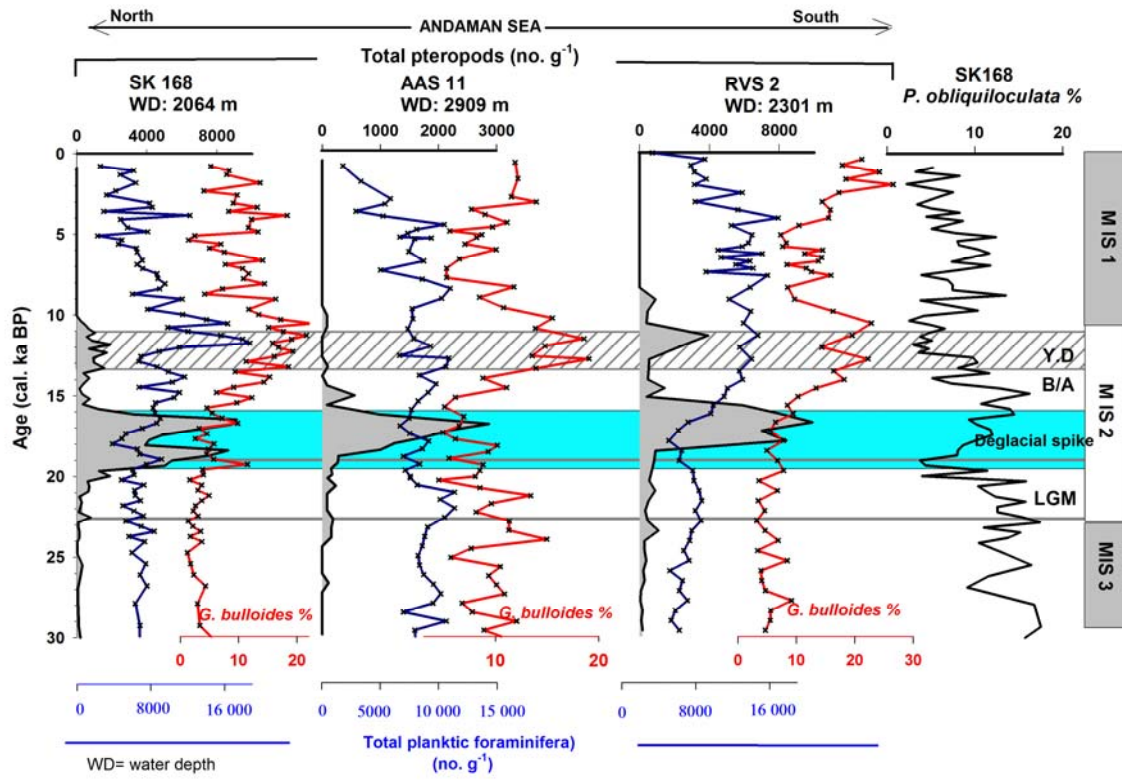


Fig. 7

