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Timing and preservation mechanism of deglacial pteropod spike from the Andaman Sea, northeastern Indian Ocean

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The aragonite compensation depth (ACD) fluctuated considerably during the last glacial until the Holocene with a dominant pteropod preservation spike during the deglacial period, which is prominently seen in three well-dated cores covering the Andaman Sea, northeastern Indian Ocean. The precise time period of the preservation spike of pteropods is not known but this knowledge is crucial for stratigraphical correlation and also for understanding the driving mechanism. Isotopic and foraminiferal proxies were used to decipher the possible mechanism for pteropods preservation in the Andaman Sea. The poor preservation/absence of pteropods during the Holocene in the Andaman Sea may have implications for ocean acidification, driven by enhanced atmospheric CO_2 concentration. Strengthening of the summer monsoon and the resultant high biological productivity may also have played a role in the poor preservation of pteropods. 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 CO_2 concentration. Isotope data suggest the prevalence of a 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 a weakened summer monsoon and reduced foraminiferal productivity. Based on the preservation record of pteropods, it is inferred that the ACD was probably deepest (>2900 m) at 16.5 cal. ka BP. The synchronous regional occurrence of the pteropod preservation spike in the Andaman Sea and in the northwestern Indian Ocean could potentially be employed as a stratigraphic marker.

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Pteropods are marine gastropods made up of aragonitic shells. Aragonite is a metastable polymorph of $CaCO_3$ that is more susceptible to dissolution than calcite. Preservation and accumulation of pteropods on the sea floor are 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 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, Atlantic and 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, the Mediterranean Sea (Chen 1968) and the 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 red tide-induced mass mortality (Diester-Haass & Van der Spoel 1978) and rapid growth of the 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 revealed that the good preservation is due to the strong winter monsoon, enhanced ventilation, the resultant weakening of the oxygen minimum zone and deepening of the ACD (Klöcker & Henrich 2006; Böning & Bard 2009; Sijinkumar *et al*. 2010).

The occurrence and abundance of aragonitic pteropods during the latest Holocene is a subject of

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renewed interest owing to the fact that they are the most vulnerable amongst 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). A study by Sabine *et al.* (2002) in the Indian Ocean revealed the anthropogenic effects on aragonite preservation. The aragonite saturation depth (ASD) during recent times shoaled significantly by 25–155 m in the Indian Ocean because of the absorption of anthropogenic CO_2 in the subsurface water-masses and also because of increased organic matter decomposition rates (Sabine *et al.* 2002; Sarma *et al.* 2002). The aragonite saturation level of the present day in the Indian Ocean is significantly shallower than in pre-industrial times. For example, the 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).

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

Oceanographical setting

The Andaman Sea (maximum water depth 4400 m) is a semi-enclosed marginal sea in the eastern part of the northern Indian Ocean. The Andaman Sea exchanges water-masses with the Bay of Bengal in the north Indian Ocean and also with the marginal seas of the 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 the Bay of Bengal is hampered by several sills that have a 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 that the surface oceanographical processes in these seas are comparable above the sill depth. As in the northern Indian Ocean, the Andaman

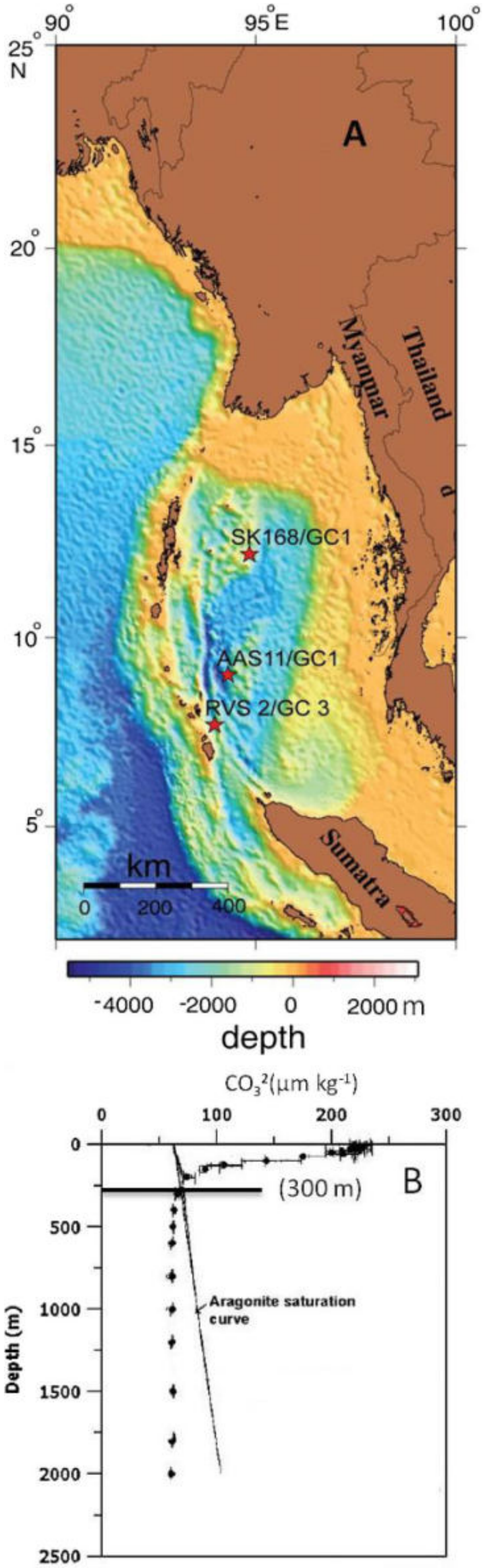

Fig. 1. A. Location map of the Andaman Sea showing core locations. B. Depth-wise averaged vertical distribution of aragonite saturation values in the Andaman Sea (ASD is marked by the horizontal line at 300 m) (modified from Sarma & Narvekar 2001). This figure is available in colour at http://www.boreas.dk.

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 (Wyrtki 1973). The Andaman Sea is characterized by a low surface salinity ranging from 31.8 to 33.4 psu due to the influence of freshwater discharge from the Ayeyarwady–Salween river system (Sarma & Narvekar 2001). According to Milliman & Meade (1983), the Ayeyarwady River drains ~428 km^3 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 the 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), whereas the ASD is situated at ~300 m water depth (Fig. 1B; Sarma & Narvekar 2001).

Material and methods

The deep-sea sediment cores SK 168/GC 1 (hereafter SK 168) (latitude 11°42′N; longitude 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. Core AAS 11 was collected during the 11th expedition of the research vessel 'A. A Sidorenko' and core RVS 2 was collected onboard the 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 was constructed mainly based on the dates obtained by accelerator mass spectrometer (AMS) ^{14}C dates of planktic foraminiferal tests (mixed *Globigerinoides ruber* and *Globigerinoides sacculifer*) (Sijinkumar *et al.* 2011). Calendar age calibration was based on the CalPal 2007 program (Weninger *et al.* 2010; http://www.calpal.de; Table 1). The age model indicated varying sedimentation rates of 8, 9 and 23 cm ka^{-1} in 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

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

Depth in core (cm)	Material	Accession no.	Radiocarbon age (^{14}C a BP)	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*.

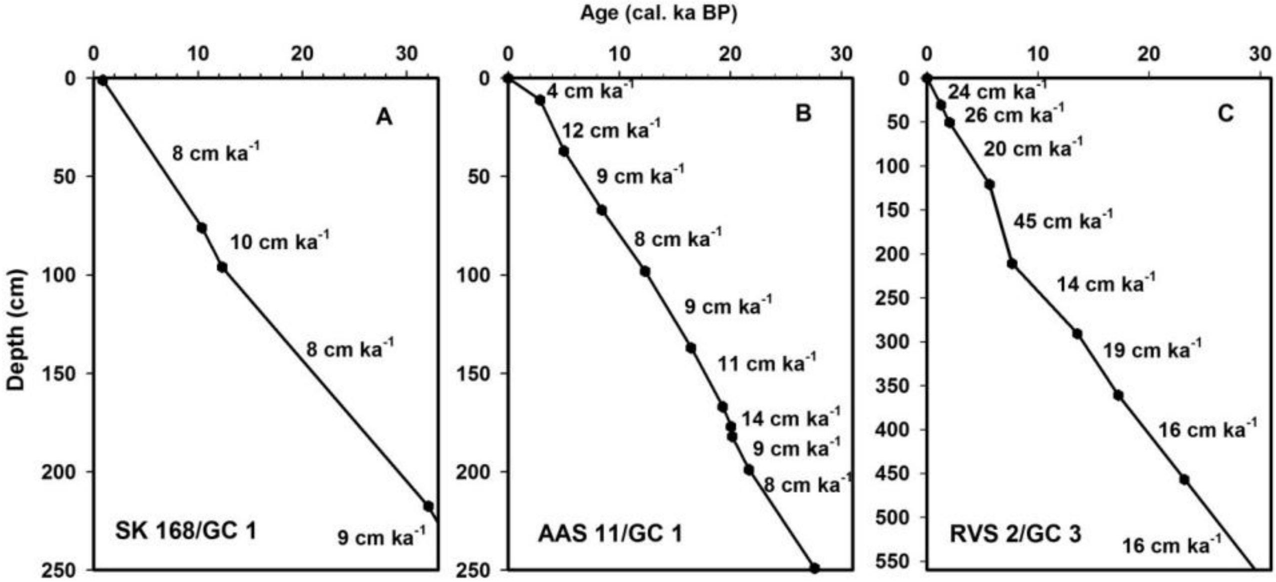

Fig. 2. Age-depth model with sedimentation rate. A. Core SK 168. B. Core AAS 11 (Sijinkumar *et al.* 2011). C. Core RVS 2. The age model based on accelerator mass spectrometer ^{14}C dates of planktic foraminiferal tests and their calendar age calibration was based on the CalPal 2007 program.

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* and 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 were added and the crushed shells were cleaned using an ultrasonic bath for 8–10 s. These cleaned tests were used for oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopic measurements using a 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 Pee Dee Belemnite (PDB) standard. Analytical precision was 0.10‰ for $\delta^{18}O$ and 0.05‰ for $\delta^{13}C$. Replicate measurements were performed to ensure reproducibility.

Results

The study documented the late Quaternary record of total abundance/preservation of pteropods for three cores from the Andaman Sea. A total of 15 pteropod species was 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 down-core variation in the important pteropod species for the cores AAS 11 and RVS 2 is shown in Fig. 3A, B. The species diversity and down-core variation of core SK 168 has already been published in Sijinkumar *et al.* 2010. *L. inflata* is the most abundant species in all of the cores and its variation is similar to the total pteropod abundance variation, with maximum abundances observed during the deglacial period (19 to 16 cal. ka BP; Fig. 3A, B). Similarly, all other major species showed maximum abundance during the 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 good preservation during the last glacial to deglacial and a total absence of pteropods during the Holocene. The presence of transparent *L. inflata* species in all the cores during the deglacial period suggests better preservation during the pteropod spike. The maximum abundance of pteropods is seen in the shallowest core (SK 168) followed by the southern core (RVS 2) with the lowest abundance in the deepest core, AAS 11 (Fig. 4). The ratio of planktic to benthic foraminifera is lower during late MIS 3 and higher during the Younger Dryas (YD), deglacial and Last Glacial Maximum (LGM) (Fig. 4). In all of the cores, the ratios of planktic to benthic foraminifera are high during the deglacial preservation/abundance spike, indicating the prevalence of good carbonate preservation.

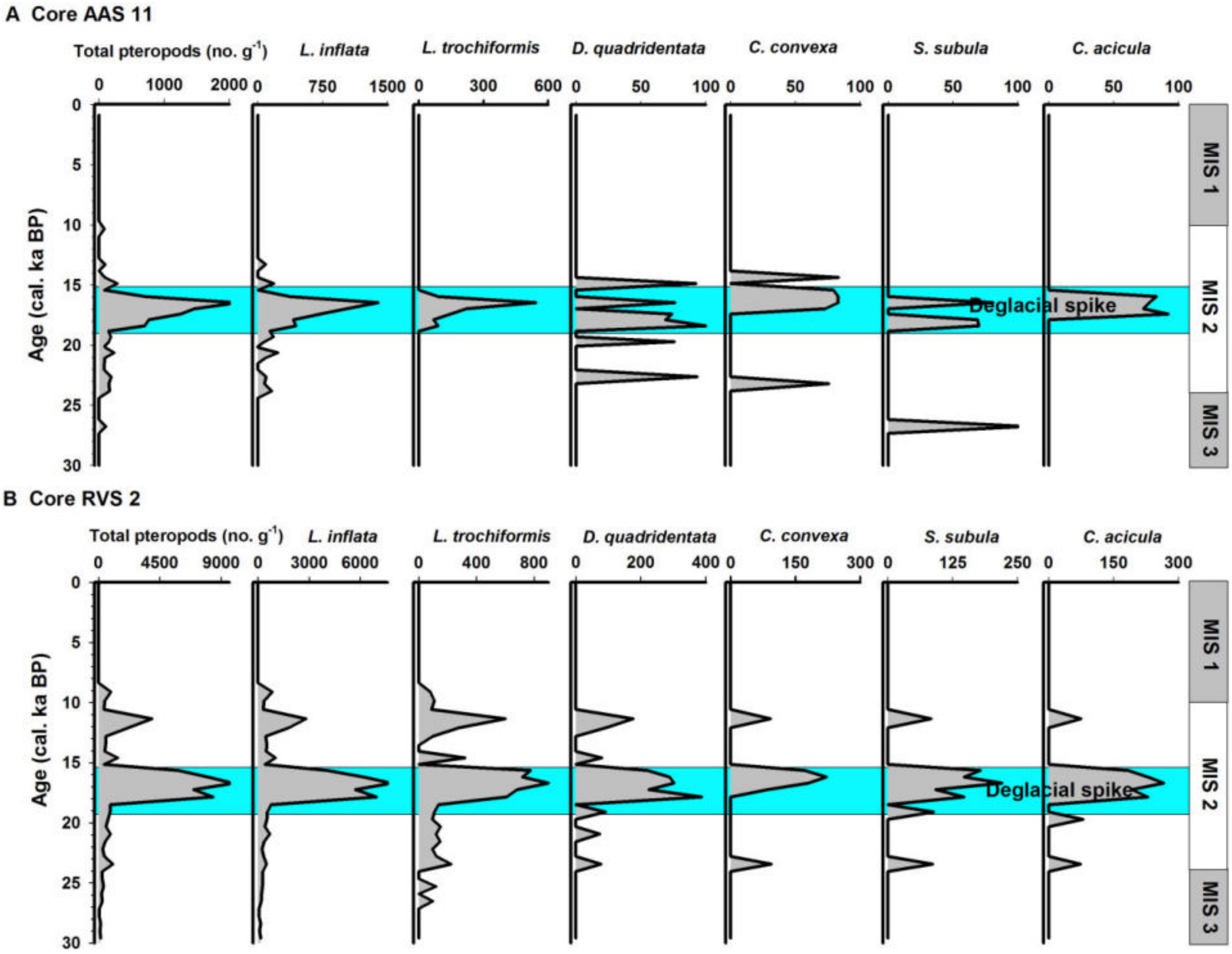

Fig. 3. Absolute abundance of total pteropods and major species (*Limacina inflata*, *L. trochiformis*, *Diacria quadridentata*, *Clio convexa*, *Styliola subula* and *Creseis acicula*) in core AAS 11 (A) and that of core RVS 2 (B). This figure is available in colour at http://www.boreas.dk.

The $\delta^{18}O$ and $\delta^{13}C$ values of the planktic foraminifer *G. ruber* (white) in the past 30 ka were compared with the pteropod preservation spike (Fig. 5A, B). In core SK 168, the $\delta^{18}O$ 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). The oxygen isotope records of AAS 11 and SK 168, first published by Sijinkumar *et al.* (2011), were plotted with that of RVS 2, along with the carbon isotopes and total pteropods for all three cores (Fig. 5). In core RVS 2, the $\delta^{18}O$ 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 the LGM, deglacial and YD, which corresponds well with good pteropod preservation/abundance. All of the cores show distinct last glacial to Holocene variability in $\delta^{13}C$ values. The $\delta^{13}C$ 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 the deglacial and enriched values during the LGM and late Holocene. In the Andaman Sea, $\delta^{13}C$ variations do not correlate with the $\delta^{18}O$ record, suggesting a possible role of nutrient generation through winter mixing. The deglacial pteropod spike is characterized by lighter $\delta^{13}C$ values whereas enriched values are seen during the Holocene (Fig. 5C). The deglacial pteropod spike is also characterized by reduced sea surface temperature (Fig. 5D; Rashid *et al.* 2007).

In order to assess the role of the summer and winter monsoon system on pteropod abundance/preservation, we used *G. bulloides*, total foraminifera (summer monsoon) and *Pulleniatina obliquiloculata* (winter) abundances. The comparisons between the summer monsoon upwelling proxy *G. bulloides*, total foraminifera (productivity), *P. obliquiloculata* (winter monsoon) and total pteropod abundance are shown in Fig. 6. *G. bulloides* is an important upwelling indicator, ranging from 1.5 to 22.5% in all of the cores (Fig. 6). Its increased abundance is observed in the last glacial to

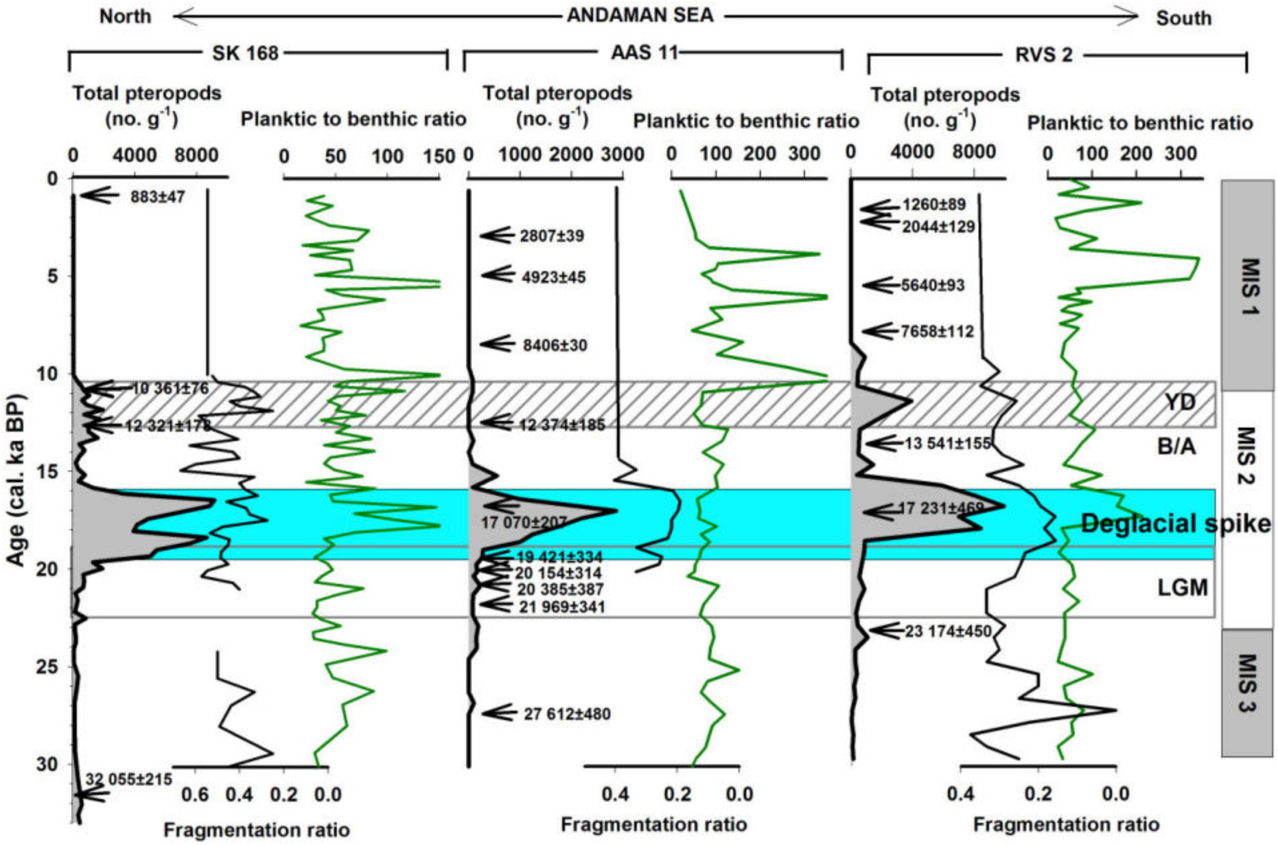

Fig. 4. Proxies for aragonite dissolution (pteropod fragmentation ratio) and carbonate dissolution (ratio of planktic to benthic foraminifera) in all three cores from the Andaman Sea with respect to deglacial spike and climatic events such as Younger Dryas (YD), Bølling/Allerød (B/A) and Last Glacial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

interglacial transition whereas its minimum abundance occurred during the LGM and deglacial pteropod preservation spike. Total planktic foraminifera abundance significantly increased during the last glacial to interglacial transition and decreased during the deglacial pteropod spike (Fig. 6). Increases in the abundance of *P. obliquiloculata* are seen during the deglacial spike and YD. Late Quaternary pteropod preservation records of the northern Indian Ocean were compared with CO_2 record from the Vostok Ice Core (Fig. 7A–I). All of the available records show good preservation during the deglacial (corresponding to Heinrich Event 1) and YD, and poor preservation during the Holocene (Fig. 7). The preservation spike of the Andaman Sea matches the record for the Arabian Sea (Tables 2 and 3).

Discussion

Poor pteropod preservation periods in the Andaman Sea

The most prominent period of poor preservation/absence of pteropods is during the Holocene. The poor preservation or absence of pteropods began between 10 cal. ka BP (SK 168 and AAS 11) and 9 cal. ka BP (RVS 2). The poor preservation/absence of pteropods from the 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 and references therein). The CO_2 concentration in the surface waters has sharply increased from the early Holocene onwards (Barnola *et al.* 2003), which is in close agreement with the absence of pteropods in the sediments (Fig. 7A). This study shows that there is a sharp rise in the ACD from the early Holocene to the present and core locations may have remained below the ACD. The increased concentration of atmospheric CO_2 during the Holocene resulted in ocean acidification and affected pteropod preservation (Fig. 7A) by reducing the saturation levels of the ACD of the oceans (Kleypas *et al.* 1999; Feely *et al.* 2004). The climate changes caused by global warming play a prominent role in the dissolution of carbonate.

The second important period of poor preservation of pteropods is seen during the Bølling/Allerød (B/A), in which preservation is very low in comparison with the

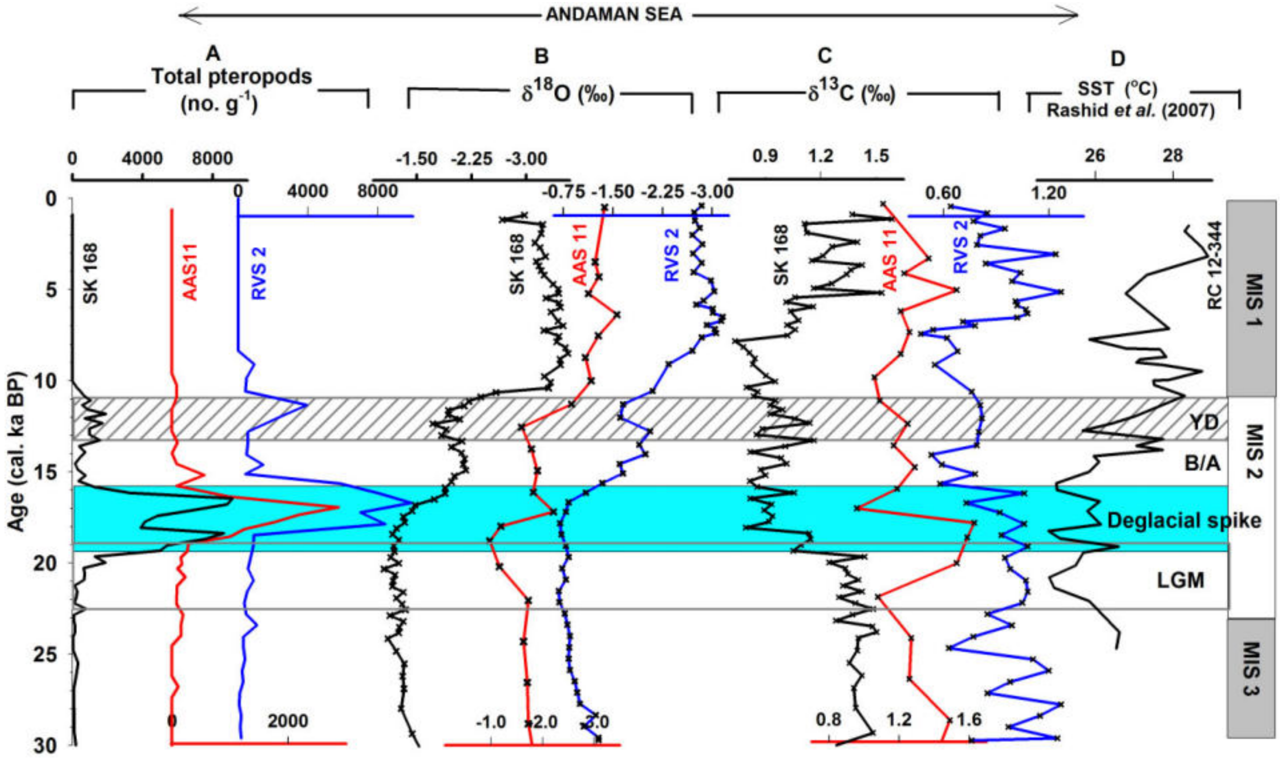

Fig. 5. Comparison of deglacial pteropod spike with oxygen and carbon isotope records from the Andaman Sea. A. Total pteropod records of cores SK 168 (Sijinkumar *et al*. 2010), AAS 11 and RVS 2. B. Oxygen isotope record of the three cores C. Carbon isotope record of the three cores. D. Sea surface temperature record of the Andaman Sea (Rashid *et al*. 2007). This figure is available in colour at http://www.boreas.dk.

preceding deglacial and following YD (Fig. 4). The poor level of preservation during the B/A coincides with a 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 the early B/A, which affected pteropod preservation by high biological productivity. Increase in the concentration of dissolved inorganic carbon by high input and remineralization of organic matter resulted in the lowering of pH (Millero *et al*. 1998). It is also reported from the Andaman Sea that during the B/A and Holocene, the summer monsoon was stronger (Rashid *et al*. 2007) whereas the winter monsoon was 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 stratigraphical correlation and also for understanding the driving mechanism behind the spike (Berger 1977). Earlier studies from the Pacific revealed that the preservation spike is centred at 13.5 ka BP, whereas in the western equatorial Pacific, it is centred at 14 ka BP (Berger & Killingley 1977). In the Gulf of Mexico, a high abundance/preservation of pteropods is encountered at 15 to 12.5 ka BP. However, in the Equatorial Atlantic, it is centred between 13.5 and 14 ka BP (Wiseman 1965). Preservation spikes during the deglacial period have also been observed off the coast of Morocco (Diester-Haass *et al*. 1973) and in the South China Sea (Wang *et al*. 1997).

Pteropod preservation spikes from the Andaman Sea and other late Quaternary records for 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 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, whereas the exact timing of the 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 centred 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 the Pakistan coast (Klöcker & Henrich 2006; Fig. 7G). A preservation spike is observed between 18.8 and 14 cal. ka BP in the Gulf of Aden (Fig. 7F) (Almogi-Labin *et al*. 2000) and between 17 and 13 cal.

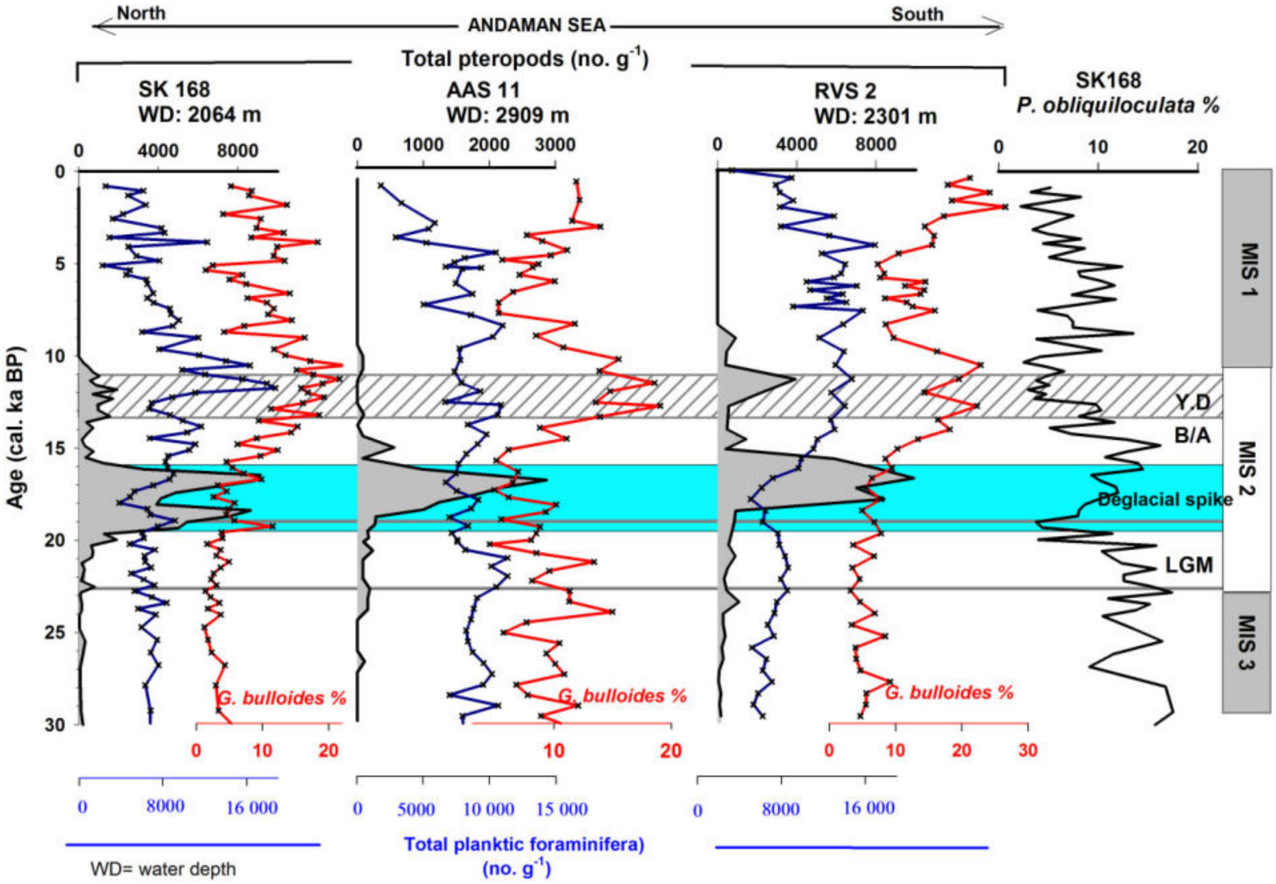

Fig. 6. Pteropod spike versus monsoon proxies (summer – *Globigerina bulloides* %; Sijinkumar *et al.* 2010 and total planktic foraminifera) records in cores SK 168, AAS 11 and RVS 2 and *Pulleniatina obliquiloculata* of core SK 168 (winter – Sijinkumar *et al.* 2011) from the Andaman Sea. This figure is available in colour at http://www.boreas.dk.

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 levels of preservation between 18 and 14.4 ka BP (Fig. 7I;Böning & Bard 2009). Overall, in the Indian Ocean, the maximum duration of this preservation event is seen in the cores from the Arabian Sea taken from intermediate water depths (~1600 m depth), whereas the pteropod preservation event based on shallower cores (573, 828 and 840 m) has a shorter duration. For the Andaman Sea, cores recovered from deeper water depths (~2000, 2300 and 2900 m) show an even shorter duration. The Andaman Sea records apparently represent the deepest records so far of this event. This indicates that the preservation is to a large degree a phenomenon of intermediate water depths.

Based on the available data from the Pacific and Atlantic, Berger (1977) suggested that the pteropod spike had its maximum abundance at about 14 cal. ka BP. The observed lag in the occurrence of the 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 are often inferred from the presence/absence of pteropods. Based on the preservation record of pteropods from the Andaman Sea, it is inferred that the ACD was probably deepest (>2900 m) at 16.5 cal. ka BP, which then shoaled over a brief period during the B/A and then deepened again during the YD. According to Berger (1977) the depth of the 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 indicate the presence of well-resolved preservation spike with their maxima at 16.5 cal. ka BP (Fig. 7B–I), which in turn act as useful stratigraphic marker in the Andaman Sea.

What drove the pteropod preservation spike in the Andaman Sea?

The pteropod preservation spike in the deglacial period has been attributed to various controlling factors. According to Weyl (1968), the preservation spike is the result of deepening of the ACD driven by the increase in temperature of deep ocean waters during the deglacial

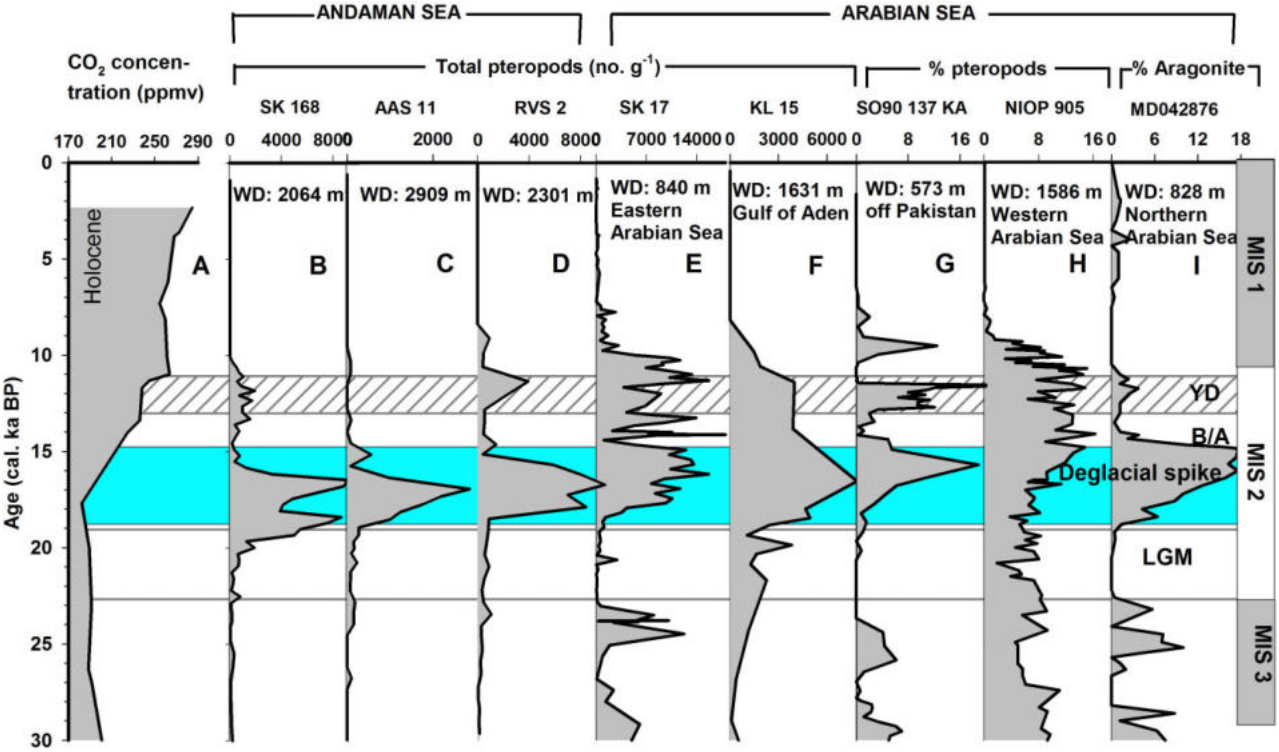

Fig. 7. Ice-core CO_2 concentration record versus deglacial pteropod preservation spikes in the Northern Indian Ocean. A. Atmospheric CO_2 concentration (record from the Vostok Ice Core; Barnola *et al.* 2003). B. Total pteropod abundance in SK 168 (Sijinkumar *et al.* 2010). C. Total pteropod abundance 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 pteropod abundance in core KL 15 from the Gulf of Aden (Almogi-Labin *et al.* 2000). G. Pteropod % in SO 90/137 KA, off Pakistan (Klöcker & Henrich 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). WD = water depth. This figure is available in colour at http://www.boreas.dk.

period. This is further substantiated by evidence from the Atlantic Ocean (Streeter 1973; Duplessy *et al.* 1975). However, in the Andaman Sea, the sea surface temperature was relatively low (26°C), contradicting the view of warming of seawater during the deglacial period (Fig. 5D). Diester-Haass & Van der Spoel (1978) were of the opinion that the preservation spike was driven by red tide-induced mass mortality, whereas Shackleton (1977)

Table 2. Timing of the preservation spikes 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 pteropod preservation (age in cal. ka BP)	References
1	SK 168 Northern Andaman Sea	15.5–18.5	16.5	Sijinkumar *et al.* (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 *et al.* (2006)
5	KL 15 Gulf of Aden	19.0–14.0	17.0	Almogi-Labin *et al.* (2000)
6	SO90 137 KA Off Pakistan	18.0–14.0	16.0	Klöcker & Henrich (2006)
7	NIOP 905 Western Arabian Sea	19.0–14.0	15.0	Klöcker *et al.* (2006)
8	MD042876 Northern Arabian Sea	19.0–14.0	16.0	Böning & Bard (2009)

Table 3. Total pteropod numbers in 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		

attributed it to rapid growth of the biosphere during deglaciation leading to the increased uptake of atmospheric CO_2 and to carbonate preservation. Worthington (1968) proposed that low salinity meltwater during the deglaciation acted as a lid, leading to stagnant bottom waters and therefore affecting carbonate preservation. This may not be the case in the Andaman Sea, as salinity was higher during the deglacial period by 1 psu more 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 to account for the better preservation. However, no considerable change in sedimentation rate during the deglacial was noticed in the Andaman Sea (Fig. 2). The pteropod preservation spike in the Atlantic Ocean has also been interpreted as the combined effect of climatically induced non-dissolution and hydrothermally induced preservation (Melkert *et al.* 1992).

The *G. ruber* $\delta^{13}C$ record in the Andaman Sea showed a rapid change in the chemistry of ocean water corresponding to the deglacial preservation spike. The *G. ruber* $\delta^{13}C$ record shows significantly enhanced nutrient generation during deglacial times beginning from 18 cal. ka BP to the early Holocene, which corresponds with good pteropod preservation levels. Older waters that have long been isolated from the atmosphere have lower $\delta^{13}C$ levels because of organic matter oxidation. The depleted $\delta^{13}C$ values during the deglaciation correlate with the increased abundance of pteropods, suggesting enhanced ventilation and nutrient-rich surface water driven by the enhanced winter monsoon in the Andaman Sea. During the last glaciations, the supply of ^{12}C-rich deep water was reduced because of weak upwelling and weakening of the summer monsoon, which led to enriched $\delta^{13}C$ values during the LGM. The changes in intermediate to deep-water circulation during the last glacial to the early Holocene had a significant role in pteropod preservation in the Indian Ocean. In the Andaman Sea, the Antarctic Intermediate Water enters through the shallow sills connected with the Bay of Bengal which is a mixture of overlying watermass containing Subantarctic Mode Antarctic Intermediate Waters, high saline waters of Persian and Red Sea and the underlying North Atlantic Deep Water (Naqvi *et al.* 1994). These water-masses may have profoundly influenced pteropod preservation during the last glacial to deglacial. The high level of aragonite preservation in the Arabian Sea during the glacial has been attributed to enhanced ventilation and a strengthened influx of intermediate water from Antarctica and weakening of the oxygen minimum zone (Böning & Bard 2009). These intermediate 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 a low supply of O_2 combined with elevated O_2 demand controlled by monsoon-related productivity (Böning & Bard 2009).

In addition to circulation and ventilation changes during the deglacial period, another possible factor controlling pteropod preservation spikes may be the changing intensity of monsoons in the region. The high abundance and good preservation of pteropods during the deglacial is associated with lower abundances of *G. bulloides* and total foraminifera (Fig. 5), suggesting that pteropod preservation is strongly influenced by the strength of the summer monsoon in the Andaman Sea. Upwelling and the 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 the summer monsoon was stronger during the B/A, last glacial to Holocene transition and early Holocene, and was weaker during the late glacial (see also Rashid *et al.* 2007). By contrast, the high abundance of *P. obliquiloculata* during the LGM and the deglacial spike suggests an enhanced winter monsoon. In the Andaman Sea, the abundance of this species has varied with changes in the winter monsoon and thermocline depth (Sijinkumar *et al.* 2011). Increased *P. obliquiloculata* abundances also coincide with increased nutrient generation (shown by the *G. ruber* $\delta^{13}C$ record), which in turn corresponds to the preservation spike. This increased nutrient generation is not reflected in the abundance of *G. bulloides* as this is an established summer upwelling species. Hence, the abundance of *P. obliquiloculata* is potentially related to winter monsoon changes. Enhanced winter monsoon strength relative to the summer monsoon during the LGM to the deglacial has been reported from the northern Indian Ocean (Duplessy 1982; Sarkar *et al.* 1990). Increased winter monsoon activity during the LGM probably caused deeper convective winter mixing; ventilation of the oxygen minimum zone, deepening of the ACD and reduced atmospheric CO_2, which in turn improved the aragonite preservation potential in the region. The present study clearly suggests that the global nature of the deglacial pteropod preservation spike has been controlled by different mechanisms such as intermediate water circulation, changes in monsoon-induced seawater chemistry, and global lowering of atmospheric CO_2 and the resultant increase in the alkalinity of seawater. As far as the Indian Ocean is concerned, the dominant factors are changes in intermediate water circulation and in the chemistry of seawater driven by the monsoon climate.

Conclusions

It is inferred from the present study that the pteropod preservation records from the Andaman Sea have shown significant variation from the last glacial to the Holocene, with a prominent deglacial preservation spike centred at ~16.5 cal. ka BP. Observations of pteropod preservation/abundance from the Indian Ocean show that the total absence of pteropods during the 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 part of the present interglacial period. The increased concentration in atmospheric CO_2 during the Holocene has also contributed to the poor preservation via the acidification of ocean water and resultant reduction in the saturation state of the oceans with respect to calcium carbonate. The poor preservation during the B/A was the result of enhanced upwelling and resulting high biological productivity because of strong summer monsoons. The deglacial pteropod spike is characterized by a very high abundance/preservation of pteropods between ~19 and 15 cal. ka BP, associated with very low atmospheric CO_2 concentrations. The time period of the preservation spike in the Indian Ocean is consistent between 19 and 13 cal. ka BP. Isotope data suggest a 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 occurrence of a weaker summer monsoon and reduced foraminiferal productivity in the region. Two possible factors responsible for the deglacial pteropod preservation spike are changes in intermediate water circulation and the chemistry of seawater driven by the monsoon climate. The synchronous regional occurrence of the pteropod preservation spike in the Andaman Sea as well as in the northwestern Indian Ocean could potentially be employed as a stratigraphic marker.

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