

## A review of the studies on pteropods from the northern Indian Ocean region with a report on the pteropods of Irrawaddy continental shelf off Myanmar (Burma)

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Ever since the Challenger Expedition the Indian Ocean pteropods have been recognized as important constituents of biogenic flux. Initially they were of interest only to biologists or the fishery departments and their distribution was studied only in plankton tow samples. Over the past three decades micropalaeontologists have paid attention to investigate pteropods from water and sediment samples to understand their distribution and ecological significance. Since then substantial work has been reported in the Gulf of Aqaba, Red Sea, northern Arabian Sea, along west coast of India and around the Andaman Nicobar Archipelago. Work has neither been attempted in the Bay of Bengal nor in the northern Andaman Sea. These aragonitic microfossils have proved to be reliable indicators of bathymetry, productivity, upwelling, current circulation, intensity of Aragonite Compensation Depths, Oxygen Minimum Zone and monsoons, thus very useful in palaeoclimatic reconstructions. Works on its counterparts such as foraminifers and ostracods have been reviewed earlier and this is the first time a review of the pteropod studies in the northern Indian Ocean is being attempted, in view of the vast data generated in this region. The pteropod assemblages from two cores collected on the Irrawaddy continental shelf, in the northern Andaman Sea is also reported for the first time. The downcore distribution of pteropods suggests that no significant sea level change has occurred over the past ~1280 Cal yrs.

**[Key words:** Pteropods, Indian Ocean, aragonite compensation depth, oxygen minimum zone, Irrawaddy continental shelf, Myanmar, Burma]

### Introduction

Commonly known as 'sea-butterflies', pteropods are planktonic gastropods, adapted to pelagic life. During their lifetime they constitute significantly to the zooplankton population and upon death their shells sink to the ocean bed. Empty aragonitic shells of pteropods constitute a major portion of shallow marine sediments, especially in the tropical-subtropical regions<sup>1</sup>. Though a major group of marine microfossils, they have received very less attention from micropalaeontologists and palaeoclimatologists till early '70s, as compared to their calcareous counterparts, such as foraminifers, ostracods or coccolithophores. The fact that their exoskeleton is made of aragonite, a less stable form of calcium

carbonate led to the belief that they have restricted spatial-temporal distribution / preservation.

Van Straaten<sup>2</sup> had demonstrated that speciation in pteropods was a function of depth and especially at depths shallower than 400 m, considerable differences of species composition in the sediment occur, compared with deeper samples. The abundance of pteropods within different water masses is controlled by specific physico-chemical properties and by the adaptive potential of the individual species. In different water masses different forms (or even subspecies<sup>3</sup>) of a certain species may develop. In regions where these water masses mix, populations may interbreed. The recognition of forms, clines and inter-breeding represents one of the important developments in recent biogeographical studies, as they have been proved to be valuable ecological indicators<sup>4-7</sup>. These developments in biogeography make pteropods an exceptionally interesting group in paleoenvironmental reconstructions<sup>8-12</sup>.

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The dissolution of carbonate particles in shallow sediments has been known for many years, but has not been widely recognized as significant to the global carbonate budget. Recent evidence, however, has suggested that the majority of the open ocean carbonate exported from the surface layer is remineralized in the upper 500–1000 m, well above the calcite lysocline<sup>13</sup>. Sabine *et al.*<sup>14</sup>, suggest that significant dissolution of carbonate occurs in the water column well above the carbonate lysocline, suggesting that aragonite is a major component of the total Dissolved Inorganic Carbon (DIC) in the oceans. Though pteropods are the main contributors to pelagic aragonite, the pteropod component is often being neglected while estimating the carbonate budget<sup>15</sup>. In such a scenario, an understanding of the pteropod distribution and preservation significantly contributes to our knowledge about the carbon cycling within the oceans.

Pteropods largely behave like planktonic foraminifera, though they are known to occur abundantly in near shore shallow water regions where the latter could be absent/low in numbers. Due to their relatively large size (1–30 mm), the settling velocities of dead pteropods are much greater than those of other pelagic organisms<sup>16</sup> and, therefore, deposition close to their habitat is expected<sup>17</sup>. Pteropods due to their aragonitic tests do have limited preservation

potential. However, this varying degree of preservation (discussed later) has been used as an indicator of past productivity, Oxygen Minimum Zone (OMZ), and variations in the Aragonite Compensation Depth (ACD) and thus proved to be very good palaeoclimatic indicators during the Quaternary<sup>18–23</sup>.

Broadened perceptions about this group of microfossils have generated quite a few data sets and palaeoclimatic interpretations from the Indian waters too, though lacks widespread awareness. Unlike number of reviews on other groups like foraminifera<sup>24–26</sup>, no significant attempt has been made to review the status of pteropods from the northern Indian Ocean region (Fig. 1), with an objective to track the varying trends in their applicability over time, identify data gaps and propose future prospects in this discipline.

#### Early pteropod studies in the Indian Ocean

Plankton tows and sediment samples collected during the historical oceanographic expeditions way back in the 18<sup>th</sup> century, gave a new insight towards pteropods as a significant biogenic flux contributing to marine sediments. This is when the first descriptions of pteropod distributions in the Indian Ocean were made<sup>27–34</sup>. Berner<sup>35</sup> prepared a global map for the distribution of pteropod ooze, based on

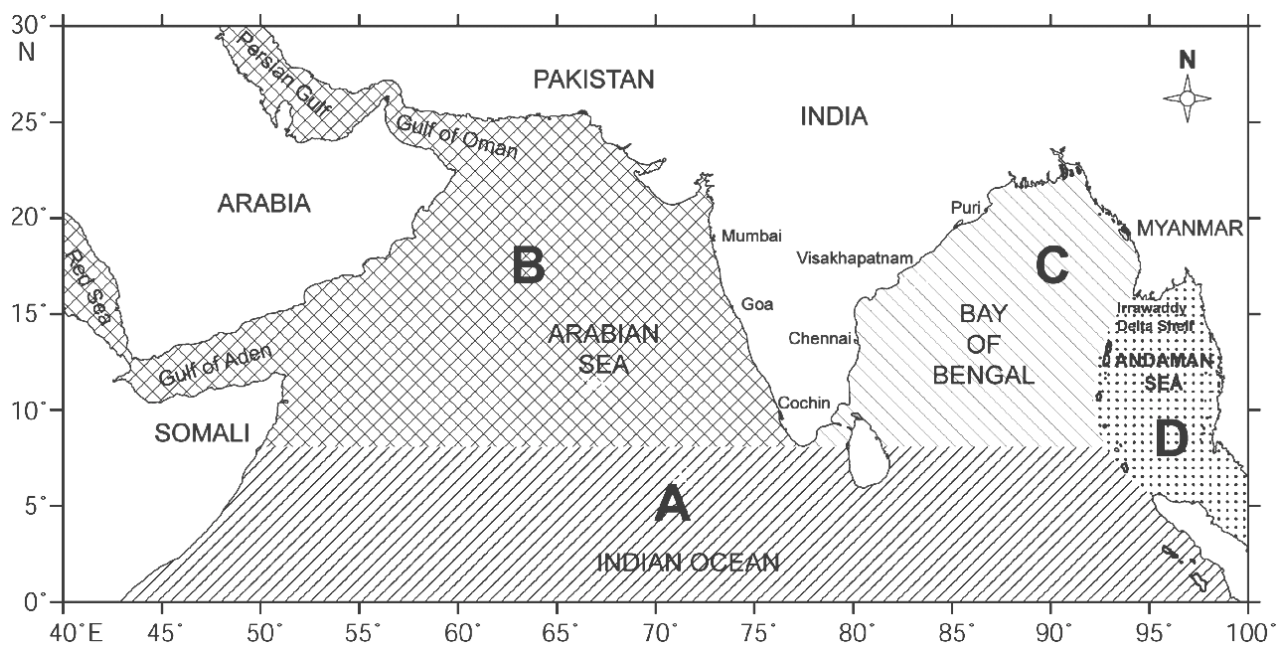


Fig. 1—Map of the study area. The shaded portion represents the regions from where pteropod studies have been carried out and reviewed under this study. Studies from area A have been tabulated in Table 1; from area B in Table 2, from area C in table 3 and area D in Table 4.

sediment distribution data generated before<sup>36-38</sup>. In the Indian Ocean he identified only 4 regions showing accumulation of pteropod ooze on the sea floor viz. (1) northern Arabian Sea near the mouth of the Persian Gulf, (2) southwest of the southern tip of India centered on 75°E, (3) along the eastern coast of Tanzania, and (4) northeast of the northern tip of Madagascar (Seychelles plateau).

#### **Pteropod studies based on plankton tow samples**

Pteropods were initially studied by biologists either as a measure to estimate biological productivity or as food for fish. Most of the studies in the Bay of Bengal were done with an objective to understand pteropod distribution with applications in the fishery industry. The Central Marine Fisheries Research Station, 1950 onwards, initiated research on food for fisheries in the Gulf of Mannar, as a part of which they generated extensive data on distribution of pteropods (all references are covered in Table 3). Using plankton tow samples, Sakthivel<sup>39</sup> studied the distribution of pteropods right from the coasts of Saudi Arabia to those of Java<sup>40,41</sup>, described seasonal variations of different species in the Indian Ocean<sup>39,42,43</sup> as well as used their spatial distribution and a marker of the latitudinal biogeographical boundary within the Arabian Sea<sup>43</sup>. Sakthivel<sup>41</sup> observed a swarm of *Cavolina uncinata pulsata*, an oceanic species indicative of the Bay of Bengal water mass in the inshore waters off Cochin in the Arabian Sea. He interpreted this phenomenon as an indicator of mixing of oceanic waters with coastal waters during the reversal of monsoon currents. Pillai<sup>44</sup> observed regular peaked abundances of a single species *Creseis acicula* in the Arabian Sea associated with low temperatures and dissolved oxygen indicating the presence of nutrient rich up-welled waters. Auras-Schudnagies<sup>45</sup> pumped the top 5m of the water column day and night, and filtered such surface water samples through the plankton net to study their distribution patterns in relation to monsoonal regimes and other ecological parameters in the northern Red Sea. Based on these studies in the northern, central and southern Red Sea, Gulf of Suez, Gulf of Aden, Strait of Bab el Mandeb and Western Arabian Sea, it was observed that the relative abundances of pteropod species was closely related to different water masses. They stated that migration of the highest abundances can be used to describe trends in the changing surface currents with time. The high total abundances of *Limacina inflata*, *Creseis acicula* and *Creseis virgula* measured in

surface waters of the Red Sea were taken as an indicator of summer upwelling. These signatures coincided with peaked abundances of foraminifer *Globigerina bulloides* in the surface sediments.

#### **Studies based on pteropods recovered from marine sediments**

Studies from the Indian Ocean reveal that most of the fossil studies have been from the Arabian Sea and around the Andaman Sea within the EEZ of India, i.e. around the Andaman Nicobar group of Islands (Tables 1-4). This could be attributed, to some extent, to the fact that according to the global pteropod distribution map prepared by Berner<sup>35</sup>, marine sediments in the Bay of Bengal were believed to be devoid of pteropods. Pati<sup>46</sup> recorded that no pteropods occurred in coastal waters off Balasore, off east coast of India while sediment trap studies reveal that <5% of the flux comprises pteropods<sup>47</sup>. Over the past two decades, the Marine Wing of the GSI (Geological Survey of India, Calcutta) has generated a wealth of information on pteropods through the examination of sea bed samples collected in the Andaman Sea within the EEZ of India most of which has been published as their official records. Pteropod distributions have been described from many regions around the Andaman Nicobar group of Islands (Table 4). However Saha *et al.*<sup>48</sup> attempted to correlate variation in their distribution based on the difference in physiographic domains of the Andaman Sea. Bhattacharjee & Mallik<sup>19</sup> reported a total of 20 species from the Carlsberg Ridge. The assemblage indicative of warm tropical environment associated with the well-known centre for winnowing action. A characteristic assemblage suggestive of a similarity with the upwelling off Somali coast was also identified. Pteropods were found at depths greater than the proposed ACD for the region. Most of the well-preserved tests were brown to dark brown in colour imparted due to Fe-Mn coating, suggesting possible hydrothermal activity in the region. Bhattacharjee<sup>49</sup> identified a variation in the Pteropod Preservation Profiles in the seabed sediments in response to the craggy volcanic arc domain around Barren Island and Middle Andaman Island. He correlated these variations to the nature of sediments, quantity of pyroclastic material and physiographic configuration in the region.

#### **Major applications attempted in the Indian waters:**

##### *Bathymetry*

Based on their habit pteropods may be classified<sup>33,50,51</sup> as epipelagic (*Creseis acicula*, *Creseis virgula conica* – most abundant in the first 100 m in

Table 1—Pteropod studies in the Indian Ocean

Region	Author & Year	Description
1 Indian Ocean	Pelssner <sup>30</sup>	Challenger Expedition
2 Indian Ocean	Meisenheimer <sup>29</sup>	Valdia Expedition
3 Indian Ocean	Stubbings <sup>31</sup>	John-Murray Expedition
4 Tropical Indo-Pacific Ocean	Tesch <sup>33,34</sup>	Dana Expedition
5 Indian Ocean	Taki & Okutani <sup>32</sup>	Umitaka Maru Expedition
6 Indian Ocean	Frontier <sup>1</sup>	Studied the occurrence and distribution of <i>Creseis chertchiae</i> in the Indian Ocean
7 Northern Indian Ocean	Sakthivel <sup>39</sup>	Distribution and relative abundance on the <i>Euthecosomata</i> with a note on the seasonal variation of <i>Limacina</i> species in the Indian Ocean
8 Indian Ocean	Sakthivel <sup>40</sup>	Reported peaked abundances of the neretic species <i>C. acicula</i> in the regions off Somalia, Saudi Arabia, west coast of India and Java.
9 Indian Ocean	Sakthivel <sup>42</sup>	Studied the occurrence and distribution of <i>Limacina inflata</i> in the Indian Ocean.
10 Indian Ocean	Sakthivel <sup>43</sup>	Studied the distribution of <i>Styliola subula</i> in the Indian Ocean and reported its absence from the modern Northern Arabian Sea, marking a latitudinal biogeographical boundary.
11 Indian Ocean	Berner <sup>35</sup>	Prepared a global map for the distribution of pteropod ooze.

Table 2—Previous studies in the Arabian Sea and adjoining water masses

Region	Author & Year	Description
1 Persian Gulf and Gulf of Aden	Frontier <sup>28</sup>	Dealt with the systematics and classification of pteropods
2 Off Bombay	Pillai <sup>44</sup>	Studied plankton off Bombay to understand hydrographic conditions. Single species <i>Creseis acicula</i> represented the pteropoda group which peaked in October associated with low temperatures and dissolved oxygen indicating presence of nutrient rich up-welled waters.
3 Arabian Sea, Indian Ocean shelf off the West Coast of India	Hermann & Rosenberg <sup>17</sup>	Reported 9 species from 10 sediment samples collected within a depth range of 40-310m.
4 Inshore waters off Cochin	Sakthivel <sup>41</sup>	Observed a swarm of <i>Cavolina uncinata</i> pulsata, an oceanic species indicator of the Bay of Bengal water mass.
5 Off Cochin	Sakthivel & Haridas <sup>70</sup>	Swarm of <i>Creseis acicula</i> Rang accompanied with a 40 mile stretch of <i>Trichodesmium</i> bloom and cladoceran <i>Penilia avirostris</i> . 80% of the haul done using a zooplankton net at a depth of 22m, comprised of <i>C. acicula</i> alone.
6 Off Karnataka	Hashimi & Nair <sup>52</sup>	Observed that pteropods are absent in the inner shelf and abundant amongst the carbonate components in the outer shelf beyond 50m depth
7 Gulf of Aqaba and northernmost Red Sea	Almogi-Labin <sup>55</sup>	Used deep sea records to study the stratigraphic and palaeo-oceanographic significance of the Late Quaternary pteropods

Contd. ....

Table 2—Contd.

Region	Author & Year	Description
8 Gulf of Aqaba and Red Sea	Almogi-Labin <sup>54</sup>	Studied the population dynamics of pteropods and planktonic foraminifera
9 Red Sea & Gulf of Aden	Ivanova <sup>56</sup>	Identified 20 species of pteropods and used them in combination with Planktonic foraminiferal assemblages to reconstruct the late Quaternary biostratigraphy and palaeotemperatures, especially those at the Last Glacial Maxima.
10 Northern Red Sea	Almogi-Labin <sup>8</sup>	Studied the abundance and mode of preservation of pteropods in a core and compared it with the oxygen stable isotopic variations as derived from foraminifera. Reconstructed the carbonate preservation over the past 380,000 years.
11 Red Sea and adjacent areas	Auras-Schudnagies <i>et al.</i> <sup>45</sup>	Studied the distributional pattern of pteropods in surface waters and core top sediments to assess the control of monsoonal regimes and other factors
12 Central Red Sea	Almogi-Labin <sup>9</sup>	Palaeo-environmental events over the past 13,000 years
13 Off Goa	Goswami & Padmavati <sup>71</sup>	Studied the distribution and abundance of varied zooplankton groups up to a water depth of 50m. Pteropods were represented by <i>Creseis acicula</i> and <i>Cavolina Spp.</i> Observed that swarming of <i>C. acicula</i> was a regular phenomenon every October as observed from 1976 to 1980.
14 Shelf off Northern Kerala, Arabian Sea	Singh & Rajaram <sup>59</sup>	Studied the distribution of pteropods in surface sediments from the continental shelf off Kerala. He reported 9 species identifying distinct assemblages for the inner and outer shelf.
15 Pakistan Margin	M. den Dulk <i>et al.</i> <sup>61</sup>	Used the degree of preservation of pteropods as an indicator of past ACD, OMZ, and productivity.
16 Shelf off Northern Kerala, Arabian Sea	Singh <sup>20</sup>	Correlated degree of preservation of pteropods to upwelling and monsoon assess intensities
17 Off Kerala Coast, Arabian Sea	Singh <i>et al.</i> <sup>53</sup>	Palaeobathymetry based on the quantitative analysis of pteropod assemblage in 13 surface samples.
18 Pakistan Continental slope	von Rad <sup>62</sup>	Used the preservation of pteropods as an indicator of re fluctuating ACD and OMZ weakening or breakdown
19 Eastern Arabian Sea, off Central West Coast of India	Singh <i>et al.</i> <sup>68</sup>	Attributed occurrence of pteropods below ACD to turbidity flow deposits and neotectonism.
20 Arabian Sea, Off North Kerala Coast	A.D. Singh <i>et al.</i> <sup>57</sup>	Reported a total of 13 pteropod species and used their down-core variations to decipher major sea-level oscillations over the past 36,000 years in the study area
21 Central West Coast of India, Eastern Arabian Sea	Bhat & Gangadharan <sup>66</sup>	Evaluated the surface palaeoproductivity based on the planktonic assemblage preserved in sediments.
22 Entire Western continental shelf of India	Singh <i>et al.</i> <sup>22</sup>	Mapped the distribution of eight species and correlated them with the bathymetry, hydrography and ACD in the region.
23 Off Goa, Eastern Arabian Sea	Singh <i>et al.</i> <sup>23</sup>	Studied the variability in productivity and intensity of OMZ along the Central West Coast of India over the past 30,000 years.
24 Western Arabian Sea	Mohan <i>et al.</i> <sup>69</sup>	Recorded 9 species sediment trap samples collected over January to September 1992.
25 Pakistan shelf and upper continental margin	Klöcker & Henrich <sup>67</sup>	Analysed pteropods from 15 surface sediments to study palaeoenvironmental changes over the past 30,000 years.
26 Off Goa, Eastern Arabian Sea	Singh <sup>21</sup>	Palaeoenvironmental changes during the Last Glacial – Holocene.

Table 3—Previous pteropod studies in the Bay of Bengal (Note that all studies are only based on plankton tows)

Region	Author & Year	Description
1 Off Madras, Bay of Bengal	Aiyer <i>et al.</i> <sup>72</sup> , Mukundan <sup>75</sup>	Generated plankton records for the years 1929-1930 and observed swarms of <i>Cresets acicula</i> Rang
2 Trivandrum, Bay of Bengal	Menon <sup>74</sup>	Observed swarms of <i>Cresets acicula</i> Rang
3 Kruvadai Island, Bay of Bengal	Chacko <sup>73,76</sup>	Reported 4 species from the waters around the coral island, <i>Cresets acicula</i> , <i>Spiratella inflata</i> (d'Orbigny), <i>S. trochiformis</i> and <i>S. bulimoides</i> . <i>C. acicula</i> was common all throughout the year with swarms in March and least abundance in January
4 Mandapam, Bay of Bengal	Prasad <sup>77</sup>	1950 onwards started study of plankton in the inshore waters in the Gulf of Mannar, as a part of the research on food for fishes initiated by the Central Marine Fisheries Research Station. They observed swarms of <i>Cresets acicula</i> and reported it to be the most common species.
5 Porto Novo, Bay of Bengal	Krishnamurthy <sup>78</sup>	Observed seasonal variation in plankton distribution at two stations, one at the mouth of the Vellar Estuary and the other at the 10-fathom line. Occurrence of <i>C. acicula</i> was common at the estuarine station with peaked abundances soon after monsoon and <i>Carolinia uncinata</i> was rare. Conversely, at the other the former was rare, especially in summer and swarmed after the 1 <sup>st</sup> rains. <i>C. uncinata</i> was a common species at this station
6 Off Krishna Estuary, Bay of Bengal	Peter & Paalimose <sup>79</sup>	Reported swarms of <i>Cresets acicula</i> Rang with highest ever density (85%), suggesting that the region off Krishna estuary is probably the most productive in terms of zooplankton in the Bay of Bengal.
7 Eastern Bay of Bengal	Nair <i>et al.</i> <sup>80</sup>	Zooplankton distribution

Table 4—Previous pteropod studies in the Andaman Sea (Note that all the studies are concentrated in the EEZ of India, around the Andaman Nicobar Archipelago)

Region	Author & Year	Description
1 Around Tillachang Island, Andaman Sea	Bandopadhyay <i>et al.</i> <sup>81</sup>	Spatial distribution of pteropods
2 Around Narcondam Island, Andaman Sea	Saha, <i>et al.</i> <sup>84</sup>	Observed a pteropod preservation spike at 90-100 cm below the surface in deep sea sediments, an event which was later dated to 13,000 years.
3 Around Narcondam Island, Andaman Sea	Bhattacharjee <sup>80</sup>	Late Quaternary palaeoceanographic significance
4 Different physiographic domains of Andaman Sea	Saha, <i>et al.</i> <sup>48</sup>	Occurrence of pteropods in different physiographic domains
5 Around Andaman-Nicobar archipelago, Andaman Sea	Bhattacharjee, 1997 <sup>85</sup>	Pteropod preservation spike
6 Around the Car Nicobar Island, Andaman Sea	Bhattacharjee, D. <i>et al.</i> <sup>65</sup>	Studied the pteropods in the surficial and sub-surficial Late Quaternary sediments to reveal that the ACD is actually deeper than the present depth.
8 Carlsberg Ridge, Andaman Sea	Bhattacharjee & Mallik <sup>19</sup>	Pteropods indicate hydrothermal activity in the region as well as deeper ACD than that reported before.
9 Andaman Sea within EEZ of India	Bhattacharjee & Bandopadhyay <sup>86</sup>	Difference in assemblage of the north and south Andaman Sea.
10 Middle Andaman Island, Andaman Sea	Bhattacharjee <sup>86</sup>	Varying Pteropod Preservation Profiles

the open ocean, commonly also known to inhabit shallow waters on the inner neretic zone), mesopelagic (*Limacina inflata*) and bathypelagic (*Limacina heli-coides*). Herman & Rosenberg<sup>17</sup> for the first time described the pteropod distribution from the Arabian Sea shelf based on 10 dredge samples. He demonstrated that species variation was depth dependent and that *Creseis* spp./*Limacina inflata* ratio was highly depth sensitive and emphasized on their potentiality at bathymetric indicators. In the carbonate sediments off Karnataka, Hashimi & Nair<sup>52</sup> noticed that pteropods are absent in the inner shelf and abundant in the outer shelf beyond a depth of 50 m. Singh *et al.*<sup>53</sup> noticed that *Limacina inflata*, *Creseis acicula*, *Creseis virgula* and *Creseis chierchiaie* are highly depth sensitive. They found that *Limacina inflata* (mesop-elagic)/*Creseis* spp. (epipelagic) were comparable with the results for bathymetry based on planktonic to benthic foraminiferal ratios in surficial sediments off the coast of Kerala. Thus they validated the earlier proposition<sup>17</sup>.

#### *Past sea level indicators*

While Chen<sup>11</sup> proposed that abundance of *Creseis acicula* indicated very low sea levels, high frequencies of this species in the northern Red Sea reveal that this pteropod species is the most resistant species to high salinities<sup>54</sup>. Thus high abundances of this species in sediments indicate periods with high evaporation rates in the Red Sea. Obviously this is the only species present during the Last Glacial Maxima, when inflow of low-saline waters was reduced due to the lowering of the sea level<sup>8,55,56</sup>. Singh *et al.*<sup>57</sup> used down-core variations in Pteropod/Planktonic and Planktic/Benthic ratios to decipher major sea-level oscillations over the past 36,000 years in the region off the northern coast of Kerala. They used their pteropod model<sup>53</sup> (discussed before) in demonstrating the sea-level history beyond the Last Glacial Maximum (LGM), suggesting that their pteropod model could be used to decipher sea level variations for periods longer than those indicated by foraminifera. Khadkikar & Rajshekhar<sup>58</sup> reported pteropods as a major constituent of the Holocene beach-rocks from the south Andaman Island.

#### *Upwelling, hydrography and currents*

On the basis of living populations and core assemblages of pteropods and oxygen isotopic measurements of pteropods and foraminifera, Almogi-Labin<sup>55</sup> derived a sequence of Late

Quaternary palaeo-oceanographic changes which were primarily influenced by productivity (in addition to temperature, salinity and depth). He noticed interglacial events characterized by oligotrophic assemblages, suggesting weekly stratified waters and higher productivity in the whole water column and vice-versa during the glacial times. Singh & Rajaram<sup>59</sup> compared the abundances of pteropods in surface sediments with the planktonic foraminiferal index for upwelling, *Globigerina bulloides* and observed that the abundances of certain pteropod species are affected by upwelling. Singh<sup>20,21</sup> correlated the variations in abundances with upwelling and monsoon intensities. On the basis of surface sediment samples collected in the continental shelf along the entire west coast of India, Singh *et al.*<sup>22</sup> mapped the distribution of eight species and correlated them with the bathymetry, hydrography and ACD in the region.

#### *Aragonite compensation depth and oxygen minima zone*

The nature of Aragonite Compensation Depth and its variation is directly reflected by the occurrence, abundance and degree of preservation within the sediments<sup>8,18,60</sup>. Almogi-Labin *et al.*<sup>8</sup> believed that the state of pteropod preservation indicated variations in carbonate chemistry of deep and interstitial waters that took place under different palaeo-oceanographic conditions. They compared downcore variation in pteropod preservation and the  $\delta^{18}\text{O}$  values in foraminiferal shells, thereby proposing a mechanism for aragonite dissolution and preservation as a result of changing  $\text{O}_2$  levels in deep waters. They also proposed that the state of aragonitic shell preservation depends on the degree of organic matter combustion in sediments. Preservation is good in sediments with low supply of organic matter and high oxygen concentrations and reduces with increased production of  $\text{CO}_2$  due to decomposition of organic matter. Five different signatures were identified to assign the degree of preservation of pteropods in a deep sea core collected from the Red Sea viz.: (i) transparent shells (excellent preservation), (ii) opaque white shells (well preserved, but transparency lost due to slight corrosion), (iii) Internal molds with remnants of original shell (extensive aragonite dissolution, shell destruction and fragmentation with traces of original structure), (iv) internal molds (entire original shell missing with 90% or more replaced by HMC i.e. High Magnesium Calcite), (v) Secondary aragonite overgrowth (original shell preserved with varying

degrees of overgrowth occurs from inner walls of the shell towards the centre of the inner space. The quality abundance of pteropods has been used as the Pteropod Preservation Index (PPI) an indicator of the fluctuating Aragonite Compensation Depth, Oxygen Minimum Zone and productivity along the Pakistan Margin<sup>61,62</sup> and along the southwest coast of India<sup>20</sup>. Bhattacharjee & Bandopadhyay<sup>63</sup> and Bhattacharjee<sup>49</sup> studied the distribution of pteropods within the entire Andaman Sea within the EEZ of India and reported a difference in the assemblage of the north and south. Based upon their degree of preservation they were able to demarcate the ACD of the two areas to 1150 and 1300 m respectively and attributed it to the influence of the Irrawaddy River. It was observed that the pteropod preservation was better in the anoxic northern bottom waters along the west coast of India in contrast to the poor preservation in well-oxygenated southern bottom waters<sup>22</sup>. The distribution of *Clio convexa* was noted to be significantly dependent on the variation in the intensity of OMZ along the western continental shelf<sup>61</sup>.

#### *Palaeoclimatic reconstructions*

Pteropod assemblages have been used in combination with planktonic foraminiferal assemblages to reconstruct the late Quaternary biostratigraphy and palaeotemperatures, especially those at the Last Glacial Maxima in the Red Sea and the Gulf of Aden<sup>9,55,56</sup>. Saha *et al.*<sup>64</sup> was the first one to observe a pteropod preservation spike in a deep sea sediment core collected near the Narcondam Islands, Andaman Sea, within the Indian waters at 90-100 cm below the surface in deep sea sediments, an event which was later dated to 13,000 y. BP. Bhattacharjee *et al.*<sup>65</sup> observed a similar event around Car Nicobar Islands and attributed both these features to reduced dissolution due to increased alkalinity, marking the beginning of deglaciation. In core sections representing 18,000 y. and 23,000 y. BP, Singh<sup>20</sup> observed that 90% of the specimens were transparent i.e. best preserved whereas the period between 15,000 and 17,000 BP is represented by maximum dissolution and corrosion. Preservation was found to be fairly good during Holocene. Singh *et al.*<sup>23</sup> reported pteropod rich layers wherein particularly those formed during cold events like the Heinrich events were bioturbated, indicating oxygenated bottom conditions. Bhat & Gangadharan<sup>66</sup> evaluated the surface palaeoproductivity based on the planktonic assemblage preserved in sediments. They delineated 4

episodes; two upwelling induced high productivity periods alternating with two low productivity phases. The top 20 cm showed depletion in pteropods marking the ACD along the Central West Coast of India. Pteropod maxima were also observed during the Heinrich events and the Younger Dryas in deep water cores collected off Goa correspond to organic carbon minima when the productivity was low, OMZ less intense and the ACD was deeper. Apparently pteropod preservation and thus representation of these events are synchronous in the Arabian Sea and the Atlantic<sup>23</sup>. Klöcker & Henrich<sup>67</sup> analysed 15 surface sediments of the Pakistan shelf and upper continental margin to assign the ACD at 250-400 m. In a sediment core accounting for 30,000 y. BP., bioturbated sequences representing Early Holocene and Younger Dryas, etc. show well to perfectly preserved pteropods and laminated sequences show only traces of them. The preservation indicates repetitive intermediate water formation in the Arabian Sea down to at least 600 m water depth in times of enhanced NE monsoons during stadials. Absence of pteropods in OMZ and laminated sediments suggests an intensified OMZ, weak NE-monsoon and shallow ACD.

#### *Turbidite deposits and neotectonism*

Singh *et al.*<sup>68</sup> reported pteropods from a depth of ~3.5 km., far below the ACD attributing their occurrence to turbidity flow transportation originating from shallow water provenances and subsequent large scale rapid burial by neo-tectonic activity. Similar observations have been made in the upper continental shelf of Pakistan<sup>67</sup>.

#### *Understanding modern processes using sediment trap samples*

Seasonal variation in the Pteropod abundances as recorded in the Western Arabian Sea revealed that they were comparable with other flux patterns such as planktonic foraminifera, and thus they could be used to reconstruct palaeoclimates of the recent past<sup>69</sup>. It was further observed that the species *Limacina inflata*, *Limacina trochiformis* and *Limacina bulimoides* can be used as reliable indicators of upwelling because they showed characteristics similar to those of the planktonic foraminifer *Globigerina bulloides*, which is an upwelling indicator. Based on sediment trap samples collected during the Bay of Bengal Process Studies (BOBPS)<sup>47</sup>, it was reported that large colonial radiolarians, pteropods, ostracods etc. constitute less than 5% of the total flux and were retained in the >1 mm fraction.



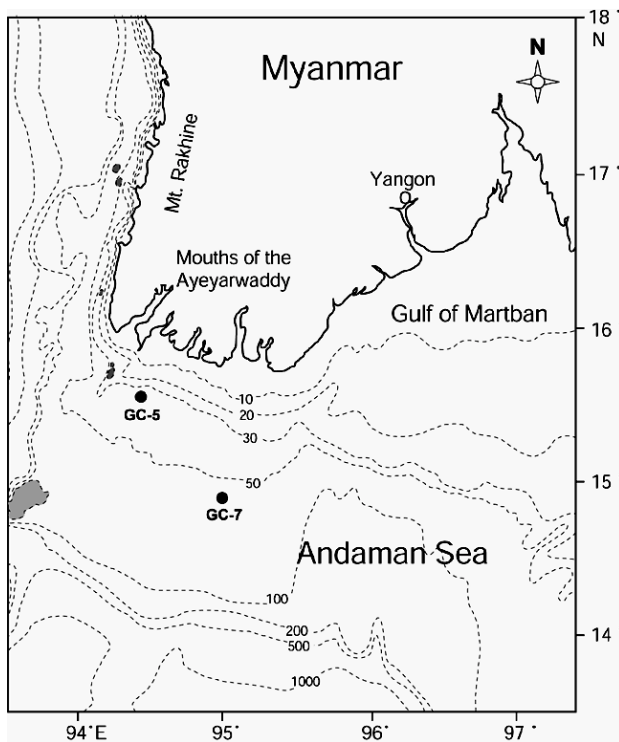


Fig. 2—Map of the Irrawaddy continental shelf showing the location of the two cores used to report pteropod assemblages in the present study.

Several other works done on the various applications demonstrated above have been quoted region-wise in Tables 2<sup>(70,71)</sup>, 3<sup>(72-80)</sup> and 4<sup>(81-83)</sup>.

#### A first report on the Myanmar (Burmese) pteropods

The Ministry of External Affairs, Government of India, initiated 'India-Myanmar Joint Oceanographic Studies' with active support from the Department of Ocean Development (DOD) and Council of Scientific and Industrial Research (CSIR), India. As part of the study, 126 surface sediment samples collected using a modified Peterson grab and 13 gravity cores ranging from a water depth of 10 to 1030 m, were collected on board *ORV Sagar Kanya* during April 2002, on the west coast of Myanmar and the northern Andaman Sea, specifically on the Irrawaddy continental shelf (Fig. 2). Two cores namely GC-5 (37 m water depth, length 1.76 m) and GC-7 (50 m water depth, length 2 m) were selected for down-core analysis of foraminiferal content. The two cores were sub-sampled (GC-5 at 2 cm intervals; GC-7- top 50 cm at 1 cm and remaining core at two cm interval). Approximately 10 g of sediment was washed over a 63  $\mu$ m sieve to obtain the sand fraction for micropalaeontological studies. A synoptic view of the sand fractions revealed that pteropods were the second most abundant group of

microfossils in the sediments on which we present a short first report from the Burmese waters. The taxonomy of euthecosomatous pteropods is well established<sup>84</sup> and therefore no reference list is presented.

The core collected at the shallower location, GC-5 was very low in carbonate content (5-20%). The sand fraction mainly comprised largely of coarse wood/vegetal matter and fine micaceous material. Pteropods were completely absent up to a depth of 80 cm after which the carbonate content also increases in the core. Pteropods appear and show rare occurrences within the profile between 80-110 cm and again at about 150-160 cm. The assemblage is represented by a single species *Creseis acicula* at this location, with a single broken shell of *Diacria quadridentata* observed at 80-82 cm depth. Quite a few specimens of *Creseis acicula* encountered within the interval 82-90 cm show transparent to smooth and shiny tests indicating very good preservation.

The scenario is completely opposite at the deeper location. More than 95% of the sand fraction throughout the length of the core comprises carbonate material, with pteropods shells and fragments varying between 5-30%. The abundance increases sharply at about 30 cm depth. The pteropod assemblage at this location comprises *Creseis acicula* (Rang), *Creseis chierchiaie* (Boas, 1886) *f. constricta* (Chen & Bé, 1964), *Creseis conica* (Eschscholtz, 1828), *Cavolina longirostris* (Lesueur), *Hyalocyclus striata* (Rang, 1828), *Diacria trispinosa* (de Blainville, 1827), *D. quadridentata* (de Blainville, 1827) and an unidentified Gymnosomata (???) with a very well-separated and distinct protoconch (Fig. 3). *Creseis acicula* is the most abundant followed by *Creseis chierchiaie*. It is common to find 1-4 specimens of *Cavolina longirostris* throughout the length of the core with intermittent occurrences of *Diacria quadri-dentata* and *Hylocyclus striata*. *Creseis conica* and larval shells of *D. trispinosa* are rare. It is however peculiar that no coiled specimen/species of *Limacina* have been found during the study.

The rare to nil occurrences of pteropods in the shallower location and the complete absence of *Limacina* spp. from the study area could have the following ecological implications:

1. The fresh water influence in the shallower location does not support the preservation of pteropods, except for occasional specimens of *Creseis*, known to tolerate a wide range of salinities.

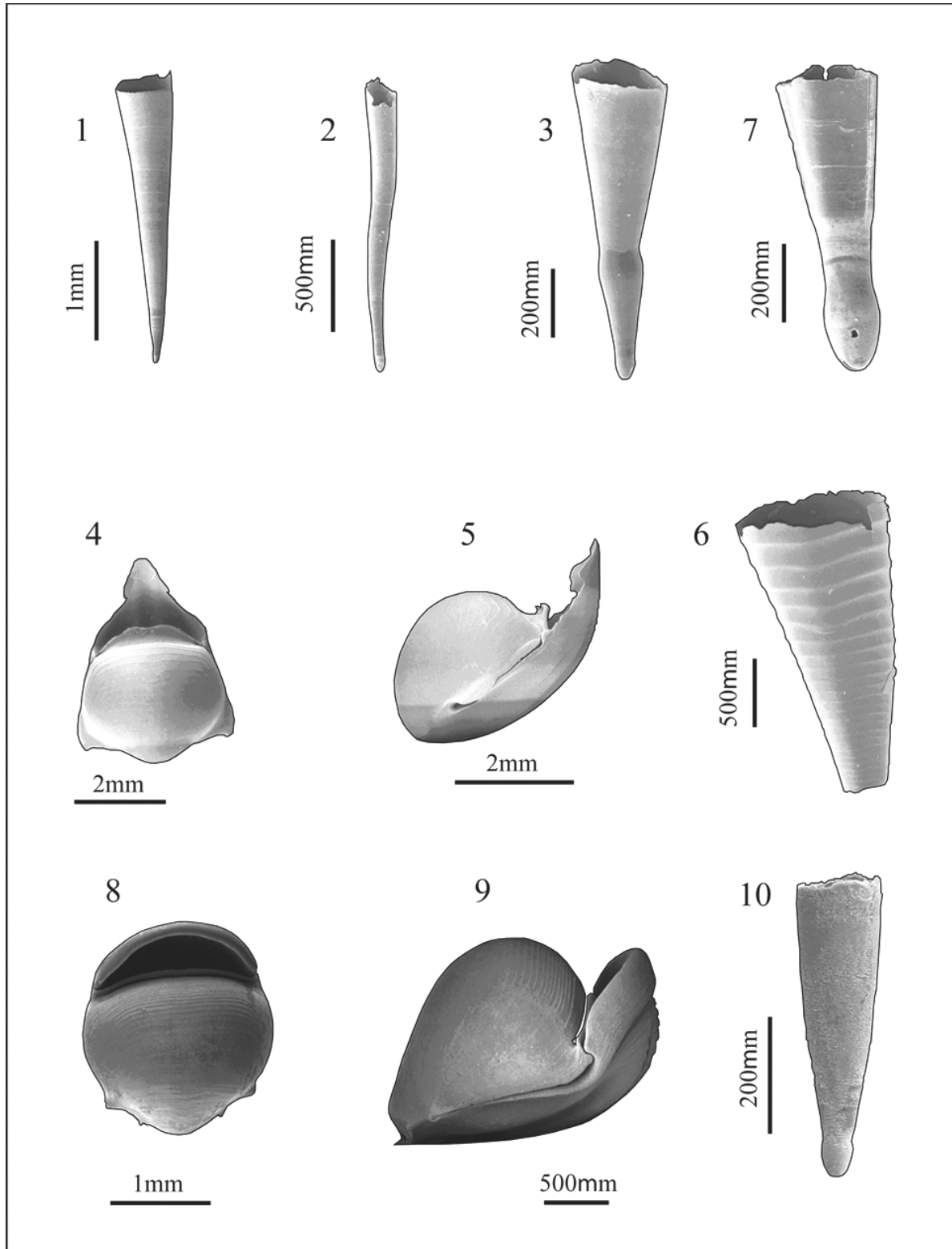


Fig. 3—1. *Creseis conica* Eschscholtz, 1929; 2. *Creseis acicula* Rang; 3. *Creseis chierchiaie* (Boas, 1886) f. *constricta* Chen & Bé, 1964; 4. *Cavolina longirostris* (Lesueur) ventral view; 5. *C. longirostris* (Lesueur), dorsal view; 6. *Hyalocylis striata* (Rang 1928); 7. *Diacria trispinosa* (de Blainville, 1827), larval shell; 8. *Diacria quadridentata* (de Blainville, 1827), ventral view; 9. *D. quadridentata* (de Blainville, 1827), side view; 10. Gymnosomata (???); note the well separated and distinct protoconch; a rather poorly preserved specimen.

Table 5—A comparison of the species occurrences in the different water masses reported by previous workers. The numbers enlisted under columns for different water masses indicate the reference number quoted in the tables 1-4.

Species	Arabian Sea	Bay of Bengal	Andaman Sea (surrounding the Andaman Nicobar Islands)	Irawaddy continental shelf, Andaman Sea (Present study)
1 <i>Limacina inflata</i>	17, 19, 20, 22, 45, 53, 55, 56, 57, 59, 66, 67, 68, 69	75, 76	19, 49, 63, 65	Absent
2 <i>Limacina trochiformis</i>	17, 19, 20, 45, 55, 56, 57, 59, 53, 66, 68, 69	75, 76	19, 49, 63, 65	Absent
3 <i>Limacina bulimoides</i>	17, 19, 45, 53, 55, 56, 57, 59	75, 76, 79	19, 49, 63, 65	Absent
4 <i>Limacina lesueurii</i>	56, 59	Nil	19, 49	Absent
5 <i>Creseis virgula</i>	25, 45, 53, 66, 68, 69	Nil	19, 49, 65,	Absent
6 <i>Creseis virgula virgula</i>	19, 55, 56, 57	Nil	19, 49, 63, 65	Absent
7 <i>Creseis virgula constricta</i>	Nil	Nil	49, 65	Absent
8 <i>Creseis virgula conica</i>	19, 53, 56, 57	Nil	49, 63, 65	Present
9 <i>Creseis acicula</i>	17, 19, 20, 22, 44, 45, 53, 55, 56, 57, 59, 66, 68, 69, 70 71	72, 73, 74, 75, 76, 77, 78, 79	19, 49, 63, 65	Present
10 <i>Creseis acicula acicula</i>	Nil	Nil	65	Absent
11 <i>Creseis acicula clava</i>	56	Nil	Nil	Nil
12 <i>Creseis chierchiae</i>	19, 20, 22, 53, 55, 56, 57, 59, 66, 68	Nil	49, 65	Present
13 <i>Clio pyramidata</i>	17, 22, 19, 56	Nil	19, 49, 63, 65	Absent
14 <i>Clio pyramidata convexa</i>	19, 20, 22, 53, 55, 56, 57, 59, 66, 68	Nil	19, 49, 63, 65	Absent
15 <i>Clio cuspidata</i>	56, 69	Nil	19, 49, 63	Absent
16 <i>Clio pyramidata lanceolata</i>	22, 57	Nil	Nil	Absent
17 <i>Clio polita</i>	56, 69	Nil	Nil	Absent
18 <i>Cavolina globulosa</i>	Nil	Nil	19, 49, 63, 65	Absent
19 <i>Cavolina longirostris</i>	17, 19, 22, 45, 55, 56, 57,	Nil	19, 49, 63	Present
20 <i>Cavolina tridentata</i>	Nil	Nil	19, 49, 63, 65	Absent
21 <i>Cavolina inflexa</i>	45, 55, 56, 66	Nil	19, 49, 63, 65	Absent
22 <i>Cavolina uncinata</i>	17, 41, 55, 56	80	19, 49, 63, 65	Absent
23 <i>Styliola subula</i>	19, 55, 56, 66	Nil	Nil	Absent
24 <i>Hylocypris striata</i>	22, 45, 55, 56, 57, 59, 66	Nil	19, 49, 65	Absent
25 <i>Cuvierina columnella</i>	Nil	Nil	19, 49, 63, 65	Present
26 <i>Diactria trispinosa</i>	19, 22, 55, 56, 66	Nil	19, 49, 63	Absent
27 <i>Diactria quadridentata</i>	17, 19, 22, 45, 55, 56, 57, 66, 68, 69	Nil	19, 49, 63, 65	Present
28 <i>Peracelis reticulata</i>	19, 45, 55, 56	Nil	19, 49, 63, 65	Absent
29 <i>Peracelis depressa</i>	Nil	Nil	49	Absent

- The region is characterized typically by an epipelagic assemblage, dominated by *Creseis* spp. The absence of *Limacina* spp. could indicate low salinities in the region throughout the past ~1280 Cal yrs. represented by the sediment cores (as derived from C-14 AMS dates on the bottom of core GC-7). This also suggests that there has been no major change in sea level during the same duration.

This is just a preliminary report and detailed descriptions of pteropod distribution based on the 126 surface sediments collected over the entire Irrawaddy continental shelf will be published separately<sup>85</sup>. In the study area, the pteropod assemblage varies spatially and temporally especially away from the mouths of the Irrawaddy. Close grid documentation of pteropods would help in delineating different assemblages within the area which is characterized by a complex salinity and sedimentation regime.

**A comparison of the assemblages within the different regions within the northern Indian Ocean:**

To enable such a comparison, the northern Indian Ocean has been delineated into 4 major regions (Fig. 1). Table 5 enlists the assemblages within the different water masses in the Indian Ocean. Most of the works reviewed above have documented pteropod assemblages from their respective study areas. *Creseis acicula* is the only species that is common to all the four regions. Limacinoids have been reported from all the water masses except for the Andaman Sea (Irrawaddy continental shelf). *Creseis acicula clava*, *Clio pyramidata lanceolata*, and *Clio polita*, have been reported only from the Arabian Sea whereas *Creseis virgula constricta*, *Creseis acicula acicula*, *Cavolina globulosa*, *C. tridentata*, *Cuvierina columnella*, *Peraclis depressa* have been reported only from the waters around the Andaman Nicobar Archipelago. *Limacina lesueuri*, *Creseis virgula*, *Creseis virgula virgula*, *Creseis virgula conica*, *Creseis chierchiaie*, *Clio pyramidata*, *Clio pyramidata convexa*, *Clio cuspidata*, *Cavolina longirostris*, *Cavolina inflexa*, *Styliola subula*, *Hylocylis striata*, *Diacria trispinosa*, *Diacria quadridentata*, *Peraclis reticulata* have never been reported before from the Bay of Bengal. However, this could be because pteropods have never been reported from this water-mass as constituents of marine sediments.

**Implications of these studies**

Pteropods have been recognized as emerging proxies for Quaternary palaeoclimates. Significant

results have been drawn to understand the ACD in almost all the studies covered under this study and to reconstruct climates of the recent past in the tectonically active regions around the Andaman Nicobar Archipelago. Surface sediment samples collected between Vishakhapatnam and Madras along the east coast of India, within a depth range of 25 to 70 m invariably show the presence of pteropods where the abundance varies between 5-10%. The present study also describes pteropods from the Irrawaddy Continental shelf, where 2-30% of the sand fraction within sediments is constituted by pteropods, where typically mesopelagic and bathypelagic forms (*Limacina* spp.) are absent.

With more and more occurrences being identified within the Indian Ocean especially in the high sedimentation coastal areas of the Bay of Bengal and Andaman Sea, pteropods could be used more reliably as bathometers, sea level and fresh water influx indicators. Close grid sampling in these potential coastal areas could help in establishing the ecology of different pteropod species and thus help in developing site specific proxies for palaeoclimatic work. If the right infrastructure could be availed, pteropods need to be cultured in the laboratory to reiterate the ecology of index species. It has been reported that during the Pleistocene, when temperatures were lower and salinities higher, most pteropod species could not adapt to the rigorous environmental conditions except for some epipelagic species like the *Creseis* and *Limacina trochiformis*. Episodic preservation of these species has been used as indicators of temporary low salinity intervals (as an effect of fresh water discharge or glacial ice water melt)<sup>32</sup>. Following this approach, downcore variations in pteropod assemblages could be studied in coastal areas as a proxy for palaeomonsoonal reconstructions.

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