# NEW DINOFLAGELLATE CYSTS FROM THE RECENT SEDIMENTS OF NORTHERN INDIAN OCEAN

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## ABSTRACT

Organic walled dinoflagellate cysts have been utilised to reconstruct paleoclimate and paleoceanographic changes mainly from the temperate and polar region with less attention from the tropics. Information on the dinocyst taxonomy and ecological affinity from the monsoon influenced Northern Indian Ocean is still in infancy. The surface sediments from the Bay of Bengal yield significant proportions of protoperidiniacean dinoflagellate cysts. In the present study four new species from the Bay of Bengal and eastern Arabian Sea are established; these are *Cryodinium? matsuokai, Lejeunecysta longistraiata, Quinquecuspis pentagona* and *Stelladinium denticulatum*. The new taxa appear to be related to high nutrient concentrations and persistent low salinity conditions.

**Keywords:** Bay of Bengal, Holocene; Indian Ocean, protoperidiniacean dinoflagellate cysts, salinity, taxonomy.

## INTRODUCTION

Organic-walled dinoflagellate cysts have been extensively used as paleoecological and paleoceanographic proxies in the Quaternary (Pospelova *et al*., 2006; Dale 2009; Mertens *et al*., 2009, 2012). The Quaternary palynology of the Indian Ocean is under-researched compared to Atlantic and Pacific. Most of the dinoflagellate studies from the northern Indian Ocean have been centered on the western Arabian Sea (Zonneveld, 1997; Zonneveld and Brummer, 2000; Reichart and Brinkhuis, 2003; Narale *et al.*, 2015). Very little information on Quaternary palaeoecology is known from the eastern Arabian Sea and Bay of Bengal (D'Silva *et al.,* 2013; Narale *et al.,* 2013).

Dinoflagellate cyst datasets from semi-enclosed embayment in the Arabian Sea and the Gulf of Mexico have demonstrated characteristic assemblages which include endemic taxa that thrive in the unique environmental settings (Zonneveld, 1997; Limoges *et al.,* 2013). Research in the western Arabian Sea has demonstrated diverse protoperidiniacean floras (Zonneveld, 1997; Zonneveld and Brummer, 2000). Dinoflagellate cyst studies from the Arabian Sea reported the several new species of viz. *Echinidinium aculeatum, Echinidinium bispiniformum, Echinidinium delicatum, Echinidinium exuam, Echinidinium granulatum, Echinidinium transparantum* and *Stelladinium robustum*. The protoperidiniaceans are heterotrophic, and frequently dominate nutrient-rich environments such as coastal areas, river influenced regions and perennial and seasonal upwelling systems (Gaines and Elbrächter, 1987; Hansen, 1991). At and near upwelling systems, diatoms exert competitive growth over autotrophic dinoflagellates due to the excess nutrient availability, and diatoms consequently dominate the phytoplankton. Because protoperidiniacean dinoflagellates largely feed on diatoms, they are abundant in nutrient-rich environments (Susek *et al.,* 2005; Holzwarth *et al.,* 2007). However, protoperidiniacean cysts are sensitive to degradation in highly oxidizing conditions, and this affects their preservation (Dale, 1976; Zonneveld *et al.,* 2001; Versteegh and Zonneveld, 2002). Despite this selective degradation, temporal variations in protoperidiniacean cysts have been used as a proxy for productivity and redox fluctuations in the Arabian Sea (Reichart and Brinkhuis, 2003).

The Bay of Bengal is a unique tropical area because its circulation and hydrography are driven by fluvial input and monsoon precipitation (Varkey *et al.,* 1997). Many of the largest rivers in the Indian subcontinent, such as the Ganges-Brahmaputra, Godavari, Irrawaddy, Krishna and Mahanadi drain into this major marine embayment. Considerable variation in precipitation and runoff discharge from north to south give rise to several salinity gradients within the Bay of Bengal. Freshwater discharge induces intense stratification and turbidity in the water column, and this influences biological productivity (Kumar *et al.,* 2010). The singularity of the Bay of Bengal makes it an ideal location to investigate the diversity and ecology of modern dinoflagellate cysts in stratified environments under the significant riverine influence. The eastern Arabian Sea also has similar circulation and oceanography with coastal region influenced by upwelling during the summer period. This study will enhance our knowledge of dinoflagellate cyst population dynamics in low saline monsoon influenced tropical Indian Ocean waters which are distant from areas of deep upwelling. Furthermore, studies of dinoflagellate cysts from modern monsoonal settings will be useful in the potential recognition of analogous assemblages in deep time.

In the last decade, studies from the tropical regions have revealed the presence of new species from the northern Indian Ocean, Andaman Sea and South China Sea which are yet to be described (Narale *et al.,* 2013; Su-Mayat *et al.,* 2013). In the present study, we report four new dinoflagellate cysts that occurred in the surface sediments of Bay of Bengal and south eastern Arabian Sea (Fig.1). The results presented herein are therefore a significant contribution to our knowledge of protoperidiniacean dinoflagellate cysts from the tropics.
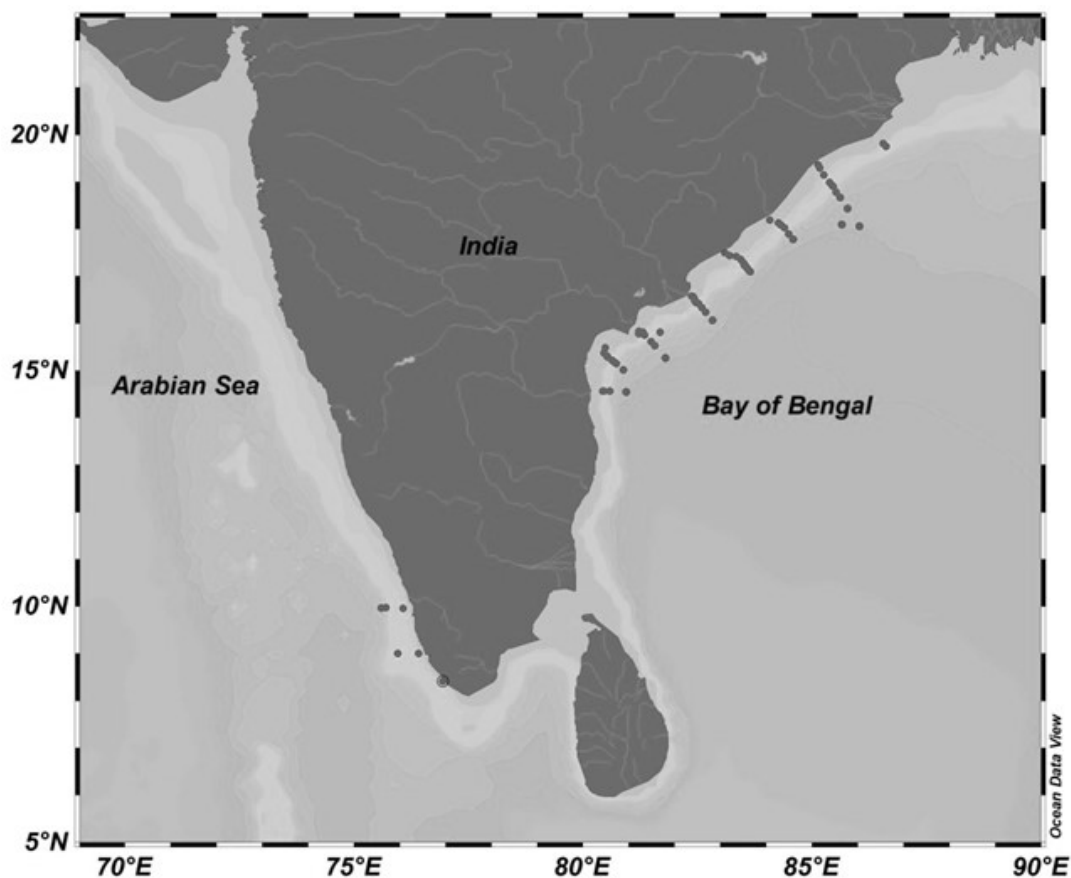
Fig. 1. Location map of the study area.

## OCEANOGRAPHIC SETTINGS

The Bay of Bengal and the Arabian Sea are land locked in the north and located in the tropical monsoon belt. The surface circulation of both the basins undergoes a reversal in the summer and winter seasons. The character and mass of the huge flux of terrigenous sediments discharged into the Bay of Bengal are influenced by the extensive fertile deltaic onshore regions north of the Ganges-Brahmaputra confluence (Singh and Swamy, 2006). Other inputs of sediment and water into the western flank of the Bay of Bengal include the Cauvery, Godavari, Hugli, Irrawaddy, Krishna, Mahanadi, Meghna, Palar and Penner rivers. The total annual continental runoff into the Bay of Bengal is around about 3000 km$^3$ (Subramanian, 1993; Sengupta *et al.,* 2006). This freshwater input significantly lowers the salinity and, together with the warm water conditions, forms a strong stratification (3-7 psu difference) in the upper water column (Vinyachandran and Kurian, 2007). In the Southeastern Arabian Sea terrestrial input is mainly from the western-Ghat Mountains.

The Arabian Sea is one of the world's most productive regions during the summer monsoon period induced by a variety of processes viz. open ocean upwelling in the central region and coastal upwelling in the Somalia, Arabia and southern part of the west coast of India. Despite the similar setting and monsoon influence, Bay of Bengal productivity is low due to the high cloud cover and turbidity (Prasanna Kumar *et al.,* 2002). However, the annual sediment flux between both the basins is comparable possibly due to eddy induced productivity in the Bay of Bengal (Prasanna Kumar *et al.,* 2002).

Both the Arabian Sea and Bay of Bengal basins are characterised by intense oxygen minima zone (OMZ) in the mid depth (200-1000 m) with southern Hemisphere water as the major source (McCreary *et al*., 2013). Although strong, Bay of Bengal OMZ is weaker than Arabian Sea OMZ due to the low detritus in the western region remaining above the denitrification threshold (Naqvi *et al.,* 2006).

## MATERIAL AND METHODS

The 64 seabed surface samples were collected using a grabber (14 samples) and multicorer (50 samples) during cruise

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**EXPLANATION FOR PLATE I**

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*Cryodinium? matsuokai* sp. nov from modern sediments of the Bay of Bengal.  EF = England Finder reference. Scale bars all 10 µm. ***Cryodinium? matsuokai*** sp. nov. Figs. 1-4. Holotype, Sample MC 64, BSIP slide 15589, EF-J 53-3, Figs. 1-2. High focus, lateral surface showing a part of archeopyle, Figs. 2, 3. Low focus showing high sutural septa, Fig. 4. Low focus on ventral surface, Figs. 5, 6. Sample Grab-14, slide no.2, 5- specimen showing high sutural septa, 6. A four sided plate exposed, 7-9, Sample Mc 64,BSIP slide 15591, EFL 52-2, Fig. 7. High focus, antapical view, Fig. 8. Mid-focus showing high sutural septa, Fig. 9. Low focus apical view.
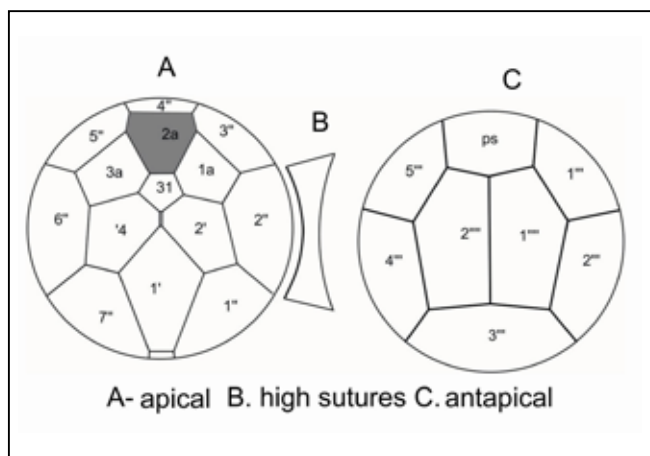
Plate I
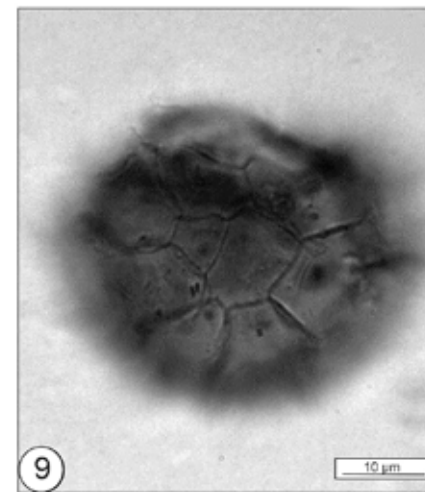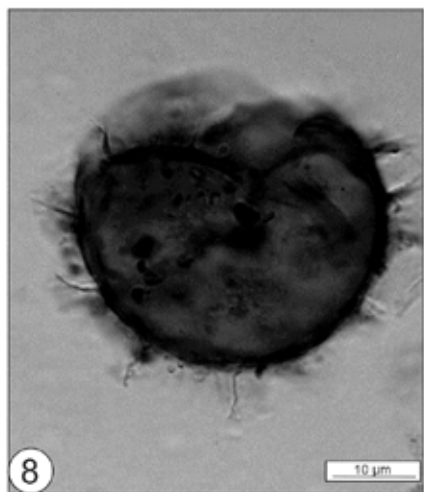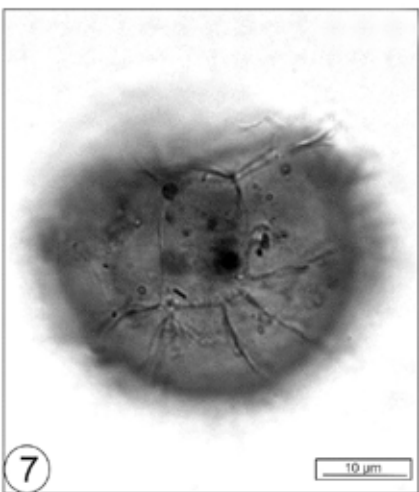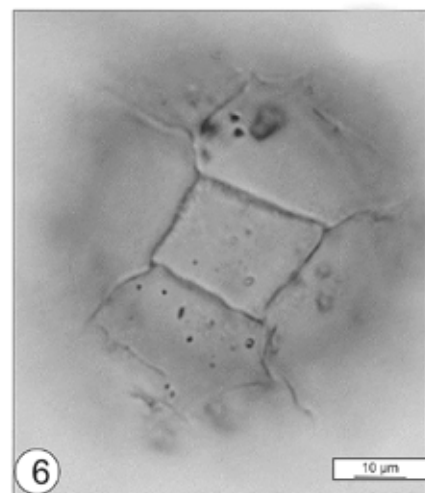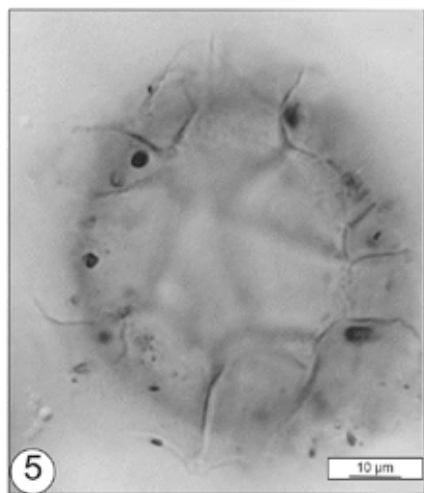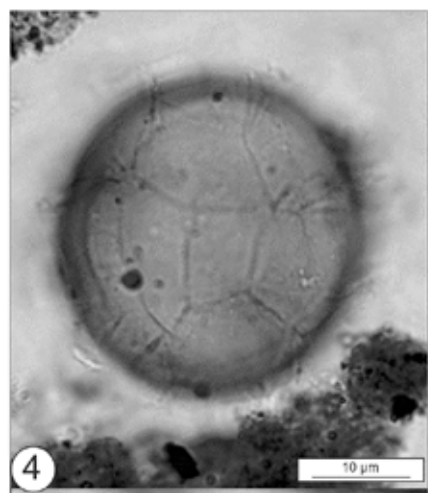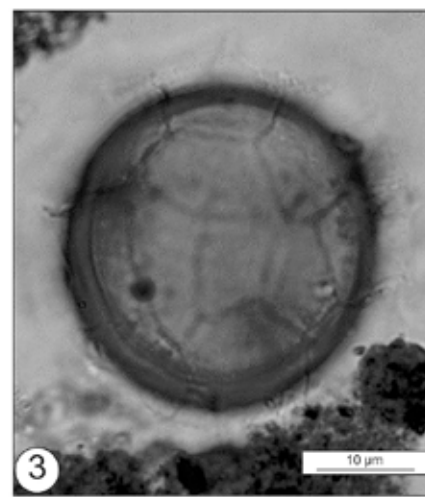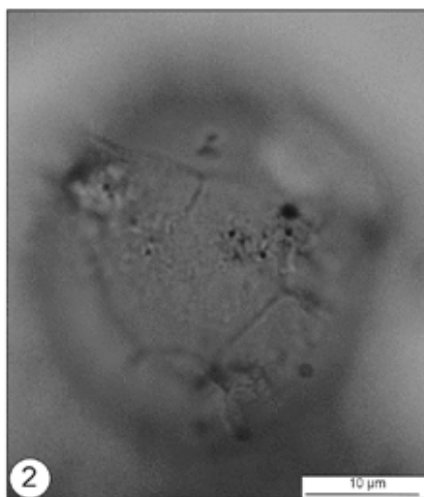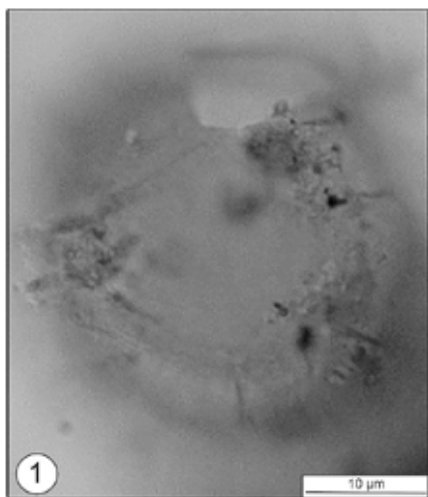
Fig. 2. A line diagram of *Cryodinium? matsuokai* sp. nov.



Fig. 3. A line diagram of *Lejeunecysta longistriata* sp. nov.

Sagar Kanya no. 308 in January 2014. Multicorer with a core tube length of 60 cm was utilized to collect the undisturbed sediment-water interface. Samples were collected in eight transects perpendicular to the coast, in water depths between 25 m and 2500 m (Fig. 1). Six surface sediments from the south eastern Arabian Sea were collected during the cruise SSK-15. All samples were processed using the methods described by Matsuoka and Fukuyo (2000). Surface sediments (multicorer samples 2 gm dry weight, Grab samples 10-100 g) were treated with 10% hydrochloric acid (at room temperature) for 24 hours to remove carbonates. After the residues were washed to neutrality, 40% hydrofluoric acid (at room temperature) was added to digest the silicate minerals. This took around two days, and the neutralized residues were passed through a 10 µm sieve. The cover slips with dried residue concentrate were mounted on microscope slides using Canada Balsam.

The types and all other figured material are curated in the Museum of the Birbal Sahni Institute of Palaeosciences (BSIP, 53 University Road, Lucknow, Uttar Pradesh 226007, India (http://www.bsip.res.in/). Furthermore, the samples, aqueous residues and microscope slides without figured or type specimens are held in the BSIP collections. The taxonomy follows Fensome *et al.,* (1993). Paratabulation follows Kofoid system.

## SYSTEMATIC PALAEONTOLOGY

*Division* **Dinoflagellata** (Bütschli 1885) Fensome *et al.,* 1993
*Subdivision* **Dinokaryota** Fensome *et al.,* 1993
*Class* **Dinophyceae** Pascher, 1914
*Subclass* **Peridiniphycidae** Fensome *et al.,* 1993
*Order* **Peridiniales** Haeckel, 1894
*Family* **Protoperidiniaceae** (Bujak and Davies, 1983) Fensome *et al.,* 1998

*Subfamily* **Protoperidinioideae** Balech, 1988
*Genus* **Cryodinium** Esper and Zonneveld, 2002
*Type species* **Cryodinium meridianum** Esper and Zonneveld, 2002

*Cryodinium? matsuokai* sp. nov.
(Pl. I, figs. 1-9; Text fig. 2)

*Etymology*: This species is named after Professor Kazumi Matsuoka of Nagasaki University, Japan.

*Holotype and type locality*: BSIP 15589, England finder coordinates: J 53-3. Recent sediments (0-1 cm) from Sk-308 MC 64 from the north-western Bay of Bengal; Off Mahanadi River (Longitude 18°55.840 °N and latitude 85°26.046 °E at 499 m water depth). Plate I; Fig, 1-4.

*Dimensions*: Central cyst body: 30-35 µm, Cyst diameter: 42.5-45 µm. The length of the parastural septa is 10-15 µm. 5 specimens were measured.

*Diagnosis*: Small to intermediate protoperidinioid cyst with a peridinioid tabulation pattern fully reflected by high sutural septa (~10 µm). Spherical, proximate brown cyst with smooth autophragm. Archeopyle intercalary presumably representing plate 2a. Operculum often adnate.

*Description:* Small to intermediate protoperidinioid cysts. Cyst body Spherical in shape. Autophragm is brown in colour, smooth to slightly granulated. Paratabulation is fully reflected. Paraplate boundaries are expressed by high sutural septa (10-15 µm). Parasutural septa are thin (< 0.1 µm), hyline to light brown in colour with smooth to weakly serrate to denticulate margin. Archeopyle is anterior intercalary in position involving mid-dorsal paraplate (type 2a). Operculum often adnate.

*Comparison*: C?. matsuokai differs from C. meridianum in having high parasutural septa. C?. matsuokai is easily identified as it is the only spherical, brown protoperidinioid species with fully expressed paratabulation.

*Comments*: The specimens of this species are often degraded or crumpled and operculum is often adnate hindering the clear

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**EXPLANATION FOR PLATE II**

*Lejeunecysta longistriata* sp. nov. from modern sediments of the Bay of Bengal.  EF = England Finder reference.  Scale bars all 20 µm. Figs. 1-4,  Holotype, Sample Gr-14, BSIP slide 15584, EF-V 37/3, Fig. 1. High focus- ventral surface, showing the striations and antapical thickening, Fig. 2. Low focus- dorsal surface, showing the distal serrated margin of archeopyle, Fig. 3. Ventral surface, sulcul region focused, Fig. 4. Sample Mc-64, BSIP slide 15589, High focus dorsal surface showing archeopyle and striations, Figs. 5, 6. Sample MC-64, Slide no BSIP 15589, EF  G 30/1, Fig. 5. High focus, dorsal surface showing archeopyle and striations, Fig. 6. Low focus.ventral surface showing sulcus.

Plate II
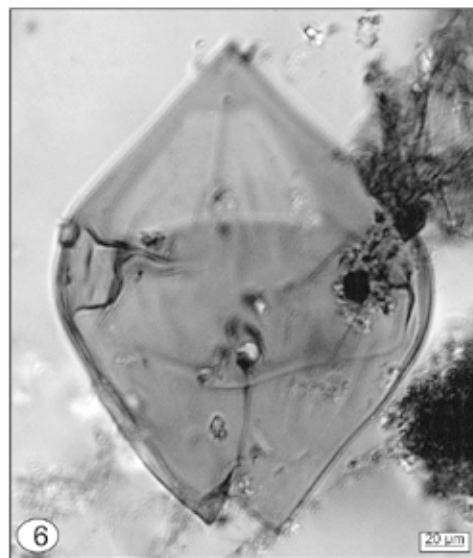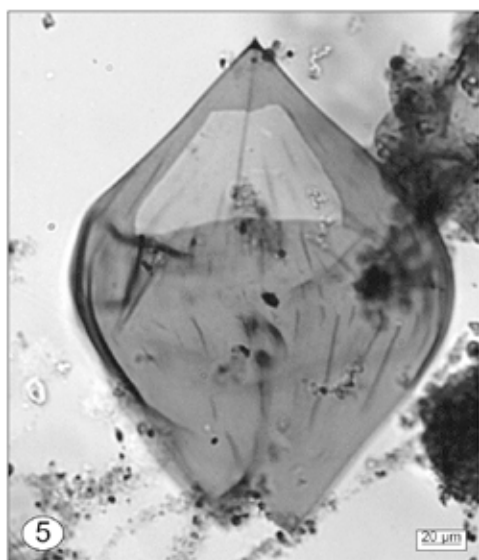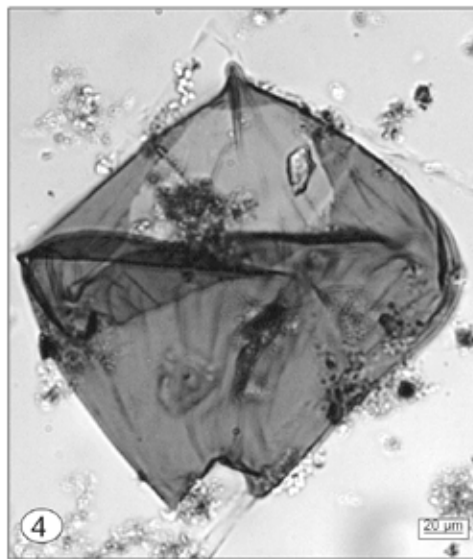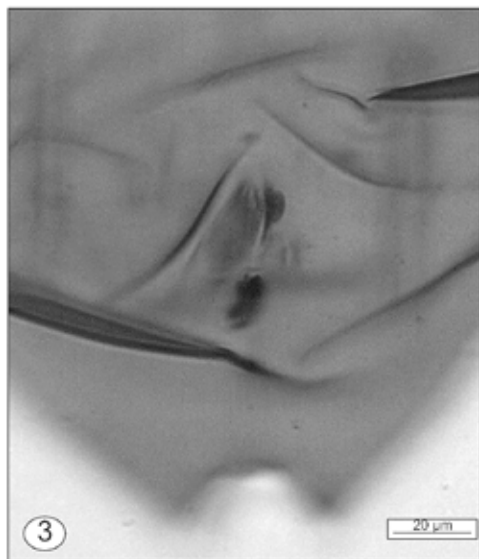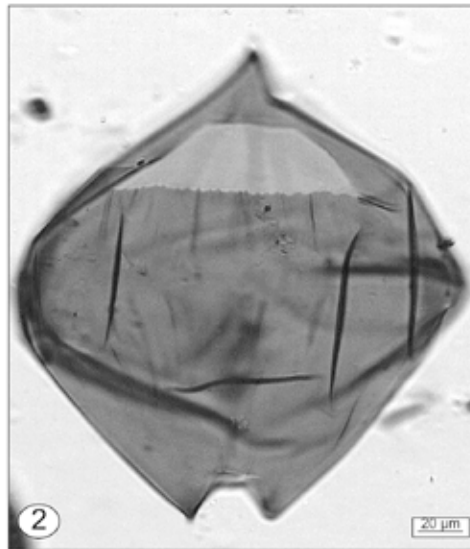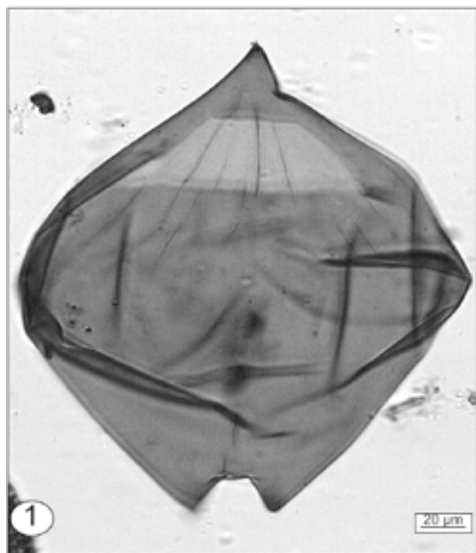
conclusion of paratabulation and archeopyle involving one or two plates. Hence the assignment of *Cryodinium* is provisional. However, the paratbulation expression in the form of parasutural septa supports its assignment to *Cryodinium*.

Genus ***Lejeunecysta*** Artzner and Dörhöfer, 1978

Type ***Lejeunecysta hyalina*** (Gerlach, 1961) Artzner and Dörhöfer, 1978

*Lejeunecysta longistriata* sp. nov.
(Pl. II, figs. 1-6; Text fig. 3).

*Etymology:* Latin, longi=long, striata=striated. This species is named after the characteristic striations on the autophragm.

*Holotype and type locality:* Slide BSIP 15584, England Finder coordinates V37/3. Holocene seabed sediments (0-1 cm) from sample SK-308 GR-14 collected in the western Bay of Bengal. This locality is offshore Visakhapattanam at longitude 19°17.734 °N and latitude 85°10.111 °E in a water depth of 55.4 m. Plate II; 1-3

*Dimensions:* The overall length is 106–110 μm, and the overall width is 98–106 μm. The epicyst and hypocyst lengths are 40-45 and 48-55 μm respectively. Eight specimens were measured.

*Diagnosis:* An Intermediate, proximate, sub pentagonal cyst with dorso-ventral compression. Epicyst slightly shorter than hypocyst, conical with concave to straight sides in dorso-ventral view with two small acuminate antapical horns and one apical horn. Cyst autophragm is brownish-pigmented consists discontinuous longitudinal striations which are 10–30 μm in length. Paracingulum is not distinctly defined. Parasulcus deep, restricted to hypocyst; the flagellar scar marked by two prominent invaginations. Paratabulation absent except for archeopyle. Archeopyle large simple intercalary, formed by the loss of paraplate 2a.

*Description:* A relatively elongate subpentagonal species with brown pigmentation. Cyst dorsoventrally compressed with small, short, sharply distally pointed, conical apical and antapical horns. The three polar horns exhibit acuminate tips with a prominent distal thickening. The epicyst and hypocyst flanks are straight to weakly convex. Hypocyst is slightly larger than the epicyst. Lateral horns or protrusions are absent. The antapical concavity is small and the paired antapical horns are located close together at the midline. The autophragm is  of moderate thickness and bears prominent, smooth, discontinuous non-tabular longitudinal striations 10-30 μm in length. Paratabulation is expressed only in the form of archeopyle. Archeopyle is large anterior intercalary type 2a, mid-dorsal in position with narrow anterior margin and broad mid-dorsal margin. The posterior margin of the archaeopyle may bear serrated margin. Hexagonal in shape occupying much of the dorsal side of the epicyst (latidelta form). Operculum open. The cingulum is not reflected; however, there is a marked mid-ventral sulcal depression.

*Comparison*: *Lejeunecysta longistriata* sp. nov. differs from *Lejeunecysta oliva* (Reid, 1977) Turon and Londeix, 1988 in
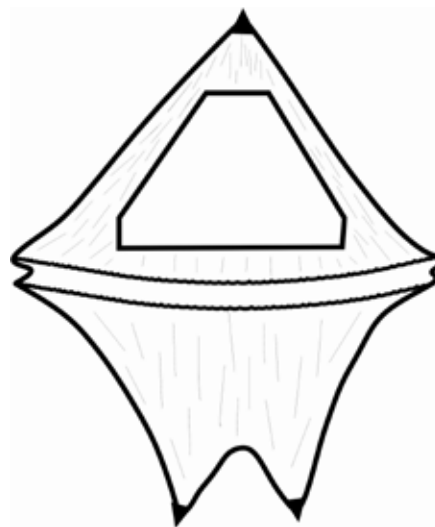


Fig. 4. A line diagram of *Quinquecuspis pentagona* sp. nov.

lacking cingular ridges, and from *Lejeunecysta sabrina* (Reid, 1977) Bujak, 1984 in being striate and having a convex epicyst. It also differs from *Selenopemphix selenoides* Benedek, 1972 in not having an echinate cingulum. This new species differs from cysts of *Protoperidinium latissimum* (Kofoid, 1907) Balech 1974 in having a six-sided, rather than a five-sided, anterior intercalary archaeopyle. It differs from *L. paratenella* in not having a prominent cingulum and apical granules. It differs from *L. epidoma* in having an apical thickening and not a prominent dome shape. It differs from *L. psuchra* in having a pointed apical and antapical horns with ornamentation on the autophragm.

*L. longistriata* differs from *Quinquecuspis concreta* in possessing in elongated sub pentagonal ambitus and in having a sulcul groove which is not deeply sunken.

Genus  ***Quinquecuspis*** Harland, 1977
Type  ***Quinquecuspis concreta*** (Reid, 1977) Harland, 1977

*Quinquecuspis pentagona* sp. nov.
(Pl. III, figs. 1-9; Text fig. 4).

*Holotype and type locality*: BSIP 15588. England Finder position: K-42/2. Recent sediments (0-1 cm) from Sk-308 MC 52 from the north-western Bay of Bengal; (Longitude 18°05.239 °N and latitude 84°19.507°E at 225 m water depth). Plate III; 1-3.

*Etymology: Quinquecuspis pentagona* is named after the characteristic pentagonal outline.

*Dimensions:* Cyst length 130-160 μm. Cyst width: 130-135 μm. Epicyst, 64-75 μm and Hypocyst, 75-85 μm. 20 specimens were measured.

*Diagnosis:* A large, proximate, pentagonal cyst compressed dorsoventrally. Epicysts smaller than hypocyst, conical with

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**EXPLANATION FOR PLATE III**

***Quinquecuspis pentagona*** sp. nov. from the modern sediments of Bay of Bengal, Figs. 1- 3-Holotype, BSIP slide 15588, EF-K 42/2, Fig. 1. High focus, dorsal view- striations, cingulum ridges focused, Fig. 2. Low focus, apical, antapical thickening visible, Fig. 3. slightly higher focus- lateral notch of the cingulum with denticulation, 4, 5. Sample MC 71 slide 1 EF C16/2, Fig. 4. Locus focus showing the ventral surface, Fig. 5- High focus, dorsal surface, dorsal view, cingular ridges highlighted, 7- 8, Sample MC 44, slide no 1, EF K 47/3, Fig. 7. Low focus- Dorsal view of dorsal surface showing archeopyle, Fig. 8. High focus, Ventral surface showing sulcus region, Figs. 6, 9. Sample Mc-44 slide 1, EF K46/4, Fig. 6. High focus, dorsal view, apex thickening visible, Fig. 9. Low focus, ventral view- showing sulcul region and striations and antapical horn thickening.

Plate III
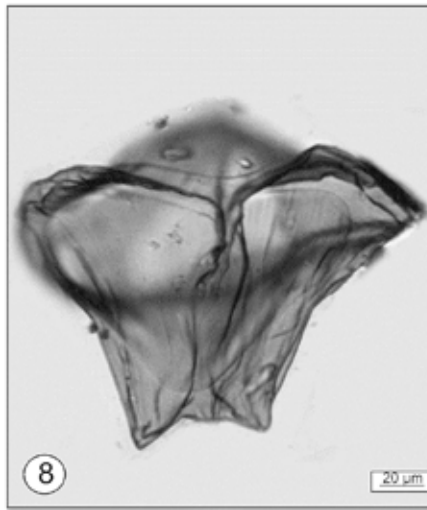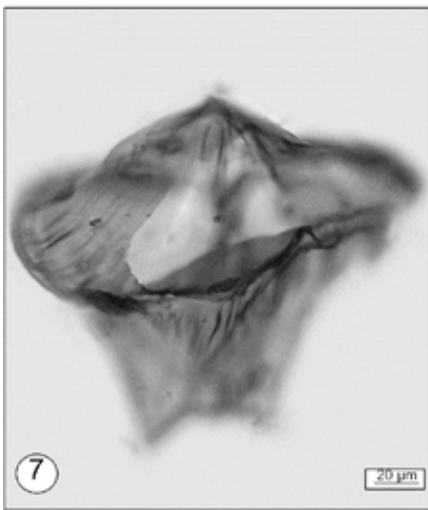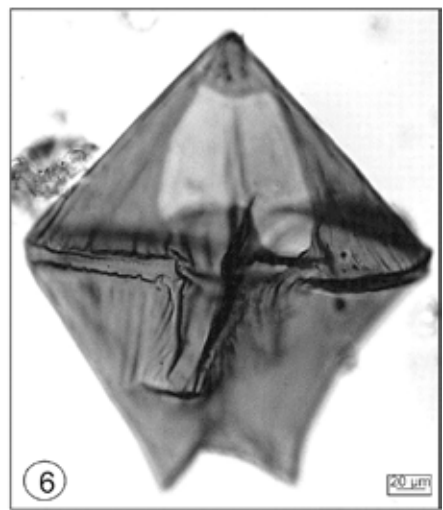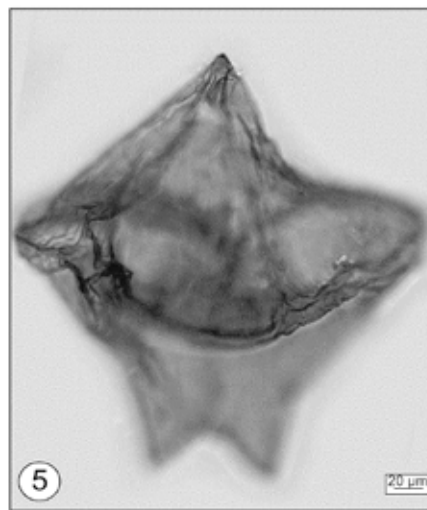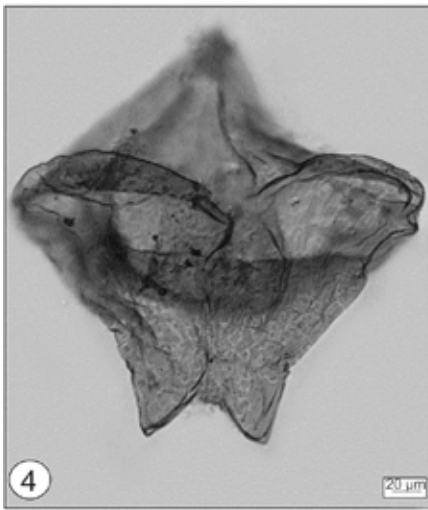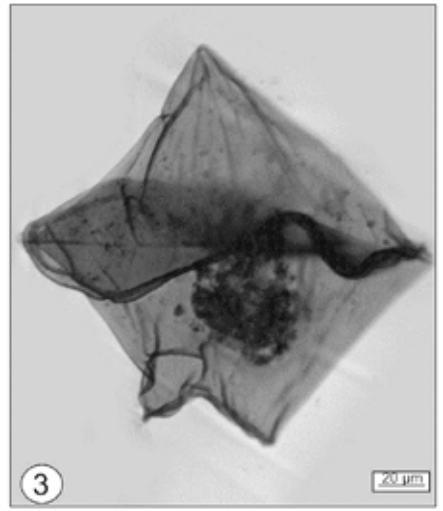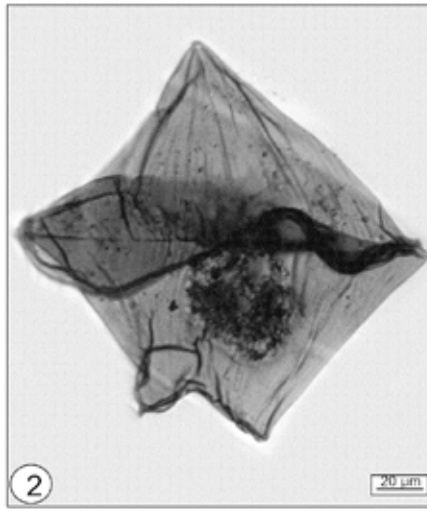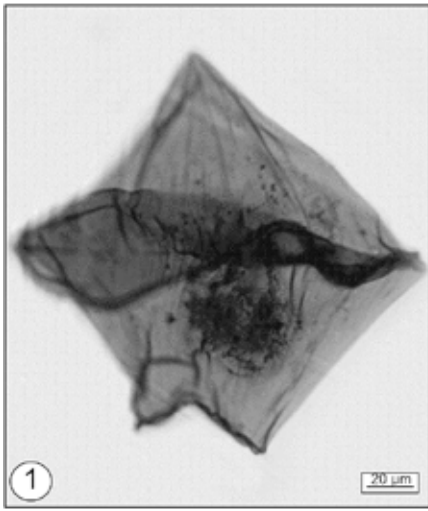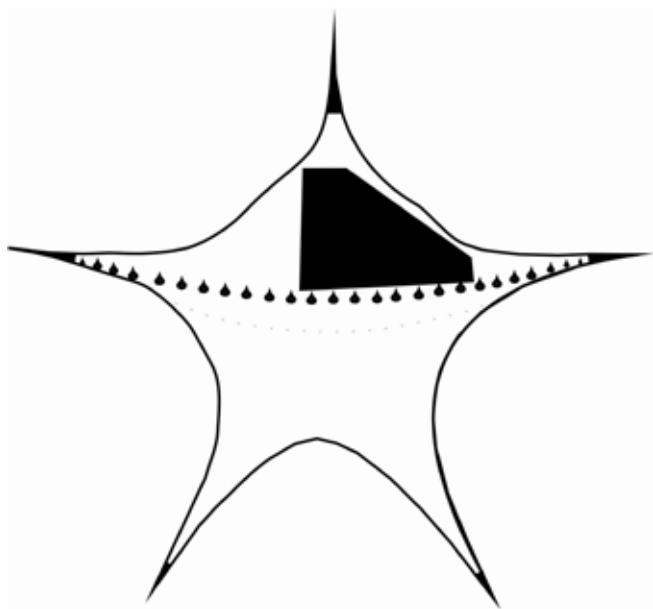
Fig. 5. A line diagram of *Stelladinium denticulatum* sp. nov.

slightly concave to straight sides in dorsoventral view with pointed, prominently thickened polar horns. Cyst wall consists of autophragm which is brown in colour. Autophragm consists discontinuous longitudinal striations (~10-30 μm) on epicysts and hypocyst. Epicyst and hypocyst are separated by two rows of cingular ridges which are finely denticulated. Sulcul depression is prominent. Antapical concavity is small. Archeopyle simple, mid-dorsal intercalary 2a type.

*Description:* Cysts large in size (130-160 μm), pentagonal in outline with strong dorsoventral compression. Cysts consist of two antapical and one apical horn with sharply distally pointed thickened tips. Lateral horns or protrusions are absent. The autophragm is brown, of moderate thickness and bears prominent, smooth, discontinuous, non-tabular longitudinal striations, 10-30 μm in length. The hypocyst is slightly larger than the epicyst. The epicyst is conical with straight to very weakly concave sides, and hypocyst is trapezoidal with straight to concave sides. The antapical concavity is small prominent and the paired antapical horns are separated apart from the midline by a prominent antapical depression. Paratabulation is expressed in the form of archaeopyle and cingulum. The archeopyle is large, simple intercalary, mid-dorsal in position involving anterior intercalary paraplate which is hexagonal (isodeltaform) in shape with a broad posterior and shorter anterior margin. The cingulum is prominent and is bordered by two denticulate sutural ridges, planar and indented. The sulcus is deeply indented.

*Comparison:* It differs from *Stelladinium* in having no extended lateral horns. It differs from the *Lejeunecysta* in having a clear deep ventral sulcus and antapical depression which

separate the antapical horns. It differs from *Quinquecuspis concreta* in being bigger in size with a large archeopyle and clear expression of cingulum represented by two denticulate ridges. When apical-antapically compressed, specimens are apparently similar to *Selenopemphix nephroides*, but these cysts are differentiated by their larger size and denticulate cingulum ridges. It differs from *Lejeunecysta paratenella* in having large ambitus and pentagonal shape. *Quinquecuspis pentagona* differs from *L. longistriata* in having bigger size and distinct cingulum.

*Remarks*: This species is very fragile and found often folded and degraded where other species of protoperidinioids are well preserved.

Genus **Stelladinium** Bradford, 1975
Type **Stelladinium reidii** Bradford, 1975

*Stelladinium denticulatum* sp. nov.
(Pl. IV, fig. 1-9; Text fig. 5)

*Holotype and type locality:* BSIP 15590. England Finder coordinates: V 44. Recent sediments (0-1 cm) from Sk-308 MC 65 from the western Bay of Bengal; Off Mahanadi River (Latitude 17°21.539 °N Longitude 83°26.840°E 102 m water depth). Plate IV; 1, 2.

*Etymology: Stelladinium denticulatum* is named after the characteristic denticulate cingulum.

*Dimensions:* Cyst Body length: 65-75 μm. Cyst width: 62-65 μm. Epicyst 25-30 μm. Hypocyst 40-46 μm. 30 specimens were measured.

*Diagnosis:* A proximate stellate cyst with strongly developed horns. Autophragm pale brown, smooth to faintly striate. Horns are charecterised by acuminate distal terminations and broad proximal bases. Cingulum is defined by sutures which are surmounted by small (<1 μm), distally pointed denticles. Archeopyle intercalary, offset, adnate laterally and apically, presumably representing plate 2a.

*Description:* A proximate stellate cysts with with five long slender, cardinal horns at each of the angle of the ambitus. All the five horns are the extension of the central cavity and have solid, acuminate, thickened distal terminations and broad proximal base. This species exhibits a strong dorso-ventral compression. Epicyst is subtriangular/conical, where as hypocyst is trapezoidal and both have concave sides. Epicyst is smaller than the hypocyst. The antapical depression is strongly concave in nature. Autophragm is brown, smooth with moderate thickness except for occasional discontinuous longitudinal folds. The Paratabulation is expressed in the form of archeopyle and cingulum. The cingulum sutures are defined by denticulate margin bearing short, triangular denticles (1 μm <). Archeopyle is large, anterior intercalary in position (type 2a), which is hexagonal in shape with rounded tips, broad posterior and a much shorter anterior margin (towards the apex), occupying much of the dorsal side of the epicyst. Archeopyle is offset to the right of the dorsoventral midline. Operculum is oftern adante laterally. The sulcus is represented by a shallow depression and restricted to hypocyst. There are no other indications of tabulation.

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**EXPLANATION FOR PLATE IV**

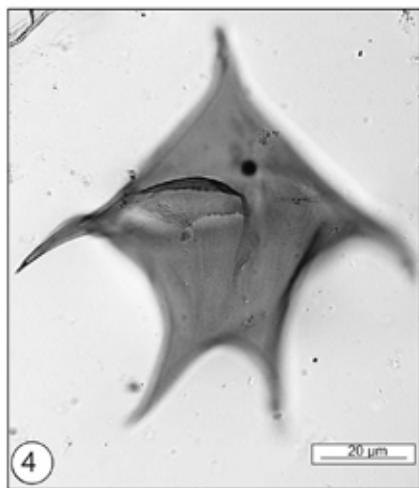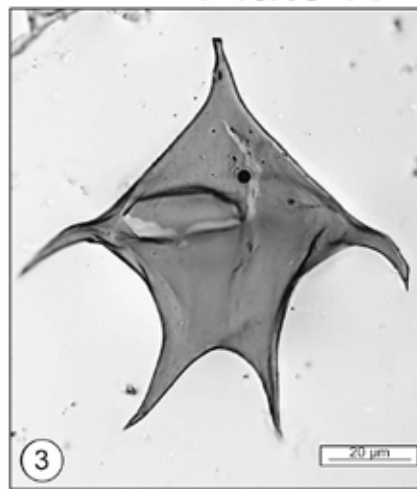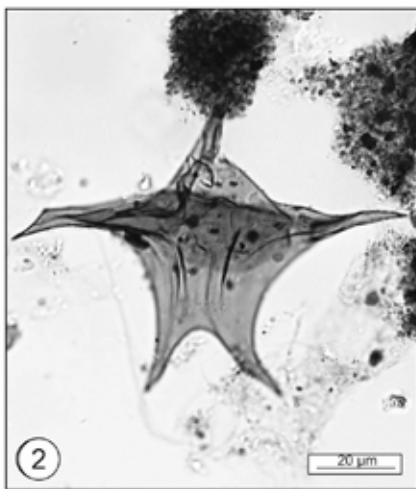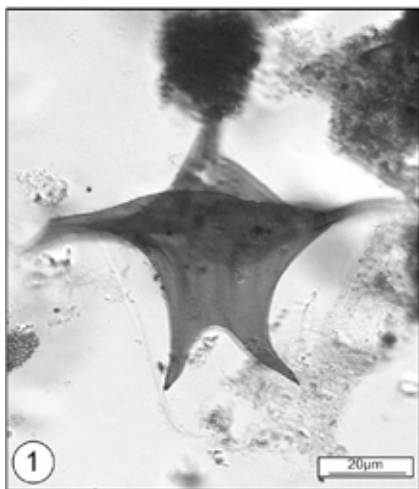*Stelladinium denticulatum* sp. nov. from the modern sediments of Bay of Bengal. Figs. 1, 2- Holotype. BSIP slide 15590, EF coordinates V-44; Fig. 1. dorsal view at high focus showing the cingulum ridge with a row of denticulation. Fig. 2. dorsal view of ventral surface showing lateral horns thickening; Figs. 3, 4, 5: Fig. 3. High focus, dorsal surface showing adnate archeopyle with posterior margin opened. 4-mid focus, ventral surface- thickening is visible along with archeopyle posterior margin, Fig. 5. low focus, dorsal surface- archeopyle posterior margin is opened. Figs. 6 and 9; Sample MC 44, slide 2, EF S32-1, Fig. 6. dorsal surface apical and antapical horn thickening is exposed, Fig. 9. Ventral surface, Figs. 7, 8. Sample MC 65 slide1 7- dorsal view showing cingulum denticles and archeopyle, 8. Archeopyle anterior margins exposed.

Plate IV
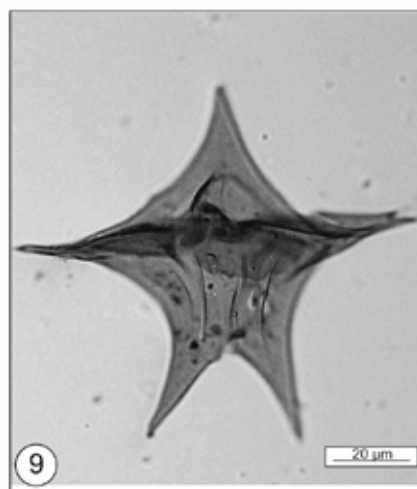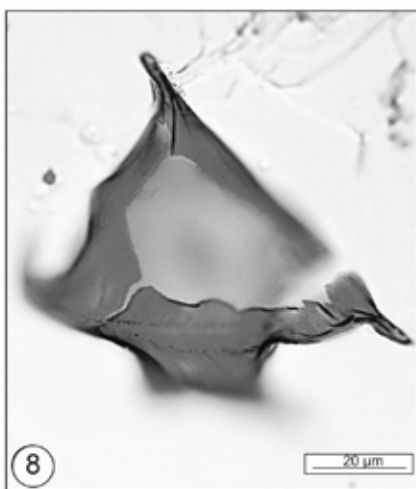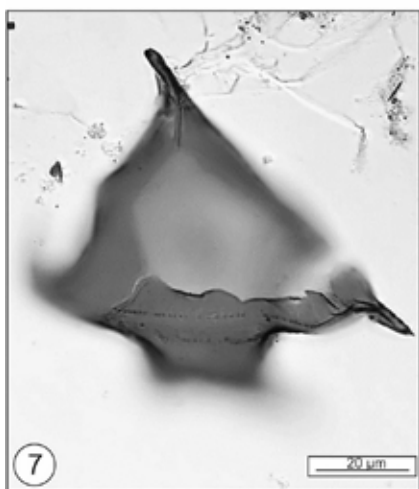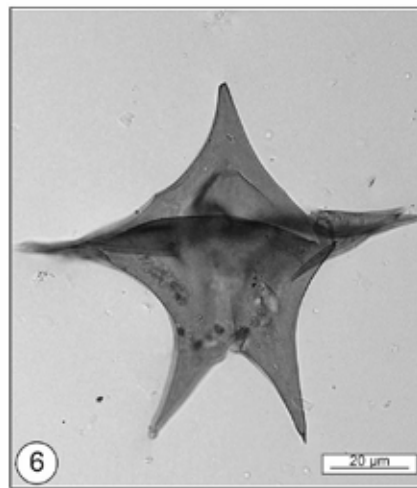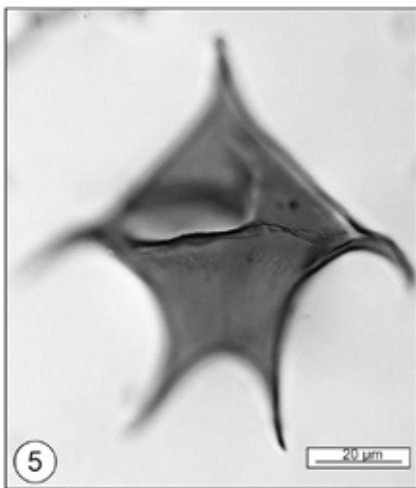
*Comparison:* S. denticulatum differs from the other four validly published *Stelladinium* species from its distinctive denticulate cingular ridges and cardinal horns. The occasional supplementary spines on the cingular region of the *S. reidii* Bradford, 1975 are entirely different in morphology to these denticles. Furthermore, the broad proximal bases of the cardinal horns in *Stelladinium denticulatum* sp., nov. are unique to this species. *Stelladinium abei* Matsuoka, 1985 and *Stelladinium reductum* Bint, 1988 have short, squat polar and lateral horns. *Stelladinium reidii* Bradford, 1975 and *Stelladinium robustum* Zonneveld, 1997 also have distinctly shorter cardinal horns than *Stelladinium denticulatum* sp. nov. Furthermore, *Stelladinium robustum* Zonneveld, 1997 is significantly larger than *Stelladinium denticulatum* sp. nov.

## DISCUSSIONS

Organic-walled dinoflagellates show high diversity in the plankton with more than 2000 species described across the world (Gomez, 2005). These include autotrophic, heterotrophic and mixotrophic species. In the Quaternary Period, the majority of autotrophs are categorized into gonyalaucales and heterotrophs into peridiniales. More than 265 species of heterotrophic dinoflagellates have been classified under the genus *Protoperidinium* Bergh, 1881 (Gomez, 2005). More than 32 species of protoperidinioides are documented to form the fossilizable resting cysts (Head, 1996; Kawami and Matsuoka, 2009).

Dinoflagellate cyst evolution can be traced back to Precambrian or early Cambrian based on the geochemical analyses whereas fossilizable dinocysts have been reported from the mid-Triassic with its highest diversity has reported during the Cretaceous period. However, the living counterparts of the dinoflagellate cysts are only known for some of the modern dinoflagellates with no possibility of knowing the cyst-theca relationship of pre-Quaternary dinoflagellate cysts. Hence, dual taxonomic systems have been followed: one centred on the motile cells and other on the resting cysts of the dinoflagellates. In recent years the developments in the cyst incubation and molecular analyses have led to establishing the cyst-theca relationship of few extant taxa, whereas many species have yet to be discovered by their biological counterpart. However paleontological approach has validity by International Code of Nomenclature for algae, fungi and plants (ICN) and has significance in the paleoecological application of cyst. Besides fresh cyst collection is often not feasible from the offshore waters, particularly when the cyst productivity is very low. Thus the paleontological approach is highly useful to understand the dinoflagellate cysts diversity. In the present study, we describe the four new species following the paleontological approach due to the difficulty of collecting fresh cysts from the offshore where these species are found. The described species are very distinct from any other species which has already been described. The cyst theca relationship will further provide the information of their respective biological counterpart when carried out successfully.

### Palaeogeographical and ecological significance

Family Protoperidiniaceae consists of Subfamily Protoperidinioideae and Subfamily Diplopsalioideae. In palaeontological approach, several species of *Protoperidinium* which are spherical round browns, devoid of ornamentation and processes were categorized into the genus *Brigantedinium*. *Dubridinium* is the only cyst based genus which accommodates Diplopsalioideae. Genus *Echinidinium* Zonneveld (1997) was proposed to accommodate several spherical cysts with numerous spines. Cyst wall, the shape of the archeopyle are the major differentiating taxonomic characters amongst these genera. All the species of *Brigantedinium* includes only saphopylic intercalary archeopyle with one or more plates with no processes on the cyst wall. Theropylic archeopyle were proposed by Matsuoka (1988) to describe the species with adnate archeopyle where archeopyle opens as a split. All of the species described under *Echinidinium* have theropylic archeopyle, which involves one to several sutures. However, in all these above-mentioned species, the expression of paratabulation is only in the form of archeopyle. The genus *Cryodinium* was erected by Esper and Zonneveld (2002) to accommodate the protoperidinioid species in which paratabulation is fully expressed in the form of low sutural septa and archeopyle. *Cryodinium meridianum* is the only round brown species which is reported to have an expression of paratabulation in the form of low sutural septa. In the present study, *C?. matsuokai* sp. nov is described which consists of paratabulation expressed by high parasutural septa. Paratabulation expressed in the form of parasutural septa is commonly found in gonyalaucoid *Spiniferites* and *Impagidinium* species. *Spiniferites* and *Impagidinium* have been reported in entire Cenozoic. *C. meridianum* is endemic to the Southern Ocean and presently described species *C?. matsuokai* is from the tropical basin and suggests that protoperidinioid species with complete paratabulation in the form of parasutural septa and archeopyle have a wide latitudinal distribution rather restriction to high latitudes.

Several studies from different ocean regimes from the Pacific, Atlantic, Arctic, Indian ocean and subtropical domain of the Southern Indian oceans reveal that protoperidinioid cysts dominate the cyst assemblage in coastal areas, shallow bays and upwelling areas which are rich in nutrients (Holzworth *et al*., 2007; Matsuoka *et al*., 2003; Ribero and Amorim, 2008; Pospelova *et al*., 2008). Their high diversity is reported from the Arabian Sea, Southern Indian Ocean, Japanese Coastal waters, East China Sea, Gulf of Mexico, NW African region and Coastal areas of the Mediterranean Sea. The majority of the protoperidinioids have a wide geographical range from polar to tropical (Marret and Zonneveld, 2003; Zonneveld *et al*., 2013), whereas some species such as *Echinidinium bispiniformum* are endemic to the Arabian Sea. Similarly, *Cryodinium meridianum* is only reported from the Southern Ocean and *Caspindium rugosum* to the Caspian Sea (Zonneveld *et al*., 2013). Presently described protoperidinioid species may be endemic to the northern India Ocean due to its peculiar oceanographic setting under tropical monsoon basinal influence and oxygen minima conditions with seasonality. However additional studies from the other tropical basins could further refute their endemic nature.

The cyst assemblage from the Bay of Bengal is studied by Narale *et al*. (2013), Uddandam *et al*. (2017) that reported the dominance of protoperidinioids from the Bay of Bengal. The assemblage consists of *Stelladinium robustum, Stelladinium stellatum, Lejeunecysta oliva, Lejeunecysta sabrina, Echinidinium bispiniformum, Echinidinium aculeatum* and *Bitectatodinium spongium* (Uddandam *et al*., 2015). This assemblage is comparable with that described from other tropical oceans such as coastal regions of Arabian Sea, Gulf of Mexico, NW Africa, Japanese Coastal areas, Tokyo Bay and Gamak Bay

(Zonneveld and Brummer, 2000; Limoges *et al.*, 2013). All these regions characteristically display eutrophic conditions with an inter-annual variability in the trophic status of the waters. The above species are also found in the shelf sediments from the southeast Arabian Sea (author's personal observation) as well as in the Andaman Sea (Su-Myat *et al.*, 2013). These nutrient-rich, low saline regimes are significantly influenced by runoff and are well connected by the ocean currents. This has not been reported from the northern and western Arabian Sea. Further studies from the tropical regions are needed to confirm their endemic behavior. Present new protoperidinioids species in the Bay of Bengal indicate low saline nutrient-rich conditions due to enhanced river discharge during the summer monsoon.

## CONCLUSIONS

This study of organic-walled dinoflagellate cyst from the western Bay of Bengal documents the occurrence of four new protoperidinioid species *Cryodinium? matsuokai, Lejeunecysta longistraiata, Quinquecuspis pentagona* and *Stelladinium denticulatum*. Unique oceanographic setting: low saline condition, high nutrient content and ample availability of prey could be the major cause of high diversity of the protoperidinioid cysts. Culture and molecular studies can reveal the motile affinity of the cyst which can give inferences regarding the evolution of various structures in the protoperidinioid species.

## ACKNOWLEDGEMENTS

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