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A STUDY OF THE DISTRIBUTION PATTERN OF DINOFLAGELLATE CYSTS FROM THE BAY OF BENGAL

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ABSTRACT

Dinoflagellates are one of the major phytoplankton groups of the marine system. The onshore-offshore trends exhibited by dinoflagellate cysts are important criteria to decipher palaoenvironmental and palaeo-oceanographic changes. Several studies have been carried out on the organic-walled dinoflagellate cyst distribution pattern in surface sediments of various marine regions of mid-high latitudes with very few studies from the tropical oceans. In the present study, dinoflagellate cyst distribution pattern was studied in proximal-distal transect of the western Bay of Bengal at a water depth of 25m to 2500m. Distribution of different species of protoperidinioid and gonyaulacoid dinoflagellate cysts were studied. Four major types of dinoflagellate cyst associations, which are characteristic of inner neritic (Inner shelf), outer neritic (outer shelf), slope and oceanic zones, have been recognized. With the exception of gonyaulacoid dinoflagellate cyst *Bitectatodinium spongium,* coastal inner and outer neritic regions of the Bay of Bengal are dominated by protoperidinioid dinoflagellate cysts (heterotrophic forms). The oceanic assemblages are characterized by a low diversity of gonyalaucoid dinoflagellate cysts (autotrophic forms) represented by *Spiniferites* species. The heterotrophic dinoflagellate cyst species, predominant in the inner, outer and slope regions, show considerable variation in the species composition in coastal to distal region of the Bay of Bengal. Diversity and abundance of protoperidinioid dinoflagellate cysts point to a high-nutrient loading and eutrophic environmental conditions of marine waters stretching as far as the slope regions of the Bay of Bengal. Based on the present study, it is deciphered that high nutrient supply and salinity fluctuations due to river runoff activity determine the distribution pattern of dinoflagellate cyst in coastal to distal parts of the Bay of Bengal.

Keywords: Dinoflagellates, Organic-walled dinoflagellate cysts, Gonyaulacoid, Protoperidinioids, and western Bay of Bengal

INTRODUCTION

The dinoflagellates are the major organic-walled phytoplankton group that inhabits the marine system from coastal to open oceans. Cysts, formed by the dinoflagellates during their sexual life cycle, consist of refractory molecules which are resistant to degradation and hence get preserved in the sediments as fossils (Zonneveld *et al*., 2008). Based on the morphological characteristics, fossil dinoflagellate cysts (dinocyst) can provide useful information regarding the palaeoproductivity, palaeoenvironment and palaeoceanographic fluctuations of the past. The two characteristic groups of dinoflagellate cysts: gonyaulacoides and peridiniodes, having autotrophic and heterotrophic mode of nutrition also show morphological variation in their respective cysts. Cysts of gonyaulacoid which are autotrophs, are generally spherical to subspherical or ovoid in shape with small and long processes as additional supportive features. The cysts of peridinoides are usually more or less pentagonal in shape with less complicated wall features and are mostly heterotrophs. Peridinoides dominate in the upwelling regions and river mouths that are characterized with high nutrient loading; on the contrary, Gonyaulacoides are found in the low productive regimes of marine waters to moderate productivity. Their distribution has been applied for the palaeoecological, palaeoenvironmental as well as palaeo-sea level reconstructions (Pospelova *et al*., 2006; Reichart and Brinkhuis, 2003; Sprangers *et al*., 2004).

Besides the productivity-related signals, dinoflagellate cysts distribution is also found to exhibit onshore-offshore trends in relation to the upper water hydrological changes. The onshore-offshore trend is mainly due to the nutrient availability and depth of the waters. Specific assemblages of dinoflagellate cysts are known to characterize the inner neritic, outer neritic as well as open oceans (Wall *et al*., 1977). This trend is expressed in the form of dinoflagellate cysts species composition and also in terms of their abundance. Temporal shifts in the characteristic dinoflagellate cyst assemblages from the stratigraphic succession are effectively utilized as proxy indicator for deciphering the past sea-level fluctuations. In the last two decades, improved ecology of dinoflagellate cysts through numerous studies from different parts of the northern and the southern hemispheric oceans allowed utilization of cyst distributions to reconstruct the palaeoclimate, palaeoecological, and palaeoceanographic changes (de Vernal *et al*., 1997, 2000, 2005; Harland *et al*., 2004; Head, 2007; Höll *et al*., 2000; Holzwarth *et al*., 2010;. Kholief *et al*., 2009; Marret *et al*., 2001; Patterson *et al*., 2011; Pospelova *et al*., 2006; Reichart and Brinkhuis, 2003; Verleye and Louwye, 2010).

As cyst distribution is defined by the complex interaction of biotic and abiotic factors such as prey availability, salinity, temperatures, their distribution exhibits differences on the regional scale (Zonneveld *et al*., 2103). Thus, the ecological signals deciphered on regional scales through modern dinoflagellate cyst distribution studies are required for their application. Such dinocyts studies from the northern Indian ocean are very limited and mainly confined to the western Arabian Sea and coastal areas of the Eastern Arabian Sea (Zonneveld, 1997, Zonneveld and Brummer, 2000, D'silva *et al*., 2011, 2012, 2013). From the Bay of Bengal, study of dinoflagellate cyst distribution is confined to the coastal regions of the western Bay of Bengal and dinoflagellate cyst distributions from the outer neritic and oceanic zones are still scanty (Narale *et al*., 2013; Naidu *et al*., 2012). Thus, the present study has been undertaken to document the distribution of dinoflagellate cysts on the seafloor of the western Bay of Bengal and to identify the

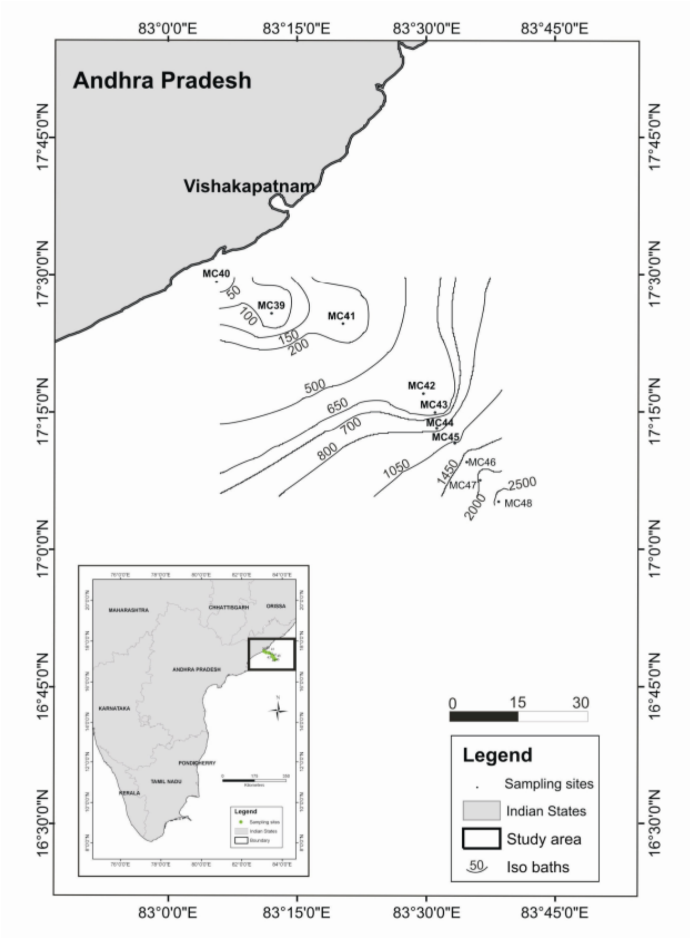

Fig 1. Study area map depicting the sample locations.

proximal distal trend in their distribution which can be utilized to decipher the productivity changes and sea-level fluctuations on regional scales.

STUDY AREA

The Bay of Bengal is a tropical basin in the northern Indian Ocean, which is situated in the monsoon belt. Hydrography of the Bay of Bengal is highly modulated by the seasonally reversing monsoon winds - southwesterly winds in the summer and northeasterly in the winter. Besides the monsoon winds, huge discharge from Ganga-Brahmaputra, Krishna, Godavari, Penner, Mahanadi and Irrawaddy rivers play a significant role in defining the physical, chemical and biological oceanography of the Bay (Varkey *et al*., 1996). The Bay of Bengal receives immense quantities of fresh water by way of heavy precipitation (~2 myr^{-1}) as well as by runoff from peninsular rivers (1.625 x 10^{-12} m^3yr^{-1}) (Prasad, 1997; Subramanian, 1993). River discharge is maximum in the summer monsoon period than other seasons. Variation in the river discharge, together with the oceanic precipitation, makes different salinity gradients spatially and temporally across the bay. In the upper 100m, vertical salinity gradient is 4.5 psu which decreases to 1.5 psu towards the central bay and along the western boundary, salinity gradient is observed as 4 psu which decrease to 1 psu towards the southern bay (Kumar *et al*., 2010). Temperature gradient is very less in comparison with the salinity gradient (Cullen, 1981; Vinayachandran *et al*., 2002). River discharge results in very low salinity as well as a strong stratification in the upper waters. Stratification in the upper waters impedes the vertical mixing of nutrients resulting in nutrient limitation for the biological productivity (Vinayachandran *et al*., 2002; Kumar *et al*., 2002).

Upwelling process which enhances biological productivity is only confined to the coastal areas in the western boundary of the Bay of Bengal (Shetye *et al*., 1991; Murthy and Varadachary 1968). Despite the tropical bay, light is a limiting factor due to high cloud cover during the summers, and high suspended sediments discharged by the rivers make light a limiting factor for the biological productivity (Kumar *et al*., 2010). Stratification, localized upwelling, absence of vertical mixing, low light intensity turns the bay as an oligotrophic region (Kumar *et al*., 2002). Meso-scale processes such as eddies and cyclones enhance the biological productivity in the Bay of Bengal (Muraleedharan *et al*., 2007). Though it is under the same climatic forcing, biological productivity in the Bay of Bengal is low in comparison with Arabian Sea (Kumar *et al*., 2002). Even though the total column productivity is low, the surface productivity is 1.25 times higher in the Bay of Bengal than the Arabian Sea (Kumar *et al*., 2010).

Table: 1. Details of the studied sample locations.

Sample name	Latitude	Longitude	Depth (m)
MC 39	17°26.282	83°12.353	54.7
MC 40	17°29.720	83°05.959	28.7
MC 41	17°25.149	83°20.663	72.9
MC 42	17°17.537	83°30.034	280.1
MC 43	17°15.518	83°31.362	520.4
MC 44	17°13.823	83°31.602	763.4
MC 45	17°12.094	83°33.667	1034.9
MC 46	17°10.076	83°35.073	1510
MC 47	17°08.063	83°36.694	2029.8
MC 48	17°05.776	83°38.790	2540.2

MATERIAL AND METHODS

Ten surface sediment samples analyzed in the present study were collected during the cruise SK-308 from the western Bay of Bengal (location 17°26-17°05 and 83°12-83°38) from a water depth of 25-2500 m. Details of the sample location is given in the Table 1; Fig. 1. Samples were collected with the multicorer and sub sampled on board with 1cm interval. Top 1cm of the sediment was processed according to the standard palynological methods. Samples were first acid digested in the 10% of HCl to remove the carbonates, followed by three decantation in the distilled water. Samples were further treated with 40% of HF to digest the silica which is removed by three decantation in the distilled water. Samples were sieved after the chemical treatment to concentrate the cysts on the 20 µm sieve and the final residue was evenly spread on the glass slides in the polyvinyl alcohol. Slides after drying were mounted in the Canada balsam. Dinoflagellate cysts identification is carried out on the basis of the published literature (Marret and Zonneveld, 2003; Radi *et al*., 2013). *Brigantedinium* spp include all *Brigantedinium* species which were unidentifiable due to the preservation effects in the present study. One whole slide is scanned to document the cyst abundances.

RESULT

In the present study, seven genera and twenty four species of dinoflagellate cysts were identified from the surface sediments of the Bay of Bengal region. Out of 24 species, 17 species are Protoperidinoides and heterotrophic in nature and 7 species are gonyaulacoid and autotrophic in nature. List of documented species are provided in the Table 2. Cyst counts varied from 2-166/slide. Maximum abundances were found in the sample mc 42 at a depth of 280m. Highest species diversity is found in the sample at a depth of 1034m of slope region and lowest from the sample from the 2019 and 2540 of oceanic region. Details of the cyst abundances at each sample are given in the Table 3; Fig. 2. Plates I and II show the identified species of the present study.

The present study has revealed four principal patterns of cyst assemblages in costal and inner neritic, outer neritic, slope and oceanic zones respectively (Fig. 3).

Group 1 coastal association

Coastal zone assemblage are composed of the following species: *Bitectatodinium spongium, Selenopemphix quanta, Spiniferites* sp, *Brigantedinium* sp, *Lejeunecysta oliva, Lejeunecysta Sabrina, Stelladinium stellatum, Stelladinium robustum, Votadinium calvum, Lejeunecysta* sp, *Operculodinium centrocarpum, Protoperidinium latissinum* and *Polysphaeridium zoharyi.*

Group 2 outer neritic association

Outer neritic assemblage is composed of *Bitectatodinium spongium, Tuberculodinium vancompoae, Trinovantedinium applantum, Quniquecuspis concreta, Selenopemphix nephroides, Spiniferites* spp, *Brigantedinium* spp, *Lejeunecysta oliva, Selenopemphix quanta, Stelladinium stellatum, Votadinium calvum, Lejeunecysta* sp, and *Operculodinium* sp.

Table. 2: List of identified dinoflagellate cysts and their motile affinity (Head , 1996).

	Cyst	Motile affinity
1.	***B****itectatodinium spongium* (Zonneveld 1997) Zonneveld et Jurkschat 1999	Unknown
2.	*Brigantedinium simplex* Wall 1965 ex Lentin et Williams 1993	*Protoperidinium conicoides* (Paulsen) Balech 1973
3.	*Brigantedinium spp.*(Reid 1977*)*	*Peridiniaceae*
4.	*Echinidinium bispiniformum* (Zonneveld 1997)	Unknown
5.	*Lejeunecysta oliva* (Reid 1977) Turon et Londeix 1988	Unknown
6.	*Lejeunecysta sabrina* (Reid) Bujak 1984	?*Protoperidinium leonis* (Pavillard) Balech 1974
7.	*Lingulodinium machaerophorum* (Deflandre et Cookson 1955) Wall 1967	*Lingulodinium polyedrum* (Stein) Dodge 1989
8.	*Operculodinium centrocarpum* Wall et Dale 1966	*Protoceratium reticulatum* (Claparde et Lachmann) Bütschli 1885
9.	Cysts of *Protoperidinum americanum* (Gran et Braarud) Balech 1974	*Protoperidinum americanum* (Gran et Braarud) Balech 1974
10.	Cysts of *Protoperidinium nudum* (Wall and Dale 1968)	*Protoperidinium nudum* (Wall and dale 1968)
11.	Cysts of *Polykrikos kofoidii* (Chatton 1964)	*Polykrikos kofoidii* (Chatton 1964)
12.	Cysts of *Protoperidinium latissinum* (Kofoid) Balech 1974	*Protoperidinium latissinum* (Kofoid) Balech 1974
13.	*Quinquecuspis concreta* Reid 1977	*Protoperidinium leonis* (Pavillard) Balech 1974
14.	*Selenopemphix nephroides* (Benedek 1972) Benedek et Sarjeant 1981	*Protoperidinium subinerme* (Paulsen) Loeblich III 1970
15.	*Selenopemphix quanta* (Bradford 1975)	*Protoperidinium conicum* (Gran) Balech 1974
16.	*Spiniferites mirabilis* (Rossignol 1967) Sarjeant 1970	*Gonyaulax spinifera complex* (Claparede et Lachmann) Diesing 1866 complex
17.	*Spiniferites* spp.	*Gonyaulax* sp. indet.
18.	*Stelladinium robustum* Zonneveld 1997	unknown
19.	*Stelladinium stellatum* (Wall et Dale) Reid 1977	*Protoperidinium stellatum* (Nie) Balech 1974
20.	*Trinovantedinium applanatum* (Bradford 1977) Bujak et Davies 1983	*Protoperidinium pentagonum* (Gran) Balech 1974
21.	*Tuberculodinium vancompoae* (Rossignol 1962) Wall 1967	*Pyrophacus steinii* (Schiller) Wall et Dale 1971
22.	*Votadinium calvum* Reid 1977	*Protoperidinium oblongum* (Aurivillius) Parke et Dodge 1976
23.	*Votadinium spinosum* Reid 1977	*Protoperidium claudicans* (Paulsen) Balech 1974
24.	*Polysphaeridium zoharyi* (Rossignol 1962)	*Pyrodinium bahamense* (Plate 1906)

Table. 3: Dinoflagellate cyst counts at each studied sample.

Sample name	*Bitectatodinium spongium*	*Tuberculodinium vancompoae*	*Spiniferites spp*	*Lingulodinium machaerophorum*	*Brigantedinium spp*	*Trinovantedinium applanatum*	*Lejeunecysta oliva*	*Quinquecuspis concreta*	*Selenopemphix nephroides*	*Selenopemphix quanta*	*Stelladinium stel-latum*	*Votadinium calvum*	*Lejeunecysta .sp*	*Echinidinium spp*	*Operculodinium spp*	*Polysphaeridium zoharyi*	*Protoperidinium latissinum*	Total
MC40	55	0	5	0	3	0	9	0	0	15	4	3	7	2	1	2	2	108
Mc39	10	0	0	0	3	0	9	1	0	4	2	0	0	0	1	0	0	30
MC41	28	0	0	0	12	1	18	6	7	1	12	1	0	0	0	0	0	86
MC42	7	1	0	0	79	0	20	2	24	2	24	3	2	2	0	0	0	166
MC43	1	1	1	1	30	1	6	0	12	0	12	1	1	0	0	0	0	67
Mc44	6	1	1	0	28	0	11	6	7	4	14	1	2	1	0	0	0	82
MC45	10	2	1	1	8	4	1	2	1	2	2	0	7	0	2	0	0	44
Mc46	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3
Mc47	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
MC48	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2

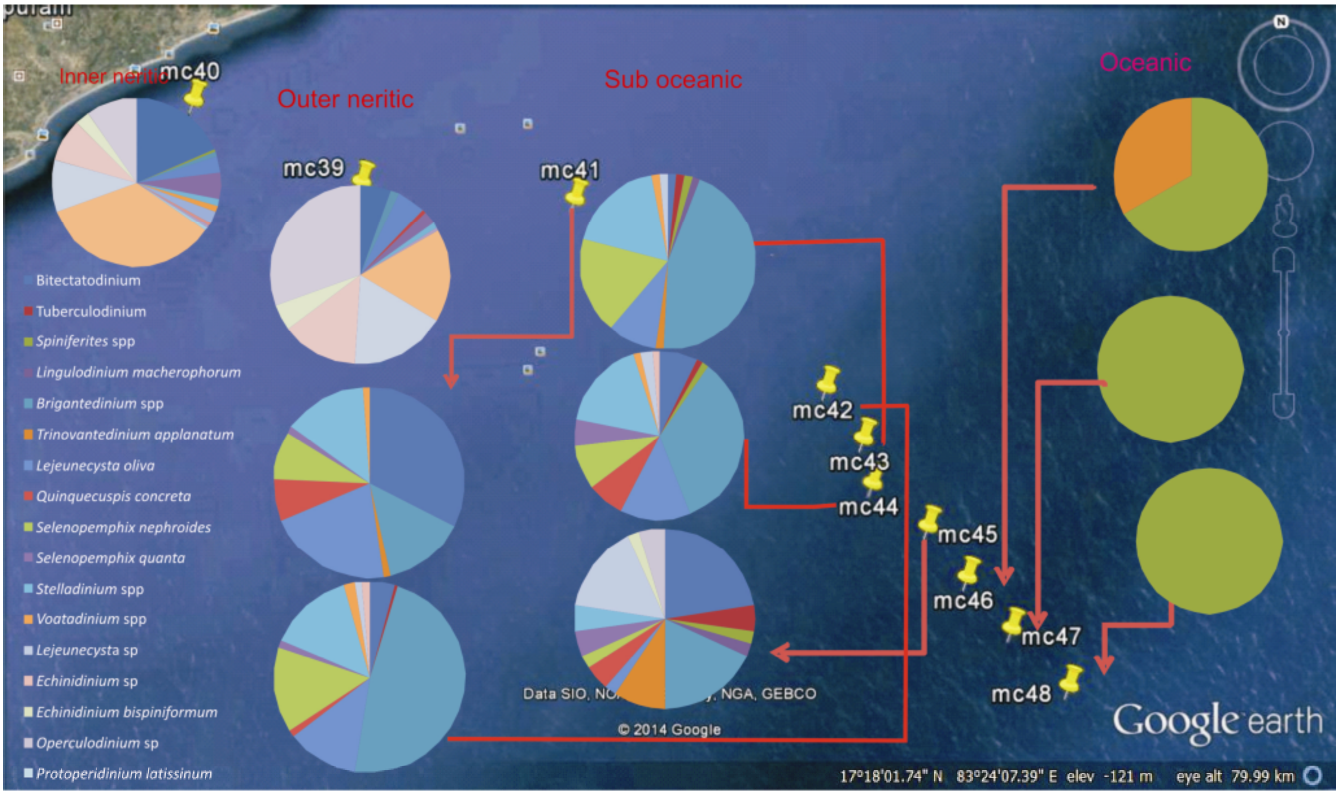

Fig. 3. Different cyst associations documented in the present study.

Group 3 slope association

Slope assemblages are composed of *Bitectatodinium spongium, Tuberculodinium vancompoae, Trinovantedinium applantum, Quniquecuspis concreta, selenopemphix nephroides, Spiniferites* spp, *Brigantedinium* spp, *Lejeunecysta oliva, Lingulodinium machaerophorum, Selenopemphix quanta, Stelladinium stellatum, Votadinium calvum, Lejeunecysta* sp, and *Operculodinium* sp.

Group 4 oceanic association

Oceanic assemblages are composed of only two species viz. *Spiniferites* sp and *Trinovantedinium applanatum.*

DISCUSSION

The Bay of Bengal is strongly influenced by freshwater influx due to monsoonal rains and large amount of river runoff. In the present study, the inner neritic or coastal region of the western Bay of Bengal which is at 28 m water depth is characterized by the dominance of autotrophic species *Bitectatodinium spongium* (55%) and heterotrophic species *Selenopemphix quanta as* the second dominant species(14%). *Bitectatodinium spongium* is considered a fully marine species and has been reported from tropical oceans (Zonnenveld *et al*., 2013). Its high abundances are also observed from the anoxic to hypoxic regions of the Arabian Sea and not reported from the ventilated waters (Zonnenveld *et al*., 2013). In the studies from the Arabian Sea, *Bitectatodinium spongium* has been documented during the active upwelling time period of southwest monsoons (Zonneveld, 1997; Zonneveld and Brummer, 2000). The second dominant species in the inner neritic zone is *Selenopemphix quanta,* which has a global distribution in the coastal regions from high latitude to equatorial regions (Marret and Zonneveld, 2003). Its high abundances are generally found in the upwelling regions, river plumes and frontal areas and have been positively correlated with the biogenic silica from off NW Africa, suggesting its relation with the diatom productivity (Zonneveld *et al*., 2010; Zonneveld *et al*., 2013; Price and Pospelova, 2011). In the Mediterranean Sea, dominance of *Selenopemphix quanta* is linked with low salinity and low bottom oxygen levels (Elshanawany *et al*., 2010). The other hetrotrophic species *Stelladinium stellatum*, *Stelladinium robustum* are also reported from the upwelling regions globally (Zonneveld *et al*., 2013*).*

It is reported that the upwelling in the Bay of Bengal is confined to the shallow waters depths (within 40km from the coasts) during the southwest monsoon period and is characterized by decrease in temperature and salinity and increase in nutrients (Vijayakumaran, 2004). In addition, low dissolved oxygen levels have also been observed during the upwelling

EXPLANATION OF PLATE I

1, ***Bitectatodinium spongium*** (Zonneveld 1997) Zonneveld et Jurkschat 1999) lateral view. 2 & 3 ***Bitectatodinium spongium*** (Zonneveld 1997) Zonneveld et Jurkschat 1999) dorsal view with archeopyle. 4, ***Spiniferites mirabilis*** (Rossignol 1967) Sarjeant 1970. 5, ***Spiniferites*** sp. 6, ***Tuberculodinium vancompoae*** (Rossignol 1962) Wall 1967showing archeopyle. 7, ***Tuberculodinium vancompoae*** (Rossignol 1962) Wall 1967 showing barrel shaped processes. 8, 9, 10, - ***Brigantedinium*** spp (Ried ,1977). 11, 12, ***Echinidinium bispiniformum*** (Zonneveld 1997). 13, ***Lejeunecysta oliva*** (Reid 1977) Turon et Londeix 1988 ventral view. 14, ***Lejeunecystsa oliva*** (Reid 1977) Turon et Londeix 1988 dorsal view showing archeopyle. 15, ***Protoperidinium latissinum*** (Kofoid) Balech 1974. 16, ***Quinquecuspis concreta*** (Reid 1977) Harland 1977.

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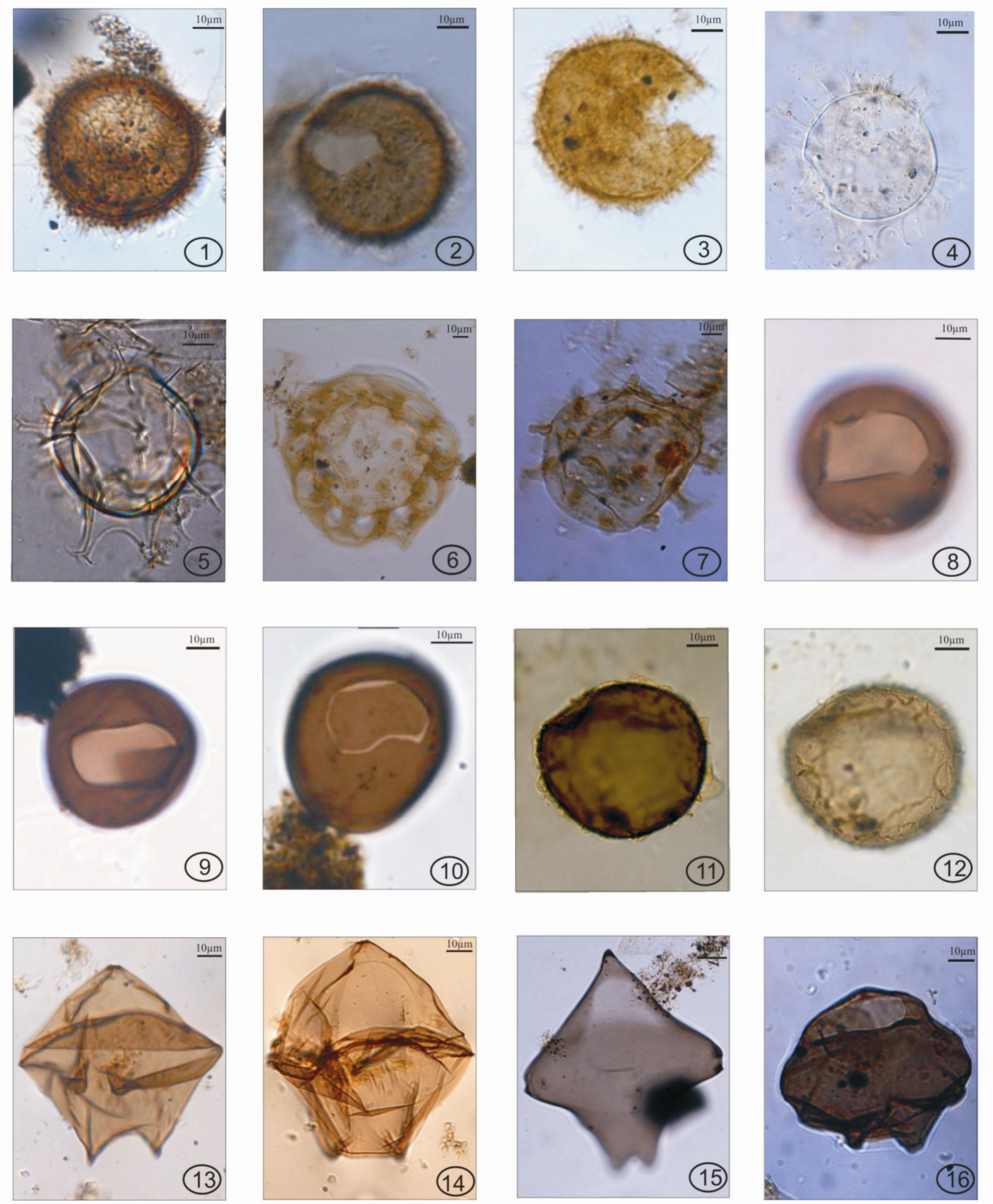
Plate I



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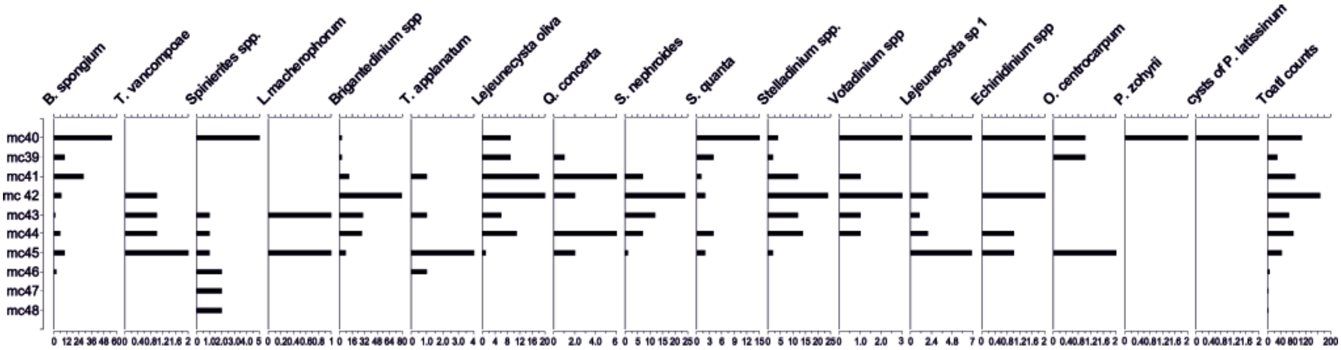

Fig. 2. Dinoflagellate cyst abundances documented in the present study.

period of summer monsoon in the coastal areas in the Bay of Bengal region (Madhu *et al*., 2006; Vijayakumarn, 2004). The dinoflagellate cyst record from the present study suggests that the dominance of *Bitectatodinium spongium* and *Selenopemphix quanta* signifies high nutrient but reduced salinity and low bottom water oxygen conditions caused by the upwelling and river runoff in the inner neritic and coastal zone of the western Bay of Bengal. It is deciphered that the coastal waters receive huge amounts of suspended sediments during summer monsoon which lowers the light penetration in the coastal waters, together with high cloud cover in the summer which acts as a limiting factor for the growth of other autotrophic dinoflagellate cysts (Phytoplankton) production.

The surface samples MC 39, MC 41 and MC 42 at depths of 55 m, 73m and 280m respectively belong to the outer neritic region in the western Bay of Bengal. The assemblage of outer neritic region shows several protoperidinioid along with single occurrences of gonyaulacoid dinoflagellate species *Bitectatodinium spongium.* However, the number of *Bitectatodinium spongium* cyst is considerably reduced in this zone as compared to the inner neritic zone. The increase in the diversity of dinoflagellate cysts indicates high nutrient but normal saline conditions as well as increase in the depth.

The surface samples MC 43, MC 44 and MC 45 from the water depth of 520, 763 and 1034 m respectively belong to slope region. This zone shows dominance and diversity of protoperidinioid dinoflagellate cysts and *Brigantedinium* species dominate within the protoperidinioid assemblage. *Brigantedinium* sp. is a cosmopolitan dinoflagellate cyst and is widespread globally from polar to tropical regions. *Brigantedinium* sp is reported from the nutrient-rich regions like the coastal areas and upwelling regions of the Benguela upwelling region and the Arabian Sea. It appears in all type of environments and observed in coastal to open ocean central gyres (Marret and Zonneveld, 2003). In the Benguela upwelling region, it is known to form 85% of the cysts association (Holzworth *et al*., 2007). In the Mediterranean Sea, their highest abundances are observed in the distal end of river plumes and also attributed to the low- oxygen conditions (Elshanawany *et al*., 2010). They are also known as round browns and are highly susceptible to oxidation (Zonneveld *et al*., 2001). *Stelldinium stelllatum, Lejeunecysta* sp*, Selenopemphix quanta* and *Selenopemphix nephroides* are the other dominant protoperidinoid species in this zone. Majority of these protoperidinioides are found in the upwelling regions of the Arabian Sea and in the oligotrophic Mediterranean Sea in low saline waters in the regions of active river discharge (Zonneveld and Brummer, 2000; Zonneveld *et al*., 2013; Elshanawany *et al*., 2010).

Protoperidinoides being heterotrophs feed on different preys such as diatoms, copeopod eggs, organic matter but their high abundances and dominance are mainly attributed to the diatom availability in several previous reports from the world oceans (Zonneveld *et al*., 2013 and references there in). Earlier studies carried out from the Bay of Bengal showed that diatoms are the dominant group of phytoplankton which makes almost 85% of the phytoplankton assemblage during all the seasons (Madhu *et al*., 2006; Gauns *et al*., 2005) which benefit from the high inputs of silica from the continents through river runoff. Thus, the present study suggests that diatom availability played a major role in defining the dinoflagellate cyst assemblage in the outer neritic and slope zones. Further, the low oxygen bottom water conditions in these regions (Madhu *et al*., 2006) have made condition suitable for the preservation of protoperidinioid dinoflagellate cysts as they are prone to oxidation.

The surface samples MC 46, MC 47 and MC 48 from the water depths of 1510 m, 2029 and 2540 m respectively belong to oceanic zone and is characterized by *Spiniferites* spp., a gonyaulacoid dinoflagellate cyst (autotroph). *Spiniferites* is a cosmopolitan dinoflagellate cyst, having wide distribution from coastal and open oceans (Zonneveld *et al*., 2013). The very low abundances of this species from the oceanic zone in the present study reflect low nutrient conditions.

The present study documents the dinoflagellate cyst distribution from the surface sediments of the western Bay of Bengal. Dinoflagellate cyst distribution reflects the environmental and trophic changes from the onshore to offshore

EXPLANATION OF PLATE II

1. ***Selenopemphix nephroides*** (Benedek 1972) Benedek et Sarjeant 1981with apical antapical compression. 2. **Selenopemphix *nephroides*** (Benedek 1972) Benedek et Sarjeant 1981 *with archeopyle.* 3, **Selenopemphix *quanta*** (Bradford 1975) Matsuoka 1985 *dorsal view.* 4, **Selenopemphix *quanta*** (Bradford 1975) Matsuoka 1985 apically antapically compressed. 5, ***Selenopemphix quanta*** (Bradford 1975) Matsuoka 1985 apical view showing archeopyle and operculum inside. 6, ***Stelladinium robustum*** (Zonneveld 1997) *showing archeopyle.* 7, ***Stelladinium stellatum*** (Wall) Reid1977. 8, ***Stelladinium robustum*** (Zonneveld 1997)*cingulum exposed.* 9, **Stelladinium *reidii*** (Bradford 1975). 10, ***Trinovantedinium applanatum*** (Bradford 1977) Bujak et Davies 1983 *dorsal surface with* cingulum *exposed.* 11, ***Trinovantedinium applanatum*** (Bradford 1977) Bujak et Davies 1983 ventral showing surface ornamentation. 12, 13, ***Votadinium calvum*** (Reid 1977) with fully detached operculum. 14, ***Votadinium calvum** (*Reid 1977) with attached operculum. 15, ***Votadinium spinosum*** (Reid 1977) operculum attached. 16, ***Votadinium spinosum*** (Reid 1977) dorsal surface showing the surface ornamentation and archeopyle

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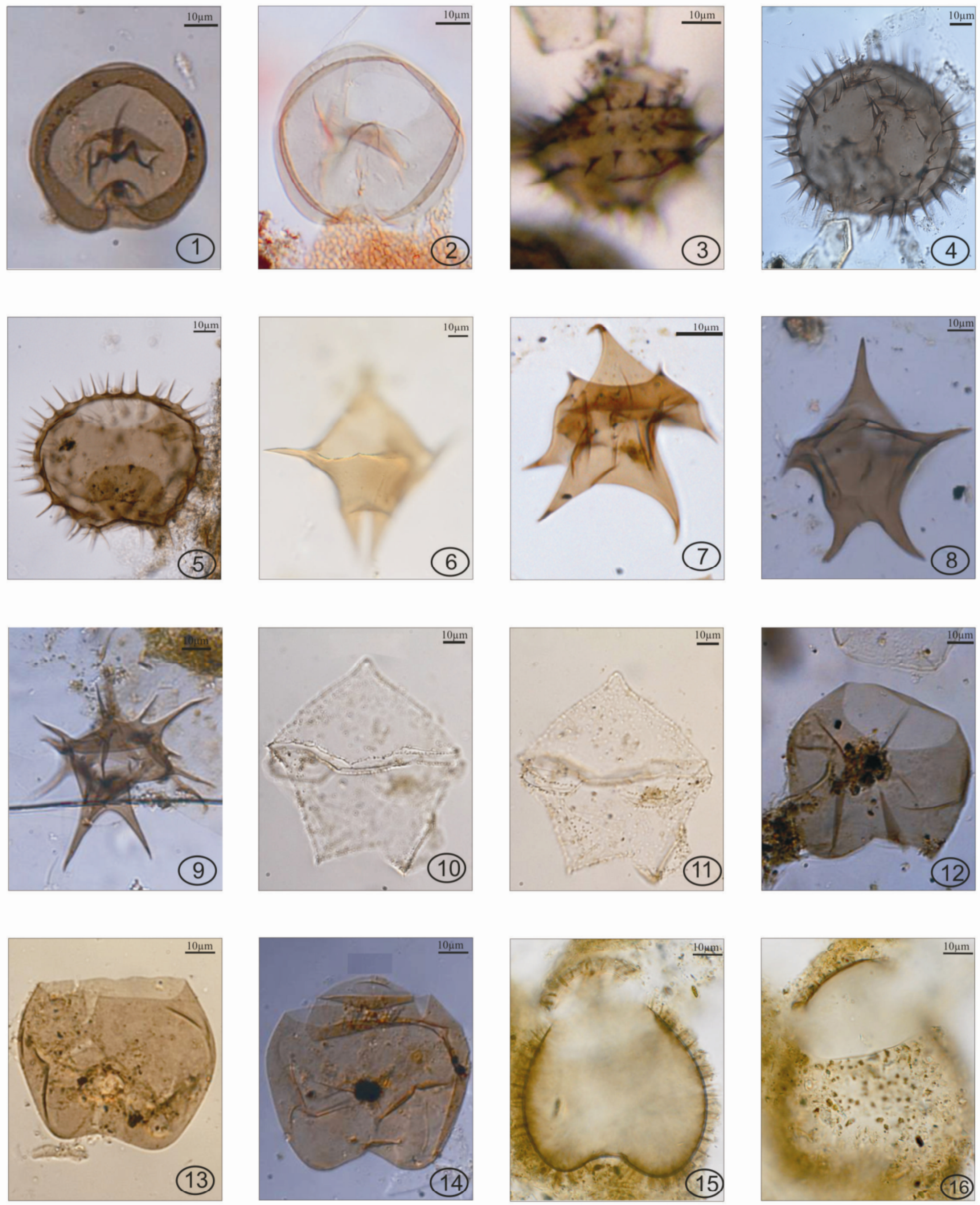
Plate II



regions. The dominance of the protoperidinioid cysts which are sensitive to oxidation and also nutrient indicators could be a potential proxy to decipher the bottom water redox conditions as well as trophic changes associated with the river runoff activity in the past. The observed proximal distal trend exhibited in the form of four major characteristic associations from onshore to offshore regions of the Bay of Bengal can be used as an analog for deciphering the productivity-related changes and climate of the past from this region.

CONCLUSIONS

The dinoflagellate cyst records from the Bay of Bengal surface sediments obtained in this study enable us to draw the following conclusions:

– Four different dinoflagellate cyst assemblages were characterized for the coastal and inner neritic, outer neritic, slope and oceanic zones in western Bay of Bengal.
– High nutrient loading due to active river discharge makes the slope region more dinoflagellate productive region as compared to the outer and inner neritic zones of the Bay of Bengal.
– Low diversity of gonyaulacoid (autotrophic dinoflagellate cysts) is observed as a result of large amounts of suspended sediments during summer monsoon, light limitation, together with a high cloud cover in the summer.
– The dominance of protoperidinioid dinoflagellate cyst (heterotrophs) is attributable to the probable increased silica mobility due to high riverine activity resulting in high diatom productivity, since diatoms are a major source of heterotrophic nutrition.

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REFERENCES

Cullen, J. L. 1981. Microfossil evidence for changing salinity patterns in the Bay of Bengal over the last 20000 years. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, **35**: 315-356.

D'Silva, M. S., Anil, A. C. and D'Costa, P. M. 2011. An overview of dinoflagellate cysts in recent sediments along the west coast of India, Indian. *Journal of Geo Marine Sciences*, **40**(5): 697–709.

D'Silva, M. S., Anil, A. C., Borole, D. V., Nath, B. N. and Singhal, R. K. 2012, Tracking the history of dinoflagellate cyst assemblages in sediments from the west coast of India. *Journal of Sea Research*, **73**: 86–100.

D'Silva, S. M., Anil, A. C. and Savant, S. S., 2013. Dinoflagellate cyst assemblages in recent sediments of Visakhapatnam harbour, east coast of India: Influence of environmental characteristics. *Marine Pollution Bulletin*, **66** (1–2): 59–72.

de Vernal, A. and Pedersen, T. F. 1997. Micropaleontology and palynology of core PAR87A-10: A 23,000 year record of paleoenvironmental changes in the Gulf of Alaska, northeast North Pacific. *Paleoceanography*, **12**(6): 821–830.

de Vernal, A., Eynaud, F., Henry, M., Hillaire-Marcel, C., Londeix, L., Mangin, S., Matthiessen, J., Marret, F., Radi, T., Rochon, A., Solignac, S., Turon, J. L. 2005. Reconstruction of sea surface conditions at middle to high latitudes of the Northern Hemisphere during the Last Glacial Maximum (LGM) based on dinoflagellate cyst assemblages. *Quaternary Science Reviews*, **24**: 897–924.

de Vernal, A., Hillaire-Marcel, C. 2000. Sea-ice cover, sea-surface salinity and halo thermocline structure of the northwest North Atlantic: modern versus full glacial conditions. *Quaternary Science Reviews*, **19**: 65–85.

Elshanawany, R., Zonneveld, K. A. F, Ibrahim, M, I. and Kholeif, S. E. A. 2010. Distribution patterns of recent organic-walled dinoflagellate cysts in relation to environmental parameters in the Mediterranean Sea. *Palynology*, **34**(2): 233-260.

Gauns, M., Madhupratap, M., Ramaiah, N., Jyothibabu, R., Fernandes, V., Paul, J. T., Prasanna Kumar, S. 2005. Comparitive accounts of biological productivity characteristics and estimates of carbon fluxes in the Arabian Sea and Bay of Bengal. *Deep-Sea Research II*, **52**: 2003-2017.

Harland, R., Nordberg, K., Filipsson, H. L. 2004. A high resolution dinoflagellate cyst record from latest Holocene sediments in Koljö Fjord, Sweden. *Review of Palaeobotany and Palynology*, **128**: 119–141.

Head, M. J. 1996. Chapter 30. Modern dinoflagellate cysts and their biological affinities, p. 1197-1248. In: *Palynology: principles and applications,* (Eds. Jansonius, J. and McGregor, D. C.), American Association of Stratigraphic Palynologists Foundation,Vol. 3.

Head, M. J., 2007. Last interglacial (Eemian) hydrographic conditions in the southwestern 776 Baltic Sea based on dinoflagellate cysts from Tistinge Kline, Denmark. *Geological Magazine*, **144**: 987–1012.

Höll, C., Zonneveld, K. A. F., & Willems, H. 2000. Organic-walled dinoflagellate cyst assemblages in the tropical Atlantic Ocean and oceanographical changes over the last 140 ka. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **160** (1–2): 69–90.

Holzwarth, U., Esper, O., Zonneveld, K. A. F. 2007. Distribution of organic-walled dinoflagellate cysts in shelf surface sediments of the Benguela upwelling system in relationship to environmental conditions. *Marine Micropaleontology*, **64**: 91–119.

Holzwarth, U., Esper, O., Zonneveld, K. A. F. 2010. Organic-walled dinoflagellate cysts as indicators of oceanographic conditions and terrigenous input in the NW African upwelling region. *Review of Palaeobotany and Palynology*, **159**: 35–55.

Kholeif, S. E. A. and Mudie, P. J. 2009. Palynological records of climate and oceanic conditions in the Late Pleistocene and Holocene of the Nile Cone, southeastern Mediterranean, Egypt. *Palynology*, **33**: 1–24.

Kumar, P. S., Muraleedharan, P. M., Prasad, T. G., Gauns, M., Ramaiah, N., de Souza, S. N., Sardesai, S. and Madhupratap, M. 2002. Why is the Bay of Bengal less productive during summer monsoon compared to the Arabian Sea? *Geophysical Research Letters*, **29**(24): 88-1-88-4.

Kumar, P. S., Nuncio, M., Narvekar, J., Ramaiah, N., Sardesai, S., Gauns, M., Fernandes, V., Paul, J. T., Jyothibabu, R and Jayaraj, K. A. 2010. Seasonal cycle of physical forcing and biological response in the Bay of Bengal. *Indian Journal of Marine Sciences*, **39**(3): 388-405.

Madhu, N. V., Jyothibabu, R., Maheswaran, P. A., Gerson, V. J., Gopalakrishnan, T. C. and Nair, K. K. C. 2006, Lack of seasonality in phytolankton standing stock (chlorophyll a) and production in the western Bay of Bengal. *Continental Shelf Research*, **26**: 1868–1883.

Marret, F. and Zonneveld, K. A. F. 2003. Atlas of modern organic-walled dinoflagellate cyst distribution. *Review of Palaeobotany and Palynology*, **125**: 1–200.

Marret, F., de Vernal, A., Benderra, F. and Harland, R. 2001. Late Quaternary sea-surface conditions at DSDP Hole 594 in the southwest Pacific Ocean based on dinoflagellate cyst assemblages. *Journal of Quaternary Science*, **16**(7): 739–751.

Muraleedharan, K. R., Jasmine, P., Achuthankutty, C.T., Revichandran, C., Kumar, D. P. K., Anand, P. and Rejomon, G. 2007. Influence of basin-scale and mesoscale physical processes on biological productivity in the Bay of Bengal during the summer monsoon. *Progress in Oceanography*, **72**(4): 364- 383.

Murty, C. S. and Varadachari, V. V. R. 1968. Upwelling along the east coast of India. *Bull. Nat. Inst. Sci. India*, **36**: 80-86.

Narale, D. D., Patil, J. S. and Anil A. C. 2013. Dinoflagellate cyst distribution in recent sediments along the south-east coast of India. *Oceanologia*, **55** (4): 979–1003.

Naidu P. D., Patil J. S., Narale D. D., Anil A. C., 2012. A first look at the dinoflagellate cysts abundance in the Bay of Bengal: Implications on late quaternary productivity and climate change, *Current Science,* **102**(3), 495–498.

Patterson, R. T., Swindles, G. T., Roe, H. M., Kumar, A. and Prokoph, A. 2011. Dinoflagellate cyst-based reconstructions of mid to late Holocene winter sea-surface temperature and productivity from an anoxic fjord in the NE Pacific Ocean. *Quaternary International*, **235**: 13–25.

Pospelova, V., Pedersen, T. F. and de Vernal, A. 2006. Dinoflagellate cysts as indicators of climatic and oceanographic changes during the past 40 kyr in the Santa Barbara Basin, southern California. *Paleoceanography*, **21**: 1–16.

Prasad, T. G. 1997. Annual and seasonal mean buoyancy fluxes for the tropical Indian Ocean. *Current Science*, **73**: 667-674.

Price, A. M. and Pospelova, V. 2011. High-resolution sediment trap study of organic-walled dinoflagellate cyst production and biogenic silica flux in Saanich Inlet (BC, Canada). *Marine Micropaleontology*, **80**: 18–43.

Radi, T., Bonnet, S., Cormier, M. A., de Vernal, A., Durantou, L., Faubert, É., Head, M. J., Henry, M., Pospelova, V., Rochon, A. and Nieuwenhove, N. 2013. Operational taxonomy and (paleo-)autecology of round, brown, spiny dinoflagellate cysts from the quaternary of high northern latitudes. *Marine Micropaleontology*, **98**: 41–57.

Reichart, G. J. and Brinkhuis, H. 2003. Late Quaternary Protoperidinium cysts as indicators of paleoproductivity in the northern Arabian Sea. *Marine micropaleontology*, **49**: 303-315.

Shetye, S. R., Shenoi, S. S. C., Gouveia, A. D., Michael, G. S., Sundar, D. and Nampoothiri, G. 1991. Wind-driven coastal upwelling along the western boundary of the Bay of Bengal during the southwest monsoon. *Continental Shelf Research*, **11**(11): 1397–1408.

Sprangers, M., Dammers, N., Brinkhuis, H., van Weering, T. C. E. and Lotter, A. F. 2004. Modern organic-walled dinoflagellate cyst distribution offshore NW Iberia; tracing the upwelling system. *Review of Palaeobotany and Palynology*, **128**: 97–106.

Subramanian, V. 1993. Sediment load of Indian rivers. *Current Science*, **64**: 928-930.

Varkey, M. J., Murty, V. S. N. and Suryanarayana, A. 1996. Physical oceanography of the Bay of Bengal and Andaman Sea. *Oceanography and Marine Biology* (*an annual Review*), **34**: 1–70.

Verleye, T. J. and Louwye, S. 2010. Late Quaternary environmental changes and latitudinal shifts of the Antarctic Circumpolar Current as recorded by dinoflagellate cysts from offshore Chile (41°S). *Quaternary Science Reviews*, **29**: 1025–1039.

Vijayakumaran, K. 2004. A simple model for predicting upwelling status along Visakhapatnam coast. *Fishery Technology*, **41**(1): 9-16.

Vinayachandran, P. N., Murty, V. S. N. and Ramesh Babu. 2002. Observation of barrier layer formation in the Bay of Bengal during summer monsoon. *Journal of Geophysical Research*, **107**(C12): SRF 19-1-SRF 19-2.

Wall, D., Dale, B., Lohman, G. P. and Smith, W. K. 1977. The environmental and climaticdistribution of dinoflagellate cysts in the North and South Atlantic Oceans and adjacent seas. *Marine Micropaleontology*, **2**: 121–200.

Zonneveld, K. A. F. 1997. New species of organic walled dinoflagellate cysts from modern sediments of the Arabian Sea (Indian Ocean). *Review of Palaeobotany and Palynology*, **97**: 319–337.

Zonneveld, K. A. F. and Brummer, G. J. A. 2000. Ecological significance, transport and preservation of organic-walled dinoflagellate cysts in the Somali Basin, NW Arabian Sea. *Deep Sea Research II* , **47**: 2229–2256.

Zonneveld, K. A. F., Marret, F., Versteegh, G. J. M., Bogus, K., Bouimetarhana, I., Crouch, E., de Vernal A., Elshanawany, R., Esper, O., Forke, S., Grøsfjeld, K., Henry M., Holzwarth, U., Bonnet, S., Edwards, L., Kielt, J. F., Kim, S. Y., Ladouceur, S., Ledu, D., Chen, L., Limoges, A., Lu, S. H., Mahmoud, M. S., Marino, G., Matsouka, K., Londeix, L., Matthiessen, J., Mildenhal, D. C., Mudie P., Neil, H. L., Pospelova, V., Qi Y., Radi, T., Rochon, A., Sangiorgi, F., Solignac, S., Turon J. L., Wang, Y., Wang, Z., Young, M., Richerol, T. and Verleye, T. 2013. Atlas of modern dinoflagellate cyst distribution based on 2405 datapoints. *Review of Palaeobotany and Palynology*, **191**:1–198.

Zonneveld, K. A. F., Susek, E. and Fischer, G. 2010. Seasonal variability of the organic-walled dinoflagellate cyst production in the coastal upwelling region off Cape Blanc (Mauritania): a five-year survey. *Journal of Phycology*, **46**: 202–215.

Zonneveld, K. A. F., Versteegh, G. J. M. and Kodrans Nsiah, M. 2008. Preservation and organic chemistry of Late Cenozoic organic-walled dinoflagellate cysts: A review. *Marine Micropaleontology*, **86**: 179–197.

Zonneveld, K. A. F., Versteegh, G. J. M., de Lange, G. J. 2001. Palaeoproductivity and post depositional aerobic organic matter decay reflected by dinoflagellate cyst assemblages of the Eastern Mediterranean S1 sapropel. *Marine Geology*, **172**: 181–195.

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