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LATE PALEOCENE TO LATE EOCENE CALCAREOUS NANNOFOSSILS IN THE MANNAR BASIN, SRI LANKA; IMPLICATIONS FOR PALEO-EUTROPHICATION CONDITIONS

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ABSTRACT

With a few paleoclimatic assessments in Sri Lanka using calcareous nannofossils as paleoclimatic proxies, the current study focuses on reconstructing the temporal evolution of sea surface paleoclimatic conditions (thermocline and nutricline levels) by studying samples from Dorado-North hydrocarbon exploration well, Mannar Basin. The recovery of well-preserved calcareous nannofossils from Late Paleocene to Late Eocene sediment samples was made possible using the standard smear slide preparation method. Semi-quantitative analysis was conducted examining the relative abundance of *Discoaster*, coccolith size distribution and stratigraphic distribution of *Reticulofenestra* and *Coccolithus* under the polarizing light and scanning electron microscopes. Observing two different co-occurrences of the above-mentioned parameters indicates growing eutrophic conditions from the Late Paleocene to the Late Eocene which were identified from the selected sediment sequence from the Mannar Basin. The sudden influx of terrigenous sediments and the intensified greenhouse climate that occurred during the Late Eocene could be considered for the observed rapid expansion of eutrophication conditions around 55 Ma.

Keywords: *Calcareous Nannofossils, Mannar Basin, Reticulofenestra, Discoaster, Coccolithus*

INTRODUCTION

Biostratigraphic studies play a significant role in converting geological evidence of deep marine sediments to a temporal framework (Backman and Shackleton, 1983). Such research is vital because it allows us to learn more about the structural evolution of earth's oceans, the history of deep and surface oceanic circulation, paleo-temperatures, the evolution of marine plankton, and the causal linkages between them. More than any other category of species, calcareous nannofossils give the most comprehensive (stratigraphic and taxonomic) evidence of biodiversity (Bown et al., 2004). Over the last few decades, a considerable amount of research has been undertaken on the sea surface climatic undulations, based on ecological and morphologic data from calcareous nannofossils. Many researchers have shown that calcareous nannofossils play a key role in the reconstruction of paleo-climatic and paleoenvironmental conditions due to their abundance, diversity, preservation potential and high sensitivity to environmental changes (D'Hondt et al., 1998, Coxall et al., 2006, Hull et al., 2011, Birch et al., 2016, Jones et al., 2019, Sato and Chiyonobu, 2009, Aubry, 1992, Henderiks and Pagani, 2008, Imai et al., 2015). The ecology of marine plankton and benthos is frequently studied as part of a trophic resource continuity. This study uses the stratigraphic distribution of *Discoaster* and size distribution of *Reticulofenestra* and *Coccolithus (RC)* calcareous nannofossil species to reconstruct paleo-eutrophication conditions in the Mannar Basin. Particularly thermocline and nutricline levels, which affect the growth of the calcareous nannofossils, were studied. The thermocline is the strong vertical temperature stratification in the ocean. It is caused by the difference in density between the surface and deep ocean waters, which is probably a result of significant density variations due to the seasonal changes in ocean temperature and salinity. The changes in nutricline levels, which are the vertical nutrient stratification, could result from the density and temperature variations of the sea water, and the amount of suspended solids in it. Eutrophic environments have a stable water column structure, a deep thermocline, and diversified phytoplankton populations dominated by warm-water assemblages, known as 'k mode' specialists in larger coccolith sizes (e.g.: *Reticulofenestra, Coccolithus, Chiasmolithus*). A well-mixed upper water column, a shallow thermocline, and low-diversity communities dominated by opportunistic organisms, particularly cold-water species or in other words, 'r mode specialists' (e.g.: *Discoasters, Fasciculithus, Sphenulithus*) as well as 'k mode' specialists with smaller sizes define oligotrophic regions (Bralower, 2002). The effect of nutrient demand and uptake rates, as well as the light absorption on cell size of calcareous nannoplankton, studied in several works of literature explains why orientation and structural patterns in phytoplankton communities occur (Falkowski, 1998, Farida et al., 2012). Changes in the size distribution of coccoliths that encased coccolithophorids have been widely documented throughout geologic history (Henderiks and Pagani, 2008; Kameo et al., 2010; Herrmann and Thierstein, 2012; Imai et al., 2013). When nutrition supply and temperature conditions are limited, it has been theoretically determined that smaller cells should have a competitive advantage over larger cells (Falkowski, 1998). As a result, during the studies on paleoceanography, it is assumed that oligotrophic environments were often characterized by communities of smaller coccolith fossils, as opposed to eutrophic and unstable environments, where larger coccolith fossils might dominate.

In recent periods as well as during the Neogene, the abundance of *Discoaster* has been found to rise in response to thermocline and nutricline deepening and stratification at the sea surface. Waters above the thermocline and nutricline are found to be oligotrophic, as evidenced by a reduction in coccolithophores stratigraphic distribution and a more significant number of small-size *RC.* Due to increased nutrient delivery to the sea surface from the lower photic zone, shoaling of the thermocline and nutricline results in a drop in *Discoaster* abundance and a rise in coccolithophores stratigraphic distribution and the relative abundance of tiny *RC* species (Fig. 1).

Although there is a wide range of calcareous nannofossil studies done worldwide, there remains a lack of published work on calcareous nannofossils locally. As the only published micropaleontological study from Sri Lanka, Singh et al., (2017) reported calcareous nannofossils from carbonate-rich deep deep-sea sediments obtained from drill cuttings of the Barracuda Petroleum Exploration Well, which is one of Sri Lanka's sedimentary offshore basins, the Mannar Basin (Fig. 2). However, the above study has been carried out for a selected sedimentary sequence and considering a single well location. They have suggested an open marine depositional context and a paucity of terrestrial biogenic sediments to the Mannar Basin from the Middle Paleocene to the Early Miocene by observing and identifying over seventy-five (75) well-preserved species, including calcareous nannofossils and palynomorphs. However, no previous research has investigated or adequately explained the role of calcareous nannofossils in terms of the paleoenvironmental reconstruction in the Mannar Basin. Palaeoclimatology, the study of historical climates and by that, reconstructing paleoenvironmental history gives a longer temporal perspective than the contemporary instrumental records on climatic changes on Earth. The importance is it helps to understand the climate in the past and how it relates to the present and future climate on the palnet.

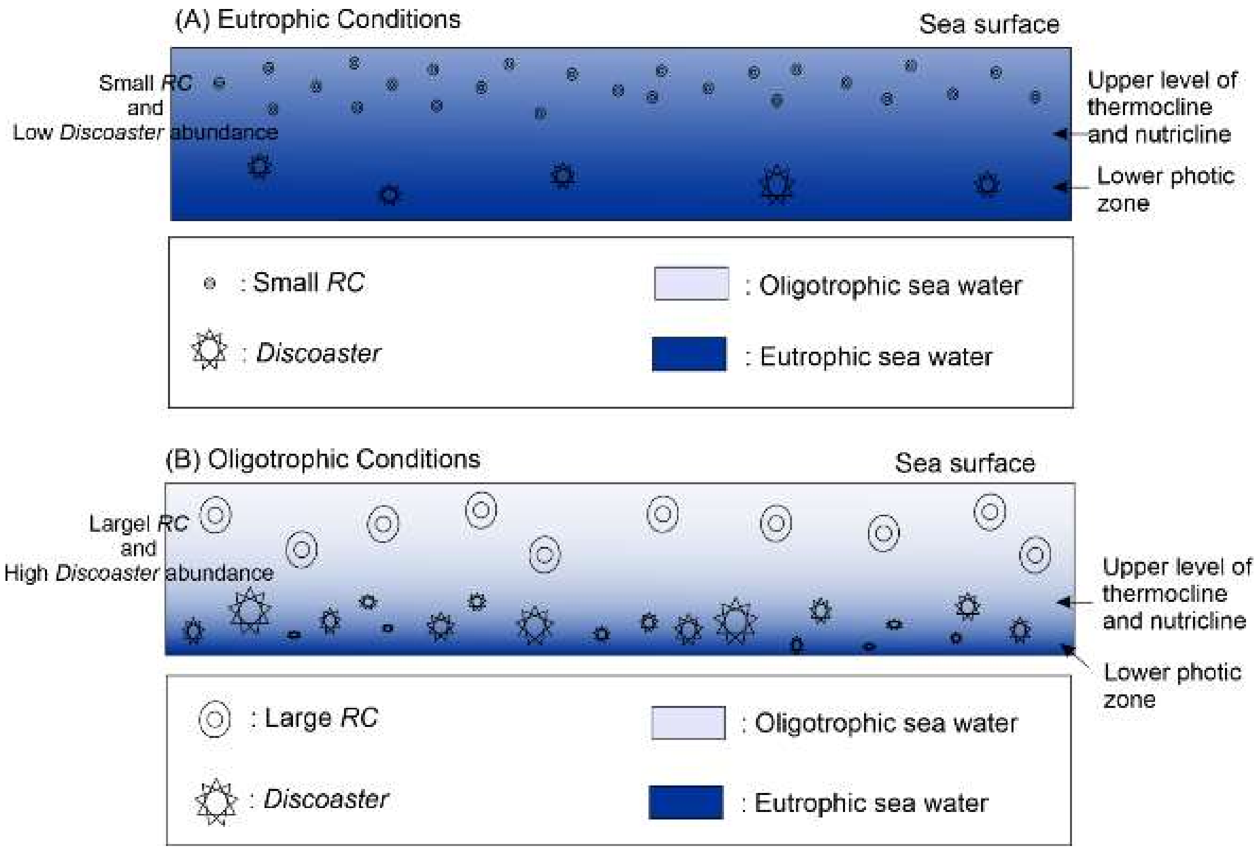

Fig. 1 *Schematic models of the vertical distribution of Reticulofenestra, Discoaster and Coccolithus species under (A) eutrophic conditions and (B) oligotrophic conditions (modified from Sato and Chiyonobu, 2009 and Imai et al, 2015)*

Therefore, the objectives of the current study were to identify the calcareous nannofossils assemblages from the Dorado-North hydrocarbon exploration well in the depth ranges from 2200 m to 2700 m and to identify the relationship between stratigraphic distribution and size variations of calcareous nannofossil species in order to interpret paleo-eutrophication conditions during deposition. According to the unpublished well reports available at the Petroleum Development Authority of Sri Lanka, the studied samples belong to the Paleocene – Eocene boundary and Eocene epoch. The Paleocene - Eocene boundary period was intriguing because it indicated the conversion between Greenhouse climatic conditions, known as Paleocene – Eocene Thermal Maximum (PETM) (Bains et al., 1999, Beerling and Jolley, 1998, Cao et al., 2018, Imai et al., 2015, Tremolada and Bralower, 2004). In this research, we have focused on the sediments deposited during the Late Paleocene to Late Eocene time and attempt to interpret the paleo-eutrophication conditions based on the variations in size and stratigraphic distribution of calcareous nannofossils. The selection of this time period is based on global records showing increases in biodiversity and evolutionary rates of calcareous nannofossils began in the Cretaceous and lasted into the Cenozoic (Agnini et al., 2017).

Geological setting

The present-day configuration of the Indian Ocean and its landmasses is a result of the tectonic evolution of the Indian plate, which was initiated during the Late Jurassic (nearly 167 million years ago) with the breakup of Gondwana (Kularathna et al., 2020). The evolution consists of a variety of plate tectonic events such as a

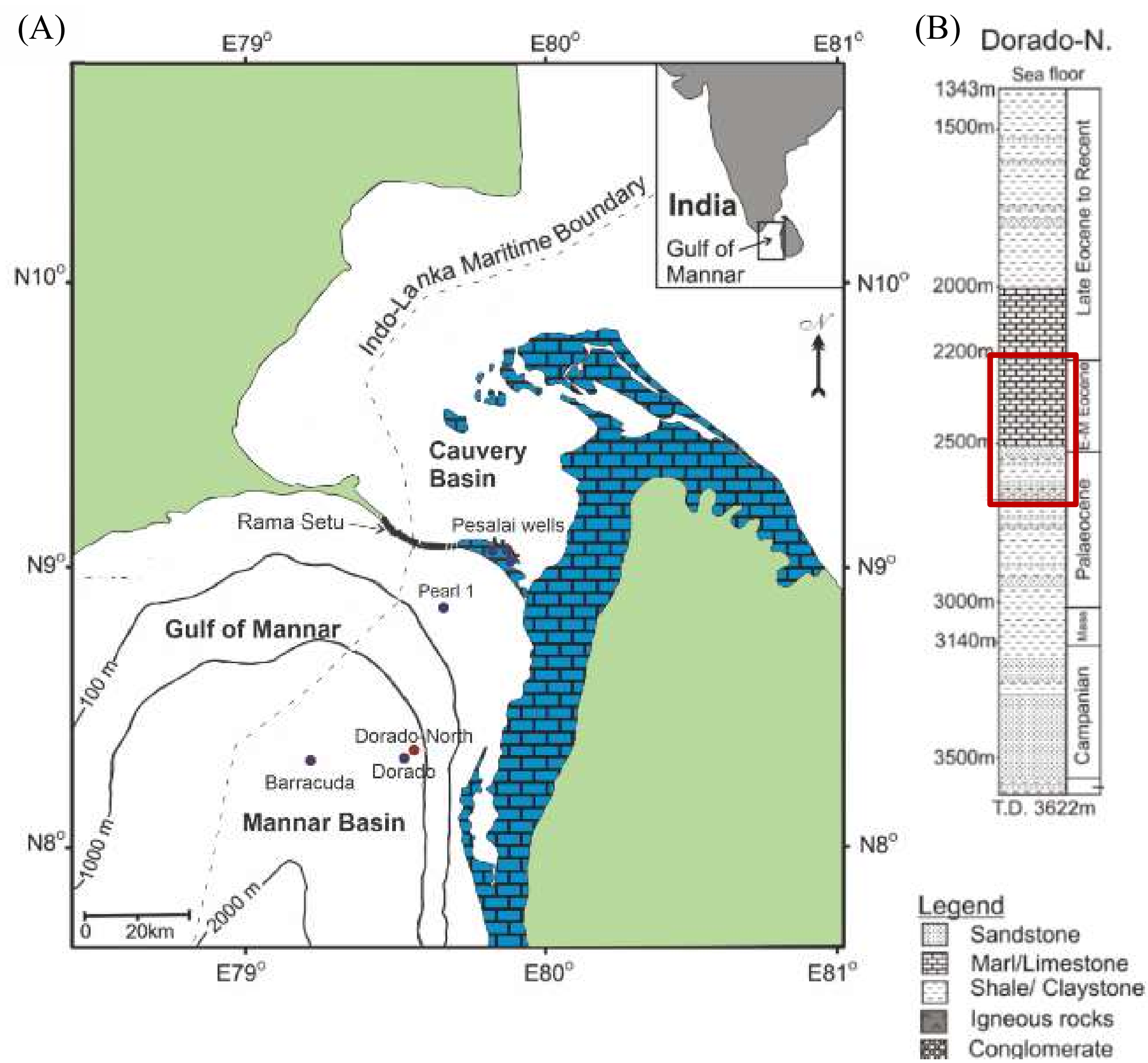

Fig. 2 *(A) Location map of the Northern Mannar Basin and exploration wells drilled in the Mannar Basin Sri Lanka. Modified after (Premarathne et al., 2016) (B) Schematic representation of the sedimentary sequence of the Dorado-North exploration well (studied sediment interval is marked in red) (Premarathne et al., 2013) (Dorado N. = Dorado North)*

continental breakup, sea-floor spreading, rifting and drifting, formation of new oceanic ridges, flood basalt volcanism, hotspot tracks, transform faults, subduction, obduction, continental collision, accretion, and mountain formation etc. (Chatterjee et al., 2013). From 200 Ma to 165 Ma, it is interpreted that the pre-rift episode of the Mannar Basin, Sri Lanka was a part of the East Gondwana (Baillie et al., 2004, Kularathna et al., 2020). During the breakup of Gondwana, the Sri Lankan landmass may have undergone at least two major rifting episodes: the first rifting phase began (165 Ma) along with a major rift system around the present-day Horn of Africa and extended south to the Falkland Islands (Baillie et al., 2004, Royer and Coffin 1992). It was followed by potential counterclockwise rotation, resulting in the present-day discontinuities of the Mannar Basin Cantwell et al., 1978, Kularathna et al., 2015; 2020, Ratheesh-Kumar et al., 2020, Yoshida et al., 1992). The second rifting phase is more noticeable, resulting in the initial formation of the Cauvery and Lanka basins. The separation of India, Madagascar, and Sri Lanka from Antarctica occurred during this event (142Ma) (Kularathna et al., 2020, Premarathne et al., 2015).

The counterclockwise rotation and ensuing strike-slip movement has occurred during the second rifting phase (Kularathna et al., 2015). As a result, additional broadening and mechanical sinking in the Mannar Basin took place (Kularathna et al., 2015, Singh et al., 2017). At the end of the rifting period, the Mannar and Cauvery basins remained a failed rift, and the Lanka basin remained a passive margin (Fig. 2) (Kularathna et al., 2015 ;2020)

MATERIALS AND METHODS

Sample collection, preparation and observation

A total of 20 drill cutting samples corresponding to 2200 m – 2700 m depths interval) were collected from the Petroleum Development Authority of Sri Lanka. The samples were selected at 25 m intervals from a 500 m thick sedimentary succession for nano-paleontological analyses. The samples were named from DN01 to DN 20.

The smear slides were prepared following the standard preparation techniques of Bown and Young, (1998), by powdering samples using an Agate mortar and pestle. Then, each powder sample of ± 0.5 mg, mixed with distilled water,

Table 1 *Calcareous nannofossil taxa identified*

Calcareous Nannofossil Species	References	Calcareous Nannofossil Type
Campylosphaera dela	(Bramlette and Sullivan, 1961) Hay and Mohler, 1967	Placolith
Coccolithus crassus	(Bramlette and Sullivan 1961)	Placolith (r-mode)
Coccolithus formosus	(Kamptner, 1963) Wise, 1973	Placolith (r-mode)
Coccolithus pelagicus	(Wallich 1877) Schiller, 1930	Placolith (r-mode)
Coroncyclus nitescens	(Kamptner, 1963) Bramlette and Wilcoxon, 1967	Placolith
Cyclicalgolithus abisectus	(Roth and Hay, in Hay et al, 1967) Bukry, 1971	Placolith
Discoaster barbadiensis	(Tan Sin Hok, 1927)	Nannolith (k-mode)
Discoaster distinctus	(Martini, 1958)	Nannolith (k-mode)
Discoaster falcatus	(Bramlette and Sullivan, 1961)	Nannolith (k-mode)
Discoaster saipanensis	(Bramlette and Riedel, 1954)	Nannolith (k-mode)
Discoaster spinescens	(Bown and Dunkley Jones, 2006)	Nannolith (k-mode)
Discoaster sublodoensis	(Bramlette and Sullivan, 1961)	Nannolith (k-mode)
Ericsonia subpertusa	(Hay and Mohler, 1967)	Placolith (k-mode)
Helicosphaera bramlettei	(Müller, 1970) Jafar and Martini, 1975	Placolith
Pontosphaera multipora	(Kamptner, 1948 ex Deflandre in Deflandre and Fert, 1954) Roth, 1970)	Murolith
Reticulofenestra bisecta	(Hay, Mohler and Wade, 1966) Roth, 1970	Placolith
Reticulofenestra dictyoda	(Deflandre in Deflandre and Fert, 1954) Stradner in Stradner and Edwards, 1968	Placolith
Reticulofenestra minuta	(Roth, 1970)	Placolith
Sphenolithus delphix	(Bukry 1973)	Nannolith (k-mode)
Sphenolithus moriformis	(Brönnimann and Stradner, 1960) Bramlette and Wilcoxon, 1967	Nannolith (k-mode)
Toweius pertusus	(Sullivan, 1965) Romein, 1979	Placolith (r-mode)

was put on a glass coverslip, flattened and then dried on a hot plate (70 °C). The dried coverslip was affixed (sample smear side down) using Canada Balsam adhesive and labelled. Identification of Calcareous nannofossils was performed using Axio polarized microscope with an oil- immersion objective lens (magnification x1000).

Determination of stratigraphic and size distribution of nannofossils

The paleoceanographic fluctuations in the Mannar Basin were reconstructed using the data analyzed by microscopic observations. Some abundant species were recognized mainly as three genera namely *Discoaster, Reticulofenestra and Coccolithus*. The stratigraphic distribution of each selected species (*Discoaster, Reticulofenestra* and *Coccolithus*) was determined manually using the criteria used in Bown and Young, 1998 and Singh et al., 2017.

A = Abundant (>5 specimen/ field of view)
C = Common (1 specimen/3-10 field of view)
F = Few (1 specimen/ 11-20 field of view)
R = Rare (1 specimen/ 21-100 field of view)

To define the stratigraphic size distribution across the selected sediment sequence, the *Reticulofenestra* and *Coccolithus* (*RC*) coccoliths were measured using an eyepiece graticule.

All the analyses were performed at the Department of Geology, University of Peradeniya, Sri Lanka.

RESULTS

Calcareous nannofossil biostratigraphy

We followed the calcareous nannofossil biostratigraphy zonation, the NP zones (Nannofossils Paleogene), defined by Martini (1971). The first occurrence (FO) and last occurrence (LO) of marker species were used to investigate the distribution pattern of biostratigraphically relevant nannofossils within the specified depth interval.

Eleven (11) genera and twenty-one (21) species of well-preserved calcareous nannofossils were identified in the studied sedimentary section, and several marker taxa were detected. Calcareous Nannofossil taxa identified in the present study are given in alphabetical order in table 1, following Bown and Jones, 2012.

Bio-events and ranges of some significant taxa were used to date the sediments at some depths because of the absence of global age diagnostic taxa. The stratigraphic ranges of the species were referred from Nannotax webpage (Young et al., 2022). The photomicrographs of the identified taxa are discussed in the discussion section.

Fig. 3 indicates the chart showing stratigraphic ranges of identified taxa recorded from the Dorado-North hydrocarbon exploration in the Mannar basin. The observations suggest that the studied sedimentary sequence correlates with Late Paleocene to Late Eocene.

Calcareous nannofossil assemblages

The assemblage of calcareous nannofossils observed within the depth ranges of 2200 m - 2300 m (DN01 to DN04) section was characterized by abundant and common (>5 specimen/ field of view and one specimen/3-10 field of view) species belonging to genera *RC*. In particular, the relative abundance of these species was found to be increased. In this section, the medium (4–6 µm) to small (1–3 µm) coccoliths were dominant. In contrast, *Discoaster* was rare in the section. Most specifically, any of the *Discoasters* were absent from 2200 m to 2280m. Gradually increased abundance of *Discoasters* was observed in the rest of the samples. Sediments between 2300 m – 2380 m (DN05 and DN06) were abundant with *Discoaster*, and only medium-sized (4–6 µm) *RC* were present. However, in the latter part of the studied sediment sequence, depths between 2400 m to 2700 m (DN07-DN20) tend to have relatively larger-sized *RC* species with a high abundance of *Discoaster.*

Coccolithus pelagicus was present more-or-less homogeneously, whereas, *Reticulofenestra,*

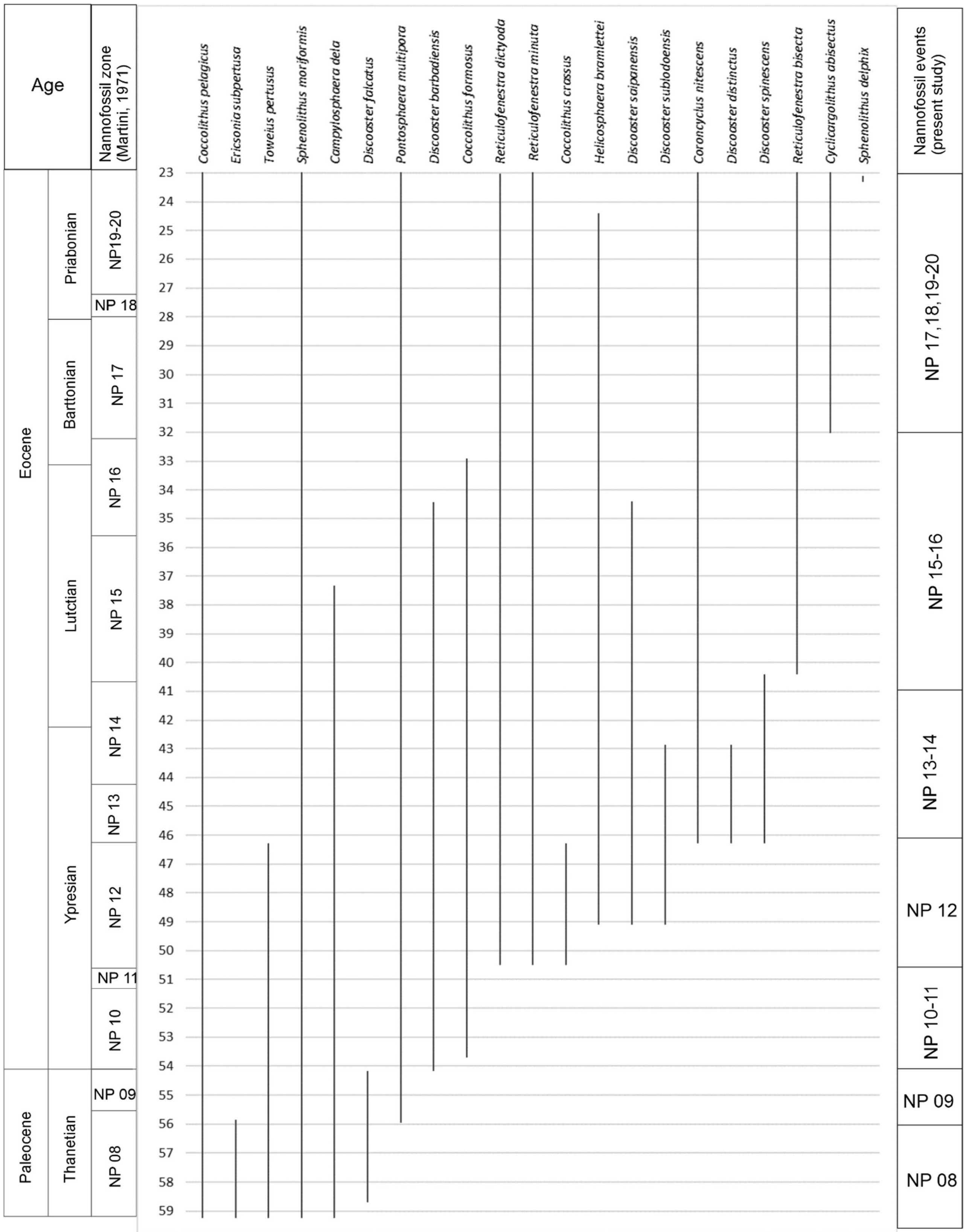

Fig. 3 Chart showing stratigraphic ranges of significant taxa recorded from Dorado-North hydrocarbon exploration well.

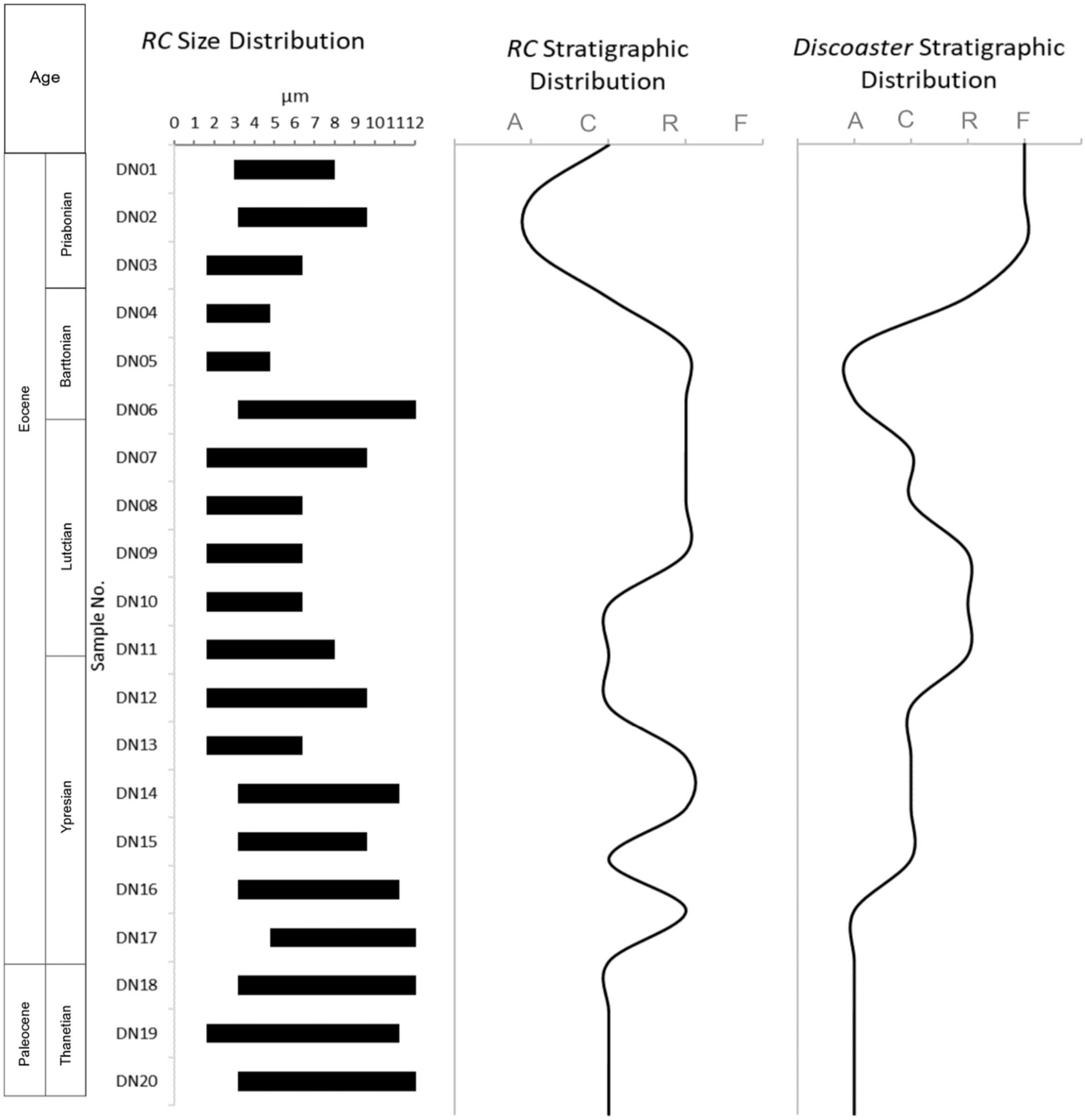

Fig. 4 *Stratigraphic and size distribution of Discoaster and RC. (A = Abundant, C = Common, R = Rare and F= Few)*

Calcidiscus, Blackites and *Sphenulithus* species were randomly identified throughout the selected sedimentary sequence. In DN02 and DN03 (2225 m – 2255 m) samples, there observed a more prolific nature of coccoliths and nannoliths compared to the other samples.

Reticulofenestra and Coccolithus Stratigraphic Distribution and Size Distribution

As illustrated in Fig. 4, the stratigraphic and the size distribution of the *RC* species have highly fluctuated. A closer inspection of the graph shows that the modal size of *RC* has gradually increased when the depth increases. The majority of the *RC* coccoliths had a medium-sized diameter between 4 and 6 µm. An abrupt decrease in the modal size of *RC* was identified in the depths between 2275 m to 2305 m (DN04 and DN05 samples), and it

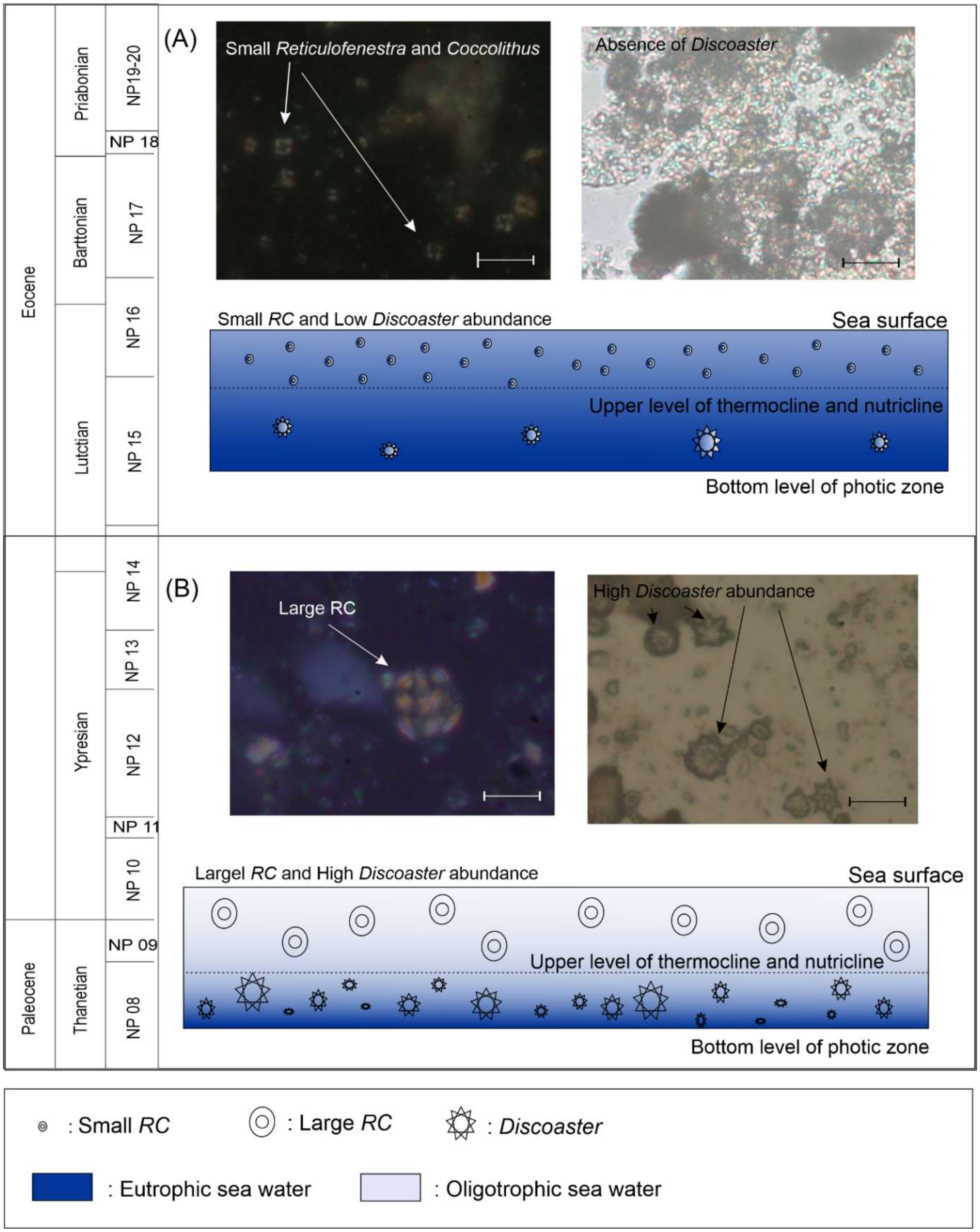

Fig. 5 *A schematic model of the estimated vertical distribution, along with photomicrographs of Late Paleocene to Late Eocene calcareous nannofossil assemblages in Dorado-North hydrocarbon exploration well (A) Eutrophic conditions and (B) Oligotrophic conditions (Scale bar = 10µm)*

was followed by a gradual size increase of coccoliths in the higher depths of the studied depth interval. *RC* coccoliths reached the maximum sizes of 9-12 µm during 2325 m – 2330 m (DN06) and the lowermost part of the studied interval. It is apparent from Fig. 4 that the stratigraphic distribution of the *Reticulofenestra* and *Coccolithus* showed an average distribution. They commonly occur as a specimen per 3-10 field of view. Our results indicate an overall gradual upward increase of *RC* modal and maximum size throughout the studied depth interval in the Dorado-North hydrocarbon exploration well in the Mannar Basin.

The relative abundance and modal size distribution of *RC* species, as well as the stratigraphic distribution of *Discoaster* species, were observed to occur in two primary combinations in the examined sediment sequence;

a) High *RC* stratigraphic distribution, the low relative abundance of *Discoaster*, and abundant small *RC*.

b) Low *RC* stratigraphic distribution, the high relative abundance of *Discoaster*, and abundant large *RC*.

Using the obtained observations, a schematic representation of both *Discoaster* and *RC* stratigraphic and size distribution and paleo-sea surface conditions is presented in fig. 5.

DISCUSSION

In this study, we have considered three genera namely, *Reticulofenestra, Coccolithus* and *Discoaster*, which are resolved to their paleontological and paleoecological indications to determine the paleo-eutrophication conditions. (see Fig. 6).

The coccolith size of *Reticulofenestra* and *Coccolithus*, in particular, is often employed as paleoenvironmental predictors and has been studied in Eocene to Pleistocene sediments from several seas and land sections (Kameo and Takayama, 1999, Kameo and Bralower, 2000). It has been interpreted that the small *Reticulofenestra* is commonly used as an indicator of eutrophic conditions, which is found in upwelling areas (e.g., Pujos, 1987; Young, 1990; Gartner, 1992; Tanaka and Takahashi, 2001; Henderiks, 2008). As in the current study, the observed relatively smaller size *RC* and a presence in high abundancy from 2200 m to 2425 m sediment interval characterize an upwelling region to suggest strong eutrophication conditions during the Late Eocene. On the other hand, the presence of larger *RC* but in low abundance from 2425 m to 2700 m indicates the gradual displacement of warmer and oligotrophic seawater conditions.

In the selected sedimentary sequence, a low *Discoaster* abundance was observed from 2200 m to 2400 m and the abundance was high from 2400 m to 2700 m. *Discoaster* species, an extinct nannoplankton, is known for its star-shaped cell structure (Young et al., 1997) and their occurrence in Neogene strata is thought to be a sign of warm oligotrophic environments (e.g., Bukry, 1973; Haq and Lohmann, 1976; Flores and Sierro, 1987; Chepstow-Lusty et al., 1989). In addition, it has been proposed that *Discoaster* dwelt in the lower photic zone (Aubry, 1992). Therefore, the observations imply warm and oligotrophic seawater conditions during Late Paleocene to Early-Middle Eocene and eutrophic sea water conditions towards the Late Eocene.

The identified co-occurrence of the two combinations of the size and stratigraphic distributions reinforces previous theoretical discussions by Sato and Chiyonobu (2009), Imai et al. (2015) and Hendrizan (2016). Sato and Chiyonobu (2009) state a positive correlation between the mentioned parameters in the sequence from Paleocene to Eocene in the Northwestern Pacific and Eastern Indian oceans. i.e. the abundance of r-mode species such as *Discoaster* indicates oligotrophic conditions in sea surface strata. Imai et al. (2015) similarly interpret that the presence of the high nannofossil accumulation rate, along with the low relative abundance of *Discoaster* and abundant small *RC*, might indicate the rise of the thermocline and nutricline to the sea surface, triggering eutrophic conditions in the Eastern Indian Ocean during Pliocene to Late Miocene. Further, the study interprets that, the low nannofossil accumulation rate, along with the high relative abundance of *Discoaster* and abundant large *RC* suggests the presence of deep thermocline and nutricline, in

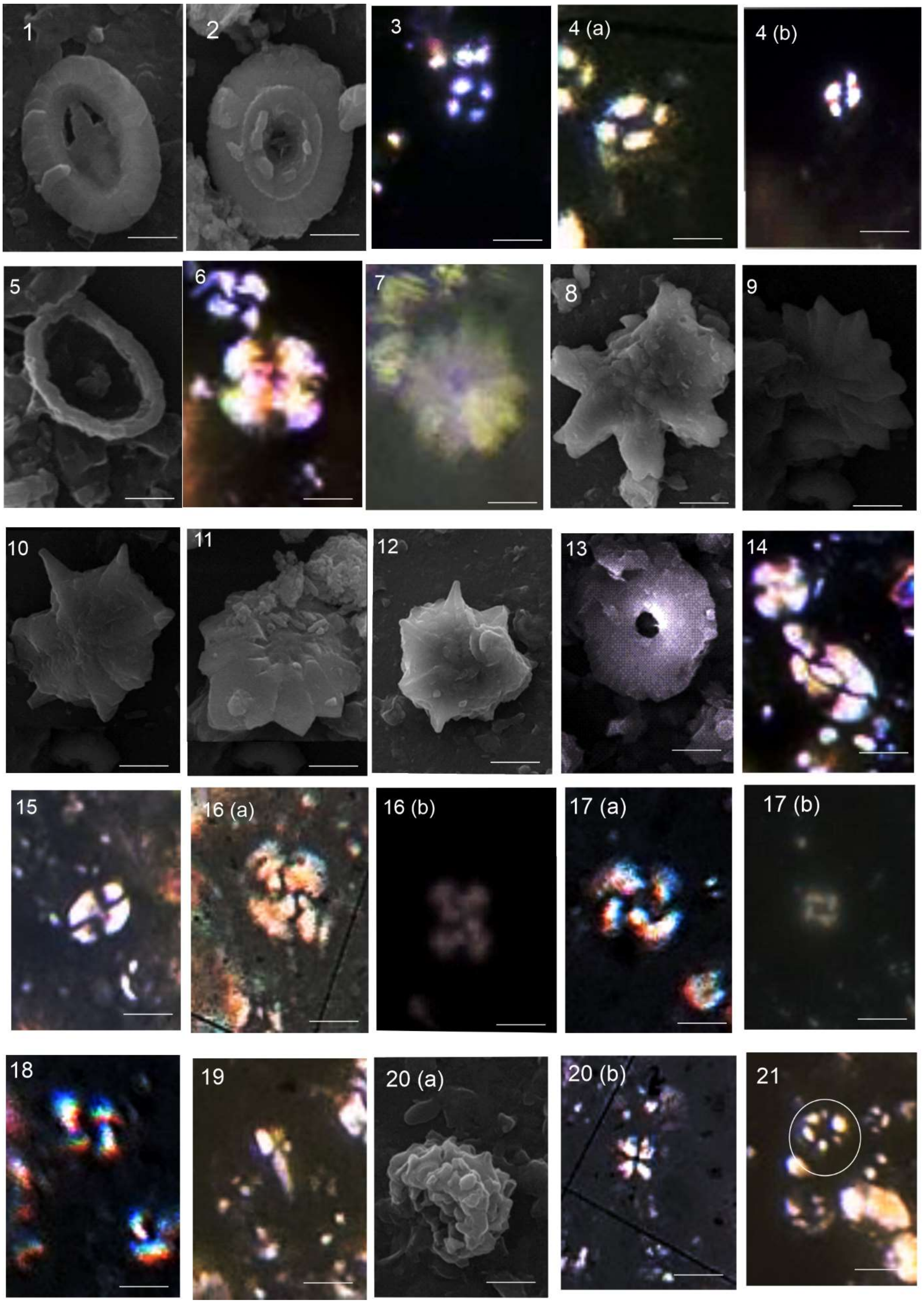
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Fig. 6 *(1) Campylosphaera dela (2) Coccolithus crassus (3) Coccolithus formosus (4 a,b) Coccolithus pelagicus (5) Coroncyclus nitescens (6) Cyclicalgolithus abisectus (7) Discoaster barbadiensis (8) Discoaster distinctus (9) Discoaster falcatus (10) Discoaster saipanensis (11) Discoaster spinescens (12) Discoaster sublodoensis (13) Ericsonia subpertusa (14) Helicosphaera bramlettei (15) Pontosphaera multipora (16 a,b) Reticulofenestra bisecta (17) Reticulofenestra dictyoda (18 a,b) Reticulofenestra minuta (19) Sphenolithus delphix (20 a,b) Sphenolithus moriformis (21) Toweius pertusus*

other words, oligotrophic conditions on the sea surface. The hypothesis of increased eutrophication conditions built-up based on the size and stratigraphic variations towards the Late Eocene can be further confirmed by the interpretation made by Rathnayake (2021). His study interpreted that the development of the calcium carbonate platform can be mainly related to the tropical climate of the Mannar Basin. As the elevating environmental temperature indirectly causes an increase of nutrient influx and algal bloom,his suggestion indirectly supports the idea of increasing eutrophication conditions from Late Paleocene time under tropical climate. Further, the same study has identified an algae-dominated organic matter from the Late Paleocene to Late Eocene sections of the Dorado-North well, which might be a result of the eutrophication condition we suggest and the high yield of planktonic species we observed

The observed results from the current study further support the idea of Imai et al., 2015, who suggested that the increased eutrophication conditions results from tectonic and climate-induced upwelling in terrestrial input and/or coastal surge of nutrients to the oceans. In this study, the improved eutrophication conditions, i.e. high nutrient influx during the Late Eocene, can be interpreted as a result of the high terrestrial sediment influx to the depocentres close to the Indian landmass, including Mannar and Cauvery Basins due to the Indo-Eurasian continental-continental collision that is estimated to have occurred between Late Eocene to Early Oligocene (e.g. Singh et al, 2017; Imai et al, 2015). Also, the increased greenhouse climatic conditions (e.g. Jones et al., 2010) during the Late Eocene might be another reason for the increased eutrophication.

CONCLUSIONS

The current study provides convincing evidence of growing eutrophication from the Late Paleocene to the Late Eocene periods. The existence of relatively small *RC* during the Late Eocene sedimentary sequence, low *Discoaster* abundance, and high *RC* stratigraphic distribution all suggest to eutrophic conditions with shallower thermocline and nutricline.

Contrarily, oligotrophic conditions are evidenced by low *RC* stratigraphic distribution, high *Discoaster* abundance, and the existence of relatively larger RC during the Early Eocene and Late Palaeocene sedimentary sequence.

The occurrence of higher nutrient levels on the sea surface during the Late Eocene could be attributed to the influx of terrestrial sediments into the Bay of Bengal during the Late Paleocene to Late Eocene period.

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