A first look into the Holocene calcareous dinoflagellate cyst record of the eastern Arabian Sea

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ABSTRACT: Marine microfossil records from the Arabian Sea (AS) are mainly limited to foraminifera, with scanty information on other phyto- and zoo-plankton remains. Calcareous dinoflagellate cysts are one of the rarely studied microfossil groups across the world. In the present study, a calcareous dinoflagellate cyst (dinocyst) record from the eastern Arabian Sea (Off-Goa (SC-26)) during the Holocene is presented. Coccoides (vegetative stage of calcareous dinoflagellates) of *Thoracosphaera heimii*, *Leonella granifera* shows a dominance of 82–92% of the total assemblage suggesting a eutrophic environment throughout the studied period. The relative percentage of the dominant species *T. heimii* and *L. granifera* shows an opposite trend. The high relative abundance of *Calciodinellum* species during the early Holocene (prior to 10 ka BP) indicates a comparatively warm and low productivity environment compared with the late Holocene. A strengthening trend in the monsoon during the Holocene since 10 ka BP is reflected by the gradual increase in *L. granifera*, which is a runoff/terrestrial nutrient indicator. The high relative abundance of *L. granifera*, eutrophic taxa, and TOC since 6 ka BP reveals high primary productivity during middle to late Holocene compared with the early Holocene in the eastern Arabian Sea. Sand % which reflects runoff and *L. granifera* records show high similarity revealing that *L. granifera* % can be used as a terrestrial nutrient indicator, which has been suggested previously in studies from the Mediterranean Sea and South Atlantic. This record reveals the potential of calcareous dinoflagellate cysts to reconstruct monsoon variation, particularly runoff changes, in the Arabian Sea.

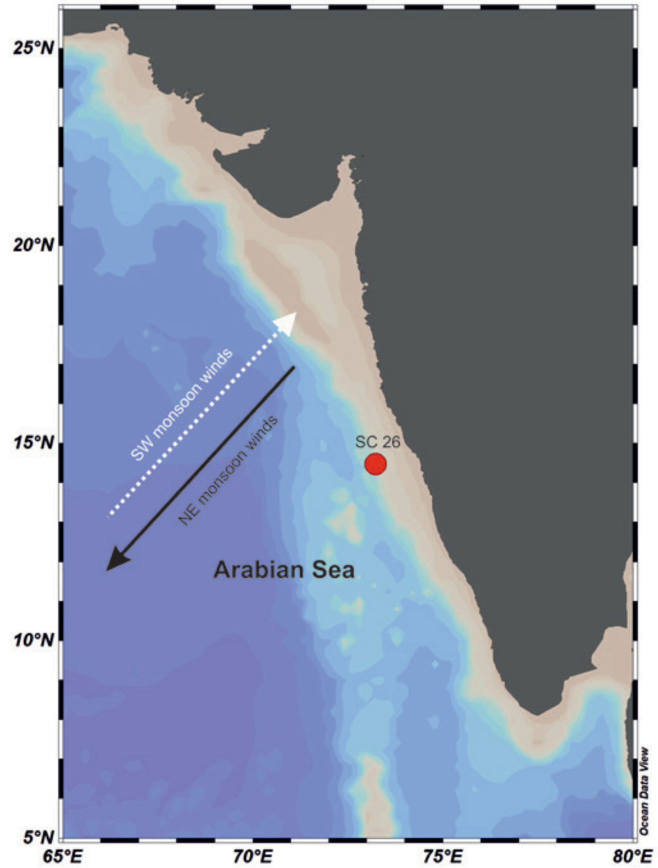
Keywords: Indian Ocean, Monsoon; Primary productivity, Runoff, Calcareous dinoflagellate cysts.

INTRODUCTION

The Arabian Sea is one of the most productive regions in the world, lying in the low latitudes (Bauer et al. 1991). The biological productivity in the Arabian Sea is profoundly influenced by seasonally reversing monsoon winds and associated processes, i.e., upwelling and winter mixing (Brink 1998; Kumar et al. 2001). These processes show spatial and temporal heterogeneity in the Arabian Sea (Gupta et al. 2003; Reichert et al. 2004; Singh et al. 2006; 2011). The summer monsoon induces intense upwelling in the western part and it is comparatively less intensified in the eastern part. The winter monsoon induces convective mixing which is prominent in the northern Arabian Sea (north of 10°N) and weaker in the remaining basin (Prasanna Kumar 1996). The southeastern Arabian Sea receives high runoff discharge from the Western Ghats during the summer monsoon which enhances productivity locally (Sarkar et al. 2000). Several studies have reported the variation in the strength of summer and winter monsoon during glacial and interglacial time scales based on the biotic and geochemical proxies (Sarkar et al. 2000; Thamban et al. 2001; Pattan et al. 2003; Singh et al. 2006; 2011; Pattan and Pearson 2009; Carbarcos et al., 2014; Naik et al. 2016). Monsoon records utilizing biotic proxies are mainly limited to foraminiferal and temporally contrasting productivity variation in the different proxies within the last glacial cycle is recorded from the eastern Arabian Sea (Singh et al. 2011; Cabarcos et al. 2014).

Dinoflagellates represent one of the major phytoplanktons with a benthic resting stage. They produce species-specific cysts that can fossilize in ocean sediments (Head 1996). The cyst wall may be organic or calcareous walled. Calcareous dinoflagellates are primary producers and live in the photic zone in the oceans. Their distribution is highly influenced by the environmental parameters including nutrients, light availability, temperature, and salinity (Esper et al. 2000; 2004; Zonneveld et al. 2000; 2005; Meier and Willems 2003; Vink 2004; Richter et al. 2007; Bison et al. 2009). In the last two decades, several studies have demonstrated their utility in palaeoclimate and paleoceanographic studies (Esper et al. 2000; 2004; Zonneveld et al. 2000; 2005; Meier and Willems 2003; Meir et al. 2004; Vink 2004; Richter et al. 2007; Bison et al. 2009; Heinrich and Zonneveld 2013).

While numerous studies are present on the organic walled dinoflagellate cysts (Narale et al. 2015; Uddandam et al. 2018), calcareous dinoflagellate cysts proxy is relatively a recent development. Calcareous dinoflagellate studies are also sparse from the eastern Arabian Sea. Previous calcareous dinoflagellate cysts studies from the southwestern and northeastern Arabian Sea oxygen minima zone (OMZ) surficial sediments emphasize their potentiality to reflect unaltered primary productivity signals (Wendler et al. 2002). Dinoflagellate cysts species are also found to sensitive to the terrestrial nutrient input (Wendler 2002). In the northern Indian monsoon summer monsoon runoff



TEXT-FIGURE 1
Study area and location map of the spade core – SC-26.

and terrestrial nutrients plays a significant role the surface hydrography, nutrients and primary productivity. It is also difficult to differentiate between the signals of upwelling related nutrients and terrestrial nutrients. Hence calcareous dinoflagellate cysts may provide ample opportunity to reconstruct terrestrial nutrients, primary productivity.

In this study, we have documented variation in the calcareous dinoflagellate cysts from the eastern Arabian Sea to reconstruct the palaeoenvironmental and productivity fluctuation during the last 12 ka BP.

Study area and oceanographic setting

Surface ocean circulation in the Arabian Sea is governed by seasonally reversing Asian monsoon winds. In the summer monsoon (June–September), winds prevail in the SW direction over the Arabian Sea (text-fig. 1). During the summer monsoon period, circulation is clockwise and, the West Indian Coastal Current (WICC) flows southward along the west coast of India and joins the eastward flowing Southwest Monsoon Current (SMC) in the south-eastern Arabian Sea (Schott and McCreary 2001). Summer wind induces upwelling in the coastal regions of the central and southern part of the west coast of India which is strong off Kochi, weak at Mangalore and weaker off Goa (Wyrtki 1973; Muraleedharan and Prasanna Kumar 1996). Intense summer monsoon rainfall on the hinterland also delivers high runoff during the summer monsoon period which forms a freshwater plume in the eastern Arabian Sea (Sarkar et al. 2000). During the winter monsoon periods (December to March) winds flow in the NE direction and the Surface ocean circulation is in a clockwise direction (Wyrtki 1973). The winds induce weak and sporadic upwelling along the west coast of India. During this period the Bay of Bengal currents bring warm low saline waters into the eastern Arabian Sea. The cold and dry NE dry winds induce winter convective mixing in the north-eastern Arabian Sea in modern times (Singh et al. 2018).

MATERIAL and METHODS

Sediment collection

In this study, we investigated sediment samples obtained from 25 cm spade core SC-26 taken at a water depth of 240 m from off Goa (14.47°N; 73.23°E), Eastern Arabian Sea (text-fig. 1). The core is sub-sampled at every 2 cm interval and are stored in clean polyethylene bags. Core lithology is mainly composed of silty-clay throughout the core.

Calcareous dinoflagellate cysts slide preparation

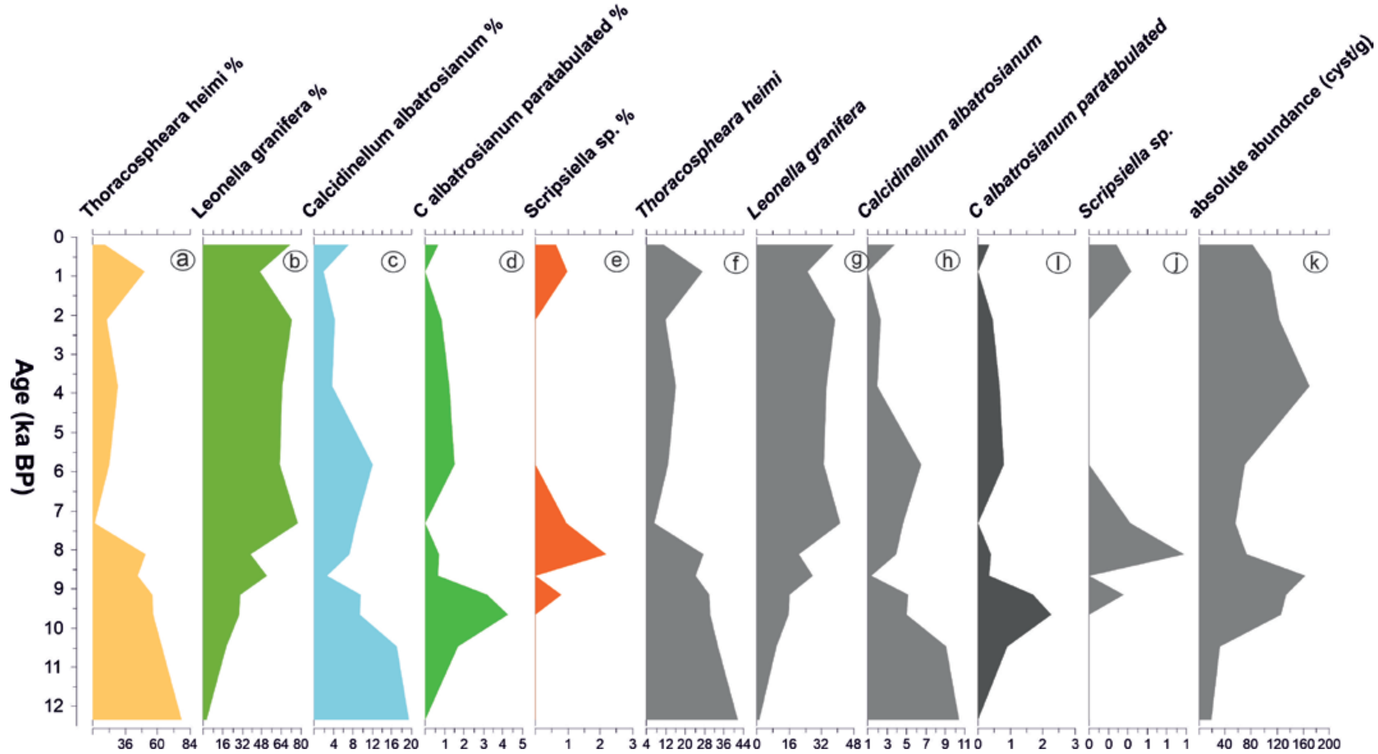
About 0.25 g dry sediment was disintegrated into tap water and few drops of liquor ammonia are added to the sample to avoid the dissolution. Samples were sieved through 63 and 10 µm meshes to eliminate the particles above 63 and below 10 µm size. The material left over on the 10 µm mesh is carefully transferred into a test tube and made up to 20 ml. Samples were well mixed and left for 15 seconds and 0.15 ml of the solution is spread on the slide on a hot plate. Slides were mounted with Canada Balsam. Specimens were identified under 1000× magnification with normal and polarised light. The whole slide is scanned under the Leitz 12 pon laborlux microscope with a polarised and gypsum light (Janofske 1996). When a slide contains less than 200 specimens additional slides were counted. Relative abundance of the individual species is calculated using total calcareous dinoflagellate cysts Absolute abundances are calculated using the formulae $A = (C*V/W*S)$, where C (Total cyst counted), V (Volume of water), W (dry weight of the sample) and S (split used for slide) are used.

Age model

Chronological control was obtained by accelerator mass spectrometry (AMS) radiocarbon (^{14}C) dating on total organic carbon on the sediment selected intervals at the Birbal Sahni Institute of Palaeobotany, Lucknow (Uttar Pradesh, India) and Silesian University of Technology (Table 1). The top of the core is assumed to be 200 years based on the sedimentation of the various cores in the studied region. 'rbacon' pakage in R software is utilised to construct age depth model (text-fig. 2). 'rbacon' is an approach to age-depth modelling that uses Bayesian statistics to reconstruct accumulation histories for deposits, through combining radiocarbon and other dates with prior information (Blaauw and Christen 2011).

RESULTS

In the present study calcareous dinoflagellate cysts are represented by five species; *Thoraccosphera heimii, Leonella granifera, Calcidinellum albatrosianum, C. albatrosianum paratabulated* and *Rhabdothorax* sp. The assemblage is dominated by the cocooides of *T. heimii* and *L. granifera* which together account for 81–92% throughout the core (text-fig. 2). The accumulation rates show a minimum at 12–9.4 ka BP. A drastic rise is observed at 11–8 ka BP followed by a gradually decreasing trend till 5 ka BP. An increasing trend is observed at 5–4 ka followed by a decrease up to ~2 ka BP and again increased till 1 ka BP. The relative absolute abundances follows the same trend



TEXT-FIGURE 2
a-e: Relative abundances & f-k: absolute abundances (*1000) of documented calcareous dinoflagellate cysts.

(text-fig. 2). The relative abundance of the *C. albatrosianum* and *C. albatrosianum* paratabulated species are comparatively high during 12–9.4 ka BP and show a decrease thereafter. The relative abundance of the dominant species *L. granifera* and *T. heimii* shows an opposite trend in the temporal variation. The relative abundance of *L. granifera* shows an overall increase trend from the early to middle Holocene.

In addition to the calcareous dinoflagellates record we also used sedimentological evidences i.e., sand% in the studied core. Sand ranges between 31 to 72% and shows a gradual increase since 12 ka BP.

DISCUSSION

Ecology of recorded species

In the present study, vegetative cocooides of *L. granifera* and *T. heimii* make 80–91.5% of the total calcareous dinoflagellate assemblage. A similar association is reported from the western Arabian Sea (Wendler 2002a, b, c). *Thoraccosphera heimii* has a wide geographic distribution between the sub-polar to tropical environments and is abundantly reported from nutrient-rich areas such as upwelling regions and river plume areas (e.g., Esper 2000; Hildebrand-Habel and Willems 2000; Zonneveld et al. 2000; Wendler et al. 2002a; Meier and Willems 2003; Meier et al. 2004; Vink 2004). High abundance of *L. granifera* is associated with nutrient-rich water column and exclusively reported from the areas with terrestrial input by fluvial origin (Wendler et al. 2002a; Vink 2004; Richter et al. 2007). *Calcidinellum albatrosianum* and *C. albatrosianum* paratabulated are spread between temperate and tropical regions in the modern-day sediments. Its relative abundance correlates with the increasing surface water temperatures (Esper et al. 2000; Wendler et al. 2002; Vink 2004; Heinrich and Zonneveld 2013).

The present study reveals the prevalence of eutrophic conditions throughout the studied period is reflected calcareous dinocyst record (text-fig. 2). However, the first two dominant species of calcareous dinocyst (*T. heimii* and *L. granifera*) show an opposite trend in their temporal variation allows to decipher the paleoenvironmental changes during the Holocene.

Preservation effects on the present record

Calcareous dinoflagellate cysts studies from the surface sediments and sediment trap material revealed that they do not reallocate during and after the deposition of the cyst. They are relatively resistant to the dissolution process in comparison to the other calcifying organisms (Vink et al. 2000; Richter 2009). All the specimens of calcareous dinoflagellate cysts are well preserved and can be identified at the species level with no signs or negligible signs of dissolution or fragmentation. In addition, high percentages of *T. heimii*, which has been found to be very sensitive to dissolution also support the lack of or negligible effect of dissolution on the calcareous dinoflagellate cysts.

Palaeoproductivity & environmental changes during the Holocene

The lowest concentrations of calcareous dinocysts and low relative abundances of eutrophic species (text-fig. 2a) are observed during the beginning of the Holocene (9.4 ka BP ka BP), reflecting low productivity. *C. albatrosianum* shows its high relative percentages up to 16–19% of the assemblage during this phase indicating a relatively warm and oligotrophic environment. The low relative abundance of L. granifera during this phase indicates the relatively low input of runoff-derived nutrients at the

TABLE 1
AMS ^{14}C ages determined on bulk sediment samples from core SC-26, and calibrated ages.

Depth (cm)	C 14 age	Calibrated age
SC-26 (10-12)	7170-6880	6002
SC-26 (20-22)	9830 ± 30	10464
SC-26 (25)	12910-12640	11869.5

beginning of the Holocene. Similar evidence of warm and weak monsoons (enriched $\delta^{18}O_{swivc}$ values) and high salinity during this period is reported from the eastern Arabian Sea (Saraswat et al. 2016). Such weak monsoon prior to the 10 Ka BP is also reported from western India (Singh et al. 1974). The planktonic foraminifera record off Goa revealed reduced biological productivity during this time (Singh et al. 2006; 2011). Total organic carbon records of the eastern Arabian Sea also suggest low organic matter productivity during the early Holocene which is also seen in the present core (Singh et al. 2006; Joshi et al. 2021; Agnihotri et al. 2003). The present study in line with the above-mentioned previous studies supports low organic matter productivity during the early Holocene (up to 10 ka BP) and weak summer monsoon runoff.

An increase in the calcareous dinocyst concentrations since 9.4 BP indicates an increasing trend in productivity. The present studied region receives high runoff (300–500 mm) during summer monsoon that drains from the Western Ghats creating a stratified and nutrient-rich environment (Sarkar et al. 2000). The studied region also experiences weak upwelling during the summer monsoon and vertical mixing during the winter periods (Colborn 1975).

An increase in the *L. granifera* since 9.4 ka BP suggest an increase in the runoff due strengthening of the summer monsoon. The gradual decrease of *C. albatrosianum*, *T. heimii* and increase in the *L. granifera* supports the increase in the summer monsoon runoff and eutrophic conditions up to 8 ka B.P. Progressive strengthening in the summer monsoon during the early to mid-Holocene has been reported from the previous studies from the eastern Arabian Sea (Thamban et al. 2001; Sarasawt et al. 2016; references therein). During the early Holocene period the sea level was low (80 m) in the eastern Arabian Sea (Hashimi et al. 1995). Shallow sea level resulting in the more proximal conditions could have led to enhanced runoff nutrients to the core site under a strengthening summer monsoon during the early Holocene between 11.5 to 8 ka BP. This phase also coincides with the early Holocene humid phase. The strengthening of the southwest monsoon at 9.6 and 8.6 ka BP is also reported from the western Arabian Sea which is attributed to a change in the insolation (Sirocko et al. 1993).

During the middle to late Holocene (since 6 ka BP), high relative abundances of eutrophic species and dinocysts concentrations indicate high productivity. High relative abundances of *L. granifera*% indicates high runoff and strengthened summer monsoon runoff to the core site. Overall low relative abundances of *Calciodinellum* and high TOC% also support eutrophic conditions and high organic matter productivity since the 6 ka BP. Sarkar et al. (2000) also showed two step increasing trend in the rainfall, i.e., up to 6 ka BP with gradual increase in the precipitation and since 6 ka BP high precipitation which shows similarity with present record. TOC% records from the eastern Arabian Sea also shows strengthening organic matter productivity since 6 ka BP (Nagoji and Tiwari 2017; Joshi et al. 2021).

The long-term increasing primary productivity and runoff nutrients trend visible in the present core is also in agreement with the summer monsoon strengthening in the early to late Holocene in the eastern Arabian Sea (Sarkar et al. 2000; Agnihotri et al. 2003). Sand record of the present core is also in agreement with the early to late Holocene strengthening in the runoff to the core site. Though the resolution of the present study is very low to decipher centennial or millennial-scale events that occurred in the Holocene period, the present study demonstrates the potentiality of calcareous dinoflagellate cyst to decipher the monsoon fluctuations, of particularly monsoon-driven runoff changes in the eastern Arabian Sea.

CONCLUSIONS

Calcareous dinoflagellate cysts study from the eastern Arabian Sea reveals productivity, and palaeoenvironmental changes during the past 12 ka BP. *Thoracosphaera heimii* and *Leonella granifera* dominate the calcareous dinocyst assemblage which is similar to the western and northeastern Arabian Sea. Calcareous dinocysts reveal warm, oligotrophic conditions and low productivity during the early Holocene. The gradual increase in the terrestrial input indicator *Leonella granifera* shows a strengthening summer monsoon from early to late Holocene. A two-step increases in an overall early to late Holocene strengthening summer monsoon, i.e., prior to 6 ka BP which is weak as compared to a higher summer monsoon since 6 ka BP. The present study reveals the potentiality of calcareous dinoflagellate cysts as a sensitive proxy to study the palaeomonsoon fluctuation in the Arabian Sea.

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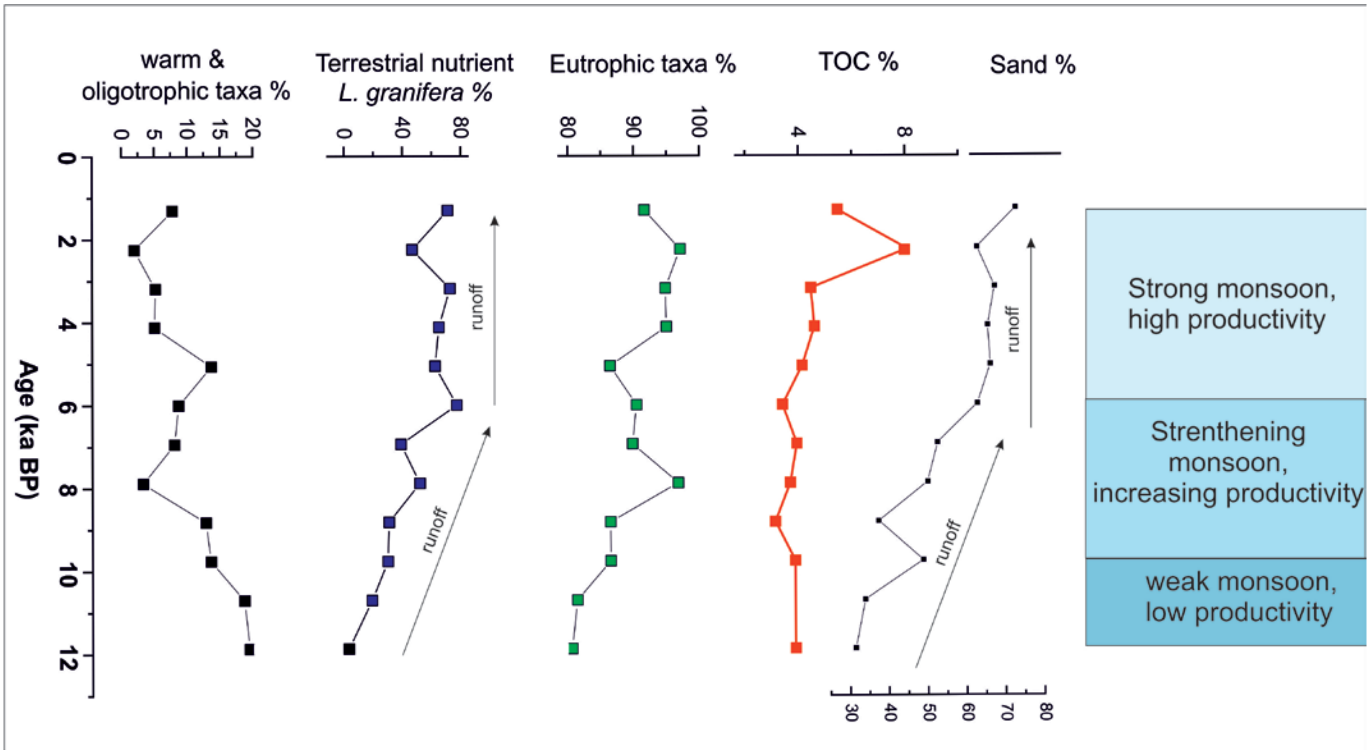

TEXT-FIGURE 3
Calcareous dinoflagellates, TOC % and Sand % data of the studied core indicating monsoon changes.

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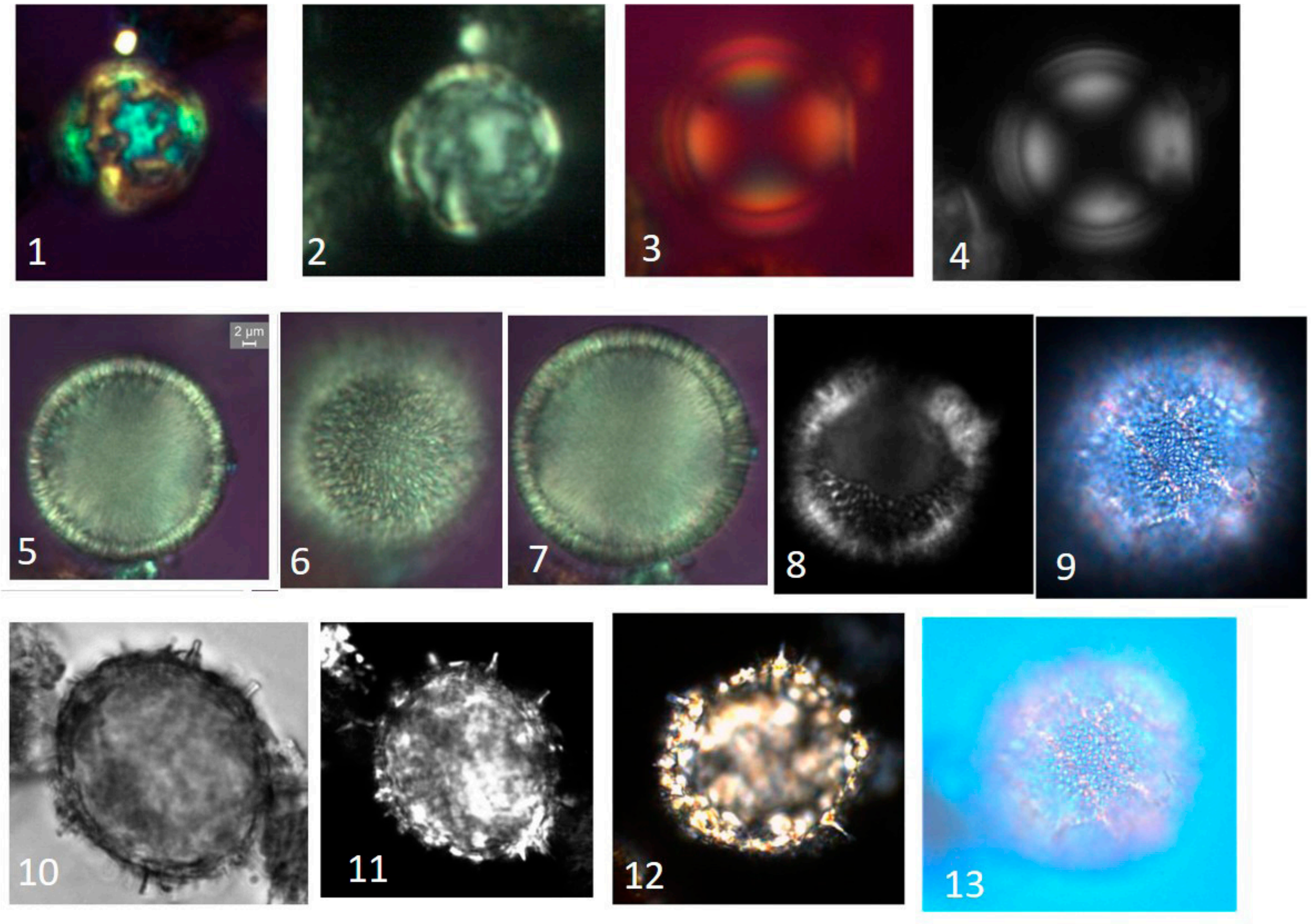

PLATE 1

1-2 *Thoraccosphaera heimmi.*

3-4 *Leonella granifera.*

5-8 *Calciodinellum albatrosianum.*

9-13 *Calciodinellum albatrosianum paratabulated.*