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Coccolithophore Assemblages from Gulf of Aqaba Sediments and their Response to Climate Change

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Abstract

The Gulf of Aqaba exhibits a nearly closed marine ecosystem, characterized by oligotrophic conditions, which give it the potential for phytoplankton to flourish. Coccolithophore samples were taken from two different sediment cores that were collected from the northern Gulf of Aqaba during the OceanX expedition. This study aims to construct the sea surface temperature over the past few hundred years by counting fossil coccolithophore communities in the northern Gulf of Aqaba through time.

The forty-eight smear slides were prepared for coccolithophore identification and paleo-ecological investigation, and then studied under a polarized microscope with 1500x magnification. Taxonomic identification of coccolithophores is based on the outer scale found in the slides. A total of 300 specimens were counted in each slide. To assess the temperature, diversity and the relationship between species abundances, statistical indices were applied on the counted specimens. Coccolithophore assemblages are extremely abundant in well-preserved conditions, allowing for clear identification and an exact assessment of climatic change based on paleo-ecological studies. The *Gephyrocapsa* group, *Emiliana* group, *Helicosphaera* spp, *Reticulofenestra* spp, *Coccolithus* spp, *Pontosphaera* spp, *Braarudosphaera* spp and *Umbilicosphaera* spp were found in high numbers throughout all the cores. The *Emiliana* Group was the most abundant genus throughout all the cores, indicating long-term warming. Throughout core 3, the results showed a strong relation between *Gephyrocapsa* spp and the other coccolithophores, such as *Coccolithus* spp, *Helicosphaera* spp, and *Braarudosphaera* spp, as all of these species prefer cold water. The fluctuations in the numbers of the cold-preference (*Gephyrocapsa*) group versus warm-preference coccolithophores (*Emiliana* Group) led to tracking periodic changes in climate. The significant increase in numbers of *Gephyrocapsa oceanica*, *Gephyrocapsa muellerae*, *Gephyrocapsa ericsonii*, and *Calcidiscus leptoporus* in some samples, relative to the *Emiliana* Group, reveals that a cold environmental period dominated the Gulf during the Holocene.

Keywords: Coccolithophores, Gulf of Aqaba, Paleoclimate, warm-preference coccolithophores, cold-preference coccolithophores

1. Introduction

The Gulf of Aqaba represents the northern extension of the Red Sea. The restriction of the Red Sea Basin imposes harsh and extreme conditions. It is characterized with low productivity, low oxygen content, and negligible drainage system (Winter *et al*. 1979; Winter 1982; Legge *et al*. 2006). The nannoplankton community in the Red Sea and Gulf of Aqaba displays a fragile pattern due to climate change. Coccolithophores, in particular, are tiny organisms that live in the photic zone and thrive in oligotrophic conditions. Nannoplankton species, therefore, can be used as paleoclimatic proxies in such environments. As an example, *Gephyrocapsa oceanica* is a cosmopolitan bloom-forming coccolithophore species (Bendif and Young 2014), but it dominated the neritic environment (Okada and Honjo 1975). *Emiliania huxleyi* is usually common in open oceans, but it is scarce in various neritic environments (Okada and Honjo 1975).

Sea surface temperature can be estimated based on the relative abundance of *Gephyrocapsa* because it has morphotypes, including a mean bridge angle of less than 27º and a length longer than 2.4 µm (Bollmann 1997; Bollmann *et al*. 2002). Moreover, good correspondence has been found between *Gephyrocapsa* and alkenone, in defining paleotemperature (Henderiks and Bollmann 2004). It has also been found that *G. oceanica* and *H. carteri* are valuable nutrient-indicator species in the Red Sea, while *U. sibogae*, *R. claviger* and *F. profunda* are oligotrophic indicators (Aljahdali 2021).

The present study investigates the coccolithophore community and its diversity in the northern Gulf of Aqaba. The investigation of changes in the abundance of calcareous nannofossil associations is fundamental for palaeoclimatic and palaeo-oceanographic reconstructions (Buccianti and Esposito 2004). This study aims to construct the sea surface temperature over the past few hundred years. It describes the seasonal dynamics of different species and assesses their relationship with different climatic conditions. This research interprets the

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distribution patterns and infers the paleoecology of fossil coccolithophore communities in the northern Gulf of Aqaba.

2. Materials and Methods

Two sediment cores (Sites 1 and 3), among seven different cores were collected from the northern Gulf of Aqaba during the OceanX expedition in July 2022 (Figure 1). A total of 48 samples were examined: eight samples from site 1 and 40 samples from site 3. Smear slides were prepared from each sample, following the standard procedure of Roth (1984). Table 1 shows the longitude, latitude and depth for each core.

Table 1. Coordinates and depth information of the studied cores.

Core number	Longitude	Latitude	Altitude (m)	Thickness (cm)
Core 1	29.494706	34.982516	-350	8
Core 3	29.417155	34.944383	-698	40

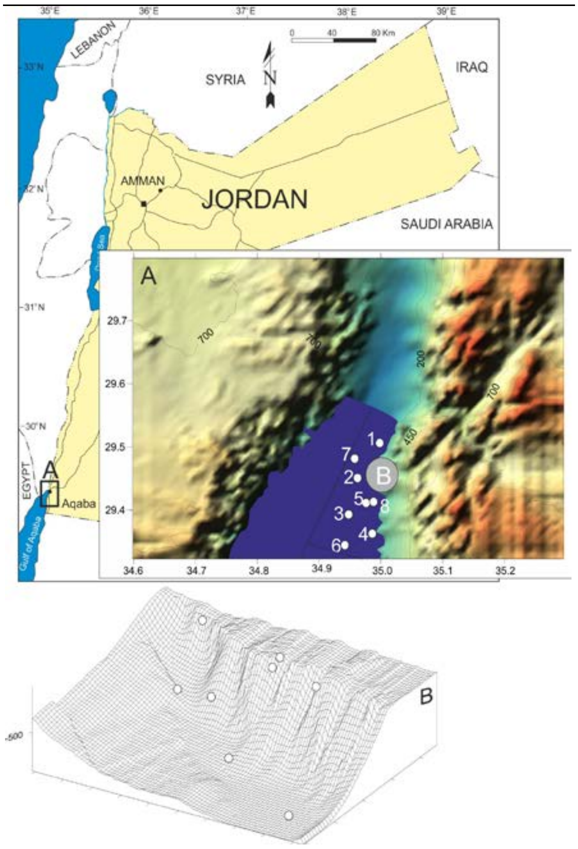

Figure 1. Map of the northern Gulf of Aqaba showing the locations of the collected sediment cores. A) Location of the eight sites within the Aqaba Economic Zone; B) Depth image illustrates the position of the eight drilled cores. Bathymetric data obtained from the OceanX expedition.

Taxonomic identifications of the coccolithophores are based on their calcitic plate (calcareous nannofossils). This was performed using a transmitted light microscope, a Nikon Type with a magnification of 1500x, located at the Department of Earth and Environmental Sciences in Yarmouk University. Due to the high abundance of the calcareous nannofossil specimens in the studied samples, relative abundances of species were measured from counting 300 calcareous nannofossil specimens per 30 fields of view in each smear slide. The Temperature Index, which is an estimation of sea surface temperature, was then calculated, in order to provide information on the paleo-environment of the Gulf. In this study, *Gephyrocapsa*, *Calcidiscus*, and *Coccolithus* were considered to be cold water species, based on the description by Bollmann (1997) and supported by Buccianti and Esposito (2004).

The diversity of the coccolithophores is expressed by two indices: the Heterogeneity Index (or Shannon Index) (H) and Dominance (D). High values of the Shannon index indicate highly diverse assemblages (Linnert *et al*. 2011). The Shannon Index equation used in this study was applied following Giraldo Gomez *et al*. (2018).

Furthermore, in order to assess the relationship between the abundance of the different species, a linear Pearson correlation and de-trended correspondence analysis (DCA) were performed. The Shannon Diversity (H), Dominance (D), and Detrended Correspondence Analysis (DCA) were performed based on the counts using the PAST software (Hammer *et al*. 2001).

3. Results and Discussion

3.1. Coccolithophore assemblages

Coccolithophores were abundant in both sediment cores and *Gephyrocapsa oceanica* (Figures 2a and b) and *Emiliania huxleyi* (Figures 2c and d) were the most common species in the samples. However, the numbers of these species fluctuated throughout the samples. Figures 3 and 4 represent numbers of the coccolithophores species counted in the sediment cores from sites 1 and 3, respectively. Numbers of *Emiliania huxleyi* species, on the one hand, exceeds 300 specimens in samples 6, 25-28, and 39 cm (site 3) and at the top 5 samples in site 1. The count of *Emiliania huxleyi* declines at the bottom of site 1 and in samples 10-17 from site 3, where 2-72 specimens were counted in those samples (Figures 3 and 4).

The number of *Gephyrocapsa oceanica* was relatively high at the base of the core samples of site 1 and site 3 and fluctuated throughout site 3. Almost 300 specimens of *Gephyrocapsa* were counted at base of site 3 (Figures 3). However, numbers of individuals dropped down to 36 specimens in sample 26. High numbers of *Gephyrocapsa oceanica* were observed to be associated with an increase in the numbers of *Helicosphaera* spp (Figures 2f and 2g), *Coccolithus* spp (Figure 2h) and *Calcidiscus* spp (Figure 2 k). Less common species, such as *Umbilicosphaera* spp (Figure 2i), *Scyphosphaera* spp (Figure 2j) and *Braarudosphaera* (Figure 2l), were also observed in the samples.

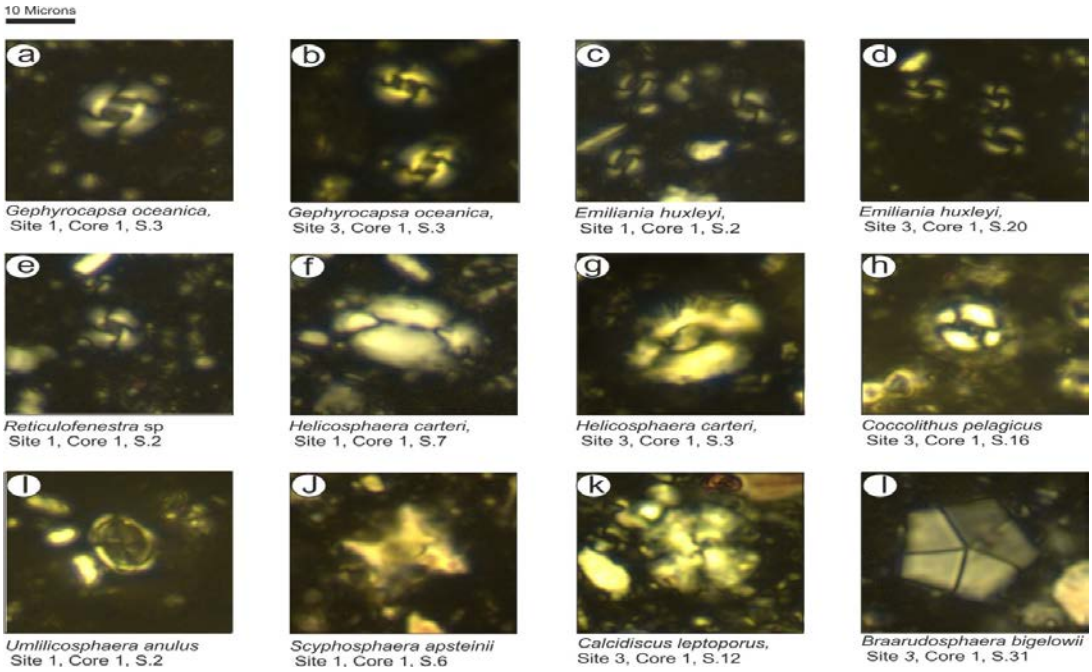

Figure 2. Nannofossil species found in sediment cores from sites 1 and 3.

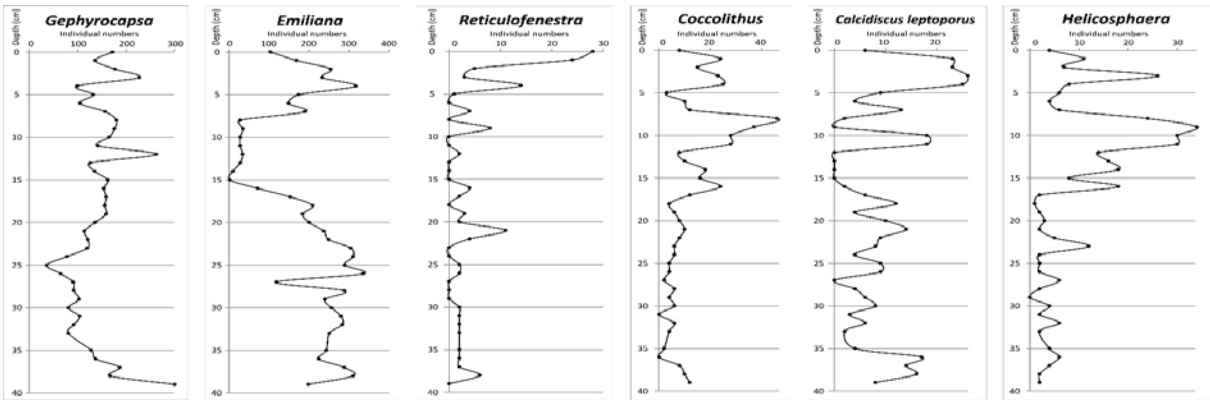

Figure 3. Relative abundances of the most common coccolithophore species from site 3, core 1. Depths in cm.

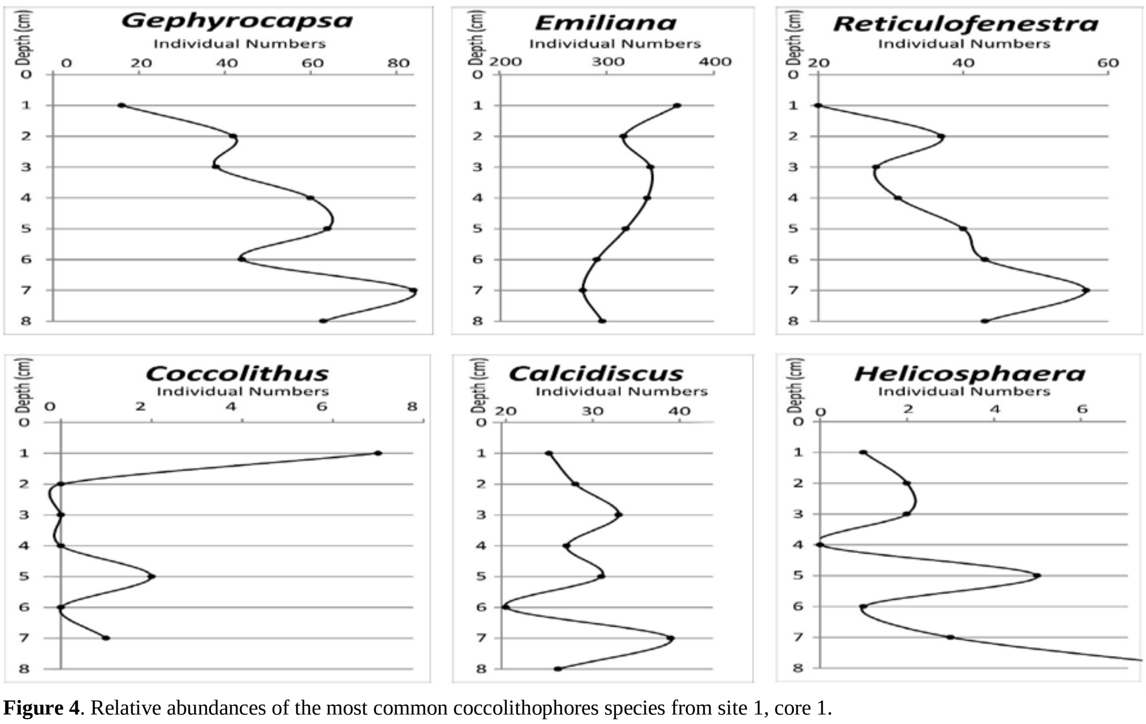

Figure 4. Relative abundances of the most common coccolithophores species from site 1, core 1.

3.2. Relative abundance

At site 3, the percentage of *Gephyrocapsa* spp ranged between 10-79%, reaching its maximum in sample 13 and its minimum in sample 26 (Figure 5). *Emilliana* spp was dominant in the samples as well, ranging between 1% in sample 16 and reaching its maximum of 84% in sample 26. There was a clear negative trend, as shown in figure 5, in *Emilliana* relative abundance, particularly in samples 10-17, compared to a relatively increase in *Gephyrocapsa* relative abundance values. *Reticulofenestra* spp had a maximum of 8% at the surface, and its percentage decreased downwards, through the core. *Coccolithus* spp reached its maximum of 15% in sample 9, *Helicosphaera* spp was 11% in sample 12, and the percentage of other species was negligible.

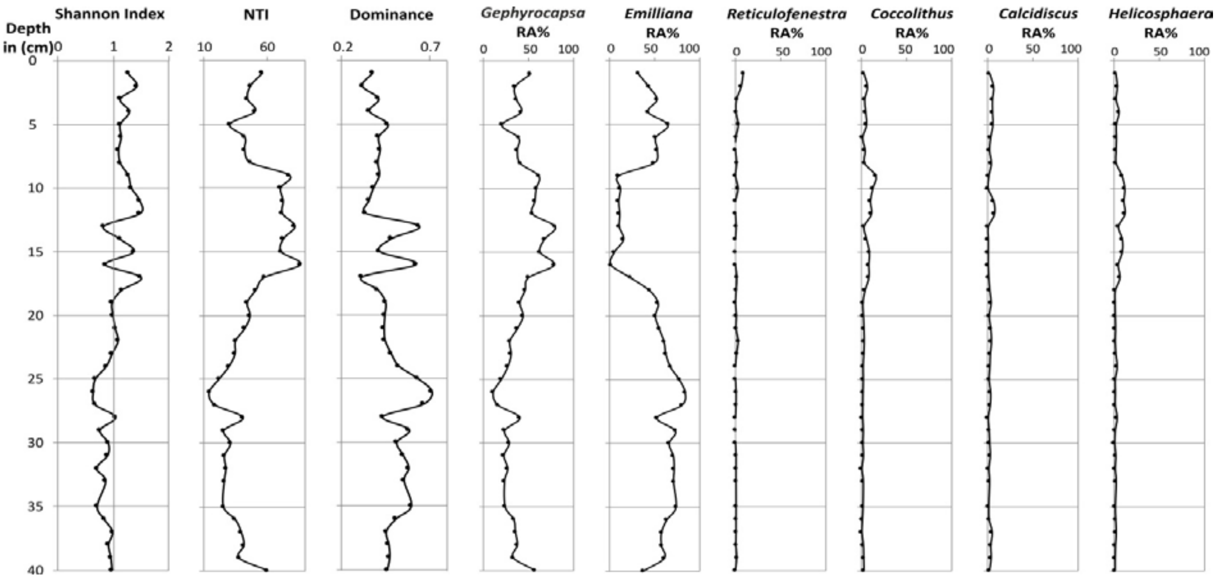

Figure 5. Diversity indices, NTI, and relative abundance of counted calcareous nannofossils from site 3.

Three groups were recognized in sample 1 (site 3, surface of sediments): *Gephyrocapsa, Emilliana,* and *Reticulofenestra*. The rest of the species were almost absent. The surface sample displayed a high percentage of *Gephyrocapsa* spp relative to *Emilliana*. In fact, the percentage of both *Gephyrocapsa* spp and *Emilliana* spp fluctuated in the site (Figure 5). Samples 2-9 showed a high percentage of *Emilliana* spp and a low percentage of *Gephyrocapsa* spp. This trend changed, as *Gephyrocapsa* spp appeared in high percentages in samples 10 to 17, in association with *Coccolithus* spp and *Helicosphaera* spp. Then, the trend was steady, with a high percentage of *Emilliana* spp, and this continued to the bottom of the core.

3.3. Diversity Indices

Two main indices were determined from the samples: the Heterogeneity Index (H) and Dominance (D). Based on the Heterogeneity Index, a diverse system was observed in four different areas, in terms of an increasing Heterogeneity Index (Figure 5); samples 2 and 4 (close to the surface), samples 9, 10, 11, and 12, a few lower samples (15 and 17), and sample 28 in the middle of the core. Three areas of Heterogeneity Index, showing a lower Shannon Index value, were observed throughout the core. The surface represents the first area and includes samples 3, 5, 6, 7 and 8. Samples 13, 14 and 16 represent another period of low diversity, and samples from 19 to 40 also showed a low diversity pattern.

The Dominance Index showed a fixed value of around 0.3 in most of the samples from site 3 (Figure 5). However, there was an observed relation between increasing Dominance Index associated with low Shannon Index values. This was clearly observed in samples 13, 16, 25, 26, and 27. The coccolithophore assemblages in these samples were dominated by one species. In another way, samples showed a drop in the Dominance Index value, which also matched an increase in the Shannon Index values, such as in samples 12, 14, 25 and 27. In these samples, coccolithophore assemblages were diverse, and many species flourished.

3.4. Nannofossil Temperature Index

Based on the Nannofossil Temperature Index (NTI) curve (Figure 5), three periods of distinctive variation in NTI values were recognised at site 3. Low values of the NTI in samples 1-8 of core 1 suggest that the sea surface temperature was high in the top 8 cm of the sediments. NTI values increased significantly and were associated with a dramatic decrease in the numbers of upper photic zone species, suggesting a lower sea surface temperature in sediment samples from 9-16 cm. The NTI values were at a minimum in the samples from 18 cm to the bottom. Coccolithophores can be divided into two groups, based on their climatic preferences: upper photic zone species, like *Emiliania huxleyi*, and lower photic zone species, such as *Gephyrocapsa* spp, *Helicosphaera* spp, and *Coccolithus* spp. The latter group showed fluctuations in their abundance. Therefore, three climatic periods can be interpreted. The first period, at the top, is characterised by a decline in cold water taxa (lower photic zone species), and is correlated with the first eight samples from the surface. The second period, where the NTI is higher than the periods above and below, is considered to be colder. In this period, cold water taxa were higher in numbers. The last period, which extends to the bottom of the core, is characterised by the dominance of warm water taxa (upper photic zone species). This implies that two warm periods were interrupted by short cooling periods in the last few hundred years (the ages and sedimentation rate have been estimated from ^{14}C dating conducted on deep sediments in the Gulf of Aqaba, by Al-Rousan *et al*. (2004)).

3.5. Correlations

The results of a Detrended Correspondence Analysis (DCA) and Pearson Linear Correlation applied to samples from site 3 are shown in Figures 6 and 7. Coccolithophore species were grouped differently along axis 1 and 2 in Figure 6. Two groups can be distinguished, and both are circled in Figure 6. *Emiliania*, *Calcidiscus* spp., *Umbilicosphaera* spp, and *Scyphoshaera* spp. are correlated in samples 3, 5, 19, 22, 23, 24, 30, 35, 37, and 38. All of these samples showed a low NTI, which correlates the abundance of these species with the warm water taxa. On the other hand, *Gephyrocapsa* spp, *Helicosphaera* spp, and *coccolithus* spp are associated with each other and with samples 2, 4, 7, 8, 18, 20, and 39, whilst samples 9, 10, 11, 12, 13, 14, 15, 16, and 17 showed extreme values where cold-water taxa were dominant, and there was a decline in warm water taxa.

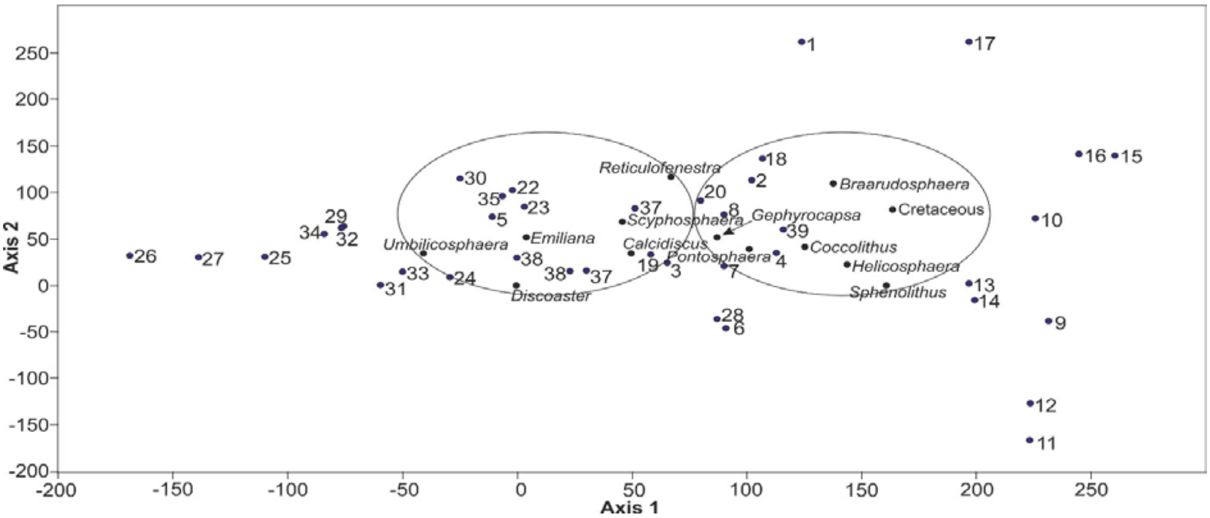

Figure 6. Detrended Correspondence Analysis (DCA) representing the abundance of certain coccolithophore species in the samples. Low NTI species grouped together within the two circles.

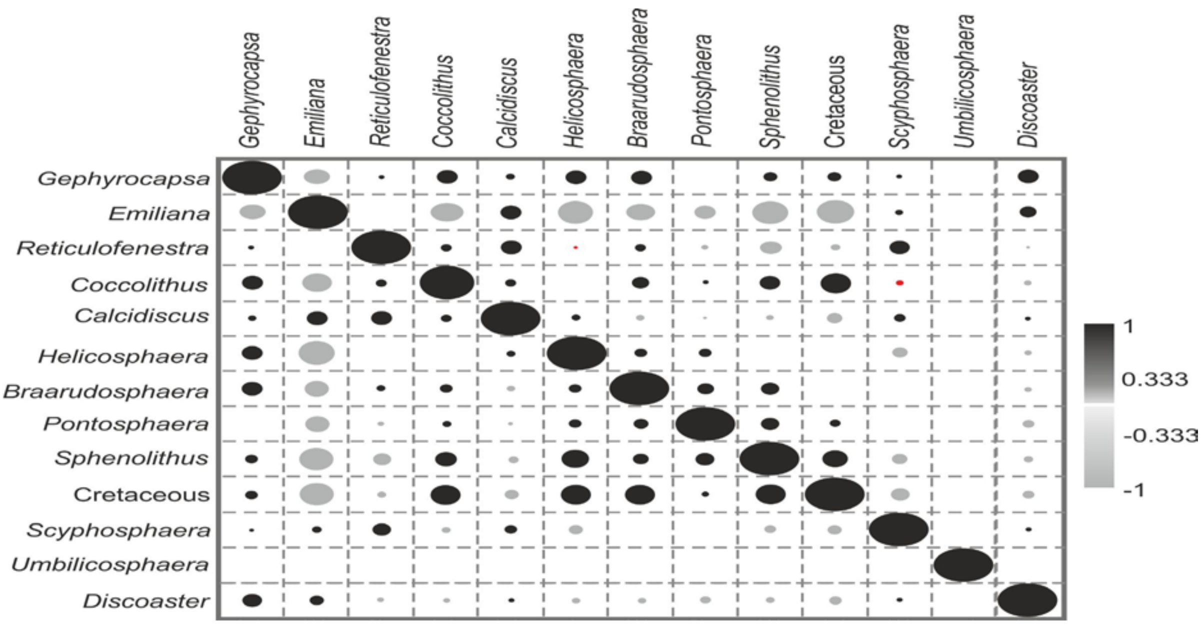

Figure 7. Linear correlation between different coccolithophore species. Black color represents the positive, and gray is for the negative correlation.

The relationship observed when Linear Correlation was applied to the results is shown in Figure 7. Black represents a positive relationship, while grey represents a negative correlation. The results showed a strong relation between *Gephyrocapsa* spp and other coccolithophores spp. such as *Coccolithus* spp, *Helicosphaera* spp, and *Braarudosphaera* spp, as all of these species are of cold-water preference. However, *Gephyrocapsa* spp was correlated negatively with *Emiliania* spp, which has a clearly negative correlation with *Helicosphaera* spp, *Sphenolithus* spp, and *Coccolithus* spp, and a weak positive correlation with *Calcidiscus* spp. Therefore, two groups can be subdivided, based on the Linear Correlation:

the *Gephyrocapsa* group and its associations, and the *Emiliania* group and its associations.

3.6. Coccolithophores in response to climatic events

The Red Sea is characterised by an elongated basin that was formed by extensional forces in the Miocene (Sharland *et al*. 2001). It has an arid environment with insignificant precipitation (22 mm/year) and runoff (Al-Rousan *et al*. 2006). Nutrients are brought into the basin through flash floods, that transfer terrestrial material into the Gulf (Manasrah *et al*. 2004), and in the Gulf there is a seasonal current flowing along the west coast, mixing up the terrestrial material into all parts of the Gulf (Genin and Paldor 1998; Berman *et al*. 2000; Manasrah *et al*. 2004, 2006). However, the absence of rivers or major streams flowing into the Gulf of Aqaba leads to a poor supply of nutrients, such as nitrogen or phosphorus compounds, to the water, keeping the planktonic primary production very low (Al-Rousan *et al*. 2006).

Calcareous nannofossils were abundant in such environment. However, diversity and abundances of nannoplanktons were dependent mostly on climate, and this decreased several times during the warming periods (Winter, 1994; Guerreiro *et al*., 2023) (Figure 8). Guerreiro *et al*., 2023 reported the relationship between diversity and abundances of coccolithophores community and stratified oligotrophic and warm conditions. However, extreme warming conditions were reflected by a significant reduction in coccolithophore numbers and, therefore, the establishment of a mono-species pattern. Species that were not adapted to cooling in the water column were reflected in fluctuations in the Heterogeneity Index (H). More specifically, despite the reduction in species numbers during extreme conditions at the sea surface, the *Gephyrocapsa* group, *Coccolithus* spp, and *Helicosphaera* spp continued, and even dispersed during the cooling of the sea surface. Guerreiro et al., 2013 related the abundances of *Gephyrocapsa* in temperate to cooling in water column. The *Emiliania* group and *Calciduscus* spp thrived in the mild or warm conditions correlated with different cases in Atlantic and Miditerranian Sea (Dimiza *et al*., 2008; Guerreiro *et al*., 2023).

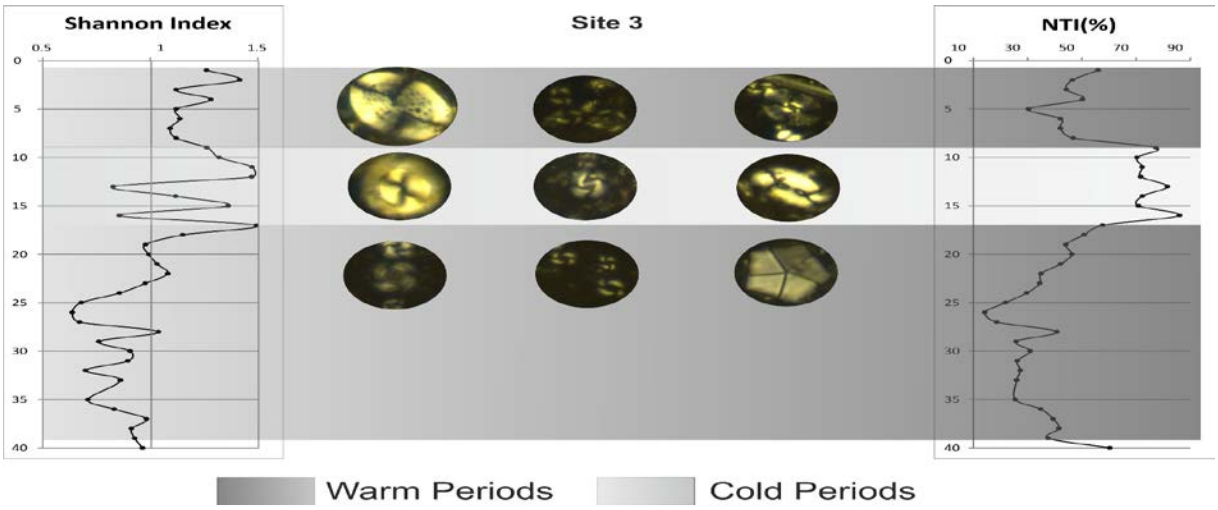

Figure 8. The three climatic periods detected throughout the sediment core based on the calcareous nannofossil study.

During the cold period, the depth of the Strait of Bab el Mandeb was reduced to 17 m, leading to an increase in salinity due to the high evaporation rate. The hypersaline conditions reached the tolerance limit for various planktonic organisms (Winter 1982; Winter *et al*. 1994), causing an absence of planktonic foraminifera and calcareous nannofossils, and the occurrence of mono-species patterns in the north of the Red Sea (Winter 1982; Winter *et al*. 1994). Legge *et al*. (2006) confirmed that extreme conditions with enhanced salinities during the cold period are characterised by high values of *Gephyrocapsa* spp. Based on the correlation analysis and the NTI values, coccolithophores can be divided into two groups, in response to climate: upper photic zone species, such as *Emiliania huxleyi,* and lower photic zone species, such as *Gephyrocapsa* spp, *Helicosphaera* spp, and *coccolithus* spp. Each group was dominant and flourished in their preferred environment.

4. Conclusion

Highly abundant and diverse nannoplankton were found in both shallow and deep sediment cores from the northern Gulf of Aqaba. *Emilliana* spp and *Gephyrocapsa* spp are the dominant species in the sediments, with low abundances of *Helicosphaera* spp, *Reticulofenestra* spp, *coccolithus* spp and *Calcidiscus* spp. Coccolithophore groups, like *Gephyrocapsa, Helicosphaera* and *coccolithus,* showed fluctuation in their abundance, reflecting changes in their preferred climatic conditions. By applying NTI on the studied samples, three climatic periods were recognized. Two warm periods were interrupted by short cooling periods over the last few hundred years. Biodiversity varied through time, where coccolithophores were not tolerant to both extreme cooling and warming conditions. Although the top intervals of both sediment cores represent stressed environments, the primary production system is functioning well.

5. Taxonomic list

Braarudosphaera Deflandre (1947)
  B. bigelowii (Gran and Braarud, 1935) Deflandre (1947)
Calcidiscus Kamptner (1950)
  C. leptoporus (Murray and Blackman, 1898)
Coccolithus Shwarz (1894)

C. pelagicus (Wallich, 1877) Schiller (1930)
Emilliana Hay and Mohler in Hey et al. (1967)
E. huxleyi (Lohmann, 1902) Hay and Mohler in Hey et al. (1967)
Florisphaera Okada and Honjo (1973)
F. profunda Okada and Honjo (1973)
Gephyrocapsa Kamptner (1943)
G. oceanica Kamptner (1943)
Helicosphaera Kamptner (1954)
H. carteri (Wallich, 1877) Kamptner (1954)
Pontosphaera Lohmann, 1902
Rhabdosphaera Haeckel (1894)
R. claviger Murray and Blackman, 1898
Reticulofenestra Hay, Mohler and Wade (1966)
Scyphosphaera Lohmann, 1902
S. apsteinii Lohmann, 1902
Sphenolithus Deflandre in Grasse (1952)
Umbilicosphaera Lohmann, 1902
U. anulus Young et al., (2003)
U. sibogae (Weber-van Bosse, 1901) Gaarder (1970)

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