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Climatic Impact on Paleoproductivity During the Last 14 Kyr in the Southeastern Arabian Sea

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Authors' contributions

This work was carried out in collaboration among all authors. Author AP wrote the original draft of the manuscript, did data curation and conceptualization. Author CJKF did data curation and conceptualization. Author YV wrote, reviewed and edited the manuscript, did data visualization and curation and supervised the study. Author MB wrote, reviewed and edited the manuscript and did data visualization. Author DS wrote, reviewed and edited the manuscript All authors read and approved the final manuscript.

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ABSTRACT

This study examines the biogenic silica (BSi) content in a sediment core from the southeastern Arabian Sea (SEAS) to reconstruct paleoceanographic changes over the past 14 kyr. The study investigates the grain size distribution and biogenic silica content of marine sediments. There is a

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significant amount of silt in the sediments in the entire core, which varies between 80% and 96%. BSi content ranged from 3.4% to 4.4%, with notable fluctuations during key climatic events. Elevated BSi during the Bølling-Allerød event (13.5-13 kyr BP) suggests enhanced productivity linked to intensified Indian Summer Monsoon (ISM) and upwelling. Conversely, the Younger Dryas (12.9-11.6 kyr BP) exhibited reduced productivity, interrupted by multi-centennial scale fluctuations. The early Holocene (11.7-8.5 kyr BP) was characterized by low BSi, indicative of reduced upwelling due to increased monsoonal precipitation and freshwater influx. The Holocene Climatic Optimum (8.5-4.5 kyr BP) saw a resurgence in productivity, correlating with heightened ISM activity and an intensified oxygen minimum zone (OMZ). By the late Holocene (~6-1.1 kyr BP), BSi content stabilized, reflecting steady paleoproductivity under a weakened monsoon regime. These findings underscore the intricate link between monsoon dynamics, upwelling, and productivity in the SEAS during the late Quaternary. Changes in marine paleoproductivity could reflect the history of the marine biogenic cycle process.

Keywords: Biogenic silica; grain size analysis; holocene; Indian summer monsoon; Southeastern Arabian Sea.

1. INTRODUCTION

The south-eastern Arabian Sea, a region marked by its intricate oceanographic and climatic interactions, plays an important role in global biogeochemical cycles, due to its unique monsoonal circulation, high primary productivity, and intense oxygen minimum zone. The global change focuses on the cycling of biogenic components, as climate shifts affect ocean productivity, which in turn influences atmospheric CO_2 levels and the carbonate dissolution cycle. Therefore, Paleoproductivity evolution is crucial for understanding climate change mechanisms across geological history [1,2,3,4].

In the ocean, silicon (Si) is a key element, necessary for the growth of diatoms, sponges, radiolarians, and silicoflagellates [5,6]. The biogenic silica (BSi), also known as opal, is the chemically determined content of amorphous silicon. The BSi in the sediments primarily comes from bone deposition after the death of siliceous organisms in the upper water diatoms, which accounts for the majority of BSi production [7]. The biogenic opal in the marine sediments is a potential paleoproductivity proxy. BSi rich sediments are found in all depths, latitudes, and climate zones of the world's oceans [8,9,10,11]. Based on the regional distribution variations of the BSi records, paleoproductivity and paleoclimate changes have been reconstructed over time, with global implications [10,12,13]. The global rate of biogenic silica production in the ocean to be between 200 and 280×10^{12} mol Si yr^{-1} [14]. Globally at least 50 % of the silica produced by diatoms in the euphotic zone dissolves in the upper 100 m, resulting in an estimated export of $100\text{-}140\times10^{12}$ mol Si yr^{-1} to the deep ocean. Estimated global mean rate of biogenic silica production between 0.6 and 0.8 mol Si m^{-2} yr^{-1}. Biogenic silica as an indicator for changes in paleo-upwelling intensity.

“In Arabian Sea diatoms represented over 90 % of the total opal microorganisms. Sediments with a high biogenic silica content are found along the margins of West Africa, Peru, and the North Pacific, around the Antarctic continent, and along the equatorial belt in the Pacific, areas where upwelling of nutrient-rich waters causes high primary production. In contrast, the northwestern Indian Ocean, which is one of the most productive regions in the world, does not show a high biogenic silica content in the sediments. On the Somali Margin, diatoms are a major component of the export flux from the productive surface layer, with biogenic silica percentages of up to 40% measured in sediment traps. However, biogenic silica content of the sediment is low, around 6%” [15]. Several reviewers have extensively examined the oceanic silicon cycle, most recently Treguer and De La Rocha [16]. An estimated 240 ± 40 Tmol Si $year^{-1}$ are produced annually in the oceans, mainly from diatoms [14]. In addition to contributing 30–40% of the primary production occurring in the surface ocean [5], diatoms contribute a molar ratio of 0.13 to the composition of the carbon cycle in the ocean as well as the silicon cycle [17]. “A large fraction of the diatom frustules and other BSi dissolves in the upper water column. The rest is exported to the deep ocean as particles, with the majority of the BSi rain at 1 km reaching the ocean floor” [18]. Much of the BSi rain to the seabed then remineralizes in the upper sediments, transforming to silicic acid that diffuses back to the overlying water. It is eventually carried back to the euphotic zone and re-used for new diatom growth.

In order to understand the global biogenic factor cycle and the role it plays in past, present and future climate change, it is important to explore the evolution and mechanism of marine productivity. Changes in marine paleoproductivity could reflect the history of the marine biogenic cycle process. The present study focusses on southeastern Arabian Sea (SEAS) sediment grain size and biogenic silica content from marine sediment.

2. MATERIALS AND METHODS

2.1 Study Area

The southeastern margin of the Arabian, i.e., the southwestern continental margin of India is the area selected for the study. This region lies in the tropical belt and experiences a humid tropical climate. The Western Ghats Mountain chains are the major physiographic feature along the coast. It is away from the Indus, Narmada and Tapti River discharges and from the major influx of dust plumes from the Arabian Peninsula. Even though no major river flows through this region, there are several medium and minor rivers and numerous streams which are not perennial in nature. This region is characterised by a weak upwelling system during the summer monsoon. It is seen that the upwelling along this coast begins during February, which is much before the onset of favourable southwest monsoon winds [19].

2.2 Collection and Processing of Core Samples

The sediment core SK 215/5 was collected during the 25th cruise of ORV *Sagar Kanya* (December 2004) from the Southeastern Arabian Sea (SEAS) at 10°30.74" N, 75°22.9" E, about 40 km off the Ponnani River, at a depth of 460 m. The core, measuring 4.2 m in length, was obtained using a gravity corer. Onboard, the core was sub-sampled at 2 cm intervals for the top 1 m and 5 cm intervals for the remaining length. All sediment samples were freeze-dried, packed, and stored under refrigerated conditions.

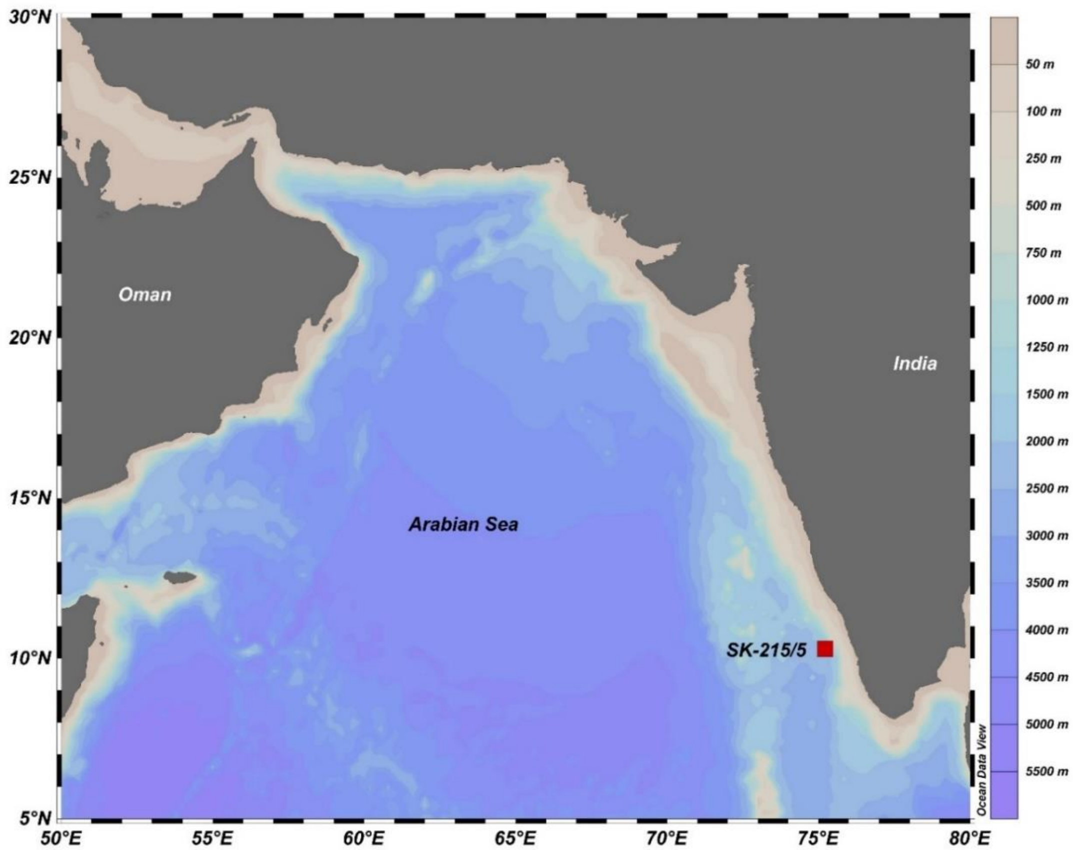

Fig. 1. Map showing the location of the sediment cores collected from the south eastern Arabian sea (labelled as SK 215/5)

2.3 Grain Size Analysis

Sediment fractions of sand, silt, and clay were quantified using standard sedimentological methods, including wet sieving and pipette analysis based on Stoke's law [20]. Sediments were rinsed with Milli-Q water, dried at ~50°C, and the <63 µm fraction was analyzed via pipette analysis. The percentage of silt was determined by subtracting the weights of clay and sand from the total sample weight. Duplicate samples yielded precision within ±3%.

2.4 Biogenic Silica (BSi) Analysis

Approximately 0.15 g of freeze-dried, ground sediment was treated with 10% H_2O_2 and 1 mol/L HCl to remove organic matter and carbonate, followed by centrifugation. The residue was dried at 60°C and treated with 2 mol/L Na_2CO_3 for 5 hours at 85°C. After centrifugation, the supernatant was reacted with ammonium molybdate and ascorbic acid to form silicomolybdate-blue. The absorbance was measured at 810 nm using spectrophotometry. Standard Si solutions were used for calibration, following the modified molybdate-blue method [21,22].

3. RESULTS AND DISCUSSION

3.1 Sediment Grain-size

The down core variations of different grain sizes of the sediment are shown in Fig. 2. The sediment mean grain size was mostly dominated by the very fine-grained sediments. Large sand fraction or medium sand grains are distributed in the surface layers of the sediment core. Sand (%) ranged from 1-13% for the last ~13.5 kyr. Depth profile of sand shows low contents ~2% in sediments deposited between ~13.5 and 8 kyr BP (Fig. 2) indicating less terrigenous input into the study area. An abrupt increasing trend of sand was evident around 8 kyr BP and reaches its maximum (13%) at ~6.4 kyr BP, suggesting increased terrigenous input between these time intervals. Sand content fluctuates between 10% and 2% in sediments deposited since 6.4 kyr BP later trend of the profile reveals that terrigenous input was constant during the middle and later part of the Holocene. Like sand, very low clay contents between 4% and 10% in core likely suggest an unchanged chemical weathering of continental rocks in the western part of India during the last ~13.5 kyr. Throughout the core, the dominant sedimentary fraction is silt, ranging from 80% to 96%. In general, the sediments of the Late Glacial Maximum and early Holocene are characterized by minimal clay and maximum silt, while the mid to late Holocene shows an increase in clay content, indicating enhanced detrital input.

3.2 Sediment Biogenic Silica

The biogenic silica content ranges from 3.4 to 4.4% over the past 14.4 kyr (Fig. 3a). This range is consistent with the range (2-4%) obtained from a nearby core in the same study area [23]. Relatively high biogenic silica contents were observed during the B-A event (ca. 13.5-13 kyr BP) and low OC contents (~1.98 and ~2.7%) mostly occurred during the early Holocene (11.7-8.7 kyr BP).

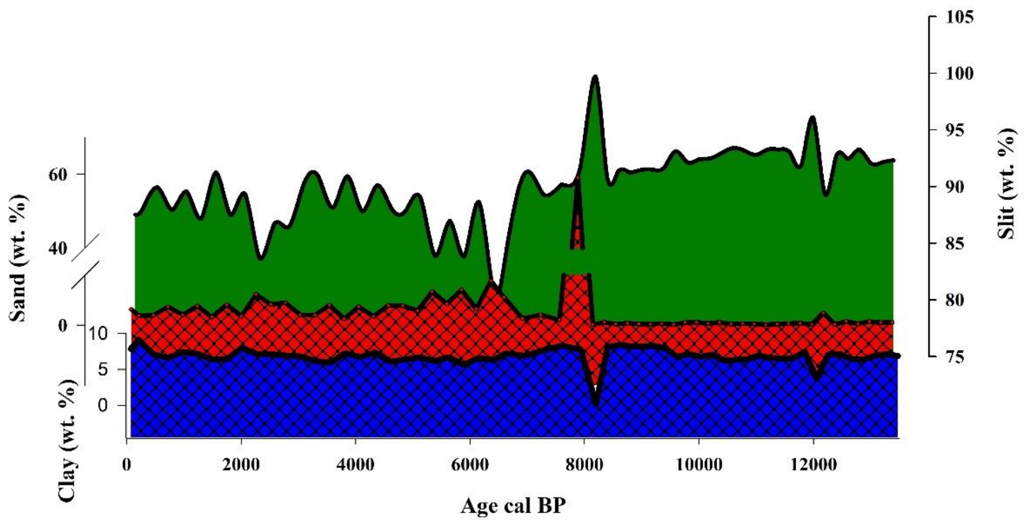

Fig. 2. Down-core profile of sand, silt, and clay in sediment core SK-215/GC5

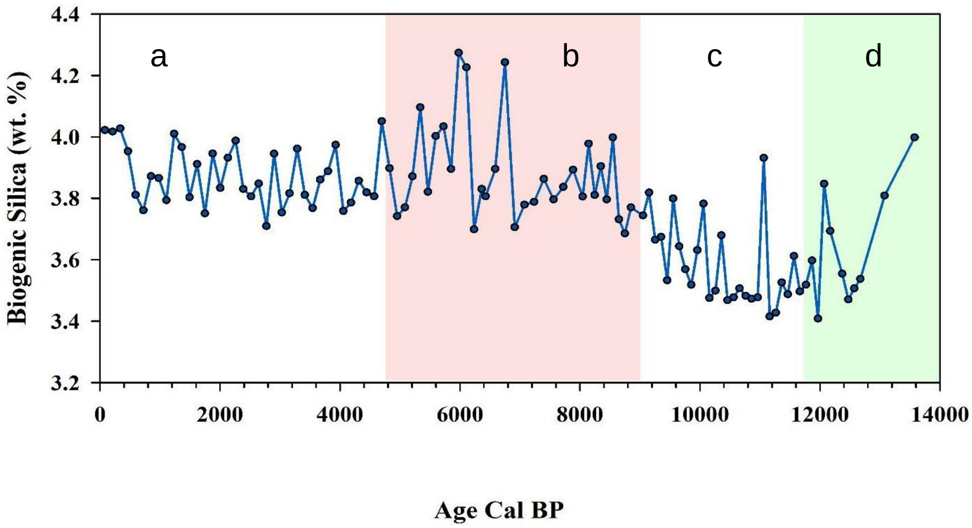

Fig. 3. The preservation of biogenic silica in sediment core (SK 215/5) (a- Late Holocene period; b- Mid Holocene period; c- Early Holocene; d- Late Glacial Period)

3.3 Bolling-Allerod Event (13.5-13.9 kyr BP)

We found high biogenic silica contents (3.9-4.5%) during the B/A event compared to the Holocene in the SEAS (Green shade in Fig. 3). In general, ISM was stronger during the warm climate [24], suggesting that stronger ISM seems to have increased upwelling and therefore enhanced water column productivity in the SEAS. Consistently, Kessarkar et al. [25] interpreted intense denitrification from the nitrogen isotope record from the eastern Arabian Sea, confirming a strengthened upwelling and intensified OMZ during the B/A event.

3.4 Younger Dryas (YD; 12.9 - 11.6 kyr BP)

An overall decreasing trend in productivity was recorded in biogenic silica content during the YD cold interval in the study area (Fig. 3). Strikingly, this decreasing productivity trend is punctuated with multi-centennial (ca. 300-500 yr) scale fluctuations that have not been reported from the entire Arabian Sea. Consistently, a decreased oxygen isotope ratio of foraminiferal carbonate ($\delta^{18}O_C$) suggested a reduced freshwater influx into the SEAS during this interval [25].

3.5 Early Holocene (~11.7 to 8.5 kyr BP)

Our core shows low biogenic silica contents (<2%) in marine sediments accumulated between ~11.7 and 8.5 kyr BP, corresponding to the early Holocene interval. A period of intensified SW monsoon in the Arabian Sea in early Holocene occurred between 8 and 10 Kyr BP which is called the Holocene humid interval that could also be increased monsoonal precipitation on the western continental margin of India [26], resulting in an enormous amount of fresh water entering the SEAS. As a result, upwelling induced surface productivity was decreased [27]. Kessarkar et al. [28] concluded that a reduced primary productivity during the Holocene might be the effect of enhanced precipitation associated with the intensified SW monsoon fortifying near surface stratification.

3.6 Holocene Climatic Optimum (HCO) (~8.5 to 4.5 kyr BP)

A sharp increase of biogenic opal content between ~8.5 and 6 kyr BP corresponds to the HCO (Fig. 3). These results indicate increased water column productivity due to increased monsoon induced upwelling in the SEAS. It is interpreted that the maximum ISM rainfall during the Holocene mainly occurred ~8.5–6 kyr BP. This is consistent with multiproxy records of Lunkaransar Lake (Rajasthan) which reached its maximum level at 6.3 kyr BP [29]. At the same time most of the southwest coast of India has been converted into carbon-rich peat land during the HCO [30]. The nitrogen isotopic record, a proxy for OMZ intensity in the Arabian Sea, revealed the occurrence of intense OMZ during the HCO [25]. The abrupt decrease in $\delta^{18}O_{sw}$

after the early Holocene inferred to indicate increased precipitation in the SEAS. Consistent to this the foraminiferal Ba/Ca record showed two-fold rise between 10.7 and 7.8 kyr BP because of higher surface runoff [31].

3.7 Late Holocene (~6 to 1.1 kyr BP)

In general, biogenic silica content has stabilized (3.7 ± 0.4) since the ~4.5 kyr BP (Fig. 3). Trends of these parameters imply that paleoproductivity was almost stabilized in the SEAS during the late Holocene. Lake sediment studies from northwestern India also revealed that the mid to late Holocene period was dry and probably windy with weak monsoon circulation [32]. The arid climate and associated strong winds during the late Holocene likely induced strong upwelling in the SEAS that might have increased paleoproductivity in the study area (Fig. 3). Consistent with our productivity proxy records, enrichment of Mo and Cr and low Mn/Al ratio indicated the presence of suboxic bottom water since the mid-Holocene in the SEAS [33,34,35].

4. CONCLUSION

We concluded that minimum clay and maximum silt characterize the sediments of late glacial maximum and early Holocene whereas, the maximum as and characterizes the mid and late Holocene, indicating enhanced detrital input. Biogenic opal analysis was carried out in the sediment core from the southeastern Arabian Sea. The measurement of the biogenic silica (BSi) content of sediments is a chemical estimate of the siliceous microfossil abundance. The concentration of opal varied with depth in the sediment core. Higher opal concentration was highest in the Late Holocene period and lowest in the Early Holocene Period. Thus, the results suggest that the productivity of the region was not only determined by the abundance of siliceous organisms, but also by other dynamic factors. The high opal content in the late Holocene period and the increasing trend of opal concentration towards the Glacial period suggests that it complies with the general view that the productivity of the eastern Arabian Sea was higher during the Last Glacial period compared to that in the Holocene.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Authors hereby declare that No generative AI technology such as Large Language Models (ChatGPT, COPILOT etc. and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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