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Surface Productivity–Bottom-Water Oxygenation Decoupling During the Last Deglaciation in the Southeastern Arabian Sea

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ABSTRACT

A benthic foraminiferal record from a 4.8 m gravity core (SK-313/GC-01, 513 m water depth, off Kerala) shows an abrupt intensification of oxygen-deficient bottom-water conditions in the southeastern Arabian Sea between about 13.7 and 11.8 ka, spanning the late Bølling–Allerød (B/A) and the Younger Dryas (YD). We have analysed 168 benthic assemblages, together with the planktic species Globigerina bulloides and Globigerinoides ruber, in an age model anchored by five AMS ^{14}C dates and interpret the changes by climatic interval: B/A (14.4–12.9 ka), YD (12.9–11.7 ka), Early Holocene (EH; 11.7–8.2 ka), Mid-Holocene (MH; 8.2–4.2 ka) and Late Holocene (LH; 4.2–0 ka). During the YD, Bolivina spp. (B. spathulata and B. subspinescens) average 81% of the assemblage (range 59–92%), Uvigerina and Bulimina marginata nearly disappear (≤5% and ≤3%), and diversity falls to its minimum (Shannon H ≈ 0.8). The same interval has the highest G. ruber (≈61%) and low G. bulloides (≈17%), pointing to a warm, stratified surface ocean rather than upwelling-driven productivity. Low-oxygen conditions ended abruptly at about 11.8 ka, followed in the EH by an Uvigerina-dominated phase (peak 63% at 11.1 ka) indicating re-oxygenation with high organic-matter flux. The MH and LH are characterised by a stable B. marginata–Uvigerina assemblage (≈65–70% combined) with low Bolivina (10–14%), while G. bulloides rises to ≈40% in the LH. The record documents a millennial-scale oxygen minimum zone (OMZ) response at the eastern margin of the Arabian Sea that is decoupled from surface productivity during the last deglaciation.

Keywords: *benthic foraminifera; oxygen minimum zone; Younger Dryas; Bølling–Allerød; Holocene; southeastern Arabian Sea; Bolivina.*

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1. Introduction

The Arabian Sea hosts the world's thickest oxygen minimum zone (OMZ), which accounts for up to about 40% of global pelagic denitrification while occupying less than 2% of the ocean area [1,2]. The OMZ emerges from high oxygen demand, fueled by monsoon-driven productivity, mixed with slow ventilation of intermediate waters, hence its extent and intensity respond to both the Indian monsoon and large-scale ocean circulation [24].

Sediment records reveal that the Arabian Sea monsoon, productivity, and OMZ changed on millennial timeframes in tandem with the North Atlantic climate. Laminated, organic-carbon-rich strata in the northeastern Arabian Sea correspond with Greenland interstadials [5]. Nitrogen-isotope data from the Oman margin show that denitrification and productivity were linked to Dansgaard-Oeschger events via the strength of summer-monsoon upwelling [68], and Holocene times with a weak summer monsoon coincided with cold periods in the North Atlantic [9].

Productivity alone does not determine oxygen levels at intermediate depths. Changes in the ventilation of thermocline and intermediate waters have been documented for the Indian Ocean on centennial to millennial timescales [10], and [11] attributed a mid- to late Holocene strengthening of the OMZ in the northwestern Arabian Sea, despite weaker monsoon winds, to changes in intermediate-water circulation rather than monsoon intensity. Model tests also suggest that stronger summer monsoon winds increase both oxygen consumption and ventilation, with the net effect varying by depth [2]. Separating productivity from ventilation requires the use of a proxy that measures bottom-water oxygen independent of surface circumstances.

Benthic foraminiferal assemblages are often employed for this purpose because species differ in their susceptibility to low oxygen as well as their response to organic matter flux [12,13]. In the northern Arabian Sea, they were utilized to reconstruct organic matter flux, bottom-water oxygenation, and OMZ intensity [14,15]. Along the eastern coast, benthic assemblages from the Goa shelf link oxic-dysoxic changes during the Holocene to monsoon variability and poorly ventilated intermediate water [16]. Planktic foraminifera from the same samples add surface-ocean context: *G. bulloides* is an established indicator of upwelling driven by the southwest monsoon [9] whereas *G. ruber* indicates warm, stratified surface water.

The majority of these reconstructions came from the northern and western Arabian Seas, or from the shelf.

There are far fewer deglacial benthic records from the top slope of the southeastern edge, where the OMZ is narrower and moderately oxygen-depleted, and a poleward undercurrent seasonally raises oxygen levels at intermediate depth [17]. Because oxygen levels are closer to the critical thresholds for benthic foraminifera, this environment may be particularly susceptible to changes in ventilation and oxygen demand.

Here we present a high-resolution benthic and planktic foraminiferal record from a gravity core SK 313/GC01 taken at 513 m off Kerala, spanning the last 14.4 kyr. Our objectives are to (1) document changes in the benthic assemblage across the Bølling–Allerød (B/A), Younger Dryas (YD), Early Holocene (EH), Mid-Holocene (MH) and Late Holocene (LH); (2) evaluate how bottom-water oxygenation relates to surface-ocean conditions inferred from planktic foraminifera; and (3) test whether the OMZ in the southeastern Arabian Sea responded to deglacial climate events in the same way as in the northern basin.

2. Study area

The 4.8 m gravity core SK-313/GC-01 was retrieved from the southeastern Arabian Sea (10°30.11′ N, 75°22.50′ E) off Kerala, at around 513 m water depth, during the 313th expedition of ORV Sagar Kanya conducted by the National Center for Polar and Ocean Research (NCPOR), Goa, India (Figure 1). The site is located on the continental slope, inside the depth range of the Arabian Sea OMZ.

The regional climate is influenced by the seasonally reversed Indian monsoon. The southwest (summer) monsoon provides strong winds and copious rainfall over the Western Ghats, which provide freshwater and terrigenous material to the Kerala shelf [18] via numerous west flowing rivers, whereas the northeast (winter) monsoon is drier and has weaker winds [19]. Surface circulation also undergoes a pronounced seasonal reversal. The Summer Monsoon Current (SMC) flows eastward across the southern Indian Ocean during the summer monsoon, whereas the Winter Monsoon Current (WMC) flows westward during winter [19]. Along the western margin of India, the West India Coastal Current (WICC) flows equatorward during the summer monsoon and poleward during the winter monsoon [1921].

The site lies within the depth range of the Arabian Sea OMZ, but in its southern, weaker part. Year-round ship observations of the eastern Arabian Sea show that the OMZ (< 20 μM O_2) occupies about 60-1350 m over an annual cycle and thins from north to south, that its perennial core (< 5 μM O_2) ends near 15° N, and that a poleward undercurrent raises oxygen in the 150-500 m layer by about 5 μM between 6.5° and 13° N [17]. At 10.5° N and 513 m, our core is just below the layer most impacted by this undercurrent and south of the perennial core OMZ, where very minor changes in ventilation or oxygen demand can shift bottom-water oxygen levels above thresholds that are important to benthic foraminifera.

Previous Holocene benthic foraminiferal research on the eastern margin has concentrated on the Goa shelf and upper slope, where oxic-to-dysoxic shifts have been connected to weakening of the summer monsoon and poorly ventilated intermediate water [16]. The deglacial history of the southeastern slope, particularly the response to the B/A and YD, is less well recorded, which motivates the current study.

3. Materials and methods

3.1 Sampling and age model

The core was sampled at [2–5] cm intervals, giving 168 samples with benthic and planktic counts.

The chronology rests on five AMS ^{14}C dates (NZA 61165–61169) at 3.5, 143, 247, 357 and 459 cm. Ages were calibrated and combined into an age–depth model with the Bayesian software Bacon (Blaauw and Christen, 2011). The model covers 14.4 kyr to the present. The youngest sample dated by the model is 1.1 ka, so the LH is represented by samples between 4.2 and 1.1 ka. We follow the climatic intervals B/A (14.4–12.9 ka), YD (12.9–11.7 ka), EH (11.7–8.2 ka), MH (8.2–4.2 ka) and LH (4.2–0 ka).

3.2 Foraminiferal analysis

The sediment samples were dried, weighed, disaggregated, and wet-sieved through a 63 μm sieve. The >63 μm fraction was dried and inspected under a stereomicroscope using conventional benthic foraminiferal processing and census procedures [22]. Benthic foraminifera were recognized at the species or genus level, with an average count of 280 specimens per sample (range 186-336). Planktic foraminifera were enumerated in the same samples and expressed as percentages of the six species *(G. bulloides, G. ruber, Neogloboquadrina dutertrei, Globorotalia menardii, Trilobatus sacculifer,* and *Orbulina universa).*

3.3 Data analysis

Benthic species were converted to relative abundances (percentages). We classified Bolivina spathulata and B. subspinescens as low-oxygen, Uvigerina peregrina and U. proboscidea as organic-flux, and Bulimina marginata and Cibicides spp. individually. Diversity was measured by the number of species and the Shannon index (H). Ward's hierarchical clustering was used to investigate assembly zones, followed by principal component analysis of square-root-transformed percentages. Pearson correlation coefficients were determined for taxa, diversity, and planktonic percentages [23]. Interval means are the arithmetic averages of all samples within each climatic interval.

4. Results

The benthic composition dramatically changes at the B/A-YD-EH sequence before stabilizing throughout the Holocene (Figure 2, Table 1). Three taxa groups dominate the record: *Bolivina* spp., *Bulimina marginata* and *Uvigerina* spp. (*U. peregrina*, *U. proboscidea*), with *Cibicides* and *Ammonia* as minor components.

4.1 Bølling–Allerød (14.4–12.9 ka)

The B/A is composed of two different components. At the onset, B. marginata dominates (up to 60% at around 14.2 ka), followed by Uvigerina (up to 28% at 13.9 ka) and, in the oldest sample, Ammonia (approximately 20%). Bolivina spp. began to replace this assemblage at 13.7 ka, accounting for more than 60% of 16 samples between 13.7 and 13.0 ka. As a result, Bolivina ranges from 2 to 85%, with a mean of 52%. G. ruber is already high (mean 57%), but G. bulloides is modest (17%, peak 22% at 13.5 ka).

4.2 Younger Dryas (12.9–11.7 ka)

The YD represents the most severe interval in the dataset. Bolivina spp. dominate all samples (59-92%, mean 81%), with 29 of 30 samples exceeding 60%. B. marginata (0-3%) and Uvigerina (1-5%) are almost extinct, cibicide use is at its lowest (2.2%), and diversity is at its lowest (H = 0.8). G. ruber achieves its highest mean (61%), whilst G. bulloides remains low (17%). With a mean spacing of 40 years, this is also the most well-resolved interval.

4.3 Early Holocene (11.7–8.2 ka)

Bolivina dominance ends suddenly around 11.8 ka, coinciding with the YD-Holocene boundary. *Bolivina* declines to an average of 18% (5-57%), whereas *Uvigerina* peaks at 63% at 11.1 ka. B. marginata recovers to a mean of 24%, with a peak of 53% at 9.5 ka. Diversity returns to H = 2.0, and *cibicides* rise to 7.2%. *G. ruber* decreases to 32%, while *G. bulloides* increases to a mean of 21% (max 34% at 10.4 ka).

4.4 Mid-Holocene (8.2–4.2 ka)

The MH assemblage is stable and dominated by *Uvigerina* (mean 37%, peak 56% at 5.2 ka) and *B. marginata* (34%, 16–49%), which account for around 70% of the fauna. *Bolivina* is modest (3-25%; average: 10%). *G. bulloides* continues to increase (mean 27%; max 45% at 5.1 ka), while *G. ruber* is at its lowest (24%).

4.5 Late Holocene (4.2–0 ka)

The LH assemblage is similar to that of the MH (*B. marginata 35%, Uvigerina 30%, Bolivina* 14%), with *Uvigerina* reaching a peak of 65% at 3.6 Ka. The greatest alteration occurs in the planktic fauna, with *G. bulloides* reaching its highest mean (40%; maximum 57% at 2.75 ka). The record's youngest sample is 1.1 ka.

4.6 Relationships between taxa

Bolivina abundance is substantially negatively connected with *Uvigerina* (r = -0.83), *B. marginata* (r = -0.82), Shannon H (r = -0.83), and marginally adversely with *Cibicides* (r = -0.50). *Bolivina* correlates positively with *G. ruber* (r = +0.79) and negatively with *G. bulloides* (r = -0.45). *Uvigerina* and *B. marginata* are positively correlated (r = +0.55). Because nearby samples are not independent, these coefficients reflect the intensity of the associations rather than their formal significance.

5. Discussion

5.1 Oxygen-depleted bottom waters during the late B/A and YD

The dominance of *Bolivina spp*. between about 13.7 and 11.8 ka indicates the most severe oxygen deficit in the previous 14.4 kyr at this site. *Bolivina* species are opportunists that adapt to extremely dysoxic, organic-rich substrates ––[1214], and in this interval they replace the *Uvigerina* and *B. marginata* assemblage that characterises the rest of the record. The simultaneous decline in diversity (H = 0.8), the near-absence of epifaunal *Cibicides,* and the fauna's near-monospecificity all point to a stressed benthic habitat with low oxygen at the sea floor. The event is abrupt on both ends, with Bolivina peaking at 60% within a few samples at approximately 13.7 ka and then decreasing again at about 11.8 ka, and it is best resolved in the YD, where the mean sample spacing is around 40 years.

The onset does not correlate with the beginning of the B/A (14.4 ka), but rather begins around 700 years later, in the late B/A. The early B/A is instead dominated by *B. marginata* (up to 60%), indicating a substantial organic-matter flux under oxygen circumstances that were still sufficient for species less resistant of oxygen depletion than *Bolivina*. Oxygen levels thus dropped in two stages: an organic-flux-rich era before 13.7 ka, followed by severe depletion until 11.8 ka.

5.2 Surface–bottom decoupling

A basic explanation for low bottom-water oxygen is increased export output driven by monsoon upwelling. Our planktic data do not support this for the YD and late B/A: *G. bulloides* remains low (mean 17%), while *G. ruber*, an indicator of warm, stratified, nutrient-poor surface water, is at its highest (57-61%). *Bolivina* is correlated positively with *G. ruber* (r = +0.79) and negatively with *G. bulloides* (r = -0.45). The low-oxygen state at 513 m appears to have been separated from the intense upwelling at the surface.

Two non-exclusive explanations are worth examining. First, reduced ventilation of intermediate waters may have reduced oxygen delivery to the slope even in the absence of increased production [2,10] resulting in greater organic-matter depletion with the same flux. Second, a stratified surface layer absorbing freshwater and terrigenous organic matter from the Western Ghats rivers may have supplied organic material to the sea floor without the *G. bulloides* characteristic of upwelling. These must be distinguished using independent proxies such as benthic and planktic stable isotopes, total organic carbon with source indicators, redox-sensitive trace elements, and sediment accumulation rates.

Records from the northern Arabian Sea link a strong OMZ and high production to warm interstadials and a strong summer monsoon [5,6], and model experiments indicate that the OMZ expands at depth when summer-monsoon winds intensify –[2]. Because the YD is a cold interval, generally associated with a poor summer monsoon [9], this framework predicts a weaker OMZ, yet the southeastern site shows its strongest depletion then. This indicates that the southeastern OMZ reacts to additional controls, including intermediate-water ventilation [10,11], Alternatively, regional variances in oxygen supply could outweigh the monsoon signal. This is a hypothesis to be explored with additional cores from the margin, rather than a conclusion based on a single record.

5.3 Early Holocene re-oxygenation

The rapid end of *Bolivina* dominance at around 11.8 ka, within the age range of the YD-Holocene boundary, indicates that oxygenation was restored within a few millennia. The *Uvigerina* peak of 63% at 11.1 ka, followed by a *B. marginata* peak at 9.5 ka, suggests that organic matter flux remained high when oxygen became sufficient for these taxa. At the same time, *G. ruber* decreases from 61% to 32%, while *G. bulloides* increases (peak 34% at 10.4 ka), indicating a shift from a stratified surface ocean to more productive, upwelling-influenced conditions, as *G. bulloides* is an established indicator of upwelling driven by the southwest monsoon[9].

5.4 Stable Mid- to Late Holocene conditions

The MH and LH are very uniform: *Uvigerina* and *B. marginata* account for approximately 65-70% of the assemblage, with *Bolivina* accounting for less than 30%. This shows that bottom-water oxygen at 513 m remained over the threshold, favoring *Bolivina.* The gradual increase in G. bulloides to about 40% in the LH has no counterpart in the benthic assemblage, which could imply that benthic fauna responded to organic-matter flux and oxygen conditions that varied little over this time period, or that the lower sample resolution (about 115 years) and relative abundances obscured changes. to such changes or that its sensitivity is not captured by relative abundances. Absolute abundances and accumulation rates are required to assess this. The stability also contrasts with the northwestern Arabian Sea, where OMZ strengthening from the mid- to late Holocene was linked to changes in intermediate-water circulation [11] implying that the southeastern margin was less vulnerable.

5.5 Limitations

Several caveats apply. Because relative abundances are closed data, the YD rise in *Bolivina* must inevitably reduce the percentages of other species. Because no data on benthic foraminiferal accumulation rates, preservation indices, or independent oxygen proxies are available, selective dissolution cannot be ruled out as a source to the YD signal. Planktic data are limited to the six most abundant species. The base of the record, with Ammonia contributing up to 20%, most likely represents shelf specimens moved downslope when sea levels were lower, and its age is near to the lowest dated level. Finally, the age model is based on five dates, therefore event boundaries are subject to age errors of a few hundred years.

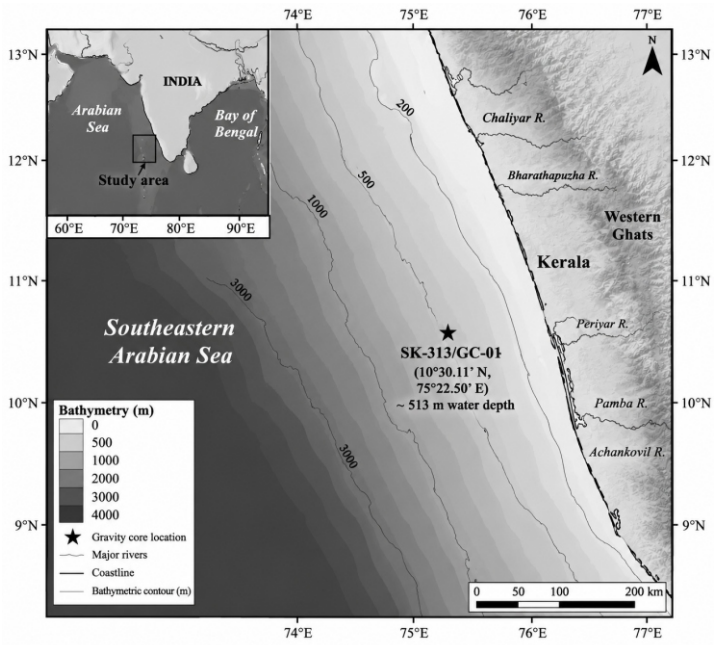

Figure 1. Map of the Arabian Sea showing the location of core SK-313/GC-01 (Star mark) off Kerala, southwest India

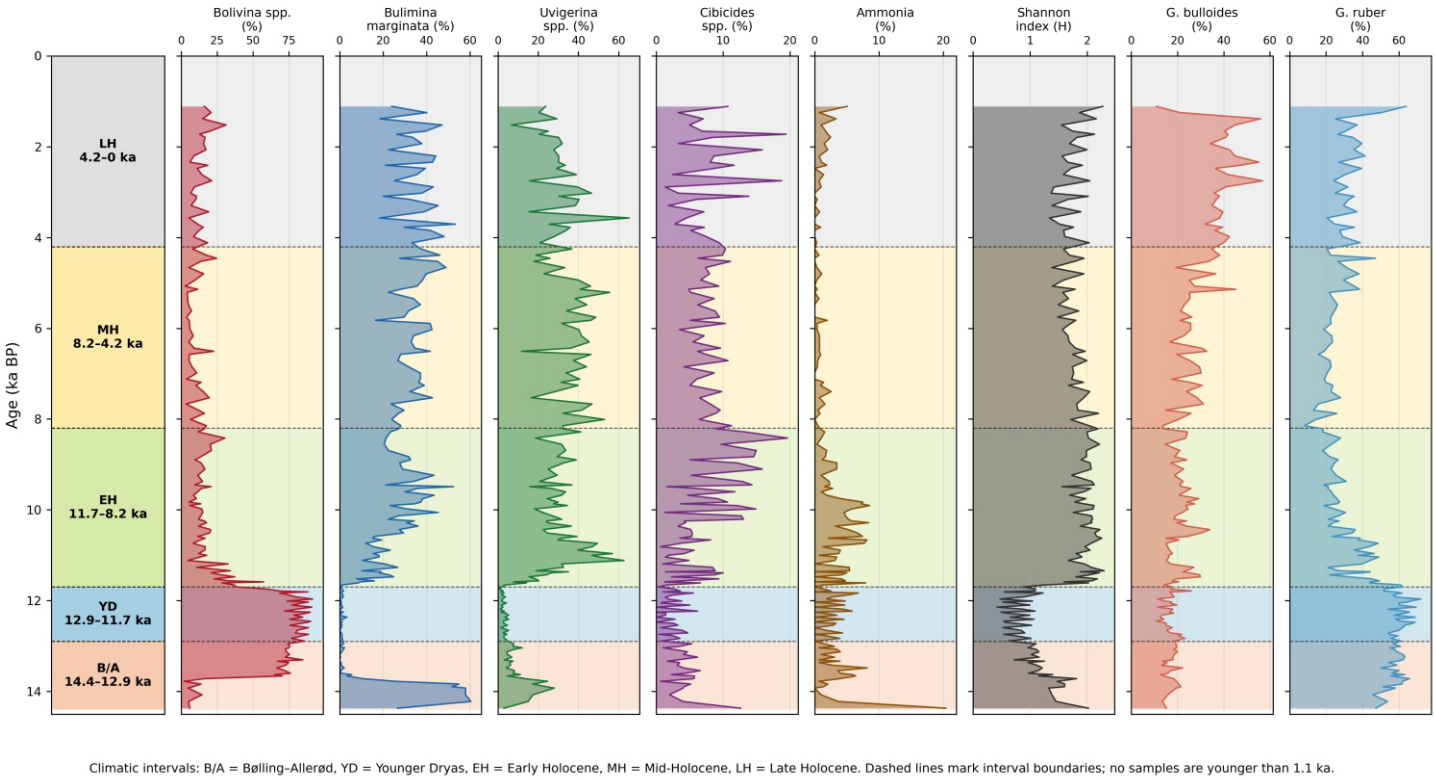

Figure 2. Downcore records of SK-313/GC-01 against age: relative abundances (%) of Bolivina spp., Bulimina marginata, Uvigerina spp., Cibicides spp., Ammonia, Shannon diversity (H), and planktic G. bulloides and G. ruber. Coloured bands and the left-hand column mark the climatic intervals: Bølling–Allerød (B/A; 14.4–12.9 ka), Younger Dryas (YD; 12.9–11.7 ka), Early Holocene (EH; 11.7–8.2 ka), Mid-Holocene (MH; 8.2–4.2 ka) and Late Holocene (LH; 4.2–0 ka). Dashed lines show interval boundaries; the youngest sample is 1.1 ka.

Table 1: Mean relative abundance (%), Shannon diversity (H) and planktic percentages in each climatic interval of SK-313/GC-01. n = number of benthic samples.

Interval	Age (ka)	n	*Bolivina* spp.	*B. marginata*	*Uvigerina* spp.	*Cibicides*	Shannon H	*G. bulloides*	*G. ruber*
B/A	14.4–12.9	24	52	15	10	4.1	1.3	17	57
YD	12.9–11.7	30	81	1	3	2.2	0.8	17	61
EH	11.7–8.2	52	18	24	29	7.2	2.0	21	32
MH	8.2–4.2	35	10	34	37	7.6	1.8	27	24
LH	4.2–0	27	14	35	30	7.7	1.8	40	34

6. Conclusions

The benthic foraminiferal record of SK-313/GC-01 shows that oxygen at 513 m off Kerala was lowest between about 13.7 and 11.8 ka, across the late Bølling–Allerød and the Younger Dryas.

1. B/A (14.4–12.9 ka): an early *B. marginata*-dominated, high-organic-flux assemblage is replaced from about 13.7 ka by *Bolivina* spp.

2. YD (12.9–11.7 ka): *Bolivina* spp. average 81% (59–92%), *Uvigerina* and *B. marginata* nearly vanish and diversity is lowest (H = 0.8), indicating severe oxygen depletion.

3. Surface–bottom decoupling: the low-oxygen interval coincides with high *G. ruber* (≈61%) and low *G. bulloides* (≈17%), so it was not driven by upwelling-related productivity; reduced intermediate-water ventilation and terrestrial organic input are testable alternatives.

4. EH (11.7–8.2 ka): *Bolivina* dominance ends at about 11.8 ka and is followed by an *Uvigerina* peak (63% at 11.1 ka), with increasing *G. bulloides*.

5. MH and LH (8.2–0 ka): a stable *B. marginata–Uvigerina* assemblage with low *Bolivina* (10–14%), while *G. bulloides* rises to about 40%.

Together, these results indicate that the southeastern Arabian Sea OMZ responded strongly to deglacial climate change, in a way that cannot be explained by surface productivity alone. Accumulation rates, stable isotopes and organic geochemistry from the same core are the next steps to separate productivity from ventilation.

Author statement

We declare that this manuscript is original it has not been published before.

Authors' contributions

Conceptualization: Dhiraj Shinde, V. Yoganandan. Data curation, Formal analysis and investigation, Methodology: Dhiraj Shinde; Supervision: V. Yoganandan, Validation: Visualization: Dhiraj Shinde ; Writing—original draft preparation: Dhiraj Shinde. All authors read and approved the final manuscript.

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