Geological Magazine

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Original Article

Cite this article: Saravanan P, Gupta AK, Zheng H, Panigrahi MK, Tiwari SK, Rai SK, and Prakasam M (2020) Response of shallow-sea benthic foraminifera to environmental changes off the coast of Goa, eastern Arabian Sea, during the last ~6100 cal yr BP. *Geological Magazine* **157**: 497–505. https://doi.org/10.1017/S0016756819000979

Received: 31 March 2019
Revised: 13 July 2019
Accepted: 17 July 2019
First published online: 14 October 2019

Keywords:
benthic foraminifera; western continental margin of India; Arabian Sea; Indian monsoon; stable isotopes

Author for correspondence:
Ponnusamy Saravanan,
Email: geosaran.jan26@gmail.com

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Response of shallow-sea benthic foraminifera to environmental changes off the coast of Goa, eastern Arabian Sea, during the last ~6100 cal yr BP

Ponnusamy Saravanan[1,2], Anil K. Gupta[2], Hongbo Zheng[1], Mruganka K. Panigrahi[2], Sameer K. Tiwari[3], Santosh K. Rai[3] and Muthusamy Prakasam[3]

[1]Research Center for Earth System Science, Yunnan University, Kunming, 650500, China; [2]Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur 721302, India and [3]Wadia Institute of Himalayan Geology, Dehradun 248001, India

Abstract

We have analysed a 6100-year record of benthic and planktonic foraminifera from inner neritic sediments from Core SK291/GC13, off the Goa coast, eastern Arabian Sea, to understand the response of benthic foraminifera to shallow-marine processes. The benthic foraminiferal assemblage is dominated by *Nonion* cf. *asterizans*, *Ammonia beccarii*, *A. gaimardii* and *Virgulinella fragilis*, which have been selected on the basis of a population of 10% or more in any three samples analysed. The planktonic foraminiferal population is sporadic and rare, with *Globigerinoides ruber* as the predominant species showing a variable trend. The foraminiferal proxies combined with total organic carbon (wt%) and $\delta^{13}C$ and $\delta^{18}O$ values of *Ammonia gaimardii* suggest distinct variations, indicating changes in productivity and salinity in the shallow eastern Arabian Sea. The coastal waters off Goa were relatively warmer and less saline between 6100 and 4600, or perhaps to 4200, calibrated years before the present (cal yr BP), corresponding to a stronger monsoon in South and East Asia. The shallow sea was cooler from ~4200 to 2600 cal yr BP in the study area, coinciding with a lower sea surface temperature in the northeastern Arabian Sea and an arid phase in the Indian subcontinent. From 2900 to 2600 cal yr BP the study core exhibits the impacts of short-term cold events, which have earlier been observed in the northeastern Arabian Sea, off Pakistan. During the Little Ice Age, the shallow sea off Goa was less productive.

1. Introduction

The climate and sea surface circulation in the Arabian Sea are influenced by seasonal reversals in the Indian monsoon system (Schott *et al.* 2009). The intensity of the southwest monsoon had a significant influence on river sediment discharge (Goodbred & Kuehl, 2000), as well as human populations in Asia during the Holocene Period (Gupta *et al.* 2003; Gupta, 2004). Coastal circulation in the eastern Arabian Sea, like in other parts of the Arabian Sea, experiences a complete seasonal reversal associated with reversals in the Indian monsoon (Shetye *et al.* 1991; Schott & McCreary, 2001). During winter, the West India Coastal Current (WICC) flows poleward, leading to downwelling off the west coast of India and well-oxygenated water over the shelf (Schott & McCreary, 2001; Agnihotri *et al.* 2008). In contrast, the summer season is marked by an equatorward-flowing WICC, a poleward undercurrent and coastal upwelling and a decrease in oxygenation (Agnihotri *et al.* 2008). The area is unique as, in addition to being marked by seasonal changes in the oceanic conditions, it also receives very high rainfall: ~3 m in four months in Goa (Agnihotri *et al.* 2008).

In the eastern Arabian Sea, very large freshwater input results in a warm, low-salinity lens that often masks the upwelled water, leading to near-surface thermohaline stratification (Agnihotri *et al.* 2008). Despite surface water stratification, the productivity is still high owing to the high nutrient concentration in the upwelled water (Naqvi *et al.* 2006; Agnihotri *et al.* 2008). The high nutrient concentration leads to intense denitrification in the deeper waters. During the winter season, the eastern Arabian Sea receives low-salinity water from the Bay of Bengal (Wyrtki, 1973). These changes in surface conditions off the west coast of India drive significant changes in the coastal faunal and floral population, including shallow-water benthic and planktonic foraminifera.

Benthic foraminifera hold great potential for understanding shallow and deep palaeoceanographic changes in the geological past (e.g. Schönfeld, 2002; Altenbach *et al.* 2003; Saravanan *et al.* 2019). On the other hand, the planktonic foraminifera capture changes in the surface ocean that are driven by wind stress and upwelling (Gupta *et al.* 2003, 2015;

Table 1. AMS ^{14}C radiocarbon dates from Core SK291/GC13 analysed by National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) at Woods Hole Oceanographic Institution (USA)

NOSAMS Lab ID	Core depth (mbsf)	Species	Radiocarbon ^{14}C age (years BP)	ΔR Value used for	Calibrated age (years BP)
120856	1.24	Mixed planktonic	1740 ± 35	252 ± 51	1036
120857	1.64	Mixed planktonic	2940 ± 35	252 ± 51	2391
120858	2.36	Mixed planktonic	3530 ± 35	252 ± 51	3108
120859	2.96	Mixed planktonic	4100 ± 35	252 ± 51	3797
120860	3.90	Mixed planktonic	5950 ± 40	252 ± 51	6098

All dates were calibrated using Calib7.1 software (http://calib.org/calib/calib.html). Mixed planktonic foraminifera mainly include *Globigerina bulloides*, *Globigerinoides sacculifer*, *Gs. ruber* and *Neogloboquadrina dutertrei*.

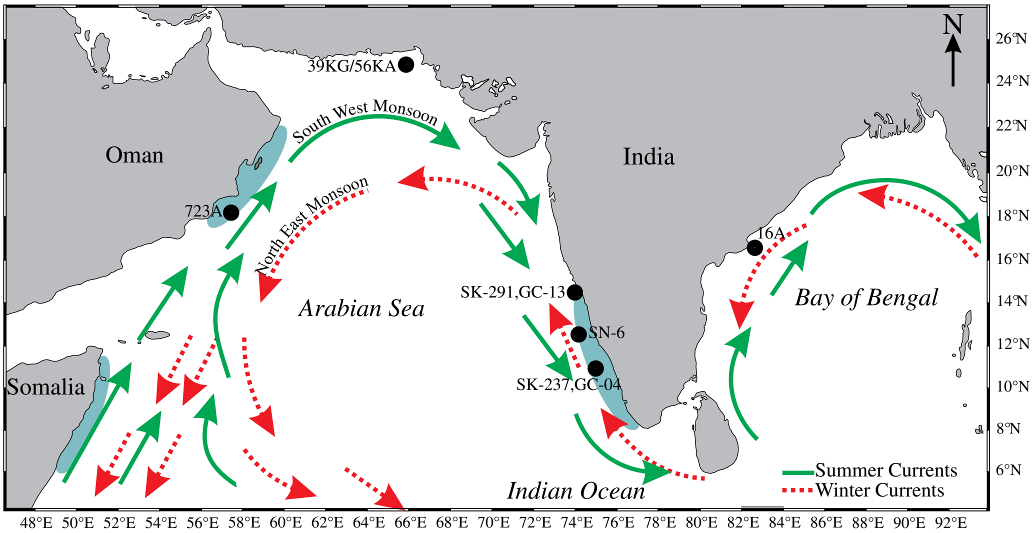

Fig. 1. (Colour online) Location map of Core SK291/GC13 (modified after Saravanan *et al.* 2019). Green and red colour arrows indicate summer and winter currents, respectively; green shaded areas represent major upwelling systems in the Arabian Sea.

Saravanan *et al.* 2019). This study aims to understand centennial-scale changes in the shelf environment condition in the eastern Arabian Sea off the coast of Goa during the middle to late Holocene transition and how marine productivity changes coupled with monsoon climate. We have carried out a multi-proxy analysis of shallow-sea benthic and planktonic foraminifera, carbon ($\delta^{13}C_{Ammonia\ gaimardii}$) and oxygen ($\delta^{18}O_{Ammonia\ gaimardii}$) isotopes of benthic foraminifera as well as total organic carbon (TOC) from sediments of the western continental margin of India off Goa, eastern Arabian Sea, to understand changes in the surface water conditions.

2. Materials and methods

The core samples were collected during the 291st cruise of the ORV Sagar Kanya organized by the National Center for Polar and Ocean Research (NPAOR), Goa. A total of 243 sediment samples of 4.5 cc volume were analysed up to 100 cm depth and 9.1 cc volume in the remaining samples encompassing a time slice of ~6100 calibrated years before the present (cal yr BP) from Core SK291/GC13 (14° 42.5′ N; 74° 00.82′ E; water depth 25 m; core length 3.90 m). The core is located on the upper continental shelf off Goa, eastern Arabian Sea (Fig. 1). The recovered sediments from Core SK291/GC13 represent a single lithologic unit, predominantly composed of clay and fine sand. Sediments that appear to be clayey in nature vary from light grey to dark grey homogeneous facies. Biogenic mass consists predominantly of different forms of foraminiferal oozes. The foraminiferal specimens are well preserved from the top to the bottom of the recovered core.

Each sample from Core SK291/GC13 was soaked in water with half a teaspoonful of baking soda for 8–10 hr and washed with a jet of water over a 63 μm size sieve. Samples with a high clay content were soaked in water with 3–4 drops of diluted H_2O_2 (2%) for clay segregation. Washed samples were oven-dried at ~50 °C and transferred to labelled glass vials. Dry samples were sieved over a 125 μm size sieve and split into suitable aliquots to obtain ~300 individuals of benthic foraminifera. The census counts of planktonic foraminifera were obtained from the >149 μm size fraction and percentages of each species were calculated.

The age model of the core was developed using five accelerator mass spectrometry (AMS) ^{14}C dates (Table 1). The AMS ^{14}C measurements were made on five samples of mixed planktonic foraminiferal tests at NOSAMS (National Ocean Sciences Accelerator Mass Spectrometry) Laboratory, Woods Hole Oceanographic Institution, USA. Approximately 8–10 mg of mixed planktonic foraminifera from each sample were picked and pre-treated with Millipore water by using an ultrasonic

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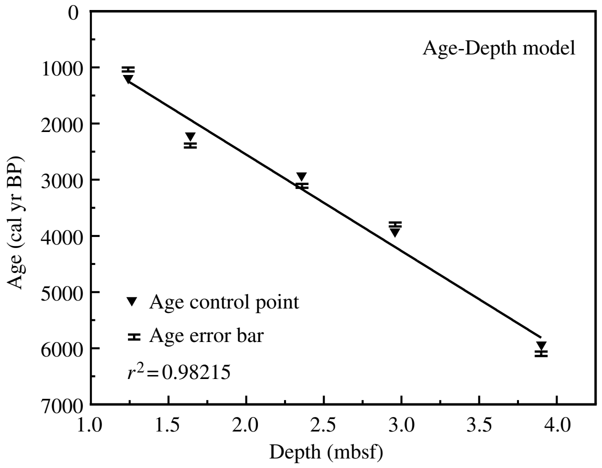

Fig. 2. Age versus depth plot showing that all the ages fall close to the linear line, indicating accuracy of the dates.

vibrator for 40 minutes to remove any foreign material. The AMS ^{14}C ages were converted into calendar ages via the Calib7.1 software using the Marine13 calibration dataset (http://calib.org/calib/calib.html) and a reservoir age of 640 years estimated for the location near Goa (Southon *et al.* 2002) (Table 1). The best-fit line for the age versus depth has an R^2 value of >0.98 (Fig. 2). The age uncertainty is about ±35 years (Table 1). The average sedimentation rate is 67 cm ka^{-1} ranging from 42 to 94 cm ka^{-1}. The average age per sample is 25 years based on interpolation of ages between the two points (Table 1).

For measuring $\delta^{13}C$ and $\delta^{18}O$ values, ~8–10 specimens of the benthic foraminifer *Ammonia gaimardii* were picked from each sample for stable isotope analysis, since this species is the most dominant taxon in Core SK291/GC13. Samples were measured using a GasBench II attached to a stable isotope ratio mass spectrometer (Delta V plus model from Thermo Fisher) at the Wadia Institute of Himalayan Geology, Dehradun. Carbon and oxygen isotope ratios are reported as δ values relative to the Vienna PeeDee Belemnite (VPDB) using per mil notation (‰). We used the international standard NBS-18 ($\delta^{13}C$ = –4.9446‰ VPDB; $\delta^{18}O$ = –22.5856‰ VPDB), as well as internal standard Merck carbonate analysed repeatedly in every analytical batch; its reported value was $\delta^{13}C$ = –46.97 ± 0.12‰ VPDB; $\delta^{18}O$ = –13.33 ± 0.05‰ VPDB, respectively, against NBS-18. For the accuracy and consistency of results, reproducibility was checked by replicate analyses of laboratory standards (Merck carbonate); the precision was ±0.1‰ for $\delta^{18}O$ and ±0.1‰ for $\delta^{13}C$ (1 sigma).

TOC analysis was performed on samples from the core following the method of Gupta *et al.* (2011). Total organic carbon and inorganic carbon (an estimate of calcium carbonate) were measured from Core SK291/GC13 using a Total Organic Carbon Analyser (TOC-VCPH; Shimadzu Corporation, Japan) at the TOC-GC Laboratory, Department of Geology and Geophysics, IIT Kharagpur. A Solid Sample Module (SSM) on the Total Organic Carbon Analyser (SSM-5000A) was used to run the TOC analysis. The machine was standardized using potassium hydrogen phthalate and dextrose. The SSM was calibrated separately for total carbon (TC) and inorganic carbon (IC). The IC calibration curve (best-fit line) was drawn through the scatter of readings of five standard $NaCO_3$ samples (0, 5, 10, 15 and 20 mg) with different concentrations. For TC calibration, we took five standard dextrose powders (0, 2.5, 5, 7.5 and 10 mg) with different concentrations.

3. Results

The most dominant benthic foraminiferal species in Core SK291/GC13 are *Nonion* cf. *asterizans*, *Ammonia beccarii*, *A. gaimardii* and *Virgulinella fragilis* (Fig. 3), each of which was selected on the basis of a population of 10% or more in any three samples analysed (Fig. 4). The planktonic foraminiferal population is marked by the highest abundances of *Globigerinoides ruber*, whereas other species of planktonic foraminifera are sporadic and rare. The relative abundances of selected species of benthic foraminifera and planktonic foraminifer *G. ruber* are plotted with TOC (wt%) and $\delta^{13}C$ and $\delta^{18}O$ values of *Ammonia gaimardii* (Fig. 4). We have also compared our dataset with proxy records from adjacent cores from the eastern and northeastern Arabian Sea and from ODP Hole 723A, western Arabian Sea, to understand regional climatic variability and its impact on the shallow Arabian Sea (Gupta *et al.* 2003) (Fig. 5). The $\delta^{18}O$ curve shows negative values with an average of −1.75‰ during ~6100 to 4200 cal yr BP, indicating a relatively fresher shallow eastern Arabian Sea. The values increase from 4200 to 2600 cal yr BP, with an average of about −1.5‰, coinciding with a cold and arid phase in the Indian subcontinent. The $\delta^{18}O_{A.\ gaimardii}$ record shows a short-lived abrupt increase from 2900 to 2600 cal yr BP, which has also been observed in the proxy records from the adjacent cores (Figs 4, 5). The oxygen isotope values show a modest decrease from ~2600 to 1000 cal yr BP, with an average value of −1.8‰ (Fig. 4a). The $\delta^{18}O_{A.\ gaimardii}$ values show a short-lived increase from ~1000 to 900 cal yr BP, coinciding with the early phase of the Medieval Climate Anomaly (MCA), followed by a short-lived decrease (Fig. 4a). During the Little Ice Age (LIA), the $\delta^{18}O_{A.\ gaimardii}$ values remained relatively higher (Fig. 4a). The record suggests that the shallow sea off the coast of Goa was marked by highly variable conditions with an overall increasing trend of nutrients (decreasing $\delta^{13}C$) during the last 1000 cal yr BP (Fig. 4b).

The TOC was higher between 4200 and 2600 cal yr BP, although the values show a variable but overall increasing trend from 6100 cal yr BP to the present (Fig. 4c). The TOC values decreased from 2800 to 2600 cal yr BP. *Globigerinoides ruber* shows a more secular trend from 6100 to 2000 cal yr BP, and a major increase from 2000 to 1400 and 900 to 600 cal yr BP (Fig. 4d). This species almost disappeared at ~400 cal yr BP and reappeared in the top samples. *Ammonia beccarii* and *A. gaimardii* show higher abundances in the older interval (6100–3000 cal yr BP) and again from 1000 cal yr BP to the present (Fig. 4e, f). *Nonion* cf. *asterizans*, in general, shows close parallelism with TOC values and an increasing trend from 6100 to 3000 cal yr BP. *Nonion* cf. *asterizans* and TOC values show opposite trends from 3000 to 1000 cal yr BP. *Nonion* cf. *asterizans* abundances decreased over the last 500 years (Fig. 4g). *Ammonia beccarii* and *Nonion* cf. *asterizans* show more or less opposite trends during the studied interval (Fig. 4). *Virgulinella fragilis* indicates low populations with secular variations from 6100 to 1000 cal yr BP (Fig. 4h). This species shows abrupt changes over the past 1000 years (Fig. 4h). The total abundance of benthic foraminifera increases from 4100 to 2700 cal yr BP, with a relatively stable trend from 1000 to 100 cal yr BP (Fig. 4i).

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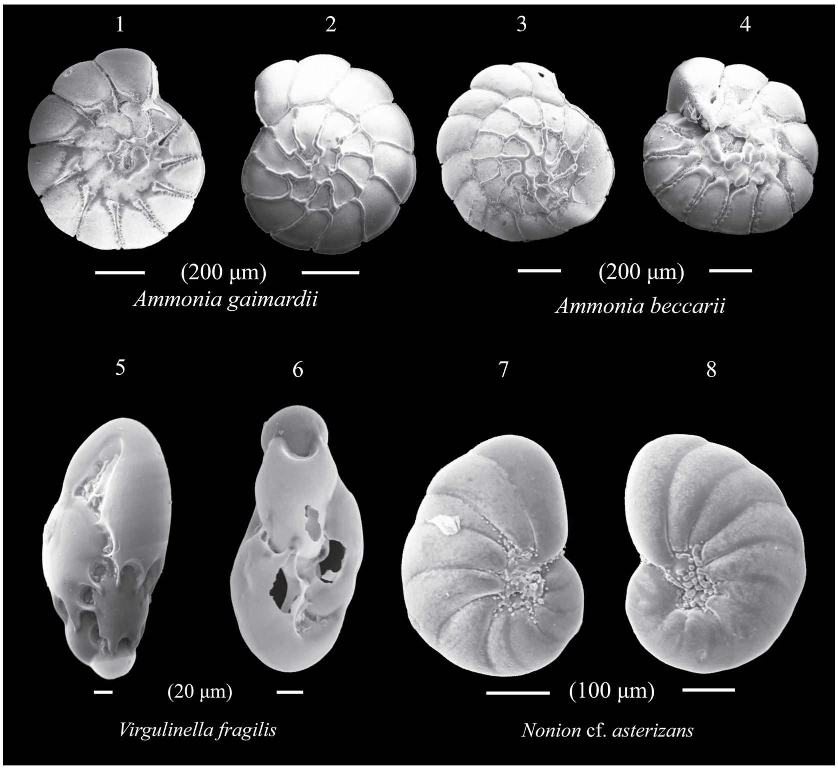

Fig. 3. Scanning electron micrographs of *Ammonia gaimardii, A. beccarii, Virgulinella fragilis, Nonion cf. asterizans used* in reconstructing palaeoenvironmental conditions in Core SK291/GC13 off Goa, eastern Arabian Sea.

4. Discussion

Coastal environments along the western continental margin of India are highly variable owing to their vulnerability to continental and oceanic climatic changes. These environments experience abrupt changes in the wind and wave energy levels and mixing of freshwaters in the surface ocean. The life in such environments is also distinct from the deep sea. Centennial- to millennial-scale changes in the coastal environments of India are driven by the Indian monsoon system and resultant coastal surface currents. These monsoon-driven currents impact benthic foraminifera and occasionally planktonic foraminifera since the latter do not prefer coastal waters. Benthic foraminifera have been widely used in palaeoenvironmental reconstructions during the Neogene Period as well as in the most recent epoch, the Holocene. The structure and composition of benthic foraminifera are influenced by numerous environmental factors including temperature, salinity, sediment properties and bottom flow of the sea water. Living benthic foraminiferal communities have been found to be related to the flux of particulate organic matter to the sea floor (Lutze & Coulbourn, 1984; Loubere & Fariduddin, 1999), the oxygen content of ambient bottom waters (Hermelin, 1992; Bernhard & Sen Gupta, 1999) and energy levels (Hess & Kuhnt, 1996; Stott *et al.* 1996). Water turbulence in shallow seas also has a great impact on benthic foraminiferal assemblages. Thus, palaeoenvironmental studies based on benthic foraminifera in coastal sediments may offer an opportunity to study both past continental and marine climate conditions. Changes in foraminiferal $\delta^{18}O$ are mainly controlled by continental ice volume or freshwater input, glacial–interglacial cycles, as well as local sea surface temperature (SST) and evaporation–precipitation (E-P) changes (Shackleton, 1967; Imbrie *et al.* 1984; Doose-Rolinski *et al.* 2001).

The ecological preferences of shallow-sea benthic foraminifera indicate varied living conditions owing to variable surface ocean energy levels and salinity as well as food supply in the shallow sea. Except for *Ammonia beccarii*, not much is known about the ecological preferences of the species used in this study. *Ammonia beccarii* is a common cosmopolitan, euryhaline species living in littoral and neritic environments (Debenay *et al.* 1998). This species has been widely used in environmental reconstructions and geological studies because of its higher abundance in neritic sediments, wide geographic distribution and long stratigraphic range since Miocene time (Debenay *et al.* 1998). *Ammonia beccarii* can be epipelic or endopelic in coarser sands, but can also be epiphytic during spring and summer (Debenay *et al.* 1998). The high abundances of *A. beccarii* are indicative of a shallow-marine environment with a sandy bottom (Sgarrella & Moncharmont Zei, 1993). Living *A. beccarii* were also reported on the rocky shore of the Mediterranean and Atlantic coasts of France (Le Campion, 1968; Vénec-Peyré & Le Calvez, 1981) and rocky shore of Japan (Kitazato, 1988). A strict interpretation based on the known modern distribution of *A. beccarii* would confine the species to upper shoreface environments (Hayward *et al.* 2004). Debenay *et al.* (1998) proposed that the seasonal variability in microhabitat preference of *A. beccarii* is a function of food availability, as the surface of seagrass growing in the intertidal zone can be densely covered by diatoms, fungi and bacteria that constitute a valuable food source for foraminifera. Based on these earlier studies, *A. gaimardii* is inferred to indicate oligotrophic conditions, preferring better oxygenated environments. *Ammonia gaimardii* has been reported from the inner sub-littoral zone under the influence of the Kuroshio Current

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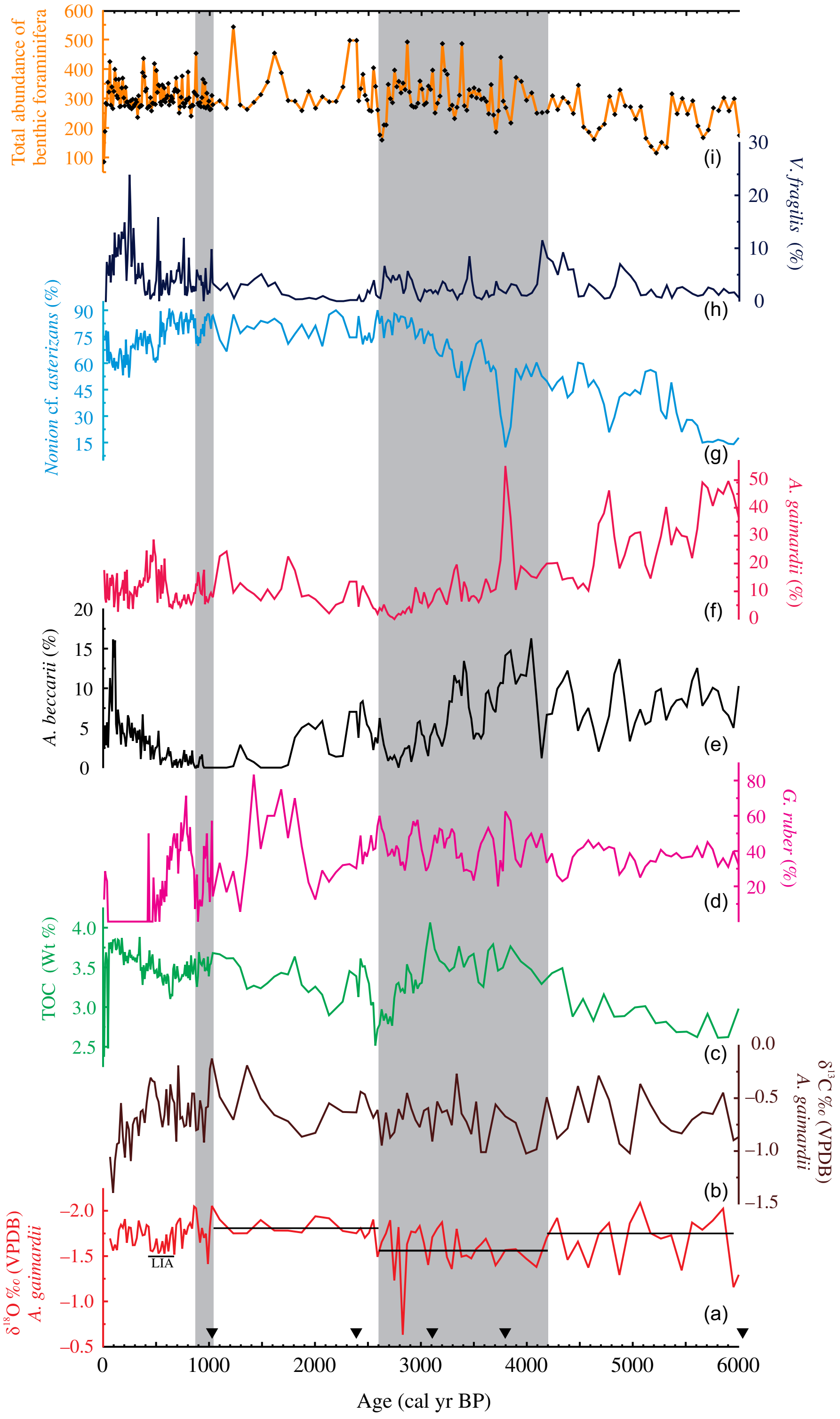

Fig. 4. (Colour online) Proxy record from Core SK291/GC13, off Goa, eastern Arabian Sea. (a) $\delta^{18}O$ values of benthic foraminiferal species *Ammonia gaimardii* (horizontal lines represent the mean value); (b) $\delta^{13}C$ values of *Ammonia gaimardii*; (c) total organic carbon (TOC) values; (d) *Globigerinoides ruber* percentage; (e–h) percentage of benthic foraminifera *Ammonia beccarii, A. gaimardii, Nonion* cf. *asterizans* and *Virgulinella fragilis*, respectively; (i) total abundance of benthic foraminifera. Grey bars indicate cold intervals when shallow sea off Goa was cooler and Indian summer monsoon was weaker. Radiocarbon dated intervals are shown by inverted triangles in the bottom panel. LIA – Little Ice Age.

in the Japan Sea, preferring higher salinities and living under the influence of warm-water sources such as the Tsushima Warm Current (Akimoto & Hasegawa, 1989; Inoue, 1989; Takata *et al.* 2016).

Virgulinella fragilis can tolerate more severe oxygen deficiencies and adjust to long periods of low-oxygen conditions in coastal lagoon environments, as well as in pelagic to hemi-pelagic settings (Takata *et al.* 2005). *Ammonia beccarii* abundance varies, possibly

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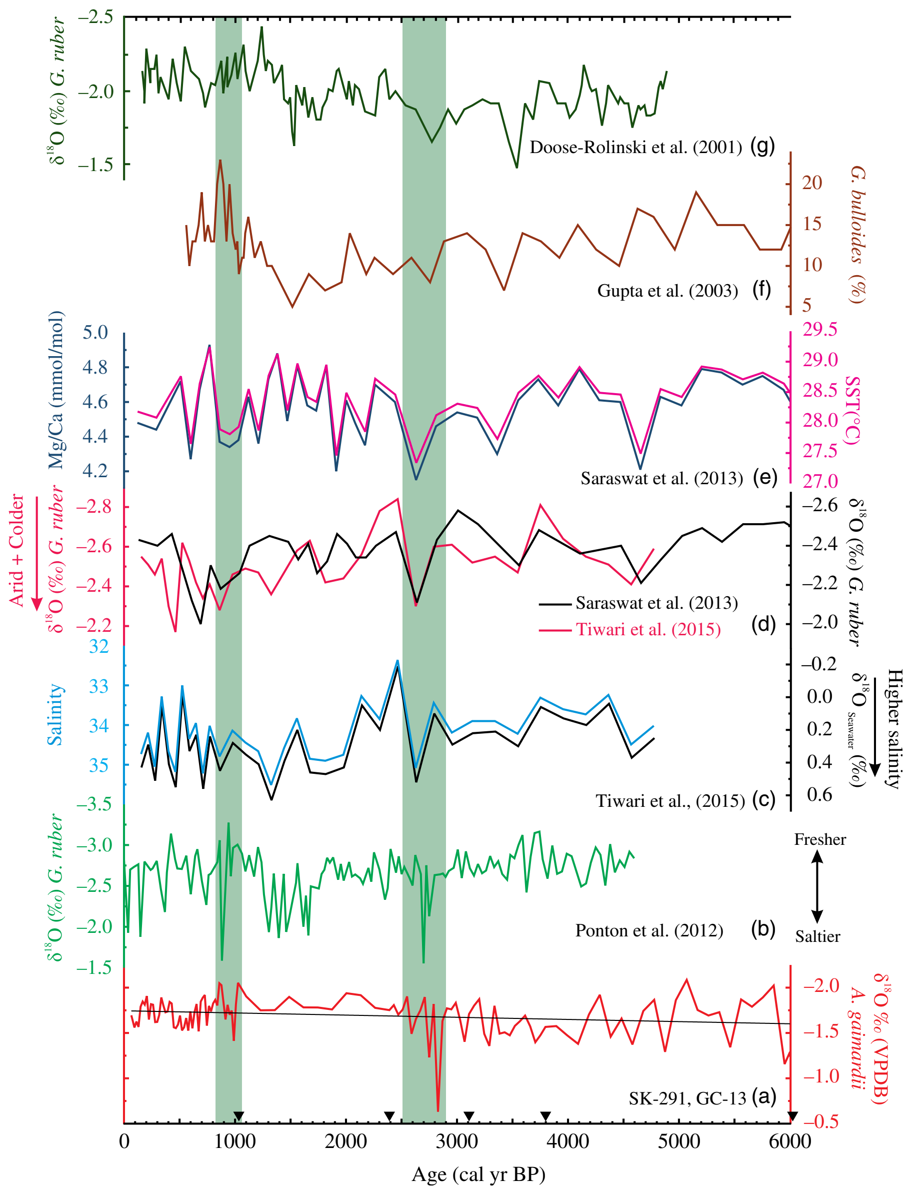

Fig. 5. (Colour online) (a) $\delta^{18}O$ values of benthic foraminifer *Ammonia gaimardii* from SK291/GC13 combined with continental and marine proxy records from the Indian Ocean region (horizontal lines represent the mean value). (b) $\delta^{18}O$ values of *Globigerinoides ruber* from Core NGHP 16A, Bay of Bengal (Ponton *et al.* 2012). (c) $\delta^{18}O$ of seawater and salinity records from eastern Arabian Sea Core SN-6 (Tiwari *et al.* 2015). (d) $\delta^{18}O$ (‰) of *Gs. ruber* from eastern Arabian Sea Site SN-6 (Tiwari *et al.* 2015) and Core SK237-GC04 (Saraswat *et al.* 2013). (e) *Gs. ruber* Mg/Ca and SST (°C) record from eastern Arabian Sea Core SK237-GC04 (Saraswat *et al.* 2013). (f) *Globigerina bulloides* (%) from ODP Hole 723A, Oman margin (Gupta *et al.* 2003). (g) $\delta^{18}O$ (‰) of *Gs. ruber* from Core 39KG/56 KA, northeastern Arabian Sea (Doose-Rolinski *et al.* 2001). Green colour vertical bar indicates cold events.

due to climate, temperature and salinity (Poag, 1978) or to food availability, feeding strategy, oxygen concentration and/or a change in the sediment type (Jorissen, 1988). In this study, *A. beccarii* shows a high percentage from 6100 to 2600 cal yr BP. A significant shift (increase) of *A. beccarii* in the younger interval (around 100 years) association and an extreme drop in TOC values all indicate decreased productivity and unfavourable neritic environmental conditions (Fig. 4c, e).

Nonion cf. *asterizans* has been observed associated with a high-productivity assemblage in conditions of comparatively low benthic oxygen respiration on the shelf in the Gulf of Cadiz and Gulf of Guinea (Schönfeld, 2002; Altenbach *et al.* 2003). In the Gulf of Cadiz, this species is reported in association with *A. beccarii* and a shelf edge assemblage (Schönfeld, 2002), whereas in the Gulf of Guinea, higher abundances of *N. asterizans* have been observed in areas of coarse-grained sediments and higher organic carbon content (Altenbach *et al.* 2003). *Nonion* cf. *asterizans* shows an increasing percentage and *A. gaimardii* a decreasing percentage from 6000 to 1000 cal yr BP, indicating high primary productivity in the shallow sea (Fig. 4f, g). *Ammonia beccarii* and *V. fragilis* show an increasing abundance trend (Fig. 4e, h), and *G. ruber*, *A. gaimardii* and *Nonion* cf. *asterizans* show a decreasing trend from 1000 to 100 cal yr BP (Fig. 4d, f, g). This period is marked by moderate oxygen levels in the studied core. The genus *Fursenkoina* is an infaunal taxon that feeds on phytodetritus (Gooday, 1993; Schumacher *et al.* 2007) and is considered a high-productivity and low-oxygen content indicator (Leutenegger & Hansen, 1979). The elongate, cylindrical forms, in general, prefer a moderately infaunal habitat tolerant of lower oxygen conditions (Gupta, 1993).

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Our data from Core SK291/GC13 show a close parallelism between *N.* cf. *asterizans* abundances and TOC values, indicating a general increase in organic flux in the study core from 6100 to 3000 cal yr BP (Fig. 4). The $\delta^{18}O_{A.\ gaimardii}$ data suggest decreasing salinity and/or a warm shallow eastern Arabian Sea between 6100 and 4600, or perhaps to 4200 cal yr BP (Fig. 4a). This was an interval of wet conditions in South Asia as well as SW China owing to intense Indian and southwest monsoons (Gupta *et al.* 2003; Zhang *et al.* 2017). The study core SK291/GC13 experienced relatively colder conditions from ~4200 to 2600 cal yr BP, contemporaneous with lower SSTs in the northeastern Arabian Sea than the present day (Doose-Rolinski *et al.* 2001) and an arid (or colder) phase in the Indian subcontinent (Staubwasser *et al.* 2003; Dixit *et al.* 2014; Dutt *et al.* 2018). During the interval between ~2900–2500 and ~1000 cal yr BP the sea-level was higher in the northern Arabian Sea, whereas the eastern Arabian Sea experienced arid and cold conditions. Reef records from the Maldives show a sea-level highstand in the Central Indian Ocean from 4000 to 2100 cal yr BP (Kench *et al.* 2009). Our data from Core SK291/GC13 show cooling from 4000 to 2100 cal yr BP when the sea-level was relatively higher (Kench *et al.* 2009), indicating that it was a local phenomenon.

The TOC was higher and $\delta^{13}C_{A.\ gaimardii}$ values were relatively negative (average value of −0.71‰) from ~4200 to 3000 cal yr BP in the study core, indicating a more productive shallow sea (Fig. 4b, c). At the same time, a higher abundance of benthic foraminifera (Fig. 4i) and higher values of $\delta^{18}O_{A.\ gaimardii}$ indicate favourable environmental conditions for the benthic foraminiferal population off the coast of Goa. The TOC values decreased from 3100 to 2500 cal yr BP and thereafter show a continuous increase in Core SK291/GC13 (Fig. 4). The interval ~2900–2600 cal yr BP is marked by abrupt cold events, as has also been observed in the northeastern Arabian Sea, off Pakistan (Doose-Rolinski *et al.* 2001; Ponton *et al.* 2012). The surface salinities increased (Tiwari *et al.* 2015) and SST decreased by 1 °C in the eastern Arabian Sea during this time (Fig. 5; Saraswat *et al.* 2013; Tiwari *et al.* 2015). Continental proxy records show a dry phase in the East Asian monsoon during this time (Wang *et al.* 2005; Hu *et al.* 2008). The significant short-term changes in the SST between ~2800 and 1000 cal yr BP might be linked to the cooling of northern latitudes as well as global cooling effects.

Core SK291/GC13 witnessed a short-lived pronounced cooling event during 1000 to 900 cal yr BP within the MCA. During the LIA, the shallow sea off Goa was cooler when the *N.* cf. *asterizans* population shows a gradual decrease. During the last 1000 years, the Goa coast, in general, was productive but marked by more frequent changes in both temperature and organic carbon fluxes (Fig. 4). The *G. ruber* population witnessed abrupt changes during the last 2000 years in contrast to the benthic foraminifera, suggesting that the conditions in surface and subsurface waters of the shallow eastern Arabian Sea were different during this time (Fig. 4). *G. ruber* shows a near absence during the last 400 years owing to seasonal variation affecting its survival (Fig. 4). Recently, the record based on sediment trap data by Jonkers & Kučera (2015) revealed that the seasonality of individual planktonic foraminifera is predominantly related to the timing of primary productivity or temperature. The warm-water species *G. ruber* exhibits moderately uniform annual fluctuation patterns with less of a seasonal peak in the tropical–subtropical areas of the ocean basins (Jonkers & Kučera, 2015). Even this species, however, displays vertical habitat variability, and its seasonal occurrence outside the tropics is limited to the warm surface layer that grows at the end of the warm season. Numerous studies have exhibited that the seasonality of temperate and cold-water planktonic foraminifer species is closely tied to phytoplankton bloom events that are principal to an increased food supply (e.g. Northcote & Neil, 2005; Storz *et al.* 2009; Jonkers & Kučera, 2015).

The oxygen isotopic composition ($\delta^{18}O$) is strongly affected by salinity in the shallow sea area. The $\delta^{18}O$ isotopic composition of sea surface water and its relationship to salinity are directly controlled by the hydrological processes, such as runoff, evaporation and precipitation, advection/upwelling and diffusion (Rohling, 2007). The salinity versus $\delta^{18}O$ relationship in the northern Indian Ocean is highly sensitive to monsoon overflow as suggested by Singh *et al.* (2010). The difference in the salinity and $\delta^{18}O$ in the eastern Arabian Sea is mainly directed by the southwest monsoon runoff from the Western Ghats (Deshpande *et al.* 2013). In the month of June to September, the summer monsoon current (flowing eastward) transports the high-salinity water from the Arabian Sea to the Bay of Bengal (Kumar & Prasad, 1999). Throughout the summer monsoon, the Bay of Bengal receives freshwater runoff from the Ganga–Brahmaputra rivers and through rainfall. During the winter (October to February), the low-salinity water is carried from the Bay of Bengal to the eastern Arabian Sea by the winter monsoon current mainly driven by the northeasterly wind system. A study by Kumar & Ramesh (2016) investigated the $\delta^{18}O$–salinity relationship in the eastern Arabian Sea, dividing it into four major regions, three of which fall under the impact of the WICCs and one under the result of the winter monsoon current.

5. Conclusions

We conclude that the western continental margin of India witnessed highly variable climatic and surface oceanic conditions during middle and late Holocene times, mainly driven by changes in monsoonal wind and rainfall intensity since 6100 cal yr BP. We further conclude that the shallow sea off the Goa coast, the eastern Arabian Sea, witnessed pronounced changes in SST, salinity and organic productivity as observed along the Pakistan Margin, northeastern Arabian Sea. During the period ~4200 to 2600 cal yr BP we observe lower SSTs in the eastern Arabian Sea than the present day, suggesting that the eastern Arabian Sea experienced relatively colder conditions. The low-salinity values signify that the summer monsoon weakened and perhaps the winter monsoon intensified. The interval ~2900–2600 cal yr BP is characterized by abrupt cold events, as has also been observed in the northeastern Arabian Sea. A short-lived pronounced cooling event is observed from 1000 to 900 cal yr BP within the MCA, coinciding with cooling of the northern hemisphere. These changes were captured by shallow-marine benthic foraminifera and the isotopic fingerprint. The higher salinities are associated with higher SSTs and high rates of evaporation when the Indian summer monsoon was stronger and wind intensity increased.

Acknowledgements. AKG and PS acknowledge financial support from the Ministry of Earth Sciences, Government of India (sanction number MoES/16/49/09/RDEAS) and a J.C. Bose Fellowship (SR/S2/JCB-80/2011). AKG thanks the Department of Science and Technology, New Delhi for a J.C. Bose Fellowship. PS and HZ acknowledge the financial support from the National Basic Research Program of China under grant (No. 2015CB953800) supported by 973 Program. The Department of Geology and Geophysics, IIT Kharagpur and Wadia Institute of Himalayan Geology, Dehradun are acknowledged for analytical facilities. The study samples were procured under NCAOR 291th ORV Sagar Kanya cruise by AKG.

https://doi.org/10.1017/S0016756819000979 Published online by Cambridge University Press

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https://doi.org/10.1017/S0016756819000979 Published online by Cambridge University Press