Geoscience Frontiers 6 (2015) 913–925

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research paper

Glacial-interglacial productivity contrasts along the eastern Arabian Sea: Dominance of convective mixing over upwelling

Kumar Avinash [a,*], Busnur R. Manjunath [b], P. John Kurian [a]

[a] Earth System Science Organization, National Centre for Antarctic and Ocean Research, Ministry of Earth Sciences, Headland Sada, Goa, 403804, India

[b] Department of Marine Geology, Mangalore University, Mangalagangotri, Karnataka, 574 199, India

ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form
11 March 2015
Accepted 17 March 2015
Available online 7 April 2015

Keywords:
Paleoproductivity
Upwelling
Convective mixing
Terrigenous sedimentation
Western continental margin of India

ABSTRACT

The western continental margin of India is one of the highly productive regions in the global ocean. Primary productivity is induced by upwelling and convective mixing during the southwest and northeast monsoons respectively. Realizing the importance of high primary productivity, a sediment core was collected below the current oxygen minimum zone (OMZ) from the southwestern continental margin of India. This was dated by AMS radiocarbon and as many as 60 paleoclimate/paceoceanographic proxies, such as particle size, biogenic components, major, trace and rare earth elements (REEs) which were measured for the first time to determine sources of sediment, biogeochemical processes operating in the water column and their variations since the last glacial cycle. R-mode factor analysis of comprehensive data indicates that the dominant regulator of paleoproductivity is the southwest monsoon wind induced upwelling. Other paleoproductivity related factors identified are the marine biogenic component and biogenic detritus (as an exported component from the water column added to the bottom sediment). All paleoproductivity components increased significantly during the marine isotope stage-1 (MIS-1) compared to those accumulated from MIS-4 to MIS-2. The second group of factors identified are the terrigenous sediments with heavy minerals like zircon and ilmenite. The terrigenous sediment, in particular, increased during MIS-2 when the sea-level was lower; however, the heavy mineral component fluctuated over time implying pulsed inputs of sediment. The diagenetic fraction and reducing component are the third group of factors identified which varied with time with increased accumulation during the MIS transitions.

The primary productivity along the southwestern continental margin of India seems to have been controlled principally by the upwelling during the southwest monsoon season that was weaker from MIS-4 to MIS-2, as relative to that during the MIS-1. In contrast, increased glacial productivity noticed in sediments deposited below the current oxygen minimum zone (OMZ) along the north of the study area that can be linked to entrainment of nutrients through the intensified convective mixing of surface water during the northeast monsoon. The sequestration of greenhouse gases by the western continental margin of India was higher during glacial than interglacial cycles.

1. Introduction

Marine sediments provide information about paleoceanographic processes and associated climate changes, such as fluctuations in the wind intensity and direction, fluvial sediment input, and biogeochemical processes operating in the water and sedimentary columns (Duplessy, 1982; German and Elderfield, 1990; deMenocal et al., 1993; Rea, 1994; Tiedemann et al., 1994; Pattan and Pearce, 2009). For a better understanding of paleoceanographic and paleo-environmental conditions, measurements of geochemical and sedimentological parameters, followed by isotope dating are necessary (Vigliotti et al., 1999; Robinson et al., 2000; Larrasoaña et al., 2003). Another important aspect of studying sediment geochemistry is to unravel the complex processes operating in the water column, sediment digenesis and post-digenetic

* Corresponding author.
E-mail addresses: kumaravinash13@gmail.com, avinash@ncaor.gov.in (K. Avinash).
Peer-review under responsibility of China University of Geosciences (Beijing).

http://dx.doi.org/10.1016/j.gsf.2015.03.003

changes (Canfield and Berner, 1987; Robinson and Sahota, 2000; Rey et al., 2005).

Trace elements such as Cu, Ni and Zn are usually associated with organic matter and may be retained with the pyrite after the oxidation of organic matter, particularly in suboxic conditions (Calvert and Pedersen, 1993). Certain elements, e.g., V, Mo, Re, etc., are enriched in sediments deposited under sub-oxic conditions, and strongly enriched in anoxic–euxinic conditions (Crusius et al., 1996; Böning et al., 2004; Brumsack, 2006). Uranium and particularly Mo tend to be enriched in organic matter under anoxic, sulphate-reducing conditions (Bruland, 1980; Crusius et al., 1996; McManus et al., 2006; Tribovillard et al., 2006). In contrast to U, Mo and Re, the distribution of Mn in marine sediment is strongly dependent on redox conditions (Calvert and Pedersen, 1993; Böning et al., 2004; Tribovillard et al., 2006). Therefore, authigenic enrichment/depletion of redox sensitive trace metals are thus useful for distinguishing the sedimentary depositional environments (Calvert and Pedersen, 1993; Böning et al., 2004; Brumsack, 2006; Tribovillard et al., 2006; McKay et al., 2007).

The Arabian Sea is an important biogeochemical region in the global ocean because of the dominance of upwelling during southwest (summer) monsoon and convective overturning of water mass during northeast (winter) monsoon (Duplessy, 1982; Naqvi et al., 1982; Madhupratap et al., 1996; Muraleedharan and Prasanna Kumar, 1996; Ducklow, 2003; Luis and Kawamura, 2004). The biannual reversal of wind patterns over the Arabian Sea drive surface water circulations. During the summer, lower tropospheric wind blowing from northeast Africa over the Arabian Sea (Findlater Jet) induces upwelling off Somalia, Oman and the southwest coast of India (Muraleedharan and Prasanna Kumar, 1996; Luis and Kawamura, 2004). Open ocean upwelling also takes place during the southwest monsoon season, which is particularly intense off Kochi ($\sim$10°N), and decreases towards the northern part of the western continental margin of India ($\sim$13°N; Muraleedharan and Prasanna Kumar, 1996). Recentsatellite remote sensing studies showed that chlorophyll-a tends to be higher in the open ocean sector during the southwest monsoon ($\sim$8° to 9°N; Jayaram et al., 2010, 2013).

The sub-surface water (between 200 and 1500 m) of the Arabian Sea is characterized by the severe depletion of dissolved oxygen, which is known popularly as the oxygen minimum zone (OMZ) that exists in the greater part of the Arabian Sea (Wyrtki, 1971; Sen Gupta and Naqvi, 1984; Calvert et al., 1995; Ingole et al., 2010; Taylor and Gooday, 2014). Numerous studies have been carried out to understand the paleoproductivity fluctuations in different regions of the Arabian Sea, such as in the northwestern and northeastern continental margins and in the deep Arabian Sea (Van Campo et al., 1982; Clemens and Prell, 1990; Shimmield et al., 1990; Shimmield and Mowbray, 1991; Prell et al., 1992; Sirocko et al., 1996, 2000; Reichart et al., 1997; Schulz et al., 1998; von Rad et al., 1999; Schnetger et al., 2000).

Paleoproductivity in the major part of the western continental margin of India seems to have been controlled by the northeast monsoon, particularly during the last glacial cycles (MIS-2 to MIS-4) as compared to the present interglacial one (MIS-1; Sarkar et al., 1993; Thamban et al., 2001; Banakar et al., 2005; Kessarkar and Rao, 2007; Kessarkar et al., 2010; Singh et al., 2011; Ishfaq et al., 2013). In contrast, the paleoproductivity scenario was found to have been different in the southeastern continental margin during the late Quaternary as there is fragmented and conflicting information (Sarkar et al., 1993, 2000; Pattan et al., 2001, 2003, 2005; Verma and Sudhakar, 2006; Narayana et al., 2009; Das et al., 2013). For instance, Pattan et al. (2001) traced the occurrence of the youngest Toba volcanic ash layer in a sediment core collected from the southwestern continental margin of India at 2300 m water depth. Further investigation of this core indicates that the paleoproductivity was considerably higher during the interglacials than that during the inter glacials (Pattan et al., 2003). However, it was later found that the rate of chemical weathering and terrigenous sediment input was higher during the glacial than the interglacial period (Pattan et al., 2005). This was particularly based on higher Al content and mass sediment accumulation rates for the glacial compared to the interglacial sequence ((4.51 $\pm$ 0.47)%, 0.105 g cm^2/ka and (3.61 $\pm$ 0.58)%, 0.084 g cm^2/ka, respectively; Pattan et al., 2005). In support of this, Narayana et al. (2009) found an increased input of terrigenous sediment during the glacial period. Further measurements of utility of redox sensitive elements in the same core (Pattan et al., 2005) indicated that the sediment deposited during MIS-1, MIS-3, MIS-4 and MIS-5 was nearer to oxic conditions (Pattan et al., 2005; Fig. 5a, c and e) than reducing conditions during the glacial periods (Pattan and Pearce, 2009). This interpretation is also in consensus with the geochemical and isotopic study carried out near the area of investigation (Sarkar et al., 1993). In contrast, the considerable increase in the sedimentation rate along with the higher content of organic carbon and the increased silicic fraction in sediment deposited along the southwestern continental margin of India is attributed to the intense southwest monsoon during the Holocene (Verma and Sudhakar, 2006). Similarly, a significant increase in the clay mineral content in the southeastern continental margin sediment is explained by the increase in fluvial activity in the hinterland of the study area as a result of the intensification of southwest monsoon during the Holocene (Das et al., 2013).

In this paper, we present for the first time comprehensive particle size, major, minor, trace and rare earth element data of a sediment core collected below the present OMZ from the southeastern continental margin of India, in order to provide a holistic view for the purpose of understanding the fluctuations of primary productivity, upwelling, and terrigenous input as well as diagenetic changes since the beginning of the last glacial cycle. An attempt on regional comparison is also made to understand the processes influencing productivity.

2. Material and methods

A gravity sediment core (3.28 m) was collected from the southwestern continental margin of India at 2700 m water depth (latitude 9°0′32″N and longitude 72°5′32″E) during the Sagar Kanya cruise (SK221/05; Fig. 1). The sediment core was subsampled onboard at 1 cm intervals for the top 1 m and at 2 cm intervals for the remaining part of the core. As the total number of sub-samples of the core amount to 214, magnetic susceptibility (MS; data not presented here) was measured for all samples. On the basis of down core distribution of MS against the age of the core, 50 samples were selected for the measurements of particle size, major and trace elements including rare earth elements.

About 30 mg of finely powdered sub-samples were digested with 48% V/V HF, HNO_3 and $HClO_4$ (supra-pure grade reagents) in the ratio of 6:3:1 respectively (Johnson and Maxwell, 1981). This was re-dissolved by adding 10 mL 1:1 HNO_3 solution. The dissolved solution was made up to 50 mL by using MilliQ deionised water. The digested samples were analysed by ICP-MS (Thermo Elemental X-7 Series) equipped with a collision cell. Continuous calibrations were monitored with standard and blank solutions during the course of measurements. In order to monitor the accuracy of the measurement of elements, an international reference material- NIST was repeatedly digested and measured along with samples. The errors of analysis were found to be <5% for elements measured. The total organic carbon (TOC) was measured after removing carbonates in sediment samples upon treatment with 2 M HCl and measured by