Environmental Earth Sciences (2018) 77:665
https://doi.org/10.1007/s12665-018-7838-z

ORIGINAL ARTICLE

Reconstruction of palaeo-depositional environment in North-Eastern Arabian Sea

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Received: 24 October 2017 / Accepted: 14 September 2018

Abstract
A sediment gravity core recovered from the North-Eastern Arabian Sea was investigated for sediment grain size, total organic carbon (TOC) and selected trace metals to understand the changes in the depositional environment over time. The core exhibited three distinct zones of sediment, the lower zone I, middle zone II and upper zone III, representing the varying conditions of sediment deposition. The lower zone is dominated by the silt-sized fraction with low organic carbon that revealed a shallow depositional environment and led to oxidation of organic matter, while the low metal concentration in this zone was either due to the low intensity of monsoon or the dilution by biogenic components and aeolian sediment influx. On other hand, the middle zone represented a transition phase where metal along with clay and organic carbon concentration started increasing due to strengthening monsoon intensity. Further, the upper zone that represented the Holocene sediments pointed to the increase in concentration of metals Al, Fe, Co and Cu that indicated an increase in the intensity of the South-West Monsoon and led to large fluvial inputs. TOC also increased towards the surface, indicating an increase in productivity that was controlled by South-West Monsoon.

Keywords Monsoon · Palaeoclimate · Arabian Sea · Sediment

Introduction

The oceans cover more than 70% of the Earth's surface and contain sediment deposited on sea floor which possesses a record of past oceanic conditions. They, therefore, act as important proxies to understand various factors or fluxes that contribute to global geochemical cycles. The ocean is subjected to changing seasonal monsoonal conditions that induce several changes in its physics, chemistry and biology. The composition of marine sediment provides important information about their origin and can be used to reconstruct the chemical and physical conditions of the marine palaeo-environment, and in some cases to identify climatic events.

Weathering is the disintegration of rock that occurs on the surface of the Earth and varies with changing climatic conditions. The resulting products are transported away by agents of erosion such as water, wind and ice to adjacent coastal areas/sea. As these terrigenous sediments get deposited on the continental margins, they offer continuous record of information about the climate of the landmasses. The distinct geochemical compositions of sediment cores can reveal the source, weathering mechanism and factors that control their composition (Alagarsamy and Zhang 2005). The concentrations of metals in marine sediments help us to understand the chemical and oceanographic processes which control their supply and distribution in the ocean (Calvert and Pedersen 1993). Metals upon discharge from their source get associated with particulates in the water column and sink to the seafloor where they get incorporated in the sediment (Forstner and Wittmann 1983; Hanson et al. 1993). These metals, however, are not sheltered permanently as the changing redox conditions may release them back to the water column by various processes of remobilization. Also, in the marine aquatic systems, sediment may be both a carrier and a source of various metals (Sruthi et al. 2014). The examination of the behaviour of a group of metals will provide valuable information on the chemical state of the palaeo-environment, provided the behaviour of such elements in the modern ocean is well understood. Previous

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Published online: 24 September 2018

studies have shown that the cyclic variability in the obliquity and precession of the Earth's orbit had affected the intensity of solar insolation and controlled the intensity of summer monsoon in the past (Prell and Kutzbach 1987; Clemens and Prell 1991). Hence, examination of marine sediments helps us to decipher the changes in depositional environment and further link it to the monsoon's intensities.

Many researchers (Paropkari et al. 1992; Reichart et al. 1997; Agnihotri et al. 2003; Kessarkar and Rao 2007; Shetye et al. 2009; Higginson et al. 2004; Banakar et al. 2005; Thamban et al. 2001; Sirocko et al. 2000; van der Weijden et al. 2006; Sruthi et al. 2014) have carried out studies in the Arabian Sea water column and sediments to understand climate change during the last glacial period, sedimentation rate, source of material, variations in the sea surface temperature and intensity of monsoon circulation.

Banakar et al. (2010) studied a gravity core from the eastern Arabian Sea and found the last 100-ka variability in climatology may have developed in response to a combination of global climatic forcings and regional monsoons. Furthermore, the most intense summer monsoons within the Holocene occurred at ~ 8 ka and were marked by sea surface temperature (SST) cooling of ~ 1 °C, sea surface salinity decrease of 0.5 psu, and $\delta_{18}O$ *Globigerinoides sacculifer* decrease of 0.2‰. Naik et al. (2017) reported a decrease in productivity in the eastern Arabian Sea during early deglaciation periods that was associated with monsoon-driven local evaporation–precipitation changes as well as the global $\delta_{13}C$ minimum at 16 ka BP. A progressive increase in productivity was also observed throughout the Holocene. Palaeoclimatic evidences reported by Chandana et al. (2018) suggested episodic weakening and intensification of the Indian summer monsoon (ISM) in the past since its initiation. Furthermore, ISM weakening was noted during glacial periods such as LGM (~ 23 ka) and Younger Dryas (~ 12.5 ka), interrupted by ISM strengthening post-Last Glacial Maximum (LGM) (~ 17 ka). The temporal variability of ISM during Holocene suggested monsoon strengthening during early Holocene (~ 10 ka) followed by gradual weakening towards mid–late Holocene. Avinash et al. (2015) studied a sediment core collected below the current oxygen minimum zone (OMZ) from the southwestern continental margin of India to determine the sources of sediment, biogeochemical processes operating in the water column and their variations since the last glacial cycle. They reported that the main regulator of palaeoproductivity is that the South-West Monsoon (SWM) wind induced upwelling. The terrigenous sediment also was noted to increase when the sea level was lower, whereas the heavy mineral component fluctuated over time implying pulsed inputs of sediment.

Azharuddin et al. (2017) studied a sediment core from the North-Eastern Arabian Sea to reveal the variations in the shelf environment of the western continental margin of India and found that there have been three periods of major changes in the monsoonal climate, productivity and sea level, viz. 12–8 ka (Younger Dryas and early Holocene); 8–4 ka (middle Holocene); and 4–1 ka (late Holocene). The studied time period was also marked by weakened SWM during the Younger Dryas and early Holocene that showed low sea level stand and less Indus River discharge. Thereafter during middle and late Holocene, the monsoon strengthened resulting in raised sea level and increased Indus River discharge.

The climate and socio-economy of the Indian subcontinent depend on the ISM and therefore it is important to understand the timescale variability. Also, the past climate linking the major events of the last few centuries is a major shortfall in the accumulation of data for rapid climate change of late Holocene and future climate changing trends. High-resolution palaeo-records that provide evidence of sea level variations are lacking and many studies of sea level changes are restricted to identifying discrete periods that correspond to either maximum high stands or minimum low stands. Therefore, a timescale reconstruction can be attained using other coastal and continental proxies for a better viewpoint of palaeoclimate and sea level variations, its interlinked processes and its association with global climate change (Chandana et al. 2018). In the present study, efforts were made to reconstruct and understand the palaeo-depositional environment through distribution of metals, total organic carbon and sediment grain size.

Study area

The Arabian Sea is a unique basin composed of complex sea floor and seasonally changing hydrography. It covers an area of about 3,862,000 km^2 and is located between 7°N and 25°N latitudes and 55°12′ and 75°E longitudes forming the northwest water body of the Indian Ocean. The Arabian Sea is bordered on the northern, eastern and western sides by the landmasses of Asia and Africa. Material is transported to the Arabian Sea via fluvial and aeolian agencies. The major fluvial agencies is the Indus in the north that discharged 400 million tonnes of suspended sediments annually until dam construction reduced the input to less than 45 million tonnes (Milliman et al. 1984), while the Narmada and Tapti rivers together contribute about 60 million tonnes of suspended matter every year (Sardessai 1994; Borole et al. 1982; Avinash et al. 2016; Ramaswamy et al. 1991; Prins et al. 2000; Sirocko and Lange 1991; Schnetger et al. 2000). Aeolian sediments are transported from the Thar and the Arabian deserts. The width of the continental shelf along the west coast of India is narrower on the southern side and wider towards the north (Laluraj and Nair 2006). Two distinct sediment types occur on the continental shelf, namely modern clastic clays on the inner shelf and relict sandy sediments on the outer shelf. Relic deposits on the outer shelf are associated with a carbonate platform. The continental slope comprises silty clays that are an admixture of dominant terrigenous and biogenic components (Rao and Rao 1995).

The Arabian Sea is a unique marine environment characterized by a seasonal reversal of monsoonal winds resulting from the SWM and the North-East Monsoon (NEM). The former being dominant, the surface winds associated during this time (June–September) blow from the SW direction leading to an increase in continental humidity and precipitation over the Indian Peninsula. These surface winds, however, reverse their direction during NEM (December–February). During the SWM, the West Indian Coastal Current (WICC) moves towards the Equator resulting in positive local temperature anomalies (LTA) on the west coast of India due to upwelling that is driven by the summer monsoonal winds (Naidu et al. 1999). However, upwelling is absent during NEM (Naqvi et al. 1990).

Materials and methods

A gravity core (SK-240/473) was collected at 21°18′N and 68°38′E in the North-Eastern Arabian Sea at a water depth of 121 m onboard the ORV Sagar Kanya (Fig. 1). The total recovered length of the core was 430 cm. The core was sampled onboard using a thin Plexiglas sheet at 1 cm intervals up to 100 cm and 2 cm intervals beyond; therefore, the total sediment samples were 133. They were immediately sealed in plastic bags and stored under refrigeration. The samples were transported to the laboratory and stored in a cold storage unit, which was maintained at − 14 °C temperature, before carrying out any analysis.

The samples were oven dried at 60 °C, finely powdered using agate mortar and analysed for total organic carbon (TOC) and trace metals. An aliquot of dried unpowdered sediment was preserved to carry out grain size analysis. TOC was estimated by Walkey and Black's (1934) method based on the oxidation of organic matter by potassium dichromate ($K_2Cr_2O_7$)–sulfuric acid mixture followed by the back titration of the excessive dichromate by ferrous ammonium sulphate ($Fe(NH_4)_2(SO_4)_2*6H_2O$). The measurement precision for organic carbon analysis was estimated to be 5% by repeated analysis. Pipette analysis was carried out to determine the percentage of sand, silt and clay (Folk 1968), based on Stoke's settling velocity principle. Trace metal analysis was carried out by the total decomposition method with HF, HNO_3 and HCl in a Teflon vessel, as adopted by Loring and Rantala (1992) and analyzed with an atomic absorption spectrophotometer (AAS) of Varian 240FS model with air–acetylene fuel mixture for metals Fe, Mn, Cr, Co, Cu and Zn, and nitrous oxide–acetylene fuel mixture for Al. Standard stock solutions were used for the calibration, and the precision of analysis was checked by replicate measurements of samples. Good precision of within 5% was observed for all metals. To determine the age of the core, the radiocarbon dating results of core GC-5/SK-148/30 (Kumar et al. 2005) were used and approximated to the core collected for the present study. The studied sediment core was found to represent the period more than 16.10 ka according to the adopted radiocarbon dates.

Results

The core was divided into three clearly differentiated zones based on the observed variation in the distribution pattern of sediment components with depth, i.e. the lower zone (zone I), the middle zone (zone II) and the upper zone (zone III). Zone I represented the depth portion between 428 and 200 cm, zone II the depth between 200 and 100 cm and zone III the depth between 100 and 0 cm.

Sediment grain size and total organic carbon (TOC)

The percentage of sand, silt and clay exhibited considerable variation among the three zones (Table 1). The sediment of zone I had the highest average percentage of silt and lowest average percentage of clay among the three zones. Sand showed a minor decrease towards the surface, while silt increased and clay displayed a uniform distribution pattern in the variation of sediment components with depth (Fig. 2). The TOC content was low in zone I and also showed uniform distribution pattern along with clay.

In zone II, the sediment was characterized by a high percentage of sand and low silt. A prominent peak of sand was observed with the highest percentage of 67.66% at 164 cm. On the other hand, silt displayed a decreased peak at 144 cm of 6.59%. Further, the percentage of clay increased towards the surface in zone II. TOC also increased towards the surface along with clay.

The sediment of zone III contained a high percentage of clay, but had a low percentage of sand. The distribution of sediment components with depth showed that sand decreased, while silt and clay increased. The sediment of zone III also had a high content of TOC, and its distribution pattern increased towards the surface along with silt and clay distributions.

The sediment core overall exhibited a high content of silt with an average percentage of 51.11% as compared to clay (25.03%) and sand (23.86%). TOC ranged between 0.21 and 1.52% (Table 2).

In general, the distribution of sediment components indicated the presence of three distinct depositional environments. The deeper sediment had high silt content and low

Fig. 1 Maps showing the location of the sediment core collection

clay and organic matter; the mid-core section sediment had high sand content and low silt, while the upper sediment had high clay and organic matter content and low sand content.

The lower portion of the core showed little change in the depositional environment over time. Also, the low TOC content indicated oxidation of organic matter and abundant supply of silt which may have been due to a low energy regime that may have facilitated deposition of fine sediments. Further, the middle core section may have experienced higher energy conditions and indicated a strong marine influence that transported to the high content of coarse material (García et al. 2010). In the upper sediment,

Table 1 Range and average values of sand, silt, clay and TOC in three different zones of sediment core

	Sand (%)	Silt (%)	Clay (%)	TOC (%)
Zone III				
Range	6.78–27.88	34.17–51.25	35.56–54.96	0.98–1.52
Average	15.13	40.11	44.74	1.24
Zone II				
Range	14.43– 67.66	6.59–68.60	8.52–48.08	0.24–1.16
Average	42.23	32.33	25.43	0.71
Zone I				
Range	12.55–37.59	56.38–79.80	3.48–11.24	0.21–0.44
Average	23.61	69.18	7.21	0.33

the high clay and organic matter content indicated considerable terrestrial influence in recent times suggesting riverine influence of input of material.

Geochemistry of metals

To well elucidate the depositional environment, geochemical analysis of metal in the sediment was carried out. The metals also exhibited differential distribution pattern within the three core zones (Fig. 3). In zone I of the core, major elements Al, Fe, Mn, Zn and Cu exhibited a uniform distribution pattern along with clay and TOC. Zn, however, showed minor fluctuations towards the surface of the section. Co concentration, however, decreased towards the surface of the section along with sand with large fluctuations, while Cr exhibited higher concentration towards the surface of the section than deeper sediments.

In zone II, all metals showed an increase towards the top of the core section along with clay and TOC that indicated the association of metals with finer sediments and organic matter.

However, in zone III, metals Al, Mn, Zn and Cu increased towards the surface of the core along with silt, clay and organic matter. On the other hand, the concentration of Fe decreased towards the surface with fluctuations, and Co decreased up to 50 cm followed by an increase towards the surface.

Table 2 Range and average values of sand, silt, clay and TOC in the sediment core

	Sand (%)	Silt (%)	Clay (%)	TOC (%)
Range	6.78–67.66	6.59–79.80	3.48–54.96	0.21–1.52
Average	23.86	51.11	25.03	0.75

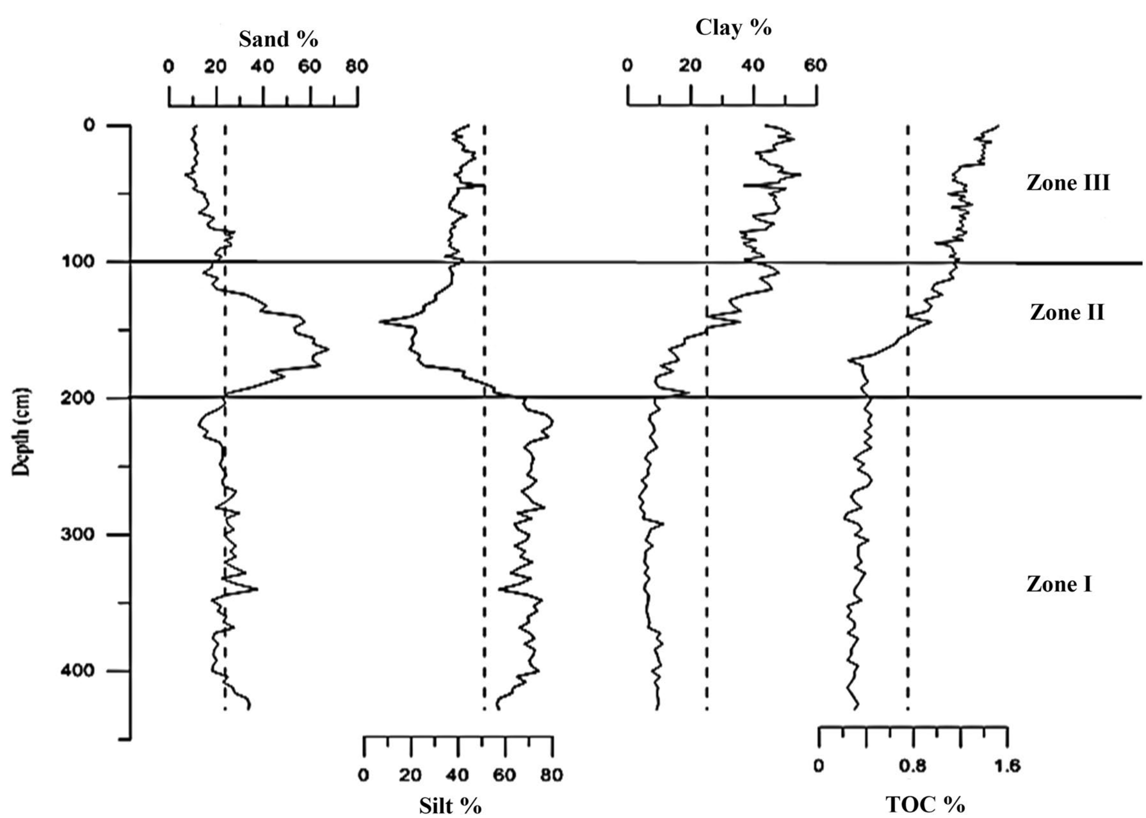

Fig. 2 Down core variation in sand, silt, clay and TOC content. Zones I, II and III separated by line. Dotted line represents average values

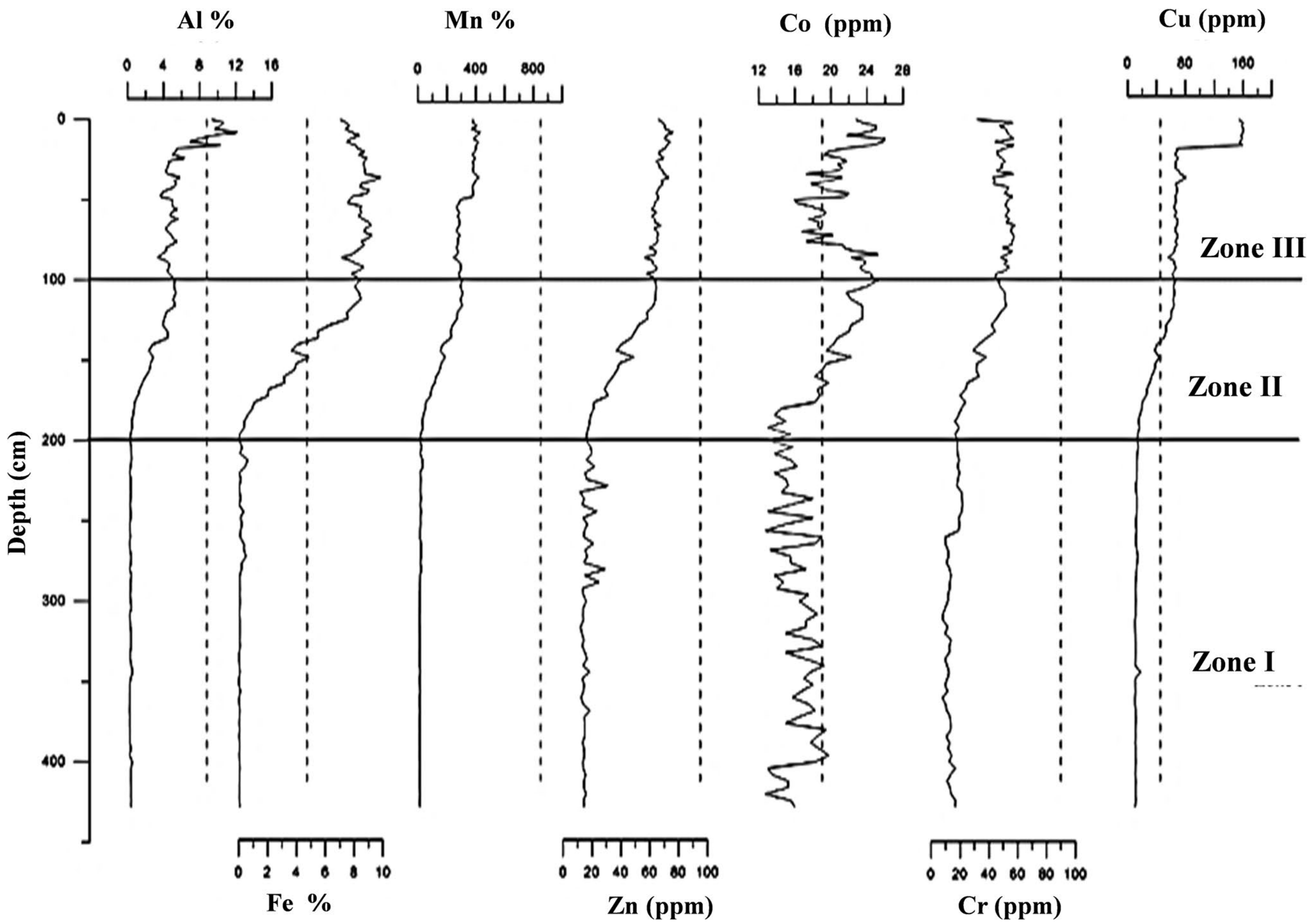

Fig. 3 Down core variation in Al, Fe, Mn, Zn, Co, Cr and Cu. Zones I, II and III are separated with line. Dotted line represents PAAS values

Overall, the highest concentration of all metals (Al, Fe, Mn, Cr, Co, Cu and Zn) was noted in the upper core section of zone III, along with a high content of clay on TOC, while the lowest concentration of all metals was found in zone I (Table 3).

To understand the association of metals with the sediment components, Pearson's correlation analysis was carried out. In zone I. Fe and Mn were positively correlated with Cr, Cu and Zn, indicating that the distribution of these elements was controlled by Fe and Mn (Table 4a). Among the sediment components, sand showed negative correlation with silt, clay, organic carbon and all the metals except for Al and Co. Also, Fe, Mn and Cr showed good positive correlation with TOC. Among trace metals, Co exhibited negative correlation

Table 3 Range and average values of metal concentration in three different zones of the sediment core

	Al (%)	Fe (%)	Mn (ppm)	Cr (ppm)	Cu (ppm)	Zn (ppm)	Co (ppm)
PAAS values	10.01	4.55	850	110	50	85	23
Zone III							
Range	3.34–12.15	7.03–9.81	245.7–431.75	31.75–58	56–160.5	56.25–76	16–26
Average	5.61	8.35	335.41	51.11	83.07	66.01	21.12
Zone II							
Range	0.31–5.33	0.037–8.43	15.75–308.75	16.5–52.00	13.25–65.00	16–64.50	13–24.00
Average	2.59	3.97	156.98	32.79	38.34	39.12	19.3
Zone I							
Range	0.20–0.57	0.01–0.62	9.25–32.5	7.75–21.75	10.25–17.25	11.5–31	12.75–19.75
Average	0.34	0.10	14.18	13.74	11.47	15.85	16.27

Table 4 Correlation between sand, silt, clay, total organic carbon (TOC) and metals in (a) zone I, (b) zone II and (c) zone III in the sediment core

	Sand (%)	Silt (%)	Clay (%)	TOC (%)	Al (%)	Fe (%)	Mn (ppm)	Cr (ppm)	Cu (ppm)	Zn (ppm)	Co (ppm)
(a)											
Sand (%)	**1.00**										
Silt (%)	**−0.93**	**1.00**									
Clay (%)	−0.15	−0.23	**1.00**								
TOC (%)	−0.31	0.33	−0.07	**1.00**							
Al (%)	0.23	−0.24	0.03	0.01	**1.00**						
Fe (%)	−0.19	0.31	−0.32	0.29	0.09	**1.00**					
Mn (ppm)	−0.37	0.44	−0.21	0.44	0.12	**0.85**	**1.00**				
Cr (ppm)	−0.29	0.18	0.28	0.44	0.15	0.27	0.53	**1.00**			
Cu (ppm)	−0.18	0.22	−0.13	0.24	0.43	0.45	0.59	0.37	**1.00**		
Zn (ppm)	−0.30	0.38	−0.22	0.17	−0.06	0.31	0.51	0.21	0.30	**1.00**	
Co (ppm)	0.02	0.01	−0.08	0.01	−0.13	−0.18	−0.23	−0.43	−0.16	−0.15	**1.00**
(b)											
Sand (%)	**1.00**										
Silt (%)	−0.64	**1.00**									
Clay (%)	−0.60	−0.23	**1.00**								
TOC (%)	−0.48	−0.30	**0.93**	**1.00**							
Al (%)	−0.50	−0.29	**0.94**	**0.95**	**1.00**						
Fe (%)	−0.48	−0.32	**0.94**	**0.94**	**0.98**	**1.00**					
Mn (ppm)	−0.47	−0.34	**0.94**	**0.95**	**0.99**	**1.00**	**1.00**				
Cr (ppm)	−0.51	−0.27	**0.92**	**0.94**	**0.98**	**0.98**	**0.98**	**1.00**			
Cu (ppm)	−0.47	−0.33	**0.94**	**0.95**	**0.99**	**1.00**	**1.00**	**0.99**	**1.00**		
Zn (ppm)	−0.47	−0.33	**0.94**	**0.94**	**0.98**	**1.00**	**0.99**	**0.98**	**0.99**	**1.00**	
Co (ppm)	−0.23	−0.53	**0.85**	**0.85**	**0.90**	**0.93**	**0.93**	**0.90**	**0.93**	**0.93**	**1.00**
(c)											
Sand (%)	**1.00**										
Silt (%)	−0.51	**1.00**									
Clay (%)	−0.79	−0.12	**1.00**								
TOC (%)	−0.52	0.47	0.27	**1.00**							
Al (%)	−0.44	0.14	0.41	0.69	**1.00**						
Fe (%)	−0.18	0.19	0.08	−0.24	−0.41	**1.00**					
Mn (ppm)	−0.83	0.57	0.55	0.59	0.53	0.02	**1.00**				
Cr (ppm)	0.20	−0.25	−0.06	−0.10	−0.06	0.15	−0.31	**1.00**			
Cu (ppm)	−0.44	0.12	0.42	0.69	**0.93**	−0.48	0.56	−0.06	**1.00**		
Zn (ppm)	−0.73	0.39	0.56	0.56	0.65	0.06	**0.82**	−0.03	0.66	**1.00**	
Co (ppm)	0.11	−0.05	−0.09	0.29	0.40	−0.43	0.25	−0.21	0.51	0.17	**1.00**

For (a), values in bold are significant at $p < 0.05$, $N = 57$

For (b), values in bold are significant at $p < 0.05$, $N = 25$

For (c), values in bold are significant at $p < 0.05$, $N = 51$

with other metals that suggested a different source or process involved in the distribution of Co.

Further, in zone II, sand and silt were negatively correlated with other parameters, whereas clay and TOC were significantly correlated with metals indicating the role of clay fraction and organic matter in the distribution and abundance of metals (Table 4b). Also, metals were significantly correlated among each other indicating common source and pathway.

Likewise, in zone III, sand was negatively correlated with silt, clay, TOC, Al, Mn, Cu and Zn, whereas clay and TOC exhibited positive correlation with Al, Mn, Cu and Zn. Al showed strong positive correlation with TOC, Mn, Cu, Zn and Co that may be attributed to their detrital origin (Table 4c). Among trace metals, Cr exhibited a negative correlation with most of the metals that implied a different source or process involved in the distribution of Cr.

Chronology of the sediment core

To determine the age of the core, the radiocarbon dating results of core GC-5/SK-148/30 analysed by Kumar et al. (2005) was used, as the core was collected from the vicinity of the present study. Core GC-5/SK-148/30 was collected at 21°12′N and 68°95′E from North-Eastern Arabian Sea at a water depth of 121 m. According to the adopted radiocarbon dating results, the studied sediment core represented the period more than 16.10 ka.

Considering the available dates, the rate of sedimentation for the core used in the present study was computed. The rate of sedimentation was around 1.02 mm/year between 365 and 138 cm, 0.11 mm/year between 138 and 102 cm and 0.135 mm/year between 102 and 30 cm. This variance indicated very high rate of sedimentation till 13.99 ka BP (365–138 cm), a change in rate of sedimentation from 10.74 ka BP to 5.41 ka BP (138–102 cm) and reduced rate of sedimentation in the late Holocene period. Somayajulu et al. (1999), however, reported a wide variation in the sedimentation rate of 0.05–1.34 mm/year during the Holocene for deeper water (480 m) in the western Indian Ocean.

Discussion

In the present study, considerable differences were observed in the distribution of sediment components and metals. There was little variation in the distribution of sediment components in zone I that represented the lower part of the sediment column. This zone was largely dominated by silt and a low amount of clay and sand. Further, the TOC profile followed the trend of silt and also exhibited a positive correlation ($r=0.33$ and $N=57$). The association of organic matter with finer sediments was much more visible in zone II, though the sand percentage in this zone was higher and clay showed significant correlation with organic carbon ($r=0.93$ and $N=25$). The association of organic carbon and finer sediments was also visible in zone III, wherein organic carbon showed positive correlation with silt ($r=0.47$ and $N=51$) and clay ($r=0.27$ and $N=51$) and sand percentage reached lower than average values.

The western margin of India or the eastern Arabian Sea receives large sediment input during SWM (June–September), as it is associated with a high amount of rainfall and its intensity. Higher sand percentage in Zone II indicated more freshwater runoff from rivers and thus reflected an intensification of SWM (Shetye et al. 2009). The sediment components of zone II when compared with zone I exhibited a significant transition, reflecting a change in the hydrodynamic conditions which is controlled by a number of factors such as SWM, sea level variation, weathering intensity and sedimentation rate, hence reflecting that the degree of hydrolysis of land mass plays an important role in the supply of sediments, particularly in regions or basins dominated by seasonal precipitation which favors weathering conditions.

The higher sand in zone II, below 138 cm reflecting large input from the land, coincided with the change in the rate of sedimentation from 1.02 mm/year in zone I and part of zone II to 0.11 mm/year in the upper section of zone II, i.e. between 138 and 100 cm. The rate of change of sedimentation indicated a decrease in the rate of melting of ice and a corresponding decrease in the rate of sea level rise. This facilitated a change of hydrodynamic conditions, allowing finer sediments to settle down along with associated large organic matter in zone III. During the Holocene period, the rate of sedimentation was around 0.135 mm/year and sand showed fluctuating decreasing trend associated with lower than average silt and higher clay and organic matter. The slower rate of sea level rise must have facilitated a quieter environment and therefore deposition of higher clay and organic matter.

Furthermore, primary productivity in surface waters is considered to be the major controlling factor for TOC distribution in sediments in the Arabian Sea (Calvert et al. 1995). The productivity of the photic zone or surface waters often closely relates with organic carbon content in the sediment column (Müller and Suess 1979). Also, the fact that only a small fraction of organic matter which is produced in the ocean is preserved in the bottom sediments (Meyers 1994) makes it important to note that surface productivity cannot always be the controlling factor in organic carbon enrichment in the bottom sediments. Factors such as texture of sediments, shelf width, slope gradient, prevailing current pattern and clay mineralogy also have to be considered (Paropkari et al. 1992). As far as Arabian Sea is concerned, it is the crucial role played by oxic and anoxic bottom waters which needs prime attention, as it controls the distribution of organic carbon (Paropkari et al. 1992). Therefore, organic carbon can be used as a Palaeo-productivity proxy, provided it is well preserved. Also, the relation of organic matter with finer sediments as finer sediments have large surface area (Thuy et al. 2000) has been well established. The pattern of increase of organic matter in the present core coincides with peak sand value at around 164 cm, indicating terrigenous input of organic matter to this part of Arabian Sea. From 138 cm to the surface, sand decreased; however, organic matter continuously increased with clay and coincided with a lower rate of sedimentation 0.11–0.135 mm/year, revealing an increased rate of productivity supported by nutrients brought from the land with intensified SW Monsoon during the Holocene. The period of intensified SW Monsoon in Arabian Sea coinciding with early Holocene has been earlier reported by Van Campo (1986); Overpeck et al. (1996) and Sirocko et al. (2000).

Additionally, a number of processes have been shown to control the accumulation and distribution of trace metals in sediment on a regional scale in the marine environment. Such controls include the composition of sedimentary detritus delivered to the ocean, the partitioning of individual elements between the solid and solution phases, the biogeochemical cycling of the elements in the ocean, the manner in which they are delivered to the sea floor and the post-depositional conditions in bottom sediments that may lead to diagenetic element recycling or precipitation (Calvert and Pedersen 1993). The Arabian Sea gets its share of trace metals supply via a number of different pathways which include detrital input from Somalia, Aeolian input from Arabia, detrital riverine input from the Indus, Tapti and the Narmada rivers, the weathering of Deccan trap, gneissic rocks, laterites and submarine weathering of Carlsberg Ridge (Shetye et al. 2009). This is further subjected to the association with various fractions of sediments by various reactions such as ionic exchange and complexation with organic substances or by incorporation in sediments (Boothman 1988).

In the present study, the concentrations of major elements (Al, Fe and Mn) and minor elements (Cr, Cu, Zn and Co) showed an increase from zone I (bottom) to zone III (surface) when average values were considered. These variations of elemental concentration are mainly controlled by geological and chemical factors such as provenance, precipitation and oxic/anoxic conditions (Wyrtki 1971). Zone I was characterized by relatively lower metal concentration in sediment as compared with the other two zones, together with lower sand and clay fractions, which suggested that the reduced freshwater runoff during this period was attributed to the weakening of the monsoon (Sarkar et al. 2000). Zone II can be referred to as the zone of transition, as metal concentrations increased and reflected an enhanced input of terrigenous material to the study area through fluvial sources. Also, the significant inter-element correlation of metals among each other in this zone showed that these elements were primarily controlled by the relative contribution of detrital and biogenic components (Reichart et al. 1997). Within zone II, between 138 and 100 cm the metals showed a change in the pattern of distribution with respect to the continuous increase in the lower part of zone III. It is appropriate to mention here that the rate of sedimentation below 138 cm in zone II was 1.02 mm/year and between 138 and 100 cm, 0.11 mm/year. This change over in rate of sedimentation was well reflected by the change in the distribution pattern of all the metals studied.

Furthermore, zone III which represented the Holocene period sediment witnessed enrichment in concentration of metals like Al and Fe in the early Holocene period when compared with the geochemical data of the post-Archean average shale (PAAS) given by Turekian and Wedepohl (1961). Al has been used as an indicator of clay detritus, mainly derived from continental weathering (Shimmield et al. 1990). The higher concentration of Al can be related to increased input of alumina–silicate minerals which tag terrestrial inputs to sediments (Kolla et al. 1981). On the other hand, higher concentration of Fe can be attributed to an increased input of smectite clay minerals derived from Deccan traps (Kolla et al. 1981; Prins et al. 2000). Al showed a strong positive correlation with TOC, Mn, Cu, Zn and Co, which supported an enhanced input of terrigenous material to the study area in recent years.

Among the metals, the rate of increase was relatively higher in zone II, i.e. Fe, Mn, Zn, Co and Cr. This distribution pattern can be alternatively interpreted as, the lower rate of sedimentation and intensified SW Monsoon that causes a higher supply of terrigenous material, must have facilitated remobilization of metals that resulted in their enrichment in the upper sedimentary layer that represented recent years.

Overall, zone I sediment contained low TOC and clay. Elemental concentrations in this zone are very low compared with the other two zones. Lower elemental concentration could be related to reduced supply from land, in accordance with the geochemical multi-tracer approach adopted by Sirocko et al. (2000), which suggested that the intensity of the SWM was low during the LGM. The low clay content, TOC and metal content, and constant trend of most of the parameters in this zone, may indicate that the sea level was higher with increased tidal forcing, which facilitated deposition of high silt-sized particles. von Rad et al. (1999) reported higher aeolian flux during glacial times in the continental margin sediments off Pakistan. Zhao et al. (2017) reported a higher sea level during the 14–0 ka BP stage, which falls in the resolution of the present study. Another possibility for lower elemental concentration could be related to dilution by biogenic components.

Zone II was a transition zone between zone I and zone III sediments that occurred at ~ 200 cm, with increase in sand, clay and silt playing a compensating role. This change in sediment components reflected a change in hydrodynamic conditions. The sediment cores collected off northwest India the continental shelf and shelf break by Rao et al. (2012) experienced similar change in composition from lime mud-dominated to terrigenous-dominated sediments after 12 ka, which was attributed to climate change and rapid rise in sea level during the early Holocene. TOC values in this zone began to increase after 168 cm. Further, increasing TOC values indicated an increase in surface productivity during this time. A similar increase in productivity is comparable to the nearby dated core by Shetye et al. (2014) that started increasing from 16 kyr up to modern age in the Arabian Sea. The high peak sand value observed in this zone ~ 164 cm might indicate the presence of re-suspended shelf material and the possibility of a turbidite (PrakashBabu et al. 2010). Elemental distribution in this zone experienced an increase

Table 5 Characteristic features of sediment patterns and elemental content in each of the three zones and the condition that may have governed the depositional environment

Zone	Characteristic features	Depositional environment conditions	Previous studies
Zone I	Dominated by silt, low TOC and clay; low elemental concentrations	Represents late Pleistocene, high water column, high aeolian supply, reduced fluvial supply from land, low intensity of the South-West Monsoon during the LGM	von Rad et al. (1999), Sarkar et al. (2000), Sirocko et al. (2000), Zhao et al. (2017)
Zone II	Increase in sand, clay and silt playing a compensatory role. Increase in concentration of elements	Represents late Pleistocene to early Holocene, transition zone, change in hydrodynamic conditions, increase in intensity of monsoon, possible climate change and rise in sea level	Van Campo (1986), Overpeck et al. (1996), Sirocko et al. (2000), Shetye et al. (2009, 2014), Rao et al. (2012)
Zone III	Increase in TOC, increase in concentration of metals such as Al, Fe, Co and Cu	Represents the Holocene period, increased intensity of monsoon	Nair et al. (1989), Sarkar et al. (2000), Sruthi et al. (2014)

in concentration. SWM experienced two abrupt increases in its monsoon intensity at around 12.5 ka and another at 10 ka (Overpeck et al. 1996). This increase in intensity must have favored enhanced input of terrigenous material which might have increased the elemental concentration.

Zone III in the present study probably represents the late Holocene period. The radiocarbon dates of core GC-5/SK-148/30 (Kumar et al. 2005) that is very close to the present study area shows that the fraction 98–102 cm is comparable to 10.74 ka BP. Thus, the sediments in this zone may represent an age around 10.74–5.41 ka BP. TOC values in this zone show continuous increase up to the surface that indicate increased productivity and may be linked to the intensity of SWM. Sediment trap studies have shown that the biological productivity and terrigenous supply in the Arabian Sea are strongly linked to the intensity of SWM (Nair et al. 1989). During NEM, biological productivity was low and the monsoonal winds during SWM caused widespread upwelling and high surface productivity in the exclusive economic zone of India in the eastern Arabian Sea (Sarupriya and Bhargava 1993). Sarkar et al. (2000) used net balance of precipitation over evaporation as an index of monsoonal precipitation in the eastern Arabian sea and, based on down core variations of oxygen isotopes of surface dwelling foraminifera, found monsoonal intensity to have steadily increased from ~ 10 to ~ 2 ka BP. This argument is well supported by the reported increase in concentration of metals like Al, Fe, Co and Cu in the late Holocene period compared with the geochemical data of the post-Archean average shale (PAAS). In the eastern Arabian Sea, the primary source for Fe is through leaching of the Fe-rich basalts from Deccan traps (Sirocko et al. 2000) and Al is mainly derived from continental weathering (Shimmield et al. 1990). This zone represents the late Holocene period with increased intensity of monsoon. Higher surface runoff during this period may have transported Al and Fe along with other elements to the study area that is mainly controlled by the intensity of the SWM in the Arabian Sea. Sruthi et al. (2014) also observed a similar enrichment of Fe, K, Mg and Al during the early Holocene period in the Arabian Sea, due to enhanced input of terrigenous material through fluvial sources.

Thus, the present study suggested that zone I sediments started depositing under higher water column conditions (Table 5). The lower elemental concentration during this period could be related to the reduced supply from fluvial/land or dilution by biogenic and aeolian components. Further, in zone II, the change in sediment components reflected a change in hydrodynamic conditions. The increasing elemental concentration during this time is attributed to the abrupt increase in SWM intensity at around 12.5 ka and 10 ka (late Pleistocene to early Holocene). Further, the increased TOC content in this zone indicated a higher surface productivity supported by the intensification in monsoon intensity. Zone III, representing the Holocene sediments, saw an increase in the concentration of metals Al, Fe, Co and Cu in the late Holocene period due to increased surface runoff that was mainly controlled by the intensity of the SWM in the Arabian Sea and deposition in the study area.

Conclusions

The sediment core collected at 21°18′N and 68°38E′ at a water depth of 121 m in North-Eastern Arabian Sea off Saurashtra was analysed for sediment components, organic carbon and selected metals with an aim to reconstruct the palaeo-depositional environment and to investigate the nature of organic carbon and factors controlling its distribution. Using the available radiocarbon dating results, the rate of sedimentation was calculated and found to be very high to 13.99 ka BP (138 cm) and with reduced rate of sedimentation in the Holocene period. The rate of change of sedimentation indicated a decrease in the rate of melting of ice and a corresponding decrease in the rate of sea level rise. The slower rate of sea level rise facilitated a quieter environment and therefore deposition of higher clay and organic matter in the Holocene. Further, the pattern of increase of organic matter along with clay coincided with the peak sand values from where clay and organic matter showed continuous increase up to the surface and sand showed a decreasing trend. This coincided with a lower rate of sedimentation, 0.11–0.135 mm/year, revealing an increased rate of production supported by nutrients brought from land with the intensification of the SW Monsoon during the Holocene. Also, the change of rate of sedimentation is also well reflected in the distribution pattern of metals. The lower rate of sedimentation and intensified SW Monsoon facilitated higher terrigenous supply, facilitating remobilization of metals and resulting in enrichment in the upper sedimentary layers representing recent years.

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