

Variation of Paleo-productivity and Terrigenous Input in the Eastern Arabian Sea during the Past 100 ka

ISHFAQ, AHMAD MIR¹., PATTAN, J.N^{1*}., MATTA, V.M². AND BANAKAR, V.K¹

¹CSIR-National Institute of Oceanography, Dona Paula, 403 004, Goa, India

²Department of Marine Sciences, Goa University, Taleigao Plateau, 403 206, Goa, India

* Corresponding author: pattan@nio.org

Abstract: A 4.1m long sediment core from the Eastern Arabian Sea (EAS) is studied using multiple geochemical proxies to understand the variation of productivity and terrigenous matter supply during the past 100 ka. The temporal variation in element concentration and fluxes of CaCO₃, organic carbon (C_{org}) and Barium excess (Ba_{exc}) together in general indicate a higher productivity during the cold climate and highest during the Last Glacial Maximum (LGM) in particular. This cold climate-increased productivity coupling may be attributed to the shoaling of nutricline due to enhanced convective mixing resulting from the intensified winter monsoon. Increased linear sedimentation rates and fluxes of Al, Fe, Mg, Ti, Cr, Cu, Zn, and V during the cold period also suggest increased input of terrigenous matter supporting intensified winter winds. However, the presence of large abundance of structurally unsupported elemental content (e.g.: Mg-86%, Fe-82% and Al-53%) indicate increased input of terrigenous material which was probably enhanced due to intense winter monsoon.

Keywords: Eastern Arabian Sea, sediment composition, productivity, terrigenous input, structurally unsupported, glacial and interglacial.

INTRODUCTION

The Indian Monsoon is characterized by seasonal reversal of winds over the Indian subcontinent and Northern Indian Ocean. Monsoon plays a dominant role in modulating the regional climate and biogeochemistry of the Arabian Sea (Duplessy, 1982; Fontugne and Duplessy, 1986; Gupta et al., 2005). Biological productivity and supply of terrigenous matter to the Arabian Sea is strongly linked to the intensity of monsoon (Gupta et al., 2005). Strong southwesterlies during the summer monsoon cause upwelling along the coast of Somalia, Oman and southwest coast of India thereby bringing nutrient rich subsurface waters to the photic zone resulting in increased productivity (Qasim, 1982; Banse, 1987). A combination of high productivity associated with a moderate ventilation of the thermocline leads to an intense oxygen minimum zone (OMZ) (Wyrki, 1973). In the Arabian Sea, biological productivity is generally high ($\sim 200 \text{ g cm}^{-2} \text{ yr}^{-1}$ of C) as shown by sediment trap studies (Nair et al., 1989), in that $\sim 70\text{--}80\%$ of the biogenic material is deposited during the summer monsoon period. It has been shown that the summer monsoon was stronger during the warm interglacial periods than in the cold glacial periods (Prell and Kutzbach, 1992; Banakar et al., 2005 and references therein). In the northern Arabian Sea, the intense cooling of the sea surface during winter is shown to induce convective mixing of the nutrient enriched thermocline waters into the surface waters resulting in increased productivity (Madhupratap et al., 1996).

A variety of sedimentary proxies such as CaCO_3 , organic carbon (C_{org}), total Nitrogen, biogenic opal, biogenic barium, and alkenones for estimating marine paleoproductivity have been used by many investigators (Moreno et al., 2002 and references therein). Elements such as Si, Al, Fe, Ti, Mg, Zr, Cr, and K in marine sediments have been used to understand the terrestrial climatic conditions, such as arid, humid or ice covered (Nesbitt and Young, 1982; Argast et al., 1987). The chemical composition of the Arabian Sea sediment has suggested a number of sources viz: dust originated in Arabia, fluvial detritus from Somalia and the Indian Subcontinent and submarine weathering products of Carlsberg Ridge (Shankar et al., 1987). In the western Arabian Sea, sediments deposited are mainly of aeolian origin (Shimmield et al., 1990), whereas, in the eastern Arabian Sea the sediments deposited are mainly of fluvial origin (Paropkari., 1990). However, in the latter region the past variations in the input of various sedimentary components are not well recorded as compared to the voluminous information available from the former region. Therefore, in the present study, we report multiple geochemical proxies to

understand productivity and terrigenous material supply during the past 100 ka in Eastern Arabian Sea (EAS).

MATERIAL AND METHODS

The sediment core used in this study (SK117-GC08) was raised from a water depth of 2500 m at 15°29' N and 72°51' E, off Goa, India, on board *ORV Sagar Kanya* (Fig.1). The core site is below the modern OMZ that occurs between 200 m and 1500 m water depth (Wyrki., 1973; Naqvi, 1987). The sediment core was sub-sampled at 2 cm intervals and these sub-samples made salt free, dried and finely powdered. Calcium carbonate content of the sediment was leached with 1 N HCl. Aliquot of ~0.2 g of residue was digested in a mixture HF, HNO₃ and HClO₄ (3:3:1 ratio) in PTFE beakers on a hot plate. The digest was dissolved in 5 ml of 6N HCl and diluted to 50 ml with 18mohm deionized water. Similarly, a standard reference material (USGS-MAG1), acid blanks and duplicate samples were also prepared. The solutions were analysed for major and few trace elements on a PerkinElmer Plasma-400 sequential Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES). The accuracy and precision of the analysis was within $\pm 3\%$. The C_{org} data used in this study is from Banakar et al., (2005). The oxygen-isotope based chronology of the sediment core is available in Banakar et al., (2005) and Chodankar et al., (2005). The CaCO₃ content of the sediment was determined by weight-loss after treating the sample with 0.5N HCl until CO₂ evolution ceased.

The carbonate-free element concentrations were converted to bulk concentration (E_{bulk})

$$E_{\text{bulk}} = E_n * (100 - \text{CaCO}_3) / 100$$

Where E_n is the element concentration in the residual fraction.

Dry bulk density (ρ_{dry}) was empirically calculated from CaCO₃ content by using the equation of Curry and Lohman (1986).

$$\rho_{\text{dry}} = 0.0066 (\% \text{CaCO}_3) + 0.29$$

Elemental excess or structurally unsupported element content was calculated following the equation of Murray et al., (1993).

$$\text{Ele}_{\text{exc}} = \text{Ele}_{\text{total}} - (\text{Ti}_{\text{sample}} * \text{Ele}/\text{Al}_{\text{PAAS}}).$$

Where PAAS is Post Archean Australian Shale

Mass accumulation rate (MAR) of the element or elemental flux (E_{flux}) were estimated by,

$$E_{flux} = (E/100) * \rho_{dry} * LSR, \text{ where,}$$

E_{flux} in $mg/cm^2.k$ a; ρ_{dry} in mg/cm^3 ; Linear Sedimentation Rate (LSR) in cm/ka

RESULTS

The LSR during the past 100 ka varies from 2.3 cm/ka to 6.1 cm/ka , with highest during the Marine Isotope Stage (MIS)-2. The $CaCO_3$, C_{org} and Ba_{exc} contents vary from 20 to 48 %, 0.5 to 1.6 % and 240 to 1260 ppm respectively (Fig. 2a). These concentrations translate to their respective fluxes of 0.31 to 1.64 $g/cm^2.k$ a, 0.004 to 0.025 $g/cm^2.k$ a and 0.001 to 0.24 $g/cm^2.k$ a (Fig. 2b). The down-core distribution of elements and their fluxes exhibit high values during MIS -2 and MIS-4 (Fig. 3a & 3b). Elements such as Al, Fe, Mg and Mn have mean E_{bulk} of 5.47%, 6.78%, 2.48% and 0.046% of which their elemental excess are 2.9%, 5.6%, 2.1% and 0.02% respectively.

DISCUSSION

Productivity variations

Calcium carbonate content on the sea floor is controlled by surface water productivity, dissolution and dilution by non-carbonate fraction. The C_{org} , which is another proxy for the productivity (Muller and Suess., 1979; Pederson, 1983, Pederson and Calvert, 1990; Sarnthein et al., 1987) is fraught with preservation problems in oxic sediments. Therefore, to understand true variations in the past productivity a more robust proxy is necessary to validate the above direct proxies. The Ba_{exc} has been proved to be a better indicator of the productivity because of its post-depositional refractory nature (Dymond et al., 1992; Gingele et al., 1999).

The variation of $CaCO_3$, C_{org} and Ba_{exc} contents and their fluxes during the past 100 ka is nearly similar (Fig. 2). Highest fluxes of calcium carbonate ($\sim 2g/cm^2/ka$), Ba_{exc} (0.025 $g/cm^2/ka$) and organic carbon (0.024 $g/cm^2/ka$) were recorded during LGM. The Holocene has recorded lower productivity, of which, the lowest productivity is evident between 10 and 8 ka. Stadial of MIS-5 (5.2) show higher productivity compared to inter stadials (5.1 & 5.3). Most part of the last glacial cycle (MIS-4 to MIS-2) in general, appears to have witnessed higher productivity than the interglacial periods. This observation is similar to several previous reports on Arabian Sea paleoproductivity (see Fontugne and Duplessy,

1986; Rostek et al., 1997; Prabhu et al., 2004, Prabhu and Shankar, 2005; Banakar et al., 2005). However, there have been few contrasting observations from northern and eastern regions of the Arabian Sea and Atlantic Ocean (see Shimmield et al., (1990; Naidu 1991; Paropkari et al., 1991; Howard and Prell, 1994 Reichart et al., 1998; Pattan, et al., 2003). Further, low content of CaCO_3 , C_{org} and Ba_{exc} at glacial termination-I (~12ka) suggest low productivity during deglaciation. Inconsistency in number of productivity proxies could be due to water depths of the sediment cores in the same basin. Alternatively, the past productivity pattern in the Arabian Sea may not be uniform because of its complex biogeochemistry involving the material supply from surrounding landmasses. The increased productivity in the glacial-EAS may be attributed to a shoaling of the nutricline during the glacial caused by intensification of winter cooling and hence enhanced convective mixing (Madhupratap et al., 1996). The association of high productivity in the EAS with the modern winter (Haake et al., 1993) and past cold periods indicates increased nutrient injection into the photic zone due to strengthened winter winds (Banakar et al., 2005). In the EAS intense upwelling as evident in western part is not prevalent during the summer monsoon. The enhanced primary productivity in the EAS mostly is linked to the strength of winter winds. Therefore, observed higher productivity in the EAS during the glacial period suggests significantly strengthened winter monsoon system.

Variation of terrigenous input

Numerous small and medium peninsular rivers originating in the Western Ghats bring terrigenous material into the EAS. In addition, the monsoon winds deliver more than 100 million tonnes of dust to the Arabian Sea every year (Sirocko and Sarin, 1989), which is mostly derived from the Arabian and Somali regions (Ramaswamy et al., 1991). Bulk Al, Fe, Ti, Mg, Cr, Zn and V concentration in the studied sediment core show mutual strong positive correlation ($r = \sim 0.8$) suggesting a single source most probably terrigenous supply. The down core variations of element contents and their fluxes are higher during the glacial periods (MIS-2 and MIS-4) as compared to interglacial periods (MIS-1, MIS-3 and MIS-5) (Fig.3a & b) suggesting enhanced terrigenous matter supply to the core location during cold and dry periods. Similarly, during the relatively colder stadial (5.2) of the MIS-5 the core site has received higher terrigenous input compared to interstadials (5.1 and 5.3). During the past ~ 5 ka, core site received lowest amount of terrigenous material (Fig.3). The present study and results of Banakar et al (2005) have recorded increased productivity in EAS during the glacial climate apparently due to intensified winter monsoon. The enhanced supply of terrigenous material to the EAS is possibly

either by fluvial input or by winter winds. The former is unlikely because the summer monsoon during the glacial periods was relatively weaker, which should have resulted in weakening of the seasonal rivers originating in Deccan Mountains. Therefore, the intensified winter winds (Northeasterlies) of the glacial period might have delivered a significant amount of terrigenous material derived from the continent to the EAS. In addition, lowering of the sea-level during the glacial period has exposed the continental shelf to increased erosion of previously deposited terrigenous material (Chodankar,2004; Prins et al., 2000;Agnihotri et al., 2003; Prabhu et al., 2004; Pattan et al., 2005).

Element_{exc} is defined as the proportion of an element in bulk sediment that is not associated with silicate fraction (Murray et al., 1993). Therefore, the Element_{exc} must have its source in the seawater and normally be associated with authigenic precipitates or biogenic skeletal parts or particle adsorbed components. In the present sediment core, the average bulk content of Al, Fe, Mg and Mn is 5.47%, 6.78%, 2.48% and 0.05% and their respective excess proportion is 2.91%, 5.62%, 2.14% and 0.02%, suggesting that ~ 53%, 82%, 86% and 50% of those elements are not associated with silicates. The distribution pattern of Element_{exc} in the sediment core is similar to each other and their concentrations are much higher during glacials compared to interglacials (Fig 4). During the LGM, the Al_{exc}, Fe_{exc}, Mg_{exc} and Mn_{exc} contents are highest (Fig.4). Therefore, a strong positive correlation ($r = \sim 0.7$) between Al_{exc} and Fe_{exc}, Mg_{exc} and Mn_{exc} is evident suggesting that they are mostly scavenged by settling inorganic particulates (Fig.5). The weak inverse correlation of Al_{exc} with calcium carbonate, Ba_{exc} and biogenic opal (biogenic opal data is unpublished with Banakar) suggest that the Al_{exc} is not associated with biogenic fraction (Fig.5).

The Arabian Sea receives aeolian dust dominantly from the Arabian Peninsula (Prins et al., 2000) and is the source for Al, Fe and other trace elements in the sediment (Honjo et al., 1999; Sirocko et al., 2000; Schubler et al., 2005). It has been suggested that the removal of Al from the water column can occur either through adsorption on to settling particles or through biological uptake (Narvekar et al., 1993 and references therein). The present study confirms the removal of Al_{exc} by particle scavenging. Among all the Elements_{exc}, Mg_{exc} exhibits highest concentration (86 % of the bulk content) and may be due to presence of significant amount of dolomite dust derived from the Arabian Peninsula and Persian Gulf (Sirocko et al., 1993) in the EAS sediment. Very high Mg_{exc} during the LGM and low content during the Holocene is consistent with the observations made earlier by Prins et al. (2000) who suggested that a large amount of carbonate dominant dust reached the Arabian Sea during the glacial

climates. During LGM, winter monsoon (northeasterlies) was stronger, and hence appear to be the most dominant monsoon circulation of the cold climate. The intensification of winter monsoon in the past caused higher deposition of dolomite in the EAS. Dolomite may be preferentially transported by the westerlies since the dolomite-containing Mesozoic strata are exposed in northern Arabian provenance. High Mg/Al ratio of 0.31 to 0.35 (sediment core NIOP469) and 0.35 to 0.46 (sediment core (NIOP489) in the Arabian Sea was attributed to an Arabian source (Prince et al., 2000 , a & b). The present sediment core showed high Mg/Al ratio (0.31 to 0.58) above the PAAS (0.133) could be derived from an Arabian source. Manganese is a redox sensitive element and hence reactive in oxic marine environment. The Mn precipitating as particulate-Mn oxide is important in a marine environment because Mn-oxide is one of the most important phases that effectively adsorbs several minor and trace elements (Jacobs et al., 1987). The mean Mn_{exc} content in the present sediment core is 50% of its bulk content and is nearly similar to the values obtained for surface (41%) and subsurface (47%) sediment trap material of the EAS (Nair, et al., 1999). Further, Nair. Et al., (1999) suggested that atmospheric input of Mn to the EAS is negligible, and hence the dissolved- Mn pool in this region is mostly due to fluvial input. An increase of continental input will result in higher Mn concentrations of the surface waters, higher Mn scavenging rates, and eventually a larger Mn flux to the deep seafloor.

Conclusions:

From the present study the following conclusions are made.

1. Productivity was higher during glacials compared to interglacials in the eastern Arabian Sea. This could be due to enhanced convective mixing caused by the winter monsoon.
2. The terrigenous representing elements have a large contribution from structurally unsupported components mostly derived by the wind during glacial period and particularly very high at Last Glacial Maxima.

Acknowledgements: The authors thank Director, N. I. O, Goa for the facility and encouragement. Thanks are also due to Mr. R.Uchil for drafting the figures. IMA is thankful to CSIR, New Delhi (India) for the Senior Research Fellowship. We thank an anonymous reviewer for his constructive suggestions. This is NIO contribution number

References

- AGNIHOTRI, R., SARIN, A.A., SOMAYAJULU, B.L.K., JULL, A.J.T., BURR, G.S. (2003). Late-Quaternary biogenic productivity and organic carbon deposition in the eastern Arabian Sea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, v.197, pp.43-60.
- ARGAST, S., DONNELLY, T.W., (1987). The chemical discrimination of clastic sedimentary components. *Journal of Sed. Petro.*, v.57, pp.813-823.
- BANAKAR, V.K., OBA, T., CHODANKAR, A.R., KURAMOTO, T., YAMAMOTO M., MINAGAWA,M.,(2005). Monsoon related changes in sea surface productivity and water column denitrification in the Eastern Arabian Sea during last glacial cycle. *Mar. Geol.* v. 219, pp.99–108.
- BANSE, K. (1987). Seasonality of plankton chlorophyll in the Central and northern Arabian sea. *Deep-Sea Res.* v.34, pp.713-723.
- CHODANKAR, A.R. (2004). The Late-Pleistocene sedimentation history in the eastern Arabian Sea; Climate weathering-productivity linkages. Goa University Unpubl. Ph. D. Thesis. 126 pp.
- CHODANKAR, A.R., BANAKAR, V.K., OBA, T. (2005). Past 100 ky surface salinity gradient response in the Eastern Arabian Sea to the summer monsoon variation recorded by $\delta^{18}O$ of *G. sacculifer*. *Global Planet. Change*, v. 47, pp.135–142.
- CURRY, W.B., LOHMANN., (1986). Late Quaternary carbonate sedimentation at the Sierra Leone Rise (eastern equatorial Atlantic Ocean). *Mar. Geol.*, v.70, pp.223-250.
- DUPLESSY, J.C. (1982). Glacial–interglacial contrasts in the northern Indian Ocean. *Nature*,v.295, pp.494–498.
- DYMOND, J., SUESS, E., LYLE, M. (1992). Barium in deep sea sediment: a geochemical proxy for paleoproductivity. *Paleoceanography*, v.7, pp.163-181.
- FONTUGNE, M.R., DUPLESSY, J.C., (1986). Variations of the monsoon regime during the upper Quaternary: evidence from carbon isotopic record of organic matter in North Indian Ocean sediment cores. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*,v.56, pp.69-88
- GINGELE, F.X., ZABEL, M., KASTEN, S., BONN, W.J., NURNBERG, C.C. (1999). Biogenic barium as a proxy for paleoproductivity: Methods and limitations of application. In:Fischer, G. and Wefer,G.. (Eds.), *Uses of Proxies in Paleoclimatology: Examples from the South Atlantic*. Springer, Berlin, pp. 345-364.
- GUPTA, M.V.S., NAIDU, P.D., HAAKE, B.G., SCHIEBEL, R. (2005). Carbonate and carbon fluctuations in the Eastern Arabian Sea over 140ka: Implications on productivity changes. *Deep-Sea Res. Part - II*, v.2, pp.1981-1993.

- HAAKE, B., ITTEKKOT, V., RIXON, T., RAMASWAMI, V., NAIR, R.R., CURRY, W.B. (1993). Seasonality and inter-annual variability of particle fluxes to the deep Arabian Sea. *Deep-Sea Res. Part -I*, v. 40, pp.1323-1344.
- HONJO, S., DYMOND, J., PRELL, W., ITTEKKOT, V. (1999). Monsoon controlled export fluxes to the interior of the Arabian Sea. *Deep- Sea Res Part-II*, v.46, pp.1859-1902.
- HOWARD, W. R., PRELL, W. L. (1994). Late Quaternary CaCO₃ production and preservation in the Southern Ocean: implications for oceanic and atmospheric carbon cycling. *Paleoceanograph*, v. 9, pp.453-482.
- JACOBS, L. EMERSON, S, HUESTED, S.S. (1987). Trace metal geochemistry in the Cariaco Trench. *Deep -Sea Res*, v.34, pp. 965-981.
- MADHUPRATAP, M., PRASANNA KUMAR, S., BHATTATHIRI, P.M.A., DILEEP KUMAR, M., RAGHUKUMAR, S., NAIR, K.K.C., RAMAIAH, N. (1996). Mechanism of the biological response to winter cooling in the northeastern Arabian Sea. *Nature*, v. 384, pp.549-552.
- MORENO, A., NAVE, S., KUHLMANN, H., CANALS, M., TARGARONA, J., FREDENTHAL, T., ABRANTES, F. (2002). Productivity response in the North Canary Basin to climate changes during the last 250000 yrs: a multi-proxy approach. *Earth Planet. Sci. Letts.*, v.196, pp.147-159.
- MULLER, P.J., SUESS, E. (1979). Productivity, sedimentation rate and sedimentary organic carbon in the ocean-1.Organic carbon preservation. *Deep- Sea Res*, v. 26A, pp.1347-1362.
- MURRAY, R.W., LEINEN, M., ISERN, A.R. (1993). Biogenic flux of Al to sediment in the equatorial Pacific Ocean: Evidence for increased productivity during glacial periods. *Paleoceanography*, v.8, pp.651-670.
- NAIDU, P.D.(1991). Glacial to interglacial contrasts in the calcium carbonate content and influence of Indus discharge in two eastern Arabian Sea cores. *Palaeogeogr. Palaeoclimatol. Palaeoecol*, v. 86, pp.255-263.
- NAIR, BALAKRISHNAN, T.M., RAMASWAMY, V., SHANKAR, R., ITTEKKOT, V. (1999). Seasonal and spatial variations in settling manganese fluxes in the Northern Arabian sea. *Deep - Sea Res. part I*. v. 46, pp. 1827-1839.
- NAIR, R.R., ITTEKKOT, V., MANGANINI, S.J., RAMASWAMY, V., HAAKE, B., DEGENS, E.T., DESAI, B.N. HONJO, S. (1989). Increased particle flux to the deep ocean related to Monsoon. *Nature*, v.338, pp.749-751.
- NAQVI, S.W.A. (1987). Some aspects of oxygen deficient conditions and denitrification of the Arabian Sea. *J.Mar.Res*, v.45, pp.1049-1072.
- NARVEKAR, P.V., SINGBAL, S.Y.S. (1993). Dissolved aluminium in the surface microlayer of the eastern Arabian Sea. *Mar. Chem*, v.42, pp. 85-94.

- NESBITT, H.W., YOUNG, G.M. (1982). Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. *Nature*, v.299, pp.715-717.
- PAROPKARI, A.L. (1990). Geochemistry of sediments from the Mangalore-Cochin shelf and upper slope off southwest India: Geological and environmental factors controlling dispersal of elements. *Chem. Geol*, v.81, pp.99-119.
- PAROPKARI, A.L., IYER, S.D., CHAUHAN, O.S., PRAKASH BABU, C. (1991). Depositional environments inferred from variations of calcium carbonate, organic carbon and sulfide sulfur: a core from southeastern Arabian Sea. *Geo- Mar Letts*, v.11, pp.96- 102.
- PATTAN, J.N., MASUZAWA, T., NAIDU, P.D., PARTHIBAN, G., YAMAMOTO, M. (2003). Productivity fluctuations in the southeastern Arabian Sea during the last 140 ka. *Palaeogeogr. Palaeoclimatol. Palaeoecol*, v.193, pp.575-590.
- PATTAN, J.N., MASUZAWA, T., YAMAMOTO, M. (2005). Variations in terrigenous sediment discharge in a sediment core from southeastern Arabian Sea during the last 140 ka. *Curr. Sci*, v.8, pp.1421-1425.
- PEDERSON, T.F. (1983). Increased productivity in the eastern equatorial Pacific during the last glacial maxima (19000 to 14000yr BP). *Geol*, v.11, pp.16-19.
- PEDERSON, T.F., CALVERT, S.E. (1990). Anoxia vs. productivity: what controls the formation of organic carbon rich sediments and sedimentary rocks? *Am. Assoc. Petro. Geol. Bull*, v.74, pp.454-466.
- PRABHU, C.N., SHANKAR, R., ANUPAMA, K., TAIEB, M., BONNEFILLE, R., VIDAL, L., PRASAD, S. (2004). A 200-ka pollen and oxygen-isotopic record from two sediment Cores from the eastern Arabian Sea. *Palaeogeogr., Palaeoclimatol., Palaeoecol*, v.214, PP. 309-321.
- PRABHU, C.N., SHANKAR, R. (2005). Palaeoproductivity of the eastern Arabian Sea during the past 200 ka: A multi-proxy investigation. *Deep-Sea Res. Part II*, v-52, pp: 1994-2002.
- PRELL, W.L., KUTZBACH, J.E. (1992). Sensitivity of the Indian monsoon to forcing parameters and implications for its evolution, *Nature*, v.360, pp.647-652
- PRINS, M.A., POSTMA, G., WELTJE, G.J. (2000 a). Controls on terrigenous sediment supply to the Arabian Sea during the late Quaternary: the Makran continental slope. *Mar. Geol*, v.169, pp.351-371.
- PRINS, M.A., POSTMA, G., CLEVERINGA, J.A., CRAMP, A., KENYON, N.H. (2000 b). Controls on terrigenous sediment supply to the Arabian Sea during the late Quaternary: the Indus Fan. *Mar. Geol*, v.169, pp.326-349
- QASIM, S.Z. (1982). Oceanography of the northern Arabian Sea. *Deep-Sea Res*, v.29, pp.1041-1068
- RAMASWAMY, V., NAIR, R.R., MANGANINI, S.J., HAAKE, B., ITTEKKOT, V. (1991). Lithogenic fluxes to the deep Arabian Sea measured by sediment traps. *Deep- Sea Res*, v.38, pp.169-184.

- REICHART, G.J., LOURENS, L.J., ZACHARIASSE, W.J.(1998). Temporal variability in the northern Arabian Sea OMZ during the last 225,000 years. *Paleoceanography*, v.13, pp.607-621.
- ROSTEK, F., BARD, E., BEAFORT, L., SONZOGNI, C., GANSSSEN, G. (1997). Sea surface temperature and productivity record for the past 240 kys in the Arabian Sea. *Deep-Sea Res. Part-II*, v. 44, pp.1461– 1480.
- SARNTHEIN, M., WINN, K., ZAHN, R. (1987).Productivity of ocean upwelling and the effect on atmospheric CO₂ and climate change during deglaciation times. In: *Abrupt Climate Change*, Berger, W.H., Laberyrie, L.D. (Eds.),. Reidel, Dordrecht, 311-337
- SCHUBLER, U., BALZER, W., DEEKEN, A., (2005). Dissolved Al distribution, particulate Al fluxes and coupling to atmospheric Al and dust deposition in the Arabian Sea. *Deep -Sea Res Part- II*, v.52, pp.1862-1878.
- SHANKAR, R., SUBBA RAO, K,V., KOLLA, V. (1987). Geochemistry of surface sediments from the Arabian Sea. *Mar. Geol*, v.76, pp.253-280.
- SHIMMIELD, G.B., MOWBRAY, S.R., WEEDON, G.P. (1990). A 350 ka history of the Indian southwest monsoon-evidence from deep sea cores, northwest Arabian Sea. *Trans. R. Soc. Edinburgh: Earth Sci.*, v.81, pp.289-299.
- SIROCKO, F., SARNTHEIN, M.(1989). Wind born deposits in the NW Indian Ocean: record of Holocene sediments versus modern satellite data. In: Leinen, M. & Sarnthein, M. (Eds) *Palaeoclimatology and Paleometerology: Modern and Past Patterns of Global Atmospheric Transport*, 401-33, NATO Advanced Research Workshop. Norwalk, MA: Kluwer Academic Publishers
- SIROCKO, F., SARNTHEIN, M., ERLLENKEUSER, H., LANGE, H., ARNOLD, M., DUPLESSY, J.C. (1993).Century-scale events in monsoonal climate over the past 24,000 years. *Nature*, v. 364, pp.322-324.
- SIROCKO, F., SCHONBERG, D.G., DEVEY, C. (2000). Processes controlling trace element geochemistry of Arabian Sea sediments during the last 25,000 years. *Global Planet. Change*, v.26, pp.217-303.
- WYRKTI, K. (1973). Physical oceanography of the Indian Ocean. In: *The Biology of the Indian Ocean*. Zeitzschel, B. (Ed.),Springer, Berlin, pp. 18-36.

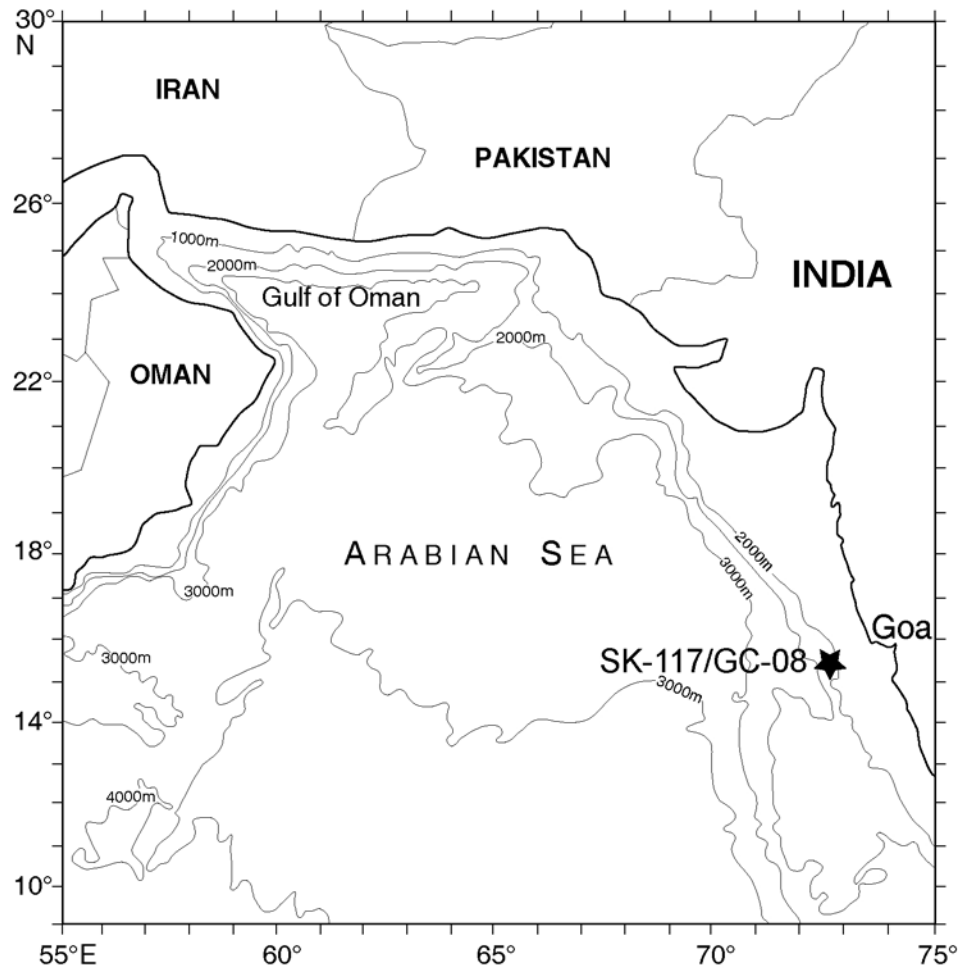


Fig.1. Map showing location of sediment core (SK-117/GC-08) from eastern Arabian Sea

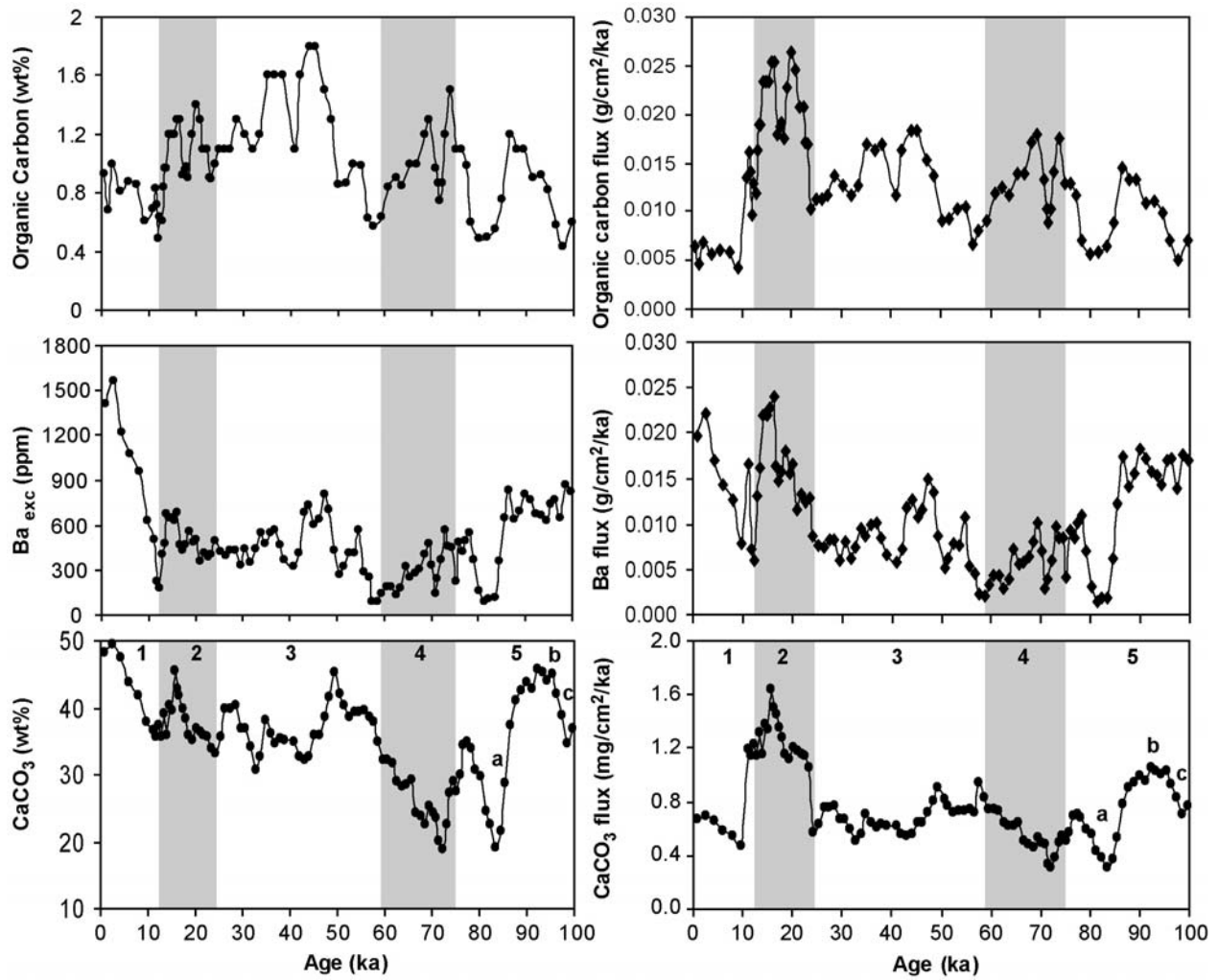


Fig.2. Variation of productivity proxies such as bulk CaCO₃, Ba_{exc} and organic carbon content and their fluxes (g/cm²/ka) during the past 100 ka in eastern Arabian Sea.

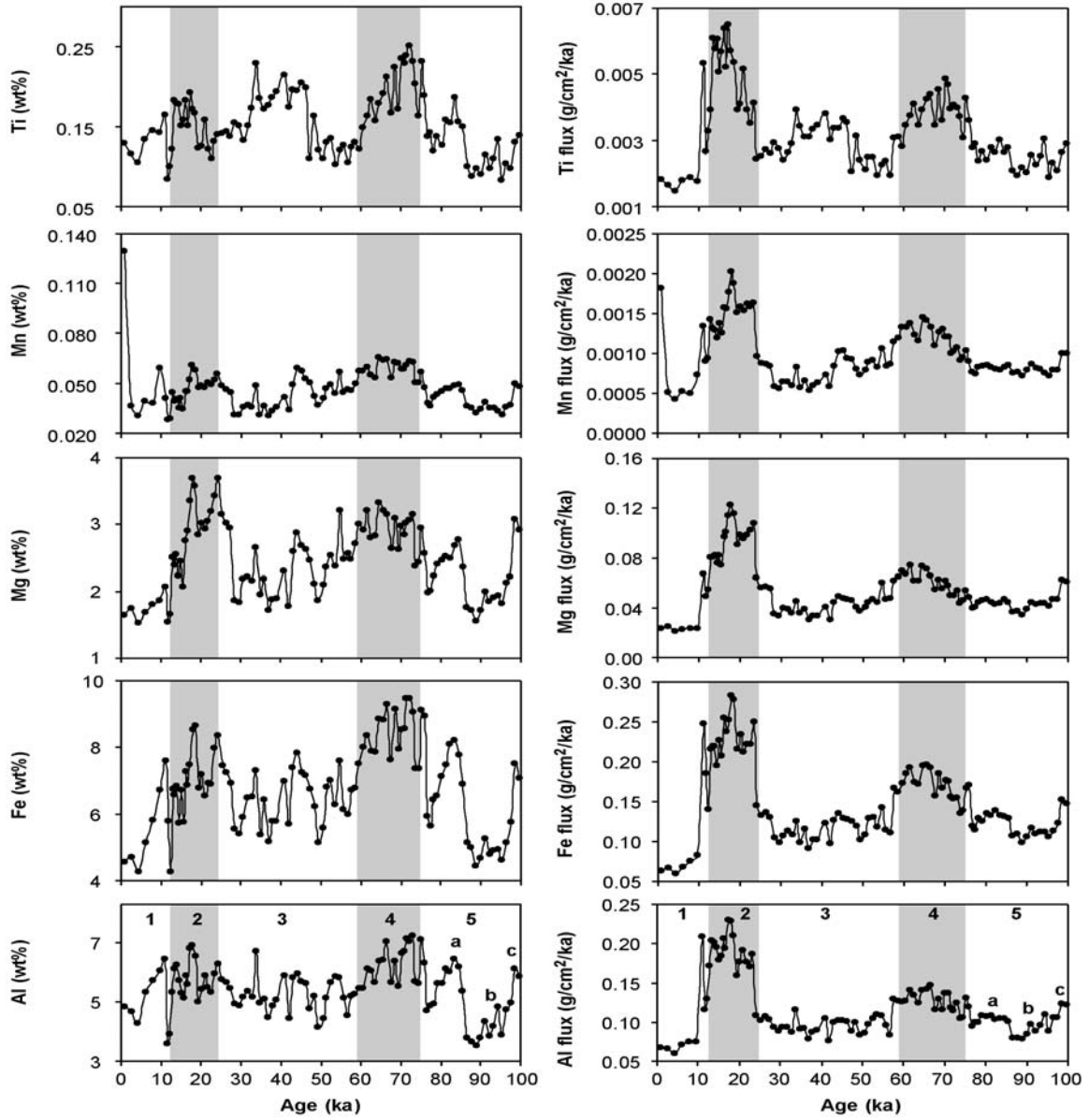


Fig.3. Variations of bulk Ti, Fe, Mg, Mn and Ti content and their fluxes during the past 100 ka .

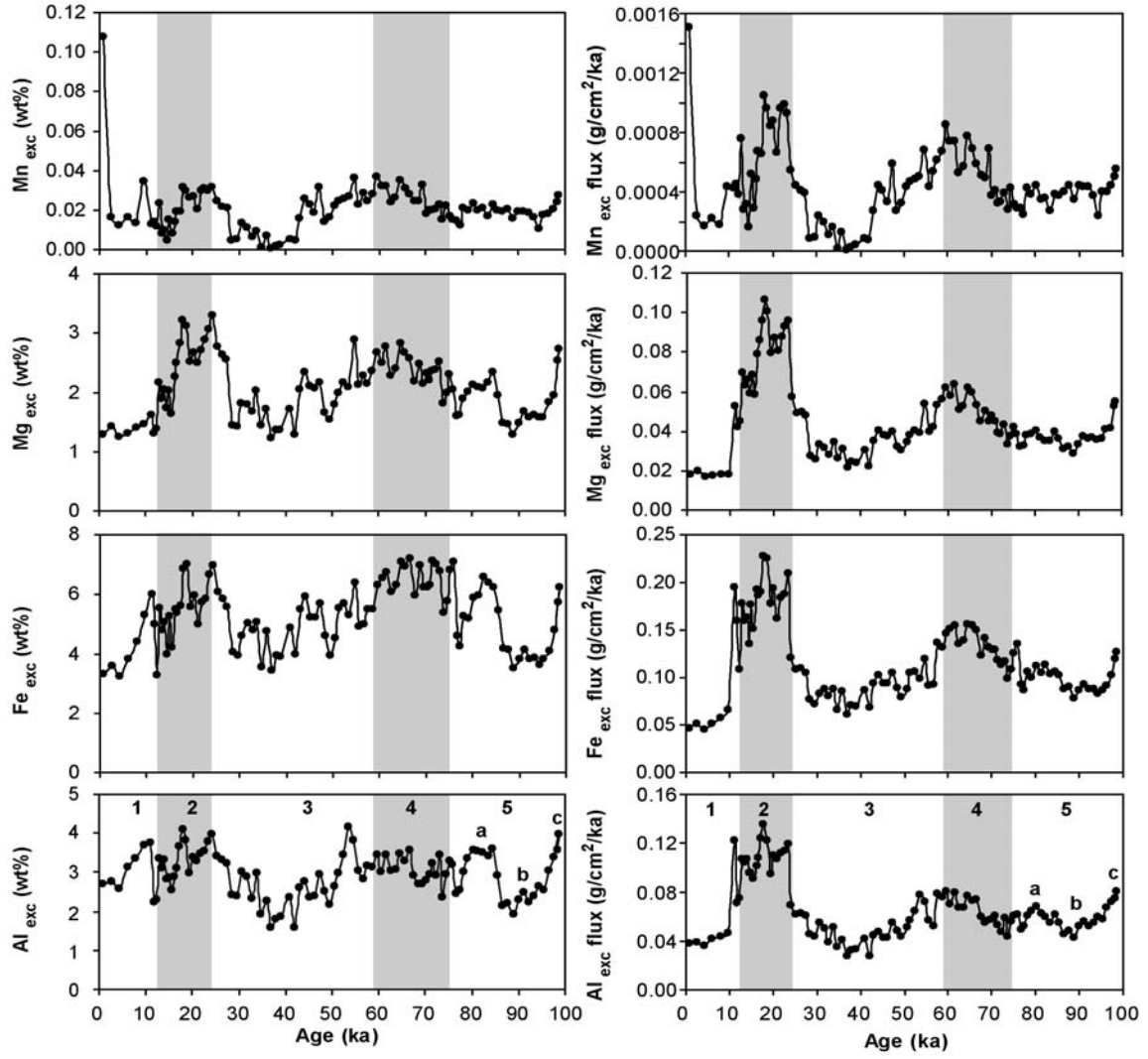


Fig.4. Variation of bulk Al_{exc} , Fe_{exc} , Mg_{exc} and Mn_{exc} and their fluxes during the past 100 ka.

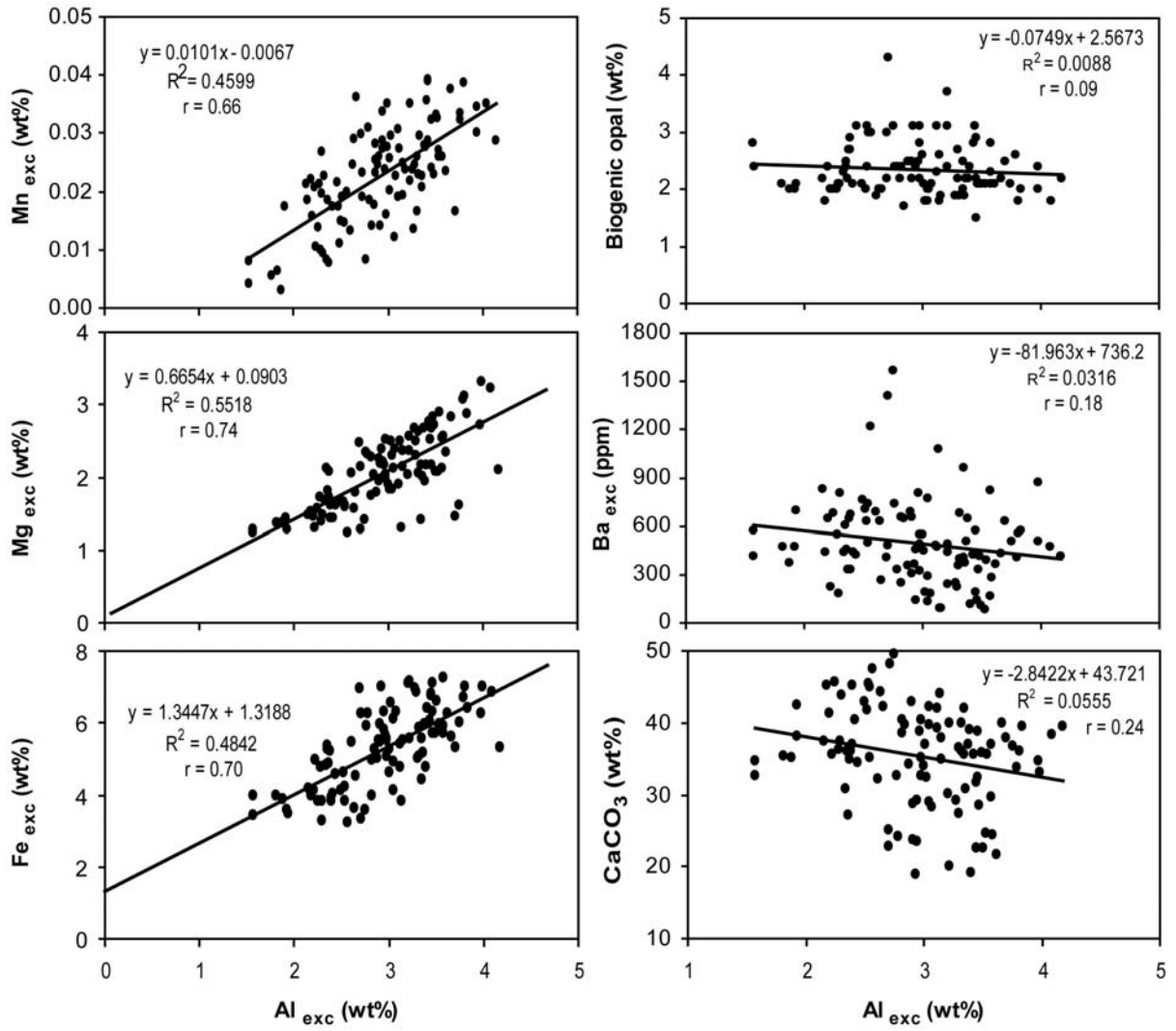


Fig.5. Scatter plots of Al_{exc} with Fe_{exc}, Mg_{exc} and Mn_{exc} and with productivity proxies