

## Geochemistry and granulometry as indicators of paleoclimate, weathering, and provenance of sediments for the past 1,00,000 years in the eastern Arabian Sea

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### Abstract

Geochemical and granulometric investigation of a 408 cm long sediment core raised from the Eastern Arabian Sea was carried out to decipher the climate, weathering, dust flux and provenance of sediments during the past 100 ka. The diagnostic ratio of Cr/Ni (0.99 to 1.77), Rb/Al (6.01 to 17.14), Ti/Al (0.02 to 0.03), Fe/Al (0.94 to 1.61), Mg/Al (0.31 to 0.59) and silt% (38.68 to 66.37) indicate hot and humid climate with the intensification of south-west monsoon during marine isotope stage (MIS) 1, 3, 5a and 5c and cold and dry climate with the intensification of the northeast monsoon and high dust flux during Younger Dryas cooling, last glacial maximum, MIS 2, 4 and 5b. The clay% (20.42 to 53.92), Silica–Titanium Index (71.88 to 86.28), Ruxton Ratio (2.89 to 7.22), and Th/U ratio (0.98 to 4.11) indicate moderate to intense chemical weathering in the source area during warmer climate. Th(ppm) versus Sc(ppm), La/Th versus Th/Yb, Al<sub>2</sub>O<sub>3</sub>% versus Fe<sub>2</sub>O<sub>3</sub>%, Th/Sc versus Sc(ppm), La/Sc versus Sc/Th ratios and La-Th-Sc plot indicate intermediate/mixed sources for sediment provenance. Sand% (2.82 to 25.3), Si/Al (2.74 to 7.43),  $\Sigma$ LREE/ $\Sigma$ HREE (7.65 to 10.40), La/Sc (2.24 to 3.55) indicate felsic sources from Peninsular India during warm climates and  $\Sigma$ RREE (103.98 to 201.17), Rb/Ga (1.36 to 4.33), Ni (70.42 to 137.3 ppm), Rb(55.39 to 138.90 ppm) indicate mafic sources from Deccan Traps and Arabian desert during cold climates. The synchronous relationship between the climate of lower and higher latitudes was observed, suggesting the global teleconnections of climate during the Late Quaternary.

**Keywords:** Geochemistry; Eastern Arabian Sea; Late Quaternary; Paleoclimate; Weathering; Provenance

## 1. Introduction

The chemistry of marine sediments provides essential clues on the role of climate processes in controlling sediment distribution, biological productivity and redox state of bottom water (Schnetger et al. 2000). Once elements are discharged into the oceans, they rapidly associate with particulates and are incorporated in bottom sediments (Hansen et al. 1993) (Pattan et al. 2012). The elements related to sediments are not buried permanently. Under changing oceanic environment may be released to the water column by various remobilization processes (Sruthi et al. 2014). Many traces and rare earth elements are present in seawater either in soluble form or adsorbed onto particles (Calvert and Pederson, 1993). A variety of processes results in element enrichments that mirror the specific conditions prevailing at the time of deposition. Post-depositional diagenetic reactions alter the composition of marine sediments (Mackenzie and Garrels, 1966). The particular source input of elements exerts a first-order controlling influence on their final chemical composition. This is because most element concentration in detrital sediments occurs in mineral structural sites rather than adsorbed onto mineral, organic matter, and oxide coatings. The sediment chemistry reflects the proportions of lithology's contributing to the total sediment. For this reason, geochemistry can be used for provenance studies (Werne et al., 2003; Calvert and Pedersen, 2007; Kurian et al. 2008; Revillon et al. 2011). Siliciclastic sedimentary rocks contain important information about changes in the supply of material from different sources over time, and the geochemical compositions of such sediments have proven to be a powerful tool for reconstructing the signature of the provenance, weathering, paleoclimate and bottom water redox conditions during which the sediments are deposited (Wronkiewicz and Condie, 1987; Murray et al. 1990, 1991a; Jones and Manning, 1994; Calvert and Pedersen, 2007; Revillon et al. 2011; Govin et al. 2012).

Geochemical studies of marine sediments for the reconstruction of provenance are done (Jones, 1972) using Fe, Mn, Ti, and P (Bostrom et al. 1973) using relationships between Fe, Ti, Al, and Mn (Wright, 1974a) using major and some trace elements (TEs). Hirst (1962b) discussed the use of trace-element chemistry for stratigraphic correlation. Similar studies have been carried by several other workers (Taylor and McLennan, 1985; Bhatia and Crook, 1986; McLennan, 1989; Zimmermann and Bahlburg, 2003; Pattan et al. 2013). Many studies, dealing with the geochemistry of Arabian Sea sediments, have focused on the elemental distribution (Schnetger et al. 2000; Nath et al. 1997). Varghese (2004) rare and trace element studies along the western continental shelf of India. Rare and trace element studies from sediment cores in the eastern Arabian sea (EAS) for provenance studies are rare. Major element chemistry from the EAS has been discussed earlier (Mir et al. 2013) to reconstruct terrigenous input variations. Rare Earth Elements (REE) are important in marine

geochemical research. REE's in sedimentary phases are increasingly being used as indicators of several geological and oceanographic processes, namely depositional environment, paleo redox conditions, and also to assess the crustal source (Taylor and McLennan, 1985; Liu et al. 1988). The chemical behaviour of the REEs has made them one of the most extensively used geochemical tracers. The relative abundance of REEs in sediments has been suggested as a tool to determine the source of rocks (Morey and Setterholm, 1997).

Monsoon modulates the biogeochemistry and climate of the Arabian Sea (Duplessy, 1982). The monsoon in the Indian Ocean and adjacent continents is one of the Earth's most dynamic climatic phenomena resulting from interactions between ocean, land and atmosphere (Prell and Kutzbach, 1992; Duplessy, 1982; Fontugne and Duplessy, 1986; Gupta et al. 2005). The higher runoff and strong winds during the monsoon especially during SWM bring enormous loads, 400 million tons annually (Kolla et al. 1981) of clastic sediments to the Arabian Sea through fluvial action. Successful monsoon in the Indian subcontinent is necessary for water sufficiency and high food production (Sikka and Gadgil, 1978; Gadgil, 1988; Gadgil and Sajani, 1998; Trenberth et al. 2000). For present monsoon studies, instrumental records are available but for paleo monsoon, only proxy methods are available. It is necessary to understand the past variation of monsoons so that the data from past and present monsoons can be used for running the climate models to predict the future monsoon (Prell and Kutzbach, 1992). Terrigenous matter input to the Arabian Sea is strongly linked to the intensity of the monsoon (Gupta et al. 2005). It has been shown that summer monsoon or south-west monsoon (SWM) was stronger during interglacial periods than glacial periods (Prell and Kutzbach, 1992; Duplessy, 1982; Fontugne and Duplessy, 1986; Gupta et al. 2005; Kessarkar et al. 2013; Saraswat et al. 2019). Sediment chemistry has been used to understand the terrestrial climatic conditions, such as arid, humid or ice-covered (Nesbitt and Young, 1982). The chemical composition of the Arabian Sea sediments has suggested multiple sources such as aeolian input from Arabia, fluvial detritus from the Indian sub-continent and Somalia and submarine weathering products of Carlsberg Ridge and sediment contribution from the Bay of Bengal waters (Shankar et al. 1987; Chauhan and Gujar, 1996). Sediments in the western Arabian Sea (WAS) are mainly of aeolian origin (Shimmield et al. 1990) and sediments in the EAS are mainly of fluvial origin (Paropkari, 1990). Kumar et al. (2020) carried out geochemical, mineralogical, and Sr-Nd isotopic studies of atmospheric mineral dust collected at the coastal location of Goa in the Northeastern Arabian Sea to understand the dust deposition over the Arabian Sea. They reported these aerosol samples mainly result from dust storms in the Middle East and southwest Asian desert region. Chauhan and Gujar (1996) and Kumar et al. (2020) reported high palygorskite content in sediments of the eastern Arabian Sea and nearby coastal

area and suggested sources from the Arabian plateau. In the present study a few major oxides, trace, and rare element results from EAS are investigated to understand paleoclimate, provenance, weathering, and tectonic setting of the sediments in EAS during the past 100 ka.

## 2. Materials and Methods

The sediments analyzed in this study are from a 408 cm long core (SK117/GC-08) raised from the EAS (Fig. 1; 15°29'71" N, 71°00'98" E; water depth: 2500 m) during the 117th cruise of ORV SagarKanya. The core was sub-sampled at a 2 cm interval on board and was later stored at the core repository of CSIR-National Institute of Oceanography (NIO), Goa, India. The carbonate ooze intermixed with clay and silt material is the dominant sediment type in the core (Banakar et al. 2005). A total of 82 sub-samples were utilized in the present study. Chodankar et al. (2005) have reported the depth–age model of the sediment core. They established the chronology of the sediment core by tuning the down-core  $\delta^{18}\text{O}_{G. \text{ sacculifer}}$  profile with the tropical stack of the SPECMAP marine isotope stages (MIS; Bassinot et al. 1994) and compared the Holocene sedimentation rate with AMS  $^{14}\text{C}$  based sedimentation rate for a nearby core (3104G; Sarkar et al. 2000). The core is turbidite-free and preserves a continuous record of sedimentation for the past 100 ka. The downcore variation in grain size of the sediment core is derived from Chodankar (2004). The sedimentation rate during the past 100 ka has varied from 2.3 cm/ka to 6.1 cm/ka, with the highest during the MIS2, (Mir et al. 2013). Youngest Toba Tuff (YTT) event has been used by many researchers as a tie point for oxygen-isotope chronology in marine sediment cores. In the present sediment core also YTT event has proved to be an excellent tie point for establishing oxygen-isotope stratigraphy, keeping the YTT event at ~74ka (Pattan et al. 2001).

The sub-samples were washed with de-ionized water to make them sea-salt-free, dried at 60°C in the oven, and finely powdered in an agate mortar. The finely powdered sediment sections were made carbonate-free by treating with 1N HCl. An aliquot of ~0.2 g of carbonate-free dried sediment was carefully weighed and transferred to Teflon beakers. The samples were treated with HF+HNO<sub>3</sub>+HClO<sub>4</sub> (7:3:1 ratio) mixture in a PTFE beaker, kept overnight, and then dried on a hot plate. This treatment was repeated till the sample in the beaker was completely digested. The final residue was dissolved in 20 ml of 1:1 HNO<sub>3</sub>. Subsequently, 5 ml of 1 ppm Rh solution was added as an internal standard. The digest was diluted to 50 ml with 18 megaohms deionized water. Similarly, a standard reference material (USGS-MAG1), acid blanks and duplicate solutions were also prepared. The solutions were analyzed for major and few TEs on an Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES, Perkin Elmer Plasma-400 sequential). The accuracy compared to standard reference material and precision of the data based on duplicate analysis were

better than  $\pm 6\%$ . The reported major elemental values are the carbonate-free basis. The content of calcium carbonate in these sediments is discussed in Mir et al. 2013.

Sediment sub-samples of core SK117-GC08 were also analyzed for trace and rare earth elements (REE). For the chemical analysis (Pattan et al. 2005), about 50 mg of sediment was weighed in a Teflon beaker. To this 10 ml of an acid mixture of HF + HNO<sub>3</sub>+ HClO<sub>4</sub> (7:3:1 ratio) was added and heated on a hot plate till it becomes like a paste. To this paste, 4 ml of 1:1 HNO<sub>3</sub> was added and heated for 5 minutes and made to a final volume of 100 ml. Similarly, the digestion procedure was followed for standard reference material (MAG-1) and blanks. These solutions were analyzed for a few major, trace and REE on an Inductively Coupled Plasma-Mass Spectrometer (ICP-MS, Thermo X Series 2). The accuracy compared to standard reference material and precision of the data based on duplicate analysis were better than  $\pm 6\%$ .

Calculation of elemental ratio and descriptive statistics from bulk geochemical data was carried out by using Microsoft Excel software and plotting of binary and triangular diagrams was carried out by using Origin 6.1 software.

Clay% (Chodankar, 2004), Silica–Titanium Index (STI), Ruxton Ratio (R), and Th/U ratio (McLennan et al. 1993) were calculated to highlight the change in weathering intensity during the past 100 ka in EAS. The selected elemental ratio (Taylor and McLennan, 1985) are expected to increase with increasing rainfall (Chodankar et al. 2005).

R is calculated using the equation of Ruxton (1968),  $R = Si/Al$ .

STI is calculated using the equation of (deJayawardena and Izawa, 1994),

$$STI = (100)[(Si/Ti)/((Si/Ti)+(Si/Al)+(Al/Ti))].$$

The silt%, Cr/Ni (Taylor and McLennan, 1985; Zhang et al. 2003), Rb/Al (Sirocko et al. 1996), Ti/Al (Nath et al. 1997), Fe/Al and Mg/Al (Sirocko et al. 2000) are used to highlight dust transport as the ratios are expected to increase with increasing dry climate (Taylor and McLennan, 1985).

The sand% (Chodankar, 2004), Si/Al,  $\sum LREE/\sum HREE$  and La/Sc (Madhavaraju, 2015) are used to reconstruct the dominant felsic provenance of sediments during warm climate and  $\sum REE$  (Nath et al. 2000; Varghese, 2004), Rb/Ga (Kurian et al. 2013), Ni(ppm)(Madhavaraju, 2015) and Rb(ppm) (Madhavaraju, 2015) are used to reconstruct the dominant mafic provenance of sediment during cold climate.

### 3. Results

#### 3.1. Grain size variation

Grain size and geochemical data are shown in Table 1. The sand content varies from 2.8 to 25.3 with a mean of 9.0 (%), silt content varies from 38.6 to 66.3 with a mean of 49.8 (%) and clay content varies from 20.4 to 53.9 with a mean of 41.1 (%). The sediment grain size is mostly dominated by silt followed by clay particles. The clay fraction is higher during MIS1, 3, 5a and 5c whereas the silt fraction is the highest during MIS2, 4 and 5b. Sand fraction is the highest during MIS1 and gradually decreases from MIS2 to MIS4 and slightly increases in MIS5 again.

#### 3.2. Geochemical variation

The concentrations of major elements in the core are presented in Table 1 and are discussed in Mir et al. (2013). The major oxide compositions vary from Si: 25.6 to 60.4 with a mean of 44.0 %, Al: 5.5 to 11.3 with a mean of 8.4 %, Fe: 6.8 to 13.8 with a mean of 10.4 %, Mg: 2.3 to 6.0 with a mean of 3.8 % and Ti: 0.1 to 0.3 with a mean of 0.2 %. The major oxide concentrations of the sediment show distinct glacial-interglacial variation. The composition of selected trace elements (TE) from the studied sediment core samples is shown in Table 1. Ga varies from 21 to 44 with a mean of 29 ppm), Ni varies from 70 to 137 with a mean of 105 ppm), Rb varies from 55 to 139 with a mean of 92 ppm), Sc varies from 9.95 to 20 with a mean of 14 ppm), Th varies from 4.78 to 13 with a mean of 8.07 ppm) and Yb varies from 1.43 to 2.77 with a mean of 1.93 ppm). The REE content for the analyzed samples is listed in Table 1. La content varies from 34 to 56 with an average of 40 ppm, Sm content varies from 3.06 to 5.89 with an average of 4.25 ppm, U content varies from 1.18 to 8.78 with an average of 4.14 ppm, total REE ( $\Sigma$ REE) concentration varies from 104 to 201 with an average of 140 ppm. The average  $\Sigma$ REE concentrations (140 ppm) for the studied sediments is lower than that of the PAAS (183 ppm). La is slightly higher than crustal averages and Sm is lower than crustal averages. The elemental ratios Ti/Al vary from 0.02 to 0.03 with a mean of 0.03), Fe/Al vary from 0.94 to 1.61 with a mean of 1.24), Mg/Al vary from 0.31 to 0.59 with a mean of 0.45), Si/Al vary from 2.74 to 7.43 with a mean of 5.15), Cr/Ni vary from 0.99 to 1.77 with a mean of 1.26), Rb/Al vary from 6.01 to 17 with a mean of 11), Th/U vary from 0.98 to 4.11 with a mean of 2.15), Th/Sc vary from 0.40 to 0.83 with a mean of 0.55), La/Sc vary from 2.24 to 3.55 with a mean of 2.80), Sc/Th vary from 1.20 to 2.44 with a mean of 1.82), Rb/Ga vary from 1.36 to 4.33. STI varies from 72 to 86 with a mean of 82 and R varies from 2.89 to 7.22 with a mean of 5.25. The ratio of  $\Sigma$ LREE/  $\Sigma$ HREE varies from 7.65 to 10 with an average of 9.37. Rb, Sc, Th and Yb are depleted than crustal averages. Rb/Al shows a higher ratio during YD, MIS2, 4 and 5b. Ti/Al shows a higher ratio during 36 ka, 72 ka and during MIS5b.

## 4. Discussion

### 4.1. Paleoclimate

In the present study silt %, Rb/Al, Ti/Al, Fe/Al, Mg/Al and Cr/Ni in EAS sediments are used to infer the dust flux conditions during the past 100 ka. In Fig. 2, it is evident that silt%, Cr/Ni, Rb/Al, Ti/Al, Fe/Al and Mg/Al are higher during YD, LGM, MIS2, 4 and 5b. Glacial periods are colder, dustier, and generally drier than interglacial periods. YD, LGM, and even-numbered MIS represent cold climate, and odd-numbered MIS represents warm climate. Southwest monsoon (SWM) was stronger during warm climate whereas NEM and dust flux was more intense during cold climates. Elemental ratios as aridity proxies and silt content as a proxy for strengthening of NEM (Fig. 2) indicate dust flux and NEM were stronger during colder climate in the EAS. The granulometry data indicate that the sediment grain size is mostly dominated by silt followed by clay particles. The higher content of sand and clay during MIS1 and 3 (Fig. 5 and 3) corresponds with the intensified SWM and resulting freshwater run-off from the rivers. High silt content during glacial reflects the intensification of NEM and high dust flux. Besides, lowering the sea level during the glacial period has exposed the continental shelf to increased erosion of previously deposited terrigenous material (Prins et al. 2000). Our observations are similar to the findings of Thamban et al. (2001); Tiwari et al. (2005) and Kessarkar and Rao (2007). The Arabian Sea receives dust enriched in Ti, Fe, and Mg through the wind supplies from the Arabian and Thar deserts. Higher ratios of Ti/Al, Fe/Al, and Mg/Al ratios in the Arabian sea sediments correlate with drier conditions during colder climates when the intensity of south-west monsoon was weak and flux of dust was high (Sirocko et al. 2000). Kumar et al. (2020) reported mineral dust from the Arabian plateau is reaching the western coast of India. Rb/Al was used as an indicator for dust flux from the Arabian deserts (Sirocko et al. 1996). Ti is a refractory element and relatively immobile. Ti/Al ratio was successfully used to study the fluctuations in the intensity of aeolian transport associated with glacial/interglacial cycles in the eastern Pacific Ocean (Murray et al. 2000). Ti/Al ratio in the Arabian Sea sediments has been used to study the wind intensity associated with monsoons. The Arabian Sea record has shown that the Ti/Al peaks are matching with other monsoonal proxies (Schulz and Stattegger, 1997; Torrence and Compo, 1998). The most common mineral from which Ni is concentrated in aeolian dust deposits is Pentlandite, a primary mineral in many ultramafic rocks, is a soft and light mineral and gets easily abraded (Zhang et al. 2003). The Cr/Ni ration (0.5-1.5) of aeolian dust (Zhang et al. 2003) is lower than fluvial sediments (3-3.5) deposited on the continental shelf (Zhao and Yan, 1992). The Cr/Ni ratio of 0.99 to 1.77 with a mean of 1.26 in EAS sediment core during the past 100 ka suggests wind supply transport which was high during colder and drier YD, LGM, MIS2, 4 and 5b. Ultramafic

rocks are common in the Oman ophiolite suite of the Arabian plateau (Hugh, 2000) and can be the most probable source of dust rich in Ni.

#### *4.2. Paleoweathering*

To quantify the degree of weathering of source rock material from studied sediments Clay%, STI, R and Th/U ratio (Fig. 3) has been applied, these are good indicators of weathering in tropical regions (deJayawardena and Izawa, 1994). The chemical index of alteration (CIA) (Nesbitt and Young, 1982; Mir and Mir, 2019) and chemical index of weathering (CIW) (Harnois, 1988; Mir and Mir, 2019) are not used in this study due to the nonavailability of few major elements. From the same sediment core  $\delta^{18}\text{O}_{G.sacculifer}$  data from Chodankar et al. (2005) is used to show the rainfall variability during the past 100 ka and its impact on weathering variations. The calculated values for studied sediment core samples are listed in Table 1. STI value of >90 indicates optimum fresh rock and 0 indicates highly weathered rock; R-value of >10 indicates optimum fresh rock and 0 indicates highly weathered rock and Th/U (McLennan et al. 1993) are also used to highlight weathering condition as the ratio of sedimentary rocks is expected to increase with increasing weathering (Taylor and McLennan, 1985). For most upper crustal rocks, the Th/U is typically about 3.5 to 4.0. Many types of sediment from active margin tectonic settings with major components of young undifferentiated crust have Th/U significantly below 3.5 accompanied by low Th and U contents and this is interpreted as dominantly reflecting a low ratio in the source rocks (McLennan, 1989). The studied sediments have STI values ranging from 60 to 78, R values ranging from 1.5 to 3.8 and Th/U ratio values ranging from 1 to 4.1, all suggesting that they were dominantly derived from moderately weathered source rocks. During colder climates (YD, LGM, MIS2, MIS4, MIS5b) the sediments from the present study have experienced less weathering than warm climates (MIS1, MIS3, MIS5a, and MIS5c). The results from this study are matching with the results of Chodankar et al. (2005); Saraswat et al. (2019) indicating strong south-west monsoon controlled high weathering during warm climates in the Indian subcontinent.

#### *4.3. The provenance of sediments*

Non-migratory elements, such as La, Th, Sc and Yb exhibit different chemical properties in felsic and mafic sources and are unaffected by the processes of sedimentation, their ratios provide valuable information about the source of the deep-sea sediments (Cullers and Podkovyrov, 2000). The triangular plot of La-Th-Sc (Bhatia and Crook, 1986); bivariate plots of Sc versus Th (McLennan et al. 1993), La/Th versus Th/Yb (Taylor and McLennan, 1985),  $\text{Al}_2\text{O}_3\%$  versus  $\text{Fe}_2\text{O}_3\%$ , Th/ScvsSc (Condie, 1993) and La/ScvsSc/Th (Mir et al. 2016 and references therein) are used to understand the provenance of sediments. All of the plots indicate intermediate/mixed sources of sediments.



Admixture of sediments derived from mafic sources from Deccan Traps, felsic sources from south India and dust from Arabian plateau and Thar desert when reaching deeper part of EAS will show intermediate signature in geochemical diagrams indicating multiple sources which are perfectly reflected in our results (Fig. 4).

Sc, Rb, and Ni are enriched in mafic and ultramafic rocks because of the smaller size of their ions which allows these elements to enter easily in the early crystallizing pyroxenes. During weathering, pyroxenes are easily broken down and Sc, Rb and Ni get enriched in residual deposits (Das et al. 2013). These residual deposits are easily transported by dust to longer distances. On the other hand, Si, Th, U and La are enriched in felsic rocks. In EAS sediment core, sand%, Si/Al and La/Sc ratios are higher during warmer and wetter climates whereas Rb/Ga ratio, Ni (ppm) and Rb (ppm) are higher during colder and drier climates (Fig. 5). This suggests that the main source was felsic rocks during warmer periods (the source of which may have been the Peninsular Gneisses of south India) and basic/ultrabasic sources during colder periods (the source of which may have been the Deccan Traps basalts and wind transported material from Arabian plateau and Thar desert). Rb/Ga ratio and Rb (ppm) were used to determine the sediment source in the Gulf of Kachchh (Staubwasser and Sirocko 2001) and the eastern Arabian Sea (Kurian et al. 2013). Rb (ppm) in general is higher in the northern part compared to the southern part of the western continental margin of India, moderate Rb values observed in coastal sediments of Kerala suggest the influence of Deccan basalts in this region (Kurian et al. 2013). The REEs distribution can also be used to reconstruct the sources of deep-sea sediments (McLennan et al. 1993; Sirocko et al. 1996). Sand%, Si/Al, La/Sc, Rb/Ga, Ni (ppm) and Rb (ppm) along with REE concentration helps in provenance studies (Taylor and McLennan, 1985). Rivers are the principal source of REE transport into oceans. Other sources do not seem to be significant. The volcanic ash, loess, and other aeolian dust sources have local importance (Jones et al. 1994). Hydrothermal input from mid-ocean ridges adds only locally and marginally to the REE supply (Olivarez and Owen, 1991). Felsic sources generally exhibit higher LREE/HREE ratios which match very well with sand%, Si/Al, La/Sc in the present study, while mafic sources produce low LREE/HREE ratios (Roddaz et al. 2006) which matches very well with Rb/Ga, Ni (ppm) and Rb (ppm). The downcore distribution pattern reveals that during cold climates (YD, LGM, MIS2, MIS4, and MIS5b)  $\Sigma$ REE is higher than during warm climate (MIS1, 3, 5a and 5b). Down the core trend of  $\Sigma$ REE distribution indicates high REE content to the core location was delivered during glacial periods when NEM rainfall and aeolian activity were stronger than SWM winds (Fig. 5). Our results support the studies of Nath et al. (2000); Varghese (2004) and Kurian et al. 2013. Among the three principal sources for sediments to the EAS (Mattait et al. 1973), the effect of the Indus decreases

from north to south and is insignificant on the southwest continental margin. Between Goa and Kochi, the shelf and slope sediments represent mostly the influence of Deccan Trap and gneissic-province indicating cross-shelf transport in this region. The present studied core is from deeper waters off Goa in the western continental margin which is dominated by sediments coming from Deccan Trap, peninsular gneisses and dust from Arabian and Thar deserts. The felsic sources of REE, are high during warmer climates when SWM was strong and was able to bring REE from gneissic-province whereas mafic and dust sources of REE are high during cold climates when NEM and dust activity was strong and was able to bring REE from Deccan Trap, Thar desert and Arabian plateau. Our results (Fig. 5) are similar to the findings of Kolla et al. (1976); Nath et al. (2000); Varghese (2004); Das et al. (2013); Kurian et al. (2013); Kumar et al. (2020), their studies also suggested mixed sources for sediments in the EAS.

#### 4.4. Characterizing the source using mixing calculations

The shale normalized REE patterns of the bulk sediments are flat. There is a slight LREE enrichment compared to HREE. REE concentrations (104-201 ppm) and the shale normalized patterns of the bulk sediments are remarkably similar throughout the entire depth of the core spanning the last 1Ma (Fig. 6) indicating that source to the REEs in the bulk sediment has remained unchanged over time. The major-element composition shown above (section 3.2) indicates two sources, viz., Deccan basalts and peninsular gneisses, are responsible for the elemental makeup of the sediments. Therefore, the shale normalized patterns of our sediments are compared to the patterns of the Deccan basalts (Lightfoot et al. 1990) and peninsular gneisses (Allen et al. 1985) in Fig. 6a. However, aeolian dust can also contribute to the sediments of the eastern Arabian sea (Kumar et al. 2020). The shale normalized patterns of the bulk sediments are remarkably similar to the shale normalized patterns of the aeolian dust (Ferrat et al. 2011) (Fig. 6). Therefore a third end member was used. Three end-member used here are i) Basalt, ii) peninsular Gneisses and iii) dust. The relative proportions contributing to the bulk sediments is assessed by modelling the REE data using ternary mixing equations

$$f_{\text{basalt}} + f_{\text{gneiss}} + f_{\text{dust}} = 1$$

$$C_{\text{mix}}^i = (f_{\text{basalt}} \times C_{\text{basalt}}^i) + (f_{\text{gneiss}} \times C_{\text{gneiss}}^i) + (f_{\text{dust}} \times C_{\text{dust}}^i),$$

where  $f$  represents the proportion of each end-member contributing to the oxides, and  $C_{\text{mix}}^i$  is the concentration of an element in the mixture.

The results of these calculations are presented on a shale normalized REE pattern in Fig. 6b. The enrichment in LREE seems to be contributed by the peninsular gneisses, while MREE enrichment is

dominantly sourced by the Deccan basalts. The flat HREE patterns of the Aeolian dust are reflected in the bulk patterns. The shale normalized REE patterns for the studied samples are reproducible using a mixture of up to 50 % basalt, 40 to 80% gneiss and 10 to 20% Aeolian dust, suggesting that the basaltic and gneissic contribution is dominant over the Aeolian source. Variations in the proportions of these components over time seem to be the reason for the variation in magnitude of the REE content in the study area. However, these calculations should be considered as indicative and may not represent the proportion in which they are incorporated during the sediment formation (see Chavagnac et al. 2005, Mascarenhas-Pereira and Nath, 2010 discussion).

#### *4.5. Regional and global climate change during the past 100 ka*

Sand%, La/Sc, Th/U ratios as an indicator of strong SW monsoon, high weathering, and acidic provenances and Ni (ppm) and Mg/Al ratios as an indicator of strong NE monsoon, low weathering, high dust flux, and basic provenances from the present study are compared with the late Quaternary temperature fluctuations record of southeastern Arabian Sea sediment core, SK237GC08 (Saraswat et al. 2019), previous studies from same sediment core (Chodankar et al. 2005) and with Greenland ice core, GISP2, (Dansgaard et al. 1993) shows a synchronous distribution suggesting a global teleconnection of climate during the late Quaternary times for lower and higher latitudes. The timing of high dust flux, strong NEM, basic rocks as dominant sources of sediments, low chemical weathering (high Ni and Mg/Al) in the EAS are consistent with temperature fluctuation records of Saraswat et al. (2019); Chodankar et al. (2005) and Dansgaard et al. (1993). Evidence is provided for a general relationship between monsoonal climate variability of lower latitudes in the northern Indian Ocean and higher latitudes that are recorded in the Greenland ice core. This study showing high sand% and high chemical weathering reflect strong SWM induced erosion, weathering, and transport of sediments from the Indian hinterland and deposition of sediments in EAS which correlates very well with the interstadial climate events in the northern Greenland region. In contrast, periods of weak SWM intensity, indicated by low sand% and less chemical weathering in EAS sediments during the YD cooling, LGM, stadials of MIS 3 to 5 are associated with intervals of high-latitude atmospheric cooling. Similarly, a high ratio of Mg/Al and Ni (ppm) in EAS reflects strong NEM precipitation and high dust flux which is also associated with intervals of high-latitude atmospheric cooling. Findings from the present study with comparison to high latitude records indicate that Dansgaard–Oeschger (DO) and Heinrich events (HE) are strongly expressed in low-latitude, monsoonal climate variability, indicating common climate forcing agents such as insolation, atmospheric moisture, atmospheric gases, and oceanic circulation (Fig. 7). Several studies from the Arabian sea (Sirocko et al. 1991; Reichert et al. 1998; Schulte and Muller, 2001) and BoB (Colin et

al. 1998; Sijinkumar et al. 2010; Gebregiorgis et al. 2016) have shown that SWM was stronger during the interglacial and interstadials whereas NEM was stronger during the glacial and stadials and its links with Greenland climate oscillations (Schulz et al. 1998; Kudrass et al. 2001; Sijinkumar et al. 2010; Gebregiorgis et al. 2016).

## **5. Conclusion**

From this study following conclusions may be drawn:

1. Various proxies indicate climate during MIS1, 3, 5a, and 5c was hot, humid and SWM was more intense whereas during YD, LGM, MIS2, 4, and 5b climate was cold, dry and NEM was more intense. Dust flux was also more intense during the cold climate.
2. Chemical weathering in the source area was moderate in cold to intense during warm climate.
3. Felsic rocks of peninsular India were the major sediment provenance during warm climates whereas mafic rocks of Deccan Traps and dust sources from the Arabian plateau and Thar desert were the dominant sediment provenance during cold climate.
4. Mixing calculations for the studied samples suggest ~ 50 % basalt, 40 to 80% gneiss and 10 to 20% aeolian dust sources of sediments. The basaltic and gneissic contribution is dominant over the aeolian source.
5. This study was compared with the other Arabian Sea and Greenland paleoclimate records for global/regional comparison. Global climate change events during Holocene, YD, LGM, deglacial, stadials and interstadials of MIS1 to 5, Dansgaard–Oeschger and Heinrich events are showing synchronous relationship with intensification and weakening of south-west monsoon.

## **Author contributions**

Ishfaq Ahmad Mir: Conceptualization, Writing, Original draft, Methodology, Formal analysis.

Maria Brenda Luzia Mascarenhas: Writing, review and editing.

Neloy Khare: Writing, review and editing.

## **Data availability**

Supplementary data to this article is not attached.

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## Figure/Table captions

**Fig. 1.** The left side shows the location of sediment core SK-117/GC-08 in EAS and the right side shows Depth (cm) versus  $\delta^{18}\text{O}$  of *G.sacculifer* values (Y-axis) and Calendar Age (ka), (X-axis). Horizontal dashed line near ~300 cm depth represents Youngest Toba Tuff event (YTT: ~72 Ka), MIS are Marine Isotope Stages. The depth-Age model is derived from Chodankar et al. (2005).

**Fig. 2.** Distribution of silt%, Cr/Ni, Rb/Al, Ti/Al, Fe/Al, Mg/Al ratios and as the proxies for the intensification of the northeast monsoon and dust flux variability during glacials and intensification of south-west monsoon during interglacials. Permission was sought from Chodankar (2004) for using the grain size data.

**Fig. 3.** Distribution of clay%, STI, R and Th/U ratios as proxies for demonstrating the degree of weathering in hinterland derived from EAS sediment core during the past 100 ka.  $\delta^{18}\text{O}_{G. sacculifer}$  (Chodankar et al. 2005), clay content (Chodankar, 2004).

**Fig. 4.** (a) Source and compositional discrimination diagrams of Sc vs. Th, after McLennan et al. (1993); (b) La/Th vs. Th/Yb plot showing felsic versus mafic character after Taylor and McLennan (1985), (c) plot of La-Th-Sc showing the provenance of the sediments to be mainly of mixed sources after Bhatia and Crook (1986), (d)  $\text{Al}_2\text{O}_3$  vs  $\text{Fe}_2\text{O}_3$ , (e) Th/ScvsSc bivariate plot for EAS core sediments after Condie (1993) and (f) La/ScvsSc/Th (Mir et al. 2016 and references therein).

**Fig. 5.** Distribution of Sand%, Si/Al,  $\Sigma\text{LREE}/\Sigma\text{HREE}$ , La/Sc as proxies for acidic provenance of sediments during warmer and wetter climates and  $\Sigma\text{REE}$ (ppm), Rb/Ga, Ni(ppm), Rb (ppm) as proxies for basic provenance of sediments during the colder and drier climates.

**Fig. 6.** Shale normalized REE patterns of bulk sediments are shown along with the possible three end members A) Basalt (Lightfoot et al. 1990), peninsular gneisses (Allen et al. 1985) and dust (Ferrat et al. 2011). B) Relative contribution to the sediments from these three end members was estimated using ternary mixing calculations. Calculations with varying end-member proportions have yielded a contribution of 50:40:10 to 1:79:20 of basalt: gneiss: dust.

**Fig. 7.** Comprehensive figure showing the variability in rainfall, temperature, weathering, dust flux and provenance of sediments in the EAS during the past 100 ka and their comparison with other Arabian sea records: sea surface temperature (SK237GC09, Saraswat et al. 2019),  $\delta^{18}\text{O}_{G. sacculifer}$  (SK117GC08, Chodankar et al. 2005) and Greenland ice core  $\delta^{18}\text{O}$  record (GISP2, Dansgaard et al. 1993). MIS1 to 5 indicate marine isotope stages; a to c indicate stadial and interstadial in MIS5; YD is Younger Dryas, LGM is the last glacial maximum and YTT is the youngest Toba tuff eruption and its traces in SK117/GC08.

**Table 1.** Descriptive statistics of selected major oxides (wt%), trace and rare earth elements (ppm), and their ratios from the present study and their comparison with Post Archean Australian Shale (PAAS), (Taylor and McLennan, 1985) and North American Shale Composite (NASC), (Gromet et al. (1984), particle size data from a PhD thesis of Chodankar (2004).

Fig. 1.

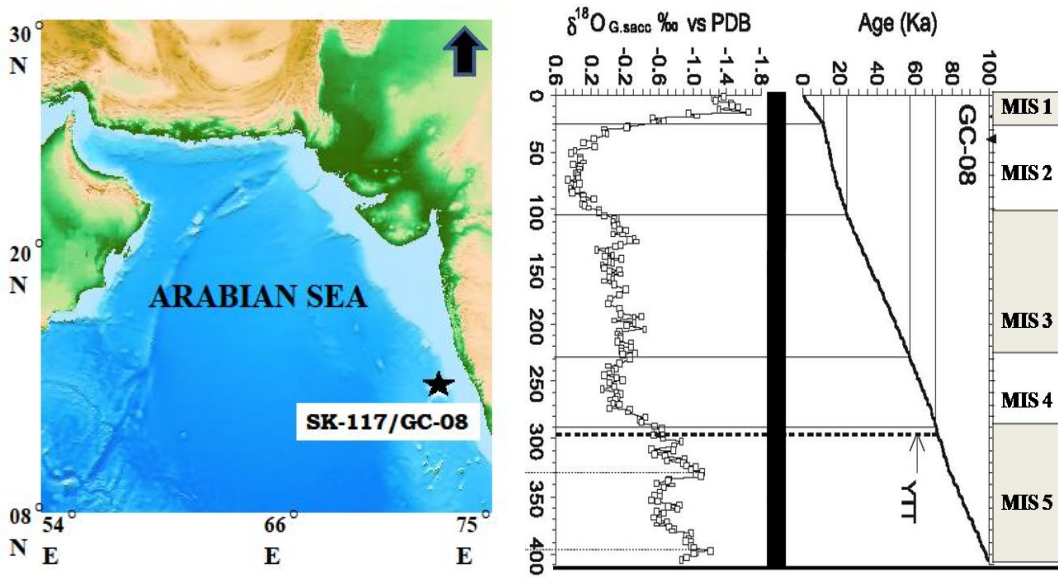


Fig. 2.

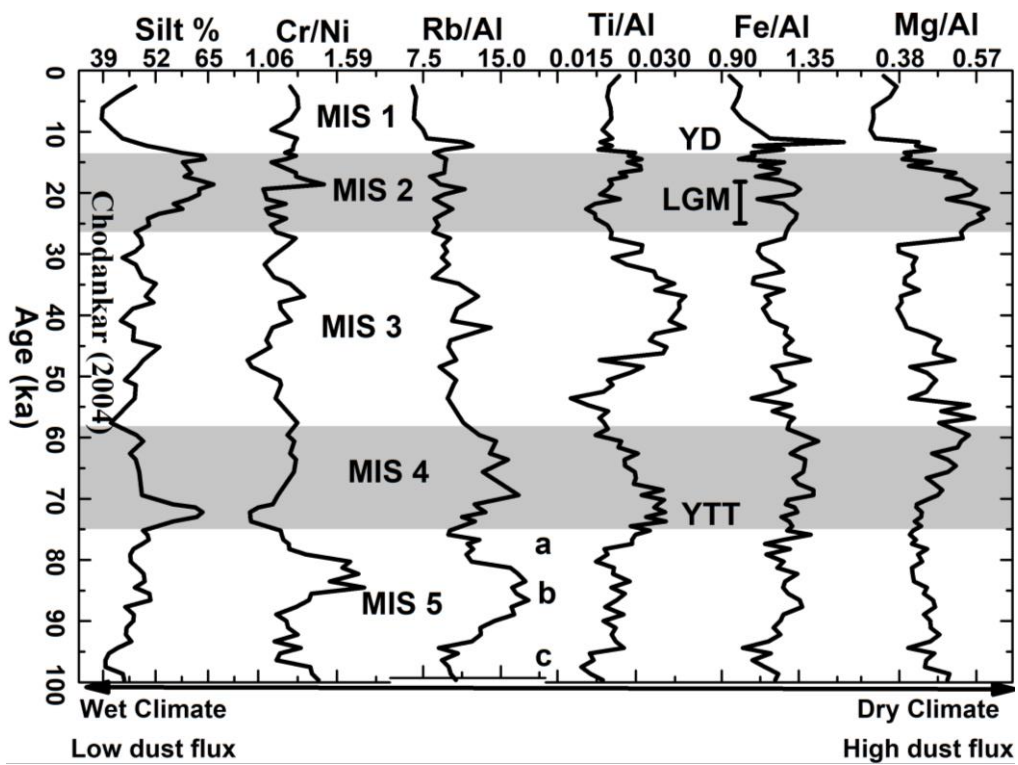


Fig. 3.

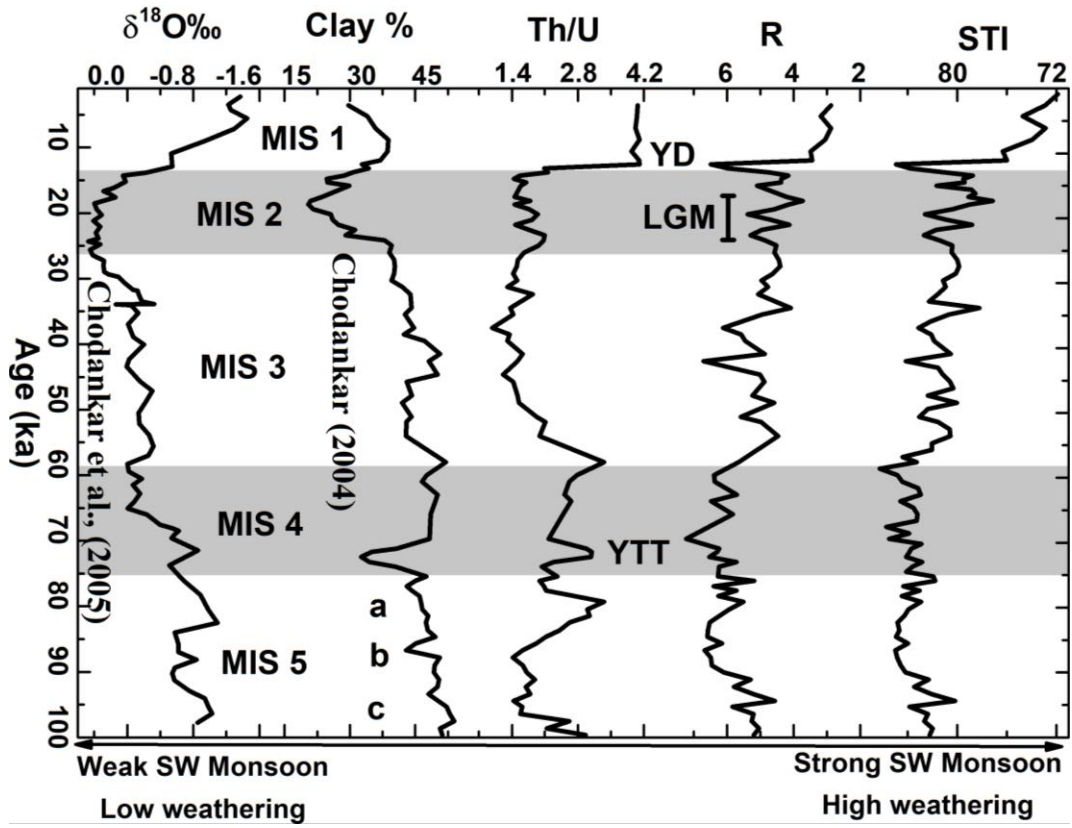


Fig. 4.

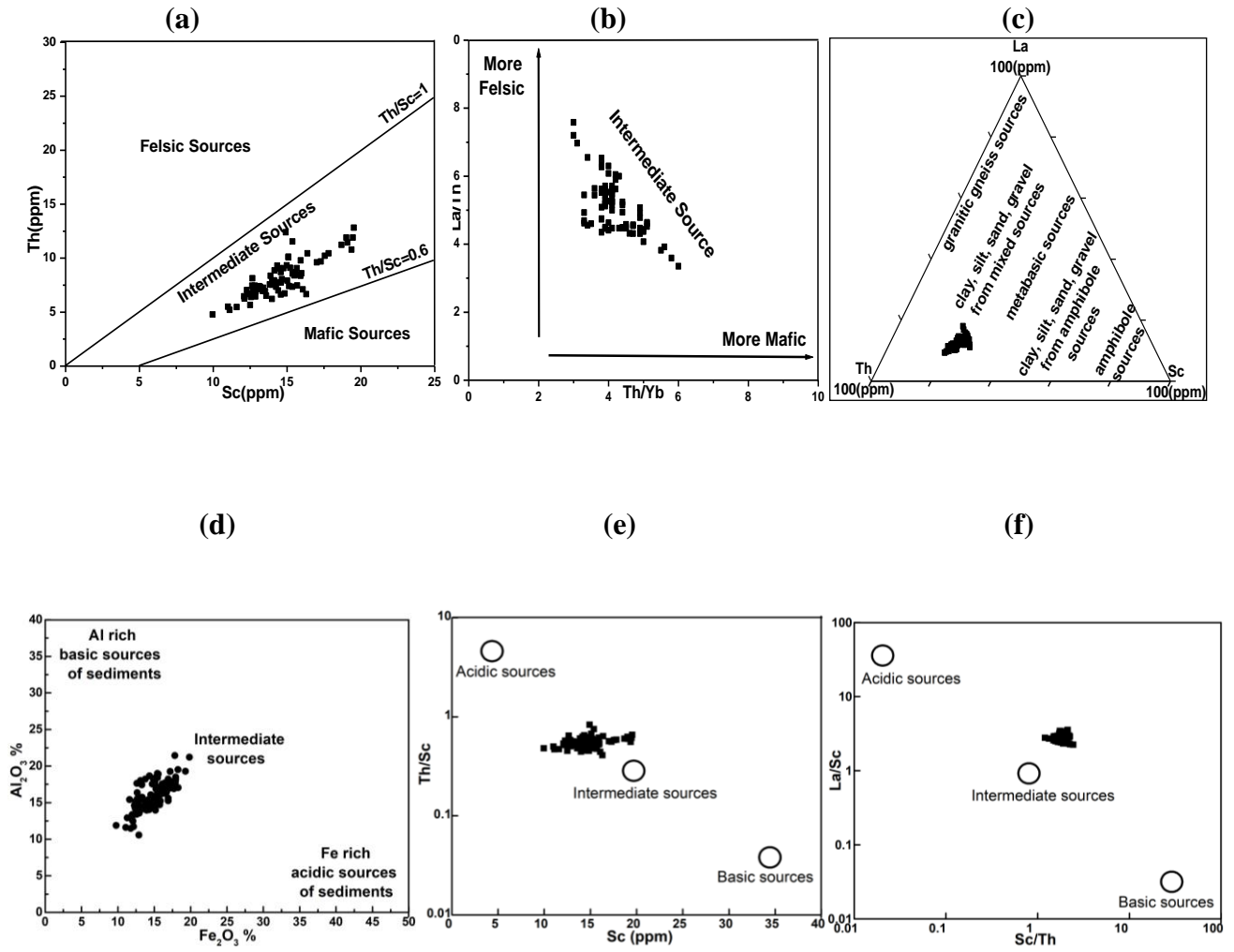


Fig. 5.

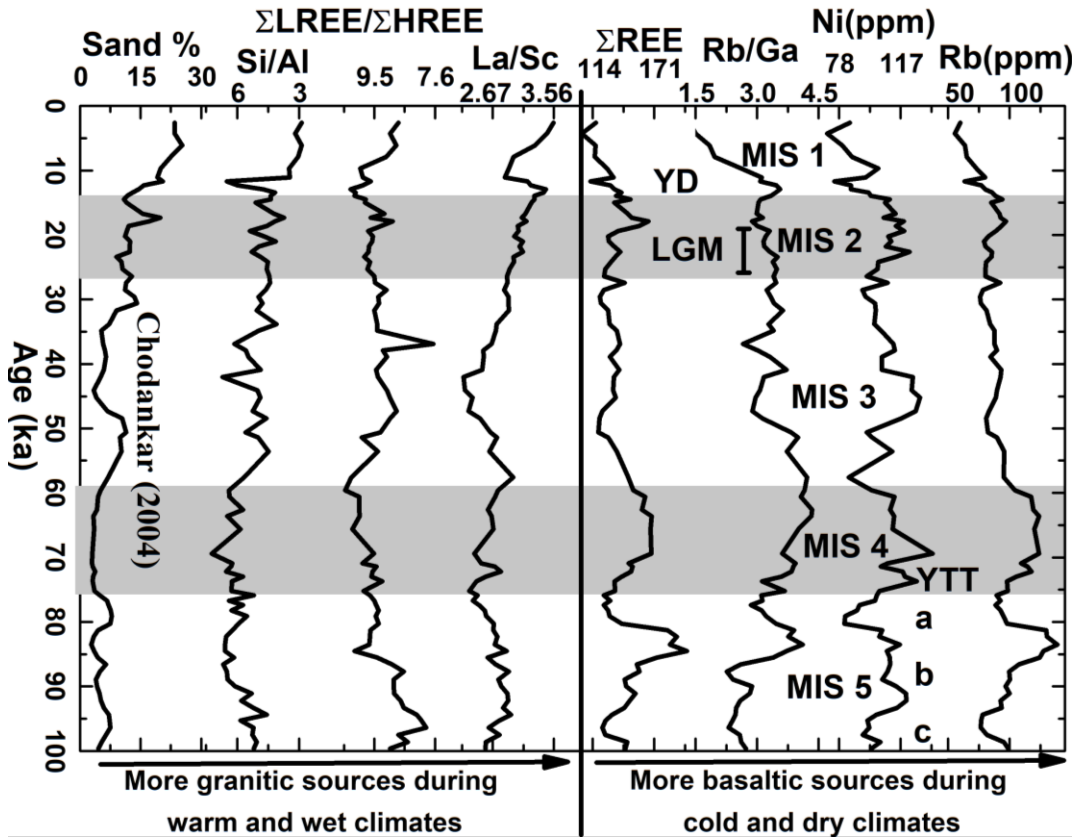




Fig. 6.

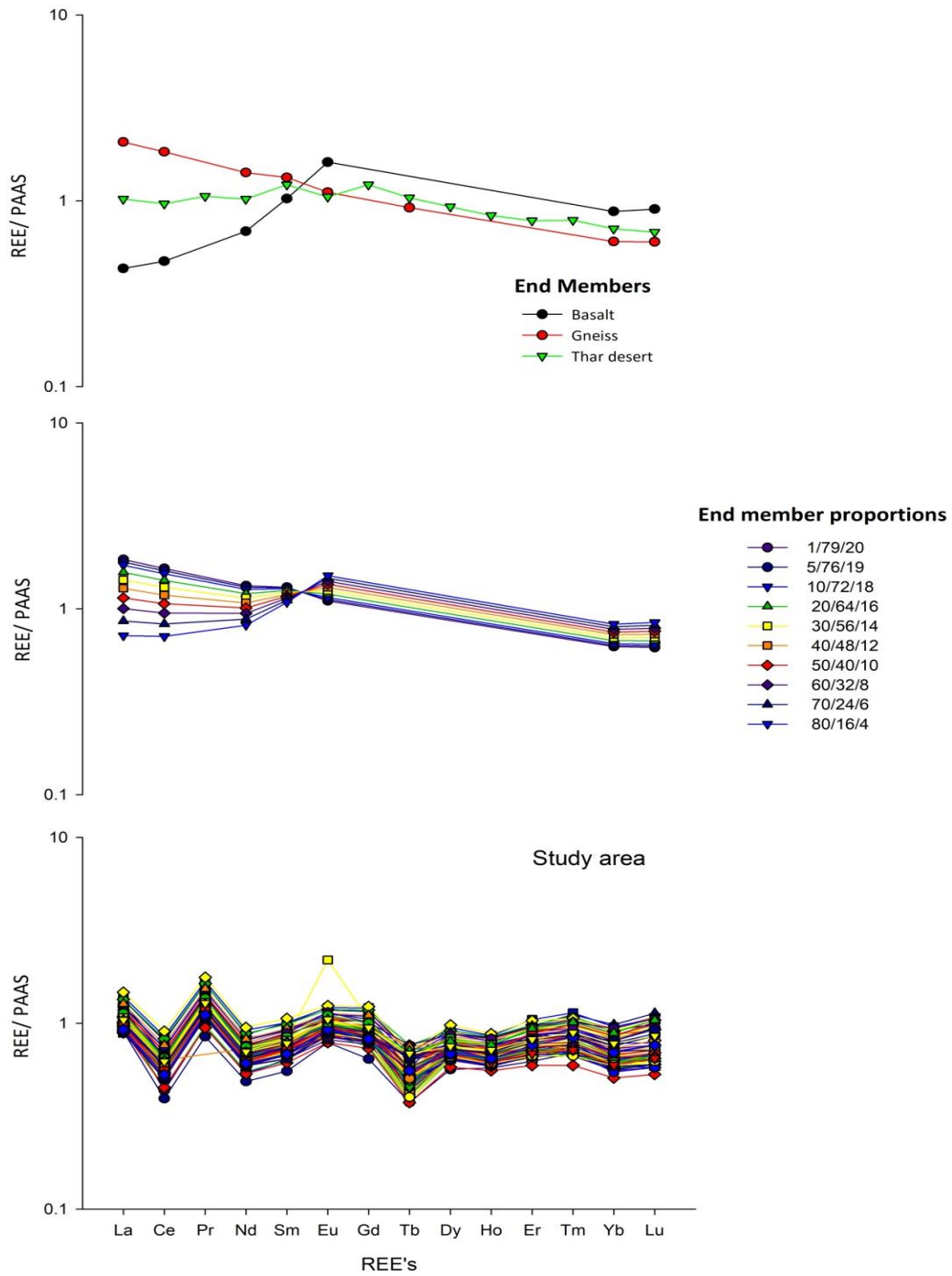


Fig.7.

