Mid-late Holocene climate variability in the Indian monsoon: Evidence from continental shelf sediments adjacent to Rushikulya river, eastern India

Ankit

A dissertation submitted for the partial fulfillment of BS-MS dual degree in Science

Indian Institute of Science Education and Research, Mohali

Certificate of Examination

This is to certify that the dissertation titled "Mid-late Holocene climate variability in the Indian monsoon: Evidence from continental shelf sediments adjacent to Rushikulya river, eastern India" submitted by Mr. Ankit (Reg. No. MS12014) for the partial fulfilment of BS-MS dual degree programme of the Institute, has been examined by the thesis committee duly appointed by the Institute. The committee finds the work done by the candidate satisfactory and recommends that the report be accepted.

Dr. Anoop Ambili
Thesis Supervisor

Dr. Baerbel Sinha

Dr. P. Balanarayan

Date: April 21 ,2017

Declaration

The work presented in this dissertation has been carried out by me under the guidance of Dr. Anoop Ambili at the Indian Institute of Science Education and Research Mohali. This work has not been submitted in part or in full for a degree, a diploma, or a fellowship to any other university or institute. Whenever contributions of others are involved, every effort is made to indicate this clearly, with due acknowledgement of collaborative research and discussions. This thesis is a bona fide record of original work done by me and all sources listed within have been detailed in the bibliography.

Ankit

Dated: April 21,2017

In my capacity as the supervisor of the candidate's project work, I certify that the above statements by the candidate are true to the best of my knowledge.

Dr. Anoop Ambili

Thesis Supervisor

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Abstract

The livelihood of approximately 40% of the world's population is dependent on Indian Summer Monsoon which is one of the largest climate systems on earth. Despite dedicated efforts, a compendious image of monsoon variability has proved evasive primarily due to the deficiency of long term high resolution records and spatial heterogeneity of monsoon precipitation. We present the results of our investigations on the radiocarbon dated core sediments from the continental shelf sediments adjacent to Rushikulya river mouth, Eastern India aimed at reconstructing paleoenvironmental changes in this climatically sensitive region. The retrieved 1.60 m long well dated core spans the past ca. 6800 cal BP. The modern spatial distribution of grain size and geochemistry of the inner-mid shelf sediments has been carried out to understand the seafloor morphology and sedimentary processes. Based on the modern investigations, the proportion of particle size (clay vs sand) and variation in elemental values (TiO_2 vs Al_2O_3) has been used to interpret the changes in terrigenous supply. The grain-size and elemental distribution data from the core sediments indicates a period of enhanced surface water runoff from 6800 to 3100 cal BP followed by a drier condition (3100 cal BP to present) suggesting weakening of monsoon. The weakening of the monsoonal strength is coeval with other records from the Indian sub-continent and suggests response of Indian monsoon to changing solar insolation during late Holocene.

Chapter 1

Introduction

1.1 Objectives

1.2 Study Area

1.3 Methodology

Introduction

The Indian subcontinent receives most of its precipitation under the influence of the Indian Summer Monsoon (ISM). The word monsoon is believed to be derived from the Arabic word 'mausim' and is explicated as the seasonal volte-face of the wind systems influenced by the annual variation of incoming solar radiation (Agnihotri et al., 2002; Gadgil, 2003). The domination of ISM over the Indian subcontinent is the propelling force behind the agricultural productivity which directly contributes to the total economy of the country (agriculture contributed 14% of total GDP of India during 2013 to 2014, source: Ministry of Agriculture, India).

ISM variability, is considered to have a significant impact on the economy as well as on the rural structure (23% of world's population) of Indian subcontinent (World bank report-2013). The magnitude and frequency of drought and floods (extreme events) has increased in recent decades (Goswami et al., 2006; Malik et al., 2011) and analysis of meteorological data also confirms an increase in spatial heterogeneity of rainfall extremes (Ghosh et al., 2011). Therefore, its socioeconomic importance is clearly understood by either drought in Jharkhand, Bihar and NE India in 2013 (Indian Meteorological Department report, 2013) or the recent floods in Kashmir (2014), Uttarakhand (2013) and Mumbai (2005) (Singh et al., 2014). However, all such records are based on instrumental records covering only a few decades. The understanding of the past and present climatic variability in the Indian monsoon realm is critical to produce better future climate forecast models. However, the available long term continental palaeomonsoon record has limited geographical coverage with majority of research carried out in NW India (e.g., Prasad et al., 1997; Enzel et al., 1999; Prasad and Enzel, 2006; Prasad et al., 2014a; Raj et al., 2015; Amekawa et al., 2016) and Himalayan region (Phadtare, 2000; Demske et al., 2009; Wünnemann et al., 2010; Anoop et al., 2013a; Leipe et al., 2014; Rawat et al., 2015; Mishra et al., 2015; Kotlia et al., 2015). To understand the variability of monsoon rainfall and the physical mechanisms inherit in it, a large dataset covering longer time scales is required from various climate sensitive regimes across the Indian subcontinent. Barring a few exceptions (e.g., Khandelwal and Gupta, 1999; Khandelwal et al., 2008) limited to palynological investigations from lacustrine sediments, the Holocene climate changes are yet to be evaluated from eastern India.

The sedimentary bodies on continental shelves have been widely used to infer the sea level fluctuations (Milliman and Emery, 1968; Gingele et al., 2004; Zhao et al., 2008; Yoo et al., 2014) and variations in terrigenous sediment input (Mendes et al., 2010; Nizou et al., 2010; Zheng et al., 2010; Rosa et al., 2011; Wang et al., 2014; Perez et al., 2016; Tu et al., 2016) interpreted in terms of past environmental changes. The terrigenous coarse- and fine-grained sediments supply to the continental shelf is mostly controlled by fluvial discharge (Prins et al., 2000; Briceño-Zuluaga et al., 2016). The paleoclimate records from continental shelves provide critical information connecting continental with deep marine records (González-Álvarez et al., 2005). However, paleoclimate records from continental shelf areas of the Indian subcontinent are very scarce. In this study, we present a continuous record of the mid-late Holocene climate obtained from a 1.60 m long sediment core (VC-04) retrieved from the continental shelf sediments adjacent to the Rushikulya river mouth (Fig. 1). The understanding of modern sedimentation patterns in the continental shelf has been used to refine paleoenvironmental interpretations and gain a long-term perspective on environmental variability. The elemental and grain-size distributions supplemented with sedimentation rate calculations obtained from the sediment core are used to quantify the paleoclimatic changes.

1.1 Objectives

The objectives of this present study are:

- To identify suitable proxies for paleoenvironment reconstruction by establishing the linkages between contemporary processes and sediment distribution in the modern Rushikulya river mouth and adjacent continental shelf sediments.
- Use of climate sensitive proxies to reconstruct paleoenvironmental conditions during mid-late Holocene.
- Regional comparison of the climate data to understand the physical mechanisms that control the spatial temporal variability in the monsoon precipitation in the region.

1.2 Study Area

1.2.1. Regional setting

The investigated region (Fig. 1.) includes inner to mid continental shelf of Rushikulya river mouth extends between 19°11.9′-19°23.4′N and 85°00.6′-85°13.9′E covering an area of 245 km2. The Rushikulya river emerges from the slopes of Araha bity and Kutrabor hills of Eastern Ghats with a drainage area of 82,100 km2 running for approximately 165 km before meeting the Bay of Bengal at Puruna Bandha of Chhatarpur region (Jain et al., 2007). The average annual water discharge of the Rushikulya river is 1800 million m3 with discharge highly seasonal due to the monsoonal conditions (Panigrahy et al., 1999).

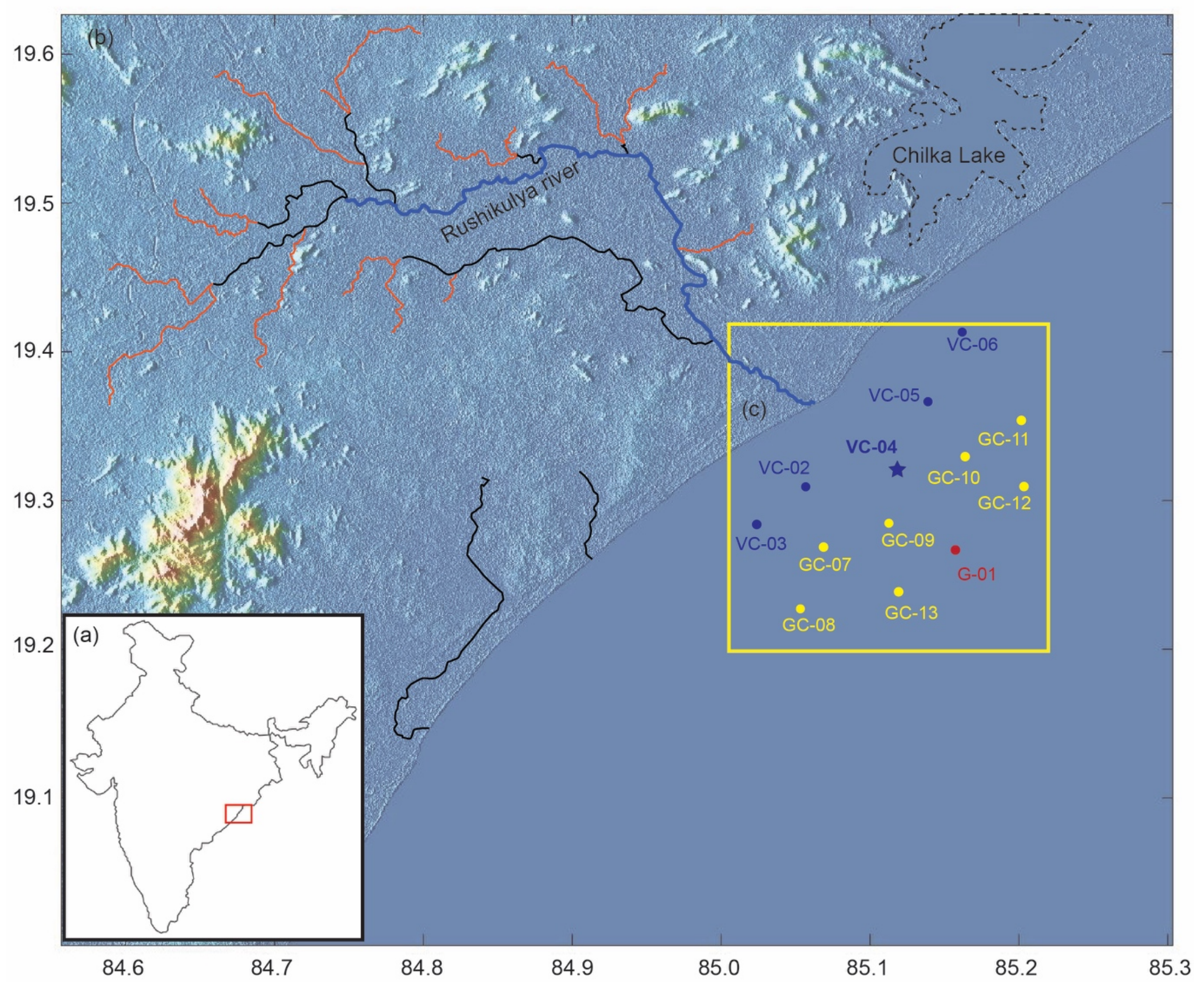

Fig. 1. Map showing study area and location of the retrieved core (VC-04) for paleoclimate reconstruction. The blue, yellow and red circles denote the location of vibro, gravity and grab samples used to understand the modern continental shelf dynamics.

1.2.2. Regional climate and geomorphology

The climate over the east coast of India is mainly tropical in nature governed by the SW monsoon between June and September, and NE monsoon during October to December. The study area experiences an average annual rainfall of 1200 mm with SW monsoon accounts for 80% of the total precipitation (Jain et al., 2007). The maximum and minimum temperatures recorded in the region are 45 °C and 12 °C respectively (Jain et al., 2007). The wind force over the region is fairly high during the period of southwestern monsoon and the whole of Odisha coast is vulnerable to frequent cyclonic storms during October–November (Mascarenhas, 2004). The high-energy waves from the south and the southeast during the monsoon season generate the longshore current that heads to- wards north and is reversed during winter months due to prevailing northeasterly waves generating littoral current that runs towards south (Mishra et al., 2001). The coastal region of the study area is characterized by major geomorphic features like beach ridges, sand spits, and barrier spits (Markose et al., 2016). The coastline adjoining the study area is straight trending 40°–50° (Varghese et al., 2015). The continental shelf in this area is smooth and gently sloping as inferred from the smooth curves of the isobaths running more or less parallel to the coastline (Varghese et al., 2015).

1.2.3. Regional geology

The mineral assemblages over the study region are derived from Eastern Ghats Mobile belt (EGMB) (Bhattacharya and Sengupta, 1994). The litho units of EGMB are divided longitudinally into four major litho zones comprising of eastern khondalite zone (EKZ), charnockite migmatite zone (CKZ), western khondalite zone (WKZ) and western charnockite zone (WCZ) (Ramakrishnan et al., 1998). The sediments deposition over beach of southern coast Odisha, Chhatarpur and Rushikulya area is known for its mineral reserves. The minerals which are economically important present in the region include ilmenite, garnet, sillimanite and rutile (Rao et al., 2001). The coastal charnockite provide main sources for garnet as beach placer, whereas garnet-quartz and sillimanite garnet quartz schists serve as important sources for rutile (Rao and Misra, 2009). These minerals over study area are carried out in form of detrital grains by seasonal (monsoon) rivers and further redistributed by marine longshore current (Rao, 1957).

1.3 Methodology

1.3.1. Sampling

The sediments cores from the inner-mid continental shelf adjacent to the Rushikulya river mouth were retrieved using 5 m long Nino's type gravity and vibro corer from the desired locations (Fig. 1). The uppermost 0–5 cm of vibro and gravity cores has been used to understand the modern sedimentation processes along the Rushikulya river continental shelf. Additionally, grab samples also have been collected using medium sized Van Veen/Peterson grab with an approximate penetration up to 25 cm. All the gravity and vibro core samples collected in PVC liner were split and logged visually as per variation in sediment color, texture, compaction and relative proportion of biogenic and terrigenous constituents. Immediately after collection, samples were kept frozen till brought to lab for further studies. The down core variation of major oxides and grain size distribution is studied for the ca. 160 cm long vibro core VC-04 collected (42.8 m water depth) adjacent to the Rushikulya river mouth. The elemental and grain size measurements were carried out at 10 cm resolution.

1.3.2. Analytical methods

1.3.2.1. Geochemistry

The sediment samples for XRD analyses were crushed into a fine-grained powder using a diamond mortar followed by wet grinding. The pestle was put on a glass sample holder that was placed on the sample rotation stage (120 rpm) of the instrument. The analysis was carried out on a Rigaku Ultima IV diffractometer equipped with a 3-kw sealed tube Cu Kα X-ray radiation (generator power settings, 40 kV and 40 mA) and a DTex Ultra detector using parallel beam geometry. The data were collected over an angle range of 5°–90° with a scanning speed of 5° per minute with a 0.02° step.

For elemental analysis, approximate 20 gm of air dried subsamples were desalinized thrice using distilled water before chemical treatment. The desalinized samples were crushed in an agate mortar until entire quantity passed through 100–120 ASTM mesh size. The powdered samples were digested with a mixture of concentrated HF–HNO3–HClO4 following the method of Zhang and Liu, 2002. A fraction (0.25 gm) from each subsample was treated with Aqua Regia followed by treatment with Hydrofluoric acid (HF) to remove the silicates. Perchloric acid was used to remove the organic content in the sediments before the samples were made up to a 100-ml solution using the dilute nitric acid. The samples in the nitric medium fed to a Varian 720-ES Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) for major oxide analysis.

P2O5 is determined by color development with Ammonium Molybdate Ammonium Meta Vanadate solutions with subsequent measurement on Spectrophotometer at 465 nm. Precision for major oxides is generally better than 2%.

1.3.2.2. Grain size analysis

The sample pre-treatment for grain-size analysis includes organic matter removal by addition of H2O2 followed by dispersal of aggregates using ammonia. The sediment samples were then washed with distilled water and oven-dried at 45 °C. In the present case, grain size distribution (GSD) of the samples was studied using a combination of sieve method for sand dominated sediments and pipette analysis for silt and clay rich sediments (Folk, 1980; McCave and Syvitski, 1991; Miall, 2006).

1.3.3. Chronology

The age model for VC-04 is obtained based on the four AMS (accelerator mass spectrometry) 14C dates of bulk organic sediments (Table 1). The 14C dating points were chosen according to changes in the lithology and elemental values. Radiocarbon dating was carried out at Radio Chronology lab in University of Laval, Canada. The obtained 14C dates were then converted from conventional 14C ages into the calendar ages using Ox Cal 4.1 software (Ramsey, 2001, 2009) with the IntCal13 calibration curve (Reimer et al., 2013). The age-depth relationship was modeled using linear interpolation between adjacent radiocarbon dates.

1.3.4. Data analysis

Principal component analysis (PCA) was carried out for geochemical concentrations of the surface and core sediments to explore element associations and their origins. PCA analysis is a multivariate technique which explains the major variations within dataset by generating factors which represent cluster of interrelated variables (Reid and Spencer, 2009). The analysis enables a reduction in the dimensionality of a dataset by means of small number of components (Loska and Wiechula, 2003). The principal components (PC) should account for 75% of the total variance (Morrison, 1967). The varimax rotations of the generated PCs are performed to maximize the variation in the data for easy interpretation (Juahir et al., 2011; Sappa et al., 2014). However, the obtained PCs of the geochemical data are readily interpreted; therefore, varimax rotation has not been applied. PCA analysis was performed using XLSTAT, an add-in software package for Microsoft Excel (Addinsoft Corp.).

Chapter 2

Results and Discussion

2.1 Results

2.2 Conclusion and Discussion

2.1 Results

2.1.1. Geochemistry and grain size analysis of surface sediments

The XRD investigations of the modern sediments revealed that the dominant siliciclastic minerals constitute quartz, biotite, orthoclase, rutile, sillimanite, wollastonite and muscovite (Table 1) The aragonite and kaolinite represent dominant carbonate and clay mineral phases respectively.

Minerals	Reported Data	Observed Data	References
Aragonite	3.3957, 4.2115, 1.9770	3.4080, 4.2168, 1.9815	American mineralogist 56 (1971) 758-767
Biotite	10.00, 3.33, 2.7080	10.0181, 3.3370, 2.6971	American mineralogist 24 (1939) 729-771
Diopside	2.9838, 2.8884, 2.5284	2.9902, 2.8913, 2.5233	American mineralogist 58 (1973) 594-618
Kaolinite	7.1526, 4.2579, 2.3480	7.1513, 4.2618, 2.3493	Zeitschrift fur kristallographie 83 (1932) 75-88
Magnetite	2.5314, 1.4842, 1.6158	2.5506, 1.4959, 1.6277	American mineralogist 69 (1984) 754-770
Orthoclase	3.4675, 3.7830, 3.0013	3.4666, 3.7796, 2.9944	American mineralogist 68 (1983) 122-124
Quartz	4.2574, 3.3446, 1.8184	4.2541, 3.3428, 1.8173	American mineralogist 65 (1980) 920-930
Rutile	3.2435, 2.4836, 1.6845	3.2411, 2.4837, 1.6849	American mineralogist 80 (1995) 448-453
Sillimanite	2.2061, 3.3656, 2.5431	2.2108, 3.3641, 2.5444	American mineralogist 64 (1979) 573-586
Wollastonite	2.9716, 3.3133, 3.5145	2.9638, 3.3237, 3.5274	American mineralogist 63 (1978) 274-288
Muscovite	3.3231, 9.9693, 2.5757	3.3197, 9.9580, 2.5605	American mineralogist 83 (1998) 775-785

Table 1: XRD investigation for the surface sediments.

The PCA analysis of the surface sediments extracts two principle components axis explaining 79.7% of the total variance (F1- 55.5%; F2- 24.2%) (Fig. 2a). The important characteristic of the PCA analysis is the existence of two clusters for the ‘terrigenous’ elements that are anti-correlated (Fig. 2a) (Table 2). The F1 shows high correlation with the elements Fe_2O_3, Al_2O_3, K_2O and Na_2O, whereas F2 suggests its close relation with the elements TiO_2 and MnO (Fig. 2a). The elemental concentrations of CaO shows low positive loadings in F1 and F2 axis attributed to the contribution from dual sources- calcium bearing detrital minerals and authigenic aragonite shells present within the surface sediments. Based on the PCA results, Al_2O_3 and TiO_2 have been taken as representative elements to understand the modern dynamics in the inner to mid continental shelf. The trend in the elemental distribution of Al_2O_3 display high values towards the deeper part of the continental shelf, whereas TiO_2 shows higher values close to the shore region (Fig. 3a and 3b).

The grain size exhibit specific variability trends in their inner-mid shelf distribution along the study area (Fig. 3c–e). The grain size distribution of the shelf sediments shows high variability characterized by 2–97% of sand, 1–93% of silt and 1–21% of clay. The spatial distribution of the grain size in the surface sediments shows an increasing trend of finer fractions (e.g. silt and clay) with increasing water depth, whereas coarser fraction (e.g. sand) shows a decreasing trend (Fig. 3c–e).

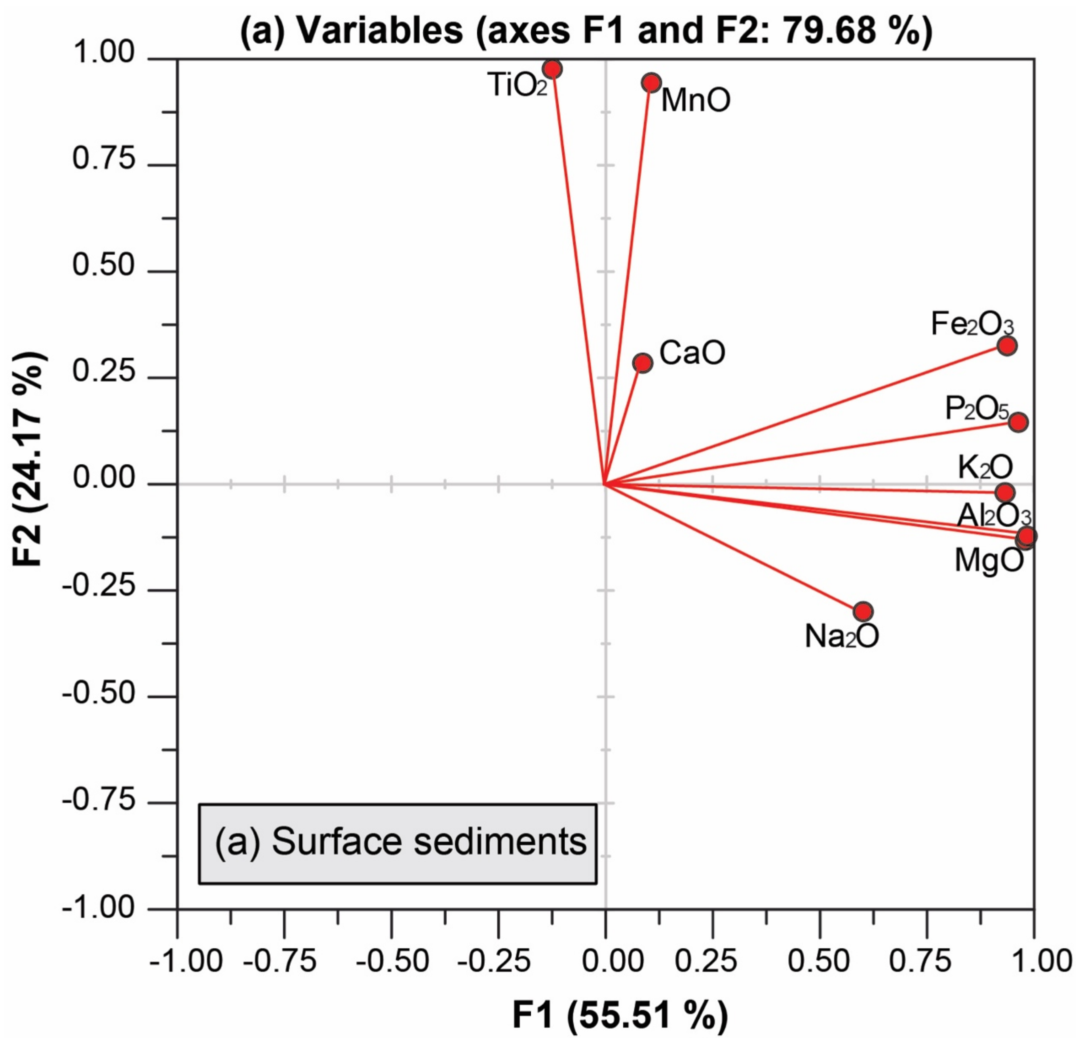

Fig. 2a. Biplot of F1 axis vs. F2 axis based on the principal component analysis of geochemical parameters from continental shelf surface sediments.

Variables	Al_2O_3	Fe_2O_3	MgO	CaO	MnO	Na_2O	K_2O	TiO_2	P_2O_5
Al_2O_3	**1**	**0.892**	**0.997**	0.052	-0.035	**0.537**	**0.882**	-0.272	**0.953**
Fe_2O_3	**0.892**	**1**	**0.896**	0.151	0.403	0.404	**0.838**	0.189	**0.969**
MgO	**0.997**	**0.896**	**1**	0.059	-0.023	**0.554**	**0.888**	-0.259	**0.953**
CaO	0.052	0.151	0.059	**1**	0.018	-0.223	0.102	0.198	0.162
MnO	-0.035	0.403	-0.023	0.018	**1**	-0.078	0.070	**0.935**	0.210
Na_2O	**0.537**	0.404	**0.554**	-0.223	-0.078	**1**	**0.594**	-0.261	0.408
K_2O	**0.882**	**0.838**	**0.888**	0.102	0.070	**0.594**	**1**	-0.114	**0.845**
TiO_2	-0.272	0.189	-0.259	0.198	**0.935**	-0.261	-0.114	**1**	-0.008
P_2O_5	**0.953**	**0.969**	**0.953**	0.162	0.210	0.408	**0.845**	-0.008	**1**

Table 2: Pearson correlation coefficient matrix (significant correlations denoted in bold) for the geochemical parameters of the inner-mid shelf surface sediments

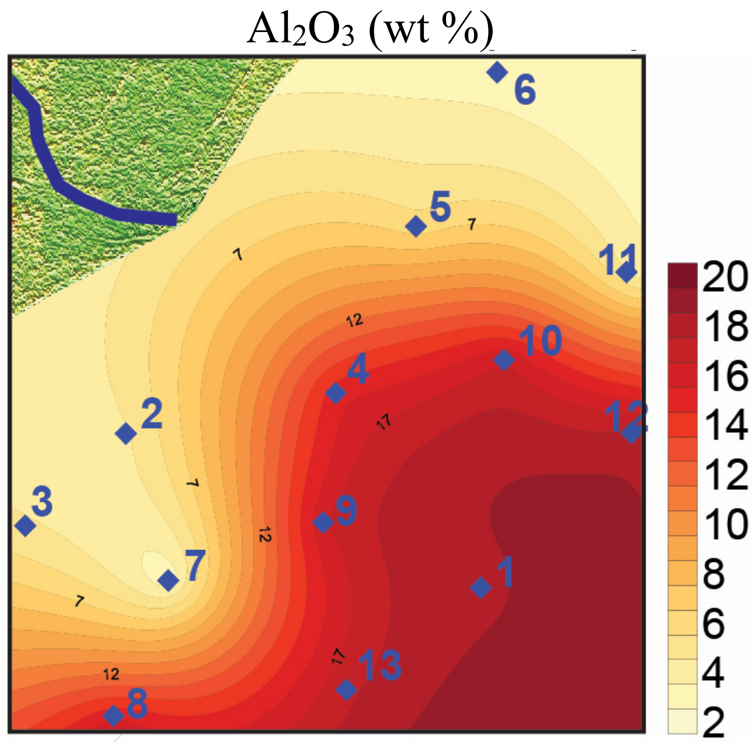

Fig. 3a. Spatial distribution of Al_2O_3 (wt%) in the inner-mid continental shelf sediments.

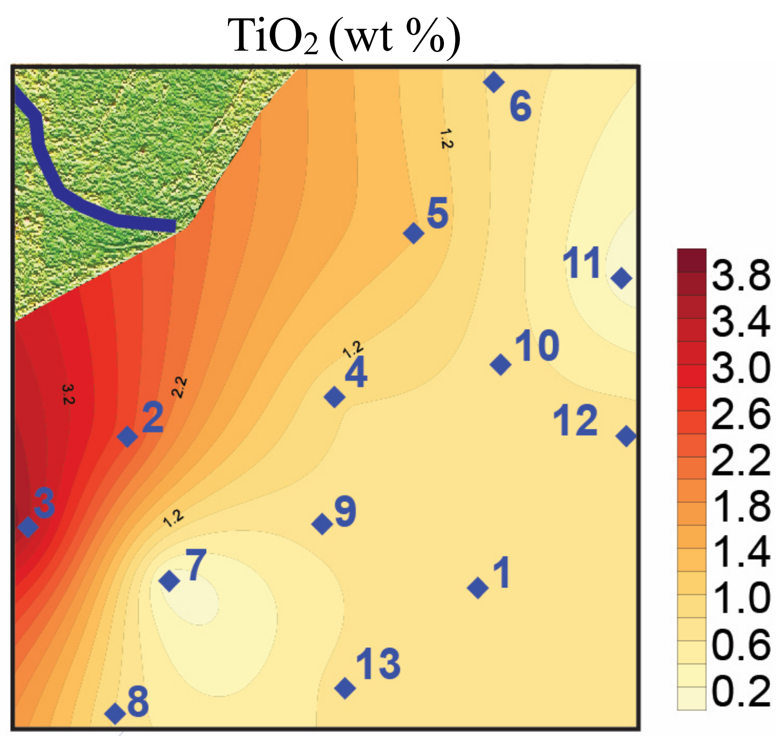

Fig. 3b. Spatial distribution of TiO_2 (wt %) of the inner-mid continental shelf sediments.

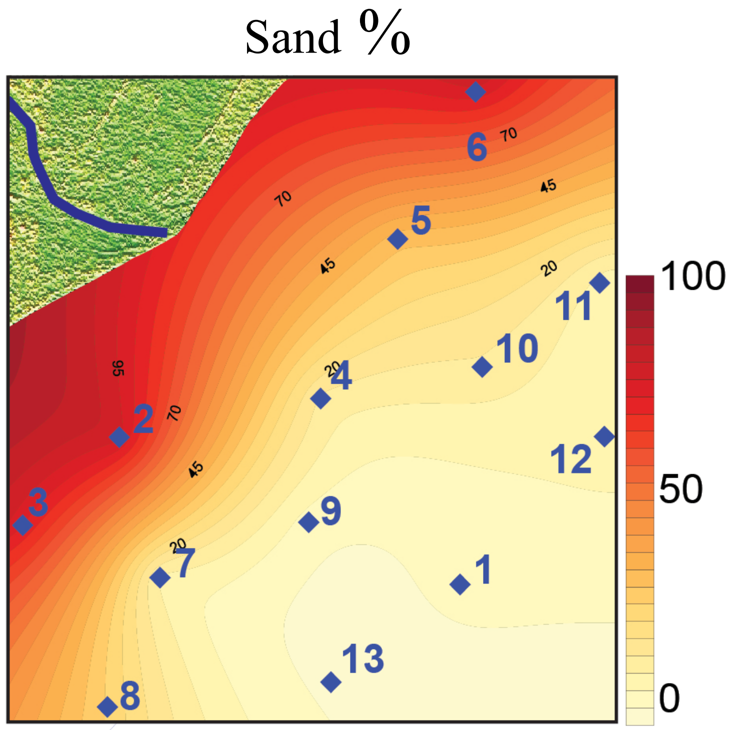

Fig. 3c. Spatial distribution of Sand (%) in inner-mid continental shelf sediments.

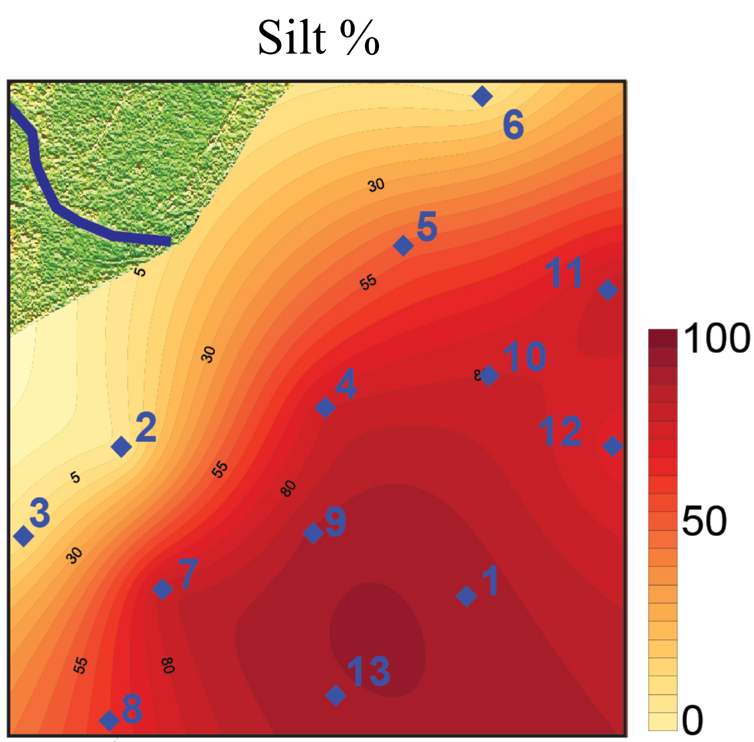

Fig. 3d. spatial distribution of Silt (%) in inner-mid continental shelf sediments.

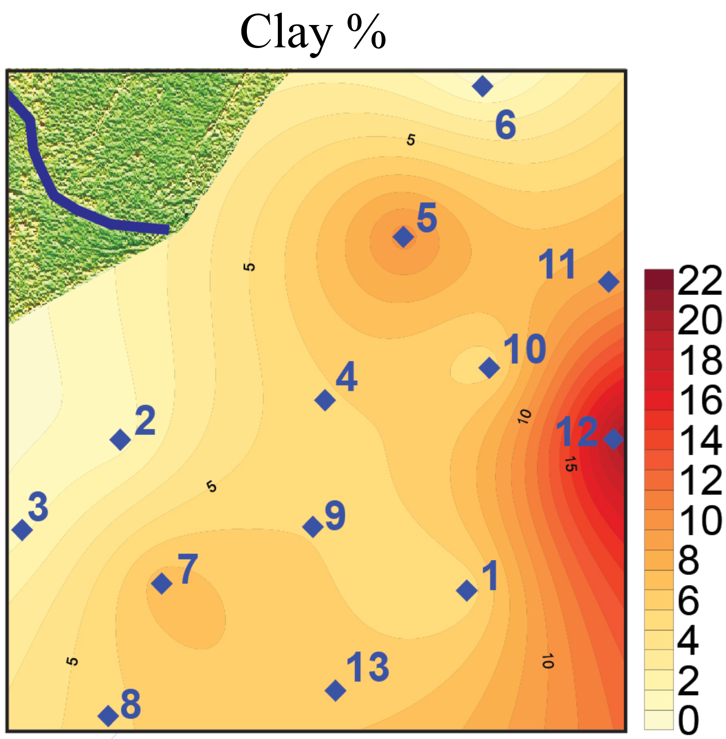

Fig. 3e. Spatial distribution of clay in inner-mid continental shelf sediments.

2.2. Core data (VC-04) from continental shelves

2.2.1. Lithology

Based on the geochemistry and visual observation, lithology of the core sediments (VC-04) shows two major distinct units. The unit I (0–0.72 m) comprises of olive gray loose silty clay with forams, whereas unit II (0.72–1.60 m) consists of very fine sand with silt and frequent shell fragments.

2.2.2. Chronology

The uncertainty associated with 14C ages of the bulk organic matter (OM) derived from the near shore marine environment involves incorporation of old plant-derived terrigenous organic carbon resulting in anomalously old 14C ages and age reversals (Eglinton et al., 1997; Zheng et al., 2002). However, the modern age of the bulk OM from the top of the sediment cores provides evidence for absence of possible contamination. Additionally, stratigraphically consistent 14C dates further indicate the reliability of the 14C dates (Table 3). The sedimentation rates of the VC -04 display elevated sedimentation rate (0.26 mm/yr) in the lower part (160-70 cm) of the core, whereas in the upper part (70-0 cm) the sedimentation rate was low and stable (average = 0.20 mm/yr.) (Fig. 4a).

No	Depth (cm)	Lab No.	Age (pMC*/^{14}C)	Age (cal yr BP) (1σ)
RS-5	0	ULA-6259	112.73 ± 0.18*	Modern
RS-6	15	ULA-6260	880 ± 15	788 ± 43
RS-7	65	ULA-6261	2975 ± 15	3139 ± 51
RS-8	160	ULA-6262	5980 ± 20	6816 ± 36

Table 3: AMS radiocarbon dates for core VC-04.

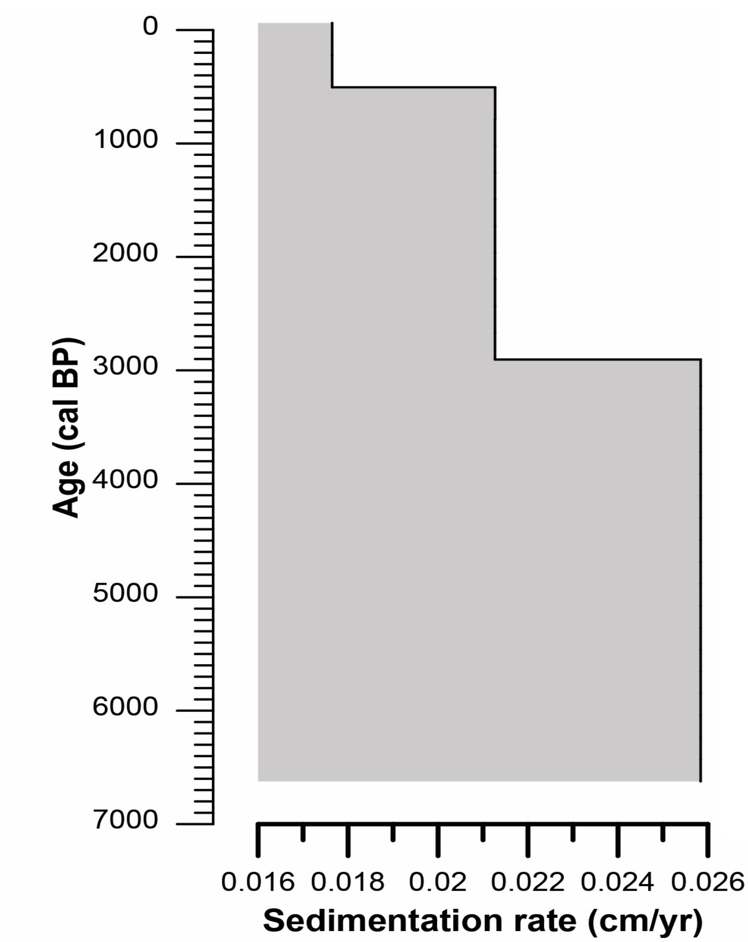

Fig. 4a. Temporal variation in sedimentation rate

2.2.3. Geochemical and grain size data of VC-04

The principal component analysis of the core sediments (VC-04) extracted two principal components that account for 92.98% of the total variance. The first axis (F1) explains 77.21% of the total variance, whereas the second PCA axis (F2) explains 15.77% of the total variance (Fig. 2b). The first axis (F1) shows high positive factor loadings for Al_2O_3 –Fe_2O_3-K_2O-Na_2O, whereas the second axis (F2) shows high positive factors loadings for TiO_2. The PCA analysis of core sediment (VC-04) reveals similarities with the modern shelf distribution showing anti-correlation of TiO_2 with other detrital elements (Al_2O_3 –Fe_2O_3-K_2O-Na_2O). The Al_2O_3 and TiO_2 of the core sediments range from 4.06 to 16.15% and 0.46–1.81% respectively. During 6800 to 3100 cal BP the core shows a low concentration of, Al_2O_3 whereas the upper part (3100 cal BP to present) display high and stable contribution of Al_2O_3 (Fig. 4b). The core VC-04 shows a rather high TiO_2 from 6800 to 3100 cal BP, and relatively low values from 3100 cal BP to present (Fig. 4b).

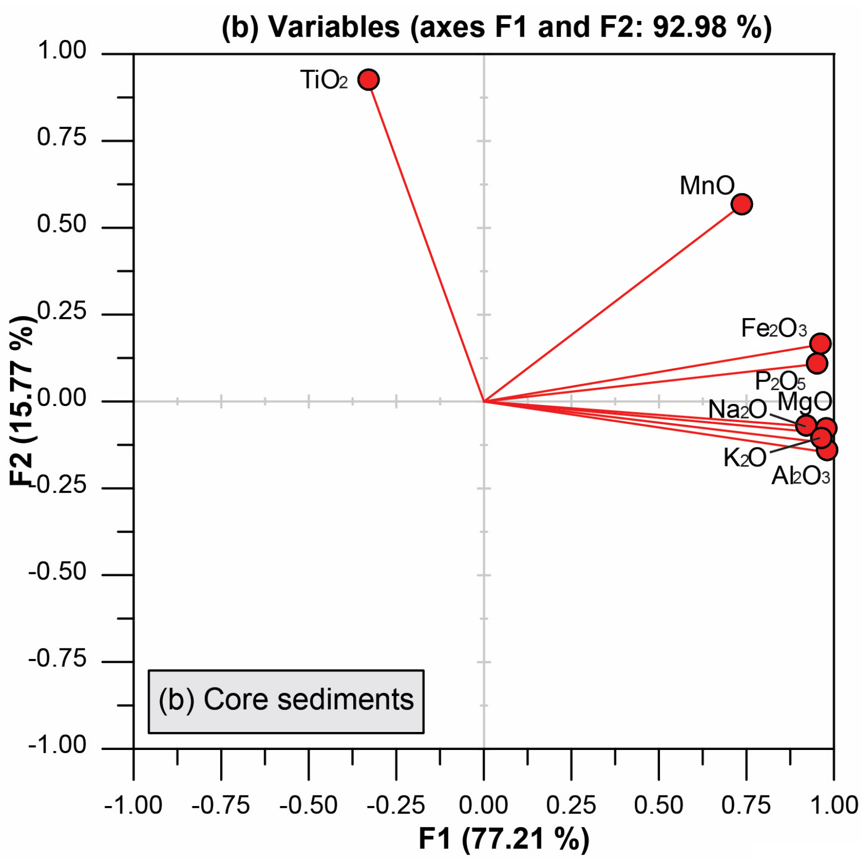

Fig. 2b. Biplot of F1 axis vs. F2 axis based on the principal component analysis of geochemical parameters from core sediments (VC-04).

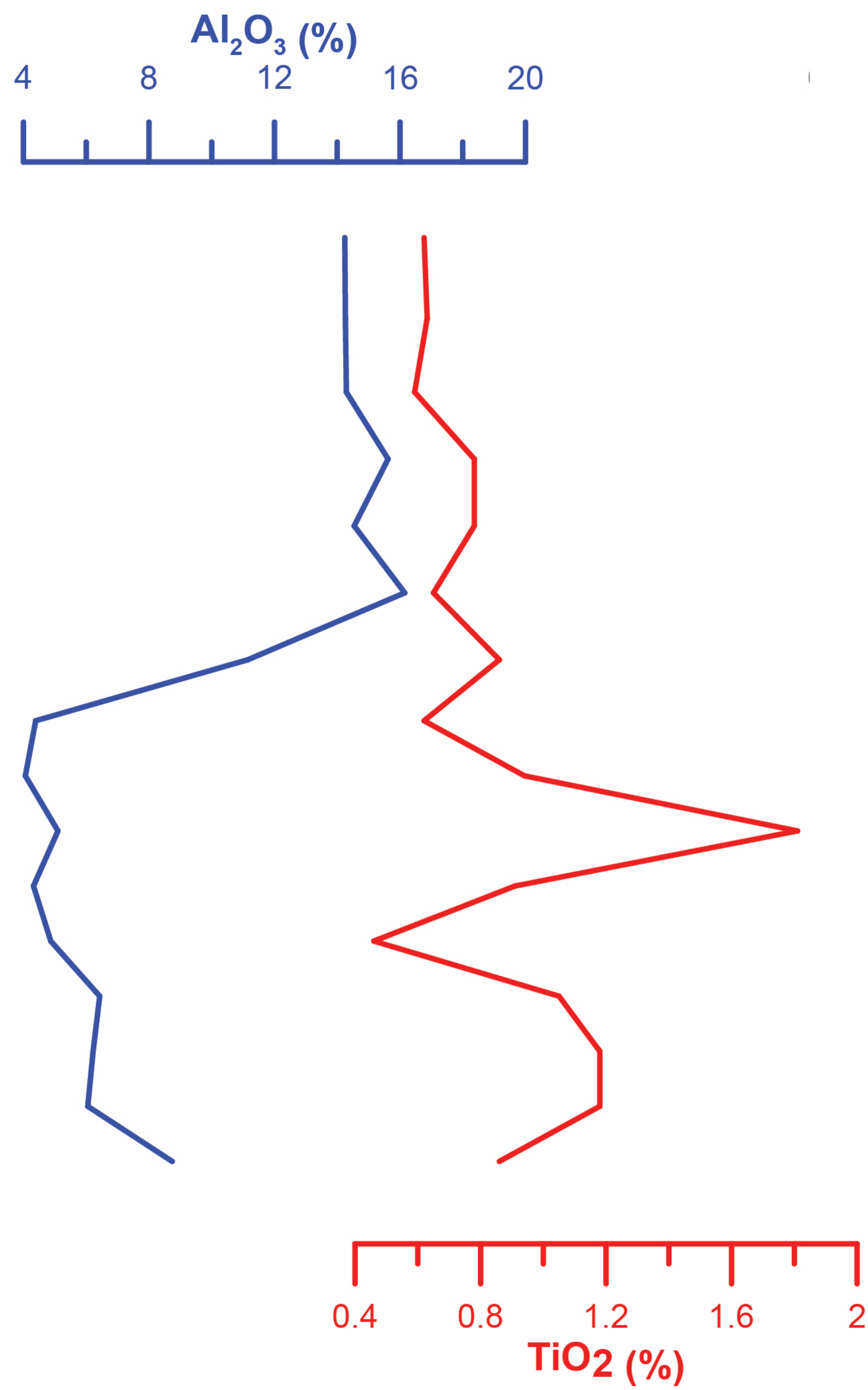

Fig. 4b. Temporal variation in geochemical data (Al_2O_3 and TiO_2) of core VC-04.

The particle size data for the core sediments shows fluctuations of 5–96%, 4–57% and 0–46% for sand, silt and clay respectively. The grain-size data of the VC-04 shows two phases of grain size distribution, coarser sand fraction (average = 94.5%) between 6800 and 3100 cal BP and finer clay and silt sediments (average = 92.5%) from 3100 cal BP to present (Fig. 4c).

Fig. 4c. Temporal variation in grain size data of core VC-04.

2.2 Conclusion and Discussion

2.2.1. Modern proxy development

2.2.1.1. Grain size distribution

The sediment distribution patterns in the continental shelves are mostly controlled by type, proximity of the sediment sources and prevailing coastal conditions (e.g., Rosa et al., 2011). Grain size is mostly dependent on the process of weathering, erosion, transport, and sedimentation rate (Hjulstrom, 1935, 1939; Visher, 1969). In the study area, the modern sedimentation pattern follows a classical nature of sedimentation i.e. coarser size sediments deposited near shore reflecting high energy flow, while the finer sediments toward the pelagic depth reflecting low energy flow.

2.2.1.2. Geochemical characterization of the surface sediments

The relation between TiO_2 and Al_2O_3 are used to investigate the variation in detrital input, rainfall intensity and runoff contribution from the catchment (Minyuk et al., 2013), assuming that the Ti and Al both are conservative in nature during the weathering process (Boës et al., 2011). However, in the sediment from the Rushikulya River, there is poor correlation between Al_2O_3 and TiO_2 ($r = -0.27$) suggesting that both are either controlled by (i) grain size variability or (ii) having a different source of sediments. Fig. 3a and 3e shows that the Al_2O_3 concentration is highest at the deepest part of the study area following the trend of clay size grain distribution. However, TiO_2 is dominant at the shallow part of the shelf and showing high correlation with sand suggesting its association with the coarser grain size sediments.

The surface sediments from the continental shelf show a high correlation between Al_2O_3 and silt ($r = 0.59$), K_2O ($r = 0.89$), Fe_2O_3 ($r = 0.89$) and MgO ($r = 1.00$). The close association between these elements may suggest the contribution of mica group of minerals. In addition, the geology of the catchment shows dominance of granitic gneiss and augen-gneiss which act as a provenance of the sediments rich in mica group of minerals. Furthermore, Ti is a common lithophile element that occurs in several minerals such as ilmenite ($FeTiO_3$), rutile, brookite (both TiO_2), and sphene ($CaTiSiO_5$). The poor correlation of Ti with Fe and Ca suggests that rutile could be the key source of Ti in Rushikulya river sediments. The semi quantitative mineralogical analysis of the sediments also supported the presence of rutile in the sediments. The high concentration of TiO_2 near the river mouth following the trend of sand size sediments indicates that the grain size controls the elemental distribution of TiO_2.

2.2.2. Interpretation of core sediment (VC-04)

The sharp lithological contrasts and the trends of geochemical and sedimentological variables indicate the contribution of two distinct intervals with different environmental conditions in the study region during the last 6800 cal BP. The sandy nature of the lower half of the core near the Rushikulya river indicates the contribution of coarse grained fluvial sediment. In order to deposit sand layers on a high stand mid continental shelf, high energy processes must be invoked. The intermittent layers of sand and silt are due to occasional supply of large amount of sediment by Rushikulya river during monsoon season followed by period of less sediment supply. We exclude the influence of sea level fluctuations for the observed variations as investigations from western India continental margin shows minor sea level fluctuations for the past 7000 years (Hashimi et al., 1995). The sea-level curve presented from the eastern coast of southern India also indicates a gradual and slow sea-level rise since 9000 to 1800 yrs BP (Hameed et al., 2006). Additionally, the geochemical and palynological analyses of relict mudflat from southern Saurashtra coast also reveals wet climatic conditions with simultaneous occurrence of marginally high sea-level between 4710 and 2825 cal BP (Banerji et al., 2015). The sharp sedimentary change observed at 3100 cal BP represents the transition from a shelf dominated by monsoonal terrigenous supply to a low-energy environmental condition.

2.2.3. Regional comparison of paleoclimate data

Grain-size and elemental distribution data from the core sediments (VC-04) indicates a period of enhanced surface water runoff from 6800 to 3100 cal BP followed by drier conditions to present (Fig. 5a). The enhanced precipitation in Rushikulya during ca. 6800-3100 cal BP is synchronous with the climatic reconstruction based on lake sediments from Nal Sarovar, central Gujarat (Prasad and Enzel, 2006) with high lake stand during ca. 4800-3000 cal BP (Fig. 5b). Likewise, the pollen and phytolith based investigations from western India, Pariyaj lake (Raj et al., 2015) and Wadhwana Lake (Prasad et al., 2014a) also shows a wet phase between 4680 and 3500 cal BP 7500–5560 cal BP respectively. The wetter conditions in Rushikulya region during 6800–3100 cal BP is also in good agreement with the record based on carbon isotopes of sedimentary leaf waxes from core monsoon zone (Ponton et al., 2012) and mineralogical and isotopic investigation of Lonar core sediments from central India (Anoop et al., 2013b; Prasad et al., 2014b) (Fig. 5c and 5d). This humid phase also matches with the paleorecords from mid-late Holocene from the ISM dominated Himalayan and Tibetan region (Dodia et al., 1984; Demske et al., 2009; Trivedi and Chauhan, 2009; Günther et al., 2015; Kotlia, 2015; Rawat et al., 2015; Mishra et al., 2015) (Fig. 5e) suggesting common forcing factor in governing the climate variability in the Indian sub-continent.

The onset of weakening of the ISM recorded from VC-04 is in phase with the gradual onset of aridity and lowering of the sea-level observed between 2825 and 1835 cal BP from the Saurashtra coast in western India (Banerji et al., 2015) (Fig. 5f). Furthermore, the results are also in line with the high resolutions record from NW India: Nal Sarovar lake (Prasad et al., 1997); Pariyaj Lake (Raj et al., 2015) Lunkaransar and Didwana Lakes (Wasson et al., 1984; Enzel et al., 1999). The findings of drier conditions in Rushikulya region after ca. 3100 cal BP is good accordance with the sedimentary leaf waxes record from core monsoon zone (Ponton et al., 2012) and mineralogical and isotopic data from Lonar sediments in central India (Anoop et al., 2013b). The variations of the mid-late Holocene hydrological changes have shown significant linear response to gradually changing insolation (e.g., Prasad et al., 2014b; Mishra et al., 2015). The spatial variability in paleo data has been mostly explained by changes in moisture sources or monsoonal teleconnections (e.g., ENSO, Indian ocean dipole (IOD) (Hong et al., 2005; Sinha et al., 2011; Prasad et al., 2014b). The changes in terrigenous supply of fluvial discharge recorded by VC-04 core fit well with the decrease in the insolation during the late Holocene. We propose that the river runoff gradually decreased following the summer insolation. The findings of the present study will help in the characterization of the evolutionary patterns of river-influenced continental shelf areas in Indian subcontinent.

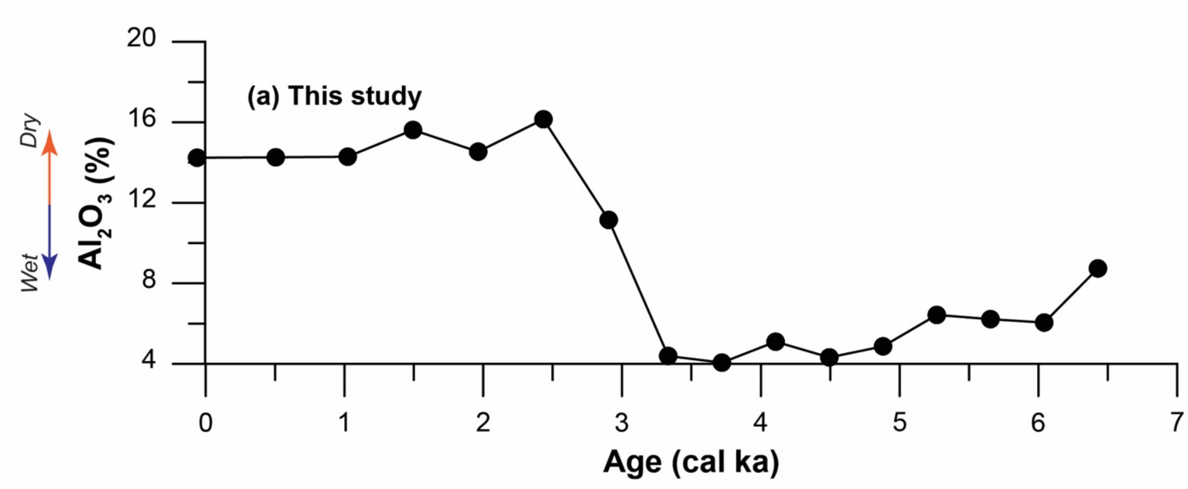

Fig. 5a. Variation in Al_2O_3 (wt%) of the core sediment (present study).

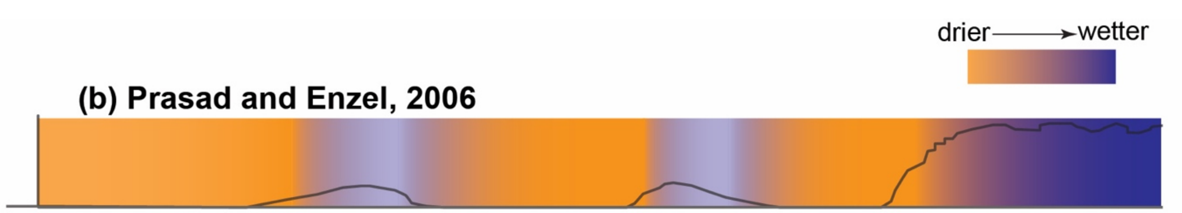

Fig. 5b. Schematic curve of climate change derived from Nal Sarovar data (Prasad and Enzel, 2006).

Fig. 5c. Carbon isotope data from biomarkers derived from the Godavari catchment (Ponton et al., 2012)

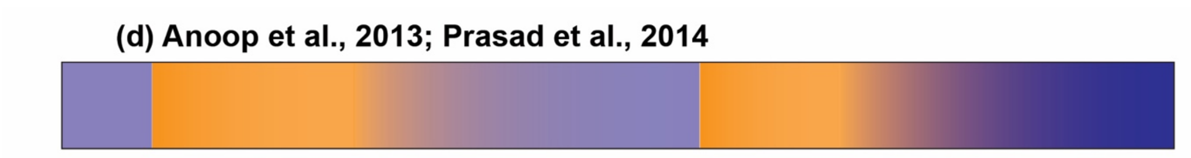

Fig. 5d. Climate information from Lonar lake based on the presence of evaporite minerals (Anoop et al., 2013a,b; Prasad et al., 2014a,b)

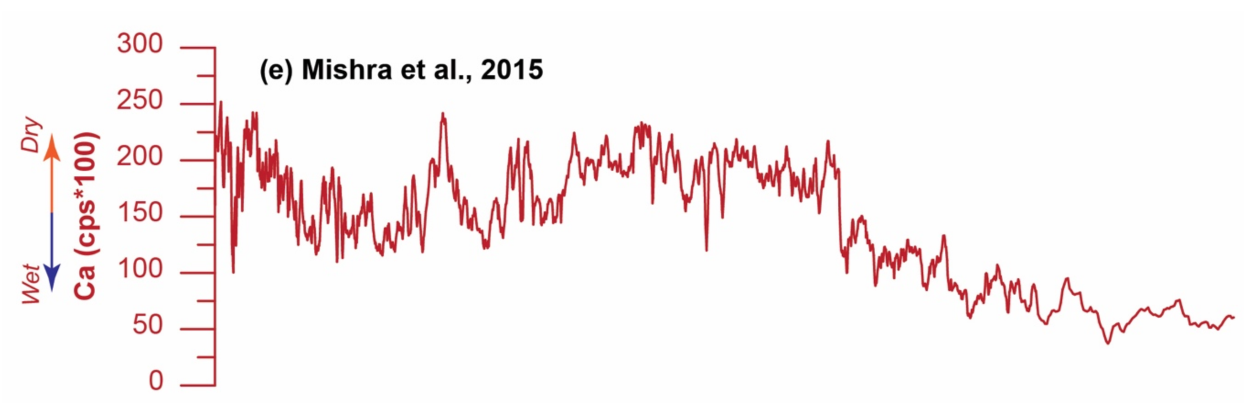

Fig. 5e. XRF profile of calcium (in cps) of Tso Moriri core sediment (Mishra et al., 2015).

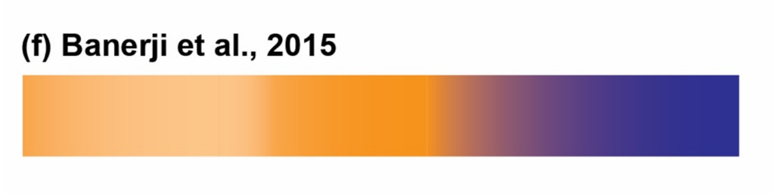

Fig. 5f. Climate information based on geochemical and palynological analyses of relict mudflat from Saurashtra coast (Banerji et al., 2015).

2.2.4. Conclusion

The elemental distributions, sedimentation rates and grain size investigations performed on core sediment retrieved from the continental shelf adjacent to Rushikulya river mouth allowed us to identify paleoclimatic changes. The modern investigations of the surface sediments from the inner-mid continental shelf were conducted to understand the coastal dynamics and refine paleoenvironmental interpretations. The grain size distribution and elemental data of the surface sediments show that in the modern-day condition, the elemental distribution such as TiO_2 and Al_2O_3 is largely controlled by the grain size of the sediments. The proportion of grain size (clay and silt vs sand) and elemental values (TiO_2 vs Al_2O_3) has been used to infer the changes in past terrigenous supply. Our results pointed out the period of higher river discharge from 6800 to 3100 cal BP followed by reduction of monsoonal strength. The drier conditions recorded off core sediments are corroborated with climatic changes recorded from other parts of Indian summer monsoon domain.

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