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Geochemistry and distribution of sediments in the East Indian shelf, SW Bay of Bengal: implications on weathering, transport and depositional environment

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Forty-two substrate sediment samples and three cores procured from the shelf region between Chennai and Cuddalore were analyzed to understand the spatial and vertical sediment distribution. Samples subjected to grain size, bulk and clay mineralogical analyses, REE and trace element geochemistry yielded interesting results about the sediment characteristics with respect to the modern day environment. The present study revealed that the study area is characterized by high energy environment marked by predominant composition of medium sand. Results confirmed the evidence of more illite than kaolinite, smectite, and chlorite in the clay mineral assemblage indicating a terrigenous source. Geochemical data also revealed that the enrichment of light rare earth elements (LREE) in the sediments is due to continental source of Precambrian times. High feldspar content in the sediments which is emphasized by bulk mineralogical data displayed positive Eu anomaly. By using the paleoredox index, the area of interest is considered to have undergone no major changes in its depositional settings.

Keywords. Shelf sediments; grain size distribution; clay minerals; geochemistry; Chennai–Cuddalore.

1. Introduction

Continental shelf, a transitional zone that lies in between the continent and the deep oceanic basins is a huge depositional complex. The distribution pattern of sediments as observed in the shelves is almost irregular owing to the highly variable sediment characteristics. The detrital sediments in the Bay of Bengal is mostly supplied by the peninsular (Mahanadi, Godavari and Krishna) and extra-peninsular rivers (Ganges and Brahmaputra) that drain into the bay eventually. The Ganges and Brahmaputra rivers derive their sediments from the Himalayas, whereas the peninsular rivers derive their sediment load mainly from the Deccan traps that cover an area of 3×105 km^2 in the Indian peninsula (Goldberg and Griffin 1970). Thus the estimated amount of suspended sediments in the bay is nearly 1350 million tons/year (Subramanian *et al.* 1985; Milliman 2001). The sediments supplied to continental shelf through riverine input, erosion of coasts or the accumulation of biogenic matter are largely controlled by various environmental factors. However, the geological setup prevailing in the shelf region modifies the depositional history of the sediments. Therefore, it is necessary to analyze the grain size data which is considered as the most fundamental tool to study in detail the depositional history of an area (e.g., Folk and Ward 1957) keeping in view the geology of that particular area. The sediment distribution analysis also helps to understand the mode of transportation of sediments (Mason and Folk 1958; Friedman 1961, 1967, 1979; Passega 1964; Visher 1969). Textural parameters namely mean, sorting, skewness and kurtosis aid in deducing the depositional phase and the environment that would have prevailed during the time of deposition of sediments (Folk and Ward 1957; Mason and Folk 1958; Friedman 1961, 1967, 1979). The analysis of Rare Earth Elements (REE) in marine sediments serve as powerful indicators of anthropogenic pollution (Borrego *et al.* 2004), bio-geochemical reactions (Oliveri *et al.* 2010), provenance studies (Taylor and McLennan 1985), to understand the sediment pathways and decipher the factors controlling dispersion of trace elements (Piper 1974; Toyoda *et al.* 1990; Murray *et al.* 1991; Piper *et al.* 2007; Censi *et al.* 2010).

2. Study area

The east coast is a wave-dominated zone and has a coastline of 2,493 km which experiences storm surges due to cyclones generated in the Bay. Much of the sediment input is contributed by major rivers such as the Ganges, Brahmaputra, Mahanadi, Godavari, Krishna and Cauvery and lesser input is from minor rivers such as Gingee, Palar, Ponnaiyar and Gadilam. The area chosen for the present study lies within the following geographic coordinates 11°34.00–11°42.00N and 80°15.81–80°00.70E which is along the east coast of India. This is situated in the southwestern Bay of Bengal bordered by Chennai and Cuddalore in Tamil Nadu. The continental shelf in the area of interest has an average width of 35 km. The shelf is relatively broader in the northern side and narrows down in the south. The shelf region off Chennai is wide (50 km) with a gentle gradient whereas it is narrow (only 25 km wide) and has a steep slope between Pondicherry and Cuddalore (Udayaganesan *et al.* 2011). The Cuddalore shelf is concave shaped and narrow with an average width of 79 km and a gentle gradient up to 3000 m of water depth (Murthy *et al.* 2006). The shelf breaks on an average of 90–120 m of water depth (Rana *et al.* 2007). The continental slope occurs at a depth of 3000 m in the southern part of the bay as compared to its occurrence at <2000 m in the further north owing to relatively less sediment input from the southern rivers.

Therefore, the present study is carried out (i) to know the sediment distribution pattern in the surface and core sediments from the study area, (ii) to understand their mineralogical composition, (iii) to comprehend the REE and trace element distribution in the sediments, and (iv) to trace the source of these sediments using the above results.

3. Material and methods

Surface sediment samples were collected along eight transects spanning the shelf region between Chennai and Cuddalore and core samples were obtained from the offshore side of Chennai, Edierthittu and Cuddalore (figure 1). The substrate samples were collected from different depths ranging from ∼10 to ∼300 m depth of water column using van Veen grab sampler during RV Sagar Paschimi cruise. Three core samples were procured using a gravity corer from *ORV Sagar Manjusha* where a 35 cm long core was collected off Chennai (C1) from 40 m of water depth. Second core (C2) measuring 60 cm was taken from 60 m depth off Edierthittu and another core (C3) of a length of 36 cm was taken from off Cuddalore around water depth of 12.5 m. The geographic co-ordinates of the sample sites along with the depth of collection of surface sediments and the core samples are as given in table 1.

3.1 *Grain-size analysis*

Approximately, 500 g of sediment collected wherever possible was air-dried and oven-dried following which 100 g of homogenized sample was obtained using coning and quartering method (Tyler 1967). In the case of core samples, subsamples of the same quantity were taken from every 5 cm interval of the core section. For grain size analysis, samples were pretreated with H_2O_2 to remove organic matter and sodium hexametaphosphate was used as a dispersing agent to deflocculate the sediments. Sieving technique was used for samples with abundant coarser (>63 μm) fraction and pipette method for samples with sufficient (<63 μm) fraction.

3.1.1 *Sieve method*

One hundred grams of each sample was then placed in a stack of ASTM sieves with 1/2 Φ (phi) interval (2.0 mm = 1 Φ, 1.0 mm = 0 Φ, 0.5 mm = 1 Φ, 0.25 mm = 2 Φ, 0.125 mm = 3 Φ and 0.63 mm = 4 Φ) and shaken for 10 min. The raw weight of each fraction was noted and expressed as its weight

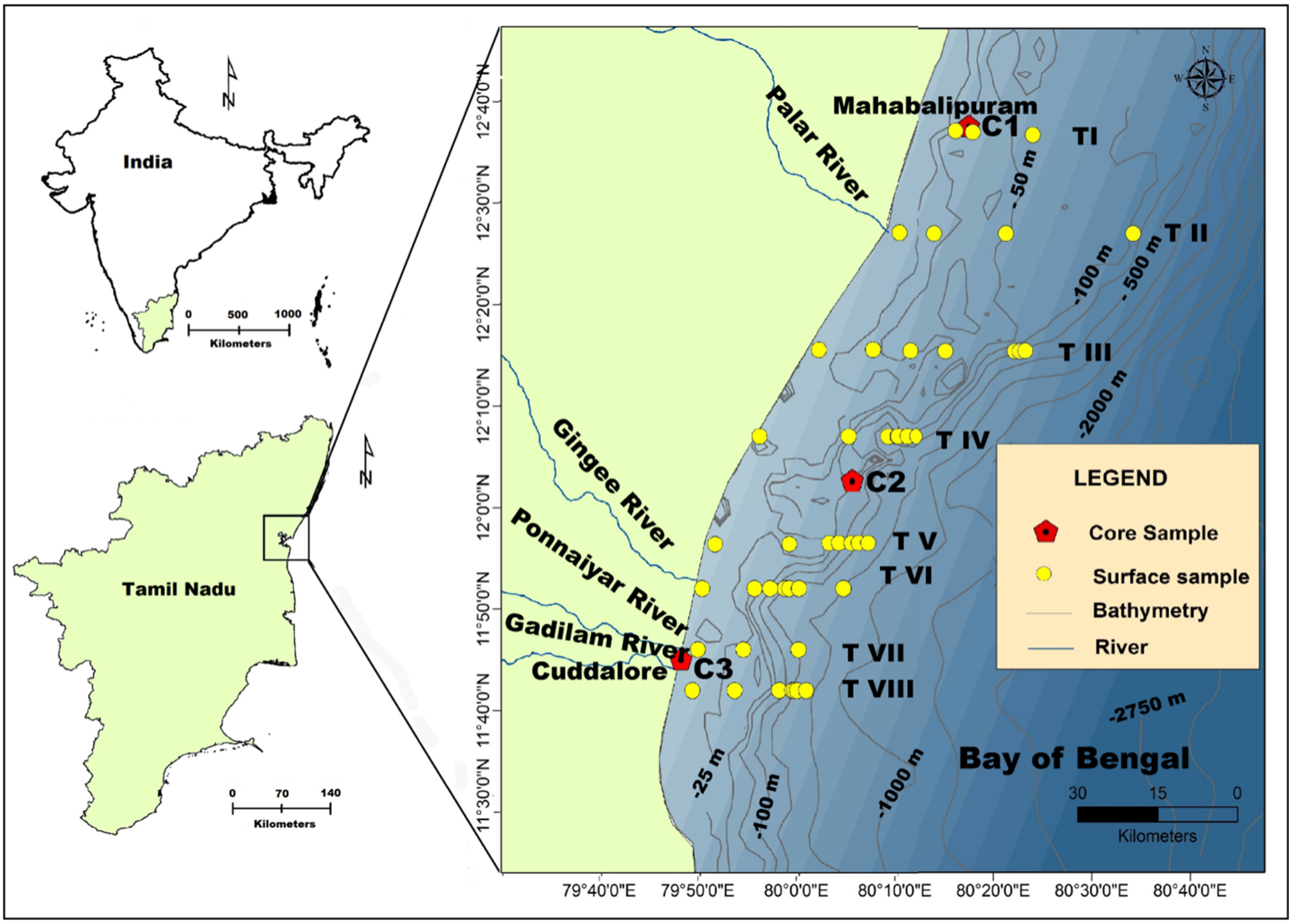

Figure 1. Sample sites in transects I–VIII and core locations C1–C3.

percentage. The gravel, sand and mud content were known using the Udden–Wentworth scale for grain size analysis. However, textural class was assigned based on the mud content after Reineck and Siefert (1980) and Pejrup (1988), modified by Flemming (2000).

3.1.2 *Pipette method*

The finer fraction (<4 Φ) was determined by the pipette method (Carver 1971). The sample collected in the pan was made up to 1000 ml in the measuring jars and stirred gently for few seconds. Twenty millilitre of the makeup solution was drawn at an interval of 20 s from the 20 cm depth which gives the coarse and fine silt + clay reading. Again 20 ml was drawn from another depth of 10 cm after an interval of 1 min and 45 s, for fine silt + clay content. Twenty millilitre was drawn for the third time at 3 hr and 10 min from 5 cm depth for clay.

3.2 *Mineralogy*

3.2.1 *Bulk mineralogy*

A few selected samples were subjected to bulk mineralogical studies. Samples were crushed in FRITSCH Pulverisette 7Agate Ball mill at 450 rpm for 20 min in one cycle and were repeated till all the samples were crushed into fine powder.

3.2.2 *Clay mineralogy*

Clay mineralogical studies were attempted by pipetting out 20 ml of solution from 5 cm depth of a 1000 ml measuring jar in standard intervals of time for settling of clay. This was repeated several times till sufficient aliquots of clay were obtained. Then the solution was centrifuged in R-8C BL centrifuge machine for 25 min at 3500 rpm until clear supernatant liquid is obtained. The clay collected at the bottom of the centrifuge tubes is retrieved carefully and was finally mounted on glass slides for further analysis in X-ray diffractometer.

Table 1. *Geographic co-ordinates of sample locations and depth in metres.*

Transects/sample sites	Sample id	Depth (m)	Latitude	Longitude
I-Off Mahabalipuram	S1	20	11°34.00N	80°15.81E
	S2	32	11°34.00N	80°25.50E
	S3	63	11°34.00N	80°34.89E
II-Off Palar river	S4	8	12°27.00N	80°10.20E
	S5	21	12°27.00N	80°14.00E
	S6	35	12°27.00N	80°21.30E
	S7	63	12°27.00N	80°34.20E
III-Off Edierthittu	S9	28	12°15.50N	80°07.50E
	S10	46	12°15.40N	80°11.30E
	S11	71	12°15.40N	80°15.16E
	S12	86	12°15.40N	80°22.20E
	S13	156	12°15.40N	80°22.70E
	S14	205	12°15.44N	80°23.24E
IV-Off Kazhikuppam	S15	6	12°07.00N	79°56.00E
	S16	25	12°07.00N	80°05.03E
	S17	53	12°07.00N	80°09.05E
	S18	79	12°07.00N	80°10.00E
	S19	100	12°07.00N	80°10.05E
	S20	167	12°07.00N	80°11.00E
	S21	176	12°07.00N	80°12.00E
V-Off Muthialpet	S22	9	11°56.40N	79°51.50E
	S23	26	11°56.41N	79°59.01E
	S24	51	11°56.50N	80°03.05E
	S25	91	11°56.50N	80°04.05E
	S26	138	11°56.50N	80°05.30E
	S27	176	11°56.50N	80°06.05E
	S28	308	11°56.50N	80°07.00E
VI-Off Gingee river	S29	8	11°52.00N	79°50.20E
	S30	25	11°52.00N	79°55.50E
	S31	45	11°52.00N	79°57.07E
	S32	95	11°52.00N	79°58.60E
	S33	130	11°52.00N	79°59.00E
	S34	149	11°52.00N	80°00.00E
VII-Off Ponnaiyar river	S36	11	11°46.00N	79°49.74E
	S37	32	11°46.00N	79°54.35E
	S38	74	11°46.00N	79°59.95E
VIII-Off Cuddalore	S39	9	11°42.00N	79°49.20E
	S40	15	11°42.00N	79°53.50E
	S41	26	11°42.00N	79°58.00E
	S43	119	11°42.00N	79°59.50E
	S44	161	11°42.00N	79°59.80E
	S45	282	11°42.00N	80°00.70E

3.2.3 *Mineralogical analyses by XRD*

Each powdered sample to be analyzed for its bulk mineralogical composition was loaded in a sample holder and was scanned from 10 to 75° 2θ in PANalytical X'Pert Pro™ X-ray diffractometer with a copper target (CuK α radiation). For clay mineral identification, X-Ray analysis was carried out such that (i) untreated, (ii) glycol-treated, and (iii) heat-treated patterns were obtained for each sample. Untreated clay analysis was done by smearing the clay on to a glass slide and then scanned at room temperature. Two different aliquots of clay were saturated with Ca and K prior to glycolation and heat treatment following the ion saturation procedure of Brown and Brindley (1980). Ca-saturated glass slides were subjected to glycol treatment by exposing them to 250 ml of ethylene glycol in the desiccator (Brunton 1955) and kept in an oven at 60°C for 4 hr for semi-quantification of samples containing smectite. To obtain diffractometer patterns by heat treatment, K-saturated clay slides were kept in a furnace at 550°C for 4–5 hr and run in XRD. Each sample was scanned using a continuous scan mode from 2 to 40° 2θ for 60 min with a scan speed of 0.6° 2θ/min at 40 kV and 25 mA. The data thus measured was compared with the reference database (ICDD) in PANalytical X'Pert High Score v.2.0a (2.0.1) and phase identification was determined as a result.

3.3 *REE and trace element study by Quadrupole ICP-MS*

Seven millilitre Savillex® Teflon vials used for digesting the samples, TARSON bottles and scintillation vials used to store the stock and diluted solution of the digested samples were thoroughly washed many times with milliQ and dried. 0.01 g of sample was weighed and taken in Savillex Teflon pressure decomposition vessels. The samples were pre-treated with 1:1 H_2O_2 solution following which 2 ml of concentrated HNO_3 and 3–4 ml of an acid mixture containing a 7:3:1 ratio of HF, HNO_3 and HCl were added to the vials. To ensure the removal of fluoride complexes and to obtain a clear solution, 2–3 ml of concentrated HNO_3 was added further. The residue was made up to 100 ml clean TARSON bottles in room temperature and the stock solution was stored for analysis. Empty weights and sample+weight of the polyethylene bottles were also recorded. Two millilitre of the stock solution was again made up to 10 ml in clean scintillation vials and then run in Thermo Scientific XSERIES 2 Quadrupole ICP-MS for analysis of trace elements which has a scan speed of >9000 microseconds per element. The instrument was calibrated and corrected for isobaric interferences by standardizing using internal and USGS standards (SDC-1 and BCR-2).

4. Results

4.1 *Grain-size distribution*

The results are based on the analyses carried out on a suite of 68 samples, i.e., 42 surface sediment samples along with 26 subsamples from three cores (taken from every 5 cm interval of the core) collected from different depths in the east coast.

4.1.1 *Surface sediments*

Shelf surface sediment distribution is very much affected by physical factors such as waves, tides and currents. Therefore, studying the spatial changes in the textural parameters such as mean, sorting, skewness and kurtosis is the most fundamental and standard way of tracing sediment transport pathways (Balsinha *et al.* 2014). These parameters were extracted by the method of moments using GRADISTAT, version 8.0 (Blott and Pye 2001) as given in table 2 and distribution maps were constructed using ArcGIS®, version.10 (ESRI). The mean values ranged between 0.10 and 3.55Φ and the average mean value of the surface sediments, 1.45Φ corresponding to medium sand showed predominant distribution. The coarser mean values are found near the coast while the finer values are slightly away from the coast (figure 2). The standard deviation values of the sediments ranged between moderately well sorted (min. 0.64) to poorly sorted (max. 1.66). More than 50% of the samples revealed that they are poorly sorted, while 38% are moderately sorted and ∼10% of them are moderately well sorted. Thus an average value of 1.04 indicates that they are overall poorly sorted. The samples displayed a good range of skewness values with relatively more negatively skewed samples and less number of positively skewed samples. The samples widely varied between platykurtic to very leptokurtic nature. Majority of the samples (41%) displayed mesokurtic character and 24% are platykurtic, 17% are leptokurtic and 19% are very leptokurtic. Among the surface samples, 76% are characterized as unimodal and 24% as bimodal in nature.

4.1.2 *Core sediments*

Three cores analyzed for down core variation of sediment distribution revealed that sand content is higher in C2 (off Edierthittu) and in C3 (off Cuddalore) while higher amount of clay was witnessed in C1 (off Chennai). The silt content encountered in the core sediments was moderate (∼10 to 20%). In Chennai core (C1), major portion (75%) of the sediments was clay (table 3). The first 5 cm of the core contained more clay content but it steadily decreased down the core by remaining more or less constant below 10 cm. The remaining bulk of the core was made up by silt and sand where silt content varied between >12 and 20% and sand

Table 2. *Grain size distribution in surface sediments.*

Sample ID	Depth (m)	Sand (%)	Mud (%)	Mean	Sorting	Equals to	Skewness	Equals to	Kurtosis	Equals to	Class	Type
S1	20	100	0	1.36	0.73	Moderately sorted	− 0.03	Near symmetrical	0.95	Mesokurtic	Sand	Unimodal
S2	32	96	4	1.43	1.27	Poorly sorted	0.18	Positive skewed	0.91	Mesokurtic	Sand	Unimodal
S3	63	99.6	0.4	0.40	1.34	Poorly sorted	− 0.14	Negative skewed	1.62	Very leptokurtic	Sand	Unimodal
S4	8	80.3	19.7	3.55	0.95	Moderately sorted	0.01	Near symmetrical	2.10	Very leptokurtic	Muddy sand	Unimodal
S5	21	100	0	0.10	0.74	Moderately sorted	− 0.30	Negative skewed	0.84	Platykurtic	Sand	Unimodal
S6	35	100	0	0.80	0.68	Moderately well sorted	0.06	Near symmetrical	0.94	Mesokurtic	Sand	Unimodal
S7	63	100	0	1.76	0.76	Moderately sorted	− 0.11	Negative skewed	0.97	Mesokurtic	Sand	Unimodal
S9	28	92	8	2.73	1.23	Poorly sorted	− 0.53	Strongly negative skewed	1.27	Leptokurtic	Sand	Bimodal
S10	46	100	0	1.23	1.26	Poorly sorted	− 0.14	Negative skewed	1.05	Mesokurtic	Sand	Bimodal
S11	71	99.9	0.1	1.69	0.92	Moderately sorted	− 0.17	Negative skewed	0.87	Platykurtic	Sand	Unimodal
S12	86	100	0	1.42	0.90	Moderately sorted	− 0.13	Negative skewed	1.01	Mesokurtic	Sand	Unimodal
S13	156	100	0	1.07	0.75	Moderately sorted	− 0.06	Near symmetrical	0.94	Mesokurtic	Sand	Unimodal
S14	205	100	0	1.47	0.73	Moderately sorted	− 0.13	Negative skewed	1.17	Leptokurtic	Sand	Unimodal
S15	6	100	0	1.12	0.81	Moderately sorted	0.09	Near symmetrical	0.87	Platykurtic	Sand	Unimodal
S16	25	100	0	0.35	0.75	Moderately sorted	− 0.18	Negative skewed	1.12	Leptokurtic	Sand	Unimodal
S17	53	99.7	0.3	1.39	1.02	Poorly sorted	− 0.13	Negative skewed	0.97	Mesokurtic	Sand	Unimodal
S18	79	100	0	1.53	0.80	Moderately sorted	0.76	Strongly positive skewed	0.88	Mesokurtic	Sand	Unimodal
S19	100	92.2	7.8	2.56	1.11	Poorly sorted	− 0.19	Negative skewed	1.19	Leptokurtic	Sand	Unimodal
S20	167	85.9	14.1	2.81	1.37	Poorly sorted	− 0.04	Near symmetrical	1.57	Very leptokurtic	Muddy sand	Bimodal
S21	176	94.3	5.7	2.75	0.96	Moderately sorted	− 0.23	Negative skewed	1.16	Leptokurtic	Sand	Unimodal
S22	9	98.5	1.5	1.06	0.86	Moderately sorted	0.15	Positive skewed	1.03	Mesokurtic	Sand	Unimodal
S23	26	98.6	1.4	0.34	1.60	Poorly sorted	0.15	Positive skewed	0.89	Platykurtic	Sand	Bimodal
S24	51	99.4	0.6	0.39	1.61	Poorly sorted	− 0.14	Negative skewed	1.54	Very leptokurtic	Sand	Unimodal
S25	91	98.9	1.1	1.42	1.15	Poorly sorted	− 0.10	Near symmetrical	0.81	Platykurtic	Sand	Bimodal
S26	138	98	2	1.60	1.15	Poorly sorted	− 0.08	Near symmetrical	0.81	Platykurtic	Sand	Bimodal
S27	176	96.5	3.5	1.49	1.19	Poorly sorted	0.21	Positive skewed	0.90	Platykurtic	Sand	Unimodal
S28	308	84.6	15.4	2.88	1.17	Poorly sorted	0.27	Positive skewed	2.19	Very leptokurtic	Muddy sand	Unimodal
S29	8	98.6	1.4	1.61	1.02	Poorly sorted	− 0.01	Near symmetrical	0.80	Platykurtic	Sand	Unimodal
S30	25	95.6	4.4	0.78	1.44	Poorly sorted	0.21	Positive skewed	1.66	Very leptokurtic	Sand	Unimodal
S31	45	88.6	11.4	2.84	1.34	Poorly sorted	− 0.11	Negative skewed	1.72	Very leptokurtic	Muddy sand	Bimodal
S32	95	92.1	7.9	2.92	1.19	Poorly sorted	− 0.10	Near symmetrical	1.80	Very leptokurtic	Sand	Unimodal
S33	130	88.1	11.9	2.46	1.58	Poorly sorted	− 0.13	Negative skewed	1.01	Mesokurtic	Muddy sand	Bimodal
S34	149	91.8	8.2	2.06	1.66	Poorly sorted	− 0.04	Near symmetrical	0.99	Mesokurtic	Sand	Bimodal
S36	11	100	0	0.84	0.83	Moderately sorted	0.10	Positive skewed	1.04	Mesokurtic	Sand	Unimodal
S37	32	100	0	1.00	0.78	Moderately sorted	0.32	Strongly positive skewed	0.94	Mesokurtic	Sand	Unimodal
S38	74	100	0	0.71	0.64	Moderately well sorted	0.10	Positive skewed	1.04	Mesokurtic	Sand	Unimodal
S39	9	100	0	0.85	1.01	Poorly sorted	− 0.01	Near symmetrical	1.16	Leptokurtic	Sand	Unimodal
S40	15	100	0	0.44	1.15	Poorly sorted	− 0.08	Near symmetrical	1.46	Leptokurtic	Sand	Unimodal
S41	26	100	0	0.92	0.63	Moderately well sorted	0.11	Positive skewed	0.87	Platykurtic	Sand	Unimodal
S43	119	100	0	1.04	0.72	Moderately sorted	0.04	Near symmetrical	0.88	Platykurtic	Sand	Unimodal
S44	161	100	0	0.83	0.64	Moderately well sorted	0.11	Positive skewed	0.98	Mesokurtic	Sand	Unimodal
S45	282	98.8	1.2	0.83	1.24	Poorly sorted	0.30	Positive skewed	0.96	Mesokurtic	Sand	Bimodal

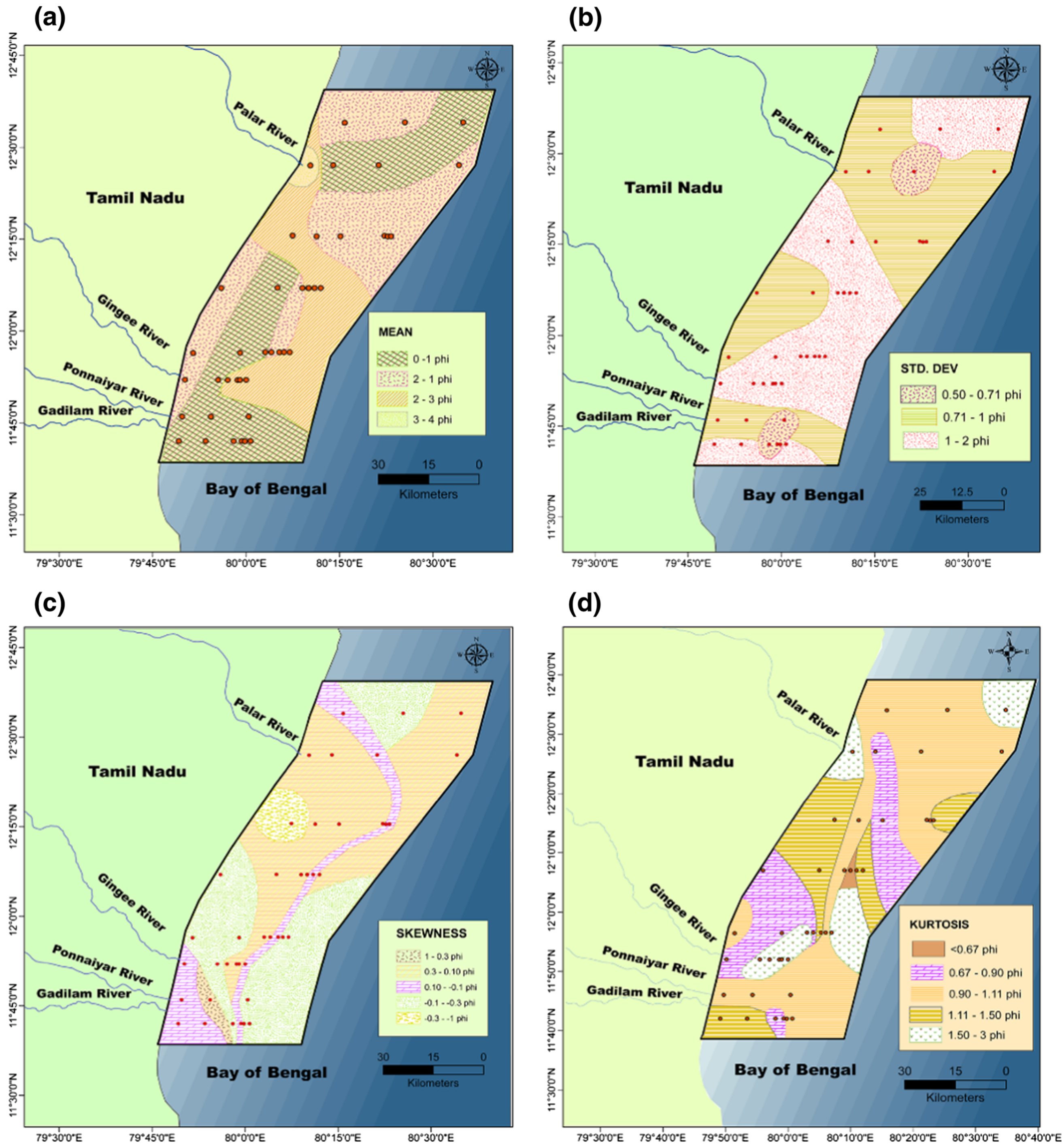

Figure 2. Distribution of textural parameters (**a**) mean, (**b**) standard deviation, (**c**) skewness, and (**d**) kurtosis of surface sediments.

content ranged between 5 and 10%. In core (C2), off Edierthittu, sand was the predominant fraction making up an average of 94% of the sediments in the core and very slight down core variation was observed. Gravel and mud showed an inverse relationship in the entire core constituting the remaining 4 and 3% of the total sediments respectively. In the third core (C3), collected off Cuddalore, sand and clay content showed an inverse relation while silt content increased gradually in the lower half of the core. Sand made up half (50%) of the core sediments while the other half of the core is composed of silt (16.5%) and clay (33.5%), respectively (figure 3).

Table 3. *Sediment distribution in cores.*

Sample id	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Class
C1-Off Chennai					
C1-1	5	5.99	12.88	81.13	Slightly sandy mud
C1-2	10	8.38	18.35	73.27	Slightly sandy mud
C1-3	15	7.3	19.09	73.62	Slightly sandy mud
C1-4	20	7.44	18.58	73.98	Slightly sandy mud
C1-5	25	8.11	17.98	73.91	Slightly sandy mud
C1-6	30	9.87	16.41	73.72	Slightly sandy mud
C1-7	35	9.08	16.28	74.63	Slightly sandy mud
C2-Off Edierthittu					
C2-1	5	0.50	94.76	4.56	Sand
C2-2	10	0.72	95.14	4.06	Sand
C2-3	15	1.98	89.31	8.71	Slightly muddy sand
C2-4	20	8.94	89.98	1.09	Sand
C2-5	25	4.27	93.92	1.81	Sand
C2-6	30	4.99	92.62	2.39	Sand
C2-7	35	3.54	96.07	0.39	Sand
C2-8	40	2.03	96.82	1.16	Sand
C2-9	45	2.71	95.87	1.42	Sand
C2-10	50	2.36	96.4	1.24	Sand
C2-11	55	6.18	92.99	0.83	Sand
C2-12	61	8.05	91.38	0.57	Sand
C3-Off Cuddalore					
C3-1	5	83.02	10.33	14.94	Muddy sand
C3-2	10	64.51	9.05	26.42	Muddy sand
C3-3	15	57.37	12.79	29.8	Muddy sand
C3-4	20	38.45	17.24	39.81	Sandy mud
C3-5	25	32.57	16.83	50.59	Sandy mud
C3-6	30	37.94	25.44	36.61	Sandy mud
C3-7	37	39	24.12	37.36	Sandy mud

4.2 *Mineralogy*

Bulk powder analysis of sediment or rock samples helps in quick mineral identification and also a detailed characterization of clay minerals present in the finer sediment fractions is carried out by XRD. Few selected surface sediment samples and subsamples from C1 (off Chennai) and C3 (off Cuddalore) cores were used for this mineralogical study.

4.2.1 *Bulk mineralogy*

The framework constituents of surface sediments were identified as quartz, plagioclase and orthoclase feldspars and calcite. However, the dominant minerals were quartz, albite, anorthite and calcite. Pyroxenes such as augite, enstatite, diopside and spodumene; sulphides such as chalcopyrite and covellite; micas such as muscovite besides rutile and zircon were present in minor amounts. Clay minerals such as kaolinite, illite and montmorillonite were also found in the sediments.

4.2.2 *Clay mineralogy*

Diffractograms from X-ray analysis revealed the presence of clay minerals such as kaolinite, illite, smectite (montmorillonite), chlorite and a few mixed-layer minerals. The non-clay minerals that were identified include chalcopyrite, sphalerite, lepidolite, microcline, albite, biotite and calcite. The samples showed kaolinite peaks at 12.38 and 24.94 2θ with the d-spacing of 7.15 and 3.57 Å, respectively. Kaolinite is identified by the disappearance of 7.15 Å reflection on heating above 500°C. Smectite peak was observed upon glycolation at 5 2θ (17.08 Å). The samples showed

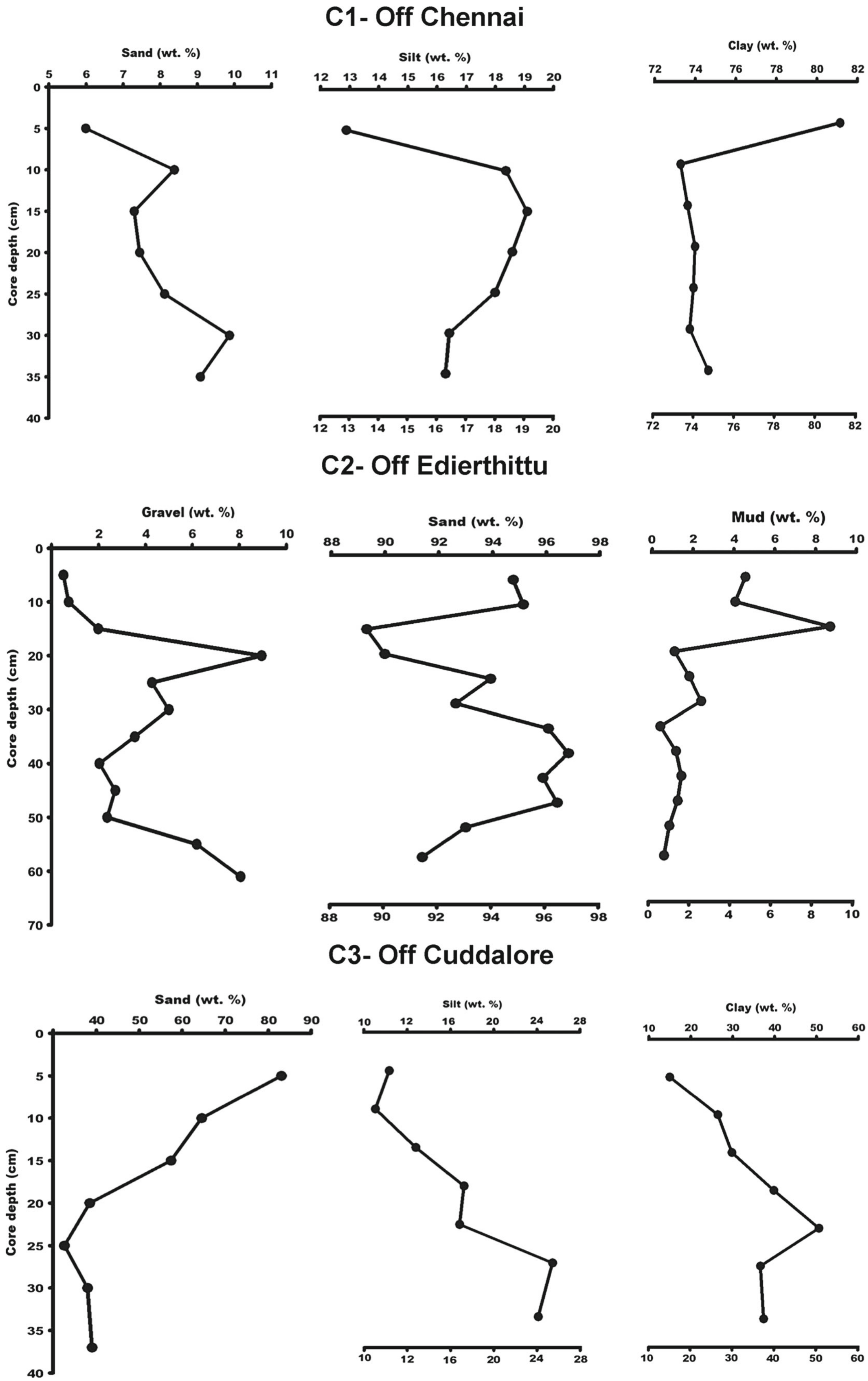

Figure 3. Down core sediment distribution in three cores.

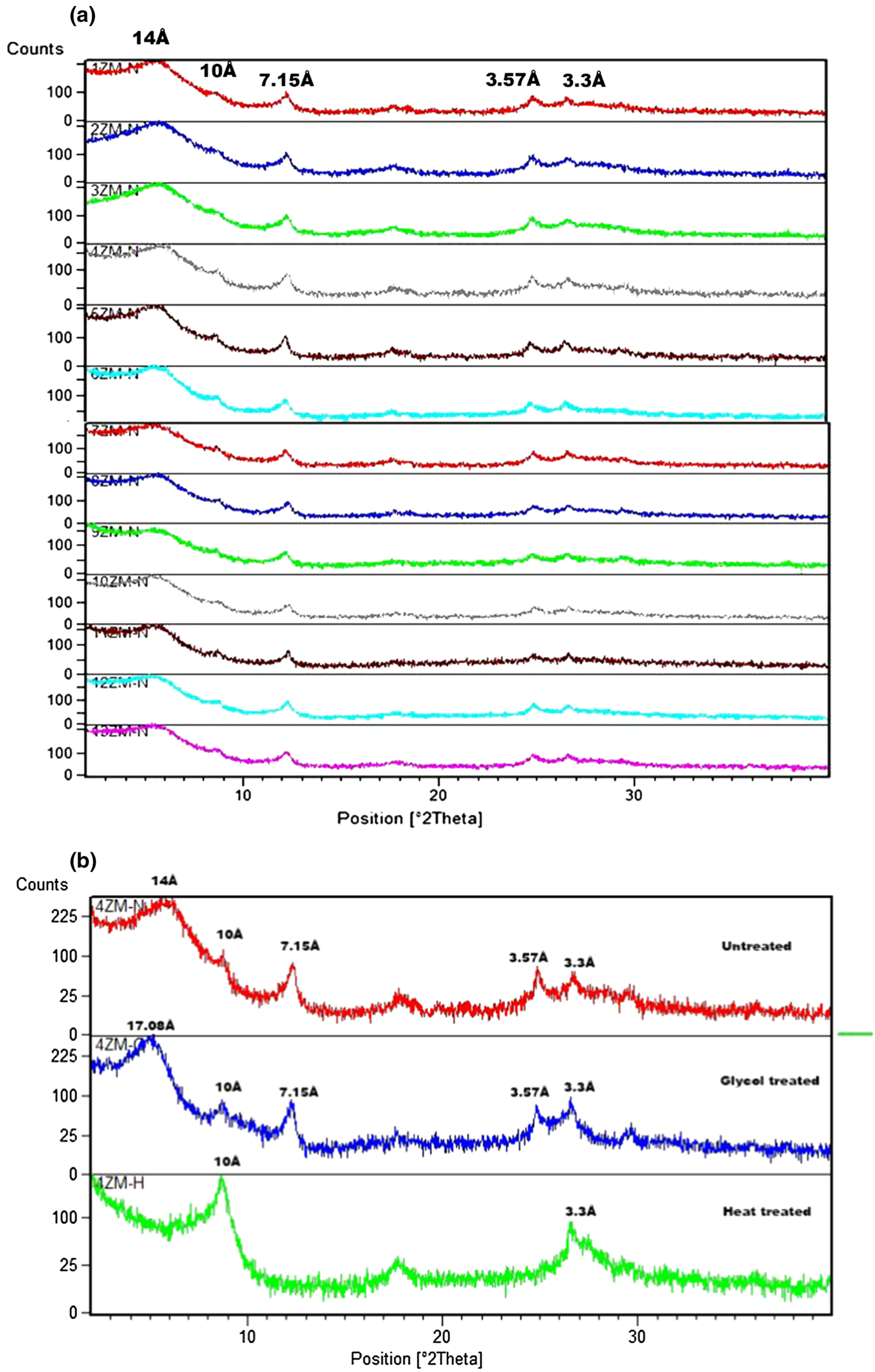

Figure 4. (**a**) XRD diffractograms of all clay minerals present in surface samples and (**b**) clay minerals in (i) untreated, (ii) glycol-treated, and (iii) heat-treated slides.

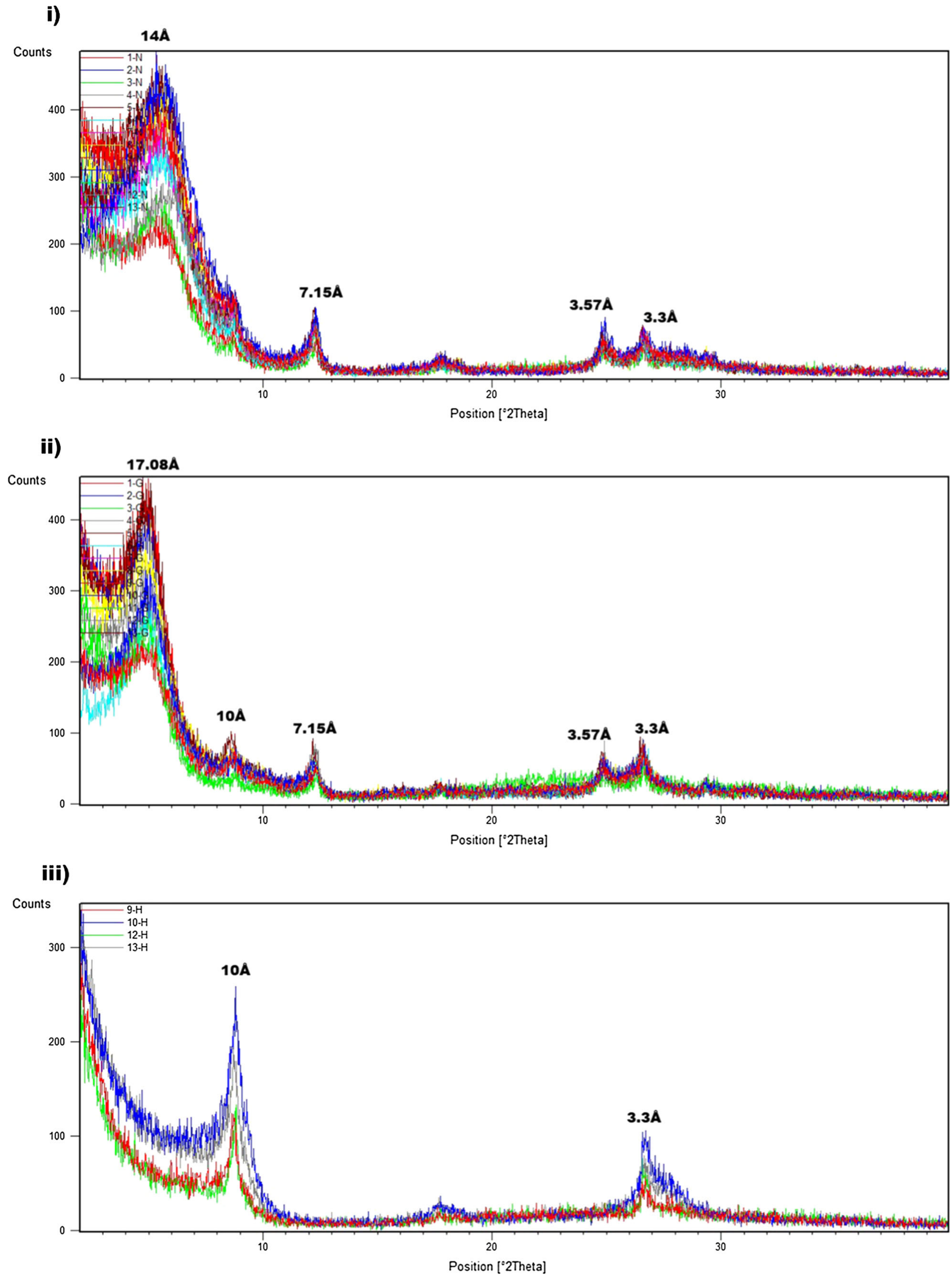

Figure 5. Diffractograms of clay minerals present in core samples C1 (off Chennai) and C3 (off Cuddalore): (i) untreated, (ii) glycol-treated, and (iii) heat-treated slides.

Table 4. *Percentage of clay minerals present in the surface and core samples.*

Sample id	Depth (m)	Illite (%)	Kaolinite (%)	Smectite (%)	Chlorite (%)
S4	8	13.61	16.06	62.24	8.09
S16	25	9.38	7.91	79.51	3.20
S17	53	10.18	6.03	81.50	2.29
S18	79	11.61	7.69	78.60	2.10
S20	167	11.10	6.12	79.19	3.59
S24	51	10.00	8.34	77.13	4.53
S25	91	12.35	9.05	75.51	3.09
S28	308	13.12	8.76	75.14	2.98
S29	8	12.58	11.00	71.70	4.72
S30	25	11.90	15.79	68.00	4.31
S31	45	8.60	9.00	77.8	4.60
S32	95	13.58	14.00	68.20	4.22
S33	130	9.80	12.70	73.00	4.50
C1-1	0.01–0.05	10.00	72.00	14.50	3.50
C1-2	0.06–0.1	11.40	70.00	16.50	2.10
C1-3	0.11–0.15	10.15	69.20	18.05	2.60
C1-4	0.16–0.2	11.00	71.00	15.90	2.10
C1-5	0.21–0.25	11.40	70.10	16.00	2.50
C1-6	0.26–0.3	11.00	70.50	16.25	2.25
C3-1	0.01–0.05	6.91	13.57	75.22	4.30
C3-2	0.06–0.1	7.50	25.00	65.00	2.50
C3-3	0.11–0.15	8.15	30.00	59.00	2.85
C3-4	0.16–0.2	15.50	38.50	40.00	6.00
C3-5	0.21–0.25	20.00	51.00	25.00	4.00
C3-6	0.26–0.3	22.50	35.00	39.00	35.00
C3-7	0.31–0.32	16.85	38.50	40.50	4.15

prominent peaks at 26.75 2θ (3.3 Å) and 8.8 2θ 10 Å corresponding to illite which is affected neither by glycol nor heat treatment. The peak corresponding to chlorite was observed at 6.3 2θ (14 Å) which is affected by glycolation and by heating due to the presence of vermiculite (Figures 4 and 5). The relative clay mineral abundances in the samples were calculated using Biscaye (1965) method as given in table 4. Surface samples showed predominance of kaolinite followed by illite whereas the dominating clay mineral in the core samples is illite. Inner shelf sandy sediments witnessed higher kaolinite content. The down core clay mineral variation as observed in C1 exhibited higher amounts of illite than kaolinite, smectite and chlorite. The sandy upper half of C3 showed abundance of kaolinite while the muddy lower half showed decrease in kaolinite and increase in illite content.

4.3 *Trace element studies*

Rare earth elements (REE) and trace elemental study was performed on two cores, C1-off Chennai and C3-off Cuddalore. The average mean values of the REEs in the core sediments are given in table 5. The average REEs is higher in C3 (28.74 ± 2.81) than C1 (25.84 ± 4.28). The trend of variation in the concentration of REEs showed that Er is greater than Eu in C1, while in C3 Eu dominated Er.

Continental shelf has sediments from terrigenous source, of authigenic origin or biogenic nature. Therefore REEs of both the cores were normalized to Post Archaen Australian Shale (PAAS), (McLennan 1989) because PAAS displays a combined effect of all the three types of sediments. The ΣREE values of C1 showed a higher value of 361.8 ppm and C3 showed a still higher value of 402.4 ppm. The patterns corresponding to C1 and C3 are shown in figure 6. They showed an enrichment of light rare earth elements (LREE) over heavy rare earth elements (HREE) in the core sediments. In order to know the degree of fractionation of LREE and HREE in the sediments, La_n/Sm_n and Gd_n/Yb_n were calculated. The La_n/Sm_n value for C1 is 1.08 and the corresponding value for C3 is 0.99. Similarly, the Gd_n/Yb_n value for C1 is 1.93

Table 5. *Distribution of REEs and Eu anomaly in the cores.*

Sample id	LREE (ppm) 139La	140Ce	141Pr	146Nd	147Sm	153Eu	157Gd	159Tb	163Dy	165Ho	HREE (ppm) 166Er	169Tm	172Yb	175Lu	ΣLREE	ΣHREE	ΣREE	La_n/Sm_n	Gd_n/Yb_n	Eu/Eu*
C1-1	65.24	143.80	13.60	50.11	9.60	2.89	8.44	1.04	5.41	1.01	2.77	0.38	2.33	0.32	293.68	13.26	306.94	1.23	1.85	1.42
C1-5	61.63	136.70	12.85	46.77	8.68	2.62	8.01	0.96	4.73	0.85	2.33	0.31	2.02	0.27	277.25	11.46	288.71	1.15	1.97	1.45
C1-8	79.90	176.20	16.94	61.65	11.23	3.31	10.70	1.36	6.42	1.19	3.33	0.45	2.84	0.39	359.93	15.97	375.90	1.08	1.78	1.63
C1-10	80.83	181.10	17.27	63.92	12.60	3.41	11.07	1.52	7.79	1.45	3.84	0.57	3.49	0.47	370.20	19.12	389.32	1.01	1.93	1.69
C1-13	84.41	196.00	18.16	66.21	12.47	3.58	11.50	1.52	7.39	1.41	3.74	0.50	3.20	0.41	392.33	18.17	410.49	1.13	1.93	1.59
C1-15	74.65	174.60	15.80	59.50	11.46	3.26	10.13	1.39	7.06	1.34	3.63	0.50	3.14	0.42	349.40	17.48	366.88	1.00	1.92	1.64
C1-18	94.38	217.10	20.02	74.11	13.90	4.29	13.05	1.68	8.61	1.59	4.35	0.57	3.63	0.49	436.85	20.92	457.78	1.05	1.96	1.71
C1-20	63.62	141.50	12.93	47.49	9.06	2.70	8.40	1.05	5.22	0.99	2.66	0.36	2.14	0.30	285.70	12.71	298.41	1.05	2.16	1.56
Mean	**75.58**	**170.88**	**15.95**	**58.72**	**11.12**	**3.26**	**10.16**	**1.32**	**6.58**	**1.23**	**3.33**	**0.45**	**2.85**	**0.38**	**345.67**	**16.14**	**361.80**	**1.09**	**1.94**	**1.59**
Std. dev	**11.48**	**28.48**	**2.63**	**9.80**	**1.87**	**0.54**	**1.77**	**0.27**	**1.37**	**0.26**	**0.69**	**0.10**	**0.62**	**0.08**	**56.58**	**3.38**	**59.96**	**0.08**	**0.11**	**0.11**
C3-1	82.92	165.50	16.39	58.44	9.76	2.82	8.95	1.11	5.83	1.08	3.11	0.43	2.93	0.41	344.78	14.89	359.67	0.99	2.19	1.51
C3-5	99.24	200.30	20.03	72.89	12.50	3.70	11.53	1.42	7.05	1.35	3.70	0.53	3.54	0.49	420.19	18.07	438.26	1.03	2.40	1.48
C3-8	78.31	158.60	16.26	60.77	10.55	3.52	9.83	1.29	6.45	1.29	3.53	0.51	3.35	0.46	337.84	16.87	354.71	1.03	2.28	1.42
C3-10	96.01	193.90	20.10	74.01	13.78	4.70	12.47	1.61	8.25	1.62	4.28	0.61	3.91	0.58	414.97	20.86	435.83	0.93	1.92	1.36
C3-13	102.00	199.70	20.18	73.44	13.06	4.10	11.31	1.46	7.40	1.42	3.80	0.54	3.55	0.47	423.79	18.62	442.41	0.98	2.18	1.41
C3-15	89.87	182.40	18.99	69.41	13.08	4.27	11.46	1.52	7.92	1.49	4.19	0.61	3.62	0.51	389.48	19.87	409.35	0.95	1.95	1.42
C3-18	80.25	161.40	16.57	60.89	11.10	3.88	10.27	1.34	6.62	1.31	3.57	0.49	3.17	0.44	344.36	16.95	361.31	0.99	2.18	1.50
C3-21	92.99	188.40	19.40	71.89	12.86	3.98	11.27	1.42	7.04	1.33	3.64	0.51	3.16	0.44	400.79	17.53	418.32	1.02	2.37	1.46
Mean	**90.20**	**181.28**	**18.49**	**67.72**	**12.09**	**3.87**	**10.89**	**1.40**	**7.07**	**1.36**	**3.73**	**0.53**	**3.40**	**0.47**	**384.52**	**17.96**	**402.48**	**0.99**	**2.18**	**1.45**
Std. dev	**8.91**	**17.20**	**1.77**	**6.55**	**1.43**	**0.56**	**1.12**	**0.15**	**0.79**	**0.16**	**0.38**	**0.06**	**0.31**	**0.05**	**37.55**	**1.90**	**39.45**	**0.04**	**0.17**	**0.05**
PAAS	38.20	79.60	8.83	33.90	5.55	1.08	4.66	0.77	4.68	0.99	2.85	0.41	2.82	0.43	171.82	12.94	184.77			

Bold indicates mean and standard deviation of core 1 and 3 separately.

Eu* is $\sqrt{(Sm_n \times Gd_n)}$.

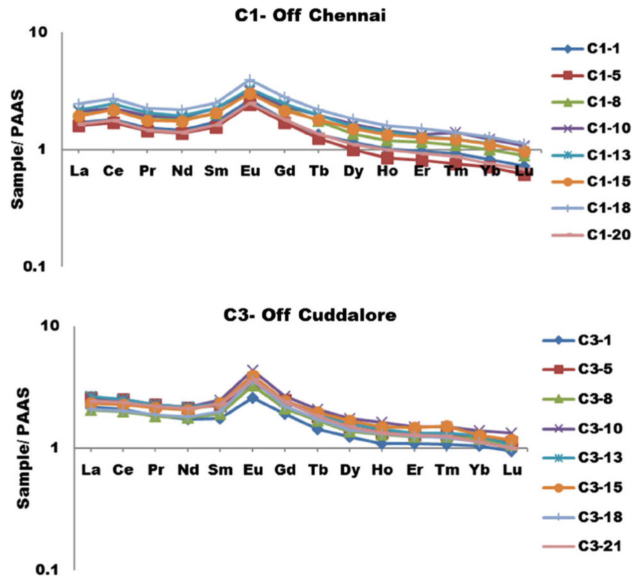

Figure 6. PAAS (McLennan 1989) normalized REE pattern for C1 and C3 cores.

and the corresponding value for C3 is 2.18. Positive Eu anomaly is observed in both the cores (figure 4). The Eu anomaly in C1 varied between 1.4 and 1.7 and ranged from 1.4 to 1.5 in C3. Trace elements such as vanadium, chromium, cobalt, nickel and zircon showed higher abundances in C1 than in C3 with Mn showing the highest concentration. Other elements such as the radioactive lead, thorium and uranium showed higher concentration in C3 than in C1 with the highest abundance of zinc in the sediments. The concentrations of these elements are given in table 6. In order to better understand the depositional conditions of sediments, Paleoredox Index (PI) was calculated using vanadium and chromium concentrations. The values of PI for both C1 and C3 ranged from 0.4 to 0.5 (table 6).

5. Discussion

The sources for the distribution of surface sediments in the bay have been previously reported by Siddique (1967), Goldberg and Griffin (1970), Kolla and Rao (1990). According to them, the peninsular India is the major source of these river borne sediments which form a significant fraction in the bay. The sediment distribution map given by Siddique (1967) reveals the presence of more than 75% of clay in the bay. Sand and silty clays are found to occur as a narrow zone along the coasts while silty sediments occupy a thin margin along the shelf. However, in the present study, sand is dominant in majority of the sample sites. The northern side of the region has very less clay content and is covered by a mosaic of medium and coarse sand. The mouth of River Palar shows significant coarse silt content which is also reported by Selvaraj *et al.* (2004). The southern side is blanketed

Table 6. Trace element distribution in the core sediments.

Sample id	51V	52Cr	55Mn	59Co	60Ni	65Cu	66Zn	90Zr	208Pb	232Th	238U	V/Cr
C1-1	46.23	92.91	1140.00	27.41	57.03	78.07	375.90	533.10	37.60	29.94	2.39	0.50
C1-5	54.25	123.00	1220.00	32.20	62.18	28.43	508.80	478.60	70.46	27.34	3.45	0.44
C1-8	50.71	110.50	1152.00	33.30	58.47	23.56	546.50	466.00	43.31	24.25	3.96	0.46
C1-10	64.10	132.20	1315.00	36.85	79.20	33.10	911.00	489.90	59.73	27.40	4.84	0.48
C1-13	57.04	115.60	1232.00	34.29	72.93	36.18	681.00	379.70	54.99	34.68	3.65	0.49
C1-15	61.86	130.80	1299.00	36.78	80.49	30.55	708.40	345.00	57.12	24.56	4.04	0.47
C1-18	52.31	110.20	1212.00	34.49	65.29	22.47	576.80	323.70	47.79	17.88	2.99	0.47
C1-20	50.76	105.10	1228.00	33.29	61.97	23.73	566.00	289.40	50.07	23.38	3.06	0.48
Mean	**54.66**	**115.04**	**1224.75**	**33.58**	**67.20**	**34.51**	**609.30**	**413.18**	**52.63**	**26.18**	**3.55**	**0.48**
Std. dev	**6.03**	**13.30**	**61.39**	**2.99**	**9.18**	**18.27**	**159.21**	**89.79**	**10.26**	**4.96**	**0.76**	**0.45**
C3-1	31.70	60.91	739.90	25.18	46.09	20.76	745.70	203.90	61.84	17.13	2.56	0.52
C3-5	28.77	51.13	661.30	22.58	39.99	15.46	793.20	140.00	52.91	18.06	2.16	0.56
C3-8	35.18	76.14	855.00	30.15	62.70	30.07	1022.00	234.00	286.10	27.47	3.80	0.46
C3-10	48.67	112.20	1071.00	43.16	97.60	51.06	2649.00	233.20	63.14	31.96	4.82	0.43
C3-13	37.77	73.18	968.30	36.49	61.11	31.02	1437.00	227.40	64.36	31.44	4.14	0.52
C3-15	37.80	70.86	886.50	33.96	59.69	45.28	1689.00	189.20	101.10	21.79	4.60	0.53
C3-18	39.23	77.44	1031.00	37.69	63.24	35.32	1052.00	224.10	86.74	44.53	6.79	0.51
C3-21	27.34	47.49	647.10	23.45	38.82	22.64	1175.00	165.50	65.19	18.64	2.98	0.58
Mean	**35.81**	**71.17**	**857.51**	**31.58**	**58.66**	**31.45**	**1320.36**	**202.16**	**97.67**	**26.38**	**3.98**	**0.50**
Std. dev	**6.80**	**20.07**	**162.74**	**7.48**	**18.75**	**12.19**	**621.64**	**34.79**	**77.72**	**9.43**	**1.48**	**0.34**

by medium and coarse sands in the inner shelf and fine sands are abundant in the outer shelf. These sands must have been carried to the deeper part by combined wave and current action (Van Rijn and Havinga 1993). The average standard deviation value of 1.04 indicates that the sediments are overall poorly sorted and texturally immature which is due to rapid transportation and fluctuating velocity conditions of the agent of deposition (Sahu 1964). The kurtosis values of the samples varied widely between platykurtic ($< 0.61\,\Phi$) and very leptokurtic nature ($3\,\Phi$) reflecting the flow characteristics of the depositing medium (Baruah *et al.* 1997; Rajganapathi *et al.* 2012). The leptokurtic nature and negatively skewed values for samples with abundant sand content is in accordance with the findings of Friedman (1962). The samples with relatively more negatively skewed values suggest erosion or non-deposition and winnowing of sediments (Duane 1964), while the less number of positively skewed samples indicate removal of coarser fraction or introduction of finer sediments (Friedman 1961). Among the few samples showing positive skewness, only few are the depositional sites of finer fractions while the others show positive skewness owing to the prevailing high energy environment confirmed by the presence of sand (Sly *et al.* 1982). Thus the frequency distribution pattern of the sediments displays unimodal to bimodal character. Finer grain size deposition in the absence of river flow is attributed to the currents and wave activity or due to the input from minor rivers flowing in this region. Clay mineral studies were attempted by a few earlier workers such as Sastry *et al.* (1958), Subba Rao (1964), Ramamurthy and Shrivastava (1979), Subramanian (1980), Rao *et al.* (1988), Kolla and Rao (1990) and Ramaswamy *et al.* (1997) in order to deduce the source of the sediments. According to Subba Rao (1964), smectite is considered to be very high in the east coast of India with equal quantities of illite and chlorite and minor amounts of montmorillonite and kaolinite. Goldberg and Griffin (1970) also observed that the eastern bay had high smectite content, very high illite and high kaolinite content. Studies reveal that eastern Bay receiving its riverine sediments from Ganges and Brahmaputra witnessed higher amounts of illite and chlorite in their clay mineral assemblages while the sediments derived from the peninsular India showed high quantities of montmorillonite (Goldberg and Griffin 1970) and smectite content (Ramaswamy *et al.* 1997). In the present study, clay mineral assemblage is characterized by higher amounts of illite, kaolinite, chlorite and minor amounts of smectite. The predominance of illite and moderate chlorite content suggests that they are derived as a result of mechanically weathered sedimentary, igneous and metamorphic rock formations (Chamley 1989) of the mainland. The significant amount of kaolinite is due to the extreme chemical weathering and leaching of rocks under tropical humid climate (Tripathi *et al.* 2007; Rajamani *et al.* 2009) more specifically, the weathering of Precambrian gneissic rocks of southern India (Das *et al.* 2013). Besides, the presence of smectite clays indicates the erosion and weathering of basaltic Deccan traps (Phillips *et al.* 2014).

According to Haque and Subramanian (1982) and many others, the REEs are more enriched in finer sediments. This is due to the high adsorption behaviour of heavy metals on the sediment surface (Rengarajan and Sarin 2004). The accumulation of REEs in the sediments can be due to use of fertilizers, mining activities and atmospheric deposition (Pan *et al.* 2002; Zhang *et al.* 2000; Tyler 2004). Based on the results, ΣREE values of C3 are greater than C1 and both the cores showed a significant deviation compared to the ΣREE value of PAAS (McLennan 1989) which is 184.76 ppm. The lower content of REEs in C1 is due to the presence of calcite in these sediments which dilutes their concentration (Antonina *et al.* 2013). The higher content of REEs in C3 indicates that they are supplied in addition to the terrigenous influx from the continental area (Prakash Babu *et al.* 2010; Deepulal *et al.* 2014) and suggest an alkaline environment (Ramesh *et al.* 2000). In the present study, the LREE content is greater than HREE content of the core sediments. Similarly, La_n/Sm_n values >1 observed in C1 shows enrichment of LREEs while the $Gd_n/Yb_n>2$ values of C3 indicate depletion of HREEs in the cores. This is in agreement with Deepulal *et al.* (2014) who observed in his study that the LREEs are present in higher concentration than HREEs in the eastern continental shelf sediments. The higher LREE/HREE values obtained in this region suggest that hot, humid climatic conditions would have prevailed during the time of weathering (Xing and Dudas 1993). According to previous workers, positive Eu anomaly is observed when hydrothermal vents are present or due to enrichment of feldspars. However, the positive Eu anomaly in the samples is due to the feldspar concentration (Elderfield 1988;

Murray *et al.* 1991) and weathering of source rocks (Ramesh *et al.* 2000). Besides, there is no evidence of hydrothermal activity in this region, thus ruling out the possibility of any hydrothermal input. The presence of feldspars is also supported by mineralogical results obtained from the present study. The average concentration of Cr, Ni and Co in clay-rich sediments was higher than in sandy sediments due to their adsorption capacity. The higher Pb, Th and U are ascribed to both natural and anthropogenic input. Also to understand the variations in paleoxygenated environment, V and Cr were chosen because vanadium is deposited under reducing conditions (Emerson and Huested 1991) and chromium is found in the detrital sediments. The V/Cr values of <2 as observed in both the cores indicate that the study area is characterized by an oxic environment (Jones and Manning 1994).

6. Conclusions

The present study reveals that the sediment distribution pattern is dominated by medium sand and is characterized by unimodal and bimodal characters. The moderately sorted to moderately well sorted sand sediments and limited deposition of very fine sediments suggest high energy environment prevailing in the sample sites. A significant number of samples showing negative skewness indicate the erosional and winnowing activity in the area of interest. The vertical sediment distribution revealed abundance of clay in the offshore regions of Chennai and to some extent in Cuddalore. The core sediments with abundant clay witnessed more illite content than other clay minerals and thereby suggest that the source is terrigenous. The lower ΣREE values noticed in C1-off Chennai are attributed to the diluting activity of biogenic matter. The higher ΣREE values in C3-off Cuddalore are due to an additional input of REEs from the land side. Positive Eu anomaly is due to the role of plagioclase feldspars in this region which is also confirmed by bulk mineralogical analyses. The trace elements showed good correlation with grain size with few exceptions. The paleoredox index using V/Cr values indicates that the study site is marked by oxygenated conditions and has no major variations in the depositional environment.

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