

Geochemical characterization of major and trace elements in the coastal sediments of India

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Abstract

Thirty-five surface sediment samples from the Indian continental shelf were recovered offshore from the mouths of the major rivers (Brahmaputra, Ganges, Narmada, Tapti, Godavari, Krishna and Cauvery) discharging into the coastal region of both east and west coast, were analysed using ICP–AES for selected major (i.e. Al, Ca, Fe, K, Ti, Mg and Na) and trace elements (e.g. Ba, Co, Cr, Cu, Ga, Ni, P and V), after total dissolution. The main objectives are to understand the processes controlling major and trace elements in the surface sediments and to identify natural and anthropogenic sources in the coastal environment using statistically regressed elemental concentrations to establish regional baseline levels. Metal enrichments observed close to the major urban areas in the east and west coast are associated with the industrialized activities areas rich in Cu and Co in both the east and west coast sediments. Normalization of metals to Al indicated that high enrichments factors in the order of Ca>Ti≥Fe>Na>Mg>Co>Cu>Ga>V>Ba except K and P depletion. This indicated the characteristic of estuarine sediment showed higher level along the west coast of India which was reflected in the coastal sediments as similar to the source of its origin from the riverine composition and its abundances.

Key words: Major and trace elements; Sediment; Continental shelf; India; Enrichment factors

Introduction

The long-term environmental monitoring requires an evaluation of the degree of contamination in marine and estuarine areas with particular emphasis upon understanding the environmental processes controlling sediment distribution in the assessment of trace elemental studies. Land-derived polluted materials have been documented in both estuaries and, to a less degree, in shelf sediments (Mil-Homens et al. 2006). However, differences in the environmental settings and the resulting sediment characteristics of different shelf areas have not been emphasized, which is necessary in order to clarify the influences upon the land-to-sea transfer of pollution. Assuming a certain amount of transfer from the estuary to the Indian Ocean, an evaluation of the Indian shelf sediment quality is needed to understand the overall fate of contaminants. In order to meet the objective of this study, the distributions of major and trace elements have been investigated for both east and west continental shelf of India, located in the vicinities of major river mouths (Brahmaputra, Ganges, Narmada, Tapi, Godavari, Krishna and Cauvery). The studies on the shelf region of India are scarce compared to other world region. The studies related to the east and west coast of India is dealt with certain part of the region (Paropkari et al 1978; Jonathan et al 2004). The geochemistry of Arabian Sea sediments have been studied by Kolla and Biscaye 1973, 1977; Kolla et al 1976a,b; Kolla et al 1981a,b; Shankar et al 1987; Paropkari 1990; Pedersen et al 1992. These studies are mainly focused on the clay mineralogy and elemental distribution in the sediment samples in Arabian Sea, the west coast of India. The present study aims to investigate on the geochemistry of the surficial sediment along the east and west coast of India influenced by the riverine input. The main objectives are (1) to characterize the behaviour of major (Al, Ca, Fe, Ti, K, Mg and Na) and trace elements (Ba, Co, Cr, Cu, Ga, Ni, P and V) in the surface sediments; (2) to establish baseline models by means of a normalization method and assess the contribution from natural and anthropogenic sources in the coastal environment; and (3) to evaluate the spatial distribution of major and trace elements in the east and west coast of India.

Materials and methods

Study Area

East coast of India

The outer limit of the eastern continental shelf of India lies at ~200 m (Fig. 1) and the inner shelf and the continental slope are covered by clastic sediments (Rao 1985). The outer shelf is covered by calcareous relict sediments and off the river mouths the shelf is covered by fine-grained

terrigenous sediments. The shelf at the mouths of the rivers receives a large part of its sediment from the rivers Ganges, Brahmaputra and Mahanadi in the north, Godavari and Krishna in the central region, all forming fertile and heavily populated deltas. Sediment from the rivers has made the bay a shallow sea, and the waters have reduced the salinity of surface waters along the shore. Sediment input and annual discharge is less from the smaller rivers such as Pennar and Cauvery in the south (Rao 1979, Rao 1985).

West coast of India

The Indus river is the largest source of sediments in the Arabian Sea, which extend outward to a distance of ~1000-1500 km (Rao and Rao 1995). It predominantly drains the Precambrian metamorphic rocks of Himalayas and to a lesser extent the semi arid and arid soils of West Pakistan and NW India (Krishnan 1968). Deccan Trap basalts (Fig.1) are the predominant rock types cropping out in the Saurashtra and the drainage basins of the Narmada and Tapti rivers, which annually discharge $\sim 60 \times 10^6$ tonnes sediment through the Gulf of Cambay (Rao 1975) where a semi-arid climate prevails. The Western Ghats are composed of basalts between Bombay and Goa, and Precambrian granites, gneisses, schists and charnockites between Goa and Cochin (Krishnan 1968). The Ghats are located on the coast between Goa and Bhatkal but are 50-80 km from the coast south of Bhatkal. The source of sediments in rivers originating in the western part of India is derived the black “cotton soils”, covering the Deccan Traps, a large percentage of which is mainly composed of montmorillonite. The drainage area in the upper reaches of these rivers is a montmorillonite-rich, zone but in the lower reaches, they drain through Precambrian formations that contain kaolinite rich soils that are of secondary significance in the shelf sediments derived from the Godavari and Krishna rivers (Rao 1991). Relic carbonate deposits are occurred on the western margin of India (Rao et al 2003). It is well established that source rock compositions and weathering mechanisms basically control the distinct geochemical compositions of sediments in the east and west coast of India (Alagarsamy and Zhang 2005).

Surface sediments from the east and west coasts of India were collected using a Van Veen Grab/Snapper during several cruises of R.V. Gaveshani (130, 139, 143 and 151) (Fig. 1; Table 1). Subsamples were taken from the uppermost layer of the sediment taking care to minimize the contamination. The samples were frozen after collection and later thawed, dried at 50-60°C in an oven and disaggregated in an agate mortar, before chemical treatment for total metal analysis. For element analysis, the known quantity (~0.2 g) of the powdered samples were digested with a mixture of concentrated HF - HNO₃ - HClO₄ for the total metal content (Zhang and Liu 2002). The solutions

were analyzed for Al, Mg, Ba, Ca, Na, K, Ti, Fe, Cr, Cu, Ni, Co, P, Ga and V using inductively coupled plasma atomic emission spectroscopy (model PE-2000).

Accuracy of the analytical methods was monitored by repeated analysis of standard reference materials (i.e. GSD-9 and NIM-G) together with batch of sediment samples. These data gave satisfactory results with analytical values within $\pm 1-10\%$ for different elements using the certified ones (GSD-9) except K and P and within $\pm 4\%$ for K and P of the certified ones (NIM-G).

Results and discussion

Average concentrations and ranges of all the measured metals in the coastal surface sediments, crustal average (Taylor 1964) and average shale (Turekian and Wedephol 1961) are depicted in Table 2. The highest values were recorded for Ca, Al and Fe, which originate in a large extent from the earth crust via weathering except Ca. Other metals which are measured in the shelf sediments, originate both from natural and anthropogenic sources. The relative abundances of these metals in the shelf sediments were as follows: Ca>Al>Fe>Na>Mg>Ti>K>Ba>P>V>Cu>Cr>Co>Ni>Ga.

Variation of elements in the east and west coast of India

When compared with shale value (Fig. 2a-b), Al, Na and V is slightly enriched in the east coast and higher in the west. This could be a dilution with lithic components that are low in Al content, such as dolomite or palygorskite affects all other elements that are not enriched in dolomite or palygorskite. Hence, the distribution patterns of all refractory elements, except Mg, reveal minimum concentrations. Mg is enriched in the west coast of India than the east; The variations of Mg in rocks can largely be attributed to three processes that enrich Mg^{2+} ions in rock forming minerals: (i) a substitution of Mg^{2+} for Fe^{2+} in crystal structures of Fe-rich minerals, preferentially in ultramafic olivines, pyroxenes, biotite and chlorite; (ii) a substitution for Ca^{2+} in carbonates. The magnitude of the Mg incorporation into the carbonates depends on the Mg concentration of the solution, where the carbonates precipitate, culminating in the formation of dolomite; (iii) adsorbed onto clay particles (the Mg^{2+} ions have a large cation exchange capacity). Ca, Ti, Fe, Cu, Co and Ga are enriched both east and west; The various carbonates, non-carbonate Ca is primarily found in plagioclase and in marine sediments in the form of apatite—a Ca-phosphate formed from fish bones and other biogenic debris (Sirocko et al 2000). This high Ti content only occurs in shallower waters near the coast, an observation which might be explained by two processes: (i) winnowing of the sediment surface by current activity which concentrates Ti-rich heavy minerals (Shimmiel et al

1990) and (ii) rapid settling of heavy mineral particles and also contributed from the area adjacent to basaltic source rocks (Deccan), which are rich in Ti (Turekian and Wedepohl 1961). Fe is leached from the Fe-rich basalts of the Deccan Traps which could enrich the Fe content in the samples. Organic matter is known to contain up to 100 ppm Co and has high flux rates of organic carbon, which apparently transfers high amounts of Co to the deep-sea where C_{org} is then remineralized—substantial proportions of Co and Ni can, however, be retained by the sediments. K, P and Ba is depleted in both the east and west coast of India with the exception of Ba enrichment observed in one station in the west. The low value of P could be due to lithic minerals, like quartz, feldspar, biotite, always exhibit values of $<0.03\%$ P. The Ba enrichment can be a result of sequestration of Ba from solution and by selected sediment components such as $CaCO_3$. The highest Ba contents are found in sediments rich in biogenic opal as diatom frustules can contain up to 30,000 ppm Ba (Collier and Edmond 1984). This Ba is removed from the water column by adsorption or by the formation of $BaSO_4$ crystals in reducing micro-environments of sinking organic particles (Bishop et al 1977). The crystals are stable in the sediments and dissolve only under extreme reducing conditions. The enrichment of Ga observed in the samples is related to weathering of basaltic rocks and high Ga values are related to alkaline igneous rocks. Cr and Ni is slightly enriched in the east coast than the west except some low values (Cr and Ga) in samples and it is not shown in the Fig. 2a-b. High Cr contents in clay-minerals (illite) that are derived from soils and trapping of Cr in strongly reducing sediments could increase the Cr content in the sediment. Like Cr and Co, Ni concentrations are highest in ultramafic rocks (Turekian and Wedepohl 1961). In ocean water, the dissolved Ni content reveals higher values well below the surface rather than at the surface, and the depth profile is similar to the dissolved Zn content, which in turn is related to the nutrient H_4SiO_4 content (Broecker and Peng 1982; Bruland 1980). The connection between Ni and the nutrient cycle is also reflected by high Ni contents found in marine organic matter (Collier and Edmond 1984). A third factor affecting Ni concentrations in sediments is its tendency to bind to metals, especially sulfides to Fe (pyrite). Copper concentrations in rocks reveal average values between 5 and 100 ppm—basalts have the highest values and feldspar-rich rocks the lowest (Turekian and Wedepohl 1961). Bruland (1980) and Broecker and Peng (1982) demonstrated that Cu concentrations in ocean waters increase with water depth—a pattern dependent on the nutrient content of the water and reflected in the chemical composition of plankton (Collier and Edmond 1984) and also by Saager et al (1992) in the Arabian Sea. Cu is found to be highly enriched in the clay fraction and associated with high organic matter content. Thus, the Cu enrichment appears to be caused by the fine-grained texture of sediments solely in this region.

Cu and Co enrichment is observed in the region close to Visakhapatnam and Mumbai coast, where industrial and harbour activities are intense. Visakhapatnam hosts several major industries viz. steel, refinery, petroleum products, petrochemicals, zinc, polymers, etc. Transportation to and from the port and industrial activities also play a major role in increasing the metal level in this region. Similarly, Mumbai coast also affected due to shipping and harbour activities, industrial and urban waste discharges and dredging etc. could contribute the enrichment of metals in the coastal environment. The sediment metal concentrations found in this study (Table 3) were of the same order of magnitude as metal concentrations found by diverse authors in sediments of Indian estuaries (Biksham and Subramanian 1988; Subramanian et al 1988; Ramesh et al 1990; Ramanathan et al 1993 and Alagarsamy 2006) except for Fe and Mn observed in the Mandovi estuary, west coast of India (Table 4). The normalised values of Mg, Ca, K, Ti and Fe with Al indicated that the estuarine sediment showed higher level along the west coast of India which was reflected in the coastal sediments as similar to the source of its origin from the riverine composition.

Geochemical normalization and enrichment factors (EF)

In an attempt to compensate for the natural variability of major and total trace elements in sediments, normalization was done so that any anthropogenic metal contributions could be detected and quantified. Loring (1991) indicated that the natural mineralogical and granular variability is best compensated by the geochemical normalization of major and trace metal data.

The following equation was used to estimate the EF of metals (Fig. 3a-b) from each sediment station using Al as a normalizer to correct for differences in sediments grain size and mineralogy:

$$EF = (Me/Al)_{\text{sample}} / (Me/Al)_{\text{crustal average}}$$

where $(Me/Al)_{\text{sample}}$ and $(Me/Al)_{\text{crustal average value}}$ are, respectively, the metal concentration ($\mu\text{g/g dw}$) except Mg, Ca, Ti, Na, K and Fe in relation to Al levels (% dw) in sediment samples, and crustal average values taken from Turekian and Wedephol (1961). EFs close to unity point to crustal origin while those greater than 10 are considered to be non-crustal source (Nolting et al 1999). EF values lower than 0.5 can reflect mobilisation and loss of these elements relative to Al, or indicate an overestimation of the reference metal contents (Zhang 1995). The higher EF values are observed in the order of $Ca > Ti \geq Fe > Na > Mg > Co > Cu > Ga > V > Ba$ except K and P depletion. The minimum EFs less than unity observed in the samples and the depletion of K and P implying that these elements are depleted in some of the phases relative to crustal abundances in the study area.

Gradient Method

The major and trace elements variation showed significant correlation against aluminium in the sediments (Tables 5 and 6). As discussed above, it was assumed priori that aluminosilicate minerals (i.e. kaolinite and smectite) are the major natural metal bearing phases in these sediments. The results appear to support this assumption since aluminium accounts for most of the variability of other metals with the exception of calcium and barium confirms that these elements are associated with aluminosilicate minerals (Rubio et al. 2000). Clearly other phases such as iron oxides and organic matter could be important contributors to total natural metal concentrations in these sediments. The relatively close relationship between iron and aluminium, however suggests that iron oxides are not important (i.e., iron is associated with aluminium in aluminosilicate phases).

For the metals that do correlate with aluminium, the relationship provides a useful method to normalize the relatively large range of observed natural metal levels in these sediments. In the case of the coastal sediments of India, aluminium clearly accounts for most of the grain size effect. As Al is mostly land-derived, the Element/Al ratios of the clay fraction give information about changes in the terrigenous fraction (Fig. 4a-c). The abundances of major elements and their ratios relative to Al is found to be higher in the west coast than the east except K. Mg/Al, Ca/Al and Na/Al ratio follow the similar trend and showed a higher enrichment of Mg/Al (2.13), Ca/Al (44.6) and Na/Al (1.46) at station 3191 which exceeded the crustal average at several stations. The higher concentration of Mg is attributed to Mg^{2+} by the ion exchange process with Ca^{2+} and the skeletal fragments and organisms from the skeletal debris are made up of high Mg-calcite contributing Mg to the present sediments and the dissolution of Mg in the shelf sediments is available for reprecipitation (Rao 1978). There was no significant change in the K/Al ratio within the sediments of east coast, suggesting that no changes in the relative illite content of the terrigenous fraction have occurred at this site. K/Al ratio is depleted compared to crustal average. One of the end products of chemical weathering of Deccan Traps is smectites, which may be trapping K and thereby contributing to its limited mobility (Das and Krishnaswami 2006). A correlation of K and Al ($R^2 = 0.87$ in the east coast; 0.76 in the west coast) suggests that in the sediments that detrital minerals exclusively control K. K is mainly held in illite and feldspar, therefore the variation in the K/Al ratio may reflect the variations in illite and feldspar present in the sediments. A higher potassium content relative to Al in sediments implies greater feldspar contribution. A low montmorillonite, high illite and kaolinite plus chlorite concentrations were observed in the sediment trap samples, which are derived from the Indus (Ramaswamy and Nair 1989). The higher Fe/Al reveals that Fe is enriched over Al in few stations in the west coast of India than the east coast along with Ti/Al. Part of Fe and/or Ti in sediments is known to be associated with the coarser size fractions whereas Al is more concentrated in the finer

fraction, clay minerals. As a result, Al and Fe (Ti) can be fractionated in solid phases of rivers draining in to the sea. This co-variation is attributable to the presence of weathering resistant Fe-Ti minerals. In general, Ti shows a tight correlation with Fe ($R^2 = \sim 0.70$) indicating a strong association between them in sediments of both east and west coast of India. Ti/Al records appears to be controlled by two mechanisms, i.e. local precipitation that is determined by changes in rainfall and laterite production and eolian transportation, which supplies Ti-rich dust from the Arabian Peninsula during dry periods. Ti/Al occurs in the coastal sediments indicating the major transition to dominance of carbonate dilution over insoluble residue. P/Al ratio indicating that the higher concentration of P was fixed in association with iron and supply of detrital phosphate or newly formed phosphatized limestone from neighbouring land (Jonathan et al. 2004). The abundances of trace elements (Ba, Co, Ni, Cu, Cr, Ga, V) and their ratios relative to Al in the sediments are highly variable in both east (abundances are higher for Cu, Ni, Ga and V) and west coast sediments. All elements except Ca, Na and Ba showed good relationship with Al and Ti probably resulting from its incorporation in Fe-rich minerals and adsorption on oxides/hydroxides for Fe.

Factors controlling the distribution of trace metals in the coastal sediments

In order to determine the factor controlling the spatial distribution of both major and trace elements, as well as the relationships between them, statistical analysis were used. Correlation analyses performed on the metal data in the shelf sediments indicate strong correlations between Al and Mg, Ti, K, Fe, P, Cr, Cu, Ni, Co, V and Ga (Tables 5 and 6), which indicate a similarity in their geochemical source, i.e., weathering of crustal rocks in the drainage area of the shelf region. Chromium, copper, nickel, cobalt, phosphorus, vanadium and gallium are significantly correlated with iron ($R^2 = 0.72-0.94$) in the shelf sediments. The relationship observed between Fe with P, Cr, Cu, Ni, Co, V and Ga may result from their similar behaviour in the redox condition, which influences the processes of their accumulation and remobilisation from the sediment. The positive correlation between trace elements and Al is related to the abundance of clays (Horowitz et al. 1988). Thus, most of the variability of those element concentrations in the sediment can be explained by the Al concentration, which reflects its texture and mineralogy. Therefore, the variation of these metal concentrations shows the same trend from one sampling point to another one. Sodium and barium did not correlate with any metals and calcium is inversely correlated with all metals except Sodium, potassium and barium.

The statistical analysis of intermetallic relationship revealed that the high degree of correlation and significant regression relation among the metals indicate the identical behaviour of

metals during its transport in the coastal environment (Tables 5 and 6). The positive correlations between Mg and transition trace elements, such as Fe, P, Cr, Cu, Ni, Co, V and Ga indicate that these elements are usually associated in sediments containing chlorite and serpentine, in turn derived from weathering of mother rocks rich in olivine, pyroxenes, and spinel; A negative correlation between Ca and Al in both east ($R^2=0.58$) and west coast ($R^2=0.71$) of India, indicating that CaO is mainly hosted within carbonates, thus precluding a significant presence of CaO-bearing silicates (Bianchini et al. 2002). The relic carbonate deposits are occurred on the western margin of India (Rao et al. 2003). Carbonates have a diluting effect on this group of elements which are of terrigenous origin (Rubio et al. 2000). In the present study, the poor association of Na and Ba with other metals (Al, Mg, Ca, Ti, K, Fe, Cr, Cu, Ni, Co, V and Ga) suggests that Na-oxide and Barite may be only a minor host phase for these elements in the coastal environment.

Anthropogenic inputs to the coastal sea along the east and west coast of India

Using the general principles applied in the examples discussed above, an attempt can be made to estimate anthropogenic inputs of metals to the coastal sea. Natural background levels and anthropogenic inputs of selected metals to the coastal sea can be estimated for each of the stations studied along the east and west coast. Ga values for the station nos. 3249, 3165, 3171, 3173, 3180, 3182, 3184 are not detectable and these are not shown in the Fig. 5a-d. Using the upper crustal average and the grain size proxy Ga normalised data on which the spidergrams (Fig. 5a-d) are based, the method involves the establishment of a background value for each element for east and west coast of India, determination of the average input of each element to the shelf region, calculation of the difference expressed as a percentage and the application of this percentage difference to calculate the percentage of the original (non-normalised) metal concentration in the shelf sediment that can be attributed to anthropogenic activity. It is necessary to use normalised data in the initial calculation of the percentage input in order to minimise the effects of different grain size distributions in the shelf sediment samples. Elements which are associated with clays or oxide coatings on clay minerals (Al, Mg, Na, K and Fe) are abundant in the sediments compared to other trace metals which showed the similar variation pattern as EF.

Conclusions

The first data presented for the concentration, distribution and possible sources of selected major (i.e. Al, Ca, Fe, K, Ti, Mg and Na) and trace elements (e.g. Ba, Co, Cr, Cu, Ga, Ni, P and V) in the coastal sediments revealed the importance of geochemical processes and possible environmental consequences of potential pollution due to the nearby industrial activities. Metal enrichments

observed close to the major urban areas in the east and west coast are associated with the industrialized activities areas rich in Cu and Co in both the east and west coast sediments. Sediment metal concentrations found in both east and west coasts were comparable to aquatic systems classified as contaminated from other regions of the world.

This study, first aimed to evaluate a reference element for normalizing sediment major and trace metal concentrations along the east and west coast of India. Application of the reference element technique identified the areas contaminated by examining bulk sediment concentrations alone. The normalisation technique enabled to assess the magnitude of enrichment relative to naturally occurring concentrations rather than relying on a limited number of measurements from the selected areas. The baseline reference element relationship will provide a tool for other scientists and managers involved in environmental monitoring and assessment programs or other research projects for assessing natural background levels of potentially important sediment contaminants in the east and west coast of India.

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Captions to figures

Fig. 1. Location of sediment sampling stations in the coastal region of India. Δ -RVG 130; \square - RVG 143; \circ -RVG 139; \bullet - RVG 151 represent the sampling sites of different cruises

Fig. 2a-b. Plot showing the variation of shale normalized metals in the east and west coast of India

Fig. 3a-b. Plot showing the variation of Enrichment Factor in the east and west coast of India

Fig. 4 a-c. Plot showing the variation of Al normalized metal in the east and west coast of India

Fig. 5a-d. Plot showing the variation of non-normalized & Gallium normalized metal in the east and west coast of India

Captions to Tables

Table 1. Sample details and locations

Table 2. Chemical composition of major and trace elements abundances in sediment, SPM, soil on a world basis and measured concentrations of metals in the coastal sediments

Table 3. Comparison of the major and trace elements abundances in the estuarine and coastal sediments from different areas of India

Table 4. Comparison of the major and trace elements abundances in the sediments from the other region

Table 5. Coefficient of determination (R^2) for metals in surface sediments of east coast of India ($R^2 > 0.24$, $p < 0.05$, $n = 14$, bold numbers are significant)

Table 6. Coefficient of determination (R^2) for the metals in surface sediments of west coast of India ($R^2 > 0.18$, $p < 0.05$, $n = 21$, bold numbers are significant)

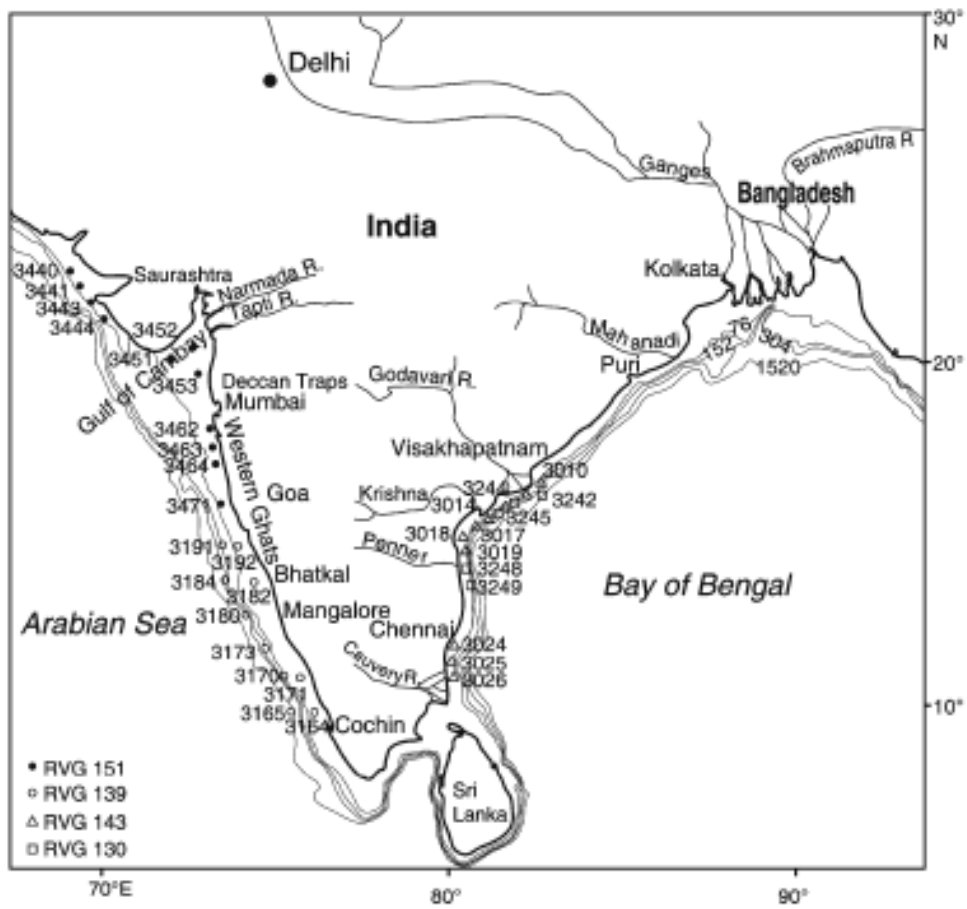


Fig.1

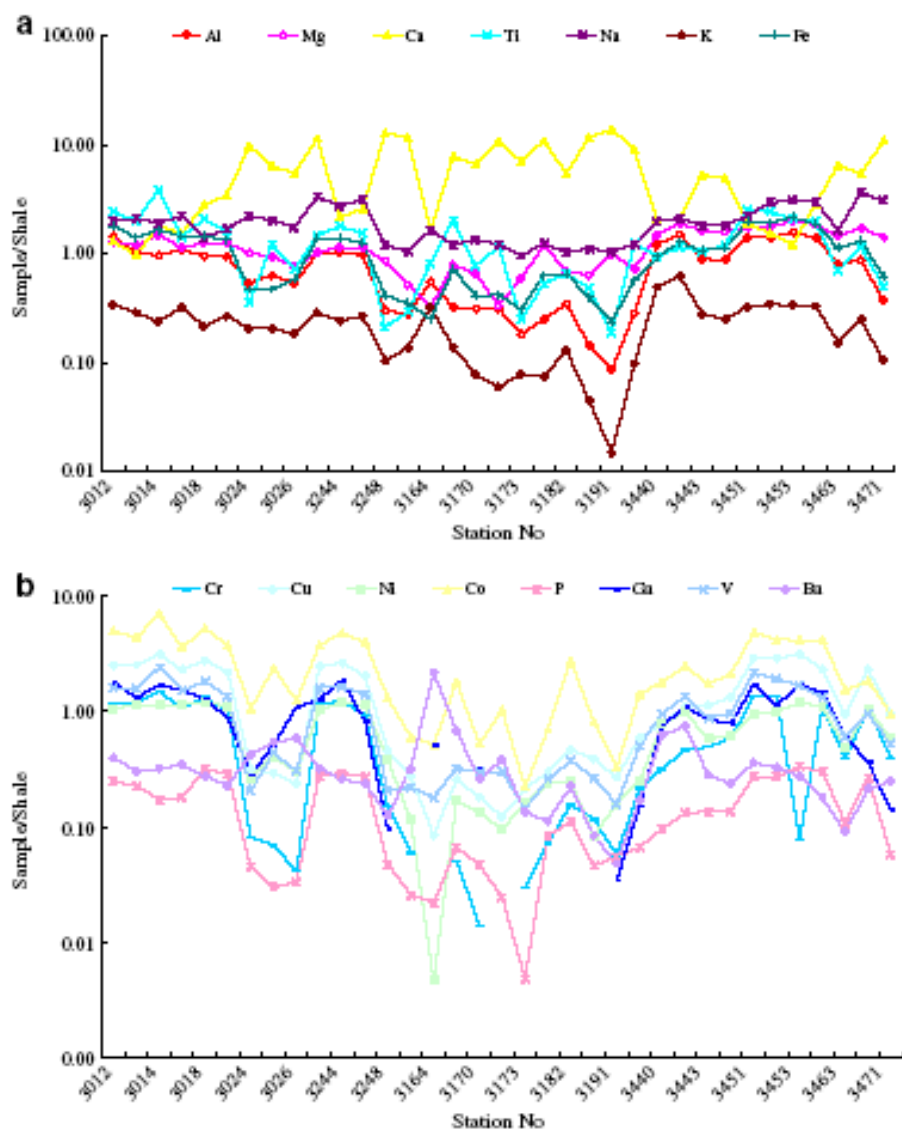


Fig.2

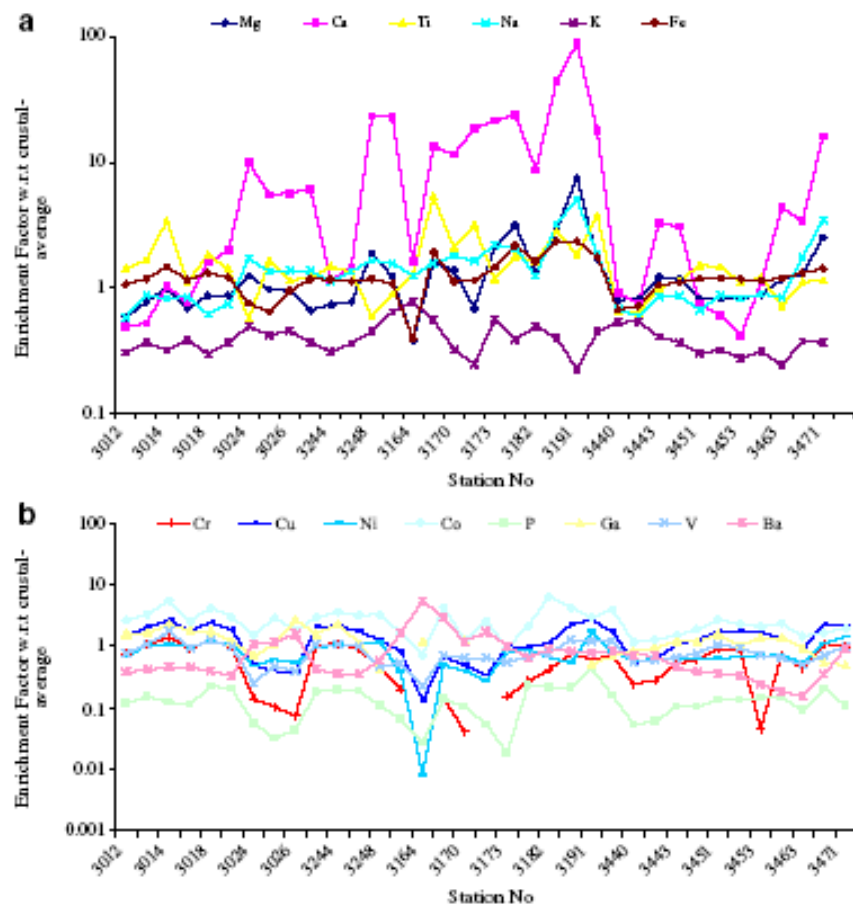


Fig.3

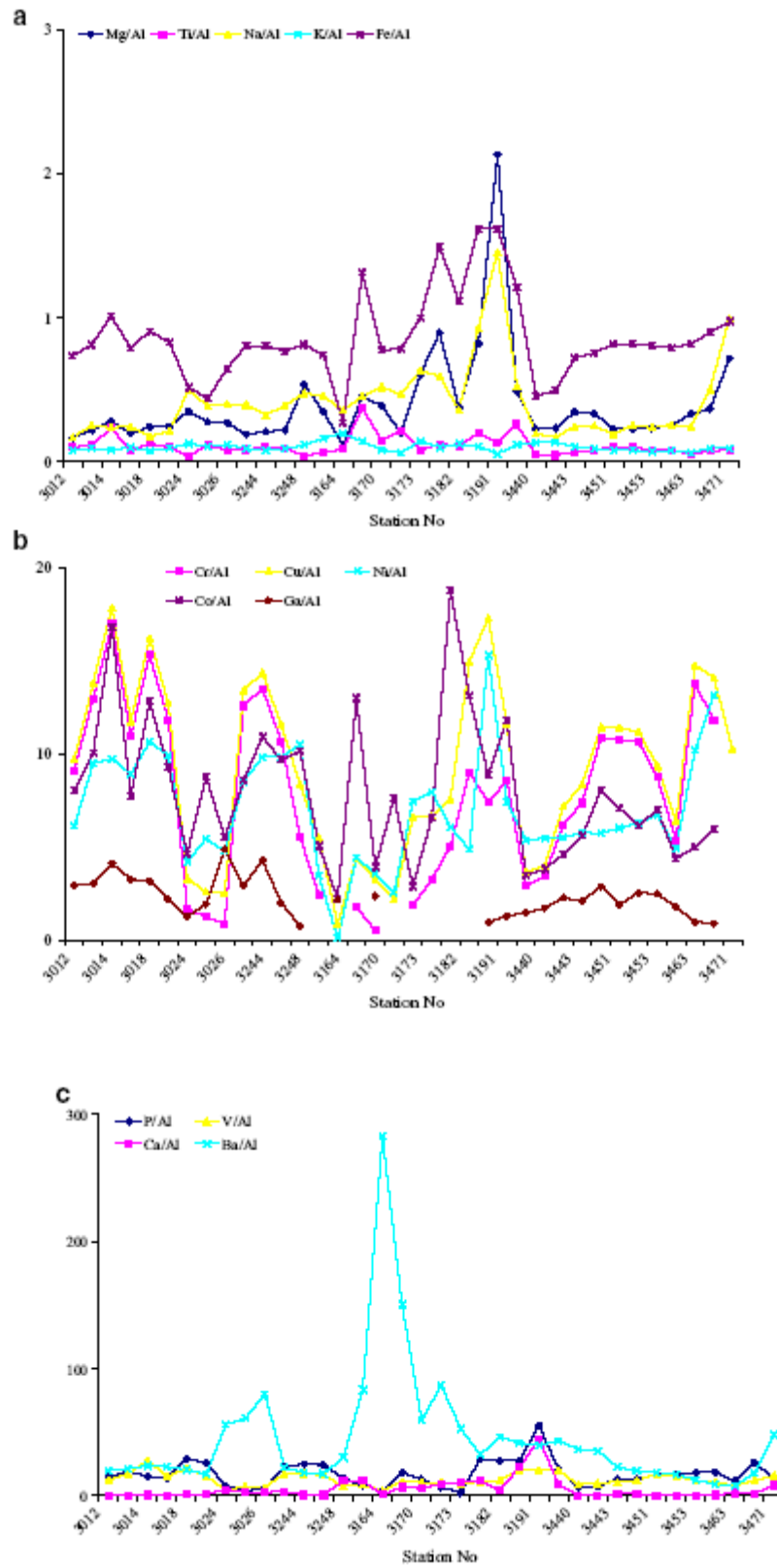


Fig.4

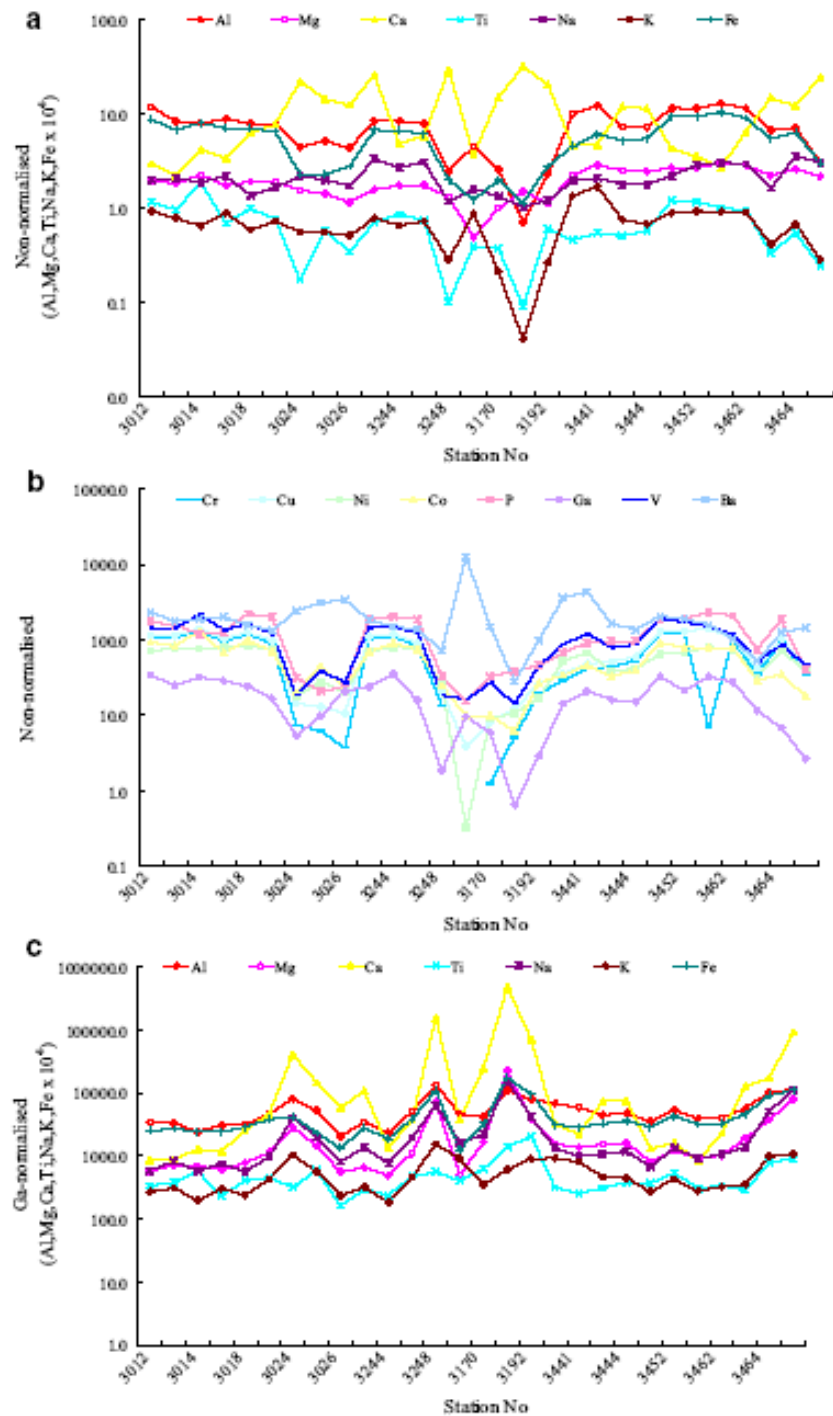


Fig.5

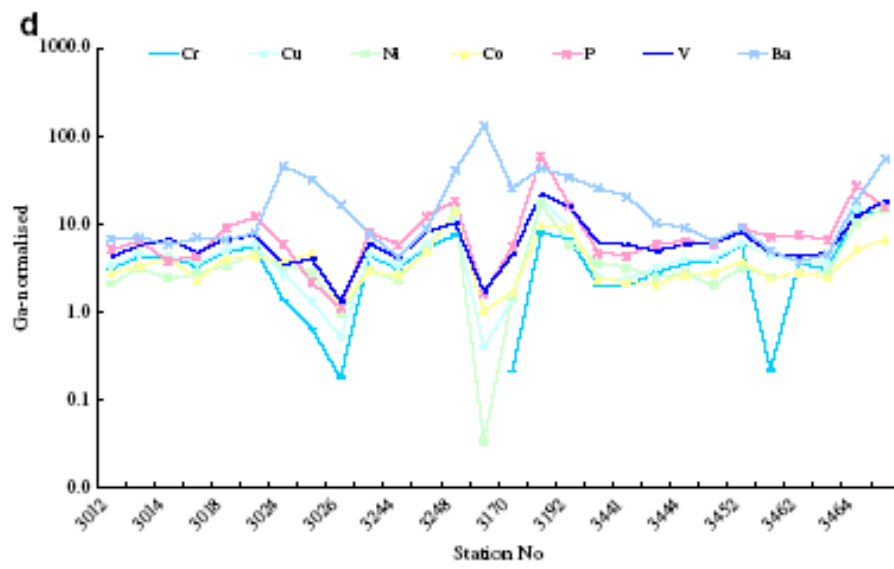


Fig.5

Table.1: Sample details and locations

	Station no.	Latitude (E)	Longitude (N)	Depth (m)
RVG 130				
1	3012	16°26'	81°31.0'	40
2	3013	16°11'	81°47.5'	55
3	3014	15°54.5'	81°14.6'	50
4	3017	15°39.5'	81°00'	48
5	3018	15°22.8'	81°33.1'	52
6	3019	15°0.3'	80°16.7'	52
7	3024	12°00'	80°05.6'	49
8	3025	12°00'	80°04.2'	50
9	3026	11°00'	80°02.5'	52
RVG 143				
10	3242	16°31'	82°30.7'	700
11	3244	15°39.1'	81°06.4'	660
12	3245	14°54.1'	80°20.5'	80
13	3248	13°30.5'	80°31.7'	120
14	3249	13°7.8'	80°32.6'	120
RVG 139				
15	3164	10°02.5'	76°00.0'	35
16	3165	10°01.0'	75°0.1'	90
17	3170	10°58.2'	75°8.7'	73
18	3171	10°58.2'	75°39.0'	33
19	3173	12°00'	74°40.0'	75
20	3180	12°59'	74°20.9'	60
21	3182	14°00'	74°19.0'	40
22	3184	14°00'	73°40.0'	78
23	3191	14°59.7'	73°20.0'	75
24	3192	14°59.6'	73°40.0'	49
RVG 151				
25	3440	22°53.7'	68°22'	23
26	3441	22° 24'	68°38'	22
27	3443	21°54.1'	68°56'	45
28	3444	21°30'	69°10'	57
29	3451	20°41'	70°44.6'	20
30	3452	20°14.1'	72°11.9'	30
31	3453	19°30'	72°16'	30
32	3462	18°20.4'	72°41.6'	25
33	3463	17° 50'	72°46'	32
34	3464	17° 19'	72°50.5'	60
35	3471	16°06'	73°00'	70

Table 2 Chemical composition of major and trace elements abundances in sediment, SPM, soil on a world basis and measured concentrations of metals in the coastal sediments

Metals	WA	WSR	WAS	Average shale	Crustal average	East coast			West coast		
						Min	Median	Max	Min	Median	Max
Al (%)	9.4	6.93	7.10	8.00	8.23	2.25	6.77	11.68	0.7	5.82	12.79
Fe (%)	4.8	3.59	4.00	4.72	5.63	1.67	5.27	8.58	1.13	4.54	10.27
Mg (%)	1.18	1.64	0.50	1.49	2.33	0.78	1.62	2.23	0.48	1.83	2.98
Ca (%)	2.15	4.50	1.50	2.21	4.15	2.17	11.85	28.77	2.7	13.80	26.18
Na (%)	0.71	1.42	0.50	0.96	2.36	1.02	2.00	3.26	1.0	1.82	3.52
K (%)	1.42	2.44	1.40	2.66	2.09	0.28	0.63	0.91	0.12	0.58	1.68
Ti* ($\mu\text{g g}^{-1}$)	4,160	3,800	5,000	4,700	5,700	0.1	0.71	1.84	0.09	0.54	1.2
P ($\mu\text{g g}^{-1}$)	1150	610	800	698.24	1050	18.07	122.31	221.89	3.38	87.77	233.64
V ($\mu\text{g g}^{-1}$)	170	97	100	90	135	18.48	104.55	144.86	14.18	68.86	194.82
Cr ($\mu\text{g g}^{-1}$)	100	97	70	90	100	3.71	70.4	133.22	N.D	45.94	135.86
Co ($\mu\text{g g}^{-1}$)	20	13	8	19	25	11.39	64.74	98.46	4.22	35.91	91.28
Ni ($\mu\text{g g}^{-1}$)	90	49	50	68	75	7.8	56.39	81.76	< 1	35.05	80.47
Cu ($\mu\text{g g}^{-1}$)	100	32	30	45	55	10.63	78.27	140.14	3.82	48.49	142.78
Ba ($\mu\text{g g}^{-1}$)	600	445	500	580	425	72.68	193.72	341.71	27.93	216.36	1258.10
Ga ($\mu\text{g g}^{-1}$)				19	15	N.D	21.04	35.57	N.D	14.70	32.46

WA World's average suspended sediments and WSR world's surface rock is taken from Martin and Meybeck (1979); WAS world's average soils from Bowen (1979). The average shale is taken from Turekian and Wedepohl (1961) and crustal average is taken from Taylor (1964). Ti* in % for east and west coast sediment samples

Table 3 Comparison of the major and trace elements abundances in the estuarine and coastal sediments from different areas of India

Metals	Ganges ^a	Brahmaputra ^a	Krishna ^a	Narmada ^a	Tapti ^a	Cauvery ^a	Godavari ^a	Hugli ^b	Coastal Bay of Bengal ^c
Al (%)	4.66	5.6	3.38	2.89	4.44	4.87	4.78	1.93-3.12	2.07
Fe (%)	2.16	2.9	4.23	3.14	1.09	1.76	6.03	2.53-4.01	1.50
Mg (%)	1.32	1.66	1.30	1.02	2.40	1.10	1.15	0.68-1	1.72
Ca (%)	2.34	1.93	5.34	2.01	8.16	1.50	3.81	0.49-0.96	0.91
Na (%)	-	-	-	-	-	-	-	0.029-0.97	1.18
K (%)	1.33	1.24	1.07	0.93	0.42	1.10	1.02	0.28-0.47	0.49
Ti ($\mu\text{g g}^{-1}$)	0.30	0.31	0.55	0.40	2.11	0.30	0.80	0.3-0.39	-
V ($\mu\text{g g}^{-1}$)	86	137	203	249	456	88	310	29-47	-
Cr ($\mu\text{g g}^{-1}$)	52	100	-	-	-	-	140	28.8-49.3	57
Co ($\mu\text{g g}^{-1}$)	22	31	47	29	36	64	50	10.4-15.9	9
Ni ($\mu\text{g g}^{-1}$)	20	47	-	-	-	-	52	26.5-44.5	30
Cu ($\mu\text{g g}^{-1}$)	21	17	49	46	126	12	73	21.5-64.1	20
Ba ($\mu\text{g g}^{-1}$)	348	347	425	330	280	444	537	75.8	58.6
Ga ($\mu\text{g g}^{-1}$)	-	-	-	-	-	-	-	5.26-9.28	-

^aBiksham and

Subramanian (1988)

^bSarkar et al. (2004)

^cSelvaraj et al. (2004)

Table 4: Comparison of the major and trace elements abundances in the sediments from the other region

Metals	Coastal sediments-Brazilian Antarctic station ^a	Peru margin ^b	Namibian mud lens ^b	Gulf of California ^b
Al (%)	3.16	4.71	1.26	4.72
Fe (%)	6.47	2.17	1.00	2.15
Mg (%)	0.14	1.19	0.46	0.95
Ca (%)	0.58	4.75	2.21	1.48
Na (%)	-	3.74	0.98	1.06
K (%)	-	1.27	0.48	1.38
Ti (%)	0.58	0.25	0.10	0.23
P (%)	-	0.36	0.21	0.10
V ($\mu\text{g g}^{-1}$)	204	152	138	101
Cr ($\mu\text{g g}^{-1}$)	31	98	83	44
Co ($\mu\text{g g}^{-1}$)	-	6.1	3.5	6.6
Ni ($\mu\text{g g}^{-1}$)	101	74	46	38
Cu ($\mu\text{g g}^{-1}$)	92	49	37	27
Ba ($\mu\text{g g}^{-1}$)	41	314	324	566
Ga ($\mu\text{g g}^{-1}$)	-	-	-	-

^aSantos et al. (2005) ^bBrumsack (2006)

Table 5: Coefficient of determination (R^2) for metals in surface sediments of east coast of India ($R^2 > 0.24$, $p < 0.05$, $n = 14$, bold numbers are significant)

	Al	Mg	Ca	Ti	Na	K	Fe	Cr	Cu	Ni	Co	P	Ga	V	Ba
Al	1.00														
Mg	0.64	1.00													
Ca	0.58	0.53	1.00												
Ti	0.55	0.74	0.52	1.00											
Na	0.27	0.10	0.04	0.05	1.00										
K	0.87	0.45	0.47	0.33	0.35	1.00									
Fe	0.89	0.73	0.56	0.70	0.16	0.69	1.00								
Cr	0.66	0.51	0.34	0.35	0.22	0.46	0.75	1.00							
Cu	0.74	0.72	0.47	0.70	0.15	0.52	0.94	0.80	1.00						
Ni	0.74	0.72	0.47	0.70	0.15	0.52	0.94	0.80	1.00	1.00					
Co	0.77	0.71	0.55	0.57	0.22	0.58	0.89	0.86	0.93	0.93	1.00				
P	0.67	0.82	0.55	0.92	0.10	0.40	0.84	0.60	0.89	0.89	0.80	1.00			
Ga	0.70	0.74	0.50	0.82	0.15	0.49	0.91	0.69	0.97	0.97	0.87	0.94	1.00		
V	0.67	0.37	0.51	0.56	0.07	0.46	0.72	0.38	0.64	0.64	0.54	0.61	0.65	1.00	
Ba	0.01	0.06	0.00	0.01	0.00	0.00	0.07	0.22	0.16	0.16	0.17	0.07	0.10	0.00	1.00

Table 6: Coefficient of determination (R^2) for the metals in surface sediments of west coast of India ($R^2 > 0.18$, $p < 0.05$, $n = 21$, bold numbers are significant)

	Al	Mg	Ca	Ti	Na	K	Fe	Cr	Cu	Ni	Co	p	Ga	V	Ba
Al	1.00														
Mg	0.70	1.00													
Ca	0.71	0.27	1.00												
Ti	0.49	0.25	0.37	1.00											
Na	0.50	0.55	0.26	0.26	1.00										
K	0.76	0.42	0.71	0.22	0.27	1.00									
Fe	0.83	0.74	0.48	0.65	0.55	0.51	1.00								
Cr	0.67	0.66	0.38	0.56	0.62	0.29	0.91	1.00							
Cu	0.69	0.67	0.38	0.57	0.67	0.37	0.91	0.93	1.00						
Ni	0.69	0.67	0.38	0.57	0.67	0.37	0.91	0.93	1.00	1.00					
Co	0.83	0.87	0.43	0.40	0.75	0.70	0.85	0.81	0.83	0.75	1.00				
P	0.69	0.48	0.47	0.74	0.35	0.30	0.86	0.79	0.77	0.47	0.64	1.00			
Ga	0.85	0.67	0.51	0.65	0.77	0.70	0.89	0.76	0.85	0.82	0.80	0.52	1.00		
V	0.84	0.47	0.61	0.72	0.18	0.77	0.79	0.63	0.62	0.56	0.56	0.67	0.78	1.00	
Ba	0.01	0.07	0.19	0.01	0.00	0.24	0.02	0.04	0.03	0.03	0.00	0.01	0.00	0.00	1.00