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Major and trace element geochemistry of the mid-Bay of Bengal surface sediments: implications for provenance

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Abstract

The major and trace elements in 110 surface sediment samples collected from the middle of the Bay of Bengal (mid-Bay of Bengal) are analyzed to investigate provenance. Si levels are highest, followed by Al, and the distributions of these two elements are identical. The average CIA* (chemical index of alteration) value is 72.07, indicating that the degree of weathering of the sediments in the study area is intermediate between those of sediments of the Himalayan and Indian rivers. Factor analyses and discrimination function analyses imply that the two main provenances are the Himalayan and the Indian continent. The inverse model calculation of the Ti-normalized element ratios of the Bay of Bengal sediments indicate an estimated average contribution of 83.5% and 16.5% from the Himalayan and peninsular Indian rivers to the study area, respectively. The Himalayan source contributes more sediment to the eastern part of the study area, whereas the western part receives more sediment from the Indian Peninsula than did the eastern part. The primary mechanisms for deposition of sediments in the study area are the transport of Himalayan matter by turbidity currents and river-diluted water and the transport of Indian matter to the study area by a surface circulation in the Bay of Bengal, particularly the East India Coastal Current.

Key words: major and trace element, Bay of Bengal, provenance, quantification, factor analyses

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1 Introduction

The elemental composition and distribution of marine sediments are generally dependent on the provenance, hydrodynamic conditions, and granular characteristics of the sediments. Elemental geochemical parameters play an important role in the evaluation of sedimentary environments, and the discrimination of sediment provenance is progressing (Zhao and Yan, 1994). Substantial effort has been expended on studies of the Bengal Fan, one of the major deposition areas for erosion from the Tibetan Plateau and Himalaya Mountains (Kolla and Biscaye, 1973; Fagel et al., 1994, 1997; Ramaswamy et al., 1997; Colin et al., 1999; Kessarkar et al., 2005; Phillips et al., 2014). Earlier studies of the provenances of the sediment in the Bay of Bengal relied mainly on clay mineral and Sr-Nd isotopic compositions. On the basis of clay mineral characteristics, Kolla and Biscaye (1973) concluded a dominant role of Himalayan sediments rich in illite and chlorite in the Bengal Fan sediments and mapped the distribution of the provenances, which indicated that the sediments in the Bay of Bengal mainly belong to the Ganga group and the Deccan group (Kolla and Biscaye, 1973). The mineral characteristics of the Bengal Fan sediments indicate that nearly all sediments are from the Tibetan Plateau and the Himalaya Mountains. Himalaya-derived illite transported by turbidity currents can reach as far as the central Indian Ocean Basin (Rao and Nath, 1988). However, a more substantial effect is evident on the edge area of the Bengal Fan: the Krishna-Godavari Basin sediments, which primarily comprise smectite-rich clay mineral assemblages, are influenced by Deccan basalts; the Mahanadi Basin sediments, which primarily comprise illite-rich clay mineral assemblages, are influenced by Precambrian rocks of the eastern Ghats Belt; sediments in the eastern Bengal Fan are notably influenced by Sunda arc volcanic material (Phillips et al., 2014). Additionally, some studies analyzed the chemical composition of the Bay of Bengal sediments (Colin et al., 2006; Prakash Babu et al., 2010). The geochemical characteristics of the eastern Bengal Fan sediments indicate that the main provenances are the Tibetan Plateau and the Himalaya Mountains (Prakash Babu et al., 2010), and the sources were likely controlled by past changes in the summer monsoon intensity (Colin et al., 2006). A quantification study is an important requisite for a "source-sink" program. However, the quantification of surface sediments in the Bengal Fan has been limited. Elements and Sr isotopes have been used to quantify erosion rates in the Ganga Basin in the Himalayas (Tripathy and Singh, 2010). Major and trace elements have been investigated to infer the contribution of different provenances to the SK187/PC33 core sediments in the western Bengal Fan. Average

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sediment contributions of 66% and 34% from the Himalayan and peninsular Indian rivers to the core site, respectively, have been estimated (Tripathy et al., 2014). The present study attempts to map the distribution of provenances, estimate the contributions of different provenances to the mid-Bay of Bengal and determine the factors that control these contributions based on variations of their major and trace elemental compositions.

The Bengal Fan, the largest submarine fan in the world, is located in the northeastern Indian Ocean and is surrounded by the Indian Peninsula (west), Bangladesh and the Himalayas (north), the Andaman Sea and Southeast Asia (east), and the central Indus Basin (south). The main rivers in this area include the Ganga, Brahmaputra, Mahanadi, Krishna, Godavari and Irrawaddy (Fig. 1). The surface currents in the Bay of Bengal are predominately controlled by the India monsoon and exhibit apparent seasonal variations: anticlockwise in winter, when the northeast wind prevails, and clockwise in summer, when the southwest wind prevails. The present study area is located in the middle of the Bay of Bengal (mid-Bay of Bengal) (Fig. 1) and features water depths of approximately 2.2–3.0 km.

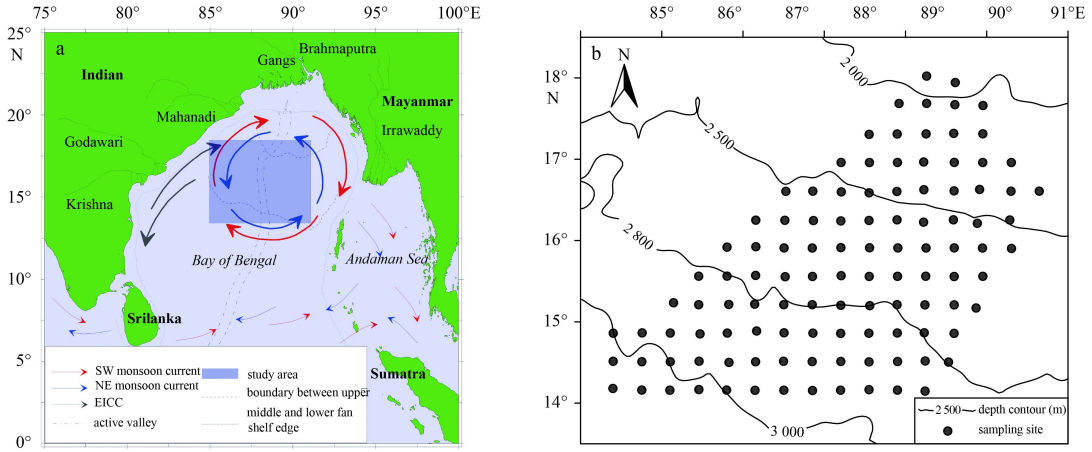

Fig. 1. Location of the Bay of Bengal (a) and sampling sites in the study area (b) (circulation patterns are modified from Kolla et al. (1976) and Zhang (2002)).

2 Materials and methods

2.1 *Sample collection*

The 110 surface sediment samples analyzed in this study were collected from the mid-Bay of Bengal between March and May 2014 by The First Institute of Oceanography (FIO), State Oceanic Administration (SOA), China using a box corer (size: 30 cm×30 cm×65 cm; a mass: 200 kg; sediment: approximately 70 kg). This corer had a small volume, was easy to operate and caused minimal disturbance, therefore, it is ideal for stratified sampling. Light yellow-colored fluid mud was observed on the surface of the samples and suggested that the surface sediments were well preserved. Sediments collected in the upper 5 cm were stored and analyzed to ensure isochronism of the samples.

2.2 *Grain size analyses*

The measurements of the grain size distributions of carbonate-free terrigenous particles were carried out using a laser grain-size analyzer (Malvern 2000, range: 0.02–2 000 μm, resolution: 0.01Φ). Prior to the analyses, 15 mL of 3% H_2O_2 and 5 mL of 3 mol/L hydrochloric acid (HCl) were added to remove organic matter and carbonate fractions, respectively. Then, the mixture was rinsed several times using deionized water and extracted via the centrifugation. After ultrasonic oscillation, the samples were measured. The relative error of repeated measurement was less than 3%. Preparation and measurement were completed at the Key Laboratory of Marine Sedimentology and Environmental Geology (MASEG), FIO, SOA, China.

2.3 *Geochemistry analyses*

The freeze-dried samples were powdered to 200 mesh and dried. Each sample (0.05 g) was weighed, placed in a polytetrafluoroethylene digestion tank, dissolved twice in HF-HNO_3 (1:1), and dried again at 190°C for 48 h. 3 mL of 50% HNO_3 was then added to each sample, and the samples were dried at 150°C for at least 8 h, removed and analyzed. Element concentrations were analyzed using an inductively coupled plasma optical emission spectrometry (ICP-OES; Si, Al, Ca, Fe, K, Mg, Mn, Na, P, Ti, Ba, Sr, V, Zn, and Zr) and inductively coupled plasma-mass spectrometry (ICP-MS; Sc, Cr, Co, Ni, and Cu). Several samples were analyzed in replicate to determine the precision of the measurements, and the elemental compositions of a GSD-9 reference standard were measured to confirm the accuracy of the analyses, which was greater than 2% for most elements. The analyses were also performed at the Key Laboratory of MASEG, FIO, SOA, China.

3 Results and discussion

3.1 *Grain size and elemental content*

The mean grain size (Mz) varies between 6.2Φ and 7.6Φ, with an average of 7.1Φ. Fine grain fractions were mainly distributed in the northern and southern parts of the area, with a size range of 7.1Φ–7.6Φ, while the coarse fraction was mainly distributed in the central part of the area, with an Mz below 7.1Φ (Fig. 2a). Four types of sediments were observed in the study area: silt, sandy silt, mud and sandy mud (Fig. 2b).

The concentrations of major and trace elements in the surface sediments are summarized in Table 1. Among the analyzed major elements, Si exhibited the maximum average concentration (18.80%) and P exhibited the minimum average concentration (0.04%). Among the analyzed trace metals, Ba exhibited the maximum average concentration (834.42 μg/g), and Sc exhibited the minimum average concentration (15.93 μg/g). Isoconcentra-

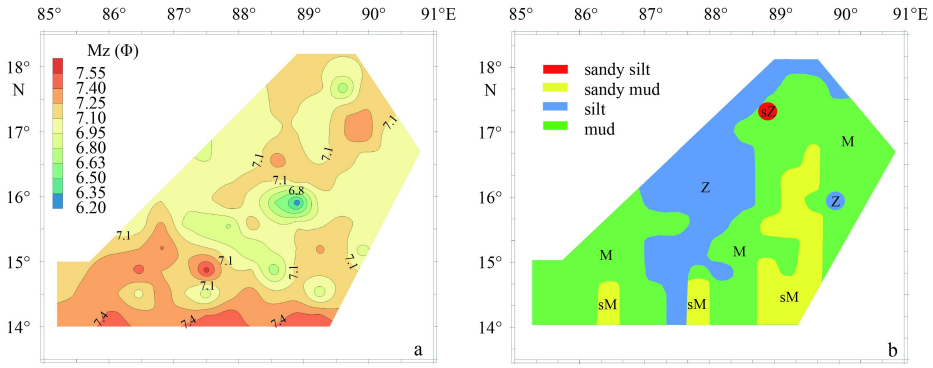

Fig. 2. Mz distribution (a) and types of sediments (b) in the study area. sZ represents sandy silt, sM sandy mud, Z silt, and M mud.

Table 1. Elemental composition of the study area and the adjacent areas

Major	Max	Min	Average	C.V.	G-B	G-K	M	Trace	Max	Min	Average	C.V.	G-B	G-K	M
Si	28.19	11.89	18.80	0.19	—	—	—	Ba	1 217.00	464.00	834.42	0.19	479.00	205.00	255.00
Al	9.05	4.13	6.56	0.17	6.30	7.60	5.14	Sr	828.00	118.90	444.49	0.43	112.00	140.00	211.00
Ca	18.68	1.05	8.62	0.56	1.15	1.70	3.93	V	174.60	75.26	111.44	0.17	96.50	192.00	310.00
Fe	7.01	2.61	4.25	0.18	3.00	6.30	5.49	Zn	182.20	70.06	112.38	0.19	88.00	151.00	200.0
K	2.91	1.13	1.88	0.24	2.05	1.69	2.22	Zr	166.90	64.36	98.45	0.22	—	—	—
Mg	1.42	0.80	1.07	0.12	1.10	1.40	1.96	Sc	23.14	11.57	15.93	0.14	—	—	—
Mn	3.23	0.07	0.68	0.73	—	—	0.70	Cr	140.30	65.56	90.38	0.14	98.50	129.00	236.00
Na	3.53	1.47	2.07	0.14	0.80	0.30	2.20	Co	50.03	16.84	28.20	0.17	15.50	30.00	43.00
P	0.06	0.03	0.04	0.15	—	—	0.15	Ni	173.09	39.95	99.96	0.28	48.00	84.00	278.00
Ti	0.61	0.24	0.38	0.21	0.38	0.70	0.31	Cu	132.20	29.57	71.54	0.19	36.00	91.00	57.00
CIA*	76.69	67.50	72.07	0.02	72.00	87.00	63.00	DF	—	—	—	—	0.15	0.24	0.51

Note: G-B is abbreviated from Ganga-Brahmaputra (data from Garzanti et al. (2011)); G-K is abbreviated from Godavari-Krishna (data from Pattan et al. (2008)); M is abbreviated from Myanmar coast (data from Roonwal et al. (1997)); CIA* is abbreviated from chemical index of alteration; DF is abbreviated from discrimination function and C.V. is abbreviated from coefficient of variation. The concentrations of Si, Al, Ca, Fe, K, Mg, Mn, Na, P, Ti are indicated in percent and the concentrations of Ba, Sr, V, Zn, Zr, Sc, Cr, Co, Ni, Cu are indicated in microgame per grame; —represents no data.

tion maps of selected typical elements are presented in Fig. 3. The distribution features of Si, Al, and Ti were similar, with higher concentrations in the southern and northern areas of the study area and lower concentrations in the northwestern, northeastern and central areas of the study area. By contrast, Ca concentrations were higher in the northwestern, northeastern and central areas. The distribution features of Cu and Co indicated relative homogenization, with no apparent higher and lower areas.

3.2 *Discrimination of main provenances*

The chemical composition of marine sediments is determined by the proportions of materials derived from detrital, authigenic and hydrothermal sources (Tripathy et al., 2014). Detrital material and biological components play dominant roles in the study area (Kessarkar et al., 2005; Pattan et al., 2008). To determine the relative contributions of different provenances, the different source materials must have different chemical compositions, and the source signatures must be well preserved in the sediments of the study area. The chemical composition of river sediments is likely to remain mostly unaltered in the sea (Tripathy et al., 2014), and consequently, the comparison of the chemical composition of river sediments with that of marine sediments can provide useful information regarding provenance contributions.

The chemical index of alteration (CIA) can provide useful information about chemical weathering. The extent of weathering loss for detrital components can be estimated by comparing the CIA values of sediments in the study area with those of the source materials. Here, the modified CIA* (no CaO included, the oxide abundances are in molar units) (Tripathy et al., 2014) is expressed as follows:

$$\mathrm{CIA}^{*}=100\times\frac{\mathrm{Al_2O_3}}{\mathrm{Na_2O}+\mathrm{K_2O}+\mathrm{Al_2O_3}}. \quad (1)$$

The CIA* values for major rivers in the potential provenances are presented in Table 1. The CIA* for the surface sediments of the study area is intermediate between the CIA* for sediments from the Himalayan and Indian rivers, with an average CIA* value of approximately 72.07. This results confirms that the composition of the source material is preserved in the Bay of Bengal sediments and therefore can be used to trace their provenances and estimate relative contributions to the study area.

The factor analyses of the geochemistry data set were performed using IBM SPSS Statistics 19.0 software to further constrain the factors influencing the geochemistry data for the surface sediments in the study area (Table 2). The following conditions must be satisfied in the factor analyses: (1) sufficient number of samples, generally, the number of samples must be at least five times the number of variables; (2) a strong correlation must exist between the original data, the factor analyses can be performed when the Bartlett test of sphericity yields a value under 0.05 or the Kaiser-Meyer-Oklin (KMO) measure of sampling adequacy is above 0.5; and (3) the common factors obtained must be significant, and a factor rotation can be used if necessary. In our study, 110 samples were analyzed, and the number of

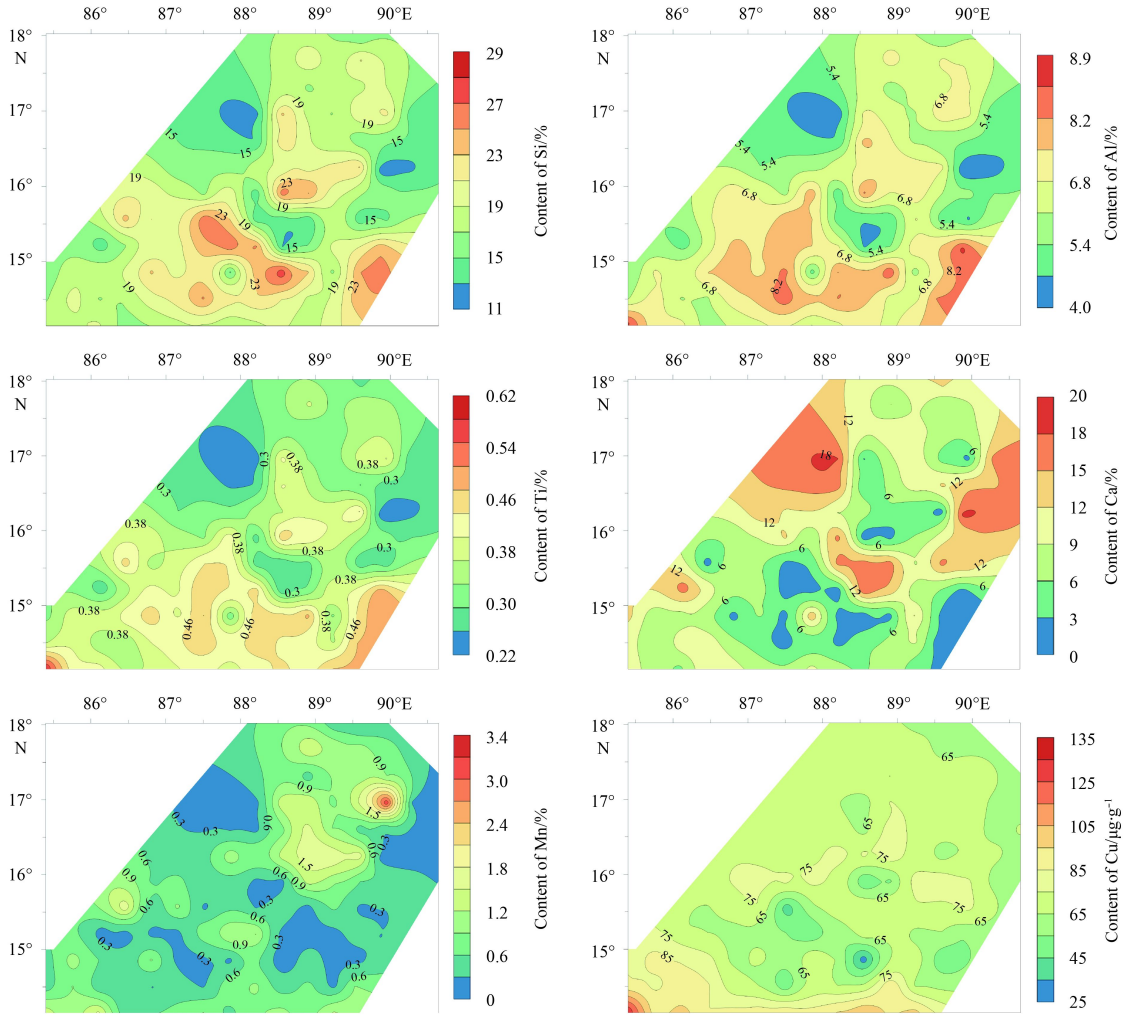

Fig. 3. Distribution of typical elements in surface sediments in the study area.

Table 2. Factor analyses of the geochemical data set and extraction of three factors with eigen values greater than 1

Major element	F1	F2	F3	Trace element	F1	F2	F3
Si	0.94	0.05	–0.28	Ba	–0.82	0.37	0.20
Al	0.96	0.09	0.07	Sr	–0.95	–0.10	0.16
Ca	–0.95	–0.16	0.14	V	0.88	0.17	0.33
Fe	0.90	0.16	0.38	Zn	0.55	0.71	0.34
K	0.93	0.00	–0.28	Zr	0.90	0.06	–0.27
Mg	0.93	0.29	0.10	Sc	0.77	0.16	0.52
Mn	0.31	0.84	–0.01	Cr	0.82	0.21	0.38
Na	0.13	0.82	0.38	Co	–0.01	0.49	0.79
P	0.67	0.39	–0.30	Ni	–0.24	0.82	0.33
Ti	0.97	0.04	0.18	Cu	–0.18	0.32	0.91
Eigen value	12.00	4.59	1.37	Eigen value	12.00	4.59	1.37
Variance/%	57.87	17.27	14.70	Variance/%	57.87	17.27	14.70

samples was five times large than the number of variables. The Bartlett test of sphericity and the KMO measure of sampling adequacy were 0 and 0.85, respectively. Thus, it was appropriate to perform the factor analyses. An oblique rotation, which requires oblique relationships between factors, was used. Three major factors with eigen values greater than 1 that together explain approximately 90% of the variance of the data set were extracted. The dominant factor (Factor 1 (F1)) explains approximately 58% of the total variance and is loaded primarily with lithogenic elements, e.g., Si, Al, Ti and Fe. Ti and Al frequently reflect the detrital component. These elements tend not to migrate in weathering processes and can preserve the source signatures; therefore, they are assigned as the detrital source in Factor 1. Factor 1 is also characterized by higher loading with various trace elements (V, Cr, Zr, and Sc, Table 2), which implies that their dominant source is also terrigenous. The higher loading of Fe and weak loading of Mn (much less than in Factor 2 (F2)) in Factor 1 and the weak correlation (0.40, Table 3) between Fe and Mn indicate that Fe in

Table 3. Correlation coefficients between chemical constituents of surface sediments from the mid-Bay of Bengal (n=110)

	Si	Al	Ca	Fe	K	Mg	Mn	Na	P	Ti	Ba	Sr	V	Zn	Zr	Sc	Cr	Co	Ni	Cu	Mz
Si	1.00																				
Al	0.88	1.00																			
Ca	–0.97	–0.91	1.00																		
Fe	0.74	0.91	–0.83	1.00																	
K	0.93	0.91	–0.89	0.72	1.00																
Mg	0.85	0.95	–0.91	0.93	0.86	1.00															
Mn	0.36	0.31	–0.47	0.40	0.27	0.52	1.00														
Na	0.05	0.23	–0.18	0.41	0.02	0.42	0.65	1.00													
P	0.69	0.66	–0.65	0.55	0.72	0.69	0.42	0.30	1.00												
Ti	0.86	0.93	–0.90	0.96	0.84	0.93	0.34	0.24	0.62	1.00											
Ba	–0.81	–0.68	0.79	–0.60	–0.75	–0.61	–0.01	0.28	–0.42	–0.76	1.00										
Sr	–0.97	–0.90	1.00	–0.81	–0.90	–0.89	–0.43	–0.13	–0.63	–0.89	0.82	1.00									
V	0.71	0.87	–0.80	0.94	0.73	0.91	0.40	0.38	0.60	0.92	–0.59	–0.78	1.00								
Zn	0.46	0.64	–0.61	0.73	0.43	0.76	0.75	0.76	0.52	0.61	–0.11	–0.56	0.74	1.00							
Zr	0.95	0.82	–0.88	0.71	0.90	0.80	0.32	0.09	0.73	0.86	–0.75	–0.88	0.69	0.41	1.00						
Sc	0.59	0.81	–0.69	0.90	0.57	0.82	0.34	0.42	0.44	0.83	–0.45	–0.67	0.83	0.71	0.56	1.00					
Cr	0.66	0.84	–0.74	0.88	0.70	0.87	0.43	0.41	0.54	0.85	–0.48	–0.72	0.88	0.72	0.66	0.87	1.00				
Co	–0.18	0.06	0.03	0.35	–0.23	0.18	0.46	0.66	–0.03	0.16	0.32	0.08	0.33	0.57	–0.16	0.46	0.40	1.00			
Ni	–0.27	–0.11	0.13	0.05	–0.32	0.06	0.55	0.73	0.03	–0.14	0.55	0.18	0.02	0.56	–0.26	0.16	0.10	0.63	1.00		
Cu	–0.40	–0.10	0.23	0.24	–0.43	0.00	0.24	0.56	–0.25	0.02	0.43	0.27	0.20	0.43	–0.36	0.38	0.25	0.87	0.58	1.00	
Mz	–0.14	0.15	–0.04	0.36	–0.12	0.19	0.13	0.36	–0.20	0.18	0.05	–0.03	0.29	0.38	–0.25	0.35	0.26	0.46	0.29	0.54	1.00

these sediments is primarily of detrital origin but is minimally related to Fe-Mn oxide. The typical biophile elements, Ca, Ba, and Sr, exhibit higher negative loadings in Factor 1 because their concentrations are primarily controlled by carbonate and biological deposition, which were eliminated in the pre-treatment process. The element associations in Factor 2 are Mn, Na, Zn, and Ni. Generally, Mn in marine sediments is derived from authigenic and detrital sources (Shi, 2012); Na is a mobile element and also tends to concentrate in fine-grained sediments as a result of adsorption and cation exchange between water and sediments (Zhao and Yan, 1994). Mn and Na exhibit no apparent correlation with detrital indicator elements (e.g., Al and Ti) (Table 3); therefore, they were assigned as the authigenic deposit in Factor 2. Co and Cu, which are essential elements for phytoplankton, are controlled by Factor 3 (F3). They can be absorbed by phytoplankton and deposited with its debris. The contents of Co and Cu in sediments are closely associated with organic matter and a primary productivity (Yu et al., 2012); therefore, Factor 3 represents the effect of the primary productivity on elemental characteristics.

The discriminant function (DF, f_d) describes the relationship between sediments in the adjacent areas (Lan et al., 2009) and is widely used for provenance discrimination. The DF is calculated as follows:

$$f_d = \left| \frac{c_{1x}/c_{2x}}{c_{1L}/c_{2L}} - 1 \right|, \quad (2)$$

where c_{1x}/c_{2x} represents the concentration ratio of two elements in the sediments in the study area; and c_{1L}/c_{2L} is the concentration ratio of two elements in the sediments in the adjacent area. Small DF values (generally below 0.5) indicate close associations between the chemical components in sediments of the study area and chemical components in sediments of the adjacent area (Li and Li, 2001). The ratios of elements to Al can eliminate the effects of the grain size variation on the element components because Al remains stable under changing environmental conditions (Kremling and Streu, 1993). Correlation coefficients between Mz and the ratios of elements to Al were calculated, and the results imply weak correlations from 0 to 0.42. The value of Mz and the ratios of the seven primary controlling elements in Factor 1 (Mg, Ti, Fe, V, Cr, K, and Zn) to Al exhibit the weaker correlations (0–0.26); thus, they were used to calculate the DF. The DF between the study area and the Himalayan source was lowest, with a value of 0.15, followed by the Indian source, with a DF of 0.24; the maximum DF value, 0.51, was observed for Myanmar. On the basis of the DF results, the primary provenances for sediments in the study area are Himalayan and peninsular India, with little contribution from Myanmar.

Owing to the dilution of terrigenous and biological (mainly from ocean processes) material (Xie et al., 2014) and the effect of the grain-size variation (Kremling and Streu, 1993), a single element index cannot accurately reflect the source, and choosing appropriate ratios between elements can eliminate these effects on the two elements simultaneously. Ti is also used to indicate the input of terrigenous material (Taylor and McLennan, 1985; Yarincik et al., 2000; Lebreiro et al., 2009). Because Ti is generally found in rocks of continental crust origin (Taylor and McLennan, 1985), is not sensitive to oxidation-reduction and is essentially unaffected by diagenesis, Ti-normalized element ratios are useful for sediments (Xie et al., 2014). As shown in Table 3 and Fig. 4, strong correlations between Ti and several elements were observed (r^2>0.7). Several elements (e.g., Al, Fe, Mg, and Cr) are supplied to the Bay of Bengal from continental aluminosilicate (Sarin et al., 1979), but the correlation among Fe, Cr, and Ti is closely related to the presence of Fe-Ti minerals from the Himalayas (Garzanti et al., 2011) and Deccan Traps (Das and Krishnaswami, 2007) and is not affected by weathering and the interchange between Cr^{3+} and Fe^{3+} in the mineral structure (Schwertmann and Cornell, 2000). This result indicates that the element concentrations in the surface sediments in the study area are dominated by terrigenous detrital material and, consequently, can provide information about sources.

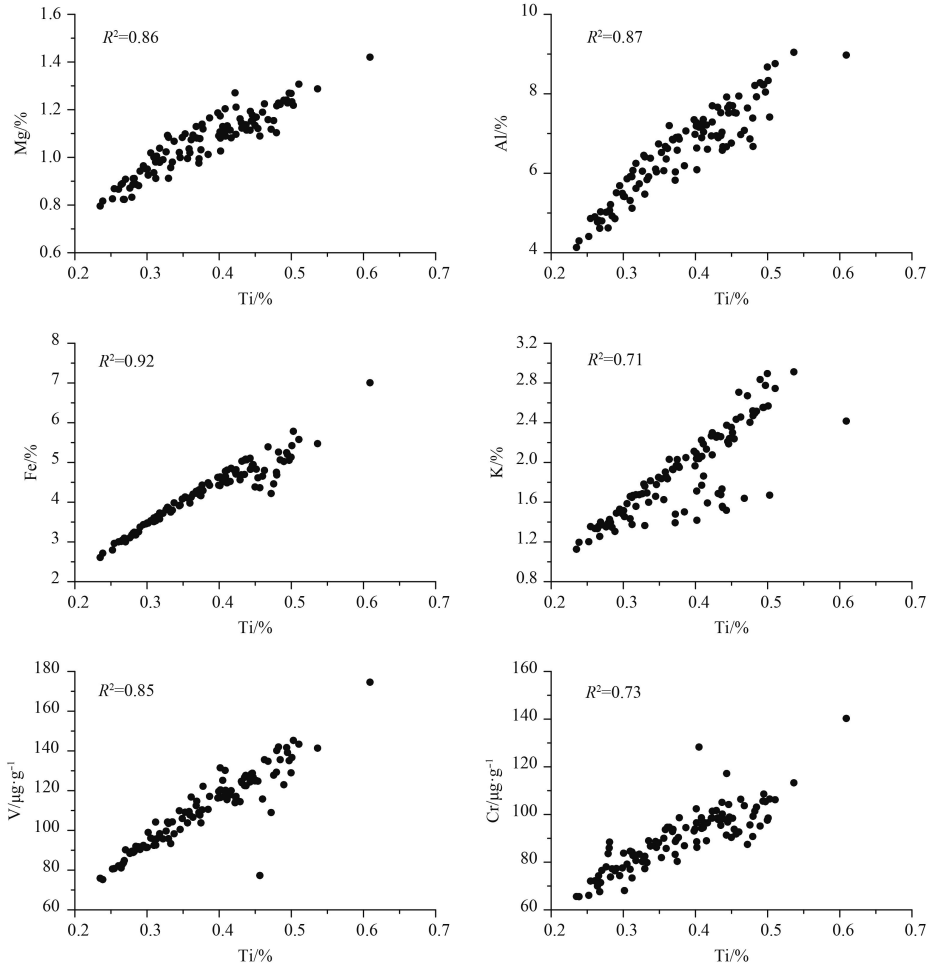

Fig. 4. Scatter diagram of Ti concentrations with those of other major and trace elements.

3.3 *Quantification of source contributions*

A geochemical data set inverse model (Tripathy and Singh, 2010; Tripathy et al., 2014) was used in this study to quantify the contribution from major provenances. This model includes a set of mass balance equations, beginning with pre-assigned elemental ratios for the sources, and evaluates the relative contributions of each of the sources to the study area (Tripathy et al., 2014). In this work, the model is used to apportion the contributions from two major sources: Himalayan (represented by G-B) and peninsular Indian (represented by G-K). Elements with high factor loading in Factor 1 (Mg, Ti, Al, Fe, V, Cr, and K) were used in the mass-balance equation (Table 2).

The equation for an element (X) in sediments of the study area can be written as follows:

$$X = \sum_{i=1}^{n} (X_i \times f_i), \tag{3}$$

$$\sum_{i=1}^{n} f_i = 1, \tag{4}$$

where X_i represents the element concentration for a given source i (i=1, G-B; i=2, G-K); f_i represents the contribution of sediments from source i to the study area; and n is the number of sources, which was 2 in this work.

For Ti-normalized ratios of the element (X), Eq. (3) can be rewritten as follows:

$$X/Ti \times Ti = \sum_{i=1}^{n} (X/Ti_i \times Ti_i \times f_i). \tag{5}$$

Equations (3), (4) and (5) for elements X=Mg, Al, Fe, V, Cr and K were used to estimate the source contributions. The element concentrations for sediments with Himalayan and Indian sources are presented in Table 1. The inverse model results are presented in Table 4. The Himalayan source supplies approximately 83.5% of the sediments to the study area, and approximately 16.5% of the sediments are derived from the Indian source.

On the basis of the model results, the Himalayan source plays a major role in the contribution of sediment, with minor contributions of the Indian source. The distributions of proportions of contribution from the Indian source and the Himalayan source are presented in Fig. 5. To better illustrate the relative contributions in different areas and considering the relatively low values of Indian provenance, a 10% interval was used. The sites with a larger proportion of sediments derived from the Indian source are mainly located in the western part of the study area, closer to the Indian continent, with contributions of Indian material mostly greater than 10%. The eastern part of the study area, which is further from the Indian continent, receives less from the Indian source than the western part of the study area, with con-

Table 4. Results of the inverse model for sediment contributions from the Himalayan and Indian river systems to the study area

Site	F1	F2	Site	F1	F2	Site	F1	F2	Site	F1	F2
1	0.58	0.42	29	0.72	0.28	57	0.93	0.07	85	0.93	0.07
2	0.71	0.29	30	0.75	0.25	58	0.98	0.02	86	0.91	0.09
3	0.60	0.40	31	0.79	0.21	59	0.93	0.07	87	0.89	0.11
4	0.66	0.34	32	0.77	0.23	60	0.91	0.09	88	0.92	0.08
5	0.68	0.32	33	0.51	0.49	61	0.85	0.15	89	0.89	0.11
6	0.65	0.35	34	0.72	0.28	62	0.90	0.10	90	0.97	0.03
7	0.76	0.24	35	0.91	0.09	63	0.93	0.07	91	0.91	0.09
8	0.76	0.24	36	0.81	0.19	64	0.46	0.54	92	0.98	0.02
9	0.76	0.24	37	0.80	0.20	65	0.70	0.30	93	0.94	0.06
10	0.73	0.27	38	0.60	0.40	66	0.91	0.09	94	0.94	0.06
11	0.80	0.20	39	0.69	0.31	67	0.96	0.04	95	0.95	0.05
12	0.74	0.26	40	0.77	0.23	68	0.92	0.08	96	0.94	0.06
13	0.67	0.33	41	0.77	0.23	69	0.94	0.06	97	0.92	0.08
14	0.81	0.19	42	0.87	0.13	70	0.78	0.22	98	0.90	0.10
15	0.84	0.16	43	0.81	0.19	71	0.94	0.06	99	0.87	0.13
16	0.82	0.18	44	0.89	0.11	72	0.89	0.11	100	0.85	0.15
17	0.77	0.23	45	0.65	0.35	73	0.93	0.07	101	0.94	0.06
18	0.79	0.21	46	0.71	0.29	74	0.87	0.13	102	0.95	0.05
19	0.89	0.11	47	0.74	0.26	75	0.83	0.17	103	0.92	0.08
20	0.94	0.06	48	0.55	0.45	76	0.92	0.08	104	0.94	0.06
21	0.82	0.18	49	0.73	0.27	77	0.92	0.08	105	0.97	0.03
22	0.78	0.22	50	0.85	0.15	78	0.97	0.03	106	0.91	0.09
23	0.84	0.16	51	0.83	0.17	79	0.96	0.04	107	0.95	0.05
24	0.80	0.20	52	0.90	0.10	80	0.97	0.03	108	0.95	0.05
25	0.76	0.24	53	0.95	0.05	81	0.96	0.04	109	0.96	0.04
26	0.48	0.52	54	0.69	0.31	82	0.92	0.08	110	0.94	0.06
27	0.71	0.29	55	0.98	0.02	83	0.93	0.07	Average	83.5%	16.5%
28	0.88	0.12	56	0.85	0.15	84	0.97	0.03			

Note: F1 and F2 refer to the percent contributions from the Himalayan source and Indian source materials, respectively.

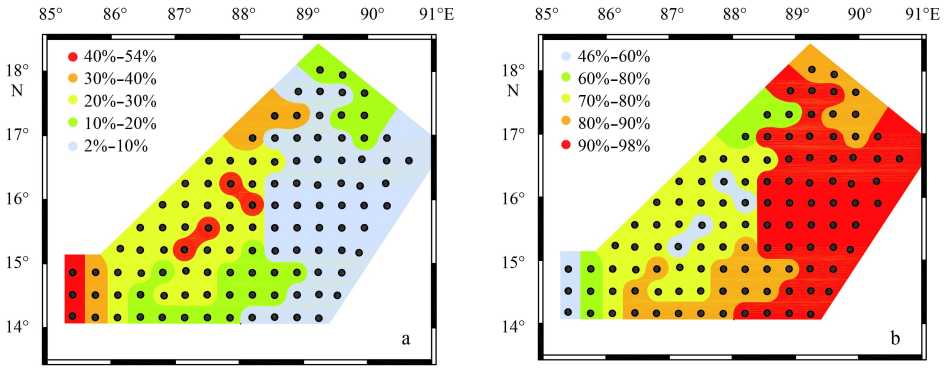

Fig. 5. Distribution of the proportions of contributions from the two provenances to the study area. a. Indian and b. Himalayan.

tributions of Indian material of mostly less than 10%. The eastern area received more material from the Himalayan source than the western area.

During sea-level high stands, such as in the present time period, the main path for sediments to the Bengal Fan is the "Swatch of No Ground", which is along a submarine canyon located in the slope of the northern part of the Bay of Bengal. The fan does not receive a direct load from the G-B rivers but does intercept sediment moving on the continental shelf (Weber et al., 1997). Slump activity in the existing submarine canyon is weak; hence, turbidity currents are weaker than during sea-level low stands and occur mostly in the upper and middle fan area (Curray et al., 2002). The currents are constrained within the large channels, and less overflow occurs. Although turbidity becomes weaker in channels from the upper fan to the middle fan, the channel area in the middle fan becomes much smaller compared with the upper fan; hence, overflow occurs, and the suspended sediments carried in this channel area are deposited as the strength of the turbidity currents decreases. By contrast, the peak input of terrigenous flux derived from the G-B rivers into the bay is during SW monsoons (Goodbred Jr, 2003; Mergulhao et al., 2013; Tripathy et al., 2014). The plume of fresh water extends southwards up to 15°N (Chauhan and Vogelsang, 2006), and suspended sediments deposit slowly during dispersion. These two mechanisms create the primary patterns for supplying sediments from Himalayan sources during the present sea-level high stands.

Submarine canyons in the slope of the western part of the bay are small in scale; therefore, there is no submarine canyon similar to the "Swath of No Ground" to transport sediments from the Indian source to the Bengal Fan. The flux of Indian rivers and their sediment flux to the bay are approximately 5 times and 4 times smaller than the G-B, respectively (Milliman and Farnsworth, 2011); therefore, the plume of fresh water has a smaller range, and surface circulation plays a more important role in the transport of the Indian source material to the study area. The transport of Indian material to the northeast is accomplished through the action of anticyclonic currents, particularly the East India Coastal Current during the SW monsoon, which carries material from the Godavari-Krishna and Mahanadi rivers and appears to affect the western part of the study area (Shankar et al., 2002; Narvekar and Kumar, 2006). Therefore, the western part of the study area receives sediments more readily from the Indian source and is affected more by this deposition than the eastern part of the study area.

4 Conclusions

This study investigated the major and trace element geochemistry of surface sediments in the mid-Bay of Bengal to track their provenances and estimate the contributions of different sources. Factor analyses and inverse model calculations were applied, and the following conclusions were drawn from the study.

(1) The geochemistry of these sediments is mainly controlled by the detrital supply, and the controlling sources are Himalayan and peninsular Indian.

(2) According to the inverse model calculation of Ti-normalized element ratios, the contribution proportions of the Himalayan source and the Indian source were 83.5% and 16.5%, respectively. The sites of deposition derived more from the Indian source were mainly located in the western part of the study area, which is closer to the Indian continent. The deposition was closely related to the sediment supply mode and the hydrodynamic conditions.

(3) Intensive studies are required to further clarify the sources and transport patterns of the sediments in the study area. Other indexes could provide useful information, such as clay mineral and isotope concentrations. In the future, we will attempt to collect end-member river samples to establish our own end-member geochemical systems. Then, a systematic study will be implemented.

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