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Provenance of terrigenous sediments in the central Bay of Bengal and its relationship to climate changes since 25 ka

Jingrui Li[1,2], Shengfa Liu[1,2], Xuefa Shi[1,2*], Min-Te Chen[1,3], Hui Zhang[2], Aimei Zhu[2], Jingjing Cui[2], Somkiat Khokiattiwong[4] and Narumol Kornkanitnan[4]

Abstract

Lithogenic grain-size, geochemical elements of core sediments from the central Bay of Bengal (BoB) were analyzed to identify sediment provenance and explore the regional "source-sink" processes since 25 ka. Based on the geochemical compositions of core BoB-88, relative contributions of three end-member sources (Himalayan, Myanmar, Indian Peninsula) were calculated and support the general understanding that Himalayan sources were dominant since the last glacial period, which could reach 70% on average in our study. However, sediments from the Indian Peninsula and Myanmar also contributed nonnegligible materials to the central BoB since 25 ka, especially the former shows an obvious increase since 7.5 ka, which was neglected in the previous studies. To trace the sedimentary processes of different provenance terrigenous materials and reveal their response to climate changes, four typical stages with obvious provenance percent variation, including the Last Glacial Maximum period (LGM), Heinrich 1 (H1), Early Holocene Climate Optimum (EHCO), and mid-late Holocene period, were highlighted and discussed. Sea-level change played a dominant role in the glacial-interglacial scale by controlling the transition of deposition center between the shelf/subaquatic delta and the Bengal Fan, especially for sediment from the Himalayan source, exerting influence on contributions from different provenance end-members between the Holocene and the last glacial period. The opposite directions of the southwest and northeast monsoon current in the BoB have a significant influence on the transfer of the Indian Peninsula and Myanmar materials to the studied core, which led to an increase of up to 11% than the average of the Indian Peninsula and a decrease of up to 9% than the average of the Myanmar source during the Holocene. The balance between sea level (limited transport to the deep sea) and ISM (improved erosion production and output to the BoB) during the mid-late Holocene period maintained the stability of Himalayan source percent. Due to the control of the ISM variations, the Himalayan source showed a decrease of up to 20% and 21% than average during the LGM and H1 period, respectively, and an increase of up to 14% than average during the EHCO. The Myanmar source exhibited fluctuations around the average value during the LGM period, but an obvious increase of up to 21% during the H1 period and a decrease up to 8% during the EHCO, while the Indian Peninsula source percent showed little variations during the LGM and H1, but a decrease of up to 6% during the EHCO. Obvious 1/4 processional and millennial periodic changes (5.0 kyr

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* Correspondence: xfshi@fio.org.cn
[1]Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266037, China
[2]Key Laboratory of Marine Geology and Metallogeny, MNR, First Institute of Oceanography, Qingdao 266061, China
Full list of author information is available at the end of the article

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and 1.1 kyr) of contribution proportions from three end-members provide additional evidences for the climate control on the regional source-sink processes and proved the controlled mechanisms of the orbital parameters and possible influence from the solar activity on millennial scales.

Keywords: Geochemistry, Indian summer monsoon, Sea level, Prevonance, Quantification

Introduction

The Bay of Bengal (BoB), which is in the northeastern Indian Ocean, is one of the major deposition areas for eroded materials from the Tibetan Plateau and Himalaya Mountains (Kolla and Biscaye 1973, France-Lanord et al. 1993; France-Lanord and Derry 1994, Colin et al. 1999, Kessarkar et al. 2005; Galy et al. 2007; Phillips et al. 2014b). The Bengal Fan is the biggest submarine fan in the world (3000 km N-S by 1400 km E-W), which is mainly fed by the Ganges-Brahmaputra (G-B) river system, and almost covered the whole sea floor of the BoB (Curray et al. 2003). The most important rivers drain into the BoB and transporting the largest fluvial sediment loads are the G-B rivers drain from the Himalayas (Kolla and Biscaye 1973). Combined with the Indian peninsular rivers (e.g., Godavari, Krishna and Mahanadi Rivers) and Southeast Asia rivers (e.g., Irrawaddy and Salween Rivers), the G-B rivers support approximately 1350 million tons of fluvial suspended sediment loads annually, which is equivalent to 8% of the global river supply to the ocean (Milliman and Syvitski 1992; Milliman 2001). The continuous sedimentation during the Late Quaternary in the Bengal Fan mainly deposits from the turbidity overflowing and the suspension materials setting (Curray et al. 2003; Curray 2014), thus they are characterized by finer size and dominated silt fractions (Weber et al. 1997; Li et al. 2017a; Li et al. 2017b; Li et al. 2018), and these sedimentation has been regulated by complex controlling factors like changing terrigenous sediment supply, sea level, oceanic circulation and the intensity of the Indian monsoon (Colin et al. 1999; Curray et al. 2003; Phillips et al. 2014b; Joussain et al. 2016). Thus, active tectonics due to Tibetan Plateau uplift, typical monsoon climate, developed large river systems, enormous terrigenous input, all these factors make the Bengal Fan an ideal natural laboratory in the northeastern Indian Ocean for the studies of Late Quaternary sediment "source-sink" process and paleoenvironment changes, especially areas out of the channel-levee system in the upper and middle fan which have relatively high sedimentary rates and steady continuous sedimentation.

Series of studies have been carried out to identify the provenances of sediments in the BoB mainly using clay minerals (Kolla and Biscaye 1973; Rao et al. 1988; Phillips et al. 2014b; Joussain et al. 2016; Li et al. 2018) and Sr-Nd isotope (Colin et al. 1999; Kessarkar et al. 2005;

Galy et al. 2008; Joussain et al. 2016; Li et al. 2018). These studies revealed that sediments in the Bengal Fan were predominately derived from the Himalayan sources, while other provenances like Indian Peninsula and Myanmar only played minor roles (Kolla and Biscaye 1973; Rao et al. 1988; Colin et al. 1999; Kessarkar et al. 2005; Galy et al. 2008; Phillips et al. 2014b; Joussain et al. 2016; Li et al. 2017a; Li et al. 2017b; Li et al. 2018). Previous studies mainly focused on the qualitative discrimination, however, quantification of sediments in the Bengal Fan has been limited; otherwise, geochemical approaches have been proven to be useful indicators in identifying sediments provenances (Yang et al. 2002; Clift et al. 2006; Choi et al. 2007; Yang et al. 2008; Dou et al. 2010; Tripathy and Singh 2010; Liu et al. 2013; Tripathy et al. 2014; Li et al. 2017a; Li et al. 2017b), but only a few studies of provenance discrimination for Bengal Fan sediments include major and trace element analysis. Appropriate index of major and trace element could provide useful information on sediment supply which is closely related to the environment change (physical/chemical weathering, precipitation, sea surface circulation, etc.) and thus can be a benefit for us to deeply understand regional "erosion-transportation-deposition" process, then provide conferences for sediment source-sink process research. Tripathy et al. (2014) used major and trace elements combined with factor analysis estimating the contribution of different provenances to the SK187/PC33 core sediments in the western Bengal Fan and indicated a result of 66% and 34% from the Himalayan and peninsular Indian rivers respectively to the core site through the last glacial period. Decreased contributions of G-B rivers during the LGM period were interpreted by the weakening of south-west monsoon (Prell and Kutzbach 1987) and larger glacier cover over the Higher Himalaya (Owen et al. 2002). Climate, especially Indian monsoon, exerts its influence on the regional source-sink process through the entire "erosion-transport-deposition" chain (Joussain et al. 2016). Therefore, sedimentary record in the BoB should be a comprehensive result reflecting sediment experience from erosion in the source area, transportation by the rivers, and sea surface circulations to deposition by turbidities and suspension settlement (Curray et al. 2003; Weber et al. 2003; Li et al. 2017a; Li et al. 2017b). Interactions between climate and sedimentary processes in the BoB

have been studied by many researchers and also in our previous works (Li et al. 2017a; Li et al. 2017b; Li et al. 2018; Li et al. 2019). The Indian monsoon and the sea-level change were suggested to play distinct roles in a different link of the source-sink process and at different scales (e.g., glacial-interglacial scale for the sea level, processional and millennial scales for the Indian monsoon) (Li et al. 2018; Li et al. 2019). Considering the periodicity of the Indian monsoon evolution, if the regional source-sink process in the BoB is mainly controlled by the Indian monsoon, relative contributions of different river end-members should show periodicity since the last glacial period, such as millennium cycle.

In this study, high-resolution analyses of grain size and geochemical compositions of a gravity core sediment were analyzed for qualitative and quantitative provenance discrimination, aimed to provide a quantitative variation of different river end-member contribution and analyze multiple climate factors controlling sediment source-sink process in the central BoB since the last glacial period.

Oceanographic setting

The BoB is a semi-enclosed bay with the southern mouth opening to the Indian Ocean and being surrounded by landmasses with input from multiple river systems (Fig. 1). Due to its special location within the Indian monsoon regime, the surface currents in the BoB are predominantly controlled by the Indian monsoon and exhibit apparent seasonal variations: anticlockwise in winter, when the northeast wind prevails, and clockwise in summer, when the southwest wind prevails. Most of the fluvial sediments are transferred during the summer monsoon rainfall period when the runoff reaches its peak, and sediments supplement can be up to ~ 95% of their annual discharges during this period (Singh et al. 2007) and results in a sea surface plume of low salinity which can be up to 15° N (Chauhan and Vogelsang 2006). Besides the G-B rivers, several Indian rivers including the Mahanadi River, the Godavari River, and the Krishna River also contributed its sediment load to the BoB. Additionally, also other large rivers poured into the northeastern Indian Ocean, such as the Irrawaddy River and the Salween River; however, their sediments are mostly transported to the neighborhood of the BoB, the Andaman Sea, with a relatively small sum transported to the BoB through the Preparis Channel (Fig. 1). Another important surface current system is the East Indian Coastal Current (EICC) mainly flows along the India Peninsula east coast and plays an important role in the transportation of Indian river materials (Tripathy and Singh 2010; Tripathy et al. 2014; Li et al. 2017a; Li et al. 2017b). The most important bottom current is the turbidity which transports the Himalayan

erosion production carried by the G-B rivers or sediments from the delta and shelf to the deep sea for the construction of the Bengal Fan (Curray et al. 2003), and that is the primary reason why the Bengal Fan exists.

Methods/Experimental
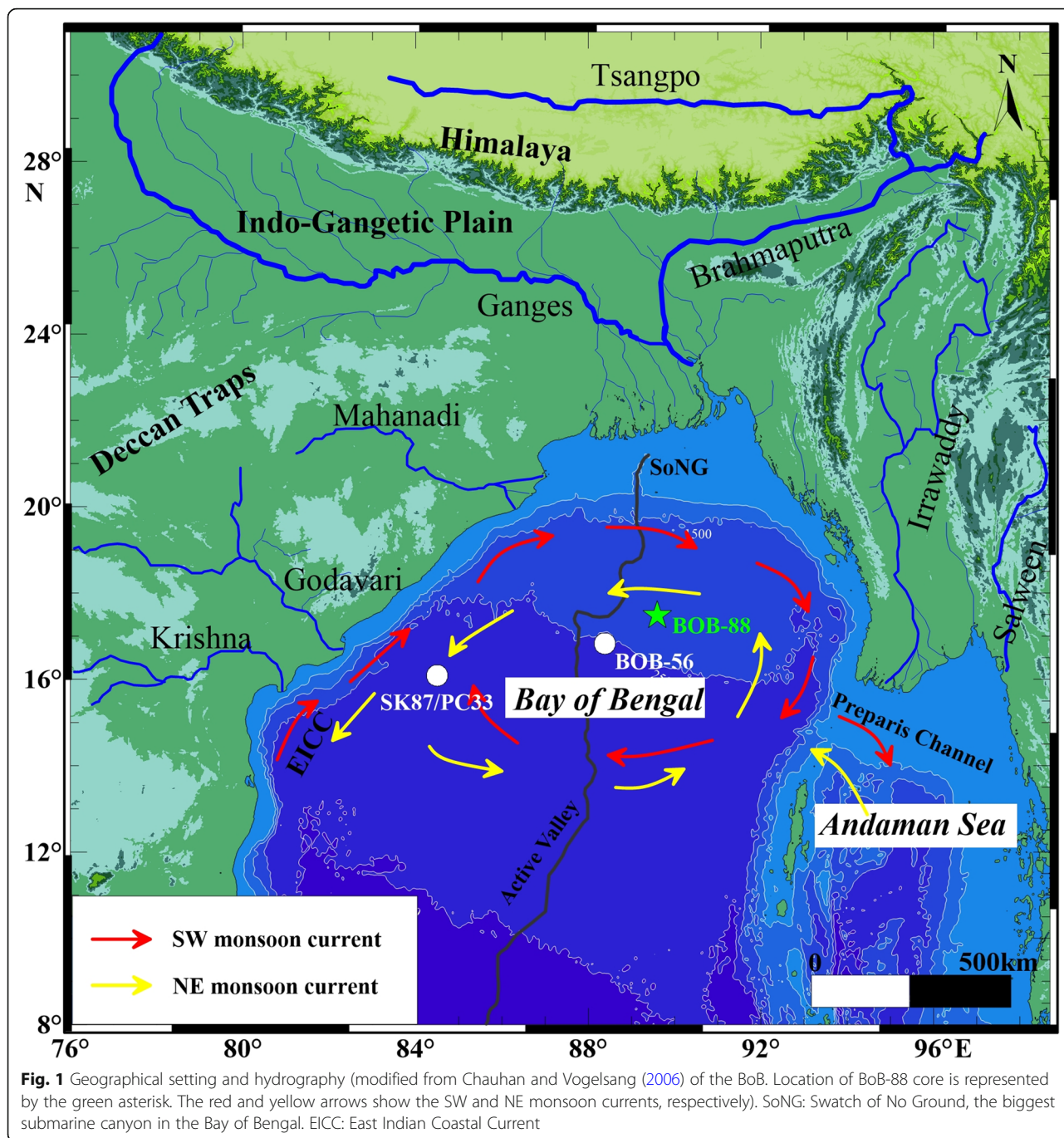### Sampling collection
Core BoB-88 (location 17.68° N, 89.61° E; length 1.95 m; water depth 2225 m) (Fig. 1) was collected using a DDC$_8$-2 gravity corer in the central BoB in 2014 by China-Thailand joint scientific cruises. Samples of BoB-88 were taken at 2 cm intervals for grain-size and geochemistry analyses.

Grain-size analyses
Grain-size distribution measurements of carbonate-free terrigenous particles were carried out using a laser grain-size analyzer (Malvern 2000, range 0.02–2000 μm, resolution 0.01Φ). Prior to the analyses, 15 mL of 3% H_2O_2 and 5 mL of 3 M hydrochloric acid (HCl) were added to remove organic matter and carbonate fractions, respectively. The mixture was then rinsed several times by deionized water and extracted by centrifugation. After ultrasonic oscillation, the samples were measured. The relative error of repeated measurement is less than 3%. Preparation and measurement were completed at the Key Lab of Marine Sedimentology and Environmental Geology (MASEG), Ministry of Natural Resources of China (MNR), China.

Elemental analyses
In this study, major element concentrations were analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES, Al, Ca, Fe, K, Mg, Mn, Na, P, Ti) and the animal glue gravimetric method (SiO_2). Detailed procedures for SiO_2 analyses have been introduced in our previous work (Sun et al. 2019). For the ICP-OES analyses, each freeze-dried sample (0.05 g) was placed in a polytetrafluoroethylene digestion tank, dissolved twice in HF-HNO$_3$ (1:1), and dried again at 190 °C for 48 h, then ~ 50 g of the liquor was prepared and measured. To determine the measurement error, nearly 10% of these samples were analyzed in replicate and the elemental compositions of a GSD-9 reference standard were measured to confirm the accuracy of the analyses. The maximum precision was 2% and the average error was 5%. Preparation and measurement of the ICP-OES analyses were also completed at MASEG, MNR, China, and the SiO_2 analyses were performed at the Laboratory Test Center of Shandong Provincial No.4 Institute of Geological and Mineral Survey.

Fig. 1 Geographical setting and hydrography (modified from Chauhan and Vogelsang (2006) of the BoB. Location of BoB-88 core is represented by the green asterisk. The red and yellow arrows show the SW and NE monsoon currents, respectively). SoNG: Swatch of No Ground, the biggest submarine canyon in the Bay of Bengal. EICC: East Indian Coastal Current

AMS^{14}C analyses

The age model was constructed based on AMS-radiocarbon ages on mixed planktonic foraminiferal species (Table 1). The radiocarbon ages were corrected for a local reservoir age of − 60 ± 51 years (Dutta et al. 2001) and converted to calendar ages using Calib Rev 7.0.4 (Reimer et al. 2013). The selections were carried out at MASEG, MNR, China, and analyses were finished at NOSAMS, Woods Hole Oceanographic Institution, USA.

Qualitative and quantitative analysis equations of provenance

Qualitative analysis

The enrichment factor (EF) and the discrimination function (DF), which have been widely applied to the sediment provenance discrimination, are proxies to examine the closeness between studied samples and the sediment from the potential sources (Lan et al. 2009) and can be calculated as following equations:

Table 1 AMS^{14}C dating age model of a core sediment

Core	Depth(cm)	Lab. no.	AMS^{14}C age (a BP)	Calendar age (a BP)	Sedimentation rate (cm/kyr)
BoB-88	3–5	OS-122129	1,840 ± 20	1447	2.8
BoB-88	17–18	OS-122130	4,100 ± 20	4237	4.8
BoB-88	33–34	OS-122131	8,210 ± 30	8812	3.5
BoB-88	48–49	OS-120119	10,500 ± 35	11821	5.0
BoB-88	67–68	OS-122132	12,600 ± 40	14174	7.9
BoB-88	92–93	OS-120238	14,000 ± 60	16466	10.9
BoB-88	130–131	OS-120125	15,400 ± 55	18294	20.8
BoB-88	160–161	OS-122133	18,300 ± 50	21753	8.7
BoB-88	191–192	OS-120126	20,800 ± 100	24612	10.8

$$\mathrm{EF} = \frac{(E/Al)_{\mathrm{samples}}}{(E/Al)_{\mathrm{UCC}}} \qquad (1)$$

$$\mathrm{DF} = \left| \frac{C_{1X} - C_{2X}}{C_{1L} - C_{2L}} - 1 \right| \qquad (2)$$

where E in Eq. (1) refers to the element used to calculate the EF and UCC refer to the upper continental crust; C_{1X}/C_{2X} and C_{1L}/C_{2L} refer to the element ratios in the samples and potential sources, respectively. If the value of EF is close to 1, then the crustal source is suggested, while non-crustal source will be indicated if it is above 10; for the value of DF, the lower value, the closer relationship between samples and the potential sources, generally, 0.5 is suggested to be the boundary between closer and further relationship (Li and Li 2001).

Quantitative analysis

A geochemical data set inverse model (Tripathy and Singh 2010; Tripathy et al. 2014; Li et al. 2017a) was applied in this study to quantify the contribution from end-member rivers. This model could evaluate the relative contributions of each end-member river to the study area based on a set of mass balance equations and begin with pre-assigned elemental ratios for the end-member rivers. The equations applied to our study are as follows:

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

$$\sum_{i=1}^{n} (f_i) = 1 \qquad (4)$$

where X_i represents the element concentration for a given source i and f_i represents the contribution of sediments from source i to the study area; n is the number of sources, which was $n = 3$ in this work. Typical terrigenous elements were chosen by the factor analysis for the major elements that represent most of the detrital contents in the sediments and used in the mass-balance equation.
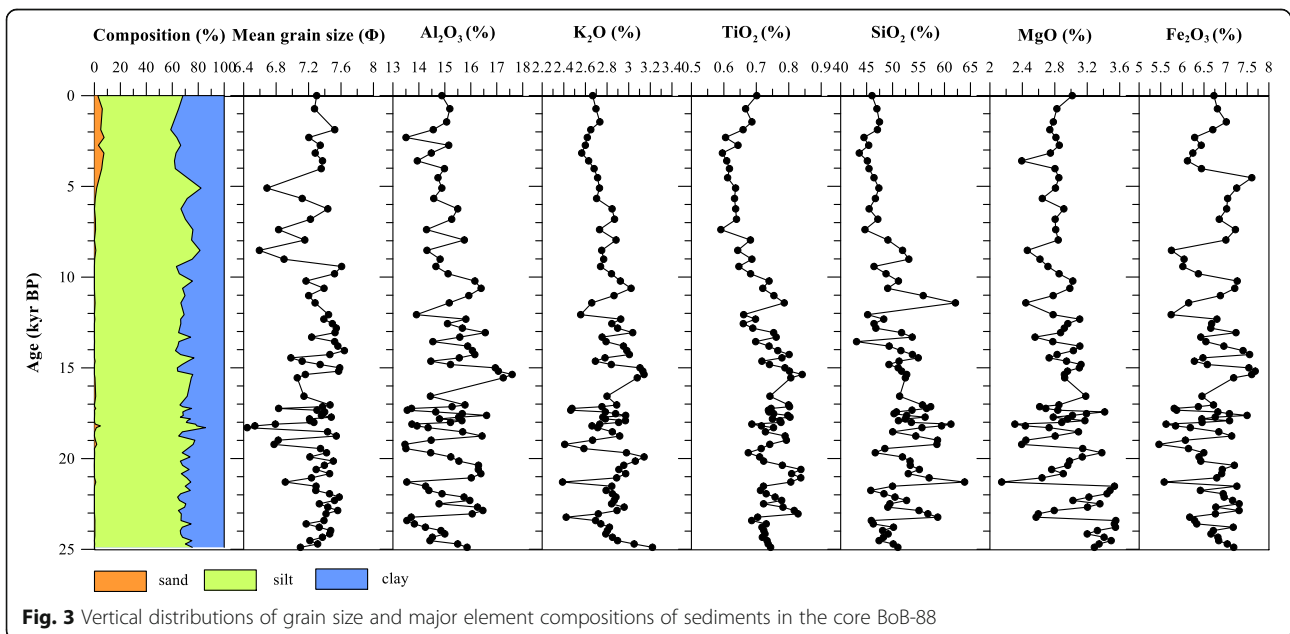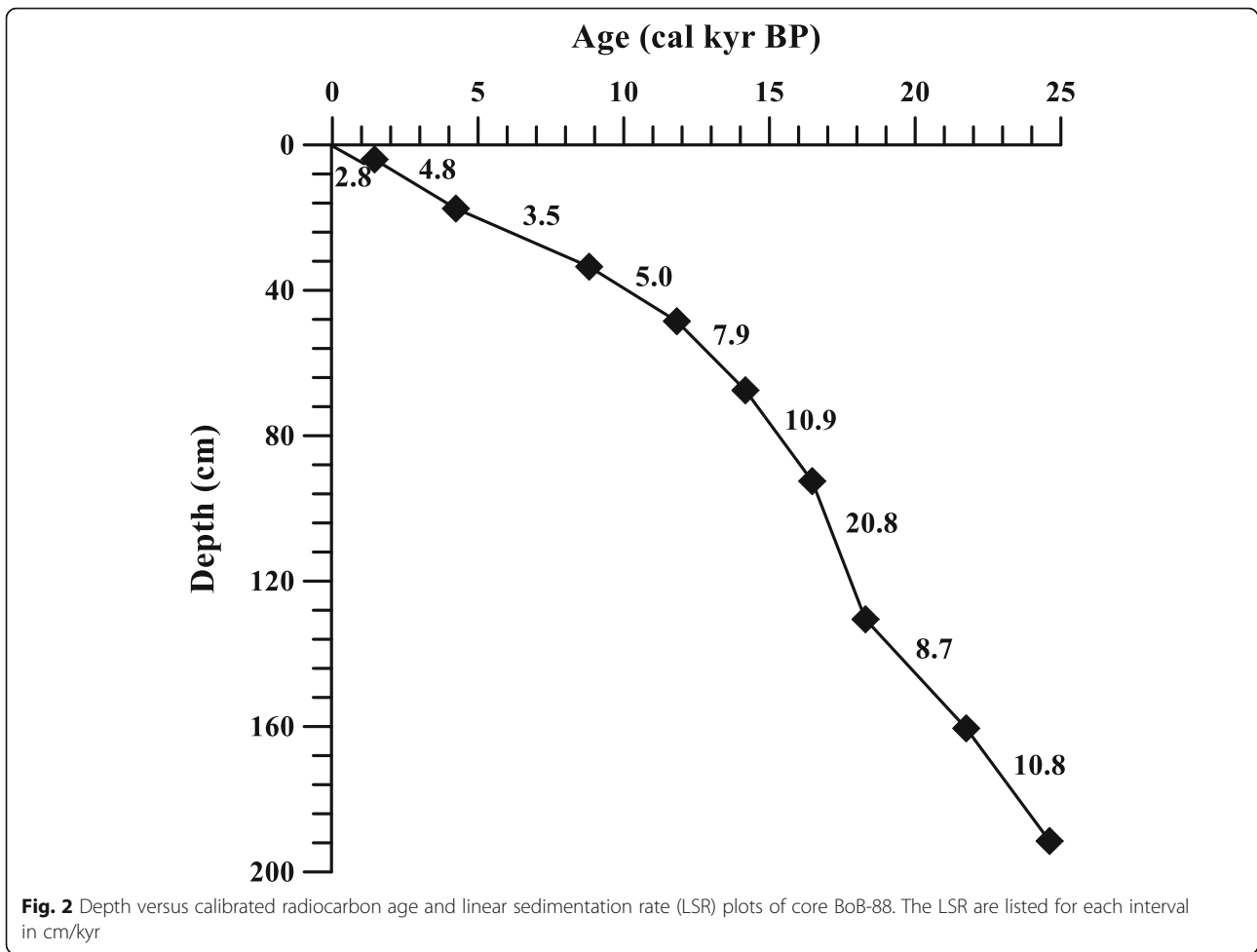
Results and discussion

Chronology, lithology, and grain size

Down-core ages were calculated by linear interpolation between dated sediment layers (Fig. 2). The ages were reported in thousands of years before the present. It showed a normal downcore age model, indicating a stable and continuous sedimentary record. The average time resolution between samples of core BoB-88 was ~ 129 years for the whole core, and ~ 248 years for the Holocene period, and 92 years for the last glacial periods. Sedimentation rates of the Holocene (average 4.0 cm/kyr) were relatively lower than the last glacial periods (average 10.8 cm/kyr), and the highest rate occurred during 16.5–18.3 ka with a value of 20.8 cm/kyr (Fig. 2).

Sediments of core BoB-88 were composed of relatively homogeneous gray clay silt except for the upper 24 cm which showed the yellow-brown color mainly due to the relative higher sand fraction (Fig. 3). Silt comprised the highest fraction (54–85%, average 69%) in the whole core samples, followed clay (14–41%, average 30%) and sand (0–8%, average 1%). The high values of the sand compositions mainly occurred in the upper 24 cm sediments (6.0 ka~) with a range of 0–8% and an average of 4%. The clay fractions show a similar trend with the sand fractions in the upper 24 cm (18–41%, average 34%). Values of mean grain size (Mz) showed limited variations in a range of 6.44–7.64 Φ, with an average of 7.27 Φ in core BOB-88 sediments which were mostly silt size.

Geochemical compositions and provenance discrimination

Sediments in the Bengal Fan are mainly terrigenous materials transported by rivers including eroded materials from the Himalaya-Tibetan plateau, India, and South Asia, with little contributions of biological (mainly calcareous) and volcanic materials (Iyer et al. 1999; Pattan et al. 1999; Weber et al. 2003; Tripathy and Singh 2010; Liu et al. 2013; Tripathy et al. 2014; Li et al. 2017a; Li et al. 2017b; Li et al. 2018). Sediments from the

Fig. 2 Depth versus calibrated radiocarbon age and linear sedimentation rate (LSR) plots of core BoB-88. The LSR are listed for each interval in cm/kyr

Fig. 3 Vertical distributions of grain size and major element compositions of sediments in the core BoB-88

Himalayas are dominating and can be tracked to the south of the equator indicating the Himalayas are the main provenance (Kolla and Biscaye 1973); other provenances mainly influence the sediments component in edges of the Bengal Fan (Phillips et al. 2014b). Eolian dust may also act as a sediment source in the northern Indian Ocean; especially in the Arabian Sea, it has a significant influence on the sediment component (Deplazes et al. 2014), but calculations for the contribution of the Eolian dust imply it is less than 11% of the terrigenous in the Andaman Sea (Cao et al. 2015). Considering the larger input of terrigenous materials of the BoB, the percent of the Eolian dust may be much smaller. Sediment geochemical compositions faithfully record the parent rock information and thus could be useful tools for provenance identification. In this study, geochemical indexes are used to determine sediment sources and end-member numbers.
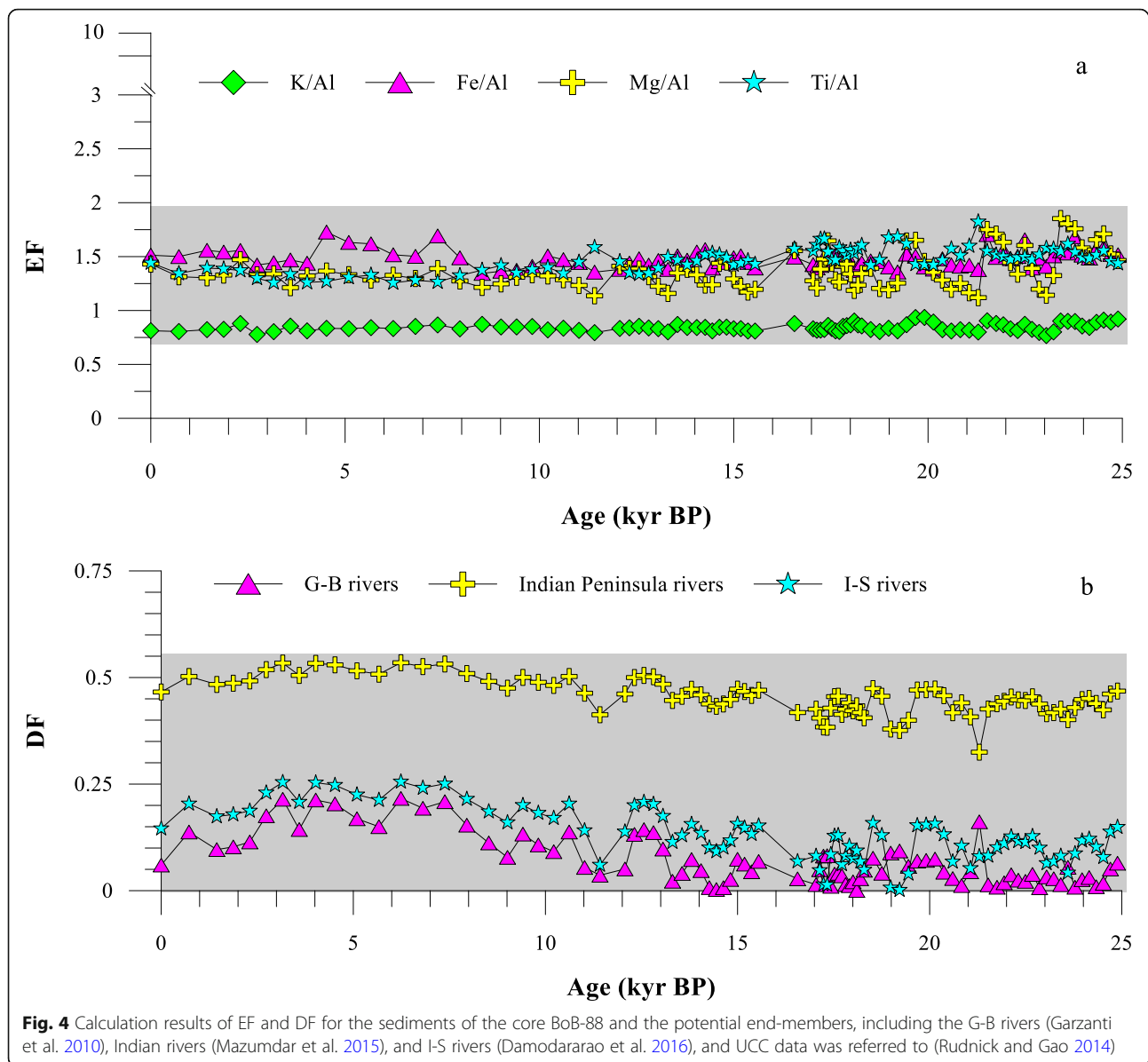
The geochemical compositions of the core BoB-88 sediments were shown in Fig. 3. Al_2O_3, K_2O, TiO_2, SiO_2, MgO, and Fe_2O_3 showed ranges of 13.46–17.59%, 2.39–3.22%, 0.59–0.84%, 43.06–63.88%, 2.15–3.15%, and 5.46–7.68%, respectively, with average contents of 15.15%, 2.81%, 0.73%, 50.98%, 2.93%, and 6.70%. Downcore variations of major elements show a distinction between the last glacial period and the Holocene period. Most of the geochemical elements and parameters show a lower value during the Holocene. Fe_2O_3 (%) showed fluctuations around the average values with no obvious increase/decrease. Elemental ratios, especially normalizing elemental concentration to Al content, are widely used to distinguish the sources of terrigenous materials from autogenic components (Cho et al. 1999; Yang et al. 2003). Previous study has proved that Al in this area has obvious low transfer characteristics in the river transportation process and dissolved Al was less than 0.1% of the particle Al (France-Lanord and Derry 1997). Generally, Al, K, Mg, Fe, and Ti are all diagenetic elements and suggested to be from the terrestrial detrital; thus, they were used to calculate the EF and DF (Eqs. 1–2). The results showed that EF was in a narrow range from 0.7 to 2.0 (Fig. 4), indicating that sediments of core BoB-88 were close to the composition of UCC and mainly from the crust source; DF results showed that three potential sources all have a close relationship with the sediment of the core BoB-88 (DF < 0.5, and $DF_{Himalayan}$ < $DF_{Myanmar}$ < $DF_{Indian\ Peninsula}$) (Fig. 4), which proved three end-members might be more reasonable for sediment provenances in the central BoB. Based on the results of the EF and DF, we infer that the sediments in the core BOB-88 were predominantly derived from the Himalayan sources transported by the G-B rivers, with relatively lower contributions from Myanmar and the Indian Peninsula.

Quantification of end-member river contributions

According to the qualitative analysis results, the inverse model is used to apportion the contributions from three major end-member rivers, the G-B rivers, Indian rivers, and the Irrawaddy-Salween rivers (I-S rivers). Five typical terrigenous elements (Al, K, Fe, Mg, and Ti) were chosen by factor analysis (Table 2) for the major elements that represent most of the detrital contents in the sediments and used in the mass-balance equation. Poor correlations between these elements and grain size further guaranteed the feasibility of this estimation (Fig. 5). The index values and their representation in this study were as follows: $i = 1$, G-B rivers; $i = 2$, I-S rivers; $i = 3$, Indian rivers; $n = 3$. Equations (3) and (4) for elements X = Al, K, Fe, Mg, and Ti were used to estimate the source contributions. The inverse model results are presented in Fig. 6. The G-B rivers supply approximately 70% on average for the core BoB-88, indicating the Himalaya was the main sources of the sediments to the study area during the studied time scale and approximately 15% from the I-S rivers and 15% from the Indian Peninsula rivers for the core BoB-88. As to the temporal variation, it does not change much overall but shows obvious increase/decrease during four typical periods (Fig. 6), the Last Glacial Maximum period (LGM), the Heinrich 1 periods (H1), the Early Holocene Climate Optimum (EHCO), and the Middle-Late Holocene periods. Similar results were also reported in provenance contribution quantitative estimation of a sediment core located in the western BoB (SK187/PC33) which also showed an obvious decreased input from the Himalayan source during the LGM and a little increased input from the Indian Peninsula during the Holocene period (Tripathy et al. 2014), but the difference was no signals from Myanmar were detected in the core SK187/PC33 due to its locations, but our core was located in the central BoB and sediment was the mixture of Himalayan, Indian Peninsula, and Myanmar three end-members. Considering the estimate error level, the results might not be accurate enough, but the abrupt increase/decrease trend was useful and credible for us to understand how different factors compete in the BoB in sediment source-sink processes. In order to show the changes of different end-member contribution values clearly and reduce the trend error caused by a single calculation point, we divided the estimated results into seven stages according to the results presented in Fig. 6 and drew histograms in Fig. 7.

Different contributions of provenance end-members and their climate-controlling mechanisms

Source-sink processes in the northeast Indian Ocean since the last glacial period was controlled by several factors, including sea-level change, Indian monsoon climate, mountain glacier scale, changes of the influx of

Fig. 4 Calculation results of EF and DF for the sediments of the core BoB-88 and the potential end-members, including the G-B rivers (Garzanti et al. 2010), Indian rivers (Mazumdar et al. 2015), and I-S rivers (Damodararao et al. 2016), and UCC data was referred to (Rudnick and Gao 2014)

river sediments, and current systems (France-Lanord et al. 1993; Kudrass et al. 2001; Owen et al. 2002; Curray et al. 2003; Singh et al. 2007; Owen and Dortch 2014). The Indian summer monsoon (ISM) has been suggested as the most important factor controlling the precipitation and the runoff, thus the fluvial input (Cullen 1981; Kudrass et al. 2001; Contreras-Rosales et al. 2014) in the Indian monsoon regime. Another outstanding factor is the seasonal variability of the surface current which is also related to the monsoon and has been confirmed to have significant effects to the transport of sediments (Chauhan and Vogelsang 2006; Joussain et al. 2016; Li et al. 2017a; Li et al. 2017b; Li et al. 2018). Sea-level changes mainly play controlling roles in the sedimentary model of the BoB in glacial-interglacial scale (Curray

et al. 2003; Weber et al. 2003; Li et al. 2019). Mountain glacier scale controls the rock exposure areas and the erosion amount (Owen et al. 2002). These factors were closely related to the global and regional environment variations. According to the estimation results, four typical periods with significant contribution variations of different end-members were chosen to decode how these competing processes controlling the source-sink processes in the study area since 25 ka.

LGM and H1
The most significant climate in our study area was the Indian monsoon, and the regional source-sink process was inevitably affected by it. Variability of the Indian monsoon might influence the erosion rates and fluvial

Table 2 Factor analysis of geochemical dataset and extraction of three factors with eigenvalues > 1

	F1	F2	F3
Eigen value	4.06	4.00	1.39
% variance	40.60	30.95	13.87
Al	0.94	− 0.12	0.01
K	0.94	0.03	− 0.02
Fe	0.93	0.17	0.07
Mg	0.77	0.50	0.03
Ca	− 0.05	0.99	− 0.04
Si	− 0.53	− 0.77	− 0.24
Ti	0.43	− 0.73	− 0.28
P	0.46	0.66	0.15
Mn	− 0.07	0.08	0.95
Na	0.39	0.55	0.56

fluxes into the BoB by controlling the precipitation in the source areas (Duplessy 1982; Kudrass et al. 2001; Tripathy et al. 2014) and the ocean circulation (SW monsoon, clockwise; NE monsoon, anticlockwise; Fig. 1) which in turn influences the sediment transportation. Previous study showed that most of the annual G-B river sediments (up to ~ 95%) are transferred during the summer monsoon rainfall (Singh et al. 2007). During the LGM, percent of the Himalayan source showed about 20% (in maximum) decline from 70 to 50% (averaged 64%) in our records (Fig. 7a, b) which is similar to the result of core SK187/PC33 (Tripathy et al. 2014) and consistent with that reported earlier based on Sr and Nd isotopic composition (Tripathy et al. 2011; Li et al. 2018). Approximate contemporaneity with this declined input, a series of oolitic beach ridges dated 19–24 ka perched near the low stand shoreline of the outer Bengal shelf, indicating their formation at the LGM when river discharge was greatly reduced, thereby favoring ooid formation in the shallow, saline waters (Wiedicke et al.
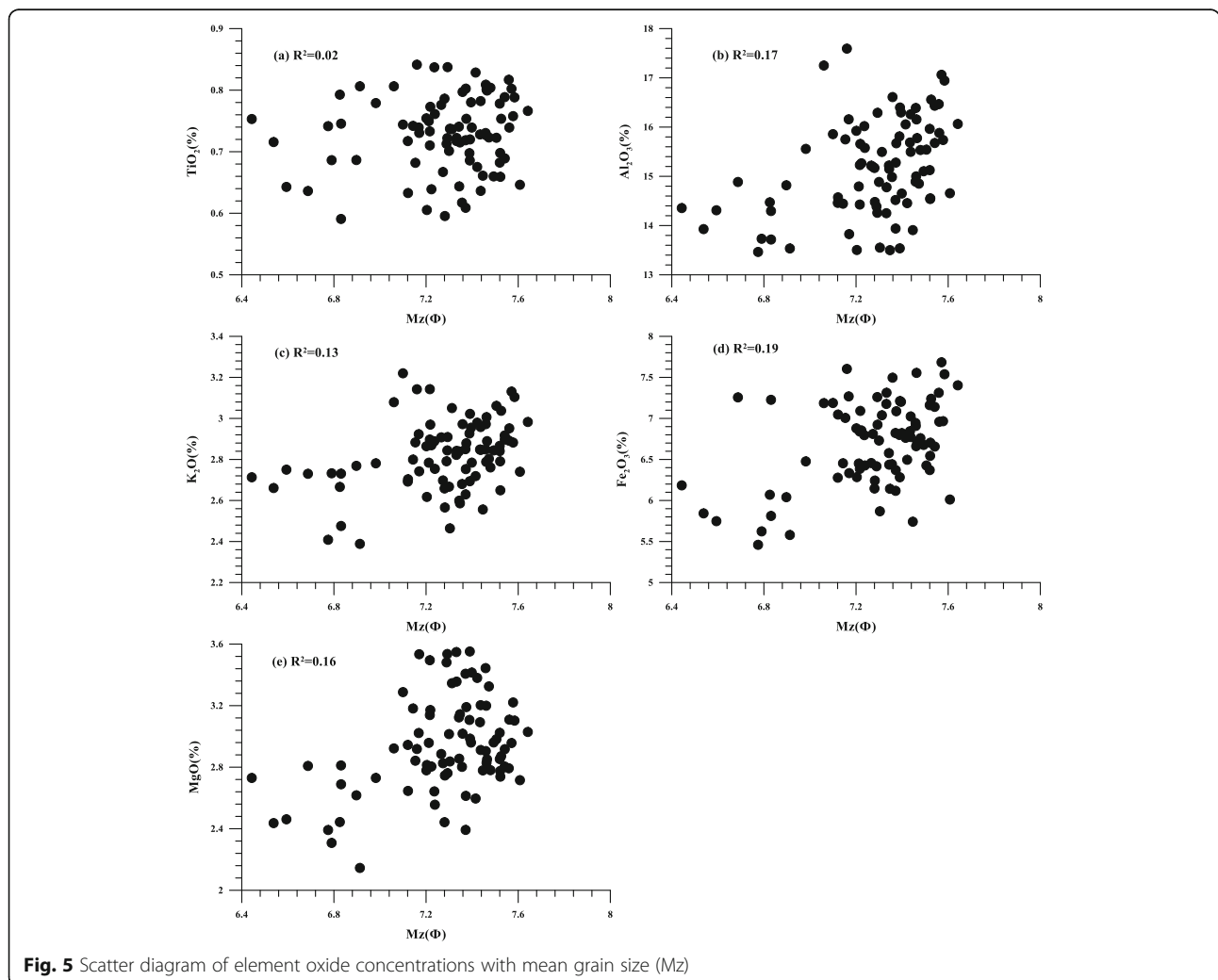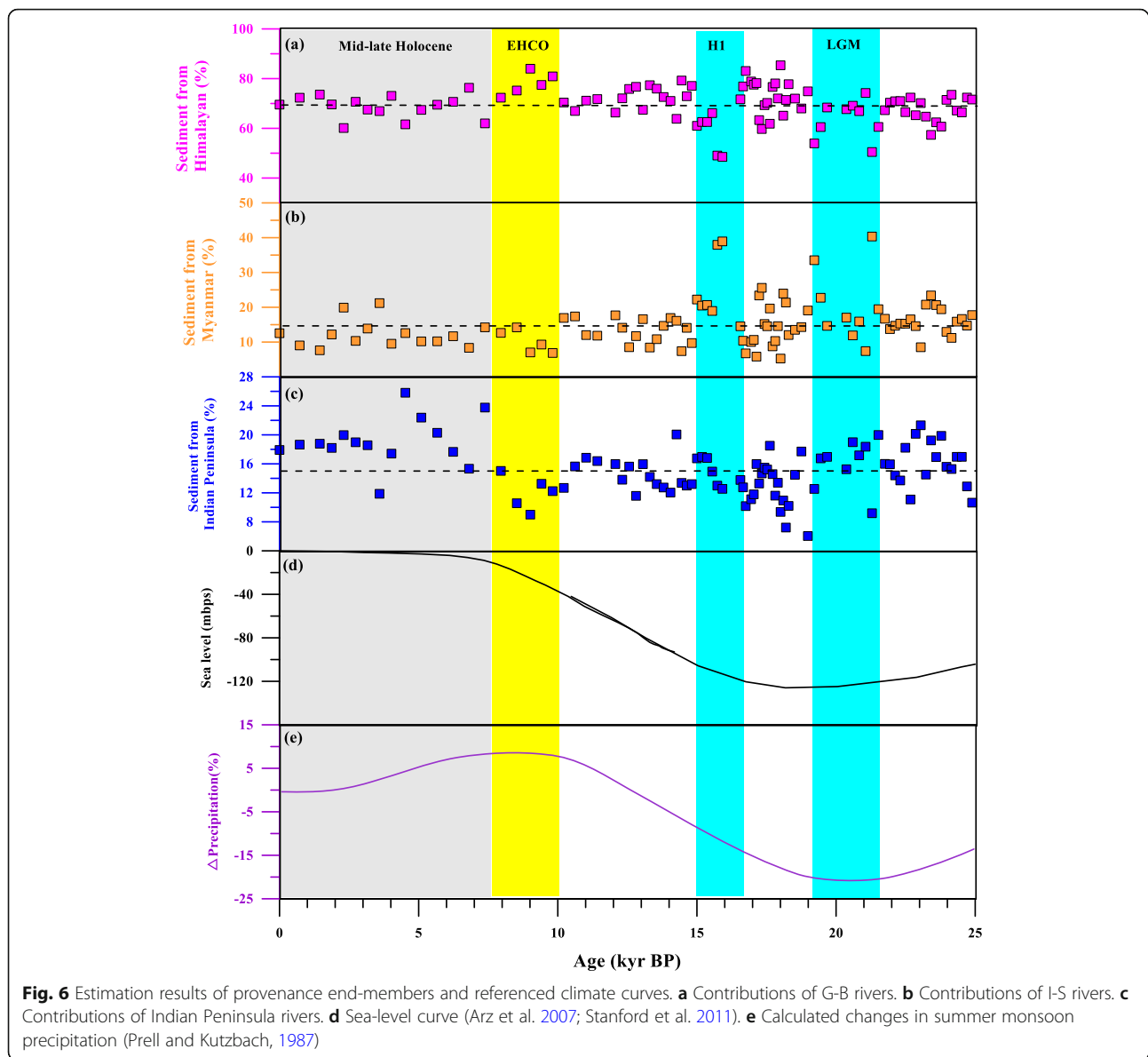

Fig. 5 Scatter diagram of element oxide concentrations with mean grain size (Mz)

Fig. 6 Estimation results of provenance end-members and referenced climate curves. **a** Contributions of G-B rivers. **b** Contributions of I-S rivers. **c** Contributions of Indian Peninsula rivers. **d** Sea-level curve (Arz et al. 2007; Stanford et al. 2011). **e** Calculated changes in summer monsoon precipitation (Prell and Kutzbach, 1987)

1999). Previous studies have discovered constrained ISM over the Indian monsoon regions during this period (Rashid et al. 2007; Anand et al. 2008; Galy et al. 2008; Mahesh and Banakar 2014; Jiang et al. 2015) largely decreased the erosion rate which had a strong dependence on the precipitation (Singh et al. 2008) and river runoff in the northeast Indian Ocean (Gebregiorgis et al. 2016). Surface salinity and $\delta^{18}O$ values in the northern BoB were significantly higher during the LGM than at present (Cullen 1981; Duplessy 1982), which was roughly equal to the global mean of 35‰ and 4‰ higher than the modern BoB (Cullen 1981), indicating the significantly decreased precipitation and the river discharge during the LGM. In addition, many studies have shown ice extension in different areas of the Himalaya (Owen

et al. 1992; Asahi et al. 2000; Richards et al. 2001; Owen et al. 2002; Hu et al. 2017). Despite much colder temperatures ($\Delta T = -5\ °C$) (Goodbred 2003), lack of meltwater and moisture made the climate condition tended to be arid. Chronology results suggested that during the LGM, glacier positions decreased significantly and lay within 10 km of their current interglacial extent (Owen et al. 2002; Finkel et al. 2003). Larger ice cover reduced the available area for erosion, thereby decreasing the sediment yield (Owen et al. 2002). These two factors were suggested to be responsible for the lower percentage of the Himalayan source and the decreased sedimentary rate of our records during the LGM (Fig. 2, Fig. 7a, b). Opposite to the result of the Himalayan source, the percentage of the Indian Peninsula showed a slightly

Fig. 7 Estimation results of river end-member contribution percentage during different stages
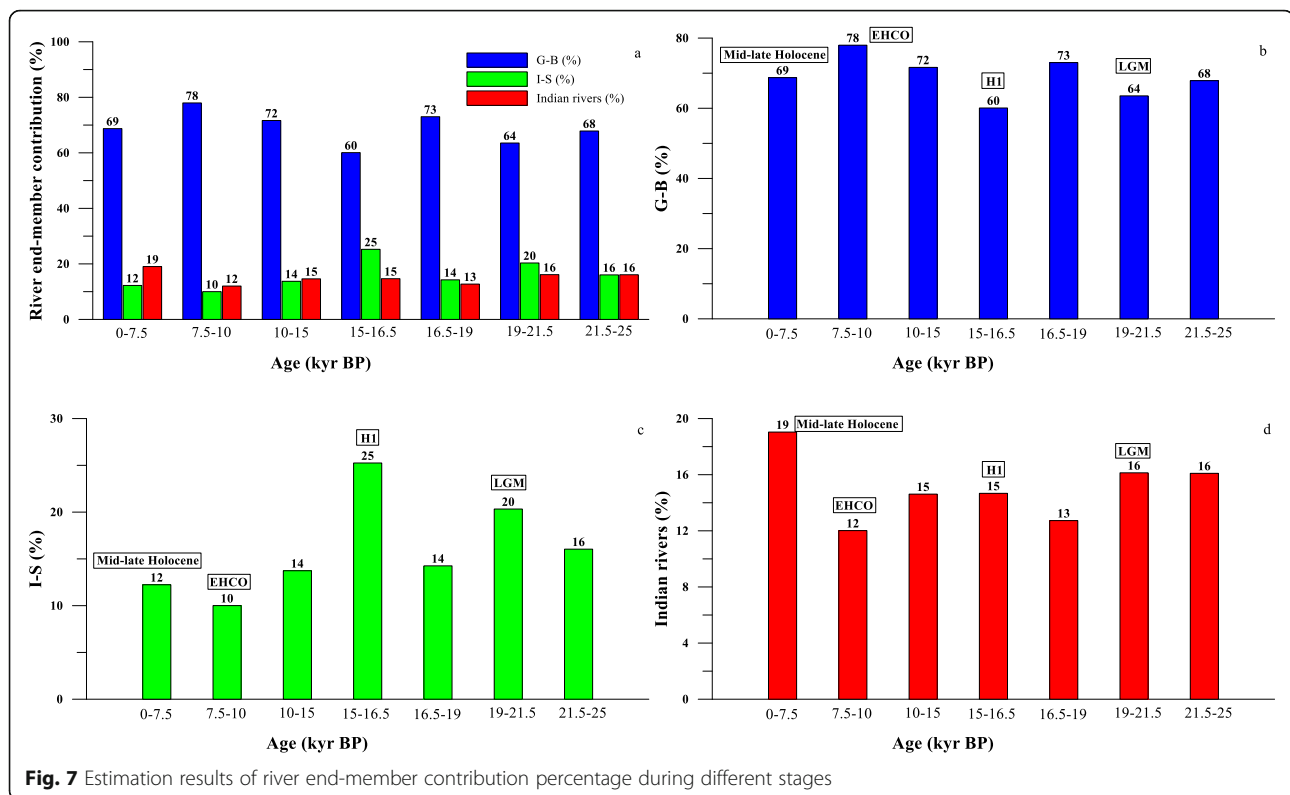
increase (~ 6%) during the LGM (Fig. 7d). It should be careful for the interpretation of this increase when considering the estimation errors, but the trends might be more meaningful than the values itself. Possible reasons might be from two aspects: covariant with the Himalayan source because the latter was the primary source or stable/increased erosion materials from the Indian Peninsula during the LGM. The latter was supported by well-dated alluvial sequences from the Ganges southern tributaries which suggested that the central Indian hills still received moderate precipitation even under a weakened monsoon due to its closer distance to the intertropical convergence zone (ITCZ); thus, Indian Peninsula rivers might still had slightly reduced discharge and continued high sediment loads (Williams and Clarke 1984).

Our results showed ~ 20% and ~ 5% decline (in maximum) of the Himalayan source (averaged 60%) and the Indian Peninsula (averaged 15%), respectively, but ~ 25% increase (in maximum) of the Myanmar source (averaged 25%) during 15–16.5 ka which was corresponding to the H1 event (Fig. 6). The Heinrich events were characterized by increased freshwater input and cold temperatures in the North Atlantic (Hodell et al. 2008), ITCZ southward shift, and a decrease in summer monsoon intensity in the monsoon areas (Zhang and Delworth 2005; Krebs and Timmermann 2007). This event was also widely recorded in the Indian monsoon realm

(Schulz et al. 1998; Hodell et al. 2008; Deplazes et al. 2014). Similar to that during the LGM, reduction of rainfall decreased erosion rate, weathering intensity, and sediment production in the source area, which was suggested to be responsible for the lower values of the Himalayan source percent (Fig. 7a, b). Besides this reason, constrained ISM also caused limited SW monsoon current in the BoB which was the main transporter of materials from the Indian Peninsula. On the other hand, enhanced NE monsoon during this period had significant improvement for the transportation of Myanmar materials to the studied core cite. Together with the reduced input of the Himalayan and Indian Peninsula source, obvious increase of the Myanmar materials occurred (Fig. 7a, c).

Holocene
Bounded by 7.5 ka, the contribution percentage of different end-members during the Holocene period could be divided into two stages, corresponding to the EHCO (7.5–10 ka) and the Middle-Late Holocene period (7.5 ka~). Himalayan source percent showed higher values (70–85%, averaged 78%) during 7.5–10 ka while declined percent occurred in Indian Peninsula (7–15%, averaged 12%) and Myanmar (8–15%, averaged 10%) sources at the same time (Fig. 7). This period corresponded to the EHCO which refers to warm and wet conditions in the Indian monsoon region (Fig. 6e) (Cullen 1981; Prell and

Kutzbach 1987; Schulz et al. 1998; Fleitmann et al. 2003; Saraswat et al. 2013). Higher precipitation enhanced erosion intensity and production in the Himalayan mountains (Cullen 1981; Goodbred and Kuehl 1999; Bush 2004; Li and Harrison 2008; Li et al. 2018). Though a sea level rising to a higher stand (Arz et al. 2007; Stanford et al. 2011) (Fig. 6d) and parts of sediment was captured by the shelf and subaquatic delta, sediment budget estimation results showed that there was still a small peak sediment storage in the canyon and Bengal Fan during this period (Goodbred and Kuehl 1999), which was matched with the higher sedimentary rate than that during the Middle-Late Holocene period (Fig. 2) and further supported our results. Consistent results have been provided by our previous studies in the adjacent core BoB-56 which also showed a small peak for terrestrial input from the G-B rivers during the EHCO (Li et al. 2018; Li et al. 2019). Correspondingly, percent of the Indian rivers and Myanmar materials decreased during this period (Fig. 7a–d) due to the controlling role of the Himalayan source, though higher terrigenous output also occurred in the Irrawaddy River and Indian rivers recorded in the Andaman Sea and Indian offshore basin (Phillips et al. 2014a; Cao et al. 2015; Sebastian et al. 2019).

ISM significantly intensified during the Holocene period than that during the last glacial period, as indicated by series of studies (Kudrass et al. 2001; Rashid et al. 2007; Rashid et al. 2011; Cao et al. 2015; Gebregiorgis et al. 2016). Thus, sediment production in the mountains and output to the BoB sharply increased. However, internal adjustment of deposition center from the Bengal Fan to the subaquatic delta and shelf in the BoB with the sea-level change (Arz et al. 2007; Stanford et al. 2011) (Fig. 6d) balanced this increment due to the large volume of sediment was captured in the subaquatic delta and shelf (Weber et al. 1997; Curray et al. 2003). Therefore, percent of the Himalayan source showed no obvious variation during this period (Fig. 7a, b). Combined with the increased erosion production, enhanced SW monsoon improved the transport of sediment from the Indian Peninsula to the studied core, higher values of Indian source contribution occurred (Fig.7a, d), which was also supported by the Sr-Nd isotopic and clay mineral results of a neighboring core BoB-56 (Li et al. 2018). Opposite conditions were responsible for the lower contribution of Myanmar materials (Fig. 7a, c) which was largely dependent on the NE monsoon current transport to the studied core cite.

1/4 precessional and millennial cycle of end-member river contributions: additional evidence for climate control and its forcing

As discussed above, regional source-sink processes were mainly controlled by the Indian monsoon and sea-level change. It could be periodic due to the periodic characteristics of the Indian monsoon. Cycles related to precession, D/O, and millennial cycles were speculated to be the possible periodicities in our studied time scale, which have been revealed by our previous work in an adjacent core BoB-56 and showed various cycles including glacial-interglacial, precessional, and millennial cycles (Li et al. 2018; Li et al. 2019), wherein sea-level change was suggested to be responsible for the terrestrial input variations at the glacial-interglacial scales and the ISM was proved to be the primary forcing factor on precessional and millennial scales. Power spectrum analysis (PSA) of contribution portions from three main provenances was conducted using REDFIT 35 (Schulz and Mudelsee 2002) to investigate the periodicity and possible forces.

The results of core BoB-88 showed reliable periodicities of three end-member river contributions mainly centered at 5.0 kyr and 1.1 kyr at a confidence level greater than 90% (Fig. 8), corresponding to 1/4 precessional and millennial cycles, respectively. It provides additional evidences for the climate control on the regional source-sink processes. The 5.0 kyr periodicity mainly reflects variations of the precession which was one of the most important earth orbit parameters reflecting the solar radiation variation in the high latitude and had a 23 kyr period. The 1.1 kyr periodicity was the millennial cycle close to the 890–950 years of solar activity periodicity reported by (Buehring 2001), implying the possible control of the solar activity. Our results presented here indicated the response of the lower latitude process to the orbital parameters and suggest a possible influence from solar activity changes on the BoB source-sink process since the last glacial period, on millennium scales.

Conclusions

Based on the geochemical compositions of core BoB-88 sediment from the central BoB, we reconstructed the evolution of sediment provenances through qualification and quantification and discussed climate control on regional source-sink processes since 25.0 ka. Interactions between climate and earth surface processes were indicated, which could provide useful information for guiding human activities, and in turn, the sedimentary records could be used to invert and predict the evolution trend of the global monsoon system. Based on these data, we can draw the following conclusions:

(1) Discrimination results by geochemical indexes show three provenance end-members of the core BoB-88 sediment since 25.0 ka, the Himalayas, Indian Peninsula, and Myanmar.

(2) Quantification results by the major elements which were chosen by factor analysis highlighted four typical
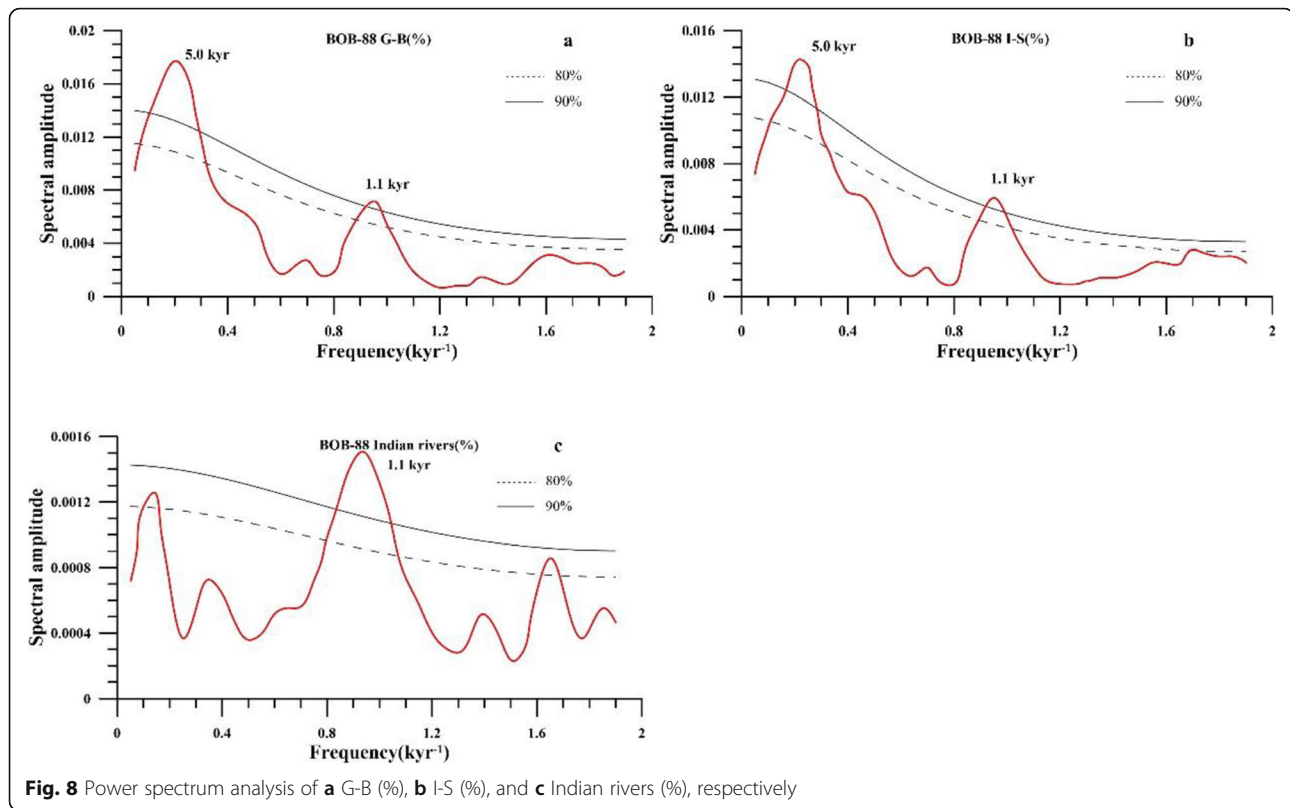
Fig. 8 Power spectrum analysis of **a** G-B (%), **b** I-S (%), and **c** Indian rivers (%), respectively

stages with obvious provenance percent variation, including the Last Glacial Maximum period (LGM), Heinrich 1 (H1), Early Holocene Climate Optimum (EHCO), and Middle-Late Holocene period. Higher values of the Himalayan proportion occurred during the EHCO (Δ = 14%, in maximum) while opposite circumstances were seen during the LGM and H1 period (Δ = 20% and Δ = 21% in maximum, respectively). Proportions of the Indian Peninsula show fluctuations during the last glacial period, but higher values occurred during the Holocene period (Δ = 11%, in maximum) which was in contrast to the Myanmar source with 9% decrease during the Holocene period. The Himalayan source proportions showed no obvious variation during the Holocene than that during the last glacial period.

(3) Sea-level change controlled the transportation and deposition regime in the glacial-interglacial time scale by a transition of deposition center between the Bengal Fan during the lower stand and the continental shelf during the higher stand, counteracting an elevated effect of ISM during the Holocene period. ISM mainly controlled regional source-sink processes by controlling the precipitation and weathering intensity in source areas, river runoff, and sea surface circulation. Ice coverage variation in the Himalaya mountains which was also suggested to be related to the Indian monsoon precipitation also exerts influence on terrigenous input, especially during the LGM.

(4) Obvious 1/4 precessional and millennial periodic changes of contribution proportions from different end-members indicated the response of lower latitude process to the orbital parameters and suggest a possible influence from solar activity changes on the BoB source-sink process since the last glacial period, on millennium scales.

Supplementary information

Additional file 1..

Abbreviations
BoB: Bay of Bengal; DF: Discrimination function; EF: Enrichment factor; EHCO: Early Holocene Climate Optimum; EICC: East Indian Coastal Current; G-B: Ganges-Brahmaputra; H1: Heinrich 1; I-S: Irrawaddy-Salween; ISM: Indian summer monsoon; ITCZ: Intertropical convergence zone; LGM: Last Glacial Maximum; Mz: Mean grain size; UCC: Upper continental crust

Authors' contributions
Jingrui Li, Xuefa Shi, and Shengfa Liu proposed the topic and conceived and designed the study. Jingrui Li wrote the manuscript. Hui Zhang, Aimei Zhu, and Jingjing Cui carried out the experimental study and data analyses. Min-Te Chen, Somkiat Khokiattiwong, and Narumol Kornkanitnan helped in their interpretation. Min-Te Chen and Shengfa Liu collaborated with the

Author details
[1]Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266037, China. [2]Key Laboratory of Marine Geology and Metallogeny, MNR, First Institute of Oceanography, Qingdao 266061, China. [3]Institute of Earth Sciences, National Taiwan Ocean University, Keelung 20224, Taiwan. [4]Marine and Coastal Resources Research and Development Institute, Department of Marine and Coastal Resources, Bangkok 10210, Thailand.

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