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Research Article

Sedimentary Response to Climate Change in the Central Bay of Bengal since the Last Glacial Maximum

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As the largest submarine fan, the Bay of Bengal (BoB) captures the abundant environment and climate fingerprints on different time scales. To investigate the sedimentary response to climate change since the Last Glacial Maximum (LGM), an integrated survey was performed to study grain size, major, and trace elements (Al_2O_3, CaO, K_2O, Na_2O, TiO_2, Sr, and Rb) of core BoB-24 sediments from the central BoB. The (K/Al)-TiO_2 (%) relationship of the sediments was taken for the discrimination of provenance, which indicated that sediments from core BoB-24 in 24~6.5 cal ka BP were primarily from terrigenous material input from the Himalayas. In contrast, the material contribution from the Indian subcontinent increased distinctly since 6.5 cal ka BP. The rising sea level severed direct material supply, thus causing the evolution of sediment provenance of the central BoB. Meanwhile, the strengthened Indian summer monsoon (ISM) in the Holocene affected detrital material transport from offshore to the central BoB. After understanding the sediment provenance in the study, we choose the sensitive grain-size fraction to show the evolution of hydrodynamic conditions. The chemical index of alteration (CIA) and Ti/Ca and Rb/Sr ratios are calculated to indicate the change in terrigenous input and weathering intensity. The contents of sediment fraction from 11.05 to 15.63 μm, CIA, and ratios of Ti/Ca and Rb/Sr in core BoB-24 showed the same trends, which were low during the last deglaciation and late Holocene but high in the Early Holocene. The trends were strongly correlated with the variation of the Indian summer monsoon, indicating the possible impact of Indian monsoon on sediment transport in the Bay of Bengal. Alternative indicators such as the contents of ratios of Ti/Ca and Rb/Sr, CIA, and sensitive grain-size content in sediments of core BoB-24 jointly record the evolution history of ISM since 24 ka BP in the Bay of Bengal. Although the sensitivity and response of each indicator to the paleoenvironment and paleoclimate change are slightly different, on the whole, the change trend is the same. Specifically, four warm-cold alternating periods (Heinrich Event 1, Bølling/Allerød, Younger Dryas, and Early Holocene Climatic Optimum) had a strong signal in these proxies that indicated that the millennial-scale climate controls the terrigenous input to the Bay of Bengal, where a high value occurs in warm events and low value in cold events. The sedimentary pattern of the northeastern Indian Ocean provides scientific evidence for an insight into the regional response to global climate change and the long-term climate change trend of the human environment across the monsoon region.

1. Introduction

The BoB has a significant monsoon climate and strong land-sea interaction since the Last Glacial [1, 2]. It is one of the main "windows" for material transport from the Himalayas and Tibet Plateau to the Indian Ocean. Sediments are produced due to erosion from the Himalayas and transported by the Ganges-Brahmaputra (G-B) Rivers from the flood plain to the estuary, delta, continental shelf, continental slope, submarine canyons, and deep-sea fan, forming a complete path of sediments from "source" to "sink," which is a proper area to study the process of "source-sink" since the Last Glacial. Rivers are not only the "link" between land and sea but also the direct "end members" of marine and terrestrial material supply. Material source identification is the core issue of marine sediment "source-sink" research. Research shows that the annual total amount of material entering the sea of rivers around the BoB accounts for about 8% of the total river sediments entering the sea in the world [3, 4]. The sediment load per unit watershed area is much higher than the average value of world rivers, which emphasizes the importance of physical erosion and chemical weathering in this area. The differences in geological background, climate zone, biological features, and human activities of G-B Rivers, Mahanadi River, Krishna-Godavari (K-G) Rivers, and Irrawaddy River around the BoB lead to different compositions of land-based sediments transported into the sea, which makes it possible to identify sediments in different homologous areas from the complex multisource sediments in the BoB [5–8]. Due to the special climate and dynamic transport conditions, the distribution and contribution of substances in different source areas in the ocean are different in time and space. This temporal and spatial difference provides us with essential information for understanding the climate and hydrodynamic environment of the study area, interpreting the past, and predicting the future environmental evolution. Therefore, it is of great scientific and practical significance to find appropriate indicators to clarify the temporal and spatial differences in the distribution and contribution of substances in different homologous areas in the ocean and to reveal their control mechanism.

Some scholars believe that the climate, especially the Indian monsoon, controls the generation of sediments in the Ganges and Brahmaputra river basins by controlling different erosion and weathering processes [9–14]. Some studies, such as those by Clift et al. [10] and Rahaman et al. [11], have revealed the response of different erosion rates in the upper and lower Himalayas to climate change in the last 10 ka. According to some studies, the physical erosion process of the river basin is largely controlled by millennium scale climate change [15–18]. In addition, some scholars are committed to studying the relationship between glacier advance and retreat and sediment erosion amount in the Himalayas [19]. Its essence is still erosion under the control of climate, especially monsoon. The change of climate and precipitation affects the scale of glaciers, causes the advance and retreat of glaciers in different periods, and changes rock exposure area. In order to assess the impact of climate change on chemical weathering in the Himalayas and the Indian Peninsula, it will be of great significance to compare the chemical weathering proxies from sediments of cores in the BoB with the variation of climate. If the chemical weathering in the source area changed due to climate change, there may be differences in the response to climate change in different source areas. If the Indian monsoon is the main controlling factor of chemical weathering in the source area, we can speculate that the relative change of weathering intensity in different source areas within the time scale of the last glacial may be characterized by the periodic change of millennium or precession.

Another important controlling factor of marine sedimentation is sea-level change, which mainly controls the change of the sedimentary model in the BoB on the time scale of the glacial interglacial period, that is, the transfer of sedimentary centers between the continental shelf and deep-sea fan in different sea-level periods [20]. In the case of low sea-level, the estuary is situated at the current shelf break, and the river sediments can directly reach the submarine canyons, resulting in rapid sedimentation of the submarine canyons. In the relatively high sea-level period, such as the current sea level, the sediments are mainly "captured" by the underwater delta and continental shelf, and the submarine canyon does not directly accept the sediments from the G-B Rivers or other large rivers. However, it captures the sediments transported on the underwater delta and continental shelf [21–24]. The turbidity current activity intensity is relatively low, which is greatly weakened in the high sea-level period and only occurs in the Upper Fan and Middle Fan [20]. Due to the underdeveloped submarine canyon across the continental slope area in the Indian Peninsula and Southeast Asia, the material supply to the Bengal fan is mainly through the surface monsoon circulation. The control of sea-level change on the sedimentary model will have different effects on material supply in different source areas.

The BoB, a marginal sea in Asia, is an important window of Tibetan Plateau material output to the Indian Ocean. Strong land-sea interactions and typical monsoon climate characteristics make it a natural laboratory to conduct a sediment "source-sink" study. However, there are some different voices on the temporal and spatial evolution of sediment provenance in the central Bay of Bengal since the last glacial under the background of the Indian monsoon. Therefore, in this study, we choose typical ocean core sediments (BoB-24) based on the high precision chronological framework which has been established by accelerator mass spectrometry (AMS) ^{14}C analysis and major and trace element analysis to extract effective tracer indicators and applied them to discuss the temporal and spatial evolution of sediment provenance of the central BoB since the last glacial maximum. Based on planktonic foraminifera *Globigerinoides ruber* shell oxygen isotope ratio ($\delta^{18}O$) and magnesium and calcium ratio (Mg/Ca) analyses from the previous study, we extract information on the salinity and temperature, which will be combined with sediment CIA, Rb/Sr, and other indicators indicating the chemical weathering intensity change in source areas, to show the response mechanism in "climate-erosion-transportation-sedimentation" process to the Indian monsoon in the millennium time scale.

2. Materials and Methods

2.1. Sample Collection. Gravity core BoB-24 (87.16°E, 15.57°N; 411 cm long; water depth of 2769 m) was gathered from the central BoB with "M.V. SEAFDEC" during the China-Thailand joint scientific cruise in April 2014

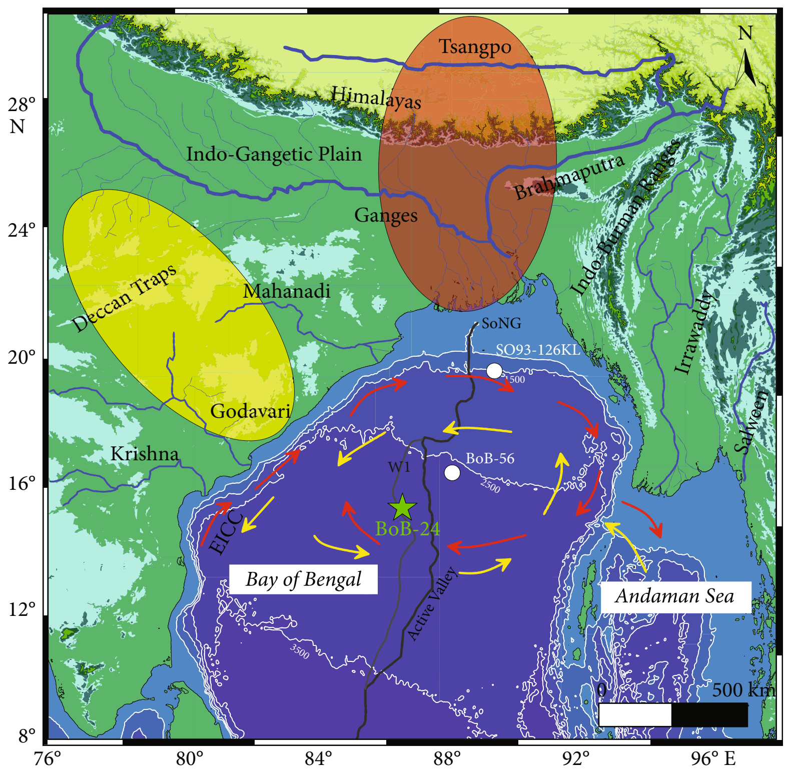

FIGURE 1: Geographic setting and circulation system (modified from Ye et al. [14]) of the BoB. The location of core BoB-24 is represented by the green star. Previous relevant studied sites are shown by the white dots. The SW and NE monsoon currents are shown by the red and yellow arrows, respectively.

(Figure 1). Subsampling of the upper 200 cm in core BoB-24 was made at the 1 cm interval, in which 188 samples were obtained for grain-size analysis and 99 samples for geochemical element analysis in the laboratory.

2.2. Methods. The Key Laboratory of Marine Geology and Metallogeny, Ministry of Natural Resources, performed the grain-size analysis on sediments. ~0.15 g of sediment samples was put into a beaker, and ~15 mL of 30% H_2O_2 was introduced for removing organic matter. The sediment's calcium cement and biological shells were removed by adding 5 mL of 3 M dilute hydrochloric acid after standing for not less than 24 h. After complete reaction, the sample was centrifuged repeatedly and washed with salt until the solution was neutral. Then, the samples were tested by a Mastersizer 2000 laser particle size analyzer after ultrasonic oscillation and dispersion. The instrument's analytical scope ranges between 0.02 μm and 2000 μm, with the relative error in repeated measurement below 3%. The particle refraction was 1.52, and adsorption index was 0.1. The pump rate was 3000 rpm. Sonication time for the sample was 15~30 s and obscuration rate ranged from 10 to 20. In data processing, the moment method is used to calculate the grain-size parameters such as mean grain-size and sorting coefficient [25].

The Key Laboratory of Marine Geology and Metallogeny, Ministry of Natural Resources, China, conducted geochemical element analysis. In the sample pretreatment process, 0.05 g freeze-dried samples milled to 200 mesh were dissolved in 1.5 mL HNO_3 plus 1.5 mL HF at 190°C in the oven for 48 h. Upon evaporation to dryness, 3 mL 50% HNO_3 was introduced for dissolving the samples at 150°C in the oven for over 8 h. Followed by solution transfer, the volume was to be determined by adding Milli-Q water. Elements/oxide (Al_2O_3, CaO, K_2O, Na_2O, TiO_2, Sr) were tested by full-spectrum direct-reading inductively coupled plasma spectroscopy (ICP-OES, ICAP6300), and element Rb was measured with inductively coupled plasma mass spectrometry (ICP-MS, X Series II). To guarantee accuracy and precision, repeated analysis ($n = 11$) and the reference standard, GBW07309 (GSD-9), on several samples were conducted, respectively. The results showed the relative error in analytical elements was below 5%.

The National Ocean Sciences Accelerator Mass Spectrometry facility at Woods Hole Oceanographic Institution, USA, conducted the AMS^{14}C analysis. For AMS^{14}C analysis, about 12~15 mg planktonic foraminiferal species (*N. dutertrei*, 300~350 μm in size, complete and clean shells) were chosen from every sample. With 7 measured samples, Calib 8.20 software [26] was adopted to correct calendar age, in which ΔR of local reservoir age (calculated with Marine20) was -195 ± 51 a [27, 28], and the age model was constructed.

3. Results

3.1. Chronology. Eleven dated sedimentary layers [29] established the age model for core BoB-24 with linear

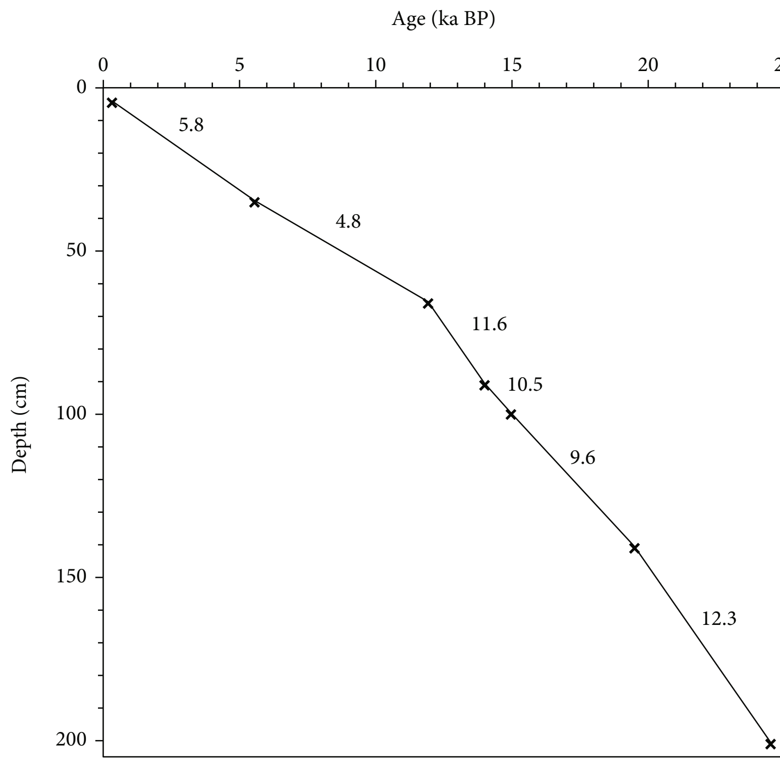

Figure 2: Depth versus calibrated calendar age plot of core BoB-24. The linear sedimentation rates are listed for each interval in cm/kyr.

interpolation, and we chose seven points at the top 201 cm to build the age frame for the sedimentary records since ~24 ka BP in this study (Figure 2). The dating results showed that the sedimentary records of BoB-24 were continuous and stable, with a higher sedimentation rate (10.7 cm/kyr) in the last glacial and deglacial period, compared to the lower value (5.3 cm/kyr) in the Holocene period. Correspondingly, the resolution in the last glacial and deglacial period (~93 a) was higher than that during the Holocene period (~189 a).

3.2. Sensitive Grain-Size Composition. Grain-size compositions in core BoB-24 had been disclosed in the former research [14]. The sediments comprised homogeneous grey clayey silt, except for the upper 40 cm, showing a yellow-brown color because of the increased concentration of sand and water contents. Grain size of sediments in core BoB-24 comprised silt, and the grain-size range was relatively concentrated, which was comprised between 5.05 and 9.81 μm with an average of 6.66 μm [14]. The composition of grain-size in the sediments of core BoB-24 ranges from 0 to 1000 μm. In the current research, the sensitive grain-size components of the grain size in core BoB-24 (Figure 3) were extracted with the computing method of grain-size class versus standard deviation [30, 31]. The grain-size class corresponding to a high value of standard deviation was the grain-size class mode showing sensitivity to the change in the sedimentary environment [30]. The principle of the grain-size versus standard deviation method is to obtain the numbers and distribution range of fraction components by studying the standard deviation of the content corresponding to each grain-size class given by the laser grain-size analysis meter. After analyzing 188 sediment grain-size samples, the grain-size class versus standard deviation curve (Figure 3) shows the variation of standard deviation in core BoB-24 with grain-size components. The curve shows a typical "unimodal distribution," indicating that there is only one grain-size component sensitive to the environment since 24 ka BP (Figure 4), and the distribution range is 11.05~15.63 μm. Component of 11.05~15.63 μm fluctuated in a higher range during 24~6.5 ka BP (averaged 12.6%) while it decreased since 6.5 ka BP (averaged 9.6%).

3.3. Element Concentrations. The vertical distribution of element concentrations of core BoB-24 is seen in Figure 5. According to the downcore variation, contents of Al_2O_3, K_2O, TiO_2, and Rb showed similar trends, whereas variations of CaO and Sr with time were opposite to the former. Overall, Al_2O_3 had a higher relative content (12.01%~17.14%, averaged 15.69%), followed by CaO (2.65%~14.03%, averaged 6.77%), K_2O (2.19%~4.00%, averaged 3.35%), Na_2O (2.03%~3.52%, averaged 2.81%), and TiO_2 (0.60%~0.81%, averaged 0.73%), while Sr (143.20 μg/g~465.00 μg/g, averaged 253.51 μg/g) and Rb (111.50 μg/g~232.20 μg/g, averaged 166.88 μg/g) had a lower relative content. Based on the downcore variation of element concentrations, we propose the following three stages: Stage 1 (24~12 ka BP), Stage 2 (12~6.5 ka BP), and Stage 3 (since 6.5 ka BP). In these stages, element concentrations varied with different trends. Stage 1 ranged from 24 to 12 ka BP, and element concentrations fluctuated intensively, showing periodic variation. The trends of Al_2O_3, K_2O, Na_2O, TiO_2, and Rb were opposite to CaO and Sr. During 12~6.5 ka

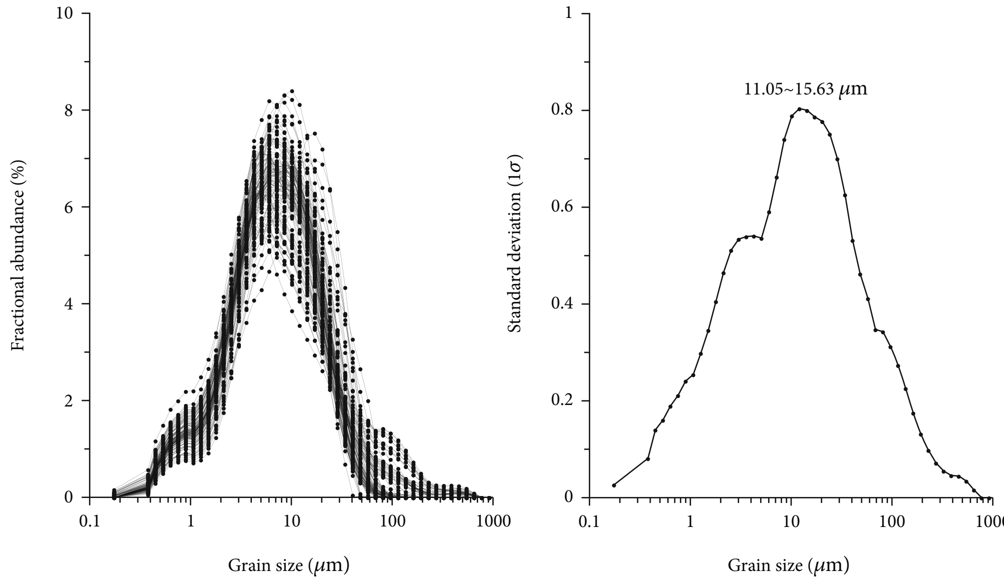

FIGURE 3: Fractional abundance and standard deviation vs. grain-size classes in core BoB-24.

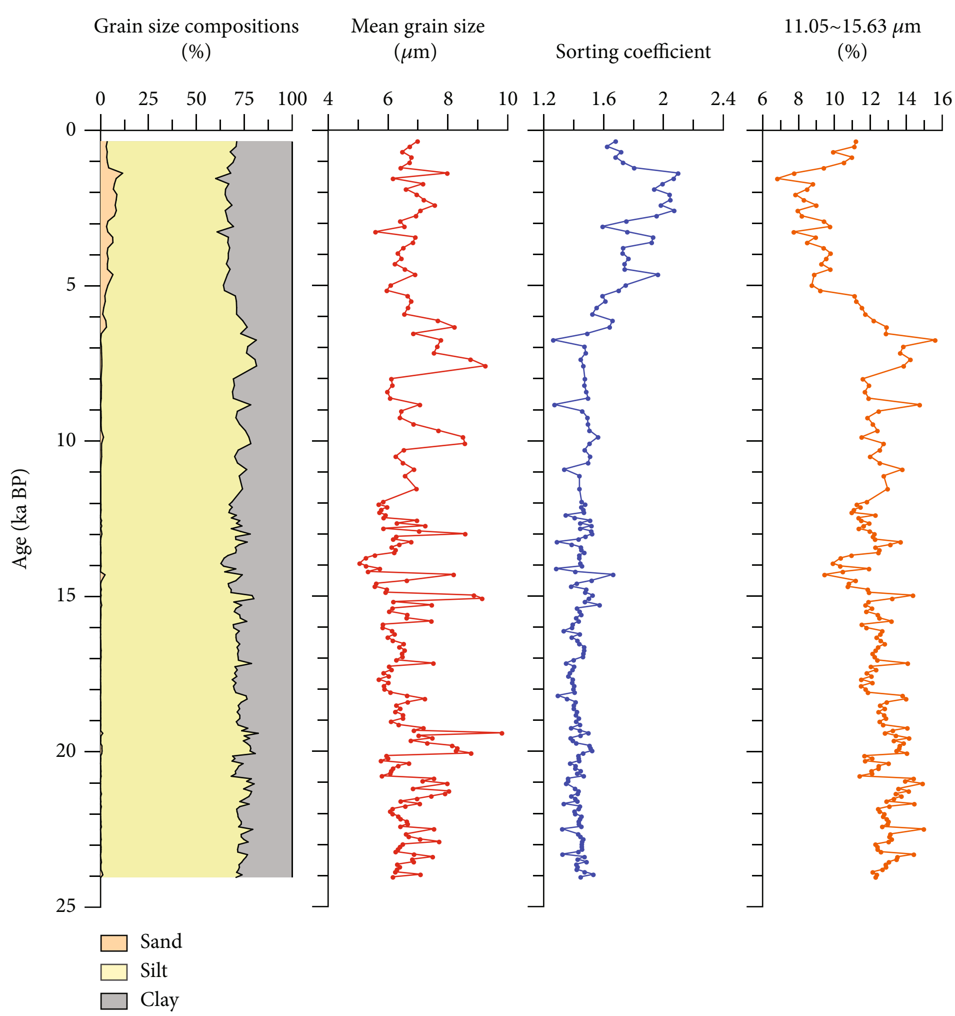

FIGURE 4: Vertical distribution of grain-size parameters of sediments in core BoB-24. Data of grain size compositions, mean grain size, and sorting coefficient were from Ye et al. [14].

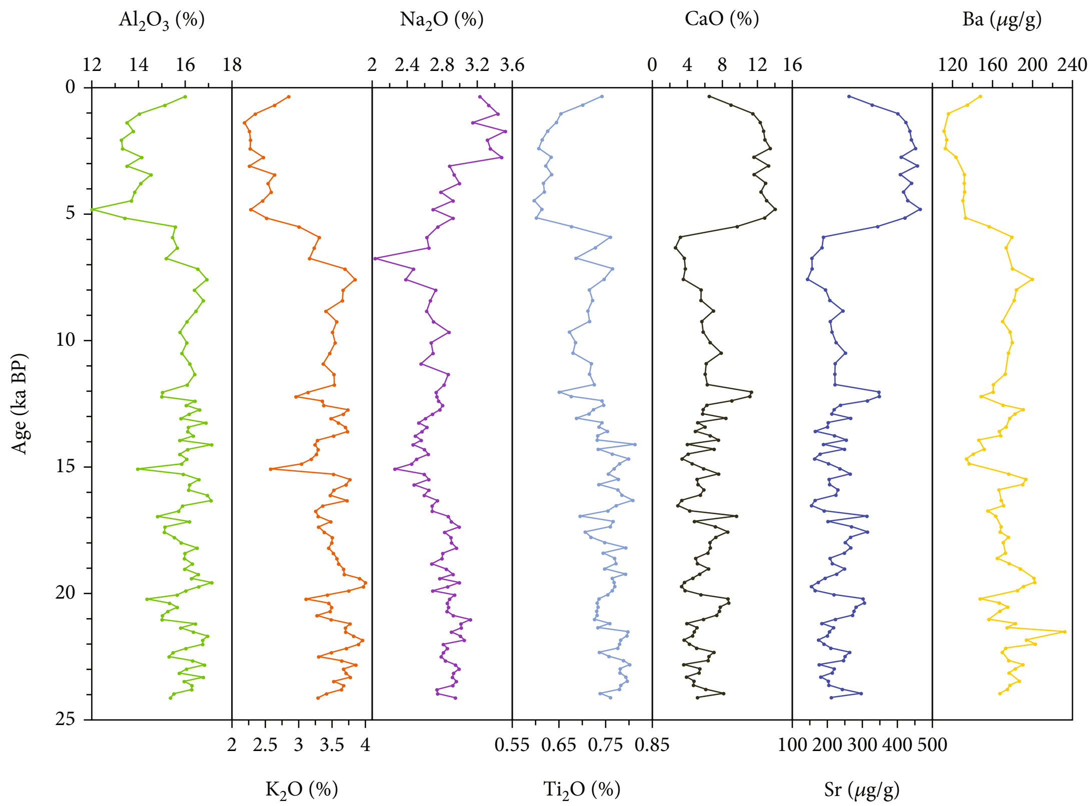

FIGURE 5: Vertical distribution of element concentrations in the sediments of core BoB-24.

BP, the element concentrations varied slightly. Al_2O_3, CaO, K_2O, Na_2O, TiO_2, Sr, and Rb varied in a narrow range. The most obvious variation occurred since 6.5 ka BP, during which Al_2O_3, K_2O, TiO_2, and Rb contents quickly reduced and progressively grew. In the meantime, CaO and Sr showed opposite trends: they rapidly increased and gradually decreased.

4. Discussion

4.1. Provenance Discrimination. Clarifying the sediment source is the premise to study the "source-to-sink" characteristics and paleoenvironmental evolution of the central BoB. Former research concerning the material source of sediments from the Bay of Bengal is mainly based on clay minerals [12, 14, 32], geochemical element characteristics [33–35], and Sr-Nd isotopic characteristics [12, 36]. According to the previous research results on the material source in the Bengal Fan, sediments were primarily terrigenous erosive materials conveyed via the Ganges or other rivers, such as the Himalayas, Tibet Plateau, India, and Southeast Asia, and biological deposits (primarily calc and siliceous deposits) as well as volcanic materials [7, 37, 38]. A previous study on clay mineral composition showed sediments of core BoB-24 in 24~6.5 ka BP that were from terrigenous material input in G-B Rivers, namely, terrigenous clastic materials in the Himalayas and Tibet Plateau [14]. Sediment provenance and corresponding contributions have varied since 6.5 ka BP [14], and the material input from K-G Rivers has increased, that is, under the influence of material input of the Indian Peninsula. However, clay minerals are generally less than 2 μm, so they mainly reflect the sedimentary characteristics of fine-grained materials. Whether the evolution of sediment provenances for the bulk sediments is the same with the fine-grained sediments has not been reported. Studies on geochemical elements of bulk sediments can show the variation of provenances more completely and clearly. The sediments we studied are a mixture of different grain sizes. Taking the geochemical elements of bulk sediments as research objects can objectively reflect the sources and transport pattern of sediments on the whole. In order to further investigate about the provenance discrimination, we use the elements of the bulk sediments to indicate the source of the core BoB-24. The elemental composition and distribution of marine sediments are usually closely related to sediment sources and hydrodynamic conditions. Element geochemical parameters play a significant role in the evolution of sedimentary environment, and many fruitful research results have been obtained [13, 33, 34].

In this paper, the major elements Al_2O_3, K_2O, and TiO_2 are selected for identifying the major source for sediments of core BoB-24. Al is relatively stable during deposition. The ratio of another element to Al can eliminate the impact of particle size change on element content [39]. TiO_2 is mainly from a land source and usually occurs in continental crust rocks [40], which remains stable during weathering and is not sensitive to redox in sediments [41]. Therefore, we chose to plot K/Al (K_2O/Al_2O_3) and TiO_2 (%) (Figure 6) to reveal

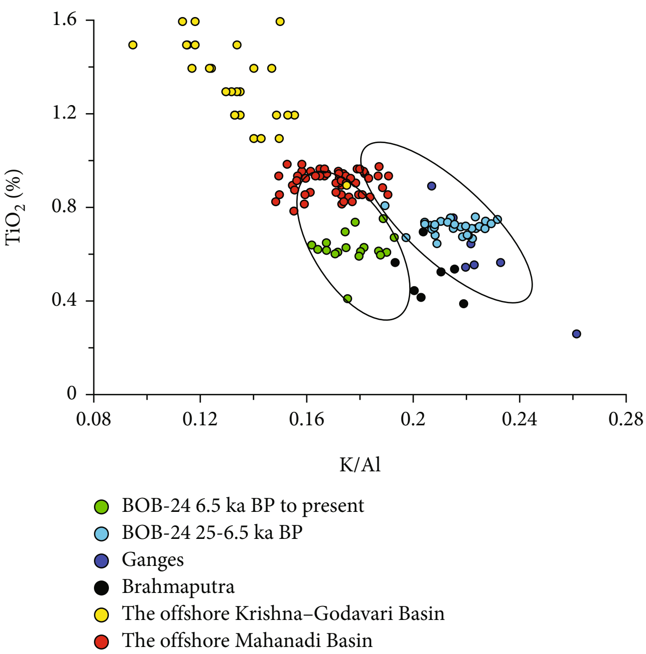

Figure 6: Provenance discrimination diagram of (K/Al)-TiO_2 (%) in core BoB-24. G-B River data from Garzanti et al. [42]; the offshore K-G Basin and Mahanadi Basin data from Mazumdar et al. [43].

the source of sediments in core BoB-24 from the perspective of elements. The (K/Al)-TiO_2 (%) values for sediments from the flood plain of the Ganges and Brahmaputra [42], the offshore basin of the K-G Rivers [43], as well as the offshore basins of the Mahanadi [43] were considered end-members in discriminating provenance. Possibly, along margin transport of K-G or G-B sediments constituted the offshore basins of the Mahanadi. However, the offshore basins of the Mahanadi were still dominated by the Mahanadi River input, and it could be a suitable end-member. Previous studies have shown that wide-range river-diluted water merely diffused to around 15°N [44], and the contourites were primarily active west of 85°E [45], which means there was little contribution from them. In addition, the submarine canyon of the Indian continental slope was underdeveloped, and only a few small canyons were seen from the western margin of the BoB.

Moreover, the amount of erosion material produced on the Indian subcontinent was restricted [46]. The geochemical composition of surface sediments in the central BoB [8] supported that Indian materials were primarily conveyed to the northern shelf of the BoB through the East Indian Coastal Current (Figure 1) controlled by ISM. Then, they were mixed with terrigenous materials from G-B Rivers and transported to the study area through "swatch of no ground" and active valleys. The study area is in the deep sea and far from the land, which limits the amount of material transported directly to the study area by ocean currents. The annual suspended sediment flux of the K-G Rivers is about 234 Mt, while that of the G-B Rivers is 1060 Mt [47]. Such disparity limits the proportion of Indian terrigenous materials in the study area. In 24~6.5 ka BP, sediments in core BoB-24 shared many similarities with those in the flood plain of G-B Rivers in element combination characteristics. Since 6.5 ka BP, sediments in core BoB-24 have turned similar to those in offshore basins of K-G Rivers and Mahanadi River in element combination characteristics, which were basically terrigenous clastic materials from the Indian subcontinent. Thus, sediments in core BoB-24 during 24~6.5 ka BP were from terrigenous material input transported via G-B Rivers (namely, terrigenous detrital material of the Himalayas and the Tibet Plateau). Since 6.5 ka BP, the source areas and corresponding contributions varied, with increased K-G River material input. The material conveyed from the Indian Peninsula greatly affected the study area.

4.2. Sedimentary Response to Climate Change since the Last Glacial Maximum. The grain-size composition and distribution of sediment can reflect the temporal and spatial variation of the hydrodynamic pattern and then reflect the information on climate and environment [30]. From the vertical distribution for sediment grain-size parameters of core BoB-24 (Figure 4), the sedimentary environment has varied since the last glacial maximum. In order to obtain the paleoclimate and paleoenvironment change information, we extracted the sensitive grain-size fractions with the computing method that combined grain-size class with standard deviation [30, 31]. The method has gained wide application in the study of paleoceanography and paleoclimatology in the East China Sea [48, 49], the South China Sea [50, 51], and the Andaman Sea [52]. The content for the sensitive grain-size fractions of the two groups was calculated (Figure 4), among which the 11.05~15.63 μm component content was consistent with the average grain-size of sediment with time, while the change trend of 2.76~4.65 μm component was opposite to the average grain size of sediment. The percentage content and the change trend of these two particle fractions indicate that the 11.05~15.63 μm component is the main factor leading to the change of the average grain size of sediment, while the 2.76~4.65 μm component is subordinate in the whole evolution process.

Generally speaking, the chemical weathering intensity of the sediment source area is subject to different climates [34, 53]. The chemical weathering intensity of the sediment source area can reflect the change in climate and environment. The study of element geochemical behavior shows that elements such as Na and K are more active and easier to be eluviated out with the increase of chemical weathering intensity while Al and Ti are different from them [54, 55]. They are more stable in the supergene environment and are not easy to be eluviated out but are enriched in the sediments during weathering. Therefore, under the condition that the sediment source area is determined, the different properties of elements are referenced in the characterization of chemical weathering intensity change of the source area. The chemical index of alteration (CIA) is usually adopted for indicating chemical weathering intensity in marine sediment studies [13, 54, 56], which reflects the chemical weathering intensity of the source area ($CIA = Al_2O_3/\ (Al_2O_3 + CaO* + Na_2O +$

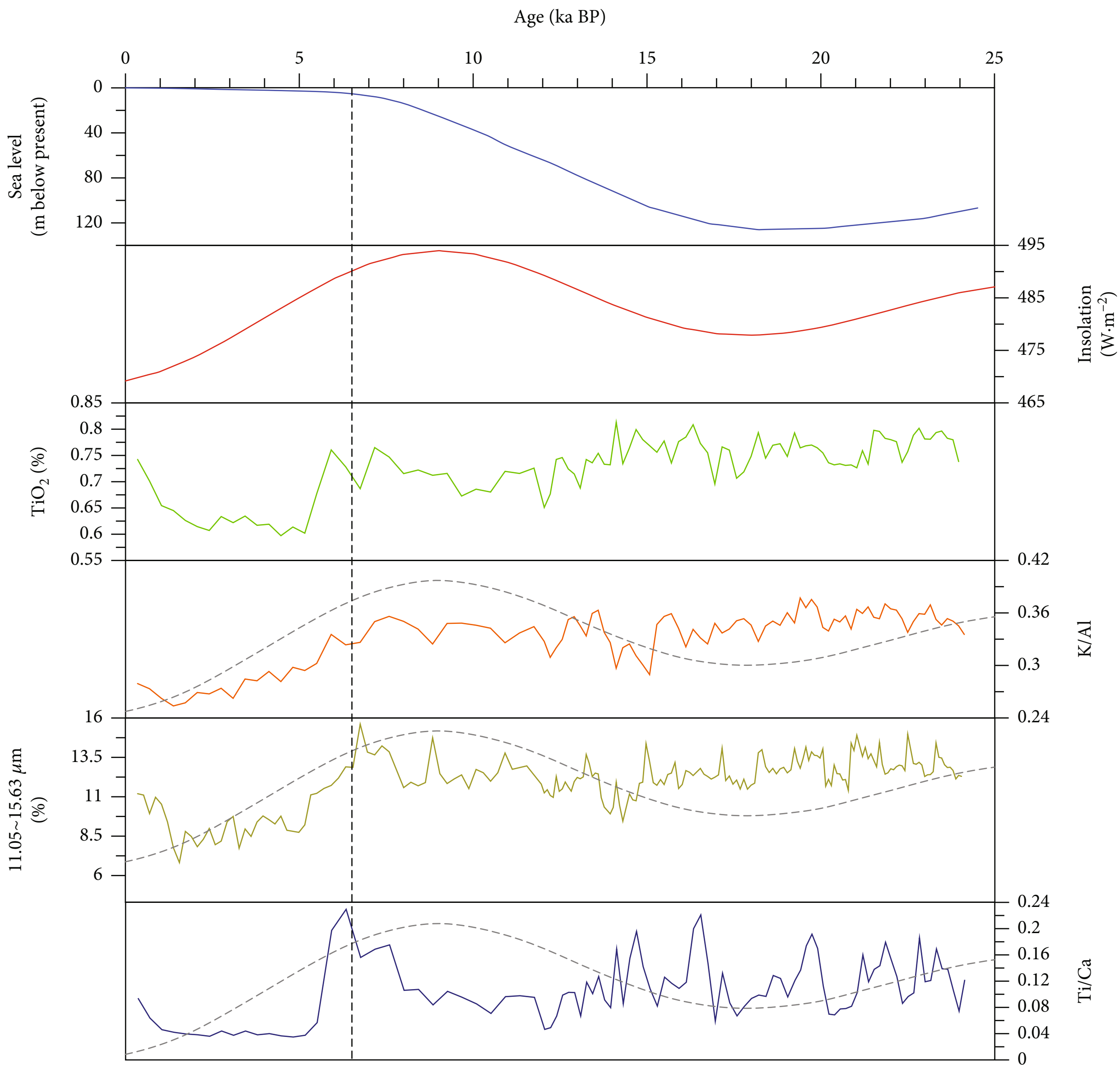

FIGURE 7: Contents of sensitive grain-size content and TiO_2, ratios of Ti/Ca and K/Al of sediments in core BoB-24; sea-level data from Arz et al. [71] and Stanford et al. [72]; data of integrated summer insolation variations at 25°N over June, July, and August from Berger [61].

$K_2O) \times 100$, molar proportions, in which CaO∗ denotes CaO content in the silicate fraction in sample, [53]).

The Ti content of sediments remains stable in hypergenesis as an inert element, and Ti is unable to generate soluble compounds by weathering. Thus, Ti of marine sediments is primarily from terrestrial clastic material input [8, 57]. Apart from protolith weathering, CaO can also be formed with biogenic input. Thus, the Ti/Ca ratio reveals the relative magnitudes of terrigenous clastic and biogenic inputs [52, 58, 59]. Based on the diverse reactions from minerals with Rb and Sr to chemical weathering, the Rb/Sr ratio is adopted as an index in the evaluation of chemical weathering intensity [60]. The higher the ratio, the stronger the chemical weathering.

The ratios of Ti/Ca and K/Al and sensitive grain-size content of core BoB-24 all showed the same trends, which were low during the last deglaciation and late Holocene but high in the Early Holocene (Figure 7). This pattern is almost the same as the variation of sea water oxygen isotope of the central Bay of Bengal calculated by Liu et al. [56] and similar to the variation of solar radiation in summer at 25°N [61], which mainly changes on the time scale of precession. Specifically, the period of high solar radiation corresponds to the period of high terrestrial input and vice versa. On the whole, these curves first showed a slowly downward trend from 24 to ~15 ka BP, then gradually increased between 15 ka BP and 6.5 ka BP, and finally decreased since 6.5 ka BP. Though they were showing some lags with the insolation, they were still in the same directions. When the solar radiation comes to its peak, the precipitation across the Indian monsoon region increases greatly but a little behind. The mineralogy in the Himalayan system sediments mainly consists of quartz, mica, feldspar, and clay minerals [62, 63]. Strengthened monsoon rainfall is expected to enlarge the material supply to the Bay of Bengal [64, 65]. There are synchronous high K/AL, Rb/Sr, Ti/Ca ratios, and CIA values in our records. When solar radiation and precipitation are at a trough during the last glacial maximum, the element ratios and CIA values show the opposite trend (Figure 7). The deposition rate is often used as an alternative index of physical erosion intensity of the source area. Therefore, the finding shows that the terrigenous input of the central BoB primarily relies on the physical erosion in the source area under the control of ISM precipitation. Former results indicate that meridional change in solar radiation leads to the North-South movement of ITCZ, thus controlling precipitation-related seasonal variation across the monsoon region [66–70]. Consequently, the change in ISM intensity significantly affects the sedimentation process of the central Bay of Bengal, and the variation in solar radiation causes the variation in ISM intensity.

The percentage content of TiO_2 and grain-size components (11.05~15.63 μm) were relatively high during 24~6.5 ka BP (Figure 7), which showed a good response to the change of sea level in general. During 24~6.5 ka BP, the sea level was at a low level (Figure 7), and the sea level of the northern Indian Ocean was ~125 m lower than the current level in the last glacial maximum (LGM) [71, 73]. Sediments reached the slope break of the continental shelf and were transported to the deep sea through submarine canyons [20, 74]. Meanwhile, the Bengal Fan was the sedimentary center [14, 20]. Since 6.5 ka BP, the values of these indicators have suddenly decreased. Corresponding to this, the sea level reached its current height at ~6.5 ka BP [71, 73]. This cut the direct transportation of sediment from the G-B Rivers to the submarine canyons [20]. The submarine canyons could not straightforwardly absorb materials of the G-B Rivers and instead captured sediments from the shelf [24]. Meanwhile, the Bay of Bengal shelf was the sedimentary center during this period [14, 20]. The rise of the sea level led to the evolution of sediment provenance of the central BoB as well as the shift of the deposition center from the Bengal Fan to the continental shelf.

4.3. Evolution of Indian Summer Monsoon and Millennial Variation Responses to the High Latitude Climate Records. As a part of the Asian monsoon system, the Indian monsoon is primarily motivated by the variation of land-sea thermal difference and the annual cycle of solar radiation angle [1, 75], which directly affects the most densely populated area in the world and is one of the most noticeable and worthy of study [52, 76]. As mentioned above, the sediments of the central BoB are primarily affected by the terrigenous materials imported from the Himalayas, Tibet Plateau, and the Indian Peninsula. The variation of ISM intensity will inevitably be recorded in the sediments. Therefore, by integrating the variation characteristics of proxies such as grain size and element geochemistry and comparing with the records of high latitude ice cores for the Northern Hemisphere, stalagmites of the East Asian monsoon region, and other records in the Indian monsoon region (Figure 8), we divide the evolution history of the Indian summer monsoon since 24 ka BP into three different stages for discussion.

4.3.1. Stage I (24~15 ka BP). This stage is characterized by typical cold climate events. The last glacial maximum is the most significant climate cooling period in the last glacial period. At this time, the reduction of solar radiation and the strengthening of glacier boundary conditions weaken the intensity of the summer monsoon, reduce the regional precipitation by ~25% [82], and reduce the runoff into the Bay of Bengal more significantly [83]. The difference between $\delta^{18}O$ in surface waters from the Arabian Sea and the Bay of Bengal reached the lowest value during this period, which confirmed that the water vapor transport from the Arabian Sea to India and the Himalayas decreased or even nearly stagnated at this time [84, 85]. During this period, erosion of the Himalayan weakened, and the sediment input from Himalayan rivers to the Bay of Bengal decreased by about 30% [34], mainly because of the weakening of the summer monsoon [84] and the expansion of large glaciers at the top of the Himalayas [19]. Meanwhile, the input of terrigenous materials is reduced, and the chemical weathering intensity indicated by the CIA is also significantly reduced.

During Heinrich Event 1 (HS1), the contents of ratios of Ti/Ca and Rb/Sr, sensitive grain-size content, and CIA recorded in the sediments for core BoB-24 showed significantly low values, indicating that the chemical weathering was significantly weakened and the terrigenous input was significantly reduced. At this time, $\delta^{18}O$ of stalagmite in Hulu Cave [81] and Dongge Cave [80] present an obvious high value, reflecting that the precipitation across the Asian monsoon area is greatly reduced at this time, while the salinity and $\delta^{18}O$ reconstructed by core SO93-126 in the northern BoB increased significantly, indicating a significant decrease in precipitation and runoff in the Indian monsoon region [77]. These indicators jointly indicate the dry and cold climates and reveal the mitigated summer monsoon intensity. Zonneveld et al. [86] believe that the change of high latitude boundary conditions during the Heinrich Events can change the southward transport of cold air and thus affect the formation and development of surface low pressure over the Tibet Plateau. The increase of regional reflectance weakens the formation of surface low pressure over the Tibet Plateau and decreases the land-sea pressure gradient, thus causing a weakened Indian summer monsoon at this time [87]. Studies on the Bay of Bengal and the Arabian Sea have revealed the regional synchronous change of the remote coupling between the variation of monsoon intensity and the temperature in Greenland [77, 88]. At this time, the rainfall in the Asian monsoon area increased significantly, which supports the view that there is a connection between the North Atlantic climate and the Asian monsoon [67, 89].

4.3.2. Stage II (15~11 ka BP). This period is characterized by the alternation of the warm period (B/A) and cold period (Younger Dryas, YD) in the northern hemisphere. During this period, the indexes fluctuated violently, showing

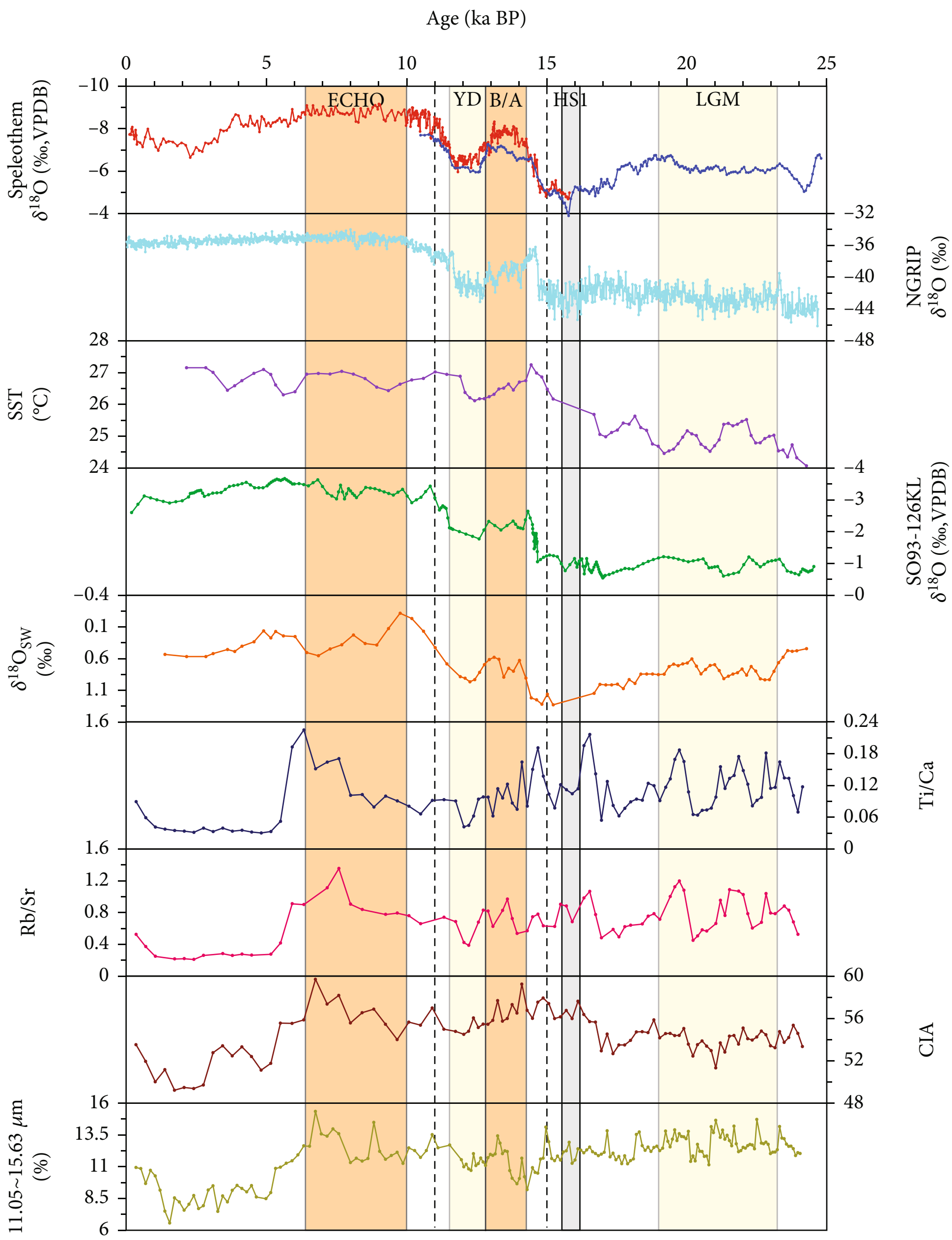

FIGURE 8: Contents of sensitive grain-size content, ratios of Ti/Ca and Rb/Sr, CIA in core BoB-24; sea surface temperature and sea water $\delta^{18}O$ data of core BoB-24 from Liu et al. [29]; foraminifera shell $\delta^{18}O$ data of core SO93-126KL from Kudrass et al. [77]; $\delta^{18}O$ data of ice core (NGRIP) in Greenland from Andersen et al. [78] and Rasmussen et al. [79]; speleothem $\delta^{18}O$ data from Dongge Cave in the southern China from Yuan et al. [80] and Hulu Cave in the eastern China from Wang et al. [81].

obvious differences between cold and warm periods. The B/A warm period after the HS1 event showed high values of CIA, element ratios, and sensitive grain size. At this time, the salinity value in the northern Bay of Bengal measured using core SO93-126KL decreased [77], indicating that the precipitation and freshwater input of the northern Bay of Bengal increased and $\delta^{18}O$ of stalagmite in Hulu Cave [81] and in Dongge Cave [80] shows an obvious low value, indicating that the precipitation of the Asian monsoon area increases. This also resulted in pollen [67], $\delta^{18}O$ of foraminifera [90], and $\delta^{18}O$ of stalagmite [91] from Oman, lake sediments and vegetation in the Arabian Peninsula [92], and lake sediments in Yemen [93]. The YD event is a rapid cooling event in the transfer from the last glacial to Holocene and rapid warming. At this time, the rainfall and runoff in the southeast of the Arabian Sea decreased significantly [94]. During the YD period, the ratios of Ti/Ca, and Rb/Sr, sensitive grain-size content, and CIA recorded in the sediments in core BoB-24 showed significantly low values. This observation was consistent with the records in the HS1 period, indicating that the chemical weathering was significantly weakened, the terrigenous input was significantly reduced, the biological productivity decreased, and the intensity of summer monsoon was weakened again.

4.3.3. Stage III (Since 11 ka BP). In the early Holocene after YD (11~6.5 ka BP), the terrigenous input increased significantly, the CIA reached the maximum value since 24 ka BP, and the salinity value of the northern Bay of Bengal recorded in core SO93-126KL decreased [77], revealing that the significant enhancement of the Indian summer monsoon caused strong chemical weathering and increased terrigenous material input in the source area. The reconstruction results of paleoprecipitation in the Bay of Bengal since 18 ka BP show that the δD value in precipitation between 10 and ~8 ka BP is the lowest when the Indian summer monsoon is significantly enhanced [95]. This resulted in pollen [67], $\delta^{18}O$ of foraminifera [90], and $\delta^{18}O$ of stalagmite [91] from Oman, lake sediments and vegetation in the Arabian Peninsula [92], and lake sediments in Yemen [93]. Together with the proxies from core BoB-24, they indicate that the source area in this period is in a humid climate under the background of the enhancement of the Indian monsoon. The sea level reached its current height at ~6.5 ka BP [71, 73]. This cut the direct transportation of sediment from G-B Rivers to the submarine canyons [20]. The submarine canyons could not straight forwardly absorb materials of G-B Rivers and instead captured sediments from the shelf [24], resulting in insufficient sediment supply in the AV channel. The turbidity current activity was weakened, the turbidity current and its overflow could no longer affect the middle Fan, and the sediment center is transferred from the deep sea to the continental shelf [7, 13, 20]. Smectite/illite increased significantly during this period [14], and the source of surface sediments changed from single source of Himalayas to the mixed source of Himalayas and Indian peninsula. In addition, the phenomenon of material resuspension in the continental shelf area is significantly enhanced. These resuspended particles were also likely to have an impact on the sediments in the deep-sea area, which together cause the inconsistency between the climate proxies and the intensity of weathering on a multimillennial timescale.

Compared with core BoB-24, core BoB-56 is also located in the central BoB, northeast of core BoB-24. Core BoB-56 is in the east of the “active valley” (AV) channel, while core BoB-24 is located in the west of the AV channel. Our previous study on the evolution process of sediment provenance in core BoB-56 [12] shows that sediment provenance varied obviously from the Holocene period to the last glacial period. The core BoB-56 sediment in the last glacial period mainly came from the erosion materials in the high-elevation regions of the Himalayas and Indo-Burman Ranges, while terrigenous material of the Indo-Gangetic Plain and Indian Peninsula grew in the Holocene period [12]. However, sediments of core BoB-24 in 24~6.5 ka BP were primarily from terrigenous clastic material input from the Himalayas and Tibet Plateau. Sediment provenance and corresponding contributions have varied since 6.5 ka BP, and the material input of the Indian Peninsula has increased. The analysis and research of sediments in core BoB-56 through geochemical element analyses and grain-size end-member extraction [12, 13] show that sediments of core BoB-56 respond to the sea-level variation on the glacial-interglacial scale and respond to the cold-warm alternating events of the high latitude area in the northern hemisphere, including B/A, YD, and ECHO. These conclusions are consistent with the results of our analysis and study on the sediments in core BoB-24 and the study on foraminifera in core BoB-24 [29]. We also identified the signal of the HS1 event in core BoB-24, which further indicates that the events of the high-latitude areas in the northern hemisphere have a very good response in the central BoB since the last deglaciation.

5. Conclusions

We analyzed grain-size parameters and element contents in core BoB-24 from the central BoB and examined the climate-controlled depositional patterns since the last glacial maximum. The (K/Al)-TiO_2 (%) values of the sediments were taken for the discrimination of provenance, which indicated that the sediments of core BoB-24 in 24~6.5 ka BP were from terrigenous material input from the Himalayas and the material input from the Indian subcontinent has increased since 6.5 ka BP. The sensitive grain-size fraction (11.05~15.63 μm) was extracted with the computing method that combined the grain-size class with standard deviation, and it was consistent with the change of mean grain size since the last glacial maximum. CIA and the ratios of Ti/Ca and Rb/Sr were calculated to explore the source area’s variation in terrigenous input and weathering intensity. Sea-level change and ISM intensity were two important factors in the depositional process of the central BoB after the LGM. They could control the amount of terrigenous materials conveyed to and deposited in the central BoB. The rising sea level caused the evolution of sediment provenance in the central BoB and the shift of deposition center from the Bengal Fan to the continental shelf. The variation in ISM controlled the change of terrigenous input and weathering intensity. During Holocene, the strengthened ISM affected the delivery of detrital materials from offshore to the central BoB. Alternative indicators such as the contents of ratios of Ti/Ca and Rb/Sr, CIA, and sensitive grain-size content in sediments of core BoB-24 jointly record the evolution history of the Indian summer monsoon since 24 ka BP in the Bay of Bengal. Although the sensitivity and response of each indicator to the paleoenvironment and paleoclimate change are slightly different, on the whole, the change trend is the same. Some important climate events, including HS1, B/A, YD, and ECHO, are consistent with the records of the Greenland ice core in the North Atlantic, which proves that its evolution is closely associated with climate variation of the North Atlantic.

Data Availability

The dataset supporting the conclusions of this article can be found in the supplementary files.

Conflicts of Interest

The authors declare that they have no competing interests.

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Supplementary Materials

The data of the original element geochemical and sensitive grain-size composition in this study are available in the supplementary materials. *(Supplementary Materials)*

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