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Sr–Nd isotope composition of the Bay of Bengal sediments: Impact of climate on erosion in the Himalaya

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A temporal high-resolution analysis of Sr–Nd isotopic composition, Fe, Al and V concentration and magnetic susceptibility (MS) has been carried out in a sediment core from the western Bay of Bengal to trace sediment sources. Significant variations in the Sr and Nd isotopic composition and corresponding MS and elemental Fe/Al and V/Al ratios are observed in the sediment core with depth (time) indicating variable contributions from sources. The observed changes in the sediment provenance correlate well with the climatic record of the region, highlighting the important influence of climate over erosion. Relatively lower $^{87}Sr/^{86}Sr$ and higher ε_{Nd} corresponding to the Last Glacial Maximum (LGM) suggests proportionally reduced sediment contribution from the Himalaya. Erosion rate over the Himalaya decreased during LGM due to combined influence of reduced intensity of the southwest monsoon and larger extent of glaciations over the Higher Himalaya, the main source of sediments to the Bay of Bengal.

Keywords: Himalaya, Bay of Bengal, erosion, climate, Sr–Nd isotopes

INTRODUCTION

The Bay of Bengal (BoB) receives sediments from various sources including the Himalaya, Trans–Himalayan plutonic belt (TPB; Mishmi Hills), Indo–Burman Ranges and the Peninsular India through the major rivers, the Ganga, Brahmaputra, Irrawaddy, Salween, Godavari, Mahanadi and the Krishna. In these river basins, erosion is regulated by both the southwest (summer) and the northeast (winter) monsoons. There are evidences to show that the intensity of these monsoons varied over millennial timescale (Duplessy, 1982; Prell and Kutzbach, 1987; Sarkar *et al*., 1990; Tiwari *et al*., 2005; Herzschuh, 2006). These variations in turn have the potential to influence the erosion pattern over the source regions and the sediment delivery to the BoB. Therefore, the variations in the sources of sediments deposited in the BoB hold clues to changes in the monsoon intensity.

In earlier studies, temporal variations in the provenance of sediments of the BoB have been tracked using Sr–Nd isotopes (France-Lanord *et al*., 1993; Colin *et al*., 1999; Pierson-Wickmann *et al*., 2001; Ahmad *et al*., 2005; Kessarkar *et al*., 2005; Galy *et al*., 2008). Over Ma time scale, the sources of sediments to the BoB have remained roughly the same since the Miocene (Bouquillon *et al*., 1990; France-Lanord *et al*., 1993). The sources are dominated by contributions from the Higher Himalaya (HH) with subordinate supply from the Lesser Himalaya (LH). However, on millennial timescale, there are evidences of variations in the provenance of sediments related to climatic changes (Colin *et al*., 1999; Goodbred, 2003; Ahmad *et al*., 2005; Bookhagen *et al*., 2005, 2006; Kessarkar *et al*., 2005; Clift *et al*., 2008; Rahaman *et al*., 2009). This is consistent with the important role that climate has on the present-day erosion over the Himalaya, with most of sediments delivered to the BoB by rivers during the southwest monsoon (Islam *et al*., 1999; Goodbred, 2003). In contrast, some of the studies carried out in the Nepal Himalaya (Burbank *et al*., 2003), have decoupled climate and erosion and have highlighted the important control of tectonics on erosion. Compared to the Himalaya, there has been paucity of information on the paleo-erosion pattern of the Peninsular India river basins and their controlling factors. Based on clay mineralogy and Sr–Nd isotopes of marine sediments from the south-west margin of India, Kessarkar *et al*. (2003) concluded that these sediments are mainly from the Peninsular India and the Himalaya (Indus basin) and that their provenance and transport pathways remained the same during the late Pleistocene and Holocene.

These limited information on the monsoon-erosion relation in the Himalaya and the Peninsular India regions, warrant a detailed study. The western Bengal fan receives

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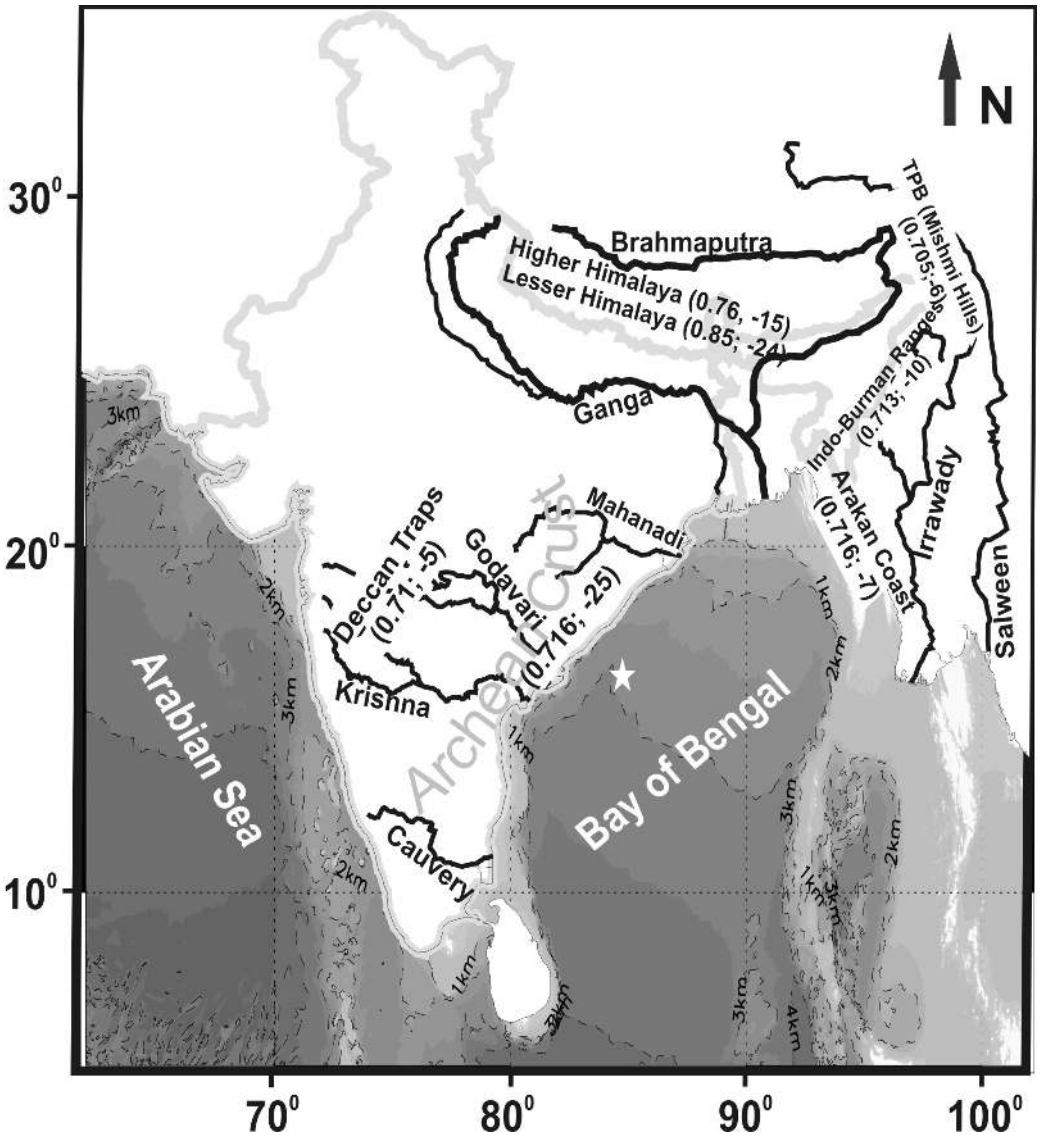

Fig. 1. Location of the sediment core SK187/PC33 (white star) in the Bay of Bengal. The various sources of sediments to the core site with their characteristic $^{87}Sr/^{86}Sr$ and ε_{Nd} are also shown (data source: Colin et al., 1999, 2006; Ahmad et al., 2009; Singh et al., 2008). Bathymetry data are from http://www.bodc.ac.uk/data/online_delivery/gebco/

sediments predominantly from the Himalaya and the Peninsular India and hence it can be used to investigate the past erosion pattern of these source regions. In the present study, efforts are made to track the provenance of the sediments from western BoB and their variations before, during and after the Last Glacial Maximum (LGM) and to identify the processes controlling the variations, based on sediment magnetic susceptibility (MS), chemical (Fe/Al and V/Al ratios) and Sr and Nd isotope compositions.

Materials and Methods

The samples for this study are from a 12.8 m long piston core (SK187/PC33) collected from the western BoB (16°16′ N, 84°30′ E; Fig. 1) during the 187th expedition of the ORV *Sagar Kanya*. The core was raised from an abyssal plain at a water depth of 3003 m (Fig. 1). Immediately after recovery, the core was subjected to non-invasive measurements using a Geotek® Multi-Sensor Core Logger. Continuous down-core measurements were made for P-Wave velocity, whole core bulk density using gamma-ray attenuation, magnetic susceptibility and non-contact electrical resistivity. The core logs showed the core to be turbidite free. The lithology is mainly silty-clay and it does not show any significant changes with depth. The core location presently receives sediments

Table 1. Basin characteristics and Sr, Nd isotopic composition of sediments at the outflow of major rivers contributing sediments to the BoB

Basin	River	Major Litho-units	Area	Runoff	Water discharge	Sediment flux	Sediments	
			10^6 km^2	mm/yr	km^3/yr	10^6 tons/yr	$^{87}Sr/^{86}Sr$	ε_{Nd}
Himalaya	Ganga[1,2]	HH, LH	0.95	619	460	520	0.762 to 0.782	–16.1 to –18.1
	Brahmaputra[1,3]	HH, LH, TPB, Indo–Burmese Ranges	0.58	1087	630	540	0.721 to 0.749	–13.6 to –16.9
	Lower Meghna[1]		—	—	—	—	0.738 to 0.753	–14.8 to –17.4
Peninsular India	Mahanadi	Archean Crust	0.132	500	66	60	—	—
	Godavari[4]	Deccan Trap, Archean Crust	0.31	350	92	170	0.720 to 0.730	–12.0 to –18.2
	Krishna[4]		0.252	266	67	16		
Indo–Burman Ranges	Irrawaddy[5]	Indo–Burmese Ranges, Arakan Mountains	0.414	1034	428	355*	0.713	–10.7
	Salween	TPB, Indo–Burmese Ranges	0.325	649	211	337*	—	—

Hydrological parameters from GEMS/Water (2002).
**Robinson et al., 2006.*
Sr and Nd isotopic data for the sediment of the rivers at their outflow are from [1]Galy and France-Lanord, 2001; [2]Singh et al., 2008; [3]Singh and France-Lanord, 2002; [4]Ahmad et al., 2009; [5]Colin et al., 1999.

Table 2. ^{14}C ages of inorganic carbon from the core SK187/PC33

Sample code	Depth (cmbsf)	Radiocarbon ages (yr BP)	Calibrated ^{14}C age (yr BP)
PRLCH-725	54 ± 17	7788 ± 295	8361 ± 953
PRLCH-766	281 ± 16	13573 ± 302	15727 ± 1277
PRLCH-770	316 ± 8	13964 ± 325	16171 ± 1333
PRLCH-776	466 ± 23	14286 ± 355	16728 ± 1572
PRLCH-777	621 ± 30	21242 ± 610	24840 ± 1613

mainly from the Himalaya and the Peninsular India. The Sr and Nd isotopic compositions of these two source regimes are distinctly different (Fig. 1; Table 1) and hence, temporal changes in the provenance of sediments and/or in their relative contributions should be reflected in their Sr and Nd isotope composition.

The depth-age relation for the core SK187/PC33 has been constrained using ^{14}C ages of bulk inorganic carbonates. The low abundance of carbonates in the sediment samples required processing of ~100 grams of bulk sediment samples for ^{14}C analysis (Bhushan *et al*., 1994). Briefly, the dried sediments were treated with H_3PO_4 in vacuum to convert the carbonate to CO_2. From the CO_2, benzene was synthesized for ^{14}C measurements and the ^{14}C activities were assayed using a low background liquid scintillation counter (Bhushan *et al*., 1994). The calculated ^{14}C ages (Table 2) were calibrated using Calib 5.2 (Stuiver and Reimer, 1993) with a reservoir age correction of $\Delta R = -60 \pm 50$ (Dutta *et al*., 2001).

The magnetic susceptibility of the sediments was measured at ~10 cm depth interval using a MS2 Bartington magnetic susceptibility meter calibrated at 0.47 kHz frequency (Kessarkar *et al*., 2005). Abundances of Al, Fe and V were measured using an ICP-AES (Jobin-Yvon, Ultima) after dissolving the water-washed sediments by repeated treatment with HF–HCl–HNO_3. The Sr and Nd concentrations and their isotopic compositions were measured in the silicate fraction of the sediments (Singh *et al*., 2008) at ~50 cm intervals. Sediment samples were decarbonated by treating them with 0.6 N HCl at ~70°C followed by washing with distilled water. Initially, there were concerns about the effectiveness of the procedure in completely decarbonating the sediments, particularly samples with high $CaCO_3$ (e.g., 221–223, 440–442, 899–901 cmbsf; Tripathy *et al*., 2008). Therefore, the high carbonate samples were reanalyzed after treating them one more time with 0.6 N HCl. The decarbonated and washed samples were ashed at 600°C to combust the organic matter. The residue (silicate phase), spiked with ^{84}Sr and ^{150}Nd, was digested with HF, HCl and HNO_3. The samples were brought to complete solution and pure fractions of Sr and Nd were separated from the solution us-

Table 3A. Elemental abundances, Sr, Nd concentrations and their isotope composition** in the sediment core SK187/PC33*

Depth (cmbsf)	Al (wt%)	Fe (wt%)	V (μg/g)	Sr (μg/g)	$^{87}Sr/^{86}Sr$	Nd (μg/g)	ε_{Nd}
10–12	8.96	6.54	130	56	0.74041	17	–15.5
18–20	7.44	4.05	90	87	0.75051	22	–16.9
28–30	8.83	6.42	125	57	0.74089	18	–14.6
109–111	7.95	6.22	119	58	0.74212	19	–15.4
149–151	8.85	5.63	115	59	0.74457	18	–15.9
201–203	8.47	4.88	106	43	0.74522	19	–15.8
221–223	2.50	2.17	30	73	0.75732	63	–21.1
249–251	8.82	5.78	112	60	0.73759	13	–15.7
300–302	7.89	5.57	108	69	0.73528	13	–15.8
320–322	6.28	3.97	77	98	0.73483	19	–15.1
340–342	n.a.	n.a.	n.a.	49	0.74273	17	–15.8
350–352	8.63	4.69	78	82	0.75150	24	–15.8
360–362	n.a.	n.a.	n.a.	43	0.74621	14	–15.6
400–402	6.41	3.87	78	87	0.73768	19	–15.3
440–442	2.84	1.84	34	84	0.74422	24	–19.6
450–452	8.27	4.97	105	82	0.73475	19	–14.9
490–492	n.a.	n.a.	n.a.	58	0.74248	17	–16.5
500–502	8.22	4.47	99	71	0.75515	21	–16.5
510–512	n.a.	n.a.	n.a.	54	0.74009	17	–15.4
550–552	6.15	2.52	49	123	0.73594	18	–14.6
600–602	6.80	4.42	104	104	0.72861	37	–15.0
650–652	7.30	4.88	115	99	0.72528	19	–13.7
700–702	7.77	4.84	112	101	0.72750	19	–14.5
750–752	7.75	3.84	83	127	0.73573	20	–14.5
800–802	8.13	4.86	89	83	0.73284	20	–13.8
849–851	6.81	3.57	79	101	0.73638	24	–15.5
889–891	n.a.	n.a.	n.a.	54	0.73062	13	–14.9
899–901	5.57	3.69	56	68	0.74026	17	–17.1
909–911	n.a.	n.a.	n.a.	61	0.73310	16	–14.0
949–951	7.87	4.82	103	97	0.73679	n.a.	n.a.
999–1001	4.55	2.63	53	89	0.73851	21	–14.9
1049–1051	8.07	4.46	94	111	0.74016	21	–15.5
1099–1101	8.72	4.98	103	105	0.73865	18	–15.9
1149–1151	7.55	3.68	73	145	0.73334	27	–14.7
1199–1201	6.00	1.86	35	172	0.72903	13	–14.5
1219–1221	9.19	4.87	96	116	0.73669	23	–14.8

n.a.: Not analyzed.

**The concentrations of Al, Fe and V are measured in bulk sediments.*

***Sr, Nd and their isotopic compositions are measured in their silicate fractions. Errors on Sr and Nd isotopic compositions are better than 10 ppm.*

ing conventional column chromatography (Singh *et al*., 2008). The Sr and Nd isotope measurements were carried out using an ISOPROBE-T TIMS in static multi-collection mode. Sr and Nd data were normalized using $^{86}Sr/^{88}Sr$ (=0.1194) and $^{146}Nd/^{144}Nd$ (=0.7219) respectively. The average $^{87}Sr/^{86}Sr$ ratio of standard NBS 987 during the period of study was 0.710229 ± 0.000014 (1σ, n = 85) and $^{143}Nd/^{144}Nd$ for JNdi-1 Nd standard was 0.512102 ± 0.000008 (1σ, n = 13), within the recommended values. The differences in Sr and Nd isotopic ratios measured in replicates are insignificant compared to the range of values measured in the sediment (Table 3A). The total procedural blank for Sr and Nd were orders of magnitude lower than total Sr and Nd processed.

Results

The concentrations of Al, Fe and V in total sediments of the core SK187/PC33 are given in Table 3A. The concentrations of Al, Fe and V vary from 2.5 to 9.2 wt%, 1.8 to 6.5 wt% and 30 to 130 μg/g respectively and show significant depth (temporal) variations. The MS of the core SK187/PC33 (Table 3B) ranges from 14 to 68 $\times$ 10^{-8} m^3/kg (Table 3B), comparable to earlier reported val-

Table 3B. Magnetic susceptibility (MS) of sediments from the core SK187/PC33[†]

Depth (cm)	MS 10^{-8} m^3/kg	Depth (cm)	MS 10^{-8} m^3/kg	Depth (cm)	MS 10^{-8} m^3/kg
6–8	25.6	424–426	22.1	833–835	23.7
12–14	29.7	452–454	18.7	835–837	24.6
22–24	33.9	476–478	29.9	837–839	23.6
30–32	33.7	510–512	25.0	855–857	26.5
38–40	27.4	512–514	24.6	857–859	25.5
50–52	24.2	556–558	34.0	931–933	19.2
56–58	20.7	568–570	33.0	933–935	21.8
70–72	23.5	578–580	52.0	935–937	22.3
82–83	36.8	592–594	35.1	937–939	20.0
91–93	34.5	612–614	24.6	941–943	20.4
97–99	25.0	624–626	34.7	943–945	20.5
109–111	33.3	632–634	31.1	959–961	19.8
121–123	30.9	644–646	37.5	961–963	26.8
173–175	18.4	648–650	36.3	967–969	27.0
183–185	17.7	660–662	21.7	969–971	24.0
185–187	17.9	670–672	28.3	1001–1003	33.0
211–213	14.0	678–680	23.1	1019–1021	45.3
221–223	15.3	690–692	46.6	1029–1031	24.0
262–264	14.7	700–702	43.3	1049–1051	22.5
268–270	20.1	710–712	26.3	1077–1079	18.3
274–276	15.3	732–734	23.4	1081–1083	17.6
284–286	17.1	760–762	35.6	1099–1101	18.0
300–302	22.2	770–772	30.4	1109–1111	22.6
308–310	19.8	790–792	23.1	1127–1129	28.4
316–318	14.3	798–800	24.3	1139–1141	21.4
336–338	14.2	810–812	40.0	1151–1153	68.0
346–348	20.3	820–821	34.0	1187–1189	47.1
362–364	16.9	821–823	25.9	1201–1203	46.8
372–374	20.4	827–829	20.6	1211–1213	22.3
402–404	23.3	831–833	22.2	1217–1219	30.4

[†]*Measured at frequency 0.47 kHz*

ues for western BoB sediments (Kessarkar *et al*., 2005).

The Sr, Nd concentrations in the silicate fraction and their $^{87}Sr/^{86}Sr$ and ε_{Nd} values also show significant variations with depth (Fig. 2; Table 3A). The abundances of Sr and Nd vary from 43 to 172 μg/g and from 13 to 63 μg/g respectively whereas the $^{87}Sr/^{86}Sr$ ratios vary from 0.72528 to 0.75732 and ε_{Nd} from –21.1 to –13.7 (Table 3A). The Sr isotope composition of these sediments is very radiogenic with values generally exceeding 0.735 (Table 3A), with corresponding ε_{Nd} values often less than –15. These values are within the range of isotopic composition of various sources supplying sediments to the core site (Fig. 3), though a dominance of the Himalayan source, as supplied by the Lower Meghna, exists (see Discussion). Among the 36 samples analysed for Sr and Nd isotopic composition, two samples at depths of 222, 440 cmbsf show a sharp decrease in the ε_{Nd} (and increase in $^{87}Sr/^{86}Sr$ ratios) compared to samples from adjacent depths (Table 3A). The cause for these ε_{Nd} and $^{87}Sr/^{86}Sr$ anomalies is unclear. It may be the result of a unique event, such as significant sediment delivery during flood events from a tributary flowing through lithology with low ε_{Nd} and $^{87}Sr/^{86}Sr$ such as the Mahanadi and Pennar rivers draining Archean crust. These two samples have not been considered in the analysis of the isotope data to determine their general trend with depth (Fig. 2).

DISCUSSION

$^{87}Sr/^{86}Sr$ and ε_{Nd} in contemporary sediment sources to the BoB

The different sediment sources to the BoB show characteristic Sr and Nd isotopic compositions (Fig. 1, Table 1). For example, Himalayan rivers (such as the Ganga) supply sediments with highly radiogenic Sr and less radiogenic Nd compared to that of the sediments from the TPB, the Indo–Burmese ranges, the Arakan mountains and the Deccan Plateau, which are less radiogenic in Sr and more radiogenic in Nd (Table 1, Fig. 1; France-Lanord *et al*., 1993; Colin *et al*., 1999, 2006; Galy and France-Lanord, 2001; Singh and France-Lanord, 2002; Singh *et al*., 2008; Ahmad *et al*., 2009). The Godavari and the

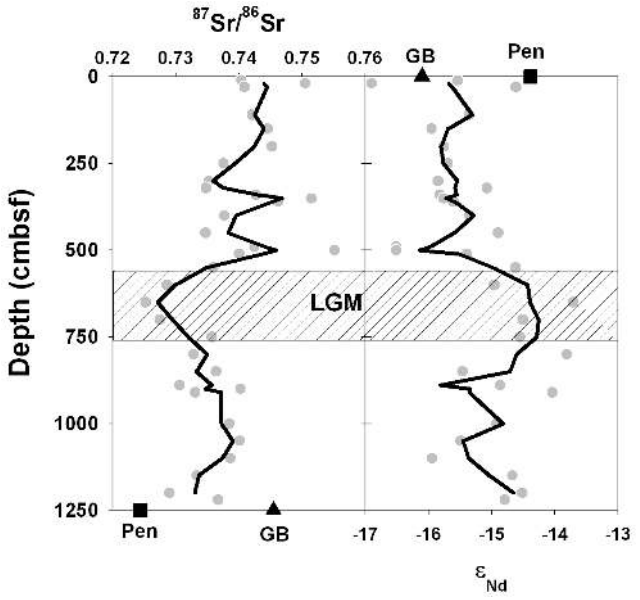

Fig. 2. Depth profile of Sr and Nd isotope composition of sediments from the core SK187/PC33 (dots). The solid line is the 3-point moving average of the data. Data show a dip in $^{87}Sr/^{86}Sr$ and a hump in ε_{Nd} excursions at ~600 cmbsf coinciding with the Last Glacial Maximum. Two anomalous samples at depth ~220 and 440 cmbsf are not included. The squares in the figure represent the average Sr–Nd isotopic values for the contemporary Peninsular Indian river sediments (Pen; Ahmad et al., 2009) and the combined flow (Lower Meghna) of G-B river sediments (Triangle (GB); Galy and France-Lanord, 2001).

Krishna rivers drain the basaltic terrain of the Deccan traps upstream and the Archean cratons downstream. Therefore, the Sr and Nd isotopic composition of these river sediments (0.720 to 0.730 and –12.0 to –18.2 respectively; Ahmad *et al*., 2009) depend on the relative contribution from these two sources. The representative Sr, Nd isotope compositions for the Archean crust (Fig. 1) used in this study are 0.716 and –25 respectively, compiled from earlier studies (Kessarkar *et al*., 2003, 2005).

Temporal variations in the erosion pattern of Himalaya and Peninsular river basins of India

Depth-Age model The availability of an depth-age model for the SK187/PC33 core is a prerequisite to infer the temporal variations of the sources supplying sediments to the core location. The depth-age model has been established based on ^{14}C of total inorganic carbon. The age distribution with depth in the core suggests that the LGM (18–21 ka) occurs at the depth range of ~600–700 cmbsf. The sedimentation rate of the core varies with depth with the lowest value at around LGM (460–620 cmbsf; 0.2 mm/yr) and about an order of magnitude higher (2.7 mm/yr) following the LGM (320–460 cmbsf). Similar pattern in sedimentation, with high rates following the LGM have also been reported by Kessarkar *et al*. (2005) and Galy *et al*. (2008).

Since the ^{14}C analyses were made in bulk carbonates, there could be an overestimation of the ages due to potential contribution of dead carbon from detrital carbonates. Earlier studies on ^{14}C measurements in coarse and fine fractions of bulk carbonates showed that the finer fractions (comprising primarily of carbonate powder and nanoplanktons) were generally older than the coarser fractions (mature forams) by ~3 ka (Sarkar, 1989; Sarkar *et al*., 1990). The older age in the finer fraction was attributed to incorporation of dead detrital carbonates. Subsequently, Tiwari *et al*. (2005) by comparing $\delta^{18}O$ spike in two cores, one dated by AMS on forams and the other (near-by core) by ^{14}C on total carbonates, suggested that the age differ by ~3 ka, the AMS dates being younger. An independent estimation of age correction can be obtained from the inorganic carbon contents of sediment sources and that in the SK187/PC33 core. The average carbonate content (expressed as $CaCO_3$) is 8.6% in the five sections of SK187/PC33 analysed for ^{14}C, compared to ~3% in the Lower Meghna sediments (Galy and France-Lanord, 2001). Dilution of SK187/PC33 carbonates with the dead riverine carbonate would overestimate the age by ~3.5 ka. The comparison of the pattern of MS profiles of the core analyzed in this study with that in an AMS ^{14}C dated core from the western BoB (Kessarkar *et al*., 2005), provides another approach to constrain the depth-age model. This approach essentially uses MS as a stratigraphic marker (Ninkovich *et al*., 1966; Bloemendal *et al*., 1995). Matching the prominent changes in the MS profiles in the top layers of the two cores (assuming that they are synchronous) indicates that the bulk carbonate ages of SK187/PC33 are older by ~4 ka. The AMS dated western BoB core (Kessarkar *et al*., 2005) had an age reversal at ~100 cm, therefore the MS pattern of the two cores below this depth are not compared. In this study, samples having comparable calcium carbonate content (~8%) were analyzed for ^{14}C chronology so that the level of correction due to presence of detrital carbonate could be similar. Thus, based on available evidences, the bulk radiocarbon ages measured in the study could be ~3–4 ka older than actual ages. This suggests that the depositional age of the sample at depth 621 cmbsf, for which the measured ^{14}C calendar age is ~24 ka (Table 2), could be about 20 ka representing the LGM. In addition to the five samples in Table 2 one sample from 222 cmbsf depth with high $CaCO_3$ (~50%) content was also analyzed for ^{14}C. This sample yielded an age of 22000 ± 600 yr (PRLCH-724) significantly different that expected based on the depth-age model of the sample in Table 2. It is worth mentioning here that this sample also has anomalous $^{87}Sr/^{86}Sr$

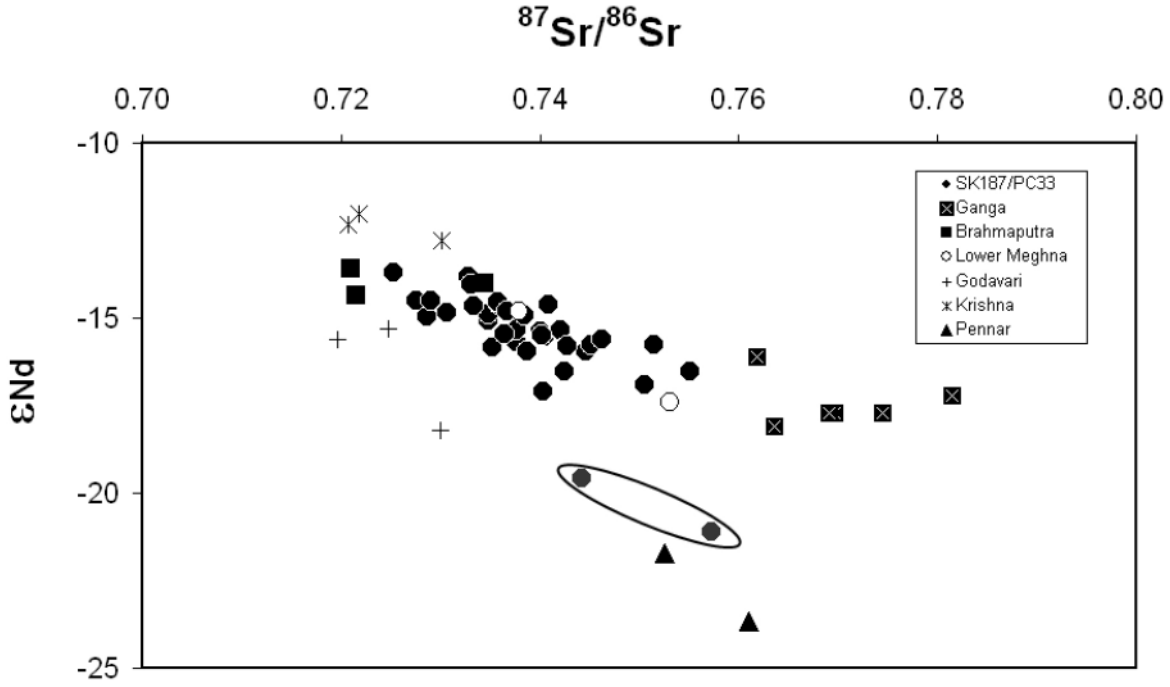

Fig. 3. $^{87}Sr/^{86}Sr$ vs. ε_{Nd} of the sediments from core SK187/PC33. The isotope composition of various sources contributing to these sediments is also given. The Sr and Nd isotope composition of SK187/PC33 sediments falls within the isotopic values of riverine sediments from the Himalaya and the Peninsular India. The two samples (encircled) having low ε_{Nd} seem to be anomalous and could be deposited by flood events in particular rivers such as the Mahanadi or the Pennar flowing though an Archean crust with radiogenic Sr and unradiogenic Nd.

and ε_{Nd} values (Table 3; Fig. 3). As a result, this data is not included for the depth-age relation.

Temporal variations in geochemical and Sr–Nd isotopic signatures in the BoB sediments The depth profiles of Sr and Nd isotope compositions of the core show significant temporal variations (Fig. 2). The range in $^{87}Sr/^{86}Sr$ (0.725–0.757) and ε_{Nd} (–13.7 to –16.9) indicate the dominance of the Himalayan source with minor contributions from the Peninsular Indian regions (Fig. 3). The $^{87}Sr/^{86}Sr$ and ε_{Nd} of the SK187/PC33 sediments (Table 3A) are bracketed by sediments from the Ganga, Brahmaputra and rivers from the Peninsular India and overlap with a few available data of the Lower Meghna (combined flow of the Ganga and the Brahmaputra in Bangladesh) indicating these rivers to be the major sediment supplier to the core site (Fig. 3).

The Sr–Nd isotope depth profiles (Fig. 2) show a striking change in isotopic compositions around 600 cmbsf. Considering the age model of the sediment core, these major changes in $^{87}Sr/^{86}Sr$ and ε_{Nd} coincide with the LGM. The $^{87}Sr/^{86}Sr$ of the samples during LGM is ~0.725 compared to their values of ~0.745 prior and after LGM (Fig. 2). The less radiogenic $^{87}Sr/^{86}Sr$ of the sediments during LGM indicate a relatively reduced supply of sediments from the Himalayan rivers, particularly that of the Ganga (which is characterized by a highly radiogenic Sr signature; Table 1) compared to that during pre- and post-LGM relative to the Peninsular Indian rivers. This inference based on the $^{87}Sr/^{86}Sr$ data is also supported from the trend of ε_{Nd} values which shows a broad hump (~–14) during the LGM compared to pre- and post-LGM values (–16; Fig. 2). The concomitant changes in both $^{87}Sr/^{86}Sr$ and ε_{Nd} argue in favor of provenance changes and not due to particle sorting/weathering processes (cf., Walter *et al*., 2000; Tutken *et al*., 2002; Colin *et al*., 2006).

Similar to Sr–Nd isotopic signatures, the Fe/Al and V/Al ratios and MS (Fig. 4) of the sediment core also show significant variations with depth (time) indicating changes in relative proportion of sediments supplied from various sources. The Sr, Nd isotopes-based inference that the sediment contribution to the core site from the Himalayan source is relatively diminished during LGM is also confirmed by the V/Al and Fe/Al ratios. Distinctly higher V/Al and Fe/Al ($(60–70) \times 10^{-4}$ and 1.01 ± 0.21; Pattan *et al*., 2008) characterize the rivers flowing through the Peninsular India compared to that of the G-B sediments (V/Al = $(20–25) \times 10^{-4}$ and Fe/Al = 0.44 ± 0.10; Pattan *et al*., 2008). The humps in V/Al and Fe/Al profiles observed during LGM in SK187/PC33 (Fig. 4) attest to the relatively enhanced sediment supply from

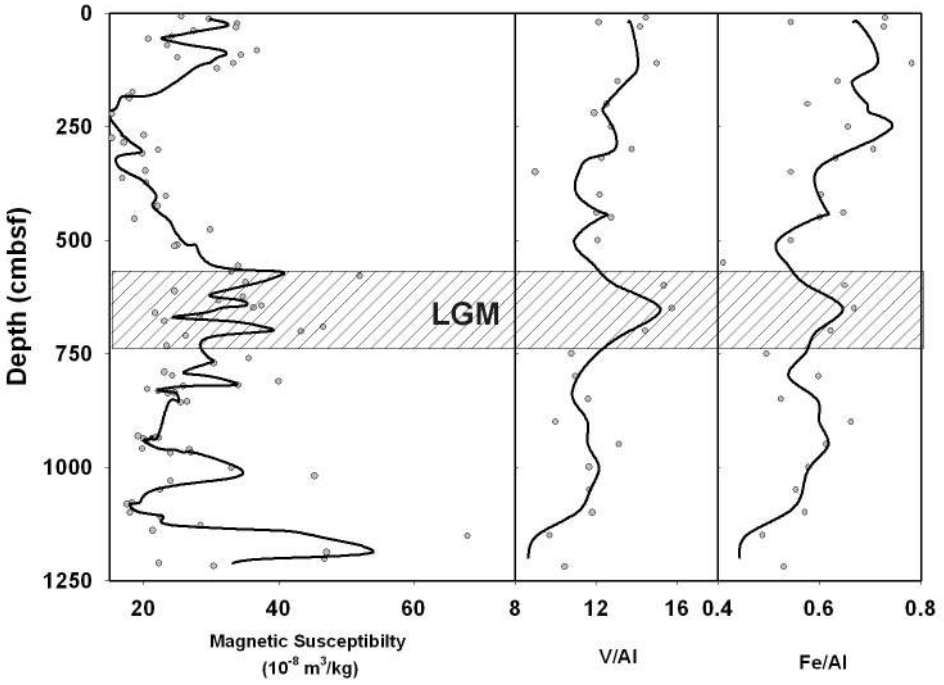

Fig. 4. Depth profiles of magnetic susceptibility (MS), Fe/Al and V/Al ratios for the SK187/PC33 sediments. The higher values of MS, V/Al and Fe/Al during the LGM indicate a relatively lower contribution from the Himalaya. The solid lines are the 3-point moving average of the data.

the Peninsular Indian rivers. This is also supported by the variation in the MS values. The magnetic susceptibility of sediments depend mainly on the abundance of detrital magnetic minerals present in them. The low carbonate content of the sediments from SK187/PC33 ensures that the magnetic susceptibility is a good tool to infer sediment provenance changes in the past (Bloemendal *et al*., 1993). Temporal variations of MS of the sediments show an increasing trend at around LGM (Fig. 4), suggesting higher abundances of ferromagnetic minerals (such as magnetite) and Fe-bearing silicates in the sediments. A very likely source for the high MS values during LGM is relatively enhanced contribution of sediments from the Peninsular Indian region. This inference draws support from the significantly higher MS values for the fluvial sediments from Peninsular Indian regions compared to that from the sediments from the river basins of the Himalaya (Sangode *et al*., 2007). The high MS value for the sediments from the Peninsular India particularly that for weathered products of the Deccan basalts, is due to the abundance of titanomagnetite with minor hematite (Courtillot *et al*., 1986; Sager and Hall, 1990). A similar high MS value during LGM in the western Bengal fan was also reported by Sangode *et al*. (2001) and this change was attributed to weakening of sediment contribution from the Himalaya.

The above discussion, based on the isotope and trace element composition of the core SK187/PC33 along with its magnetic susceptibility reveal significant variations in the relative supply of sediments from the Himalaya and the Peninsular India over glacial-interglacial timescale. However, this conclusion rests on the assumption that the isotopic and chemical characteristics of these sources did not change since the LGM. This assumption seem to be valid for the G-B rivers as the Sr–Nd isotope ratios of the BoB sediments near the mouth of this river system has remained roughly the same since the LGM (Galy *et al*., 2008). Rahaman *et al*. (2009), however, observed significant excursion in $^{87}Sr/^{86}Sr$ (and ε_{Nd}) in sediments of the Ganga upstream, during the LGM. If this finding is typical of the entire G-B basin, then it would require that the relative proportion of G-B sediments in the SK187/PC33 core during LGM would have to be lower than that estimated based on their present-day $^{87}Sr/^{86}Sr$ ratios.

The rivers draining the Peninsular India flow through multiple lithologies (Archean crust and Deccan traps) with their own distinct Sr–Nd isotope composition. Therefore, any change in the relative proportion of sediments from these two lithologies can alter the Sr–Nd isotopic signature of the peninsular sediments being delivered to the BoB. However, there is no evidence at present to suggest

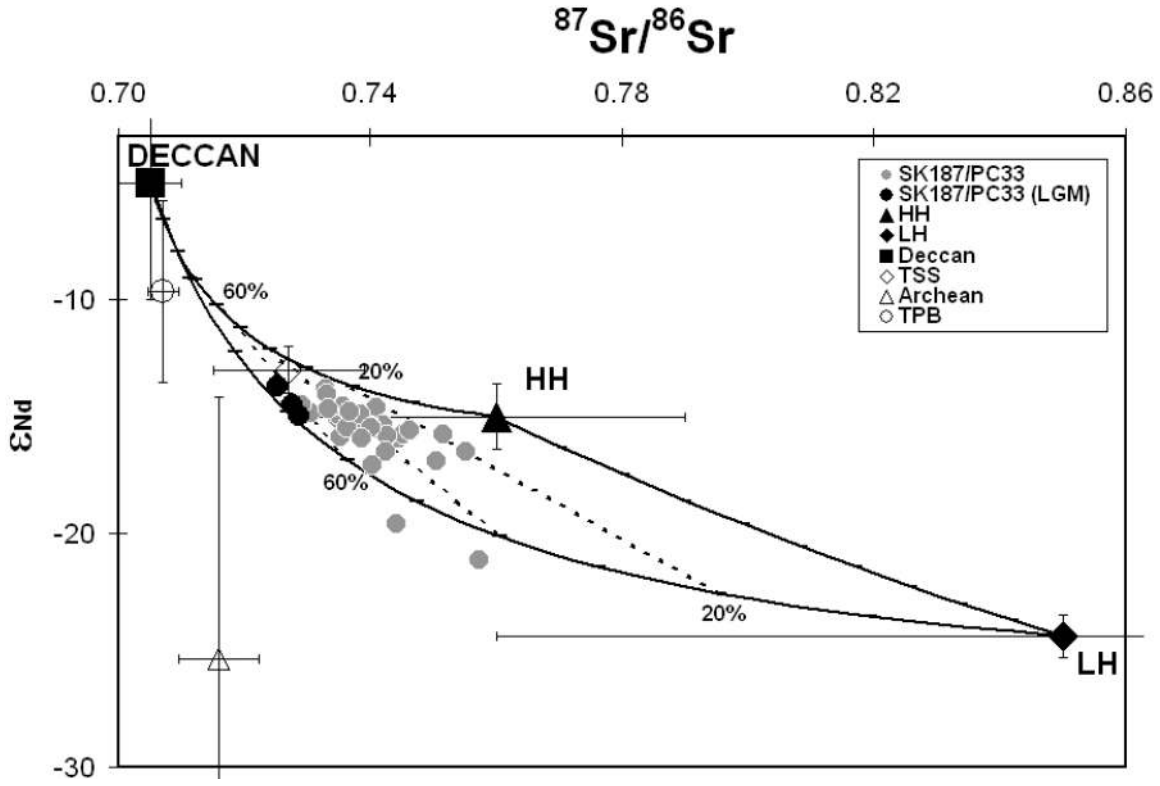

Fig. 5. Sr and Nd isotopic mixing plot for the SK187/PC33 sediments along with isotopic values of their dominant sedimentary sources. The dominance of the Himalayan sources, particularly HH, is observed for most of the samples with enhanced contribution from the Deccan traps during the LGM. The hyperbolic curve shown is the mixing trend among the sources calculated using the average Sr, Nd concentrations and isotope ratios of the Deccan (228 μg/g, 11 μg/g, 0.705, –5), HH (80 μg/g, 18 μg/g, 0.76, –15) and the LH (94 μg/g, 26 μg/g, 0.85, –24.4) respectively. The representative isotopic values for the sedimentary sources are from Singh et al. (2008), except for the TPB (Average of predominantly TPB flowing (Lohit and Dibang) river sediments; Singh and France-Lanord, 2002) and Archean terrains (Compiled from Kessarkar et al., 2003, 2005).

that the provenance of sediments of the Peninsular Indian rivers has changed in the past (Kessarkar *et al*., 2003). Increase in NE monsoon during LGM could enhance supply from the peninsular river basins. But this could result in a decrease of ε_{Nd} unlike what has been observed in this study. Figure 5 shows the Sr–Nd isotopic composition of the SK187/PC33 sediments along with the isotopic compositions of their dominant sources (*viz*. Higher Himalayan Crystallines, Lesser Himalayan silicates, Deccan traps and Archean). The dispersion of sediment data in the plot shows that their supply to the present core site is mainly from the HH, LH and the Deccan traps throughout the core length. The mixing curve (Fig. 5) among the major sources show that ~40% of the sediments are supplied from the Deccan and rest from the HH and the LH. However, the sediments deposited during LGM, with lower $^{87}Sr/^{86}Sr$ and high ε_{Nd} values, have relatively larger contribution of sediments from the Peninsular India (both Deccan traps and Archean crust) sources. The relative proportion of Peninsular India sediments to the core site during LGM (~60%; Fig. 5) increases significantly compared to that during the interglacial periods (~40%). The LGM shift in the SK187/PC33 sediments lean towards the mixing curve of Deccan and LH (Fig. 5), indicating relatively enhanced contribution from LH than that of HH during LGM. This is consistent with the results of Rahaman *et al*. (2009).

Impact of climate on continental erosion

The excursions in Sr and Nd isotope composition of the sediments during LGM is compatible with the Asian monsoon strength variability (Prell and Kutzbach, 1987; Herzschuh, 2006). Climatic records show that during the LGM the intensity of the SW monsoon decreased (Prell and Kutzbach, 1987; Herzschuh, 2006) and that of NE monsoon increased (Duplessy, 1982; Prell *et al*., 1980; Sarkar *et al*., 1990; Tiwari *et al*., 2005). The decrease in intensity of SW monsoon during LGM would limit its penetration into the Higher Himalaya, which is the dominant source of sediments to the Ganga and the

Brahmaputra at present (Singh *et al*., 2008). In addition, during the LGM the extent of glacial cover over the Higher Himalaya was larger (Owen *et al*., 2002), further limiting physical erosion in the region. In contrast, there are evidences that during the LGM, the NE monsoon was more intense (Duplessy, 1982; Prell and Kutzbach, 1987; Sarkar *et al*., 1990; Tiwari *et al*., 2005). This situation enhanced the sediment delivery from the rivers draining the Peninsular India and part of the drainage basin of the Brahmaputra (TPB), all of which have lower $^{87}Sr/^{86}Sr$ and higher ε_{Nd} (Fig. 1). Thus, the combination of decrease in SW monsoon and increase in NE monsoon during LGM contributed to decrease in the relative proportion of sediments from the Himalaya to the core site, resulting in the $^{87}Sr/^{86}Sr$ dip and ε_{Nd} hump (Fig. 2). The link between monsoon activity and sediment supply is consistent with the results of Bookhagen *et al*. (2006), who have shown that intensification of monsoon enhances sediment supply from the HH. Further, the recent study of Rahaman *et al*. (2009) on a sediment core from the Ganga plain showed a decrease in sediment contribution from the HH to the Ganga plain during the LGM, supporting the observation of the current study.

An alternative, but unlikely hypothesis to explain the observed variation in the relative proportion of sediment from the Himalaya and the Peninsular India is to invoke the role of hydrography and sea level changes in the Bay of Bengal in the dispersion of sediments. It can be argued that sediments from the Himalaya were transported directly to the central BoB during LGM due to lower sea level resulting in lower sediment proportion from the Himalaya at the core site. This proposition can be ruled out in case of sediments from the western BoB and particularly from the core site of SK187/PC33, as this core is from a water depth of ~3000 m and during LGM the Eastern Indian Coastal Current (EICC) was southwestward (Sarkar *et al*., 1990; Schott and McCreary, 2001; Tiwari *et al*., 2005). The EICC was directed N-S during LGM and hence, is expected to have focused more sediments from the Himalayan rivers to the western BoB compared to present-day, where the EICC is directed S-N. If so, the western BoB would have received higher proportion of Himalayan sediments during the LGM, which is contrary to the observations of the present study.

The variations in the Sr and Nd isotope composition of core SK187/PC33 attest an existing relation between past climatic changes and continental erosion. This hypothesis is also supported by earlier results on the variation of the Nd isotope composition of seawater and bulk sediments in the Bay of Bengal and in the Indian Ocean during the LGM and the Holocene (Burton and Vance, 2000; Stoll *et al*., 2007; Gourlan *et al*., 2010). Burton and Vance (2000) and Stoll *et al*. (2007) attributed changes in the Nd isotopic composition of seawater and bulk sediments during LGM to reduced erosional fluxes from the Himalaya caused by decrease in rainfall. This is consistent with the observation of this study.

Clift *et al*. (2008) investigated ε_{Nd} of sediments from the Indus delta. Their results show variability consistent to those observed in this study i.e., decrease in ε_{Nd} following LGM. This decrease can be attributed to relatively higher contribution of sediments from the Himalaya, particularly that from the Ganga basin, due to increase in monsoon intensity and decrease in snow cover. This interpretation is also supported by earlier observations of two-fold increase in the sediment supply from the Himalaya to the Bengal basin during these periods (Goodbred and Kuehl, 2000). In contrast to this, the results of Galy *et al*. (2008), based on Sr and Nd isotopic signatures of sediments from the channel-levee system in Bengal Fan, reported constancy in their sources since LGM. The reason behind this difference is unclear. One possible cause could be that the sampling site of Galy *et al*. (2008) is a channel-levee system, where sediments can undergo recycling. Further, the core site of Galy *et al*. (2008) receives sediments predominantly from G-B river, whereas the core SK187/PC33 receives sediments from the G-B rivers along with Peninsular Indian rivers and hence is able to better trace the signals of source variability.

The physical (MS), chemical and isotopic signature of SK187/PC33 showed a reduced Himalayan contribution to the BoB during LGM. These signatures of change in erosion pattern of the Himalaya during LGM are well preserved in the BoB sediments, which demonstrate the high efficiency of the Himalayan Rivers in transferring the sediments from their source (Himalaya) to the sink (BoB) with an insignificant time-lag between production of sediment in the Himalaya and their deposition in BoB. This observation hints that the residence time of the sediment of the Himalayan rivers in the plain seem to be very low, far less compared to that (~100 ka) proposed by Granet *et al*. (2007) based on the U–Th data of the sediments of the Gandak river.

CONCLUSIONS

The sediments from a core in the western Bay of Bengal are characterized by highly radiogenic Sr and low ε_{Nd} values. This suggests relatively higher contribution of Himalayan-derived sediments to the core site than those from Peninsular India. The Sr and Nd isotope compositions show significant temporal variations suggesting considerable changes in the relative contributions from the Himalaya and the Peninsular India sources in the past. These variations in $^{87}Sr/^{86}Sr$ and ε_{Nd} support the hypothesis that during LGM, sediment contribution from the Himalaya was reduced due to decreased intensity of SW

monsoon and increased extent of glacial cover over the High Himalaya.

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