Climate induced temporal change in Sr–Nd isotope ratios in the valley-fill deposits of the Ganga river

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The $^{87}\text{Sr}/^{86}\text{Sr}$ values in carbonate nodules and $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values in silicate samples from the valley-fill deposits of the Ganga river have been used to ascertain temporal changes in sediment provenance during the last glacial–interglacial cycle. To understand the changes, a 25 m long core named as the Firozpur core has been sampled for carbonate nodules and sediments. The $^{87}\text{Sr}/^{86}\text{Sr}$ values in carbonate nodules (0.71846 to 0.71965) of the Firozpur core are significantly more radiogenic during Last Glacial Maxima (LGM) and pre-LGM time and suggest that the Ganga river is characterized by higher $^{87}\text{Sr}/^{86}\text{Sr}$ values compared to global average river water (0.7119) at all times in the past and present. Sr and Nd isotopic data in silicate vary significantly with depth, 0.73580 to 0.77894 and –14.3 to –17.6, respectively and falling within the range of silicate rocks of the Higher Himalaya (HH) and the Lesser Himalaya (LH), the two major sediment sources to the Ganga river. The strong anti-correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd again confirm this hypothesis. Together with the $\delta^{18}\text{O}$ values and $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values of the Firozpur core suggest low precipitation over the HH during LGM caused less sediments supply from it and enhanced sediments supply from the LH. It shows significant influence of climate on erosion in the Himalaya.

Keywords: Ganga Plain, Sr and Nd isotope ratio, Peninsular India, Himalaya, plains-fed river

INTRODUCTION

The rivers that drain the Himalaya respond to varying climate and tectonic conditions and acts as a medium for sediment erosion and evacuation (Gupta, 1997; Goodbred, 2003; Srivastava *et al.*, 2008). The Himalayan rivers like Ganga and Yamuna, travels through different lithology and provide variable amount of sediments into the Ganga Plain. Apart from the Himalayan rivers, Peninsular rivers (Chambal, Betwa etc.) also contribute sediments to the Ganga Plain. The Sr and Nd isotope composition of the Himalayan and Peninsular rivers are quite distinct and is reflected by their bank sediments and river water (Krishnaswami *et al.*, 1992; Jacobson and Blum, 2000; Bickle *et al.*, 2001, 2003, 2005; Dalai *et al.*, 2003; Tripathi *et al.*, 2004; Das *et al.*, 2006; Rengarajan *et al.*, 2009; Singh *et al.*, 2008; Tripathy *et al.*, 2010). A significant amount of Ganga Plain sediments are reworked by plains-fed river and again re-deposited within the Ganga Plain (Sinha and Friend, 1994; Gibling *et al.*, 2005; Tripathi and Rajamani, 1999; Sinha *et al.*, 2007; Tripathi *et al.*,

2007). These sediments also have contrasting Sr and Nd isotopic compositions (Singh *et al.*, 2008) depending on the geographical position of the rivers. Hence, the variations in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and ϵNd value in the Ganga Plain is likely to be governed by the relative supply of sediments from the rivers originating from 1) the Himalaya, 2) Peninsular India and 3) foothills of the Himalaya and Ganga alluvial plain. Therefore, the Sr and Nd isotopic composition of the Ganga Plain sediments cannot be directly interpreted in term of past Himalayan erosion unless the sedimentary processes over the Ganga Plain is thoroughly understood.

The sediments of the Bay of Bengal have been studied to understand past Himalayan erosion history and their causative factors in million as well as millennial scale (France-Lanord *et al.*, 1993; Colin *et al.*, 1999; Pierson-Wickmann *et al.*, 2001; Ahmad *et al.*, 2005; Galy *et al.*, 2010). Such studies suggest that the sediments derived from the Higher Himalaya (HH) and Lesser Himalaya (LH) has varied with time under the influence of climate and tectonics. Considering the fact that sediments of the Bay of Bengal are a complex mixture of material derived from multiple sources and different geological terrains, therefore, precise sediment source inferences from the Bay of Bengal sediment may not be straightforward. Compared

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Fig. 1. (a) Part of the Ganga Plain in Himalayan foreland basin (Gibling *et al.*, 2005) showing position of the Himalayan (Ganga and Yamuna rivers) and Peninsular rivers (Chambal, Betwa and Ken rivers) and locations of the Firozpur core (solid triangle). (b) Map shows locations of the Firozpur and IITK cores, cut-off meanders and small plains-fed river (Sinha *et al.*, 2007) (Pandu river). (c) Cliff section (Bithur section; marked by floodplain, aeolian and lacustrine unit) and two drill cores based (IITK and Firozpur cores) stratigraphy of the valley-margin and valley-fill deposits of the Ganga river and adjacent interfluve (locations shown in (a) and (b); Sinha *et al.*, 2007).

to sediments of the Bay of Bengal, information are scanty on erosion pattern of the Himalaya and their controlling factors from the Ganga Plain (Agrawal *et al.*, 2013a, b). The sediments accumulated in the Ganga Plain are characterized by alternate floodplain and channel deposits. Carbonate nodules are the common constituent of the Ganga Plain sediments and have high abundance of Sr. The carbonate nodules record Sr isotope composition of soil solution infiltrating through the base of the soil in transit to the water table and eventually goes to the river and determine the river water chemistry (Quade *et al.*, 1997). Hence, these carbonate nodules have potential to provide information regarding the contemporaneous $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of river water and can be linked to the source rock (Quade *et al.*, 1997; Agrawal *et al.*, 2013a, b). On the other hand, the Sr and Nd isotope ratios in the silicate fraction have widely been used as a source indicator under the assumption that their source signatures are preserved in sediments (Goldstein and O'Nions, 1981; Dia *et al.*, 1992; Allegre *et al.*, 1996; Winter *et al.*, 1997; Pierson-Wickmann *et al.*, 2001). Hence, Sr and Nd iso-

topic composition and environmental signature encoded in the Ganga Plain sediments can be used to reconstruct river water chemistry and sources of sediments eroded from the Himalaya with time.

In the present study we investigate valley-fill deposits of the Ganga river from the Firozpur region (Fig. 1). Sr isotope ratio in carbonate nodules as well as Sr and Nd isotope ratio in silicate have been analyzed. These data have been used to identify the source of sediments for the Firozpur core location. Finally by comparing Sr and Nd isotope data with $\delta^{18}\text{O}_{\text{SC}}$ values based monsoonal rainfall (Agrawal *et al.*, 2012), attempt has been made to ascertain processes that regulated the sediment supply.

STUDY AREA

Ganga Plain is bordered by the Himalaya in the north and Peninsular India in the south and covers around 250,000 km² area between 77°E to 88°E longitudes and 24°N to 30°N latitudes (Fig. 1a). It acts as a transient storage space for sediments derived from the Himalaya

Fig. 2. (a) Litholog of the Firozpur core and variation in (b) $^{87}\text{Sr}/^{86}\text{Sr}$ value in carbonate nodules, (c) $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values in silicate and (d) $\delta^{18}\text{O}_{\text{SC}}$ values (Agrawal *et al.*, 2012) with respect to depth. Comparison among $^{87}\text{Sr}/^{86}\text{Sr}$ value in carbonate nodules, $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values in silicate and $\delta^{18}\text{O}_{\text{SC}}$ suggest low monsoonal rainfall causes relatively higher sediments input from the LH during Last Glacial Maxima (LGM; light grey shade) and high monsoonal rainfall is the cause of higher sediments input from the HH during pre-LGM (dark grey shade).

and Peninsular India. The Ganga is one of largest rivers that drain from the Himalaya and deposits huge amount of sediments into its modern foreland commonly called as the Ganga Plain before finally depositing into the Bay of Bengal. The study area lies within the western Ganga Plain (Fig. 1a) where late Quaternary sequences are exposed along incised valley of major rivers (Gibling *et al.*, 2005; Sinha *et al.*, 2007, 2009). The Firozpur core was obtained from the paleo-meanders of the Ganga river (Fig. 1b) and represents valley-fill deposit of the Ganga river (Sinha *et al.*, 2007, 2009) (Fig. 1c). The Firozpur core site is about 25 km north of the present location of the Ganga river and located far from northern limit of peninsular sourced sediments (Sinha *et al.*, 2007, 2009). Sinha *et al.* (2007) have dated the sediments of the Firozpur core by Optically Stimulated Luminescence (OSL) dating technique and obtained three ages i.e., 8.5 ± 1.2 , 10.5 ± 1.7 and $>31.6 \pm 2.7$ ka at about 4.6, 7.6 and 18.5 m

respectively (Fig. 2a). In addition, Sinha *et al.* (2007) have done detailed study of sedimentary facies which suggest that the Firozpur core is marked by channel and floodplain deposits with two fining-upward cycles (Fig. 2a) representing repeated events of valley aggradations (Sinha *et al.*, 2007) in contrasting climatic regimes.

The lower part of the core is mainly composed of floodplain facies and contains laminar carbonate nodules (Fig. 2a). This floodplain facies is capped by ~3 m thick channel sand facies that grade up into very fine sand to silt, overlain by ~9 m of red-brown floodplain mud. Overall, this thick sand and floodplain strata represent first fining upward cycle (Fig. 2a). On the basis of the ages of the Firozpur core and sedimentary facies study Sinha *et al.* (2007) suggested that the first fining upward cycle (Cycle I) began at >31.6 ka (at about 25 m depth) and terminated during the LGM (at about 11 m depth) reflecting decreasing monsoonal rainfall. Due to decrease in

Fig. 3. (a) Soil carbonate nodules from the Firozpur cores (Agrawal *et al.*, 2012). Photomicrograph of soil carbonate nodules from the Firozpur cores (a1 and a2) displaying mostly micritic nature. Absence of sparry calcite indicates that no major recrystallization has taken place after precipitation of carbonates. (b) Ground water carbonates from floodplain and channel sand of Firozpur core (Agrawal *et al.*, 2012). Photomicrograph of ground water carbonates from the lower part of the Firozpur core shows floating grains of quartz (b1) in micritic groundmass (Agrawal *et al.*, 2012) whereas as carbonate nodules from the channel unit shows abundant floating grains (mainly quartz and small amount of muscovite and biotite) in a spar groundmass with flow structure (b2).

monsoonal rainfall during the LGM, the Ganga river turned to under-fit condition at the Firozpur area which resulted in formation of lakes and beginning of eolian activity on the valley-margins of the Ganga river (Bithur area; Figs. 1b and 1c; Gibling *et al.*, 2005; Sinha *et al.*, 2007). The second fining upward cycle (Cycle II) started during the Holocene (at about 10 m depth; Fig. 2a) with ~8 m of channel sand. This is overlain by intercalated finer sands and yellow-brown mud, capped by a modern soil. Therefore, the Firozpur core is inferred to span part of the Marine Isotopic Stage 1 (MIS 1; <6 ka) to MIS 3 (>30 ka) and represents the late Quaternary window through valley-fill deposits of the Ganga river.

The floodplain and channel facies of the Firozpur core contain carbonate nodules (Sinha *et al.*, 2007; Agrawal *et al.*, 2012). On the basis of field observation, physical appearance, size and shape of carbonate nodules these carbonate nodules are classified as pedogenic as well as non-pedogenic or ground water carbonate (Sinha *et al.*, 2007; Agrawal *et al.*, 2012). The pedogenic or soil carbonate nodules in the Firozpur core are characterized by

rough surface (Fig. 3a) which indicate that these carbonate nodules are formed in the soil zone during the pedogenesis (Agrawal *et al.*, 2012). It is also supported by the presence of dark mottling and rhizoconcretion which again indicate pedogenic activity. Agrawal *et al.* (2012) have done detailed microscopic study of these soil carbonate nodules. The soil carbonate nodules of the Firozpur core are characterized by micritic nature and the absence of sparite suggests that these soil carbonate are not significantly re-crystallized (Figs. 3a1 and 3a2). On the other hand, megascopically, the non-pedogenic carbonates are characterized by thick sheet like structure with smooth surface, indicative of ground water origin (Fig. 3b). Microscopically, these carbonate nodules are commonly characterized by microspar and sparry groundmass with floating grains of mica and quartz (Fig. 3b1) and flow structure (Fig. 3b2).

METHODOLOGY

In order to determine the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in the carbon-

Table 1. $\delta^{18}\text{O}$ (Agrawal *et al.*, 2012) $^{87}\text{Sr}/^{86}\text{Sr}$ values, and Sr concentration in carbonate nodules and $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd value in silicate from the Firozpur core

Sample number	Depth (m)	$\delta^{18}\text{O}_{\text{sc}}$ (‰, VPDB)	$^{87}\text{Sr}/^{86}\text{Sr}$ in carbonate nodules	Sr concentration (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}$ in silicate	ϵNd
FP 1	11.0	-6.2	0.71846	401	0.77890	-17.6
FP 4	13.5	-7.2	NA	NA	0.74891	-15.4
FP 5	13.9	-7.3	0.71916	257	0.75228	-15.0
FP 5 (R)	13.9	NA	0.71889	NA	NA	NA
FP 6	14.4	-7.7	0.71937	247	0.74776	-15.5
FP 6 (R)	14.4	NA	NA	NA	0.74447	-15.1
FP 7-1	14.9	-7.2	0.71965	NA	0.74460	-15.1
FP 7-2	15.0	-7.5	NA	NA	NA	NA
FP 8	15.1	-7.8	0.7192	206	0.74738	-15.0
FP 8 (R)	15.1	NA	0.71892	NA	NA	NA
FP 10	16.0	-6.9	NA	NA	0.75352	-15.8
FP 15	17.0	-7.1	0.71898	158	0.76942	-16.5
FP 16	17.9	-6.8	0.71891	264	0.77628	-17.2
FP 16 (R)	17.9	NA	0.71898	NA	NA	NA
FP 17	17.9	-7.3	NA	NA	NA	NA
FP 18	18.0	-7.4	0.71925	302	0.76970	-17.1
FP 18 (R)	18.0	NA	0.71921	NA	0.77049	-17.0
FP 19	18.5	-7.1	NA	NA	NA	NA
FP 20*	18.7	-7.1	0.71913	209	NA	NA
FP 21	19.0	-7.0	0.71917	227	0.76929	-16.9
FP 22	19.3	-7.1	NA	NA	NA	NA
FP 23*	20.0	-6.9	0.71907	188	0.77350	-17.3
FP 24*	20.3	-7.0	0.71924	194	0.77065	-17.3
FP 25	23.1	NA	NA	NA	0.75030	-15.2
FP 26	23.8	NA	NA	NA	0.73580	-14.6

(R), repeat samples; *Ground water carbonate; NA, not available.

ate fraction, 10 mg of powdered carbonate nodules was reacted with 1M acetic acid for 30 seconds. Subsequently, the sample was filtered to remove undigested silicate minerals and dried over a hot plate. For Sr and Nd isotope studies, bulk sediments were dried in an oven and powdered to less than 200 ASTM mesh size. The sediments were pre-treated to remove carbonates and organic matters. The procedure given by Anand and Balakrishnan (2010) and Agrawal *et al.* (2013a) is adopted for digestion of silicate phase and chemical separation of Sr and Nd. The isotope ratios are measured using multi-collector Thermal Ionization Mass Spectrometer (TRITON, Thermo-Finnigan) at National Facility for Isotope Geosciences, Pondicherry University, India. The isotopic compositions were corrected for mass bias using internal normalizing ratios of $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, for Sr and Nd respectively. Multiple measurements of the International Standard SRM 987 was also carried out ($^{87}\text{Sr}/^{86}\text{Sr} = 0.710255 \pm 7$, $n = 20$; recommended, $^{87}\text{Sr}/^{86}\text{Sr} = 0.710244$). The procedural blank for Sr and Nd during isotope analysis were around 400 and 59 pg respectively, whereas, sample quantities

analyzed were more than thousand times of the blank values and hence no blank correction was applied.

Sr concentration in carbonate nodules was measured by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES = 0.001 ppm). The ICP-AES was calibrated using multi elemental standard solution of known concentration.

RESULTS

In the present study, a total of 12 carbonate nodules have been analysed for Sr isotope composition and eleven samples for Sr concentration from the Firozpur core. In addition, fifteen bulk silicate samples were analysed for their Sr and Nd isotope ratios.

Sr isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) and concentration in carbonate nodules

The $^{87}\text{Sr}/^{86}\text{Sr}$ values and Sr concentration in soil carbonate range from 0.71846 to 0.71965 and 160 to 400 ppm, respectively, and in ground water carbonate the values range from 0.71907 to 0.71924 and 188 to 209 ppm,

respectively (Table 1). There is no apparent isotopic and concentration difference observed between the soil carbonate and the ground water carbonate. To assess heterogeneity in $^{87}\text{Sr}/^{86}\text{Sr}$ values within carbonate nodules found in the Firozpur core repeat analysis were performed on duplicate samples. These duplicates show a range of variability between 0.00004 and 0.00028 (Table 1). The $^{87}\text{Sr}/^{86}\text{Sr}$ values are lowest at ~11 m depth and highest at ~15 m depth (Fig. 2b).

$^{87}\text{Sr}/^{86}\text{Sr}$ values and ϵNd in silicate

The $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values in bulk silicate range from 0.73580 to 0.77894 and -14.3 to -17.6 , respectively (Table 1). The $^{87}\text{Sr}/^{86}\text{Sr}$ value and ϵNd of bulk silicates of Firozpur core at ~20 and 11 m are characterized by high $^{87}\text{Sr}/^{86}\text{Sr}$ and lower ϵNd (Fig. 2c), whereas, bulk silicates at ~23.8 and 15 m depth are characterized by low $^{87}\text{Sr}/^{86}\text{Sr}$ and high ϵNd value (Fig. 2c).

DISCUSSION

Significance of Sr ratio in carbonate nodules and Sr and Nd isotopes in silicate and source effect

The sediments and water carried by the Himalayan rivers into the Ganga Plain show large spatial geochemical variability. The Ganga river water is characterized by high $^{87}\text{Sr}/^{86}\text{Sr}$ whereas the sediments of the Ganga river are highly radiogenic in Sr while less radiogenic in Nd compared to other Himalayan rivers like Yamuna and Brahmaputra (France-Lanord *et al.*, 1993; Galy and France-Lanord, 2001; Singh and France-Lanord, 2002; Singh *et al.*, 2008). Authogenic minerals like carbonate nodules formed in the sediments deposited in the Ganga Plain during the pauses in sedimentation and these carbonate nodules are widely distributed in the Ganga Plain. It is well established that the carbonate nodules precipitate from soil solutions and the chemistry of the soil solution is mainly determined by the weathering of sediments. In the soil profile, this soil solution infiltrate downwards at the base of the soil in transit to the ground water and finally flow into rivers and affect the river water chemistry (Quade *et al.*, 1997). Therefore, the soil solution from which carbonate nodules precipitate provides a time average chemistry of sediments as well as past river water (Jenny, 1980; Machette, 1985; Retallack, 2005; Quade *et al.*, 1997). Sr is one such element whose isotopic signature in carbonate nodules can be used to characterize the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the lowland river water and the sources of sediments through time (Quade *et al.*, 1997; Agrawal *et al.*, 2013a, b). On the other hand, Sr and Nd isotope ratios in silicate phase are used to delineate the sources of sediments in different geological time scales under the assumption that their source signatures are preserved in sediments. The Sr–Nd isotopic composition in

Fig. 4. The cross plot between $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values in silicate shows negative correlation for the Firozpur core, indicate that the Sr and Nd isotopes of the Firozpur core sediments are result of mixing between the sediments derived from the Higher and Lesser Himalaya.

silicates of HH and LH are quite distinct and show large variations. Singh *et al.* (2008) have investigated Sr and Nd isotope compositions of the bulk bank and suspended sediments, along the course of the Ganga river, from Gangotri to Rajmahal which range from 0.7577 to 0.7879 and -21 to -15.5 , respectively. From isotopic characteristics, Singh *et al.* (2008) have interpreted the sediments of the Ganga river system as derived by mixing from two potential isotopic end-members. These sources correspond to the isotopic composition of HH with ϵNd -15 ; $^{87}\text{Sr}/^{86}\text{Sr}$ 0.76 and LH with ϵNd -23.5 ; $^{87}\text{Sr}/^{86}\text{Sr}$ 0.85 (Singh *et al.*, 2008).

The Sr isotope ratios in carbonate nodules and Sr and Nd isotope ratios in silicate from the valley-fill deposits of the Ganga river (i.e., Firozpur core) vary significantly with depth. For example, Sr isotope ratios in carbonate nodules at about 11 m and 20 m depth are characterized by low values (Fig. 2b). On the other hand, $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values in silicate at the same depth are quite radiogenic in Sr and un-radiogenic in Nd and are falling within a range of the values reported by Singh *et al.* (2008) for the HH and LH rocks. The anti-correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd for the Firozpur core ($r^2 = 0.94$; Fig. 4) suggesting that ϵNd values in the sediment are decreasing with increasing $^{87}\text{Sr}/^{86}\text{Sr}$ which is clearly indicating the varying proportion of sediments from the HH and LH at the core location (Fig. 4). In addition to the HH and LH rocks, enhanced dust deposition and redistribution of sediments by plains-fed rivers within the Ganga Plain can alter the $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values in sediments at the Firozpur core site. However, study based on the Sr iso-

tope ratios in aerosol over the Ganga Plain show that the aerosol are characterized by very low Sr isotope ratio (Tripathi *et al.*, 2004; Yadav and Rajamani, 2004), which are contrary to the results of the Firozpur core. The role of redistribution of sediments by plains-fed river can also be ruled out by the following arguments: i) $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values found in the Firozpur core sediments are very similar (0.73580 to 0.77894 and -14.3 to -17.6 , respectively) to the values obtained in the modern Ganga river bank sediments at Kanpur ($^{87}\text{Sr}/^{86}\text{Sr} = 0.77989$) and Allahabad ($^{87}\text{Sr}/^{86}\text{Sr} = 0.77723$ and $\epsilon\text{Nd} = -17.6$; Singh *et al.*, 2008) which seems to indicate exclusive Himalayan source for sediments, (ii) the Firozpur core was taken from the paleo-meanders of the Ganga river implying sediments of the Firozpur core were not deposited by plains-fed rivers (Sinha *et al.*, 2007; Figs. 1b and 1c), and iii) detailed sedimentological study (Section “Study Area”) shows that the Firozpur core records major channel deposition, implying that the Ganga river lay close to its present site through that period (Sinha *et al.*, 2007, 2009; Fig. 1c). The opposite trend of both $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values (Fig. 4) again indicate that these are related to the provenance changes and not due to the results of redistribution of sediments within the basin. Overall, on the basis of sedimentological study, geographical position (Figs. 1b and 1c; Sinha *et al.*, 2007) and isotopic evidences it can be suggested that the sediments of the Firozpur core represents exclusive Himalayan source.

Tracing provenance and processes regulating sediment supply

Sediments in the modern Himalayan river are mostly characterized by detrital silt and sand with the silicate phase overwhelming the carbonate phase (Galy and France-Lanord, 1999). The input of sediments into the Ganga river mainly depends on the relative contribution from the Tethyan Sedimentary Series (TSS), HH and LH. TSS contributes minor amounts of sediments ($\sim 4\%$) to the Ganga river as it lies in the Himalayan rain shadow zone (Garzanti *et al.*, 2007; Foster and Carter, 2007), therefore, the percentage of sediments will depend on erosion in the HH and LH (Singh *et al.*, 2008). The HH silicates are less radiogenic in Sr and highly radiogenic in Nd compared to the LH silicates. The Sr–Nd isotope ratios in the silicate of the Firozpur core show a striking change in isotopic compositions which suggests that the source of sediment eroded in Himalaya and deposited in the Ganga Plain remained un-stable. The $^{87}\text{Sr}/^{86}\text{Sr}$ of the bulk silicate samples at about 20 and 11 m depth is more radiogenic in Sr i.e., ~ 0.76929 and 0.77890 , respectively compared to the values of ~ 0.73580 and 0.74460 at about 23.8 and 15 m depth, respectively (Fig. 2c). On the other hand, ϵNd values at about 20 and 11 m depth are characterized by less radiogenic Nd (-17.3 and -17.6) compared

Fig. 5. Two isotope system plot (after Singh *et al.*, 2008) of $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd in silicates of the Ganga Plain sediments (Rahaman *et al.*, 2009; Agrawal *et al.*, 2013a) and Bay of Bengal sediments (Galy *et al.*, 2010). Plot shows that the isotope ratios of the Firozpur core samples are within the range of the Higher and Lesser Himalayan rocks.

23.8 and 15 m depth (-14.6 and -15.1 ; Fig. 2c). In $^{87}\text{Sr}/^{86}\text{Sr}$ vs. ϵNd plot (Fig. 5), values at about 23.8 and 15 m depth are falling within the field of HH silicates suggesting dominant HH source of sediments at the core site. In contrast, the $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values at about 20 and 11 m depth are falling outside of the fields of the HH silicates, suggesting the involvement of an additional source of sediments. The source for these sediments appears to be the LH. A rough estimate of contribution to Ganga river sediments have been made by taking average Sr isotopic ratios and ϵNd values of the HH as 0.76 and -15 , respectively and for the LH Sr and Nd values are 0.85 and -23.5 , respectively (Singh *et al.*, 2008). The estimate yields 30% of sediments in the Ganga Plain is from the LH at about 20 and 11 m whereas at about 23.8 and 15 m depth 100% sediments contribution from the HH. Overall, comparison of results obtained in this study along with the end member isotope values show that the sediments derived from the HH and LH have varied.

It is well known that climate changes and tectonic event regulated the sediments supply from the Himalaya to the Ganga Plain. However, tectonically induced change in sediment supply is legitimate for long time scale changes such as those recorded in the Siwaliks (Quade *et al.*, 1997). For shorter time scale of few kyrs as observed in this study, tectonic controlled sediments supply might not be important as changes in tectonic activity within few kyrs is unlikely. In contrast, there are records which show significant effect of climate on the erosional pattern over the source terrain in millennial time scale. For

example, Bookhagen and Burbank (2006) showed that modern erosion rates over the HH and LH are strongly dependent on rainfall amount with two rainfall maxima along strike of the Himalaya, one at the southern margin of the LH and another at the rising limb of the HH. Erosion rate at latter place is much higher due to its higher elevation and steep gradient. A comprehensive study of the Sr and Nd isotopic composition of sediments from the Ganga river and its major tributaries indicated that under high rainfall condition the HH contributes higher amount of the sediments in the Ganga main stream (Singh *et al.*, 2008). Agrawal *et al.* (2012) have analyzed $\delta^{18}\text{O}$ values in soil carbonate nodules collected from the Firozpur core which shows more negative $\delta^{18}\text{O}$ in soil carbonate at about 15 m depth and less negative $\delta^{18}\text{O}$ values at about 20 m and at about 11 m depth (Fig. 2d). Using amount effect they interpreted more negative $\delta^{18}\text{O}$ value as a phase of higher monsoonal rainfall and less negative intervals as periods of lower monsoonal rainfall (Fig. 2d). Therefore, we compared $\delta^{18}\text{O}$ values of soil carbonate (Agrawal *et al.*, 2012) with Sr and Nd isotope ratios in silicate (Fig. 2) to understand processes regulating sediment supply over the Ganga Plain. The Sr isotope ratios and ϵNd values of silicate are showing good co-variations with the $\delta^{18}\text{O}$ values of soil carbonate nodules. For instance, the $\delta^{18}\text{O}$ values show lower monsoonal rainfall at about 20 and 11 m depth and at the same depth $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values are characterized by high and low values, respectively. On the other hand, high monsoonal phase is characterized by lower $^{87}\text{Sr}/^{86}\text{Sr}$ and high ϵNd values. Hence, it can be suggested that the higher monsoonal rainfall (Fig. 2d) produced more sediment from the HH and resulted in high ϵNd values (i.e., -15.0) in silicate. It is also supported by the Sr isotopic composition in silicate that suggest exclusive HH source of sediments. The low ϵNd value (-17.6) in silicate at about 20 and 11 m depth could be due to relatively higher contribution from the LH which resulted from low monsoonal rainfall. The silicates of the Firozpur core at the same depths are characterized by a high $^{87}\text{Sr}/^{86}\text{Sr}$ values (Fig. 2c). These values are comparable with the HH and LH rocks and suggest relatively higher contribution of sediments from the LH. It is noteworthy to observe that Sr isotope ratios in silicate and in carbonate nodules in the Firozpur core correlate negatively i.e., the peaks of the $^{87}\text{Sr}/^{86}\text{Sr}$ in silicate coincide with the dips of the $^{87}\text{Sr}/^{86}\text{Sr}$ in carbonate nodules (Fig. 2). This could be due to enhanced chemical weathering of minerals in the plain (Lupker *et al.*, 2012; Huyghe *et al.*, 2011) because under dry conditions, weathering especially concerns carbonate than silicates.

Previous studies suggested that the valley aggradation occurred during the humid climatic condition whereas it ceases in dry climatic condition when the channel net-

work is reduced (Rinaldo *et al.*, 1995; Tucker and Slingerland, 1997). In the Firozpur core region, valley aggradation started at about 25 m depth (>31 ka) under the humid climatic condition. Interestingly, at the time $^{87}\text{Sr}/^{86}\text{Sr}$ values in silicate (0.73580) suggest dominant HH source for sediments. It is also supported by the ϵNd which shows less negative value (-14.6 ; Fig. 2c). The enhanced strength of Indian summer monsoon during >31 ka could have increased its penetration into the HH, which is the dominant source of sediments to the Ganga (Singh *et al.*, 2008) and may have caused valley aggradation in the Firozpur core region. On the other hand, the valley aggradation ceased at about 11 m depth (LGM) which could be due to the reduced monsoonal rainfall. Interestingly, the Sr isotope also show a remarkable change in isotopic compositions and characterized by highly radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (0.77894) in the sediments during the LGM indicates relatively higher supply of sediments from the LH. This inference based on the $^{87}\text{Sr}/^{86}\text{Sr}$ data is also supported from the ϵNd values which shows more negative value (-17.6) during the LGM compared to Pre-LGM (-14.6 ; Fig. 2c). Overall, on the basis of above discussion it can be suggested that the sediments input from the LH and HH varied with time under the influence of climatic changes.

COMPARISON WITH EXISTING SR ISOTOPIC RECORDS OF GLOBAL RIVER WATER AND SR AND ND ISOTOPIC RECORDS FROM THE BAY OF BENGAL AND GANGA PLAIN

We have compared the Sr isotope ratio in carbonate nodules with the Sr isotope ratios in global river water. The $^{87}\text{Sr}/^{86}\text{Sr}$ of the major global rivers water ranges from 0.7089 to 0.7291 in which the Ganga river water is characterized by the highest Sr isotopic ratio (0.7291) whereas the Danube river water have lowest Sr isotope ratio (0.7089) (Goldstein and Jacobsen, 1987; Krishnaswami *et al.*, 1992; Palmer and Edmond, 1992; Pande *et al.*, 1994; Trivedi *et al.*, 1995; Yang *et al.*, 1996; Gaillardet *et al.*, 1999; Galy *et al.*, 1999; Millot *et al.*, 2003; Tipper *et al.*, 2006; Moon *et al.*, 2007, 2009; Pattanaik *et al.*, 2007; Xu and Marcantonio, 2007; Peucker-Ehrenbrink *et al.*, 2010; Noh *et al.*, 2009). The rivers like Amazon, Orinoco etc. are characterized by intermediate values. Palmer and Edmond (1989) have calculated the average Sr isotope ratio of the global river water i.e., 0.71190. The average Sr isotope ratios in carbonate nodules analyzed in the present study is 0.71909. This ratio is much higher than the Sr isotope ratio of global average river water. It indicates that the Ganga river water is characterized by high Sr isotope ratios in the past and present.

We also compared Sr and Nd isotopic composition of the Firozpur core sediments with the existing records

generated from the Bay of Bengal (France-Lanord *et al.*, 1993; Galy *et al.*, 2008, 2010; Colin *et al.*, 1999, 2006) and the Ganga Plain sediments (Rahaman *et al.*, 2009; Agrawal *et al.*, 2013a). France-Lanord *et al.* (1993) investigated variations in the Sr and Nd isotopic ratios in a sediment core from the Bay of Bengal spanning 17 Ma time period and showed that the dominant source of these sediments is the Higher Himalayan Crystallines with lesser contribution from the LH. Further, France-Lanord *et al.* (1993) suggested that the source of sediments remained nearly constant during last 17 Ma. Galy *et al.* (2010) have analyzed the Sr and Nd isotopic composition of sediments deposited in the deep Bengal Fan spanning 12 Ma time period which range from 0.7163 to 0.7526 and -10.7 to -16.5 , respectively. On the basis of these values Galy *et al.* (2010) suggested that the sediments of the deep Bengal Fan were mainly derived from the High Himalaya Crystallines with subsidiary contributions from the Trans-Himalayan batholiths and LH. Further, Galy *et al.* (2008) observed that the Sr and Nd isotopic composition of sediments deposited into the Bay of Bengal during the last 20 ka was very similar to that deposited during the past 12 Ma. It confirms the stable erosion regime of the Himalaya during millennium and millennial time scale. Colin *et al.* (1999, 2006) used Sr and Nd isotope composition of sediment core collected from the Bay of Bengal and the Andaman Sea to identify the sources of sediments. On the basis of Sr and Nd isotope Colin *et al.* (1999, 2006) suggested that these basins receive sediments from multiple sources. For instance, sediments supply into the western Bay of Bengal was mainly dominated by the Ganga–Brahmaputra rivers whereas the Andaman basin mainly received sediments from the Irrawaddy river. In addition, the sediments deposited during the LGM into the Bay of Bengal and the Andaman Sea are characterized by more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ compared to interglacial sediments, but, the ϵNd values are fairly stable during that time. The lack of correlation between the Sr and Nd isotope composition guided to interpret the $^{87}\text{Sr}/^{86}\text{Sr}$ results in terms of variations in chemical weathering intensity rather than to provenance changes. However, distinct temporal variations (Fig. 2c) and strong negative correlation between Sr and Nd isotopic ratios (Fig. 4) in the Firozpur core sediments suggest these signals are related with the provenance changes during the late Quaternary. It seems to indicate that the foreland basin i.e., Ganga Plain may respond faster to the cause of variations in sediment provenances (Goodbred, 2003) than the Ocean. Apart from the Bay of Bengal, the sediments of the Ganga Plain have been used to understand change in sediments sources. Based on Sr and Nd isotopic data in silicate which range from 0.72701 to 0.76708 and -16.6 to -14.4 respectively, Rahaman *et al.* (2009) showed that 50 m thick floodplain sediments

of Indian Institute of Technology Kanpur (IITK) core, collected from the interfluvial area of the Ganga–Yamuna river (Fig. 1), are directly deposited by the Himalayan river and the observed variations in Sr and Nd isotopic ratios is linked with variable proportion of mixing of the HH and LH sediments under the influence of climate. However, the two isotope system plot of Sr and Nd isotope data from the IITK core (Rahaman *et al.*, 2009) clustered within range of the HH rocks. This kind of clustering can only be observed in the sediments of Bay of Bengal (Galy *et al.*, 2010; Fig. 5) and is attributed to integrated effect of erosion and transportation. The isotopic values found in the Firozpur core are at odd with values reported by Rahaman *et al.* (2009) from the IITK core sediments which is ~ 25 km away from the Firozpur core in the southwest direction (Fig. 1). Indeed, the isotopic values of the Firozpur core clearly contain contrasted contribution of sediments from the HH and LH. Moreover, the Sr and Nd isotopic data in the IITK core is comparable with the isotopic values found in the Kalpi core sediments (Agrawal *et al.*, 2013a) which suggest mixed Himalayan and Peninsular India sources for sediments (Fig. 5). From the distribution of the data points in Fig. 5, it is apparent that the sediments of the IITK core were not only a mixture of the HH and LH lithologies, but could certainly include Peninsular components (Tripathi *et al.*, 2013). Therefore, the temporal variations in $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values of IITK core directly related to the erosion over the Himalaya seems unlikely and may directly be linked to the redistribution of sediments within the alluvium (Sinha *et al.*, 2007, 2009; Srivastava and Shukla, 2010). This is further supported by the detailed study of sedimentary facies, mineralogy and magnetic data of the IITK core which suggests that these sediments represent redistributed Himalayan and Peninsular sediments and may have deposited by plains-fed river (Sinha *et al.*, 2007, 2009). Further, Sinha *et al.* (2007) showed that the IITK location was too far from the marginal part of the Ganga river for last 100 ka and the main channel was situated in the Firozpur region (Gibling *et al.*, 2005; Figs. 1b and 1c). Therefore, it can be suggested that the isotopic variations in the IITK core have originated due to redistribution of the Himalayan and Peninsular sediments as postulated by Sinha *et al.* (2007, 2009) and Srivastava and Shukla (2010). Consequently, we suggest that the well dated sedimentary section from the valley fill deposits of the Ganga river from the Ganga Plain with high resolution isotopic records would shed light on the relationships between environmental conditions and erosion history over the Himalaya during the last glacial cycle.

CONCLUSIONS

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in carbonate nodules and Sr–Nd

isotopic composition in silicate from Firozpur core in the valley-fill deposits of the Ganga River exhibit significant temporal variation. The $^{87}\text{Sr}/^{86}\text{Sr}$ in carbonate nodules of the Firozpur core suggest that the Ganga river is characterized by higher $^{87}\text{Sr}/^{86}\text{Sr}$ values compared to global average river water (0.7119) at all times in the past and present. The Sr and Nd isotopic composition in silicate suggest considerable changes in the relative contributions of sediments from the HH and LH during the late Quaternary. These variations in $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd support the hypothesis that during LGM, sediment contribution from the HH was reduced due to decreased intensity of Indian monsoon. Our study suggests significant influence of climate on erosion in the Himalaya during LGM and pre-LGM time.

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