Sr and Nd isotopes in river sediments from the Ganga Basin: Sediment provenance and spatial variability in physical erosion

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[1] Sr and Nd concentrations and isotope compositions in sediment of the Ganga River, from Gangotri to Rajmahal, and its tributaries have been measured to determine provenance and the spatial variability in physical erosion among the Ganga subbasins. Sr and Nd in silicates range from 37 to 138 and from 10 to 36 μg/g, with $^{87}Sr/^{86}Sr$ and ε_{Nd} of 0.7474–0.8428 and −25.5 to −15.5, respectively. The results suggest that >65% of Ganga mainstream sediments are derived from the Higher Himalayan Crystallines highlighting intense physical erosion in this region. The $^{87}Sr/^{86}Sr$ values of sediments in the Gangetic plain show nearly identical trends during two seasons, with a sharp and significant decrease at Barauni downstream of Gandak confluence. This brings out the major impact of the sediment contribution from the Gandak to the Ganga mainstream. Model calculation suggests that about half of the Ganga sediment at Rajmahal is sourced from the Gandak. The erosion rates in the Himalayan subbasins of the Ganga range between 0.5 and 6 mm/a (where a is years), with the Gandak having the highest erosion rate. High relief and intense precipitation over the headwater basins of the Gandak appear to drive the rapid and focused erosion of this basin. The results of this study and those in literature suggest that the eastern syntaxis (Brahmaputra), the western syntaxis (Indus), and the Gandak have much higher physical erosion rates than the other Himalayan basins. Focused erosion in the hot spots of these river basins contributes significantly to the global riverine sediment budget and influence regional tectonics.

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1. Introduction

[2] The Himalaya is drained by many rivers, the Ganga and the Brahmaputra being two of the major river systems. These two rivers together discharge ~1050 km^3 of water annually to the Bay of Bengal containing ~100 million tons of dissolved solids [*Galy and France-Lanord*, 1999; *Galy and France-Lanord*, 2001; *Fekete et al.*, 2004; *Sarin et al.*, 1989] and ~1000 million tons of sediments [*Galy and France-Lanord*, 2001; *Hay*, 1998; *Islam et al.*, 1999]. It is evident from these solutes and sediment fluxes that physical erosion accounts for ~90% of total erosion in their basins. The available data on sediment fluxes of the Ganga and the Brahmaputra [*Galy and France-Lanord*, 2001; *Hay*, 1998], though limited, seem to indicate that the Brahmaputra basin is eroding more rapidly (~3 mm/a (where a is years)) than the Ganga basin (2 mm/a) because of the combined influence of climate and tectonics. Further, studies of spatial variations in physical erosion among the subbasins of the Brahmaputra show that it is highly variable, with the Eastern Syntaxis region undergoing the maximum erosion of ~14 mm/a [*Garzanti et al.*, 2004; *Singh*, 2006; *Singh and France-Lanord*, 2002]. In contrast to the Brahmaputra basin, information on the spatial variability of erosion rates in the Ganga basin is sparse, though such variations can be expected considering the differences in climate and relief among its subbasins. Further, such data on basin-scale erosion rates would help constrain the effects of erosion on regional morphology, particularly pertaining to local uplift [*Finlayson et al.*, 2002] and the relative significance of climate, tectonics and stream power in regulating erosion in the region [*Burbank et al.*, 2003; *Craddock et al.*, 2007; *Molnar*, 2003; *Singh and France-Lanord*, 2002; *Wobus et al.*, 2003].

[3] Sr and Nd isotope studies of sediments from the Bay of Bengal [*France-Lanord et al.*, 1990] and the Brahmaputra basin [*Singh and France-Lanord*, 2002] suggest that the sediment budget in these basins is dominated by supply from the Higher Himalaya. Similarly, the limited available results [*Galy*, 1999; *Galy and France-Lanord*, 2001] from the Ganga basin in Bangladesh also seem to show the dominance of the Higher Himalayan source in its sediment budget, but the contributing role of various subbasins is only poorly understood. A detailed and comprehensive study of the chemical and Sr, and Nd isotopic composition of sediments from the Ganga system and its major tributaries

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has been carried out to address some of these issues, particularly to (1) trace the sources of contemporary sediments to the rivers of the Ganga System and the Ganga mainstream in the plain in terms of major geological units, (2) determine the fraction of sediments supplied from various subbasins to the Ganga in the plain, and (3) estimate the physical erosion rates over the western and the central Himalaya to assess their spatial variability, their controlling factors and their impact on regional geomorphology.

2. Ganga River System

2.1. Hydrology

[4] The "Ganga" is formed at Devprayag by the confluence of the Bhagirathi and the Alaknanda (Figure 1a). Upstream of Devprayag, the river Bhagirathi is often referred to as the Ganga. The mainstream Ganga descends to the plain at Rishikesh after cutting across the Siwaliks ranges. In the plain, the Ganga receives a number of tributaries from the Himalaya (the Ramganga, the Ghaghra, the Gandak and the Kosi) and from the peninsular India (the Yamuna, the Tons and the Son) (Figure 1b). Among the tributaries the Yamuna originates from the Yamunotri glacier in the Higher Himalaya and flows through the Ganga plain before merging with the Ganga at Allahabad. Major tributaries of the Yamuna originate and drain peninsular India. The headwaters of the Ghaghra, the Gandak and the Kosi originate in Nepal. The Ghaghra merges with the Ganga upstream of Doriganj, the Gandak downstream of Patna, and the Kosi upstream of Rajmahal (Figure 1b).

[5] Water discharge and drainage area of the Ganga and of its major tributaries are given in Table 1. The water discharge of the Ganga at Farakka near the Indo-Bangladesh border is 380 km^3/a and the total drainage area is $\sim$935 $\times$ 10^3 km^2 [*Fekete et al.*, 2004]. Of the total drainage, $\sim$176 $\times$ 10^3 km^2 lies in the Himalaya, $\sim$350 $\times$ 10^3 km^2 in peninsular India and the balance in the Ganga plain [*Galy*, 1999; *Rao*, 1975]. Rainfall during the southwest monsoon (June–September) is the major source of water to the Ganga system. Rainfall contours over the Ganga drainage (Monthly TRMM and Other Data Sources Rainfall Estimate (3B43 V6) Database, http://disc2.nascom.nasa.gov/Giovanni/tovas/TRMM_V6.3B43.shtml, GSFC Earth Sci., Greenbelt, Md.) for January 1998 to May 2007 (Figure 2) show large variations. Belts of higher rainfall are observed close to and paralleling the Main Central Thrust (MCT), particularly over the Gandak subbasin and in the Son and Ken headwaters in peninsular India, and lower rainfall is found in the plains and over catchments of the southern tributaries. High precipitation is also observed over the Lesser Himalayan catchment of the Ganga subbasin around Rishikesh. This variability in precipitation among different regions of the Himalaya and the plain results in significant regional differences in runoff and in contribution to the water budget of the Ganga. Thus the Himalayan basin of the Ganga has a runoff of about 1m/a and accounts for $\sim$54% of its water discharge, while in comparison the peninsular rivers contribute $\sim$22% of water discharge with a runoff of $\sim$0.3 m/a [*Galy*, 1999; *Rao*, 1975].

2.2. Geology of the Basin

[6] The Ganga system drains three distinctly different regions in terms of geology and climate. These are the Himalaya, peninsular India, and the Ganga plain.

[7] 1. The Himalaya: The dominant geological units in the catchment of the Ganga and its Himalayan tributaries are the Tethyan Sedimentary Series (TSS), the Higher Himalaya (HH), the Lesser Himalaya (LH) and the Siwaliks [*Bickle et al.*, 2001; *Gansser*, 1964; *Le Fort*, 1975; *Sarin et al.*, 1989; *Valdiya*, 1980]. The lithology of each of these units over the entire Himalayan range, from east to west, is roughly the same [*Gansser*, 1964; *Le Fort*, 1975; *Valdiya*, 1980]. The headwaters of the Alaknanda, Ghaghra, Gandak and the Kosi lie in the TSS, which is composed of carbonates and clastic sedimentary rocks [*Oliver et al.*, 2003]. The HH consists of orthogneisses, paragneisses, migmatites, and metamorphosed carbonates and calc-silicates. Granites, gneisses and leucogranites which form the Higher Himalayan Crystallines (HHC) are exposed widely in this region. South of the HH, and separated by the Main Central Thrust (MCT) is the Lesser Himalaya (LH). The lithologies of the LH are meta-sedimentary rocks which include limestones, dolomitic carbonates, shales, slates, quartzites, evaporates, and calcsilicates. The LH is divided into two sedimentary sequences, the outer and inner belts, separated by the Lesser Himalayan Crystallines (LHC) consisting of granites and gneisses [*Valdiya*, 1980]. The Siwaliks is the southernmost unit of the Himalaya formed by the uplift of sediments deposited in its foreland basin during the Mio-Pliocene [*Valdiya*, 1980]. It consists mostly of sandstones.

[8] 2. The Peninsular Drainage: The Tons and the Son, tributaries of the Ganga, and the Chambal, the Betwa and the Ken, tributaries of the Yamuna, drain peninsular India (Figure 1b). The Deccan basalts, the Vindhyan sediments and the Bundelkhand crystallines (Archean basement) are the major lithologies exposed in this drainage [*Krishnan*, 1982]. The basement granites are exposed at many locations in the Son basin.

[9] 3. The Ganga plain: The Ganga plain is composed of alluvium, sand and gravel, derived from the source regions of the Ganga and its tributaries. Carbonates transported from the Himalaya and formed locally from river and groundwater are also present in these sediments.

3. Materials and Methods

3.1. Sampling

[10] Sediment samples from the Ganga mainstream and its major tributaries, both in the Himalaya and the plain,

Figure 1. Sampling locations of sediments from the Ganga basin: (a) the Himalayan drainage and (b) Plain. The locations of samples collected in 2004 are marked in the map. Bank sediments from the Ganga mainstream and its major tributaries were collected all along the course of the Ganga, from its source (Gangotri) to Rajmahal near the Indo-Bangladesh border. Dashed line in Figure 1a defines the headwater drainage of the Ganga, whereas in Figure 1b it represents country boundary and the dotted line marks the boundary of the Ganga drainage. Main Central Thrust (MCT) and Main Boundary Thrust (MBT) are marked in Figure 1b.

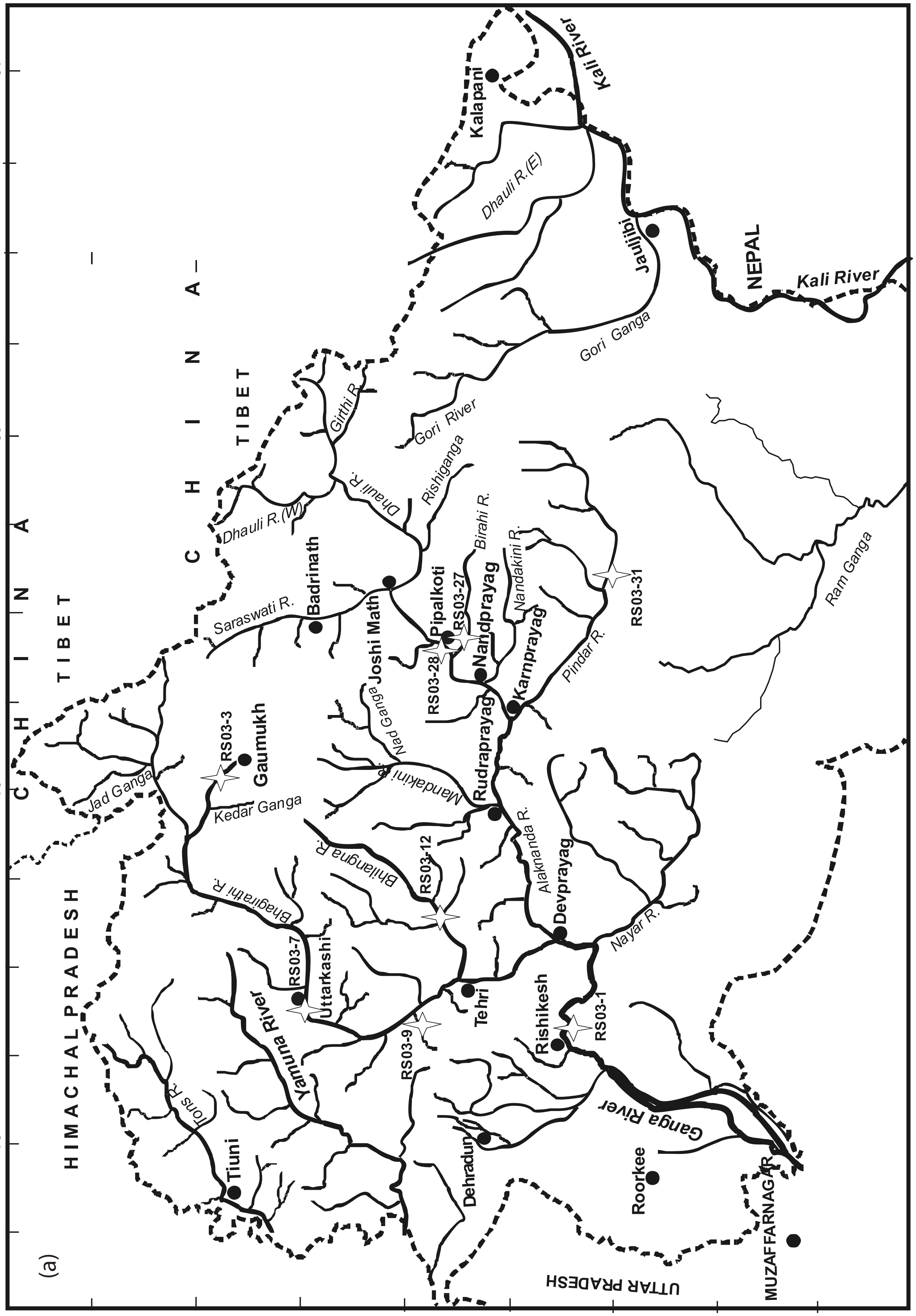
(a)
CHINA
TIBET
NEPAL
HIMACHAL PRADESH
UTTAR PRADESH
Kali River
Kalapani
Dhauli R.(E)
Jauljibi
Gori Ganga
Gori River
Girthi R.
Dhauli R.(W)
Dhauli R.
Rishiganga
Birahi R.
Nandakini R.
Badrinath
Saraswati R.
Joshi Math
Pipalkoti
RS03-27
RS03-28
Nandprayag
Karnprayag
Pindar R.
RS03-31
Ram Ganga
Nad Ganga
Mandakini R.
Rudraprayag
RS03-3
Gaumukh
Jad Ganga
Kedar Ganga
Bhilangna R.
RS03-12
Alaknanda R.
Devprayag
Nayar R.
Bhagirathi R.
RS03-7
Uttarkashi
Tehri
RS03-9
Rishikesh
RS03-1
Yamuna River
Tons R.
Tiuni
Dehradun
Ganga River
Roorkee
MUZAFFARNAGAR
31°
30°
78°
79°
80°
81°

Figure 1

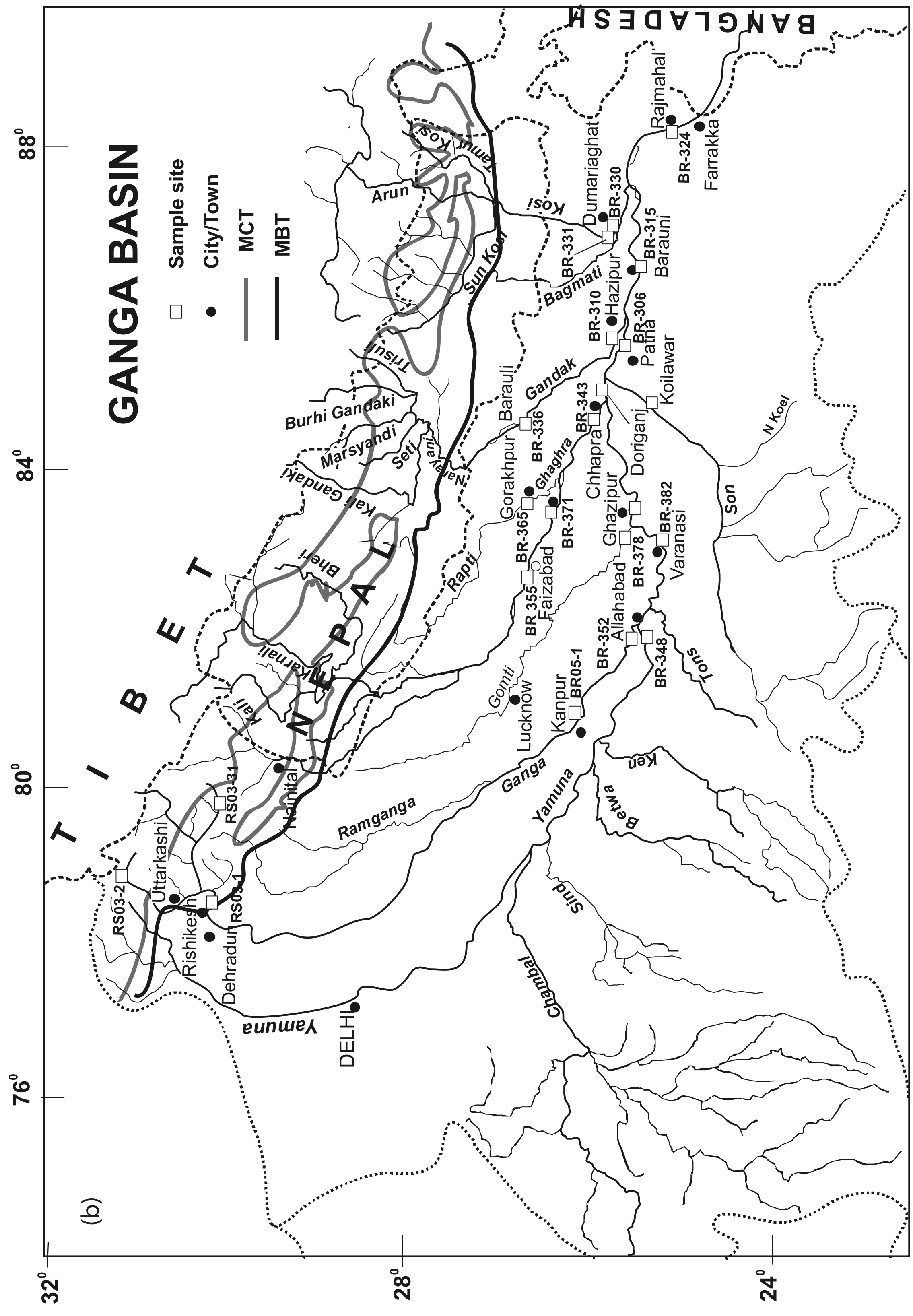

Figure 1. (continued)

Table 1. Drainage Area and Discharge of Major Rivers of the Ganga System[a]

		Area (10^3 km^2)		Water Discharge (10^9 m^3/a)	
River	Location	Total	Himalaya	Total	Himalaya
Bhagirathi	Devprayag	7.8	7.8	8.3	8.3
Alaknanda	Devprayag	11.8	11.8	14.1	14.1
Ganga	Rishikesh	21.7	21.7	23.9	23.9
Ramganga[b]		32.5	2.5	15.6	9.8
Yamuna	Allahabad	366	9.8	93.0	10.8
Tons[b]		16.9	nil	5.9	nil
Gomti[b]		30.5	nil	7.4	nil
Ghaghra[b]		128	57.6	94.4	63.4
Gandak[b]		46.3	31.8	52.2	49.4
Kosi[b]		74.5	51.4	62.0	48.2
Son[b]		71.3	nil	31.8	nil
Ganga	Farakka	935	176	380	206

[a]Data from *Galy* [1999], *Fekete et al.* [2004], and *Rao* [1975].
[b]Before confluence with the Ganga.

were collected from their banks within a few meters of water. In addition, sediment samples richer in fine fractions were also collected, generally from sandbars exposed in mid-channel of rivers. The sampling spanned the entire stretch of the Ganga, from its source at Gangotri to near its outflow at Farakka (Figures 1a and 1b). The sampling was done during May 2003 (summer) from the Himalayan sector and during May 2004 (summer) and October 2006 (monsoon/post monsoon) from the plain. In addition, a single sample of the Ganga at Kanpur was collected in May 2005. The repeat sampling in the plain was done to assess the temporal variability in the chemical and isotopic composition of sediments along the Ganga mainstream and the role of tributaries in contributing to this variability. During sampling, wherever possible, 5–6 samples were collected from an area of ~500 × 500 m and were mixed and homogenised at site to yield a *representative* sample of sediment from that location. Sampling locations and their details are given in Figures 1a and 1b and Table 2.

3.2. Analysis

[11] The chemical and isotopic measurements were made on bulk (total) sediments and on the <4 μm fraction in summer samples and on total sediments in the monsoon samples. Analysis of the <4 μm fraction was done to obtain data on fine fraction of sediments, which generally is an important component of riverine suspended matter. The

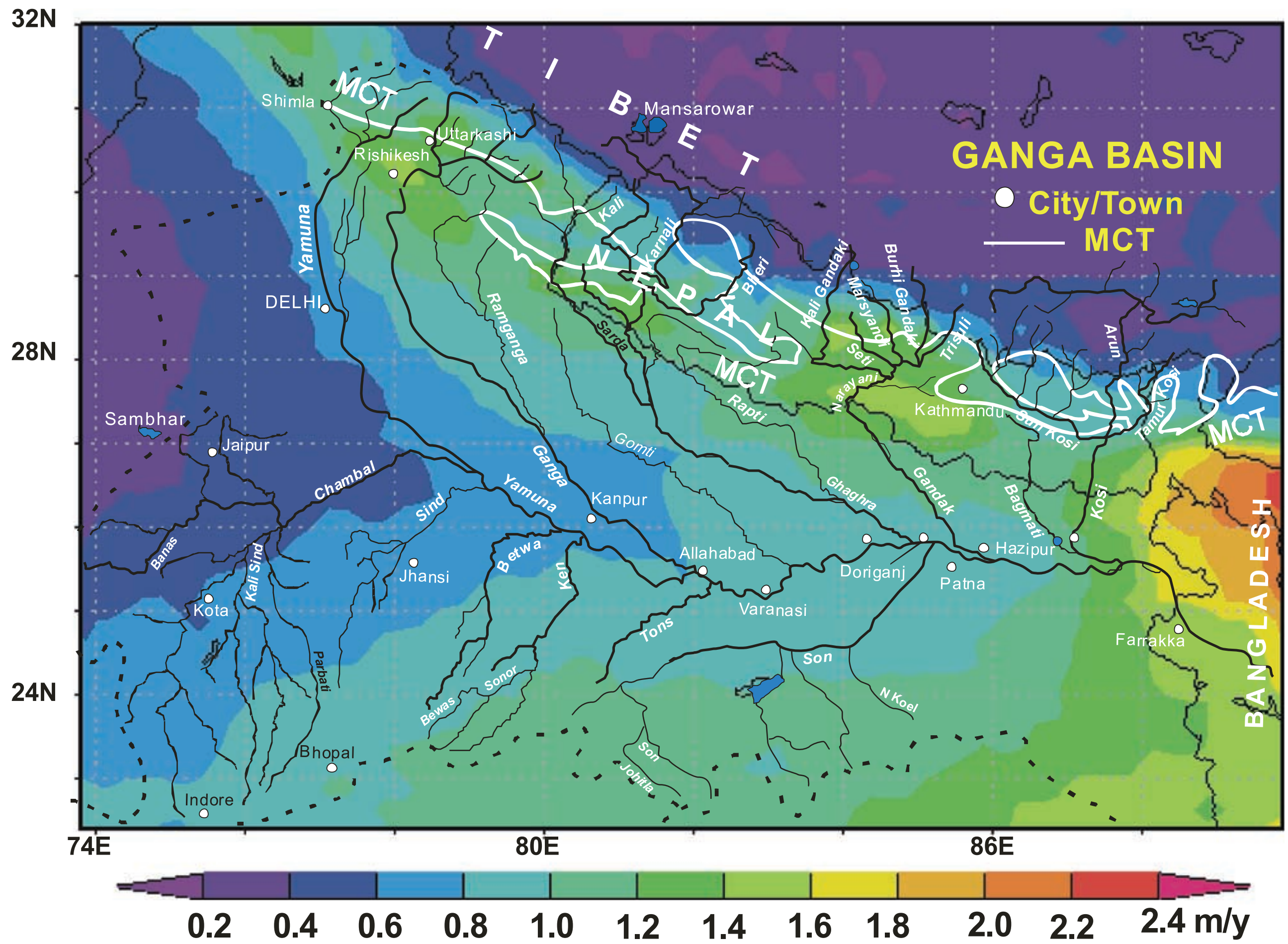

Figure 2. Precipitation over the Ganga drainage for the period January 1998 to May 2007 from TRMM. The precipitation over the Gandak drainage in the Higher Himalaya is much higher compared to those over the Ghaghra and the Kosi headwaters. The region of higher rainfall in the Gandak drainage coincides with the high relief. The Main Central Thrust is marked by the white line.

Table 2. Sampling Details of Sediments

Sample	River	Date	Location	Latitude (N)	Longitude (E)	Altitude (m)	Drainage[a]
			Ganga Mainstream				
RS03–3	Bhagirathi	2 May 2003	Gangotri	30° 60′	78° 56′	2968	HH
RS03–7	Bhagirathi	3 May 2003	Uttarkashi	30° 44′	78° 27′	1192	HH
RS03–1	Ganga	1 May 2003	Rishikesh	30° 31′	78° 21′	335	HH, LH
BR05–1	Ganga	25 May2005	Kanpur				GP, SW, LH, HH
BR352, 351[b]	Ganga	14 May 2004	Allahabad	25° 26′	81° 53′		GP, SW, LH, HH, P
BR06-12-2	Ganga	20 Oct 2006	Allahabad	25° 30′	81° 52′		GP, SW, LH, HH, P
BR382, 383[b]	Ganga	17 May 2004	Varanasi	25° 18′	84° 00′		GP, SW, LH, HH, P
BR06-14-2	Ganga	21 Oct 2006	Varanasi	25° 18′	83° 01′		GP, SW, LH, HH, P
BR06-10-1	Ganga	19 Oct 2006	Ghazipur	25° 32′	83° 12′		GP, SW, LH, HH, P
BR06–802	Ganga	19 Oct 2006	Doriganj	25° 44′	84° 49′		GP, SW, LH, HH, P
BR306	Ganga	7 May 2004	Patna	25° 37′	85°09′		GP, SW, LH, HH, P
BR06–303	Ganga	16 Oct 2006	Patna	25° 37′	85° 09′		GP, SW, LH, HH, P
BR315, 314[b]	Ganga	8 May 2004	Barauni	25° 23′	86° 00′		GP, SW, LH, HH, P
BR06–404	Ganga	17 Oct 2006	Barauni	25° 22′	86° 00′		GP, SW, LH, HH, P
BR324, 325[b]	Ganga	9 May 2004	Rajmahal	25° 04′	87° 50′		GP, SW, LH, HH, P
BR06–101	Ganga	15 Oct 2006	Rajmahal	25° 03′	87° 50′		GP, SW, LH, HH, P
			Alaknanda				
RS03–28	Alaknanda	5 May 2003	Birhai, Before Confluence[c]	30° 25′	79° 23′	1037	LH, HH
RS03–27	Birahi Ganga	5 May 2003	Birahi			1039	LH, HH
RS03–31	Pindar	5 May 2003	Pindar Valley	30° 05′	79° 28′	1034	LH, HH
			Bhagirathi Tributaries				
RS03–9	Syansu Gad	3 May 2003		30° 29′	78° 24′	838	LH, HH
RS03–12	Bhilangna	3 May 2003	Ghanshyali				LH, HH
			Tributaries in Plain				
BR348	Yamuna	15 May 2004	Allahabad	25° 25′	81° 50′		GP, SW, LH, HH, P
BR06-13-2	Yamuna	20 Oct 2006	Allahabad	25° 25′	81° 50′		GP, SW, LH, HH, P
BR365, 364[b]	Rapti	15 May 2004	Gorakhpur	26° 44′	82° 21′		GP, SW, LH, HH
BR378	Gomti	16 May 2004	Before Confluence	25° 30′	83° 08′		GP
BR06-11-3	Gomti	19 Oct 2006	Before Confluence	25° 30′	83° 08′		GP
BR355, 356[b]	Ghaghra	15 May 2004	Ayodhya	26° 49′	82° 12′		GP, SW, LH, HH
BR371, 372[b]	Ghaghra	15 May 2004	Doharighat				GP, SW, LH, HH
BR343, 344[b]	Ghaghra	12 May 2004	Revelganj	25° 49′	84° 35′		GP, SW, LH, HH
BR06–905	Ghaghra	19 Oct 2006	Revilganj	25° 49′	84° 36′		GP, SW, LH, HH
BR06–205	Son	16 Oct 2006	Koilawar	25° 34′	84° 48′		P
BR336[b], 335[b]	Gandak	11 May 2004	Barauli	26° 22′	84° 45′		GP, SW, LH, HH
BR310	Gandak	7 May 2004	Hazipur	25° 41′	85° 11′		GP, SW, LH, HH
BR06–701	Gandak	18 Oct 2006	Hazipur	25° 41′	85° 11′		GP, SW, LH, HH
BR330, 331[b]	Kosi	10 May 2004	Dumarighat	25° 32′	86° 43′		GP, SW, LH, HH
BR06–502	Kosi	18 Oct 2006	Dumarighat	25° 33′	86° 43′		GP, SW, LH, HH
BR06–603	Baghmati	18 Oct 2006	Dumarighat	25° 33′	86° 43′		GP, SW, LH, HH

[a]The drainage basin upstream of sampling site. Here HH is Higher Himalayan Crystallines, LH is Lesser Himalaya, SW is Siwaliks, GP is Ganga plain, and P is Peninsular.

[b]From these locations two samples were collected, bank sediments and the other richer in fine fraction from sandbars or depositing from still water condition within a few of meters from the bank.

[c]Before confluence with mainstream.

<4 μm fraction was separated from the sediments by gravitational settling in water. The abundance of <4 μm fraction in all sediments were low. In samples from the upper reaches (i.e., upstream of Rishikesh) (Figure 1a) it was almost absent and hence in many of them only total sediment analyses could be made.

[12] In the laboratory, the sediments were dried at about 50°C for 2–3 days and about 250 g of dried samples were powdered to $\leq$100 μm size in a ball mill using an agate container and balls. Sr and Nd isotope measurements were made on the *silicate fraction* of sediments. Toward this, ~1 g of powdered sample was decarbonated by leaching with 0.6 N HCl at 80°C for ~30 min with intermittent ultrasonic treatment. The slurry was centrifuged, the residue washed with Milli-Q water, dried and ashed at ~600°C to oxidize organic matter. A known weight (~100 mg) of carbonate and organic matter free sediments were transferred to Savillex® vials and brought to complete solution by HF-HNO_3 acid digestion in the presence of ^{84}Sr and ^{150}Nd spikes. Sr and Nd were separated from the solution following standard ion exchange procedures [*Galy*, 1999; *Alibert et al.*, 1983; *Richard et al.*, 1976]. Sr and Nd concentrations and their ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd were measured on an Isoprobe-T Thermal Ionization Mass Spectrometer in static multicollection mode. Mass fractionation corrections for Sr and Nd were made by normalizing

^{86}Sr/^{88}Sr to 0.1194 and ^{146}Nd/^{144}Nd to 0.7219. During the course of analyses, SRM987 Sr and JNdi-1 Nd standards were repeatedly measured, these yielded values of 0.710230 ± 0.000013 (1σ, $n = 72$) for ^{86}Sr/^{88}Sr and 0.512105 ± 0.000006 (1σ, $n = 9$) for ^{143}Nd/^{144}Nd, well within the recommended values. Several Sr and Nd total procedural blanks were processed along with the samples. These blanks are several orders of magnitude lower than typical total Sr and Nd loads analyzed and hence no corrections for blanks were made. A few samples were processed in duplicate to check the reproducibility of results. In addition, Sr isotope composition was measured in six samples after decarbonating with 1N acetic acid to assess the impact of HCl leaching. Al and Rb concentrations in the total sediments were determined by ICP-AES and Atomic Absorption Spectrophotometry (S. K. Rai, Geochemical and isotopic studies of ancient and modern sediments, Ph.D. thesis dissertation in preparation, 2008).

4. Results and Discussion

4.1. Sr and Nd Concentrations and ^{87}Sr/^{86}Sr and ε_{Nd}

[13] The Sr and Nd concentrations and ^{87}Sr/^{86}Sr and ε_{Nd} are given in Table 3. In the May samples (summer) Sr and Nd in total silicates range from 37 to 138 and 10 to 36 μg/g, respectively. This compares with the range of 63 to 108 μg/g for Sr in the October (monsoon) samples collected from the plain. The observed range in Sr and Nd concentrations can be due to variability in their source composition, for example Sr in HHC and LH rocks ranges between 4 to 270 and 7 to 166 μg/g, respectively (S. K. Rai, Ph.D. thesis dissertation in preparation, 2008). In HH, the HHC has been considered to represent its silicate component. Another factor that can contribute to variation in elemental abundances of sediments is their mineralogical composition. This suggestion draws support from the observation that the Al concentration in the sediments analyzed averages only 4.4 wt %, (on $CaCO_3$ free basis) a factor of ~2 lower than that in granites and gneisses of the drainage basin (~7% [*France-Lanord and Derry*, 1997]). This can be explained in terms of proportionally higher abundance of Al-poor minerals (e.g., quartz) in sediments. The impact of such a dilution on Sr and Nd abundances in sediments is difficult to quantify because of large variability in their source concentrations. In spite of the spatial variability in Sr abundance, its concentration in samples from the same location collected during May and October show that on average they are within ±10% of each other.

[14] The range in ^{87}Sr/^{86}Sr and ε_{Nd} in total silicates of May samples are 0.74738 to 0.84280 and −25.5 to −15.5, respectively (Table 3). The ^{87}Sr/^{86}Sr of October samples from the Ganga plain, 0.74620 to 0.80369 (Table 3) is nearly within the range of May samples. The average uncertainty as determined from repeat measurements of the same samples is ±0.0005 for ^{87}Sr/^{86}Sr ($n = 5$ pairs) and 0.2 ε units for Nd ($n = 2$ pairs). These are significantly larger than analytical precision and therefore have to be explained in terms of sample heterogeneity. The ^{87}Sr/^{86}Sr of total silicates separated by acetic acid leach and 0.6N HCl leach agree on average within ±0.0004 ($n = 6$), within the uncertainty of repeat measurements, suggesting that 0.6N HCl leaching does not measurably alter the ^{87}Sr/^{86}Sr of silicates.

[15] ^{87}Sr/^{86}Sr values of silicates sampled during summer and monsoon exhibit measurable differences but without any systematic trend. The average difference for the 10 locations sampled is ±0.0056, much higher than the average uncertainty of repeat measurements (0.0005). This reflects the spatial and temporal heterogeneity in ^{87}Sr/^{86}Sr of sediments and therefore provides a more realistic estimate of uncertainty in ^{87}Sr/^{86}Sr data. *Galy and France-Lanord* [2001] reported ^{87}Sr/^{86}Sr in three bed load samples of the Ganga mainstream collected from Rajshahi, Bangladesh. In the two monsoon samples of 1996 and 1998, the ^{87}Sr/^{86}Sr values were quite similar, 0.7696 and 0.7691, and in the third sample collected in March 1997 (late winter/early summer), it was marginally higher, 0.7744. The spread in these three numbers from the same location is 0.0053, within the uncertainty of ±0.0056 derived in this study. More importantly the two monsoon samples, collected 2 years apart, had quite similar ^{87}Sr/^{86}Sr. Such estimates for uncertainty in ε_{Nd} values could not be derived as ε_{Nd} measurements were made only during one season, summer.

[16] Sr in <4 μm silicates is lower than that in the corresponding total silicates (Table 3), in contrast to Al and Nd which show enrichment in the <4 μm fraction in the majority of the samples. A cause for the difference in these trends lies in their geochemical behavior during chemical weathering. Sr, being more mobile, is released to solution, depleting its abundance in the residual solids, whereas Al (Nd), being more resistant to weathering, is retained and enriched in the residue. The depletion of Nd in some of the <4 μm fraction of samples relative to the total (Table 3) therefore has to be due either to mineral sorting occurring naturally or in the laboratory during size separation or to differences in mixing proportions of end-members in total sediments compared to that in their fine fractions. These explanations can also account for the measurable differences in ^{87}Sr/^{86}Sr and ε_{Nd} between silicates of total sediments and their <4 μm fractions (Table 3) (S. K. Rai, Ph.D. thesis dissertation in preparation, 2008).

[17] In spite of these differences, Sr and Nd isotope composition of total silicates would be affected, if at all, only marginally by contributions from <4 μm silicates because their isotopic compositions are not too different, and the latter forms only a minor component of the total sediments.

4.2. Sources of Sediments to the Ganga Plain

[18] Potential sources of sediments to the Ganga in the plains are (1) the tectonic units of the Himalaya, the TSS, the Higher Himalaya Cystallines (HHC), the Lesser Himalaya (LH) and the Siwaliks and (2) peninsular India rivers draining the Deccan Traps, the Vindhyan and the Archean crust. The TSS falls in the rain shadow zone and its occurrence is limited to a small fraction of the drainage area of the headwaters of some of the Himalayan tributaries. The contribution of sediments from the TSS to the Ganga system, based on mineralogy of Marsyandi sediments [*Garzanti et al.*, 2007] and Nd isotope and fission track studies on sediments from the Trisuli river and the Bengal delta, is found to be minor (4% [*Foster and Carter*, 2007]). The Siwaliks foreland basin sediments are essentially

Table 3. Sr, Nd, $^{87}Sr/^{86}Sr$, and ε_{Nd} in Silicate Fraction of Bank Sediments of the Ganga River System[a]

Sample	River	Location	Al (%)	Rb (μg/g)	$[Sr]_{Sil}$ (μg/g)	$(^{87}Sr/^{86}Sr)_{Sil}$	[Nd] (μg/g)	$\varepsilon_{Nd(CHUR)0}$
Ganga Mainstream								
RS03–3	Bhagirathi	Gangotri	6.3	212	58	0.78793	14	−18.2
RS03–7	Bhagirathi	Uttarkashi	3.9	46	95	0.78159	35	−19.9
RS03–1	Ganga	Rishikesh	5.1	111	78	0.78652	18	−18.1
RS03–1 (<4 μm)	Ganga	Rishikesh	-	-	72	0.77489	15	−17.4
BR05–1	Ganga	Kanpur	-	-	64	0.77989	-	-
BR352	Ganga	Allahabad	4.2	106	138	0.77726	14	−17.3
BR351 (<4 μm)	Ganga	Allahabad	12	-	38	0.77164	33	−15.7
BR06-12-2	Ganga	Allahabad	3.3	73	64	0.77485		
BR382	Ganga	Varanasi	3.5	80	69	0.77137	33	−17.1
BR383 (<4 μm)	Ganga	Varanasi	11.6	200	44	0.74807	18	−18.8
BR06-14-2	Ganga	Varanasi	3.2	52	63	0.78280	-	-
BR06-10-1	Ganga	Ghazipur	3.2	85	67	0.78089	-	-
BR06–802	Ganga	Doriganj	3.2	72	67	0.78168	-	-
BR306	Ganga	Patna	3.9	86	74	0.76887	35	−21.3
BR06–303	Ganga	Patna	3.4	71	75	0.76830	-	-
BR315	Ganga	Barauni	4.1	100	90	0.75769	21	−19.1
BR314 (<4 μm)	Ganga	Barauni	11	84	45	0.75527	24	−16.7
BR06–404	Ganga	Barauni	3.4	70	82	0.76225	-	-
BR324	Ganga	Rajmahal	5	116	92	0.76355	30	−18.1
BR325 (<4 μm)	Ganga	Rajmahal	12.4	229	41	0.76179	26	−16.1
BR06–101	Ganga	Rajmahal	4.2	103	102	0.76482		
Alaknanda								
RS03–28	Alaknanda	Birahi, Before Confluence[b]	5.1	121	84	0.75900	33	−17.1
RS03–27	Birahi Ganga	Birahi	2.7	50	48	0.80009	19	−25.5
RS03–31	Pindar	Pindar Valley	4	67	117	0.75379	36	−18.4
Bhagirathi Tributaries								
RS03–9	Syansu Gad		5.7	125	37	0.77909	21	−15.5
RS03–12	Bhilangna	Ghanshyali	5.6	130	69	0.84280	27	−23.3
Tributaries in Plain								
BR348	Yamuna	Allahabad	3.4	72	101	0.76241	10	−17.7
BR06-13-2	Yamuna	Allahabad	3.1	70	88	0.75338	-	-
BR365	Rapti	Gorakhpur	2.7	63	37	0.76148	15	−17
BR364 (<4 μm)	Rapti	Gorakhpur	12.4	258	41	0.76570	18	−15.9
BR378	Gomti	Before Confluence	4.1	112	81	0.79774	11	−19.4
BR06-11-3	Gomti	Before Confluence	3.2	82	73	0.79276	-	-
BR355	Ghaghra	Ayodhya	3.5	89	67	0.78572	11	−18.9
BR356 (<4 μm)	Ghaghra	Ayodhya	11.7	278	37	0.77001	20	−17.2
BR371	Ghaghra	Doharighat	3.7	91	76	0.77619	18	−18.5
BR372 (<4 μm)	Ghaghra	Doharighat	11.8	263	41	0.76787	-	-
BR343	Ghaghra	Revilganj	3.9	89	80	0.77081	17	−18.2
BR344 (<4 μm)	Ghaghra	Revilganj	10.9	249	50	0.77493	27	−17.4
BR06–905	Ghaghra	Revilganj	3.1	79	66	0.78955	-	-
BR06–205	Son	Koilawar	2.2	82	65	0.77788	-	-
BR336	Gandak	Barauli	4.5	112	105	0.75777	23	−19.1
BR335 (<4 μm)	Gandak	Barauli	-	-	64	0.76708	26	−18.8
BR310	Gandak	Hazipur	4.2	84	109	0.74738	33	−18.6
BR06–701	Gandak	Hazipur	4.0	87	108	0.74620		
BR330	Kosi	Dumariaghat	4.8	114	79	0.80178	16	−18.6
BR331	Kosi	Dumariaghat	5.9	129	-	-	34	−19.1
BR331 (<4 μm)	Kosi	Dumariaghat	13.2	305	33	0.80331	24	−18.6
BR06–502	Kosi	Dumariaghat	4.3	114	90	0.80369	-	-
BR06–603	Bagmati	Dumariaghat	5.5	157	81	0.80237	-	-

[a]Sr and Nd concentrations and their isotope ratios in silicate fractions. Al and Rb concentrations in bulk samples. Errors in Sr and Nd concentration are <2% (±2σ) and <20 ppm (±2σ) for ratios.
[b]Before confluence with mainstream.

reworked material from the HHC and LH. The observation of *Sinha and Friend* [1994] that the sediment yield of rivers draining the Siwaliks almost exclusively (for example, the Baghmati) is low indicates that, like the TSS, the Siwaliks are also unlikely be a significant source of sediments to the Ganga. The sediment yield of the Baghmati river [*Sinha and Friend*, 1994] if assumed to be typical of the entire Siwaliks range in Ganga system, indicates that it can account only for

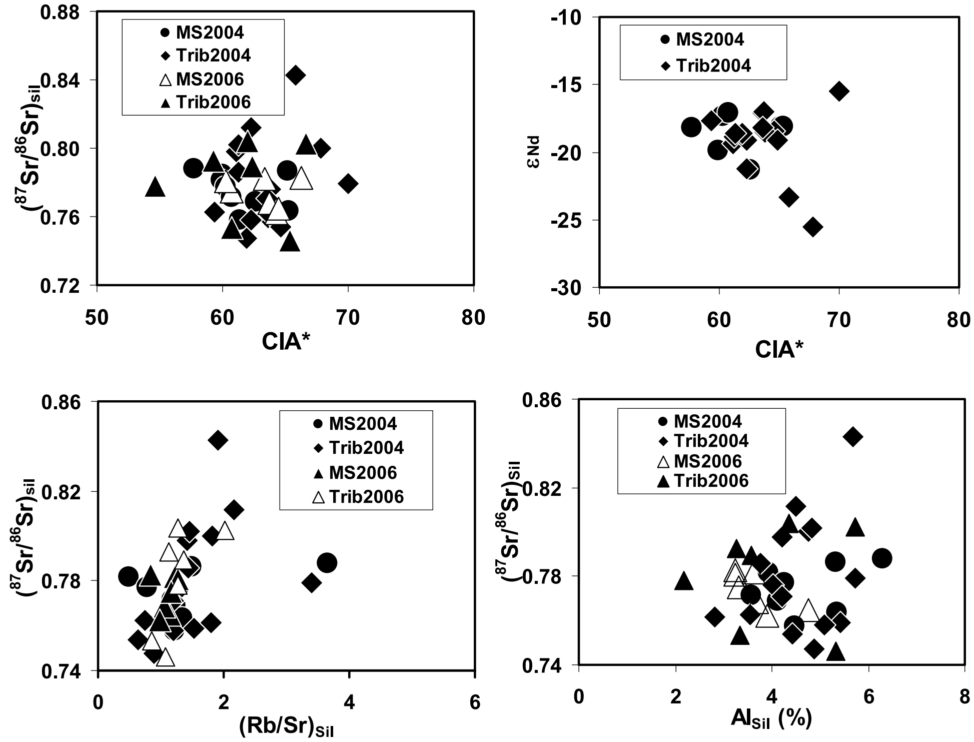

Figure 3. (top) Scatterplots of CIA* (Al_2O_3 * 100/(Al_2O_3 + Na_2O + K_2O) in bank sediments with their $^{87}Sr/^{86}Sr$ and ε_{Nd} values. (bottom) Scatterplots of $^{87}Sr/^{86}Sr$ versus Rb/Sr and $^{87}Sr/^{86}Sr$ versus Al. The data do not show any systematic trend. The scatter is most likely a result of source variability in both CIA*, elemental abundances and isotopic composition. Here MS is Mainstream and Trib is Tributaries.

<3% of sediment flux to the Ganga. Factors that can contribute to this low sediment contribution are (1) the low relief of the Siwaliks basins which limits the intensity of physical erosion and (2) the minor fraction of its aerial coverage in the Ganga basin. *Campbell et al.* [2005] inferred from the He-Pb ages of zircons of the Ganga sediments that the contribution from the Siwaliks to the Ganga system is only minor. This makes the HHC and LH the dominant sources of sediments from the Himalaya to the Ganga system.

[19] The peninsular rivers supply sediments only to the Yamuna and the Son, the southern tributaries/subtributaries of the Ganga. These rivers merge with the Ganga downstream of Allahabad (Figure 1b). Therefore, the contribution of peninsular drainage to sediments of the Ganga in the plain needs to be considered only downstream of Allahabad.

[20] The Sr and Nd isotope composition of sediments has been employed to trace their sources to the Ganga at its outflow in terms of major lithological units and constrain their contributions following similar approaches reported for other regions [*Bouquillon et al.*, 1990; *Clift et al.*, 2002; *Colin et al.*, 2006; *France-Lanord et al.*, 1993; *Galy et al.*, 1996; *Singh and France-Lanord*, 2002]. This approach relies on the assumption that the sediments retain the isotopic signatures of their sources. The interrelation of $^{87}Sr/^{86}Sr$ and ε_{Nd} with selected chemical parameters of sediments helps to probe how well this requirement has been met. The intensity of chemical weathering these sediments have undergone, as assessed by comparing their Chemical Index of Alteration (CIA [*Nesbitt and Young*, 1982]) with that of source rocks, suggest that they at best have been subject to minor chemical weathering. Part of Ca of the sediments of the Ganga is associated with the carbonates making it difficult to quantify accurately Ca from silicates. Hence in this study modified Chemical Index of Alteration (CIA*), which does not include Ca, has been used. The modified Chemical Index of Alteration [*Colin et al.*, 1999], given by CIA* (= $Al_2O_3/(Al_2O_3 + Na_2O + K_2O)$) of sediments averages 63 ± 3, overlapping within errors with values of 58 ± 6 for crystallines in the Himalaya, (S. K. Rai, Ph.D. thesis dissertation in preparation, 2008), 58 ± 7 for LH and 65 for the HHC [*France-Lanord and Derry*, 1997]. The variations of $^{87}Sr/^{86}Sr$ and ε_{Nd} with CIA* and Al (Figure 3) do not show any systematic trend. Analysis of the Sr isotope data by subgrouping the samples in terms of summer and monsoon collections from mainstream and tributaries also does not exhibit any common trend with Al and $(Rb/Sr)_{sil}$ (Figure 3). Thus, the variations in $^{87}Sr/^{86}Sr$ and ε_{Nd} in sediments can be interpreted in terms of their variability in source composition and their mixing and not due to processes occurring during their transport through rivers (S. K. Rai, Ph.D. thesis dissertation in preparation, 2008). It is, however, recognized as mentioned earlier that erosion and transport process can modify elemental abundances (e.g., Sr and Al) due to mineralogical sorting, e.g., dilution by mixing with minerals such as quartz.

[21] The Sr and Nd isotope composition of sediments are plotted on a two isotope diagram (Figure 4). Figure 4 also includes isotope data for the possible sources, HHC, LH,

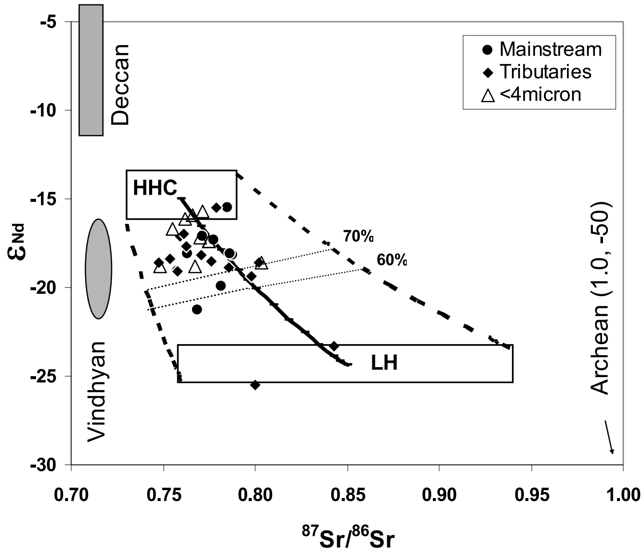

Figure 4. Two isotope system plot, $^{87}Sr/^{86}Sr$ and ε_{Nd}, in silicates of bulk sediments and their <4 μm fraction. The range in isotopic composition of potential sources of sediments to the Ganga system is also given (see Table 4). Plot shows that the isotope ratios of most of the sediment samples cluster around the range of values for the HHC. Also shown is the expected isotopic composition for 70:30 and 60:40 of HHC:LH mixtures calculated on the basis of end-member values bound by the dotted lines. The data suggest that erosion in the Higher Himalaya accounts for more than 65% of sediments of the Ganga system.

Deccan basalt, Vindhyan sediments and Archean crust (Table 4). Among these end-members, Deccan Basalts of the peninsular drainage are the least radiogenic in $^{87}Sr/^{86}Sr$ (~0.710) and most radiogenic in ε_{Nd} (−13 to +5) (Table 4). The Vindhyan sediments are marginally more radiogenic in Sr but quite depleted in ε_{Nd} compared to Deccan Basalt (Table 4 and Figure 4). For the Archean craton, only very limited data are available [*Sarkar et al.*, 1984, *Saha et al.*, 2004] making it difficult to provide ranges in isotope composition and typical values. The Sr and Nd isotope compositions of the total silicates along the course of the Ganga, from Gangotri to Rajmahal, are in the range 0.7577 to 0.7879 and −21 to −15.5, respectively (Table 3). Comparison of these $^{87}Sr/^{86}Sr$ and ε_{Nd} values with those reported for the HHC and LH (Table 4) suggest that most sediment values are closer to the HHC (Figure 4). The two samples falling in the LH box (Figure 4) are from the Birahi Ganga and the Bhilangna. These two rivers drain the LH almost exclusively. The Sr and Nd isotope mass balance of the sediments analyzed on the basis of two component (HHC and LH) mixing suggests that the Higher Himalayan Crystallines is the dominant contributor to them, accounting for >65% of the sediments of the Ganga all along its course in the plain (Figure 4). A similar conclusion was reached for the Brahmaputra [*Singh and France-Lanord*, 2002] regarding the source of its sediments. Studies on sediments from the Bay of Bengal [*Derry and France-Lanord*, 1997; *France-Lanord et al.*, 1990; *Galy et al.*, 1996] also suggest that the HHC makes up most of the silicate sediments in the Bay over the past several Ma. Dominance of the HHC in contributing to sediments of the Ganga in its plain is also born out from the studies of U-Pb ages and exhumation rates based on He ages of zircon [*Campbell et al.*, 2005] and Nd and fission track studies of sediments of the Trisuli river in the central Himalaya and the Bengal delta [*Foster and Carter*, 2007]. The end-member values (Figure 4) could also lead to the inference that mixing of Deccan Basalts with Archean sources can, in principle generate the measured isotope composition of the Ganga in the plain. However, such an inference would be incorrect considering that (1) Deccan and Archean sources can contribute to the Ganga sediments only downstream of Allahabad and (2) the contribution of Deccan Basalts to total silicate of the Ganga at Allahabad can be estimated to be a maximum of ~15% at Varanasi (Figure 1b) and decreases to a few percent downstream (see later discussions).

[22] The Sr isotope composition of the Yamuna sediments at Allahabad, upstream of its confluence with the Ganga, is 0.76241 and 0.75338 for the two seasons sampled (Table 3). The Yamuna drains the Higher and the Lesser Himalaya, Deccan and Vindhyans. The $^{87}Sr/^{86}Sr$ values of the Yamuna sediments are within the range of values for the HHC and close to the lower bound values for the LH, and are significantly more radiogenic than the values for the Deccan Traps and Vindhyans through which many of its tributaries flow (Figure 1b). These results are an indication of the dominance of the Himalayan sources in contributing sediments to the Yamuna at Allahabad. The ε_{Nd} value of −17.7 for the Allahabad sample (Table 3) is significantly more depleted than that the lowest value of the Deccan Basalts, consistent with inference based on Sr isotopes that the Himalayan sources dominate the Yamuna sediments.

[23] A rough estimate of the peninsular contribution to the Yamuna sediments can be made by assuming that it is a mixture of sediments from the Himalayan ($^{87}Sr/^{86}Sr$ of 0.786, same as the Ganga sediments at Rishikesh) and the Deccan/Vindhyan ($^{87}Sr/^{86}Sr$, 0.710) sources with the same

Table 4. $^{87}Sr/^{86}Sr$ and ε_{Nd} of Various Lithounits of the Ganga System[a]

	$^{87}Sr/^{86}Sr$		ε_{Nd}	
Lithology	Range	Typical	Range	Typical
		Higher Himalaya		
TSS	0.71–0.73	0.727 ± 0.012	−15 to −12	−13
HHC	0.73–0.79	0.76 ± 0.03	−16.4 to −13.6	−15 ± 1.4
		Lesser Himalaya		
Pc carbonates	0.71–0.85	0.715 ± 0.003	-	-
LH	0.72–0.94	0.85 ± 0.09	−25.3 to −23.5	−24.4 ± 0.9
Siwaliks	0.72–0.76	0.738 ± 0.018	−19 to −15	−17.2 ± 1.2
		Peninsular Drainage		
Deccan Traps	0.704–0.716	0.71	−13 to +5	−5
Vindhyan	0.72	0.72	−23 to −14	
Archean Craton	0.72–2.55	1.0?	−34 to −50	−50?

[a]Data from *Bickle et al.* [2005, 2001], *Chakrabarti et al.* [2007], *Derry and France-Lanord* [1996], *Galy* [1999], *Galy and France-Lanord* [1999], *Mahoney* [1988], *Oliver et al.* [2003], *Peng et al.* [1998], S. K. Rai (Ph.D. thesis dissertation in preparation, 2008), *Saha et al.* [2004], *Sarkar et al.* [1984], and *Singh et al.* [1998].

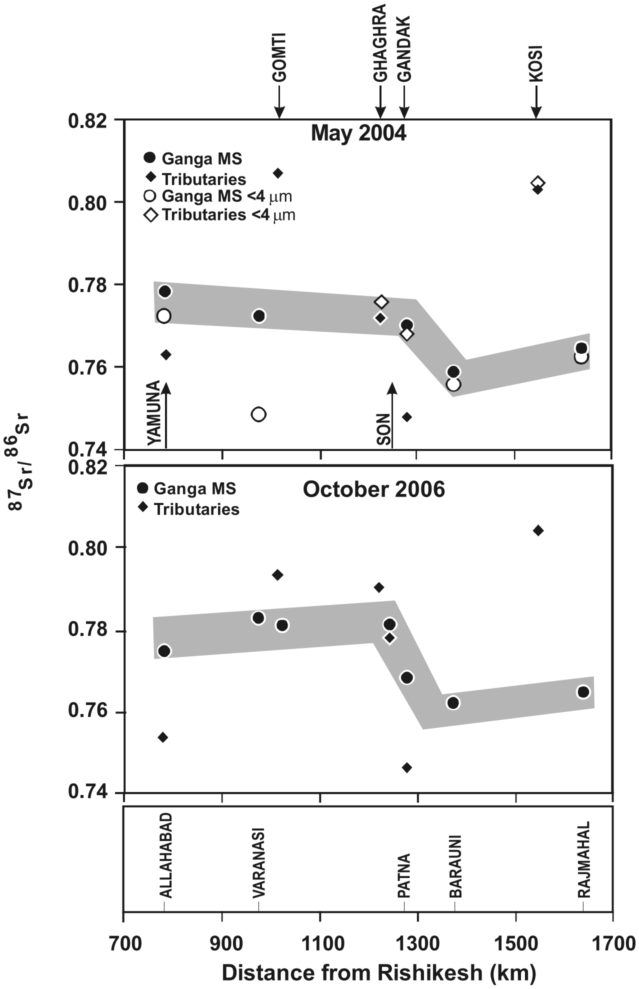

Figure 5. Downstream variations in $^{87}Sr/^{86}Sr$ values of silicates of the Ganga sediments during May 2004 and October 2006. During both the sampling periods, $^{87}Sr/^{86}Sr$ of the Ganga mainstream sediments decrease sharply at Barauni after the confluence with the Gandak and then increase marginally at Rajmahal after mixing with more radiogenic sediments of the Kosi. Sharp and consistent decrease in $^{87}Sr/^{86}Sr$ during both the summer and the monsoon seasons at Barauni bring out the impact of the Gandak contribution to the sediment budget of the Ganga. Gray band denotes the $^{87}Sr/^{86}Sr$ evolution of Ganga mainstream sediments.

Sr concentrations. The estimate yields values of ~30 and ~40% for the peninsular component in the Yamuna sediment at Allahabad for May 2004 and October 2006, respectively. The peninsular contribution to the Ganga mainstream at Varanasi, calculated on the basis of the $^{87}Sr/^{86}Sr$ of the Ganga at Kanpur and Varanasi is ~15%. The mainstream sample collected from Allahabad has not been used for this calculation as the location is within the mixing zone of the Ganga and the Yamuna and therefore is not a "pure" Ganga end-member. The Deccan basalt and Vindhyan components will decrease further downstream and attain a value of few percent at the outflow of the Ganga (see later discussion) as a result of sediment input from other Himalayan tributaries, the Ghaghra, the Gandak and the Kosi (Figure 1b). These estimates compare with the reported [*Wasson*, 2003] contribution of ~2.5% sediments from the peninsular drainage to the Ganga system. The contribution from the southern tributaries to the <4 μm silicate fraction is higher at ~35% at Varanasi. Analogous to the total silicates, the contribution to the <4 μm silicate fraction from peninsular drainage also becomes less significant at the Ganga outflow (Rajmahal). Thus, from the above discussions, it is evident that only two sources, the HHC and LH make up most of the silicates in the total sediment load of the Ganga in the plain, with the HHC contributing about two thirds of the total.

4.3. Estimation of Sediment Contribution From Subbasins to the Ganga Mainstream

[24] The spatial trend of $^{87}Sr/^{86}Sr$ along the mainstream Ganga (Figure 5) is quite similar during both May and October sampling. These results, along with Sr isotope composition of tributary sediments, can yield estimates of their mixing proportions with sediments of the Ganga mainstream, provided the isotopic composition of the mixing end-members is distinctly different, and outside the average uncertainties. In this work for $^{87}Sr/^{86}Sr$, the average difference in two season sampling from ten locations, ±0.0056 has been used as the uncertainty in the end-member values. The $^{87}Sr/^{86}Sr$ of the Ganga at Varanasi and the Ghaghra at Revilganj for the 2004 sampling, and the Ganga at Ghazipur, the Ghaghra at Revilganj, the Ganga at Doriganj and the Son at Koilawar for the 2006 sampling, fall within this uncertainty. This precludes the estimation of mixing proportion of the Ghaghra and the Son sediments with that of the Ganga mainstream.

[25] The $^{87}Sr/^{86}Sr$ of the Ganga mainstream sediments shows a sharp decrease at Barauni (Figure 5) during both May and October after the confluence of the Gandak. During both these seasons the lowest $^{87}Sr/^{86}Sr$ value in the Ganga mainstream is observed at Barauni as a result of mixing with relatively less radiogenic Sr from the Gandak sediments. The $^{87}Sr/^{86}Sr$ of the Gandak at Hazipur upstream of its confluence with the Ganga is 0.7474 and 0.7462 for May 2004 and October 2006, respectively. Another sample of the Gandak sediments collected from Barauli ~100 km upstream of Hazipur has $^{87}Sr/^{86}Sr$ of 0.7578. All the three $^{87}Sr/^{86}Sr$ values of the Gandak sediments are less radiogenic than those of the other Himalayan tributaries, the Ghaghra and the Kosi, both of which have $^{87}Sr/^{86}Sr \geq 0.77$ (Table 3). The lower $^{87}Sr/^{86}Sr$ of the Gandak compared to the Ghaghra and the Kosi could be due either to spatial variability in $^{87}Sr/^{86}Sr$ of HHC or to relatively higher contribution from TSS to the sediments of the Gandak [*Galy*, 1999]. Considering that Hazipur is close to the mouth of the Gandak (Figure 1b), the $^{87}Sr/^{86}Sr$ of samples from this location is taken to be representative of the Gandak sediments discharging into the Ganga for calculating mixing proportions. After mixing with the Gandak sediments, the $^{87}Sr/^{86}Sr$ of the Ganga mainstream sediments drops from 0.77137 (Varanasi) to 0.75769 in May and 0.78168 (Doriganj) to 0.76225 in October. This drop is several times the uncertainty in the end-member values (±0.0056) and orders of magnitude higher than the precision of repeat measurements. These results suggest that the sediment budget of

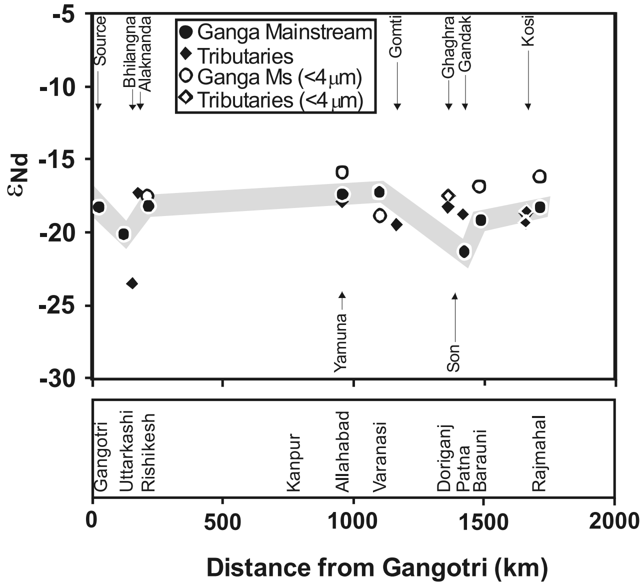

Figure 6. Downstream variation in ε_{Nd} of the Ganga mainstream sediments. Analogous to $^{87}Sr/^{86}Sr$, the downstream variations of ε_{Nd} is due to mixing of sediments from the Ganga mainstream with sediments of its tributaries.

the Ganga is influenced significantly by the contribution from the Gandak. The impact of the Gandak contribution on the $^{87}Sr/^{86}Sr$ of the Ganga mainstream is discernible even in the sample from Patna, as this sample falls within the mixing zone of the Gandak, particularly during high flow. Further downstream, the $^{87}Sr/^{86}Sr$ of the Ganga sediment increases to 0.76355 (summer) and 0.76482 (monsoon) at Rajmahal, due to mixing with more radiogenic Sr sediments from the Kosi (Figure 5).

[26] The $^{87}Sr/^{86}Sr$ of <4 μm silicate fraction follows the trend of the total silicates (Figure 5), but it shows a sharp decrease, from 0.77164 at Allahabad to 0.74807 at Varanasi. This is likely due to supply of Yamuna sediments rich in fine fraction and low in $^{87}Sr/^{86}Sr$. The difference in $^{87}Sr/^{86}Sr$ between the total and <4 μm silicate fraction is maximum at Varanasi. Further downstream the Sr isotope composition of the <4 μm silicate fraction converges with that of the total.

[27] The ε_{Nd} of total sediment silicates of the Ganga also varies along its course within a narrow range (Figure 6). The ε_{Nd} at Rishikesh is -18.1 which increases to -17.3 at Allahabad and decreases to its lowest value of -21.3 at Patna. This can be interpreted in terms of supply from the Son catchment which has exposures of Archean basement. Data on ε_{Nd} of the Archean basement though are very limited, values as low as -50 have been reported [*Saha et al.*, 2004 and references therein]. The Son contribution, however, does not influence the $^{87}Sr/^{86}Sr$ of the Ganga mainstream as their $^{87}Sr/^{86}Sr$ values are similar (Table 3). On the basis of ε_{Nd} of Ganga sediments from Varanasi and Patna and assuming ε_{Nd} of ~-50 for the Son, its sediment contribution to the Ganga at Patna can be estimated to be $\sim$15%. Further downstream there is a steady increase of ε_{Nd} because of inputs from the Gandak and the Kosi. The ε_{Nd} values of the <4 μm silicate fraction (Figure 6) track the trend of the total silicates.

[28] The spatial variability in physical erosion rates among the three subbasins of the Ganga upstream of Patna (comprising the basins of the Alaknanda, Bhagirathi, Yamuna and the Ghaghra), the Gandak and the Kosi has been assessed by evaluating the sediment budget of the Ganga mainstream (downstream of Patna) on the basis of a two end-member mixing model (for example, for the Ganga at Rishikesh, the two end-members are the Bhagirathi and the Alakananda; for the Ganga at Rajmahal, the end-members are the Ganga at Barauni and the Kosi). The mixing proportions are calculated [*France-Lanord et al.*, 1993; *Galy et al.*, 1996; *Singh and France-Lanord*, 2002] on the basis of the measured isotope ratios of appropriate end-members of Ganga mainstream and tributary sediments.

[29] In this study, estimates of mixing proportion rely more on $^{87}Sr/^{86}Sr$ data as the range in $^{87}Sr/^{86}Sr$ of the sediments is much wider compared to ε_{Nd} (Table 3). The results of these calculations (Table 5) suggest that the contributions of sediments to the Ganga in the plain from the three subbasins differ significantly, with the Gandak subbasin dominating the sediment budget. This subbasin supplies about 45 and 51% of total sediments of the Ganga at Rajmahal during the 2004 and 2006 sampling, respectively. The contribution of the Gandak in the 2004 sample is calculated using the $^{87}Sr/^{86}Sr$ data of the Ganga at Patna and Barauni and the Gandak at Hazipur. This can be an underestimate as sediments of the Ganga at Patna may have some contribution from the Gandak. For the 2006 sampling it is based on data from the Ganga at Doriganj and Barauni and the Gandak at Hazipur. (The Gandak proportion changes to 37% and 54% for the 2004 and 2006 sampling if the calculations employ both $^{87}Sr/^{86}Sr$ and Sr concentration, the latter expressed in terms of Sr/Al). The Ganga subbasin upstream of Patna (comprising of the Bhagirathi, Alaknanda, Yamuna, and the Ghaghra) (Figure 1b) and the Kosi contribute about 43 and 6–13%, respectively, to the sediment budget of the Ganga. The sediment contribution from the Kosi increases to $\sim$18% if the $^{87}Sr/^{86}Sr$ of the Ganga bed load at Rajshahi, Bangladesh [*Galy and France-Lanord*, 2001] is used as the end-member for calculation.

[30] Attempts to estimate the mixing proportions on the basis of ε_{Nd} have not been very rewarding. The ε_{Nd} values of the Ganga mainstream samples have a limited range, -18 ± 1, the only exception being the Patna sample which has a value of -21.3 (Table 3). Among the tributaries, other than for the Birahi Ganga and the Bhilangna, all the others also have ε_{Nd} values in same range as the Ganga mainstream, -18 ± 1. This narrow range coupled with additional uncertainties that can arise from temporal variability make it difficult to obtain reliable estimates of mixing proportions from the ε_{Nd} data. In spite of this, analyses of ε_{Nd} summer data show the dominance of the Gandak contribution to the sediment budget of the Ganga in the plain. The ε_{Nd} mass balance yields a value of $\sim$80% for the Gandak component during summer.

[31] The estimates of sediment contributions by these three subbasins are disproportionate to their aerial coverage in the Ganga drainage, as the Gandak occupies only $\sim$5% of the total area, the Kosi $\sim$8% and the Ganga upstream of

Table 5. Estimates of Sediment Fraction and Erosion Rates of Various Subbasins of the Ganga[a]

River Subbasin	Area (km^2)		Discharge[b]	Runoff	Sediment Fraction (%)		Sediment Yield ($t/km^2/a$)		Physical Erosion Rate (mm/a)			
									Total Area		Himalayan Area	
	Himalayan	Total	(10^6 m^3/a)	(m/a)	2004	2006	2004	2006	2004	2006	2004	2006
Gandak	31,753	46,300	49,385	1.6	45	51	14,200	16,100	3.9	4.4	5.7	6.4
Kosi	51,440	74,500	48,155	0.9	13	6	2500	1200	0.7	0.3	1.0	0.5
Ganga upstream Patna (GA + RG + YAM + GH)[c]	91,537	794,100	107,884	1.2	42	43	4600	4700	0.2	0.2	1.8	1.9

[a]Area and discharge data from *Galy* [1999] and *Rao* [1975].
[b]At foothills of the Himalaya.
[c]Here GA is Ganga, RG is Ramganga, YAM is Yamuna, and GH is Ghaghra.

Patna ~80% (Table 5). The results yield a wide range of specific sediment discharge (sediment flux normalized to drainage area) for the three subbasins suggesting significant variation in erosion rates among them.

4.4. Spatial Variability in Erosion Rate

[32] Spatial variability in erosion in the Ganga basin has been determined from the available data on total sediment flux from the Ganga and the fractional contribution from the various subbasins as derived on the basis of $^{87}Sr/^{86}Sr$. Estimates of suspended load supply from the Ganga at Farakka range from 500 to 700 million tons/a [*Hay*, 1998; *Islam et al.*, 1999]. Recently, *Galy and France-Lanord* [2001], using Si, Al, and Fe budgets of sediments, estimated that the bed load/floodplain sequestration can be a major component of sediment flux and that the total sediment flux from the Ganga could be as high as ~1000 Mt/a (million tons/a). This value has been used in the following calculations of erosion rates. Further, the impact, if any, of aggradation and degradation of the Ganga plain [*Jain and Sinha*, 2003] has not been considered in the erosion rate calculations.

[33] The sediment yield for the three subbasins of the Ganga (calculated on the basis of 1000 Mt/a flux from the Ganga at its outflow and fractional contribution of 45 and 51% from the Gandak, 13 and 6% from the Kosi and the balance from Ganga upstream of Patna and areas of their drainage basin in the Himalaya) vary from ~1200 to 16,100 $t/km^2/a$. This translates to erosion rates of ~0.5 to ~6 mm/a in the Himalayan sector of the drainage assuming that all sediment is of Himalayan origin. Further, among the three subbasins the Gandak in the Himalaya has the highest erosion rate, ~6 mm/a and the Kosi the lowest, ~1 mm/a (Table 5). The sediment fluxes of the Gandak and the Kosi for the two seasons range from 450 to 510 and 60–130 Mt/a, respectively. *Sinha and Friend* [1994] reported that the contribution of the Gandak to the particulate matter flux of the Ganga at Farakka is a factor of two higher compared to that of the Kosi. This trend in the sediment fluxes (Gandak and Kosi) is consistent with that observed in this study, however the range in fluxes differs significantly.

4.4.1. Uncertainty in Estimation of Sediment Fraction and in Erosion Rate

[34] The estimated sediment fluxes and erosion rates of the individual subbasins are subject to uncertainties arising from errors in the total sediment fluxes and variability in isotope composition of sediments. The former though will not affect the calculated relative fluxes and erosion rates among the various subbasins (Table 5), but are a source of error in the determination of their absolute values. This in turn can impact on the inferences drawn from intercomparison of results from this study with those based on other methods for the Ganga basin and for the other river basins (e.g., Brahmaputra, Indus). The uncertainty in isotope composition of end-members is another factor determining error in fluxes and erosion rates of subbasins. In this study, as mentioned earlier, the measured average difference of the two season sampling (±0.0056) is assumed as the uncertainty in $^{87}Sr/^{86}Sr$. Propagation of this error in $^{87}Sr/^{86}Sr$ results in an uncertainty of 54% in the contribution of sediments from the Gandak and the rest of the basin upstream of Doriganj for monsoon samples. On the basis of this, the contribution from the Gandak is estimated to be 51 ± 27% and 43 ± 23% for the Ganga basin upstream of Doriganj. A 50% uncertainty in the sediment fraction estimates translates to similar fractional uncertainty on the erosion rates of various subbasins, for example, considering the uncertainty in the sediment fraction, the erosion rates in the Gandak subbasin will be ~6 ± 3 mm/a. It may be possible to reduce the uncertainties in the erosion rate estimates through time series sampling over long periods. In summary, the estimates of sediment flux from the Gandak based on two season sampling spread over about 2 years are quite consistent. This suggests that, despite the larger uncertainty in the estimated sediment fraction, the sediment budget of the Ganga River is dominated by contribution from the Gandak. It is also recognized that the absolute value of the total sediment flux from the Ganga and its associated uncertainties are key factors determining the accuracy and precision of erosion rate estimates.

[35] The occurrence of alluvial fans formed by the tributaries upstream of their confluence with the mainstream is another factor that can introduce uncertainties in their estimated sediment contribution. The Ghaghra, the Gandak and the Kosi form large fans in the Gangetic plain [*Gupta*, 1997]. The role of these fans in determining the sediment contribution of these rivers to the Ganga is not well established. It is suggested that among these, the Gandak and the Kosi fans store sediments causing aggradation [*Sinha*, 2005], with the Gandak having a larger fan area [*Goodbred*, 2003; *Gupta*, 1997; *Shukla et al.*, 2001].

[36] Another concern is the impact, if any, of flash floods or transient events in a particular tributary which can supply enormous amount of sediments in a short time span and thereby can significantly influence the sediment budget of the Ganga mainstream. The observation that the trend of

Table 6. Erosion Rates Over the Himalaya Determined by Various Techniques

Area/Location	Technique	Erosion Rate (mm/a)	Reference	Timescale
		Ganga Basin		
Marsyandi Basin	Sand petrology and mineralogy	1.6–5.2	*Garzanti et al.* [2007]	Present-day
Marsyandi Basin	Apatite Fission Track (AFT)	2–5	*Burbank et al.* [2003]	Million years
Marsyandi Basin	^{14}C Method, river depth	~13	*Pratt-Sitaula et al.* [2007]	5 ka
Marsyandi and Nyadi Catchment	Fission track	~3.1	*Huntington et al.* [2006]	0.5–9 Ma
Gandak Basin in Himalaya	Isotopic study of bed sediments	6	This study	Present-day
Kosi Basin in Himalaya	Isotopic study of bed sediments	0.5–1	This study	Present-day
Ganga Upsream Patna (Himalayan Drainage)	Isotopic study of bed sediments	2	This study	Present-day
		Brahmaputra Basin		
Eastern Syntaxis in Himalaya (Brahmaputra)	Isotopic study of Bed Sediments	~14	*Singh* [2006]	Present-day
Namche Barwa (Eastern Syntaxis)	Isotopic and fission track dating	~10	*Burg et al.* [1998]	Million years
		Indus Basin		
Indus River Nanga Parbat (Western Himalaya)	Cosmogenic nuclides (^{10}Be and ^{26}Al)	10–12	*Leland et al.* [1998]	Present-day
Western Syntaxis	Fission Track	2–12	*Burbank et al.* [1996]	Million years

$^{87}Sr/^{86}Sr$ along the mainstream Ganga (Figure 5) is very similar for samples collected nearly 2 years apart and during different seasons, leads to the inference that such transient events were unimportant during period of study.

4.4.2. Comparison With Available Erosion Rates Over the Himalaya

[37] Different approaches have been used to determine erosion rates of river basins. The time interval over which the deduced erosion rates are applicable depends on the approach, for example cosmic ray produced isotopes typically yield average rates over 100 to 10,000 years, fission tracks are applicable for time intervals in the range of 0.1 to 1 Ma whereas flux measurements of sediments and their components (e.g., Sr and Nd isotopes and mineralogy) represents contemporary erosion rates. Therefore, while comparing erosion rates derived from different approaches, the timescales over which they are applicable has to be borne in mind.

[38] The erosion rate estimated in this study for the Gandak basin (6 ± 3 mm/a) falls within the range of values 3–13 mm/a reported for the Marsyandi basin (Table 6), one of its major headwater tributaries (Figure 1b), on the basis of fission track, ^{14}C and mineralogical studies (Table 6) [*Burbank et al.*, 2003; *Garzanti et al.*, 2007; *Pratt-Sitaula et al.*, 2007]). The erosion rates of the Gandak, based on its suspended load abundance, are between 1.4 and 5 mm/a. *Sinha and Friend* [1994] reported a suspended load flux of 82 Mt/a for the Gandak at Dumariaghat for the 10 year period, 1980–1989. This would correspond to a total sediment flux of ~160 Mt/a, considering bed load and suspended load fluxes to be equal [*Galy*, 1999; *Garzanti et al.*, 2007]. Assuming that this sediment flux is derived entirely from the Himalayan region, this would yield an erosion rate of 2 mm/a. *Garzanti et al.* [2007] reported an erosion rate of 1.4 mm/a for the Gandak basin in the Himalaya, on the basis of a total sediment flux of ~121 Mt/a sourced from a feasibility study report [*Hydroelectric Power Development Project*, 1982]. A compilation of the sediment yield of global rivers (World River Sediment Yields Database, http://www.fao.org/ag/agl/aglw/sediment/, FAO, Rome) reports a value of 6000 t/km^2/a for the Gandak basin on the basis of the work of *Kansakar and Acharya* [1990]. This sediment yield, when adjusted to include bed load, gives an erosion rate of ~5 mm/a. The sediment flux for the Kosi determined in this study ranges between 60 and 130 Mt/a. This compares with values of 86–360 Mt/a of total sediment flux (calculated from *Jain and Sinha* [2003] and *Sinha and Friend* [1994]) and ~160 Mt/a calculated from the data for the rivers Arun, Sun Kosi, and Tamur (World River Sediment Yields Database, http://www.fao.org/ag/agl/aglw/sediment/, FAO, Rome). These comparisons show that the sediment flux and erosion rates determined in this study are within the broad range of reported values.

[39] *Lave and Avouac* [2001] reported spatial variability in erosion rates for the rivers draining the Nepal Himalaya on the basis of a model considering various parameters such as distribution of terraces in river channels, the present geometry of rivers and the shear stress exerted by flowing water. Their results show that erosion in the Higher Himalaya is significantly higher compared to that of the Lesser Himalaya, consistent with that inferred from this study. Further, their study also showed that the Kali Gandaki, the Marsyandi, the Buri, the Trishuli (headwaters of the Gandak) and the Arun and the Sun Kosi (headwaters of the Kosi) (Figure 1b) all have similar erosion rates in the Higher Himalaya. This result differs from that of the present study which suggests that the Gandak subbasin erodes at a higher rate than that of the Kosi. The causes for the inconsistency between the two approaches are unclear but could be a result of difference in spatial and temporal scales and uncertainties in various model parameters. For example, this study estimates the erosion rate over the entire subbasin, whereas the model calculations present the rate of incision of the rivers.

[40] Erosion rates in the Himalayan drainage of the Kosi and the Ganga (upstream of Patna/Doriganj), estimated in this study, are 0.5 to 2 mm/a (Table 5), respectively, similar to both short-term and long-term "typical erosion rates" for the Himalayan range, such as the Alaknanda basin of the

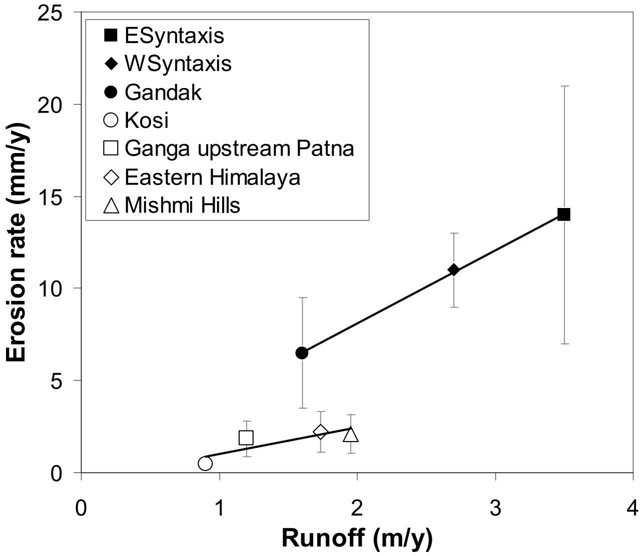

Figure 7. Physical erosion rates in the Ganga-Brahmaputra-Indus basins as a function of runoff. Two trends are seen, one with gentler slope, for rivers with lower precipitation and lower relief and other for those with higher precipitation and higher relief. Data for the Kosi, Ganga (upstream of Patna), and the Gandak are from this study and others are from *Leland et al.* [1998] and *Singh* [2006]. The erosion rate for western syntaxis is a long-term average [*Leland et al.*, 1998], whereas for the other basins it is present-day value.

Ganga (Table 6) [*Vance et al.*, 2003] and the Jia Bhareli and Manas basins of the Brahmaputra (Table 6) [*Singh*, 2006]. The erosion rate for the Himalayan drainage of the Gandak, ~6 mm/a (Table 5), though highest among the Ganga subbasins, is lower than both long-term and short-term erosion rates reported for the syntaxes of the Himalaya [*Burg et al.*, 1998; *Leland et al.*, 1998; *Singh*, 2006]. The erosion rates over the Ganga system determined in this study coupled with those reported for the Brahmaputra [*Burg et al.*, 1998; *Finlayson et al.*, 2002] and the Indus [*Leland et al.*, 1998] systems suggest that typical erosion rates over the Himalaya (combined Higher and Lesser Himalaya) are ~1–3 mm/a. A few hot spots such as the syntaxes and the Gandak subbasin, have significantly higher erosion rates, in the range of ~6 to ~14 mm/a. These hot spots determine the sediment fluxes of the Ganga-Brahmaputra-Indus river basins and therefore the sediment budget of the Bay of Bengal and the Arabian Sea [*Stewart and Hallet*, 2004]. These three hot spots in the Himalaya account for a significant fraction of global sedimentary budget. They contribute ~8% of global riverine sediment flux [*Hay*, 1998] though they occupy only 0.07% of the total exorheic continental area.

4.4.3. Control on Erosion

[41] Synthesis of available data on erosion rates in the Himalaya show two trends with runoff (Figure 7). The first trend is a group of four basins (Kosi, Ganga upstream of Patna, Mishmi Hills and Eastern Himalaya) having lower erosion and shallower slope with runoff and the other is a group of three basins (the Gandak and the eastern and western syntaxes) with much higher erosion and steeper slope with runoff. It has been shown for the Brahmaputra that physical erosion is controlled by a combination of climate and tectonics specifically by runoff and relief [*Singh*, 2006; *Singh and France-Lanord*, 2002]. Among the three subbasins of the Ganga system, the erosion rate of the Gandak is significantly higher than that of the Kosi and the Ganga basins upstream of Patna (Figure 7). This is an indication that in the Gandak basin there are additional factors which enhance its physical erosion, such as higher relief and focused precipitation. Available data [*Bookhagen and Burbank*, 2006] on elevation and relief for the Alaknanda, the Ghaghra, the Gandak and the Kosi show that among them relief is highest for the Gandak. The Gandak basin is also characterized by pockets of very high precipitation, particularly in the Higher Himalaya over its headwaters (Figure 2). The precipitation in these regions is much higher compared to that over the Ghaghra and the Kosi (Figure 2) [*Bookhagen and Burbank*, 2006]. Further, within the Gandak basin in the Higher Himalaya, the highest precipitation coincides with high relief on its southern slope. This combination of high precipitation and high relief seem to be driving the high erosion rates in the Gandak basin. It has been reported [*Hodges et al.*, 2004; *Thiede et al.*, 2004; *Wobus et al.*, 2005] that in general, high precipitation over the southern slope of the HH promotes high erosion in the region. Over and above the general trend, there are regions of focused erosion in the Higher Himalayan sector of the Gandak basin, where intense precipitation (Figure 2) and high relief overlap. The headwaters of the Ganga around Rishikesh also receive intense precipitation over the Lesser Himalayan drainage (Figure 2). The relief of the Lesser Himalaya is low and hence intense precipitation does not lead to enhanced erosion rate.

[42] Thus the results for the Gandak, the Brahmaputra [*Singh*, 2006] and the Indus [*Leland et al.*, 1998] basins indicate that intense precipitation over regions of high relief promotes high erosion rates. Relief of the Brahmaputra around the syntaxis is higher than 3.3 km [*Finnegan et al.*, 2008] and comparable to that of the Gandak. The erosion rates in the syntaxes are ~10–14 mm/a along the Brahmaputra [*Burg et al.*, 1998; *Singh*, 2006] and 3–12 mm/a along the Indus [*Burbank et al.*, 1996; *Garzanti et al.*, 2005; *Leland et al.*, 1998], however, are higher than that of the Gandak basin, ~6 mm/a. This study, thus, brings out the role of hot spots within the HH where the physical erosion rates are much higher than average because of cumulative effect of high relief and high precipitation.

[43] High and focused erosion around the eastern syntaxis in the Brahmaputra, around the western syntaxis in the Indus and in the Gandak subbasin are unloading large amount of sediment from the Himalaya. Because of this localized unloading, regions around them are uplifting more rapidly compared to other regions [*Molnar and England*, 1990; *Montgomery*, 1994; *Zeitler et al.*, 2001]. This in turn, can be responsible for high peaks of the Annapurna and Dhaulagiri in the Gandak basin similar to those of the Namche Barwa and Gyala Peri in eastern syntaxis and the Naga Parbat in western syntaxis basins [*Zeitler et al.*, 2001].

The uplifting blocks may also be responsible for the microseismicity observed around MCT/MBT [*Kayal*, 2001; *Pandey et al.*, 1999].

5. Conclusions

[44] Sr and Nd isotope compositions of silicate fractions of the Ganga sediments in the plain have been used as proxies to trace sediment sources and to determine the spatial variability in physical erosion among the various subbasins of the Ganga system. These studies reveal that more than two thirds of the sediments of the Ganga plain are derived from the Higher Himalaya and that the Gandak subbasin contributes about half of the Ganga sediments at Rajmahal near to its outflow. The erosion rates in the Himalayan drainage of the different subbasins of the Ganga, calculated on the basis of the sediment proportions derived in this study and available sediment flux data, range from 0.5 ± 0.25 to 6 ± 3 mm/a. The highest erosion rate is in the Himalayan drainage of the Gandak basin, ~6 mm/a resulting from the combined effect of intense rainfall in its headwaters and high relief. Results of this study along with those available in literature, suggest that, in general, the erosion rates in the HH are higher compared to other regions of the Himalaya, however even within the HH, there are hot spots where physical erosion is very rapid, 6 to 14 mm/a. These regions are the gorges of the Brahmaputra, the Indus and the Gandak. These hot spots undergo mechanical erosion quite disproportionate to their aerial coverage and contribute ~8% of global riverine sediment flux to the oceans.

Appendix A

[45] Fraction of sediment contribution from different subbasins to the Ganga mainstream has been estimated using mass balance relation. For example, the fractions of sediment at Barauni from the Gandak and Ganga mainstream upstream Doriganj were estimated by using following relation:

$$f_{\rm Gandak} = \frac{\left[\left\{\left(\frac{\rm Sr}{\rm Al}\right)_{\rm GB} * R_{\rm GB}\right\} - \left\{\left(\frac{\rm Sr}{\rm Al}\right)_{\rm GD} * R_{\rm GD}\right\}\right]}{\left[\left\{\left(\frac{\rm Sr}{\rm Al}\right)_{\rm GH} * R_{\rm GH}\right\} - \left\{\left(\frac{\rm Sr}{\rm Al}\right)_{\rm GD} * R_{\rm GD}\right\}\right]}. \quad \text{(A1)}$$

Where, f_{Gandak}: fraction of sediment contributed from Gandak to the Ganga mainstream at Barauni. Here Sr/Al is the concentration ratio of Sr and Al, $R = \frac{^{87}\rm Sr}{^{86}\rm Sr}$, GB is the Ganga at Baurauni, GD is the Ganga at Doriganj, and GH is the Gandak at Hazipur.

[46] It has been assumed that Sr/Al in the sediments of all the end-members are same and hence equation reduces to

$$f_{\rm Gandak} = \frac{(R_{\rm GB} - R_{\rm GD})}{(R_{\rm GH} - R_{\rm GD})}. \quad \text{(A2)}$$

An uncertainty of ±0.0056 on $\frac{^{87}\rm Sr}{^{86}\rm Sr}$ of each of these end-members are propagated in equation (A2) to get the uncertainty in the estimated fraction.

[47] Fraction of contribution of sediments from Rest of the Ganga upstream Doriganj equals

$$1 - f_{\rm Gandak}. \quad \text{(A3)}$$

Similar calculation has been done at Rajmahal between Ganga at Barauni and Kosi. Data of two season samplings have been used separately.

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