ELSEVIER

Earth and Planetary Science Letters 202 (2002) 645–662

EPSL

www.elsevier.com/locate/epsl

Tracing the distribution of erosion in the Brahmaputra watershed from isotopic compositions of stream sediments

Sunil K. Singh *, Christian France-Lanord

Centre Recherches de Pétrographiques et Géochimiques-CNRS, 15, Rue Notre Dame Pauvres, B.P. 20, 54501 Vandœuvre-les-Nancy Cedex, France

Received 3 April 2002; received in revised form 28 June 2002; accepted 5 July 2002

Abstract

Bank sediments and suspended loads of the Brahmaputra River and its important tributaries were collected from the Himalayan front to Bangladesh along with most of the important tributaries. Chemical and isotopic compositions of the sediments are used to trace sediment provenance and to understand erosion patterns in the basin. Overall isotopic compositions range from 0.7053 to 0.8250 for Sr and ε_{Nd} from −20.5 to −6.9. This large range derives from the variable proportions of sediments from Himalayan formations with high Sr isotopic ratios and low ε_{Nd}, and Transhimalayan plutonic belt with lower Sr isotopic ratios and higher ε_{Nd}. The latter are exposed to erosion in the Tsangpo and in the eastern tributary drainages. Overall erosion of the Himalayan rocks is dominant, representing ca 70% of the detrital influx. Compositions of the Brahmaputra main channel are rather stable between 0.7177 and 0.7284 for Sr and between −14.4 and −12.5 for ε_{Nd} throughout its course in the plain from the Siang-Tsangpo at the foot of the Himalayan range down to the delta. This stability, despite the input of large Himalayan rivers suggests that the Siang-Tsangpo River represents the major source of sediment to the whole Brahmaputra. Geochemical budget implies that erosion of the Namche Barwa zone represents about 45% of the total flux at its outflow before confluence with the Ganga from only 20% of the mountain area. Higher erosion rates in the eastern syntaxis compared to the other Himalayan ranges is related to the rapid exhumation rates of this region, possibly triggered by higher precipitation over the far-eastern Himalaya and the high incision potential of the Tsangpo River due to its very high water discharge.

Keywords: Brahmaputra River; Himalayas; erosion; Sr-87/Sr-86; Nd-144/Nd-143; stream sediments

1. Introduction

The Ganga–Brahmaputra ranks first among the world's river systems in terms of sediment discharge [1,2]. There are various estimates of the suspended load flux of these two river systems to the Bay of Bengal which range from 316 to 729 and from 402 to 1157 million tons per yr for the Ganga and the Brahmaputra respectively ([3] and references there in). In most of these studies the sediment flux of the Brahmaputra River system is consistently estimated to be higher than that of the Ganga River system. This is despite the fact that the Brahmaputra River drains a shorter arc of the Himalaya than that of the

* Corresponding author.
E-mail addresses: sunil@crpg.cnrs-nancy.fr (S.K. Singh), cfl@crpg.cnrs-nancy.fr (C. France-Lanord).

0012-821X/02/$ – see front matter
PII: S0012-821X(02)00822-1

Ganga. Based on sediment flux and basin area, the average denudation rate in the Brahmaputra Basin is estimated higher than that of the Ganga Basin. Higher sediment flux from the Brahmaputra Basin than from the Ganga Basin may be related to several processes. The monsoon climate generates higher runoff for the Brahmaputra than for the Ganga. Tectonic uplift may be more active in the eastern side than on the western side of the Himalaya. The erosion in the non-Himalayan parts of the basin, such as the Indo-Burmese Range, the Shillong Plateau and the Tibet-Tsangpo Basin may be important. Finally, the wide floodplain of the Ganga may favour sediment sequestration, whereas Brahmaputra is more channelised between the Himalayan arc and the active Burma arc and Shillong Plateau. However, geochemical budgets of erosion do not support this hypothesis and suggest that the total erosion rate in the eastern Himalaya is about 1.5 times higher than that in the central and western Himalaya [4]. Nevertheless, little is known about erosion in the eastern Himalaya and it is difficult to analyse the origin of the difference between the two Himalayan basins.

In this study we trace the erosion distribution in the Brahmaputra Basin using the river sediment chemistry and their Sr and Nd isotopic compositions. The approach is based on a geochemical budget of the sediment provenance using specific isotopic signatures for all the important tributaries of the Brahmaputra. In this type of study, there could be possibility of mineral bias due to preferential dissolution of fragile minerals such as feldspar, however, in case of the Himalayan rivers and particularly for the Brahmaputra River it can be ruled out as sediment transport is very fast. Such isotopic tracers have already been used to trace sediment provenance in the Bengal Fan [5], the Nepal rivers [6,7] and Indus [8]. Though both the Ganga and the Brahmaputra River systems are draining through almost similar type of lithologies, i.e. the Himalayan terrain, their Sr, Nd and Os isotopic compositions in both dissolved and particulate phases are quite different. The sediments of the Brahmaputra River system are less radiogenic for Sr, Os with higher ε_{Nd} [6,9]. This results from the erosional contribution of Transhimalayan formations in Tibet and in the eastern syntaxis. This isotopic contrast allows to estimate whether the whole eastern Himalaya is eroding faster or if certain regions are having higher erosion rates compared to the rest of them. Attempts have been made to evaluate the possible cause for higher or differential (if any) erosion rates.

2. The Brahmaputra Basin

The Brahmaputra River originates in a great glacier mass in the north of the Himalaya, at Kailash Mountain, at an elevation of about 5200 m and east of the Mansarovar Lake. Named Tsangpo, Zangbo or Yarlung Tsangbo, it flows eastward along the depression of the Indus-Tsangpo Suture for about 1300 km in Tibet. On the plateau the river erodes Paleozoic to Eocene sedimentary rock along with the plutonic and volcanic rock of the suture. The plutonic rocks are the Transhimalayan batholith (gabbros and diorites), lying adjacent to the Indus-Tsangpo Suture zone and the granitic belts farther north [10,11]. The river takes a turn to the northeast near Pai at an altitude of 3000 m. After taking a sudden U-turn around Namche Barwa, it assumes a southwesterly course and enters Arunachal Pradesh (India) where it is named Siang or Dihang. Namche Barwa, an antiformal metamorphic massif with extremely rapid exhumation, exhibits Pleistocene metamorphic and structural overprinting of Proterozoic Indian basement [12]. The Namche Barwa Massif is surrounded by Paleozoic and Mesozoic sediments along with calc-alkaline plutons of the Transhimalayan plutonic belt [12]. These sediments are intruded by various dykes and plutons. The massif core consists of migmatitic gneiss, comprising mafic, pelitic and rare carbonate intercalations. The presence of basic serpentine lenses in the adjoining northeastern and southeastern segments of the syntaxis suggests that this boundary is the eastern continuation of the Indus-Tsangpo Suture, with remnants of meta-ophiolites, folded around the Himalayan derived core migmatites.

Upstream of Namche Barwa knickpoints in the river channel act as natural barriers where sediment accumulates [13,14]. Around Nanche Barwa, the river slope is extreme dropping ca 2000 m over less than 200 km. The river takes another right angled turn to the southeast near Singing and cuts through the Lesser Himalaya and the Sub-Himalaya. It enters the Brahmaputra (Assam) plain at Pasighat at an elevation of about 170 m. In Arunachal Pradesh, the Siang River drains through the Tuting Granite, the Siang Group metamorphics, Mori Group sedimentary rocks (quartzite, dolomite, limestone, etc.), Abor Volcanic, rocks of Gondwana belt and the Upper Tertiary Siwalik belt [15–17]. From the north, principal Himalayan tributaries of the Brahmaputra are the Subansiri, the Ranga Nadi, the Jia Bhareli, the Puthimari, the Manas and Tipkai (Bhutan), and the Tista (Sikkim). The Subansiri River originates in the Tethys Himalaya of Tibet, and flows through the same lithologies as the Himalayan part of the Siang [17]. Other Himalayan tributaries flow through the different geological units of the Himalaya [17,18]. As in the western Himalaya the formations include: (1) Tethyan sedimentary series, (2) High Himalayan Crystallines with gneisses, migmatites and leucogranites massives, (3) Lesser Himalayan formations with schists, quartzites, graphitic schists and limestone, and (4) Siwaliks sedimentary series at the front of the range. The Dibang and the Lohit are two main eastern tributaries of the Brahmaputra. Both of these rivers drain through the Mishmi Hills and are originating on either side of the northwest–southeast trending range. The Himalaya at its eastern end gets terminated along the Tidding Suture and meets another chain of mountains – the Mishmi Hills. These mountain ranges are in continuation of the hill ranges of the northern Myanmar [19,20], but are also considered to be a continuation of the Transhimalayan range lying to the north of the Indus-Tsangpo Suture [21]. This succession is made up of tholeiitic metavolcanic rocks and a calc-alkaline diorite granodiorite complex, with geochemical characteristics of island arc tholeiites, similar to the Dras Volcanic Group and the Kargil igneous complex of the Ladakh magmatic complex [21]. The rivers drain through the graphitic schists, grey slates and marble bands of Yang Sang Chu Formation, metavolcanic rocks having altered to chlorite phyllite as well as limestone of the Tidding Formation, and diorite and tonalite of the Mishmi formations. In the Lohit valley hornblende schists, marble with diorite and diorite-granodiorite intruded by mafic rocks and schist are exposed [22].

The Burhi Dihing, the Dhansiri and the Kopili rivers are the main southern tributaries of the Brahmaputra which flow through the Naga-Patkoi Ranges including Shillong Plateau and Mikir Hills. These ranges are made up of the Tertiary sequences of Assam deposited over the Precambrian basement. The rivers of this region flow through the sedimentary rocks of Arakan-Assam Basin which resulted due to the collision of the Indian Plate with the Tibetan and the Central Burmese plate. The western part of the Indo-Burman Ranges, along the Arakan coast consists of Cretaceous and Oligocene shales hosting volcanic dykes and ophiolites. Some of the sediments in this region were derived from the inner volcanic arc of Burma [23].

Overall the Brahmaputra watershed covers more than 630 000 km^2. The Tsangpo Basin is a little less than a third of the total area with an average elevation higher than 4700 m. The Himalayan drainage area is ca 120 000 km^2 including the eastern syntaxis basin. The southern drainage is minor with 5–7% of the total area. The total area of alluvial plain in Assam and Bangladesh is ca 200 000 km^2. The course of the river is relatively flat in Tibet, then extremely steep across the Himalaya. On the alluvial plain the course is remarkably flat, with a change in elevation of less than 150 m from eastern Assam to the confluence with the Ganga. Despite this flat course, the Brahmaputra reaches 10–15 km in width and presents remarkable braided geometrics [24]. While the Tibetan, Himalayan and Plain sub-basins have very different elevation and relief characteristics, their climates also contrast strongly. In Tibet, the arid condition generates a runoff of 0.3 m/yr and the Tsangpo flux before Namche Barwa is less than 10% of the Brahmaputra flux in Bangladesh. The Himalayan basin is exposed to heavy rainfall, especially in its eastern part and we estimate the

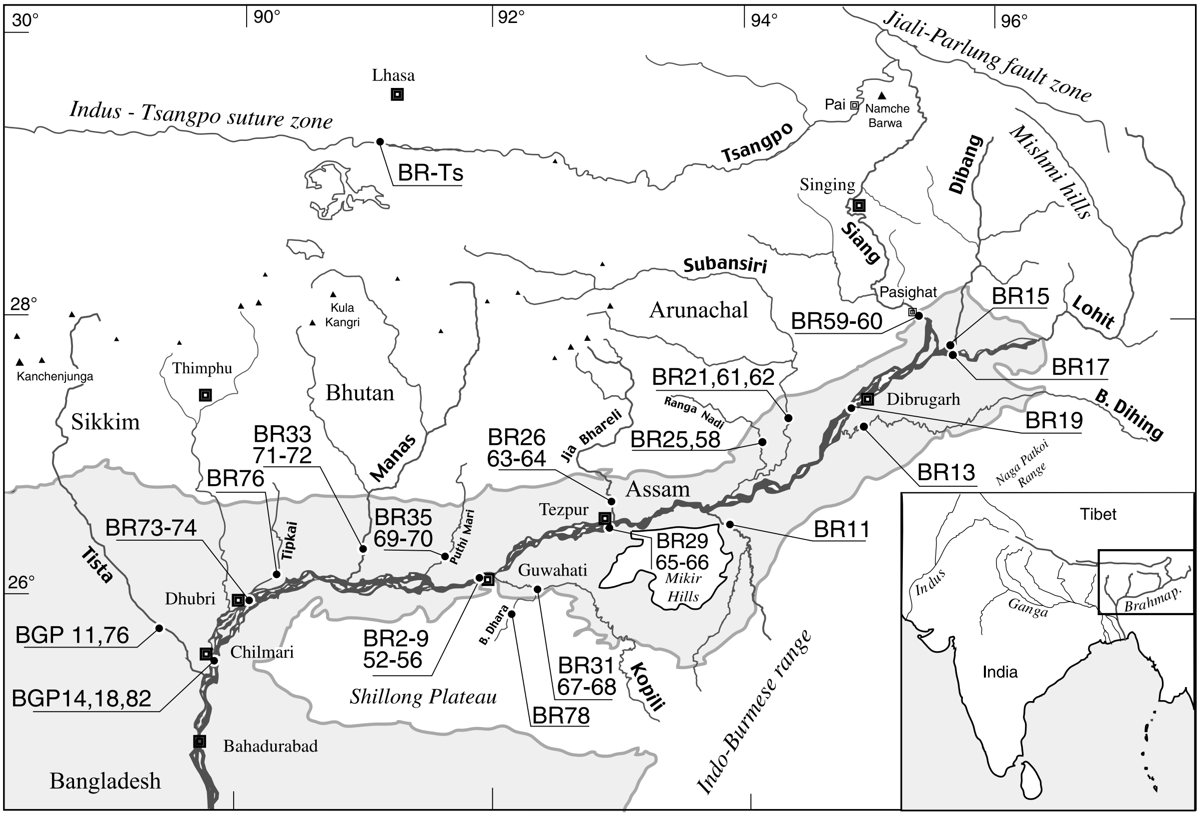

Fig. 1. Map of the Brahmaputra River system showing the sample locations. Suspended load and bank sediments were collected during monsoon and post-monsoon season. The basin comprises several zones with very contrasting geomorphology. The Tsangpo Basin in Tibet is relatively flat but at high elevation. The Siang Basin makes the transition between Tibet and the floodplain in Assam across the eastern syntaxis of the Himalaya. In the basin, the Siang incises the Namche Barwa area with the steepest gorges of the world. At the foot of the Himalaya, the Brahmaputra forms from the confluence of the Siang and the eastern tributaries (Lohit and Dibang). The floodplain (shaded area) extends from the eastern end of Assam at about 170 m elevation to the Bangladesh delta. Over more than 1000 km downstream, the Brahmaputra collects six major Himalayan tributaries from Arunachal, Bhutan and Sikkim and increases its runoff by more than 50%. For some of the samples, names are shortened (e.g. BR 59SL is shown as BR 59).

average Himalayan runoff to about 2 m/yr. The Himalayan rivers excluding the Tsangpo, the eastern and southern tributaries represent 35, 11 and 8% of the total flux respectively. Rainfall on the plain lies between 1.5 and 3 m/yr and produces one third of the total flux [25,26].

3. Samples

Samples for this study were collected during post-monsoon, October 1999 and the monsoon season of July 2000. Some of the samples of the Brahmaputra and the Tista were taken in Bangladesh [6] and one sample of the Tsangpo [9] was also included in this study. Most of the important tributaries from east, north and south along with the main Brahmaputra were sampled. Along its course, the main Brahmaputra has been sampled at four stations, Dibrugarh, Tezpur, Guwahati and Dhubri (Fig. 1; Table 1). At Guwahati, during both field campaigns vertical profiles of suspended load were collected at various depth in the centre of the stream, as well as near the bank of the Brahmaputra River. The Siang River (before it takes the name of Brahmaputra after the confluence with Dibang and the Lohit) was also sampled in Pasighat during the monsoon campaign (Fig. 1). In total, sampling was done in a stretch of about 1000 km, from Pasighat to Bangladesh (Fig. 1).

Because transport and deposition processes mineralogically fractionate the sediments [4], we sampled both suspended load and deposited sediments, referred here as 'bank sediments'. The later were collected either from the bank or from the middle of the channel from sand till. Most of the bank sediments are silty-sand except for the Kopili (BR 31) which is clay-rich. Suspended load samples were collected using a 5-l plastic carboy, which was opened at the required depth. For depth profile, care has been taken not to drift too much from the centre of the river using GPS navigator. The container was then kept standing for about 3–7 days during which the particles were allowed to settle. The water column above the sediments were siphoned out and the sediments were collected.

To the notable exception of the Kopili sample BR 31, all samples are strongly dominated by primary minerals. These are dominated by quartz, muscovite, feldspars, biotite and lithic fragments. Suspended load samples are silts with clay fractions (< 2 μm) measured by laser granulometry representing 0.5–3% of the total sediment. X-ray diffraction data from these clay assemblages show that they contain illite, vermiculite and chlorites and no detectable proportion of kaolinite or smectite. Therefore, even in suspended load sediment, the abundance of secondary minerals produced during weathering is remarkably low. This point is important to underline because secondary mineral may have isotopic compositions modified by weathering process. This effect is major for secondary mineral produced by complete re-crystallisation such as smectite or kaolinite whereas it is minor for clays produced by hydration such as vermiculite or illite [27]. Because sediments are dominated by primary minerals, their isotopic composition reflects the original isotopic signature of source rock.

4. Analytical methods

All the bank sediment and suspended load samples were dried at 50°C in an oven and powdered using a Tema agate mill. Care was taken to avoid any contamination during drying and powdering. A small fraction of the suspended load was removed for grain size analyses prior to drying.

Major and trace elements were measured by inductively coupled plasma-mass spectrometer and inductively coupled plasma-atomic emission spectrophotometer (SARM-CRPG, Vandoeuvre-les-Nancy). Rb, Sr, Sm and Nd concentrations and Sr and Nd isotopic compositions were measured using the procedures followed in our laboratory [6,28]. Sr concentration and isotopic composition of these samples were measured in the carbonate and silicate phases separately whereas Sm–Nd systematics were measured only in the silicate phases.

Sr concentration and isotopic composition were measured on the multicollector Finnigan Mat 262 mass spectrometer. The Sr isotopic ratios were normalised to $^{86}Sr/^{88}Sr = 0.1194$. During these measurements the $^{87}Sr/^{86}Sr$ for NBS 987 standard was 0.710197 ± 0.000038 (2σ). Total Sr blanks were always less than 1 ng for both the carbonate and silicate phases. Hence, no correction has been made for these blanks. Rb concentration was measured on Elan 6000 ICP-MS using isotope dilution.

Sm and Nd concentrations and Nd isotope composition of these samples were also measured on the multicollector TIMS (Finnigan Mat 262) in static mode. The Nd isotopic ratios are normalised to $^{146}Nd/^{144}Nd = 0.7219$. During the whole course of sample measurement J&M Nd standard gives a mean value of $^{143}Nd/^{144}Nd = 0.511107 \pm 0.000040$ (2σ). The Sm and Nd total procedural blanks for the whole analyses were 30 pg and 200 pg respectively which were insignificant compared to the amount measured.

Calcite and dolomite contents of these samples were measured by treating them with 100% phosphoric acid at 25°C and measuring the amount of CO_2 manometrically after 3 h for the calcite fraction and after 1 week for the dolomite fraction.

Table 1
Major element composition of sediments of the Brahmaputra River System

Sample	Type	River	Locality	Date	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	P_2O_5 (%)	LOI (%)	Ct (%)	Dol (%)	Carb (%)
Brahmaputra main channel																		
BR 19	bank sed	Brahmaputra at Dibrugarh	94°46.387′E 27°46.3874N	26.10.1999	70.37	12.52	4.52	0.08	1.93	3.15	2.42	2.62	0.54	0.11	1.4	0.19	0.41	0.6
BR 19 clay	bank sed	Brahmaputra at Dibrugarh	94°46.387′E 27°46.3874N	26.10.1999	43.03	19.60	15.35	0.39	6.18	1.41	1.11	3.46	3.3	0.24	8.68	–	–	–
BR 29	bank sed	Brahmaputra at Tezpur	92°51.221′E 26°36.734′N	28.10.1999	76.06	10.59	3.94	0.07	1.28	2.09	1.8	2.32	0.53	0.1	1.22	0.02	0.07	0.09
BR 65SL	susp load	Brahmaputra at Tezpur	92°51.182′E 26°36.655′N	29.07.2000	62.06	15.79	6.35	0.09	2.44	2.32	1.66	3.17	0.77	0.17	5.06	–	–	–
BR 66	bank sed	Brahmaputra at Tezpur	92°51.182′E 26°36.655′N	29.07.2000	73.1	11.4	4.38	0.06	1.68	2.42	1.93	2.46	0.59	0.12	1.74	–	–	–
BR 2	susp load	Brahmaputra at Guwahati	91°44.380′E 26°11.478′N	24.10.1999	65.43	13.98	6.04	0.08	2.39	2.61	1.84	2.53	0.75	0.13	4.08	–	–	–
BR 3	susp load	Brahmaputra at Guwahati	91°44.390′E 26°11.775′N	24.10.1999	63.03	15.02	6.63	0.09	2.56	2.4	1.71	2.62	0.82	0.14	4.85	–	–	–
BR 4	susp load	Brahmaputra at Guwahati	91°44.220′E 26°11.617′N	24.10.1999	66.79	13.7	5.75	0.08	2.23	2.41	1.88	2.56	0.69	0.13	3.63	–	–	–
BR 6	susp load	Brahmaputra at Guwahati	91°44.220′E 26°11.617′N	24.10.1999	60.02	16.27	7.37	0.1	2.74	2.17	1.59	2.7	0.89	0.15	5.88	–	–	–
BR 7	susp load	Brahmaputra at Guwahati	91°44.297′E 26°11.236′N	24.10.1999	69.85	12.91	4.9	0.07	1.74	2.16	1.87	2.46	0.58	0.1	3.2	–	–	–
BR 8	susp load	Brahmaputra at Guwahati	91°44.273′E 26°11.210′N	24.10.1999	65.33	14.25	6.14	0.08	2.37	2.44	1.83	2.52	0.73	0.12	4.05	–	–	–
BR 9	bank sed	Brahmaputra at Guwahati	91°45.019′E 26°11.563′N	24.10.1999	72.07	11.29	5.37	0.1	1.76	3.17	1.93	2.09	0.73	0.11	1.25	0.1	0.08	0.18
BR 9 clay	bank sed	Brahmaputra at Guwahati	91°45.019′E 26°11.563′N	24.10.2000	42.42	22.14	13.8	0.28	4.61	1.06	0.82	3.25	2.5	0.35	10.88	–	–	–
BR 52SL	susp load	Brahmaputra at Guwahati	91°45.168′E 26°11.705′N	26.07.2000	69.07	12.65	5.26	0.08	2.13	2.89	1.96	2.47	0.68	0.14	2.54	–	–	–
BR 53SL	susp load	Brahmaputra at Guwahati	91°45.175′E 26°11.675′N	26.07.2000	69.15	12.88	4.99	0.07	2.09	2.59	2	2.61	0.6	0.14	2.75	–	–	–
BR 54SL	susp load	Brahmaputra at Guwahati	91°45.130′E 26°11.695′N	26.07.2001	59.5	16.35	7.05	0.1	2.94	2.69	1.68	3.1	0.82	0.18	5.46	–	–	–
BR 55SL	susp load	Brahmaputra at Guwahati	91°45.170′E 26°11.711′N	26.07.2000	59.43	16.27	6.99	0.1	2.91	2.72	1.69	3.08	0.82	0.18	5.68	–	–	–
BR 56	bank sed	Brahmaputra at Guwahati	91°45.156′E 26°11.304′N	26.07.2000	70.78	11.7	5.17	0.08	2.12	3.64	2.11	2.07	0.79	0.19	1.25	–	–	–
BR 73SL	susp load	Brahmaputra at Dhubri	89°59.757′E 26°1.115′N	30.07.2001	60.1	16.81	6.86	0.09	2.74	1.92	1.5	3.38	0.78	0.16	5.53	–	–	–
BR 74	bank sed	Brahmaputra at Dhubri	89°59.757′E 26°1.115′N	30.07.2000	76.05	10.63	3.63	0.06	1.34	2.48	1.95	2.13	0.45	0.11	1	–	–	–
BGP 14[a]	bank sed	Brahmaputra	Chilmari	05.08.1996	73.02	11.88	4.19	0.05	1.72	1.99	1.82	2.5	0.53	0.1	2	0.02	0.53	0.55
BGP 82[a]	bank sed	Brahmaputra	Chilmari	07.03.1997	76.51	10.3	3.88	0.09	1.23	2.36	2.02	1.99	0.57	0.098	0.83	0.003	0.004	0.01
BGP 18[a]	susp load	Brahmaputra	Chilmari	05.08.1996	60.74	16.86	6.81	0.1	2.87	2	1.53	3.25	0.79	0.17	4.76	0.15	1.07	1.22
Eastern tributaries																		
BR 15	bank sed	Dibang	96°35.253′E 27°47.874′N	26.10.1999	64.7	12.62	6.72	0.11	3.04	5.96	2.44	1.33	0.82	0.15	2	1.6	0.52	2.12
BR 17	bank sed	Lohit	96°36.732′E 27°47.926′N	26.10.1999	55.87	13.52	9.96	0.19	4.97	8.76	2.38	1.07	1.18	0.2	2.08	2.76	0.25	3.01
Tsangpo																		
BR Ts[b]	bank sed	Tsangpo	near Lhasa	–	68.33	12.82	5.35	0.07	1.64	2.82	1.95	2.25	0.75	0.14	3.76	–	–	–
Siang																		
BR 59SL	susp load	Siang	95°20.153′E 28°4.671′N	28.07.2000	64.02	14.32	5.81	0.08	2.67	3.44	1.86	3.35	0.76	0.18	3.37	–	–	–
BR 60	bank sed	Siang	95°20.153′E 28°4.671′N	28.07.2000	68.11	10.59	5.57	0.1	2.59	5.48	1.88	2.18	0.81	0.27	2.69	2.15	2.18	4.33
Himalayan tributaries																		
BR 21	bank sed	Subansiri bank	94°15.095′E 27°26.900′N	28.10.1999	80.69	8.38	4.32	0.12	0.83	1.1	0.93	1.89	0.41	0.06	1.09	0.1	0.25	0.35
BR 61SL	susp load	Subansiri	94°15.416′E 27°26.741′N	28.07.2001	64.63	15.14	5.98	0.14	1.46	1.36	1.39	2.16	0.61	0.12	6.83	–	–	–
BR 62	bank sed	Subansiri bank	94°15.416′E 27°26.741′N	28.07.2000	78.29	9.24	3.78	0.06	1.04	1.46	1.23	2.04	0.58	0.08	2.03	–	–	–
BR 25	bank sed	Ranga Nadi bank	94°3.527′E 27°12.240′N	29.10.1999	81.41	8.48	3.22	0.06	0.71	0.76	1.19	2.2	0.45	0.09	1.87	0.01	0.04	0.04
BR 58	bank sed	Ranga Nadi bank	94°3.636′E 27°12.320′N	27.07.2001	83.69	7.26	2.52	0.05	0.5	0.53	0.92	2.21	0.3	0.05	1.78	–	–	–
BR 27	bank sed	Jia Bhareli bank	92°52.568′E 26°48.599′N	29.10.1999	79.59	10.02	2.9	0.05	0.63	0.86	1.66	2.78	0.31	0.06	1.36	0.05	0.01	0.06
BR 63SL	susp load	Jia Bhareli	92°52.768′E 26°48.645′N	29.07.2000	70.23	13.05	4.62	0.05	1.31	1.03	1.36	3.09	0.57	0.11	4.42	–	–	–
BR 64	bank sed	Jia Bhareli bank	92°52.768′E 26°48.645′N	29.07.2000	81.67	8.01	3.11	0.03	0.76	0.56	0.79	2.21	0.39	0.05	2.23	–	–	–
BR 35	bank sed	Puthimari bank	91°39.224′E 26°26.037′N	30.10.1999	77.69	9.85	3.5	0.04	0.94	0.69	0.7	2.43	0.59	0.07	3.37	0.1	0.63	0.73
BR 69SL	susp load	Puthimari	91°39.202′E 26°22.008′N	30.07.2000	64.42	15.04	5.53	0.06	2.01	2.43	1.82	3.24	0.67	0.16	4.45	–	–	–
BR 70	bank sed	Puthimari bank	91°39.202′E 26°22.008′N	30.07.2000	76.85	9.47	3.3	0.07	1.49	2.19	1.36	2.21	0.34	0.07	2.46	–	–	–
BR 33	bank sed	Manas bank	90°54.953′E 26°29.699′N	30.10.1999	76.0	9.34	3.73	0.05	1.5	2.64	1.46	2.11	0.55	0.11	2.35	2.04	1.79	3.83
BR 71SL	susp load	Manas	90°55.170′E 26°29.732′N	30.07.2000	66.56	14.08	5.27	0.08	1.76	1.01	0.71	3.12	0.64	0.13	6.49	–	–	–
BR 72	bank sed	Manas bank	90°55.170′E 26°29.732′N	30.07.2000	79.99	8.62	3.3	0.04	0.96	0.61	0.63	2.12	0.51	0.09	2.97	–	–	–
BR 76	bank sed	Tipkai	90°8.279′E 26°13.108′N	30.07.2000	86.69	6.63	1.84	< dl	0.48	0.3	0.94	1.75	0.15	0.06	0.92	–	–	–
BGP 11[a]	bank sed	Tista	Kaunia	04.08.1996	73.72	12.22	4.39	0.05	1.56	1.44	1.77	2.55	0.58	0.16	1.32	0.003	0.01	0.01
BGP 76[a]	bank sed	Tista	Kaunia	07.03.1997	69.87	13.99	4.94	0.06	1.94	1.16	1.78	3.08	0.67	0.139	2.01	0.001	0.01	0.01

Table 1 (*Continued*).

Sample	Type	River	Locality	Date	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	P_2O_5 (%)	LOI (%)	Ct (%)	Dol (%)	Carb (%)
Southern tributaries																		
BR 31	bank sed	Kopili bank	92°21.267′E 26°9.908′N	28.10.1999	77.39	9.68	4.61	0.09	0.68	0.36	0.56	1.85	0.83	0.08	4.3	0	0.06	0.06
BR 67SL	susp load	Kopili	92°21.216′E 26°9.932′N	29.07.2000	57.52	17.66	7.03	0.13	1.19	0.79	0.52	2.24	0.98	0.18	11.61	–	–	–
BR 68	bank sed	Kopili bank	92°21.216′E 26°9.932′N	29.07.2000	92.8	3.55	2.17	0.04	0.22	0.28	0.32	0.87	1.19	0.13	0.96	–	–	–
BR 11	bank sed	Dhansiri	93°43.877′E 26°37.869′N	24.10.1999	69.02	13.56	7.21	0.06	1.28	0.28	0.83	1.86	1	0.1	4.69	0.01	0.01	0.02
BR 13	bank sed	Buri Dihing	94°53.015′E 27°18.743′N	25.10.1999	79.27	9.01	3.33	0.07	1.5	1.18	1.5	2.22	0.44	0.07	1.65	0.02	0.01	0.02
BR 78	bank sed	Basistha Dhara	near Guwahati	01.08.2000	89.67	4.82	1.33	< dl	0.23	0.28	0.51	2.02	0.09	< dl	0.81	–	–	–
BR 36	gneiss		91°42.710′E 26°9.694′N	30.10.1999	77.34	12.26	1.22	< dl	< dl	0.6	3.44	4.68	0.05	0	0.18	–	–	–

dl: determination limit, –: not measured, LI: loss of ignition, Dol: dolomit, Ct: calcite, Carb: carbonate content, sed: sediment, susp: suspended.

[a] Data from [6].

[b] From [9].

5. Results

5.1. Major elements

The major element compositions of these samples are given in Table 1. As a general observation, bank sediments have higher SiO_2 content and lower Al_2O_3 content than suspended load. For the Main Brahmaputra, the SiO_2 content of the suspended load varies between 59 and 70%, whereas for the bank sediment it is between 70 and 77%. The shallow suspended load samples tend to have higher Al/Si ratios compared to deeper samples. In such river sediments, SiO_2 variations compared to Al_2O_3 are controlled by mineralogical sorting during transport. Quartz and coarser minerals tend to concentrate in the bank sediments whereas suspended load tends to be enriched in phylosilicates and clay minerals. When compared to the Ganga sediments or to the western Himalayan river sediments [4,6], the Brahmaputra and most of its tributaries show comparable characters. All of them have lower Na and K contents compared to that of average continental crust [29], showing that sources are recycled crustal formations. The two eastern tributaries are having contrasting compositions with higher Ca and Mg and lower SiO_2 contents consistent with the presence of mafic, ultramafic and volcanic rocks in their catchment area.

5.2. Carbonates

One striking difference of the Brahmaputra sediments compared to Ganga is their low content of carbonate. Carbonate content does not exceed 0.6% in the Brahmaputra sediments whereas it is 4–7% in the Ganga. Carbonate content is only significant in the Siang (4%) and the two eastern tributaries, the Dibang and the Lohit (2–3%). At Dibrugarh, 30 km after their confluence, only 0.6% of carbonate have been measured in the Brahmaputra bank sediment and 0.1% further downstream at Tezpur. This implies strong dissolution in the plain, possibly related to the high precipitation in eastern Assam (about 2.5 m/yr at Dibrugarh [26]. Other Himalayan tributaries also have less carbonate content, except the

Table 2
Rb, Sr, Sm, Nd concentrations and Sr and Nd isotope compositions of the sediments of the Brahmaputra River system

Sample	Type	River	Date	Sr (ppm)	$^{87}Sr/^{86}Sr$	Rb (ppm)	Sr (ppm)	$^{87}Sr/^{86}Sr$	Sm (ppm)	Nd (ppm)	$^{143}Nd/^{144}Nd$	ε_{Nd}
				Carbonate		Silicate						
Brahmaputra main channel												
BR 19	bank sed	Brahmaputra at Dibrugarh	26.10.1999	–	–	112.4	242.85	0.718655	4.95	27.6	0.511986	−12.6
BR 19 clay	clay	Brahmaputra at Dibrugarh	26.10.1999	–	–	224.1	108.97	0.720540	6.27	30.07	0.511993	−12.4
BR 29	bank sed	Brahmaputra at Tezpur	28.10.1999	–	–	115.6	159.74	0.728481	6.93	38.41	0.51191	−14.04
BR 65SL	susp load	Brahmaputra at Tezpur	29.07.2000	–	–	196.4	195.2	0.719199	7.26	38.31	0.511914	−13.96
BR 66	bank sed	Brahmaputra at Tezpur	29.07.2000	–	–	113.6	157.1	0.725211	4.97	25.5	0.511931	−13.63
BR 2	susp load	Brahmaputra at Guwahati	24.10.1999	–	–	125.7	187.07	0.72105	5.96	31.56	0.51192	−13.02
BR 3	susp load	Brahmaputra at Guwahati	24.10.1999	–	–	146	175.05	0.722013	6.9	36.83	0.51194	−13.4
BR 4	susp load	Brahmaputra at Guwahati	24.10.1999	–	–	145.4	184.45	0.720567	6.02	31.01	0.511953	−13.2
BR 6	susp load	Brahmaputra at Guwahati	24.10.1999	–	–	146.7	169.84	0.720553	6.82	36.36	0.511987	−12.5
BR 7	susp load	Brahmaputra at Guwahati	24.10.1999	–	–	127.5	211.22	0.719331	6.87	37.2	0.511957	−13.13
BR 8	susp load	Brahmaputra at Guwahati	24.10.1999	–	–	128.6	198.23	0.719791	6.21	31.25	0.511878	−14.66
BR 9	bank sed	Brahmaputra at Guwahati	24.10.1999	–	–	82.7	208.24	0.717726	8.25	48.92	0.511941	−13.4
BR 9 clay	clay	Brahmaputra at Guwahati	24.10.1999	–	–	234.9	91.1	0.717923	8.25	41.24	0.511991	−12.5
BR 52SL	susp load	Brahmaputra at Guwahati	26.07.2000	–	–	126.1	231.7	0.719656	–	22.4	0.511949	−13.29
BR 53SL	susp load	Brahmaputra at Guwahati	26.07.2000	–	–	148	167	0.720589	2.65	–	–	–
BR 54SL	susp load	Brahmaputra at Guwahati	26.07.2000	–	–	180	193.7	0.721623	4.91	–	–	–
BR 55SL	susp load	Brahmaputra at Guwahati	26.07.2000	–	–	182.3	160.2	0.721859	3.88	16.93	0.511974	−12.79
BR 56	bank sed	Brahmaputra at Guwahati	26.07.2000	–	–	81.1	244.4	0.718249	12.11	66.2	0.511941	−13.44
BR 73SL	susp load	Brahmaputra at Dhubri	30.07.2000	–	–	224.4	147.7	0.734388	5.81	30.66	0.511912	−14.01
BR 74	bank sed	Brahmaputra at Dhubri	30.07.2000	–	–	100.4	195.9	0.721507	5.97	33.2	0.511894	−14.36
BGP 14[a]	bank sed	Brahmaputra at Chilamari	05.08.1996	–	–	125.6	147.58	0.734572	7.26	39.01	0.511771	−16.9
BGP 82[a]	bank sed	Brahmaputra at Chilamari	07.03.1997	–	–	74.2	183.17	0.721019	8.69	50.92	0.511943	−13.6
BGP 18[a]	susp load	Brahmaputra at Chilamari	05.08.1996	–	–	186.7	89.44	0.748838	6.51	34.3	0.511801	−16.3
Eastern tributaries												
BR 15	bank sed	Dibang	26.10.1999	580.71	0.71085	44.3	363.23	0.705296	5.93	30.27	0.512275	−6.9
BR 17	bank sed	Lohit	26.10.1999	407.19	0.70888	33	428.44	0.708810	9.23	51.95	0.511995	−12.4
Yarlang Tsangpo												
BR Ts[b]	bedload	Tsangpo		–	–	–	–	–	–	37.8	–	−10
T1[c]	bedload	Tsangpo		–	–	165	277	0.709597	–	–	–	–
T2[c]	bedload	Tsangpo		–	–	104	233	0.714306	–	–	–	–
T3[c]	bedload	Tsangpo		–	–	109	176	0.715917	–	–	–	–
T4[c]	bedload	Tsangpo		–	–	49	670	0.704593	–	–	–	–
Siang												
BR 59SL	susp load	Siang	28.07.2000	–	0.71566	175.3	202.4	0.725241	6.88	33.87	0.51188	−14.63
BR 60	bank sed	Siang	28.07.2000	203.87	0.71607	93.7	213.9	0.720604	10.67	58.8	0.512013	−12.03
Himalayan tributaries												
BR 21	bank sed	Subansiri bank	28.10.1999	–	–	88.5	74.8	0.735633	6.83	39.63	0.511833	−15.6
BR 61SL	susp load	Subansiri	28.07.2000	–	–	127.2	116.56	0.730133	6.17	36.35	0.511977	−12.74
BR 62	bank sed	Subansiri bank	28.07.2000	–	–	88	70.7	0.741897	2.79	15.3	0.511908	−14.09
BR 25	bank sed	Ranga Nadi bank	29.10.1999	–	–	75.9	89.27	0.730654	3.46	19.74	0.511976	−12.76
BR 58	bank sed	Ranga Nadi bank	27.07.2000	–	–	105.6	70.4	0.738124	3.02	17.1	0.512001	−12.27
BR 27	bank sed	Jia Bhareli bank	29.10.1999	–	–	138.1	69.15	0.777051	3.92	22.59	0.511794	−16.31
BR 63SL	susp load	Jia Bhareli	29.07.2000	–	–	187.2	56.3	0.776816	7.76	42.11	0.51178	−16.58
BR 64	bank sed	Jia Bhareli bank	29.07.2000	–	–	181.7	53.2	0.777346	3.46	18.8	0.511791	−16.36
BR 35	bank sed	Puthimari bank	30.10.1999	–	–	208.1	61.26	0.758673	5.37	29.82	0.511715	−17.9
BR 69SL	susp load	Puthimari	30.07.2000	–	–	211.8	69	0.7703	6.42	35.7	0.511726	−17.64
BR 70	bank sed	Puthimari bank	30.07.2000	–	–	110.9	39.2	0.764176	2.08	9.9	0.51173	−17.55
BR 33	bank sed	Manas bank	30.10.1999	2874.81	0.71863	121	69.57	0.764398	8.45	45.23	0.511812	−15.95

Table 2 (*Continued*).

Sample	Type	River	Date	Sr (ppm)	$^{87}Sr/^{86}Sr$	Rb (ppm)	Sr (ppm)	$^{87}Sr/^{86}Sr$	Sm (ppm)	Nd (ppm)	$^{143}Nd/^{144}Nd$	ε_{Nd}
				Carbonate		Silicate						
BR 71SL	susp load	Manas	30.07.2000	–	0.71715	256.3	101.8	0.760045	6.7	36.05	0.511747	−17.22
BR 72	bank sed	Manas bank	30.07.2000	124.07	0.72498	146.9	67	0.762298	3.52	18.3	0.511792	−16.35
BR 76	bedload	Tipkai	30.07.2000	–	–	104.3	37.6	0.784524	1.35	7.2	0.511595	−20.2
BGP 11[a]	bank sed	Tista	32723	–	–	168.1	92.49	0.809621	8.62	46.4618	0.511551	−21.204
BGP 76[a]	bank sed	Tista	32938	–	–	226.1	88.88	0.824959	7.58	40.7581	0.51158	−20.638
Southern tributaries												
BR 31	bank sed	Kopili bank	28.10.1999	–	–	94.1	58.21	0.733421	6.61	35.74	0.511978	−12.7
BR 67SL	susp load	Kopili	29.07.2000	–	–	217	85.1	0.732516	9.95	55.22	0.511855	−15.12
BR 68	bank sed	Kopili bank	29.07.2000	–	–	37.1	32.2	0.736137	16.67	97.2	0.51158	−20.49
BR 11	bank sed	Dhansiri	24.10.1999	–	–	76.5	79.9	0.718137	5.86	31.74	0.512197	−8.4
BR 13	bank sed	Buri Dihing	25.10.1999	–	–	79.9	129	0.727418	4.5	28.79	0.511672	−18.7
BR 78	bank sed	Basistha Dhara	01.08.2000	–	–	48.7	47.3	0.750154	1.57	7.4	0.511982	−12.63
BR 36	gneiss		30.10.1999	–	–	115	40.11	1.076	3.81	16.31	0.512145	−9.5

[a] From [4,6].
[b] From [9].
[c] From [7].

Manas River which has 3.8% carbonate. Sr isotopic compositions are reported only in samples with carbonate concentration above 2%. They vary from 0.7089 to 0.7108 for the eastern tributaries and from 0.7157 to 0.7250 for the Siang and Manas rivers respectively. Due to the lower carbonate content, these ratios might have contaminated with radiogenic Sr leached from silicates even with mild acids. However, the radiogenic signature for detrital carbonates in Himalayan rivers is classical. It has been shown that some Himalayan carbonates have experienced metamorphism and alteration during the Himalayan orogeny and have acquired high $^{87}Sr/^{86}Sr$ from adjacent silicates or through hydrothermal fluids [30–33].

5.3. *Sr isotopic compositions of silicate*

Sr is mobile during weathering, hence both original concentration and isotopic composition of sediments may be altered. As stated in Section 3, sediments, even the suspended load, contain less than 3% of clays. The Sr concentration is around 100 ppm for clays and 200 ppm for suspended load (Table 2). This implies that a maximum of 1.5% of the bulk sediment Sr may have been exchanged during weathering. Therefore, Sr isotopic signatures of sediment are considered as reflecting the primary isotopic signatures of the source rocks.

Sr isotopic compositions of the silicate phase exhibit large variations. A range of 0.7053–0.8250 is recorded with Sr concentration varying from 32 ppm to 428 ppm (Fig. 2A; Table 2). Rb concentrations vary from 33 ppm to 256 ppm (Table 2). Sr isotopic compositions of the silicate phase of the suspended load and bank sediment of the Siang River are 0.7252 and 0.7206 respectively. For the other Himalayan tributaries $^{87}Sr/^{86}Sr$ varies from 0.7301 to 0.8250 though the Sr concentration does not show much variability around an average of 70 ppm. These values are comparable with those of other Himalayan rivers from central and western Himalaya [6]. $^{87}Sr/^{86}Sr$ in the silicate phase for the Himalayan rivers increases moving from east to west in the drainage basins. High ratios reflect input from the Lesser

Himalayan formations. Similar to the west Himalaya, highly radiogenic rocks are also present in the Lesser Himalayan formations of the eastern Himalaya [34]. The observed east–west trend therefore likely reflects the increasing proportion of Lesser Himalaya formations in the drainage. Compared to the other Himalayan rivers, the Siang shows lower $^{87}Sr/^{86}Sr$ of 0.720 and higher Sr concentrations. Fig. 3A shows that the Sr contrast of the Brahmaputra main channel is independent of SiO_2 content and therefore derives from a source variability rather than a mineralogical effect. In contrast, the eastern tributaries have very low $^{87}Sr/^{86}Sr$ values; 0.7053 and 0.7088 for the Dibang and Lohit respectively, and show high Sr content of around 400 ppm. The low $^{87}Sr/^{86}Sr$ with high Sr contents are typical of formations of the Transhimalaya plutonic belt [11], which are likely present in the drainage of those two basins [22]. Comparable Sr isotopic compositions have been reported from the Mishmi Hills diorites-granodiotites and leucogranites [35]. Sr isotopic compositions for the sediments of the southern tributaries are varying from 0.7181 to 0.7502. No data exist for formations of the Shillong Plateau. We analysed a single sample of gneiss taken from the Indian basement at Guwahati which has a high $^{87}Sr/^{86}Sr$ of 1.076. The bank sediment of a small tributary, Basistha Dhara, flowing through this basement near Guwahati has $^{87}Sr/^{86}Sr$ of 0.750.

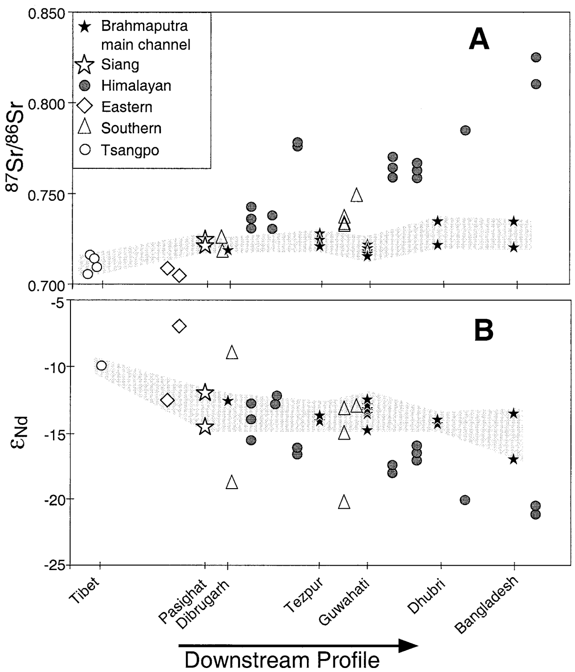

Fig. 2. Variations of $^{87}Sr/^{86}Sr$ (A) and ε_{Nd} (B) of the sediments of the Brahmaputra along the river profile. The near invariable nature of $^{87}Sr/^{86}Sr$ and ε_{Nd} along the Brahmaputra River profile (shown by grey shading) from Pasighat (BR 59 and 60) to Bangladesh shows the dominant control of the Siang River on the overall sediment budget of the Brahmaputra River System. This is despite the contribution of the eastern and Himalayan tributaries.

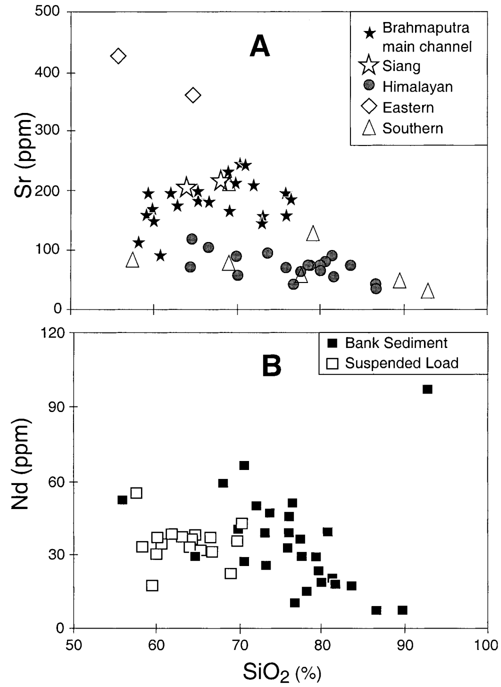

Fig. 3. SiO_2 versus Sr concentration (A) and Nd concentration (B) for the bank and suspended sediments. The Sr concentrations in the sediment are primarily governed by the source compositions rather than mineralogical sorting. Sr concentrations of the sediments of the Brahmaputra main channel are close to that of the Siang and remain rather invariable throughout its course at about 190 ppm, demonstrating its dominant control on the sediment budget of the Brahmaputra River system. For the Nd concentrations, suspended and bank sediments define two different trends. In case of bank sediments, Nd decreases as SiO_2 is increased, suggesting a control by heavy minerals. For suspended load, Nd concentration is showing no dependence on SiO_2.

The silicate $^{87}Sr/^{86}Sr$ of the Brahmaputra main channel are rather constant throughout the river course at a value of 0.721 ± 0.004 (Fig. 2A). Similarly, Sr concentration are stable at 190 ± 28 ppm. Exceptions are observed for the bank sediment at Tezpur and in Bangladesh for the samples collected during the monsoon which are more radiogenic and have lower Sr concentrations. The east–west stability of Brahmaputra compositions is remarkable given the fact that Himalayan tributaries have isotopically contrasted signatures.

5.4. Nd isotopic compositions

Sm and Nd concentrations vary from 1 to 17 ppm, and 7 to 97 ppm respectively (Table 2). Nd contents of the bank sediments show a classical negative correlation with SiO_2; however, they are almost constant with varying SiO_2 content of the suspended load (Fig. 3B). Part of this variation in bank sediments is related to the quartz dilution and is suggesting a control of heavy minerals on Nd content.

For Himalayan tributaries, ε_{Nd} ranges from −21.2 to −12.3 (Table 2). Following the trend observed for Sr, ε_{Nd} values tend to decrease toward the west, suggesting that the relative proportions of Lesser Himalayan formations is higher in Sikkim and Bhutan than in the Arunachal Himalaya (Fig. 2B). In contrast, the eastern tributaries have high ε_{Nd} values of −6.9 and −12.4 (Table 2; Fig. 2B). ε_{Nd} values for the Siang River at Pasighat are −12.03 and −14.6 for bank sediment and suspended load respectively, significantly lower than that of the Tsangpo in Tibet which is −10.0 [9]. The ε_{Nd} values for the Brahmaputra main channel are quite stable between −12.5 and −14.7, except for the two monsoon samples in Bangladesh which have lower values around −17, as observed for Sr signatures (Fig. 2B). For other locations, however, ε_{Nd} does not show any seasonal variability and has similar values for both the monsoon and post-monsoon samples.

6. Brahmaputra outflow composition

There exist only few analyses of the Brahmaputra sediments in Bangladesh and they show very variable isotopic compositions [4]. Most samples were collected just ahead of the confluence with the Tista River which drains the Sikkim Basin. One dry season sample has Sr and Nd isotope composition of 0.7210 and −13.6 respectively, whereas two monsoon samples (bank sediment and suspended load) from the same location have these compositions as 0.7346, 0.7488 and −16.9, −16.3 respectively. These latter appear more 'Himalayan' than those of the Brahmaputra upstream in Dhubri or Guwahati. No sample downstream exists and other information have to be deduced from sediments mixed with the Ganga flux. These include one sample of the Lower Meghna at the mouth of the river [4], 0–300 yr old samples from the submarine delta and the shelf canyon, the Swatch of no Ground, and 0–15 kyr old samples from the active channel levee system in the proximal Bengal Fan [28]. All these samples represent direct input of the Ganga–Brahmaputra and show quite stable Sr and Nd isotope compositions at 0.742 ± 0.003 and −14.4 ± 1 respectively. By comparison, Ganga sediments have more radiogenic Sr composition around 0.775 and lower ε_{Nd} around −17.5 [4]. This set of data (Fig. 4) implies that the average Brahmaputra composition must be close to those measured in Dhubri (BR 73–74) or during the dry season in Bangladesh (BGP 82). Nevertheless, monsoon samples BGP 14 and 18 imply that the Brahmaputra composition can be occasionally very variable. Their compositions suggest that during this particular period, the Brahmaputra flux was more under Himalayan influence than usual.

7. Sources of sediments

Compared to the Ganga [4], the Brahmaputra sediments have less radiogenic Sr compositions and higher ε_{Nd} (Fig. 4). It suggests that, in addition to erosion of Himalayan formations, the Transhimalayan plutonic belt must represent a major source of sediments to the Brahmaputra. Additional sources of sediments are the southern tributaries. Their isotopic compositions are quite variable and can overlap with those of Himalayan rivers like the Kopili, or those of the eastern tributaries like the Dhanshiri. Southern tributaries represent ca 8% of the total Brahmaputra water flux; however, published fluxes of suspended load [36] suggests that their contribution to physical erosion is negligible. They represent only 3% of the total Brahmaputra sediment flux at Bahadurabad, which is consistent with their low drainage elevation and flatness compared to those of the Himalayan or eastern rivers. In the following discussion, we will therefore neglect the southern tributaries.

Little is known of the formations present in the eastern Himalaya and even less of their isotopic signatures. For High Himalayan formations, some data exists for Namche Barwa Massif [12], Kameng district in Arunachal [34,37], and the Bhutan leucogranites [38], which suggest that High Himalayan formations of the eastern Himalaya have Sr or Nd isotopic compositions comparable to those of HHC rocks in the Western Himalaya. Few Sr isotopic data exist [34,39] for the Lesser Himalaya in Arunachal, drainage basin of the Jia Bhareli, which are similar to those of the

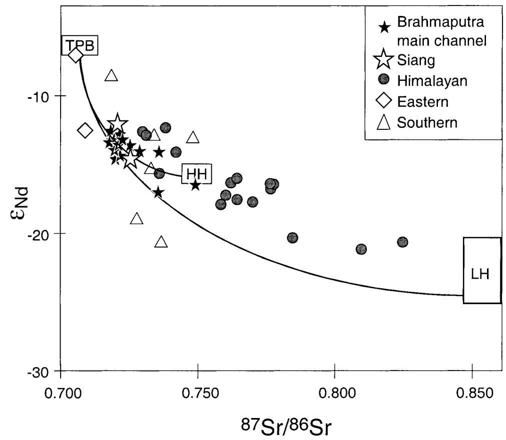

Fig. 5. Mixing diagram of $^{87}Sr/^{86}Sr$ versus ε_{Nd} of the Brahmaputra River sediments. Also plotted are the endmember values for the Transhimalayan plutonic belt (TPB), based on data from [11,35,40], the Higher Himalaya (HH) and the Lesser Himalaya (LH) [5,34,37,39,45]. Most of the Brahmaputra sediments can be explained by the mixing between 50 and 70% of the material derived from the High Himalaya, ~10% from the Lesser Himalaya and the remaining from the Transhimalayan plutonic belt. The Himalayan tributaries except the Subansiri and the Ranga Nadi are best explained by a simple mixing between HH and LH.

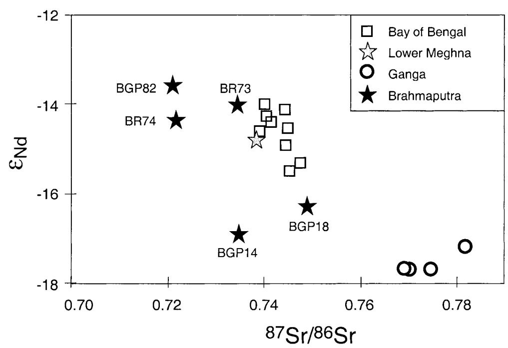

Fig. 4. Comparison of $^{87}Sr/^{86}Sr$ and ε_{Nd} of the Ganga and the Brahmaputra sediments sampled in Bangladesh with sediments of the shallow Bengal Fan [28] and Lower Meghna sediments [4]. For the Bengal Fan, we selected data from the shelf near the mouth of the delta or from the active channel levee system [44], the site where the Himalayan input is not diluted with other detrital sources. These data suggest that the Brahmaputra samples in Dhubri (BR 74, 73SL) or during the dry season in Bangladesh (BGP 82) are compatible with those of the Ganga to produce the Lower Meghna and Bengal Fan sediments. On the contrary, The Brahmaputra samples BGP 14 and 18 which have been sampled the same day during the monsoon 1997 may correspond to a particular input from an Himalayan tributary.

Western and Central Himalaya. Such formations are observed in varying proportions in all river basins from Tista to Siang. In particular, the Tista Basin in Sikkim is dominated by Lesser Himalaya formations which is consistent with its very radiogenic Sr signature and low ε_{Nd} (Fig. 5). Finally, data exist for the Transhimalaya plutonic rocks [11,35,40] and they are consistent with data measured for the eastern tributaries. It is therefore possible to approach the sources of sediments in the Brahmaputra as a three endmember mixing system consisting of Transhimalaya, High Himalaya and Lesser Himalaya as documented in the Western and Central Himalaya and in Tibet. The Sr and Nd isotopic compositions of the Brahmaputra and most of its Himalayan tributaries appears compatible with such model (Fig. 5). Only the Subansiri and one of its tributaries appears to lie outside the mixing area and would require a High Himalaya endmember with higher ε_{Nd}. Based on this source model, the Siang sediments can be explained by the mixing of 10–30% material from the Transhimalayan plutonic belt with

Table 3
Endmembers for various basins and geological units

River	Location	Sr (ppm)	$^{87}Sr/^{86}Sr$	ε_{Nd}
Basins:				
Siang	Pasighat	208 ± 5	0.723 ± 0.002	−13.3 ± 1
Eastern tributaries	before Dibrugarh	400 ± 25	0.707 ± 0.002	−9.6 ± 2
Brahmaputra	Dibrugarh	243 ± 10	0.719 ± 0.002	−12.6 ± 0.5
Arunachal Himalaya	between Guwahati and Dibrugarh	70 ± 10	0.748 ± 0.02	−14.6 ± 1
Brahmaputra	Guwahati	195 ± 15	0.718 ± 0.002	−13.3 ± 0.6
Bhutan Himalaya	between Guwahati and Dhubri	70 ± 10	0.762 ± 0.005	−16.7 ± 1.5
Brahmaputra	Dhubri	180 ± 20	0.728 ± 0.005	−14.2 ± 0.5
Geological units:				
Transhimalayan plutonic belt (TPB)		400 ± 100	0.705 ± 0.004	−6.5 ± 2.0
Higher Himalaya (HH)		70 ± 20	0.750 ± 0.02	−16.0 ± 2.0
Lesser Himalaya (LH)		70 ± 20	0.850 ± 0.05	−25.0 ± 3.0

70–90% sediments derived from the High Himalaya. These proportions remain almost the same for the Brahmaputra sediments further downstream at Guwahati and the Dhubri, suggesting the dominance of the Siang in the sediment budget of the Brahmaputra.

Determining source proportions is more complex, because the Lesser Himalaya are part of the source mixture, as shown by the compositions of most of the Himalayan tributaries. With the exception of the Tista River (BGP 11 and 76) the contribution of Lesser Himalaya to the Himalayan rivers does not exceed 20% and is likely less in the Subansiri and the Siang. Based on the Sr, Nd isotope compositions of sediments of the Himalayan tributaries and those for the LH and HH endmembers (Table 3), a proportion of 15% Lesser Himalaya in these tributaries is calculated. Considering this estimate of the Lesser Himalaya, the three endmember proportions in the Brahmaputra River would be ca 30, 60 and 10% for the Transhimalaya, High Himalaya and Lesser Himalaya respectively.

In detail, part of the isotopic signal, especially Sr, is under mineralogical control. In Fig. 6, a plot of $^{87}Rb/^{86}Sr$ against $^{87}Sr/^{86}Sr$ shows that all samples taken in the main channel of the Brahmaputra and clay extracted from samples BR 9 and BR 19 define an almost flat mixing line. $^{87}Rb/^{86}Sr$ values in those samples are controlled by the micas and clay proportions and, as expected, the bank samples have low $^{87}Rb/^{86}Sr$ compared to the suspended load. For Himalayan sources, higher $^{87}Rb/^{86}Sr$ implies significantly higher $^{87}Sr/^{86}Sr$ which is not observed for the Brahmaputra samples at Guwahati. This implies that source distribution is not homogeneous among mineral phases and that overall, fine grained fractions are more

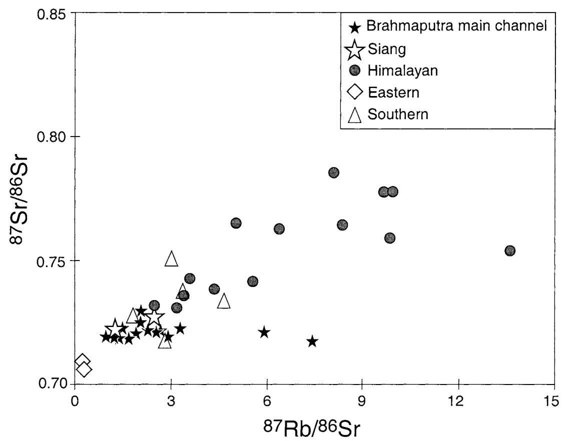

Fig. 6. $^{87}Rb/^{86}Sr$ versus $^{87}Sr/^{86}Sr$ of the sediments of the Brahmaputra River system. This plot shows that a part of the isotopic signal is under mineralogical control especially for Sr. All samples taken in the main channel of the Brahmaputra, including clay extracted from sample BR 19, define an almost flat mixing line. $^{87}Rb/^{86}Sr$ in those samples are controlled by the micas and clay proportion and, as expected, the bank sediments have low $^{87}Rb/^{86}Sr$ compared to suspended load or pure clay. For Himalayan sources, the positive correlation between $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ derives from both higher $^{87}Sr/^{86}Sr$ in phases rich in Rb and source effects.

supplied by the non-radiogenic endmember of the Transhimalaya than by Himalayan rivers.

8. Erosion distribution in the drainage basin

Isotopic compositions of the Brahmaputra sediments are quite constant all along its course in Assam, in spite of the contribution of the Himalayan tributaries (Fig. 2A,B). Downstream, this remains true if we consider the average composition of the Brahmaputra deduced from Bengal Fan sediments or samples in Bangladesh. This apparent stability implies that a large part of the Brahmaputra flux is actually derived from the Siang. Using the isotopic signatures of the different rivers, it is possible to quantify their relative contribution to the Brahmaputra at different locations along its course. We use the isotopic compositions of the different river sediments to calculate the flux of the Siang, eastern, and Himalayan tributaries at Dibrugarh, Guwahati and Dhubri. The budget is based on a two endmember mixing system using Sr and Nd data for the different locations: Siang+eastern tributaries = BR 19 (Dibrugarh); BR 19+Arunachal Himalaya = BR 2–9, 52–56 (Guwahati), and Guwahati+Bhutan Himalaya = BR 73–74 (Dhubri location or Brahmaputra outflow). For Himalayan compositions we use the average of the different tributaries weighted for their water flux. This calculation assumes that the samples are representative of the net flow. In this respect, Guwahati has been sampled in detail and illustrates a reasonable uncertainty that can be attached to our data. Table 3 shows the concentrations, isotopic compositions and uncertainties considered for this budget calculation. Nd concentrations have not been taken into account since there is no clear differences in concentration between the different endmembers. The uncertainties quoted for the different endmembers in Table 3 is propagated in the two endmember mixing equation to achieve the final uncertainty. The mixing calculations show that the Siang River dominates the particle flux at Dibrugarh with 81 ± 25% (Fig. 7). Downstream, the Himalayan input tends to dilute the Siang flux. However, this still represents 58 ± 23% at Guwahati and 49 ± 27% for the Brahmaputra outflow (Fig. 7). At the outflow, the Himalayan flux represents about 40%, the Siang 49% and the eastern tributaries the remaining 11% (Fig. 7). Uncertainties are large on these estimates and they strongly depend on uncertainties in Sr concentrations. Nevertheless, it appears consistent that the Siang flux is very high and tends to buffer the Brahmaputra compositions. By comparison to the sediment flux, the water flux of the Siang represents only 25% of that of the whole Brahmaputra and 38% of the area.

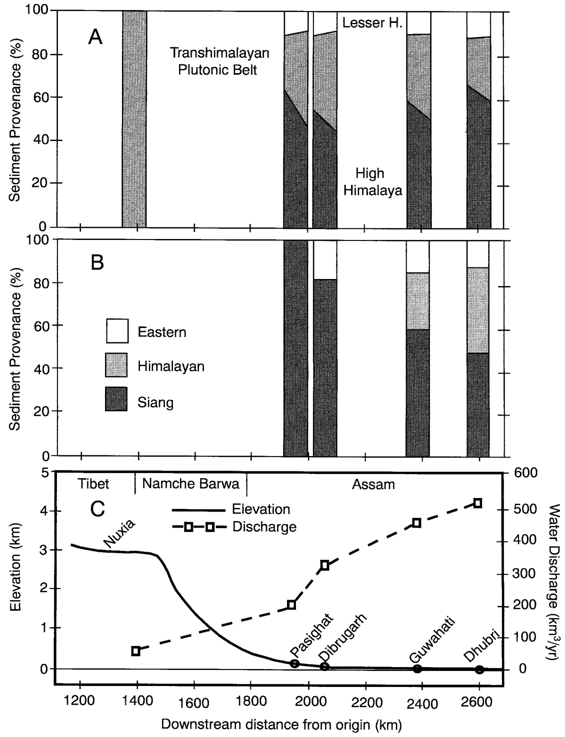

Fig. 7. Sediment provenance the Brahmaputra River at different locations. (A) In term of geological units, the Higher Himalaya is contributing significantly to the sediment budget of the Brahmaputra River, varying sizes of the rectangle show the uncertainty in the contributions. (B) In term of basin, even at the outflow of the Brahmaputra River, half of the sediment is supplied by Siang River. The sediment provenance were calculated using the endmember values of Sr, $^{87}Sr/^{86}Sr$ and ε_{Nd} of different geological units and basins given in Table 3. (C) River elevation profile and water discharge along the course.

The Siang erosion flux derives from two very different zones. The Southern Tibet or Tsangpo drainage with medium to moderate relief represents a considerable area of about 1.9×10^5 km^2. Downstream, the river traverses the eastern syntaxis of the Himalaya at Namche Barwa where incision is among the highest in the world. The area of the syntaxis watershed (around 0.27×10^5 km^2) is much smaller than that of Tibet. The climatic conditions are also contrast with semi-arid Tibet and the extremely humid syntaxis. No detailed precipitation data exist for this region; however, estimates can be derived from the few water flux data available [41]. The river runoff changes from ca 0.3 m/yr for Tsangpo upstream of Namche Barwa, to ca 0.7 m/yr for the Siang at the foot of the Himalaya. This implies that precipitation over the syntaxis zone is around 3 m/yr It is therefore interesting to determine whether the erosion flux of the Siang is derived from the whole drainage including Tibet, or if it mostly comes from the syntaxis part of the basin.

Based on the few available data for sediment flux in the Tsangpo upstream of Namche Barwa, Tibetan erosion would supply only 3% of the total Brahmaputra flux of suspended load [41]. This number is likely underestimated because bedload transport may be high in such a river. No detailed isotopic data are available for this region so it is difficult to assess the proportion of Tsangpo sediment in the Siang River. In Tibet, about 500 km west to Namche Barwa, the Tsangpo sediments have Sr isotopic compositions around 0.710 and ε_{Nd} of -10 [7]. On the syntaxis side, Namche Barwa gneisses have ε_{Nd} values between -17 and -12 [12], but this represents less than a third of the Syntaxis area. Such data base is insufficient to derive relative erosion flux. The isotopic signatures of the adjoining Himalayan basin, the Subansiri, are close to those of Namche Barwa and may represent the average 'Himalayan' contribution to the Siang. If the average syntaxis isotopic signatures are similar to those of the Subansiri, the syntaxis erosion would greatly exceed 60% of the total Siang flux. This hypothesis tends, however, to underestimate the syntaxis contribution because Transhimalayan and Mishmi Hills formations, with isotopic signatures close to those of the Tsangpo, are dominant in the northern and eastern part of the syntaxis watershed. In particular, two important tributaries, north east of the Namche Barwa, drain along the Jiali-Parlung fault zone in the Transhimalayan formations.

While it is clear that more detailed work in this region is necessary to better decipher the patterns of erosion, both published suspended load flux of the Tsangpo and the limited geochemical data indicate that Namche Barwa syntaxis erosion largely dominates the Siang flux. Overall, it likely supplies about 40 to 45% of the total Brahmaputra flux at its outflow before the Ganga confluence while this zone is only 8% of the total basin area. If we consider that erosions in Tibet and the Brahmaputra plain are negligible, the relative flux must be compared to the mountain area rather than total area. In this respect, the syntaxis area corresponds to about 20% of the mountain area of the whole basin. The erosion in the Namche Barwa regions appears therefore significantly higher than that over the rest of the Himalaya in the watershed. This fits well with the observation of very high exhumation rates observed in the Namche Barwa region [12,13] as well as the remarkable incision of this zone [42].

The above calculations show that the Brahmaputra sediment budget is dominated by the Siang River and the eastern and the Himalayan tributaries play a secondary role. This is contrary to the conclusion drawn by Goswami [36] on the basis of suspended load fluxes where the two eastern tributaries supplied sediment flux equal to that of the Siang. Given the contrasting isotopic composition of the sediments in the Dibang and Lohit River, there is no possibility of reconciling these two data sets.

9. Conclusion

This first set of geochemical data on Brahmaputra sediments highlights the characteristics of the different tributaries draining Tibet, the Himalaya and the region North of the Indo-Burmese Range. The Himalayan rivers have isotopic compositions similar to those of the central and western Himalayan rivers, implying similar lithologies in the eastern Himalaya. This study also reveals the increasing proportions of the Lesser Himalaya in east to west direction. The eastern tributaries have compositions very different from those of the Himalayan formations due to the presence of the Transhimalayan plutonic belt in their drainage. In between, the Siang-Tsangpo is characterised by a mixing between flux from these two belts. Overall, sediments of the Brahmaputra River system have High Himalayan affinity with ~30% contribution from the Transhimalayan plutonic belt. This contribution is the reason for the clear difference between the isotopic compositions of the Brahmaputra and the Ganga (i.e. the sediments of the Ganga River System have higher $^{87}Sr/^{86}Sr$ and lower ε_{Nd} compared to those of the Brahmaputra River system). This should allow the relative contribution of both river systems to the sediments deposited in the delta [43] or in the proximal Bengal Fan to be assessed. On a longer time scale, it is possible that the Tibetan drainage was not formerly connected to the Brahmaputra and this should induce a clear change in the characteristics of the Brahmaputra sediment toward Himalayan compositions.

Based on our data, the distribution of erosion in the mountain range is heterogeneous. The Namche Barwa or eastern syntaxis zone is the major source of sediments and supplies about 45% of the bulk sediment flux from only 20% of mountain area. This conclusion is based, however, on a limited number of samples and the possible variability of the system over short term makes it necessary to increase sampling to improve representativeness. Nevertheless the high sediment yield from the syntaxis region is consistent with the fast exhumation rate recorded in this region [12]. It coincides with the climatic contrast between the different drainage basins, i.e. the arid Transhimalayan zone and highly humid Himalayan zone. The tectonic and climatic factors account for the remarkably high erosion of this region, but we want to underline another remarkable characteristic of this basin. Compared to all other Transhimalayan rivers, the Tsangpo prior to crossing the high range into the syntaxis region has a much higher water discharge. For instance, the Tsangpo discharge upstream of Namche Barwa is equal to that of the Narayani-Gandak River which drains the whole basin of central Nepal [6]. In this basin, the total flux of the four rivers draining Tibet is less than 8% of that of the Tsangpo. This high flux favours the high incision in the Namche Barwa region which could trigger the high uplift rate of this region. Our data set, however, does not allow the relative importance of erosion between the Tsangpo Basin and Namche Barwa to be qualified but it is clear that isotopic tracing of sediment provenance will be an important tool for further detailed study in this area.

Acknowledgements

This work has been supported by a fellowship of MENSR for S.K.S. and grants from the French 'Programme National Sol Erosion'. We thank Amulya Narzary for help during sampling in Assam and Laurie Reisberg and Catherine Spatz for laboratory and analytical support. Reviews of Drs P. Clift, L. Turpin and M. Bickle greatly helped to improve this article. Contribution CRPG # 1600.***[BARD]***

References

[1] J.D. Milliman, R.H. Meade, World Delivery of River Sediment to the Oceans, J. Geol. 1 (1983) 1–21.

[2] J.D. Milliman, P.M. Syvitski, Geomorphic/Tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers, J. Geol. 100 (1992) 525–544.

[3] M.R. Islam, S.F. Begum, Y. Yamaguchi, K. Ogawa, The Ganges and Brahmaputra rivers in Bangladesh: basin denudation and sedimentation, Hydrol. Proces. 13 (1999) 2907–2923.

[4] A. Galy, C. France-Lanord, Higher Erosion rates in the Himalaya: geochemical constraints on riverine fluxes, Geology 29 (2001) 23–26.

[5] C. France-Lanord, L. Derry, A. Michard, Evolution of the Himalaya since Miocene time: isotopic and sedimentologic evidence from the Bengal Fan, in: P.J. Treloar, M. Searle (Eds.), Himalayan Tectonics, Geol. Soc. Lond Spec. Publ. 74, Geol. Soc. Lond., 1993, pp. 603–621.

[6] A. Galy, Etude Geochimique de l'Erosion Actuelle de la Chaine Himalayenne, Institut National Polytechnique de Lorraine, 1999.

[7] N. Harris, M. Bickle, H. Chapman, I. Fairchild, J. Bunbury, The significance of the Himalayan rivers for silicate

weathering rates: evidence from the Bhote Kosi tributary, Chem. Geol. 144 (1998) 205–220.
[8] P.D. Clift, J.I. Lee, P. Hildebrand, N. Shimizu, G.D. Layne, J.D. Blum, E. Garzanti, A.A. Khan, Nd and Pb isotope variability in the Indus River system: Implications for sediment provenance and crustal heterogeneity in the Western Himalaya, Earth Planet. Sci. Lett. 200 (2002) 91–106.
[9] A.-C. Pierson-Wickman, L. Reisberg, C. France-Lanord, The Os isotopic composition of Himalayan river bedloads and bedrocks: importance of black shales, Earth Planet. Sci. Lett. 176 (2000) 203–218.
[10] R.-H. Xu, U. Scharer, C.J. Allegre, Magmatism and metamorphism in the Lhasa Bloch (Tibet): A geochronological study, J. Geol. 93 (1985) 41–57.
[11] F. Debon, P. LeFort, S.M.F. Sheppard, J. Sonet, The four plutonic belts of the Transhimalaya-Himalaya: a chemical, mineralogical, isotopic and chronological synthesis along a Tibet-Nepal section, J. Petrol. 27 (1986) 219–250.
[12] J.-P. Burg, P. Nievergelt, F. Oberli, D. Seward, P. Davy, J.-C. Maurin, Z. Diao, M. Meier, The Namche Barwa syntaxis: evidence for exumation related to compressional crustal folding, J. Asian Earth Sci. 16 (1998) 239–252.
[13] P.K. Zeitler, A.S. Meltzer, P.O. Koons, D. Craw, B. Hallet, C.P. Chamberlain, W.S.F. Kidd, S.K. Park, L. Seeber, M. Bishop, J. Shroder, Erosion, Himalayan geodynamics, and the geomorphology of metamorphism, GSA Today (2001) 4–9.
[14] D.D. Zhang, Geomorphological problems of the middle reaches of the Tsangpo river, Tibet, Earth Surf. Process. Landforms 23 (1998) 889–903.
[15] A.K. Jain, S.K. Tandon, Stratigraphy and structure of the Siang district, Arunachal (NEFA), Himalaya, Himalayan Geol. 8 (1974) 28–60.
[16] A.K. Jain, V.C. Thakur, Abor volcanics of the Arunachal Himalaya, J. Geol. Soc. India, 1978.
[17] V.C. Thakur, Tectonic zonation and regional framework of eastern Himalaya, Sci. Terre 47 (1986) 347–360.
[18] A. Gansser, Geology of the Bhutan Himalaya, Birkhaüser, Bâle, 1983.
[19] D.R. Nandy, Tectonic patterns in northeast India, Indian J. Earth Sci. 7 (1980) 103–107.
[20] S.K. Acharya, Cenozoic plate motions creating the eastern Himalayas and Indo-Burmese Ranges around the northeast corner of India, in: N.C. Ghose, S. Varadarajan (Eds.), Ophiolite and Indian Plate Margin, 1986, pp. 143–161.
[21] K.K. Sharma, Geological settings of the ophiolites and magmatic arc of the Lohit Himalaya (Arunachal Pradesh), India with special reference to their petrochemistry, geology and geodynamics evolution of the Himalayan collision zone, Physics and Chemistry of the Earth 18 (I-II), Pergamon Press PLC, Oxford, 1991, pp. 277–292.
[22] G. Kumar, Geology of the Arunachal Pradesh, Geol. Soc. India, Bangalore, 1997, 217 pp.
[23] C. Colin, L. Turpin, J. Bertaux, A. Desprairies, C. Kissel, Erosional history of the Himalayan and Burman ranges during the last two glacial-interglacial cycles, Earth Planet. Sci. Lett. 171 (1999) 647–660.
[24] J.M. Coleman, Brahmaputra river: channel, processes and sedimentation, Sediment. Geol. 3 (1969) 129–239.
[25] K.L. Rao, India's Water Wealth, Orient Longman, New Delhi, 1979, 267 pp.
[26] P.M. Steurer, World Weather Records, Asia, U.S. Department of Commerce, 1992.
[27] L.A. Derry, C. France-Lanord, Neogene Himalayan weathering history and river $^{87}Sr/^{86}Sr$: Impact on the marine Sr record, Earth Planet. Sci. Lett. 142 (1996) 59–74.
[28] A.-C. Pierson-Wickmann, L. Reisberg, C. France-Lanord, H. Kudrass, Os-Sr-Nd results from sediments in the Bay of Bengal: Implications for sediment transport and the marine Os record, Paleoceanography 16 (2001) 435–444.
[29] S.R. Taylor, S.M. McLennan, The geochemical evolution of the continental crust, Rev. Geophys. 33 (1995) 241–265.
[30] M.J. Bickle, N.B.W. Harris, J.M. Bunbury, H.J. Chapman, I.J. Fairchild, T. Ahmad, Controls on the $^{87}Sr/^{86}Sr$ Ratio of Carbonates in the Garhwal Himalaya, Headwaters of the Ganges, J. Geol. 109 (2001) 737–753.
[31] S.K. Singh, J.R. Trivedi, K. Pande, R. Ramesh, S. Krishnaswami, Chemical and Sr, O, C, isotopic compositions of carbonates from the Lesser Himalaya: Implications to the Sr isotope composition of the source waters of the Ganga, Ghaghara and the Indus Rivers, Geochim. Cosmochim. Acta 62 (1998) 743–755.
[32] J. Quade, L. Roe, P.G. DeCelles, T.P. Ojha, The late Neogene $^{87}Sr/^{86}Sr$ record of lowland Himalayan rivers, Science 276 (1997) 1828–1831.
[33] A. Galy, C. France-Lanord, L.A. Derry, The Strontium Isotopic Budget of Himalayan Rivers in Nepal and Bangladesh, Geochim. Cosmochim. Acta 63 (1999) 1905–1925.
[34] G.R. Dikshitulu, B.K. Pandey, V. Krishna, R. DhanaRaju, Rb-Sr systematics of Granitoids of the Central Gneissic Complex, Arunachal Himalaya: Implications on tectonism, stratigraphy and source, J. Geol. Soc. India 45 (1995) 51–56.
[35] J.K. Bhalla, N. Srimal, P.K. Bishui, Isotopic study of Mishmi complex, Aruchal Pradesh, North Eastern Himalaya, Geol. Surv. India, Calcutta, 1982, 20 pp.
[36] D.C. Goswami, Brahmaputra River, Assam, India: Physiography, Basin Denudation, and Channel aggradation, Water Resour. Res. 21 (1985) 959–978.
[37] J.R. Trivedi, Geochronological studies of Himalayan Granitoids, Gujarat University, 1990.
[38] V. Dietrich, A. Gansser, The leucogranites of the Bhutan Himalaya (crustal anatexis versus mantle melting), Bull. Suisse Minéral. Pétrogr. 61 (1981) 177–202.
[39] J.K. Bhalla, P.K. Bishui, Chronology and geochemistry of granite emplacement in north eastern Himalaya 122, Geol. Surv. India, Calcutta, 1982, pp. 18–20.
[40] S. Turner, N.O. Arnaud, J. Liu, N. Rogers, C.J. Hawkesworth, N. Harris, S. Kelley, P. Calsteren, W.M. Deng, Post-cllision, Shoshonitic Volcanism on the Tibetan Pla-

teau: Implication for Convective Thinning of the Lithosphere and the Source of Ocean Island Basalts, J. Petrol. 37 (1996) 45–71.

[41] G. Zhi-hua, C. Chuan-you, Hydrographical features of the Yarlung Zangbo River, in: Geological and Ecological Studies of Qinghai-Xizang Plateau, Science Press, Beijing, Gordon and Breach, New York, Beijing, 1981, pp. 1693–1703.

[42] D.P. Finlayson, D.R. Montgomery, B. Hallet, Spatial coincidence of rapid inferred erosion with young metamorphic massifs in the Himalayas, Geology 30 (2002) 219–222.

[43] S.L. Goodbred Jr., S.A. Kuehl, Enormous Ganges-Brahmaputra sediment discharge during strengthened early Holocene monsoon, Geology 28 (2000) 1083–1086.

[44] M.E. Weber, M.H. Wiedicke, H.R. Kudrass, C. Hübscher, H. Erlenkeuser, Active growth of the bengal Fan during sea-level rise and highstand, Geology 25 (1997) 315–318.

[45] T. Ahmad, N. Harris, M. Bickle, H. Chapman, J. Bunbury, C. Prince, Isotopic constraints on the structural relationship between the Lesser Himalaya Series and the high Himalayan Crystalline Series, Garhwal Himalaya, Geol. Soc. Am. Bull. 112 (2000) 467–477.