Higher erosion rates in the Himalaya: Geochemical constraints on riverine fluxes

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ABSTRACT

The modern erosion rate of continental-scale mountains is difficult to estimate and is usually based on measurement of the suspended load flux of rivers combined with assumptions about river bedload transport and sedimentation in flood plains. These two parameters are very difficult to measure directly in continental-scale basins. In this paper we examine the chemical composition of the suspended load, bedload, and dissolved load of the Ganga and Brahmaputra Rivers and compare them with the average composition of Himalayan source rocks. A mass-balance equation of erosion fluxes shows that a Si-rich component is needed in addition to suspended and dissolved load fluxes to account for the composition of the source rock. It corresponds to bedload sediment and flood-plain deposits, which are enriched in quartz by mineral sorting during transport. The combined budget of Si, Al, and Fe in the river system allows us to estimate this Si-rich flux. By this method, the total Himalayan erosion is estimated to be twice the measured flux of suspended load. The comparison between the Brahmaputra and the Ganga shows that the eastern Himalaya has a higher erosion rate (2.9 mm/yr) than the western Himalaya (2.1 mm/yr). This is likely the result of the higher runoff in the Brahmaputra basin. The intensity of the monsoon acts as a first-order control of the erosion rate in the range.

Keywords: isotope, geochemistry, mass balance, neodymium, sediment, silicon.

INTRODUCTION

Assessing the erosional flux from the Himalaya is of first-order importance for studies of the global impact of Himalayan erosion on the carbon cycle (France-Lanord and Derry, 1997; Raymo and Ruddiman, 1992), Himalayan tectonic models (Avouac and Burov, 1996; Martinod and Molnar, 1995), or instantaneous topographic evolution of the range (Bilham et al., 1997). Since the original investigation made by Rennell (1781), measured suspended load fluxes of the Ganga and Brahmaputra Rivers have been used to assess the Himalayan erosion rate. However, such estimates reflect only a part of the Himalayan particle flux because (1) sediments are deposited in the flood plain and (2) measured suspended load fluxes do not include bedload transport. The latter, commonly considered to be 10% of the suspended load flux (Lane and Borland, 1951), is essentially unknown for this type of river (Milliman and Syvitski, 1992). The large Ganga flood plain is evidence that long-term accumulation occurred there, and the modern sedimentation rates in some areas of the Ganga-Brahmaputra flood plains (e.g., Goodbred and Kuehl, 1998) show that significant and heterogeneous sedimentation occurs before the gauging stations. Therefore, scaling the total erosional flux of the Himalaya with the measured dissolved and suspended load fluxes requires estimating the unknown quantities of sediments that are either sequestered in the flood plain or transported as bedload.

In this paper we use the mineralogical fractionation between suspended load and bedload or deposited sediment, which occurs during river transport, to estimate this unknown flux. The approach is based on a geochemical budget of major elements, assuming that the chemical composition of the average source rock must equal that of the total erosional flux: dissolved plus suspended plus bedload plus flood-plain sedimentation (e.g., Gaillardet et al., 1995, 1999; Stallard, 1995).

GANGA-BRAHMAPUTRA RIVER SYSTEM AND EROSION DATA

The Brahmaputra and Ganga Rivers represent the major drainage system of the Himalaya. Himalayan rivers are characterized by very high topographic gradients on the south Himalayan flank, which collects monsoonal precipitation and where most of the physical erosion takes place (Seeber and Gornitz, 1983). Within the Himalayan basin, modern accumulation of eroded material represents a very minor reservoir compared to the flood plain and Bengal fan. In the flood plain, the topographic gradients become very low and sedimentation is controlled by the structural evolution of the flexural basin (Burbank, 1992). While the distribution of this subsidence is heterogeneous, local studies in Bangladesh show that it could trap a significant quantity of the eroded particles, as much as 70% of the suspended load flux (Goodbred and Kuehl, 1998).

The fluxes of suspended and dissolved load of the Ganga-Brahmaputra Rivers in Bangladesh (Fig. 1) have been measured by diverse methods (Table 1). The main features is that chemical erosion represents only 9% $\pm$ 2% of the suspended load flux, which underlines the physical character of the Himalayan erosion.

In order to characterize the particulate flux, we have collected river sediments at six locations in Bangladesh (Fig. 1). Bedloads were sampled under water near the riverbanks during both the monsoon (August 1996) and the dry season (February 1997). Suspended loads were collected during the peak discharge in August by boat from the axis of the rivers and were separated by decantation in a Teflon flask. The compositions of river samples (Fig. 2; Tables 2 and 3[1]) show that suspended loads are enriched in Al and Fe and depleted in Si compared to bedload. This systematic relationship corresponds to the sorting of the main minerals during transport. Clays and primary micas are enriched in the suspended load, whereas quartz is more abundant in the coarse grain fraction and tends to settle.

CHEMICAL BUDGET APPROACH

We use this chemical difference between suspended load and bedload sediments to calculate a total erosion flux from the Himalaya using mass balance. This approach is based on the hypothesis that, before the flood plain, the bulk chemical composition of the total eroded flux (dissolved plus particulate) is equal to that of the average Himalayan crust. In the case of the Himalayan part of the basin, where erosion is largely dominated by physical processes and where internal basins rep-

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[1]GSA Data Repository item 20017, Tables 2 and 3, Chemical and isotopic (Sr, Nd) compositions of modern river sediments and average Himalayan rocks, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

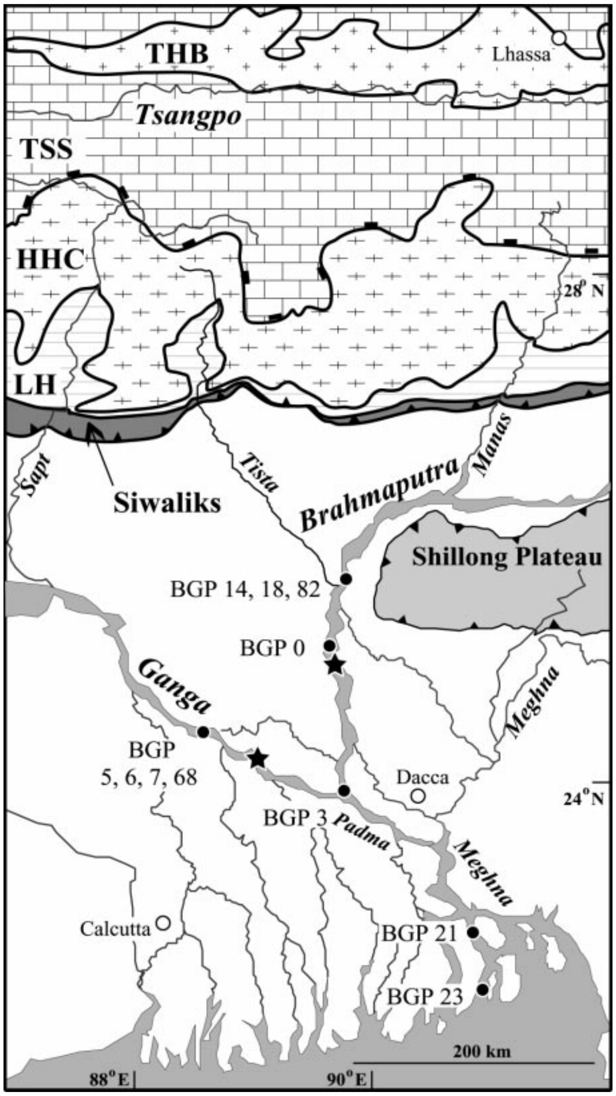

Figure 1. Sampling location of suspended load and bedload samples for Ganga and Brahmaputra Rivers in Bangladesh. Stars indicate locations of gauging stations. Compared to Ganga, Brahmaputra flood plain is reduced by uplift of Shillong Plateau. North-south tectonic structure of Himalayan range is similar within Ganga-Brahmaputra basin and defines five main geological units: Siwaliks, Lesser Himalaya (LH), High Himalaya Crystalline (HHC), Tethyan Sedimentary Series (TSS), and Trans-Himalayan Batholith (THB).

resent a minor accumulation with respect to the erosional flux, this hypothesis is reasonable.

The total Himalayan erosion flux (Φ_{Him}) is therefore equal to the sum of fluxes monitored in Bangladesh for dissolved loads (Φ_{Diss}) and suspended loads (Φ_{SL}) plus the unknown fluxes of sediments deposited in the flood plain (Φ_{FloodP}) and the bedload (Φ_{BL}):

$$\Phi_{Him} = \Phi_{SL} + \Phi_{Diss} + \Phi_{FloodP} + \Phi_{BL}. \quad (1)$$

For any chemical element (X), we can write a budget equation based on the chemical concentration as follows:

$$\Phi_{Him} \times [X]_{Him} = \Phi_{SL} \times [X]_{SL} + \Phi_{Diss} \times [X]_{Diss} + \Phi_{FloodP} \times [X]_{FloodP} + \Phi_{BL} \times [X]_{BL}. \quad (2)$$

Each combination of three equations of the form of equation 2 for different chemical elements should allow calculating the unknowns

TABLE 1. FLUXES OF MATTER FOR THE GANGA AND BRAHMAPUTRA

		Brahmaputra		Ganga	
		Mean	Range	Mean	Range
Himalayan runoff*	(mm/yr)	2100	N.A.	1180	N.A.
Total area	(10^6 km^2)	0.583	N.A.	1.06	N.A.
Himalayan area	(10^6 km^2)	0.145	N.A.	0.176	N.A.
Φ_{SL}†	(10^6 t/yr)	500	400–600	440	330–550
$\Phi_{dissolved}$§	(10^6 t/yr)	41.9	N.D.	43.1	N.D.
$\Phi_{SiO2\ diss}$§	(10^6 t/yr)	4.61	N.D.	3.49	N.D.
Calculated fluxes using Si and Al					
Φ_{Ukn}, Ukn = Quartz	(10^6 t/yr)	165	90–260	160	90–250
Φ_{Ukn}	(10^6 t/yr)	580	240–1380	540	230–1320
Calculated fluxes using Si and Fe					
Φ_{Ukn}, Ukn = Quartz	(10^6 t/yr)	270	160–400	220	120–350
Φ_{Ukn}	(10^6 t/yr)	1100	480–2880	790	330–2200
Total flux and erosion rate					
Φ_{Him}**	(10^6 t/yr)	1120	680–3520	1000	600–2790
Himalayan erosion	(mm/yr)	2.9	1.7–9.0	2.1	1.3–5.9

*Restricted to the Himalayan part of the basin.
†After River Survey Project (1996) and references therein.
§Corrected for the atmospheric contribution (Galy and France-Lanord, 1999).
**The total erosion flux is based on the Al-Si mass balance and the range of values corresponds to the propagation of the uncertainties on the Φ_{SL}, the chemistry of the source, the chemistry of the suspended load, and the chemistry of the unknown flux. Following Sr-Nd isotopic mass-balance, the source rock composition has been chosen as 80% ± 10% High Himalaya Crystalline and 20 ± 10% Lesser Himalaya giving an Al_2O_3/SiO_2 and a Fe_2O_3/SiO_2 of 0.188 ± 0.003 and 0.066 ± 0.002, respectively. For the chemical composition of the unknown flux, we have used 0.120 and 0.044 for Al_2O_3/SiO_2 and Fe_2O_3/SiO_2, respectively. The sensitivity of the calculation to the composition of the three terms in equation (4) is obtained by the propagation of the chemical variability (13%) observed between the two end-members of the unknown material: the bedload and the Siwaliks, and the chemical variability (6%) observed in suspended load.

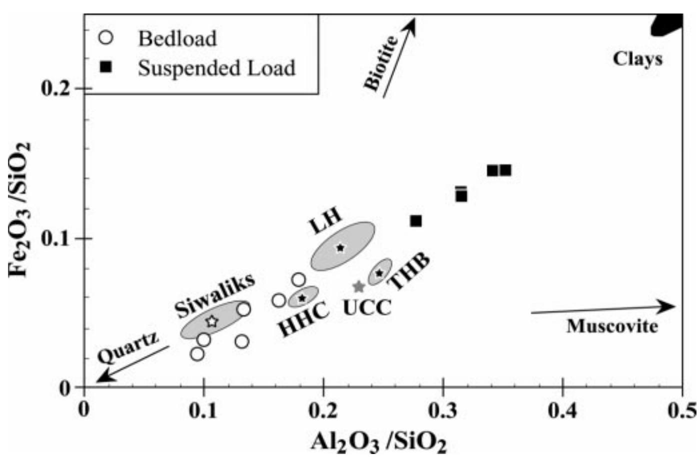

Figure 2. Al_2O_3/SiO_2 versus Fe_2O_3/SiO_2 for Himalayan source rocks (Brouand, 1989; Debon et al., 1986; France-Lanord and Derry, 1997; Pêcher, 1978), Siwaliks formations, and riverine suspended load and bedload (Data Repository; see footnote 1). Stars correspond to average of each Himalayan formation and ellipses indicate their variability. Gray star indicates composition of average upper continental crust (UCC) (Taylor and McLennan, 1995). Linear trend defined by river sediments corresponds to mineralogical sorting. Lower ratios for Siwaliks formations and river bedload indicate increase of quartz proportion with respect to source rocks, while suspended loads are enriched in phyllosilicates and clays. Abbreviations as in Figure 1.

Φ_{Him}, Φ_{FloodP} and Φ_{BL}, provided the average chemical composition of each component is known.

The chemical composition of the Himalayan crust ($[X]_{Him}$) can be assessed from the compositions of the four main geological units in the Ganga-Brahmaputra basin: the Lesser Himalaya, the High Himalaya Crystalline, the Tethyan Sedimentary Series, and the Trans Himalayan Batholith (Fig. 1). We used a database of ~400 analyses of outcrops throughout the range. Although there are large variations

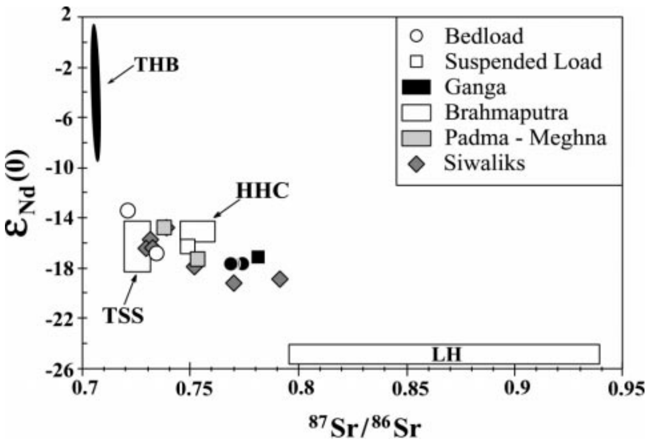

Figure 3. Sr and Nd isotopes compositions of silicate fraction of suspended load and bedload of rivers (Data Repository; see footnote 1; see also Galy et al. [1996, 1999] for methods) compared to fields of major Himalayan formations (Ahmad et al., 2000; Allègre and Ben Othman, 1980; Burg et al., 1998; Debon et al., 1986; France-Lanord et al., 1993; Schärer et al., 1984; Xu et al., 1985 and references therein) and Siwaliks formations. Eroded material stored in foreland basin (Siwaliks) and that carried by Ganga and Brahmaputra Rivers in Bangladesh mainly derives from erosion of High Himalaya Crystalline (HHC). Other abbreviations as in Figure 1.

within each unit, mean compositions are relatively similar to that of the average upper continental crust (Taylor and McLennan, 1995). The units also have intermediate compositions between suspended loads and bedloads. From our database, it would be difficult to estimate the average proportion of carbonate in the Himalaya. Therefore we only use the Si/Al and Si/Fe elemental ratios in the Himalayan source, because they are independent of the proportion of carbonate.

Because the distribution of erosion is heterogeneous over the range (France-Lanord et al., 1993; Galy, 1999; Harris et al., 1998), the mean composition of the eroded flux is not a simple average of these units. We use Sr and Nd isotopic compositions of the silicate fraction of the river sediments to estimate the proportion of the different units in the erosional flux (Fig. 3). The data show that the principal source of silicate phases corresponds to the High Himalaya Crystalline. For the Ganga the slightly lower ϵ_{Nd} indicates that the Lesser Himalaya represents a secondary source. A mixture of 10%–20% of Lesser Himalaya with High Himalaya Crystalline could explain the measured values.

The chemistry of the sediments deposited in the flood plain and the bedload is less well documented. New data on Brahmaputra bank deposits in Assam display the same range of composition as our samples (Singh et al., 2000). Flood-plain sediments can be determined from Siwaliks sediments, which represent a 10 m.y. record of deposition in the Himalayan foreland basin. We use an average composition of the well-studied Suraï Khola section (e.g., Appel et al., 1991). The chemical composition of the modern bedload overlaps those of the Siwaliks, and given the uncertainty, it is not possible to make the distinction between these two components in the mass balance. Hence, we simplify equation 2 by combining Φ_{FloodP} and Φ_{BL} into a single unknown flux (Φ_{Ukn}).

The dissolved flux is well known compared to other fluxes. We use an average composition corrected for atmospheric contribution (Galy and France-Lanord, 1999). The dissolved fluxes of Al and Fe represent <0.1% of the associated suspended load flux. Therefore, we neglect those fluxes and will consider only the dissolved flux of Si. Combining simplified equations of the type in equation 2 for Si, Al, and Fe to eliminate Φ_{Him}, equation 3 accesses the calculation of Φ_{Ukn}:

$$\Phi_{Ukn} = \langle\{\Phi_{Diss} \times [SiO_2]_{Diss} + \Phi_{SL} \times ([SiO_2]_{SL} - [Al_2O_3]_{SL} \times [SiO_2]_{Him}/[Al_2O_3]_{Him})\}\rangle \div \{([Al_2O_3]_{Ukn} \times [SiO_2]_{Him}/[Al_2O_3]_{Him} - [SiO_2]_{Ukn})\}. \quad (3)$$

The total erosion flux of the Himalaya (Φ_{Him}) can then be calculated as a function of Φ_{Ukn} in equation 4:

$$\Phi_{Him} = \Phi_{SL} + \Phi_{Diss} + \Phi_{Ukn}. \quad (4)$$

CALCULATED TOTAL HIMALAYAN EROSION FLUX

The Φ_{Him} values calculated are presented in Table 1 for different compositions of the unknown component. Absolute values of Φ_{Him} are dependent on the measured flux of suspended load. For the purpose of this study it is more important to consider Φ_{Him} relative to Φ_{SL} rather than the absolute value. This budget calculation relies on the quality and the representativeness of the data used to define the chemistry of each component. Other mineralogical data for the suspended load of the Ganga-Brahmaputra are concordant with our sample set, despite sampling periods separated by more than a decade and covering all seasons (Konta, 1985). Chemical compositions, which are estimated from these mineralogical data, are very similar to our results and display the same variability for 15 samples of both rivers. The variability observed in our samples is, therefore, a reasonable natural variability of the chemistry of the suspended load.

In addition, the chemical composition of Φ_{Ukn} also varies between the composition of the sampled bedload and the Siwaliks rocks.

Taking into account the uncertainties on the chemistry of the source rocks, the suspended load, and the unknown components, the Φ_{Him} is 60%–350% higher than Φ_{SL} (Table 1). Despite a large range of values, this simple budget shows that total erosion fluxes from the Himalaya are likely double the measured suspended load fluxes in Bangladesh. A minimum value for Φ_{Ukn} is calculated considering that bedload and flood-plain sediment would be pure quartz. Even with this extreme hypothesis, Φ_{Him} is 20% higher than the measured Φ_{SL}.

IMPLICATIONS

We estimate the total Himalayan erosion to be twice the measured flux of suspended load. The Himalayan erosion is heavily dominated by physical processes, and therefore flood-plain deposition and bedload transport are certainly higher than for other major river systems of the world. However, this case study underlines the importance of bedload transport and flood-plain sedimentation, suggesting that the modern global erosion rate based only on suspended and dissolved discharge of rivers should be reexamined. In addition, our results suggest that comparison between modern erosion rate (inferred from suspended load flux), and long-term erosion rate (deduced from geochronological information, such as Ar-Ar or U-He dating or measurement of cosmogenic-induced isotopes) are hampered by the large uncertainties on bedload transport and flood-plain sedimentation. The geochemical budget of erosion is one way to tackle this problem. It would require a detailed database on suspended load chemistry in order to reduce uncertainty.

For the evolution of the Himalayan range, higher erosion rates reinforce the effect of erosion processes on the unloading and isostatic rebound that control partially the tectonic evolution of the range (Avouac and Burov, 1996). Moreover, higher erosion rates also affect the carbon cycle throughout organic carbon burial, which is directly linked to the magnitude of the particle flux. Because physical erosion enhances the carbon storage in the sedimentary reservoir by the burial of organic matter (France-Lanord and Derry, 1997) and the weathering in the foreland basin (Galy and France-Lanord, 1999), balancing the modern carbon cycle and modeling of climate-tectonic links require a better knowledge of erosion rates in active orogens.

If we look at the result of the mass balance in more detail, a systematic difference appears between the Ganga and the Brahmaputra Rivers. The measured suspended load fluxes (Φ_{SL}) are significantly lower for the Ganga, implying either higher erosion rate in the eastern Himalaya or higher deposition of sediments in the large flood plain of the Ganga. The calculations of Φ_{Him} take into account the flood-plain deposition term and imply that the eastern Himalaya is eroding faster than the western Himalaya (Table 1). This difference must reflect a change in the parameters controlling the erosion within the range, such as lithology, morphology, climate, or the rate of uplift. Although there are no known primary morphologic and lithologic differences between the west and the east areas of the range, there is a clear eastward increase of monsoon precipitation. The difference in runoff between the two rivers illustrates this very clearly (Table 1), and higher precipitation over the eastern Himalaya could explain higher erosion rates in the Brahmaputra basin. This difference in precipitation is inherent in the monsoon system and has likely been a permanent feature for millions of years (Fluteau et al., 1999). The difference in erosion rate should therefore be established over the long term and balanced by higher exhumation rate in the eastern Himalaya. The crystallization age of High Himalayan Leucogranite in the eastern Himalaya is $\sim$10 m.y. younger than in the western Himalaya (Edwards and Harrison, 1997; Wu et al., 1998). This may correspond to a faster erosion of the south flank in that part of the range since the middle Miocene together with a younger age of the onset of the northward collapse of the Tethyan Sedimentary Series (Edwards and Harrison, 1997). More information on modern uplift and erosion rates associated with thermochronological data from the eastern Himalaya is clearly needed.

ACKNOWLEDGMENTS

This work was supported by grants from the Centre National de la Recherche Scientifique (CNRS), Région Lorraine, and the European Union (CNRS Programs PROSE, PNSE, BDI, and TMR N° ERBFMXCT 960046). The collaboration of M.D. Shafiqul Alam from the department of Archeology of Bangladesh and K. Pedoja under the auspices of ''la mission d'Orient'' made sampling in Bangladesh possible. This manuscript was improved by constructive reviews by William Ruddiman and Douglas Burbank. We are grateful to Marc Chaussidon, Nicolas Dauphas, and Lou Derry for many discussions on this study. We also thank Jérome Gaillardet for his stimulating work on chemical mass balance in riverine material. CNRS-INSU contribution 242 and Centre de Recherche Pétrographiques et Géochimiques (CRPG)-CNRS contribution 1486.

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Manuscript received May 22, 2000
Revised manuscript received September 25, 2000
Manuscript accepted October 3, 2000

Printed in USA