Chapter 12
Organic Carbon Cycling During Himalayan Erosion: Processes, Fluxes and Consequences for the Global Carbon Cycle

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Contents

Abstract The net effect of organic carbon cycling during continental erosion depends on the balance between rock-derived organic carbon oxidation and biospheric organic carbon burial in sediments. Himalayan erosion is dominated by

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physical transport and each year up to two billion tons of sediments eroded from the Himalaya are delivered to the Bengal Fan through the Ganga–Brahmaputra (G–B) fluvial system.

We developed a sampling protocol that allows the heterogeneity of the sediment load to be accounted for. In the channel of large rivers, the total organic carbon content (TOC) is variable and decreases towards depth. TOC is positively correlated to Al/Si ratio, which characterizes the mineral and grain size sorting. In the delta of Bangladesh, sediments from Ganga, Brahmaputra and Lower Meghna have similar organic carbon loading.

Coupling Raman Micro-spectroscopy and High Resolution Transmitted Electron Microscopy allows the unambiguous detection and characterization of petrogenic (rock-derived) carbon. Comparison of Himalayan rivers and G–B in Bangladesh indicates that the most graphitised forms are selectively preserved and delivered to the Bay of Bengal. Radiocarbon characterization of sediments along depth profiles yields values for the absolute concentration of petrogenic carbon in rivers sediments. Comparison of Himalayan rocks and G–B sediments in Bangladesh shows that 40% (±10) of the organic carbon contained in the Himalayan rocks is preserved and delivered to the ocean.

The evolution of stable isotopic composition ($\delta^{13}C$) from the outflow of the Himalayan range to the delta of Bangladesh shows that during the Gangetic floodplain transit, more than 50% of organic carbon derived from the Himalaya is oxidized and replaced by organic carbon derived from the floodplain.

The organic carbon loading of recent Bengal Fan sediments is comparable to that of G–B river sediments. Biomarker abundance and $\delta^{13}C$ values show that organic carbon is dominated by terrestrial inputs. The terrestrial organic carbon burial efficiency is thus close to 100%. This strongly contrasts with other large deltaic system on earth, where ~70% of terrestrial organic carbon is oxidized prior to burial. This extreme burial efficiency is sustained by high erosion rate in Himalaya that generates high sedimentation rate and low oxygen availability in the Bay of Bengal.

The balance between biospheric organic carbon burial and petrogenic carbon oxidation indicates a net CO_2 consumption of $3.2 \pm 0.8 \times 10^{11}$ mol/year. Atmospheric CO_2 consumption through organic carbon cycling during Himalayan erosion is thus an order of magnitude higher than the CO_2 consumption through silicate weathering in the Himalayan basin (6.4×10^{10} mol/year). Efficient burial of organic carbon is a characteristic of high physical erosion typical of active orogenic systems. Enhanced physical erosion and consequent organic carbon burial buffer atmospheric CO_2 thereby exerting a negative feedback on the long-term climate.

Keywords Erosional processes • Fate of soil organic carbon • Carbon burial • Sedimentation • Fluvial transport

Abbreviations

ADCP	Acoustic Doppler current profiler
G–B	Ganga–Brahmaputra
HRTEM	High Resolution Transmitted Electron Microscopy
OC	Organic carbon
RM	Raman microspectroscopy
TOC	Total organic carbon content
WARPO	Water Resources Planning Organization

12.1 Introduction

Over geologic timescales, atmospheric CO_2 concentration is controlled by the balance between processes liberating and consuming CO_2. The main sources of CO_2 are: (1) volcanism (e.g. Berner 2003; Marty and Tolstikhin 1998), (2) metamorphic decarbonation (e.g. Becker et al. 2008; Evans et al. 2008; Perrier et al. 2009), and (3) oxidation of organic carbon contained in rocks (e.g. Berner 2003; Hayes and Waldbauer 2006). On the other hand, there are two main CO_2 sinks: (1) silicate weathering followed by carbonate precipitation in the ocean (Ebelmen 1845; Rubey 1951; Garrels et al. 1976; Walker et al. 1981), and (2) organic carbon burial in marine sediments (e.g. Berner 2003; Hayes and Waldbauer 2006; Galy et al. 2007). Silicate weathering retained most of the attention during the past three decades or so. Nevertheless, since the emergence of higher (vascular) plants on the continents, organic carbon cycling (i.e. burial and oxidation) likely exerted at least at some periods of Earth history a dominant control on atmospheric CO_2 content. Organic carbon burial and oxidation thus play a major role in the long-term climate regulation and are intimately linked to the development and maintenance of life on earth. Physical erosion of the continents leads to the export of biospheric organic carbon from the continent to the ocean. But it also promotes liberation, transport and oxidation of refractory organic carbon contained in rocks. Moreover, extensive oxidation of organic carbon in the ocean prior to its burial has been documented (e.g. Ludwig et al. 1996; Hedges et al. 1997; Schlünz and Schneider 2000; Burdige 2005; Burdige 2007). The net effect of organic carbon cycling during continental erosion thus depends on the balance between rock-derived organic carbon (petrogenic organic carbon) oxidation and biospheric organic carbon burial in sediments. Hence, determining the net effect of organic carbon cycling during continental erosion (i.e. carbon source or sink) requires to determine not only the flux of organic carbon exported by rivers to the ocean but also its composition (e.g. biospheric vs. petrogenic) as well as its fate in the ocean.

Since the 90s, small mountainous catchments have been the focus of many studies because they were considered the most efficient pathways of terrestrial OC export and burial, resulting in a disproportionately large influence on the OC cycle (Milliman and Syvitski 1992; Scott et al. 2006; Hilton et al. 2008a, b). Carbon cycling in these small mountainous rivers stands in sharp contrast to many large river basins with extensive floodplains, such as the Amazon basin. The latter typically act as "reactors", efficiently recycling labile terrestrial organic material and associated nutrients, and resulting in extensive loss of organic carbon prior to its escape to the marine sedimentary sink (e.g. Mayorga et al. 2005). However, hitherto very little was known about the flux and fate of petrogenic organic carbon and the factors controlling the preservation of terrestrial biospheric organic carbon in the oceanic system. An early study of organic carbon burial over the Cenozoic in the Bengal fan turbiditic system, the sedimentary repository of Himalayan erosion, suggested that organic carbon cycling during Himalayan erosion has been a globally significant atmospheric CO_2 sink (France-Lanord and Derry 1997). Contrary to the early 90s hypothesis that Himalayan erosion was acting as a CO_2 consumer through enhanced silicate weathering (e.g. Raymo and Ruddiman 1992), this suggests that organic carbon cycling has been the dominant process able to consume atmospheric CO_2. During the past few years, we have thus been conducting a detailed study of organic carbon cycling associated to current erosion of Himalaya and sedimentary transfer in the Ganga–Brahmaputra river system (Galy et al. 2007; Galy et al. 2008a, b). Here we present a synthesis of these studies in the scope of the global organic carbon cycle. We first explore the different processes affecting organic carbon composition and flux in the Ganga–Brahmaputra system (Fig. 12.1). Then we address the question of the fate of organic carbon delivered by the G–B system to the Bay of Bengal.

12.2 Fluvial Transport in the G–B System

In large rivers, river detritus experience strong hydrodynamic forcing during transport, which results in mineral and grain size sorting. These sorting and mixing processes are in turn responsible for very large sediment heterogeneity in the river channel. Quartz and other coarse, rounded and dense particles tend to increase with water depth and in the bedload, whereas fine and tabular phyllosilicates concentrate towards the surface and are more rapidly transported downstream. The organic carbon content of the river sediments is also variable. In the river channel, total organic carbon (TOC) concentrations are depth-dependent with surface suspended particles having the highest values and bed sediments the lowest (Fig. 12.2). Taking into account the heterogeneity of the detrital load is thus essential for deriving accurate flux estimates as well as to accurately define the composition of the material delivered by rivers to the ocean. Consequently, we have applied a sampling protocol to develop a more representative picture of sediment transport in river systems. This approach, developed during detailed surveys of the Ganga–Brahmaputra and also successfully applied to the Amazon system, involves collection of suspended and bed sediments along vertical depth profiles from the surface

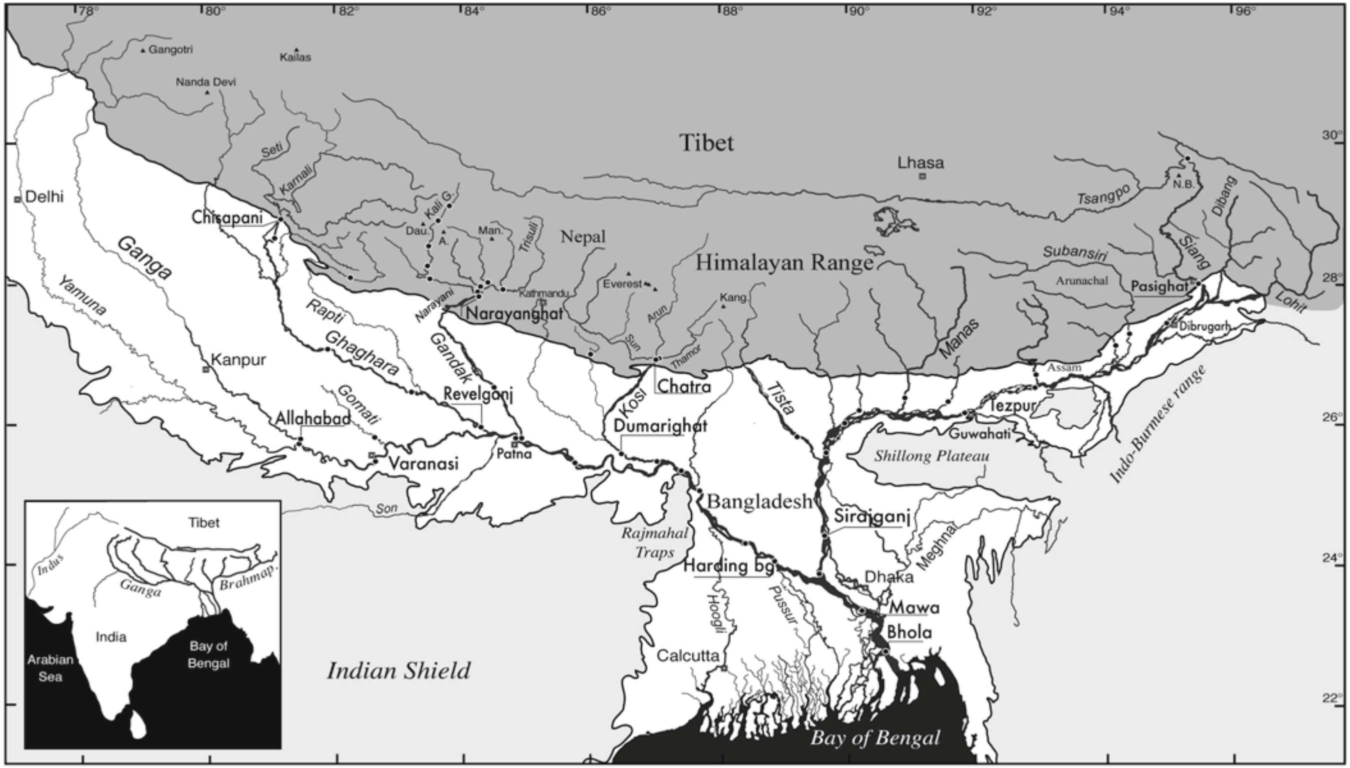

Fig. 12.1 Map of the Ganga–Brahmaputra basin showing the different physiographic units and the position of the sampling location (*black dots*)

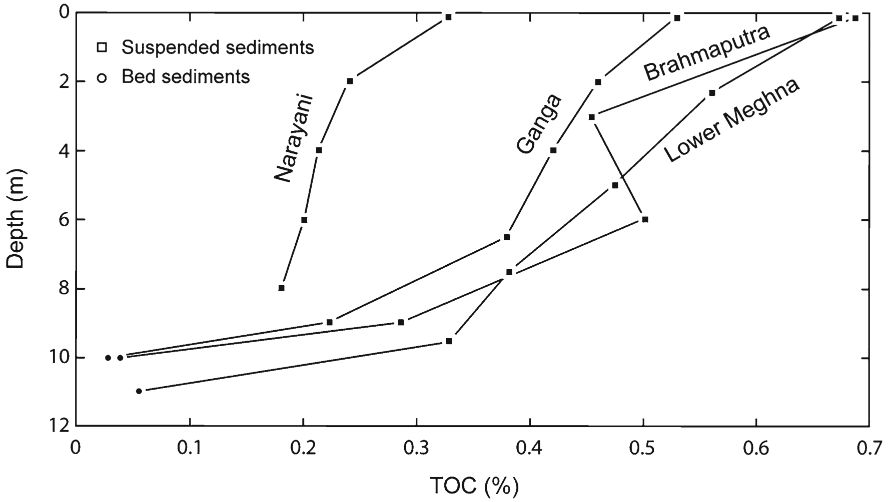

Fig. 12.2 Evolution of TOC in river sediments with sampling depth. Floodplain rivers (Ganga, Brahmaputra and Lower Meghna) as well as a large Himalayan river (Narayani) show a progressive decrease of the TOC from the surface suspended sediment to the bed sediment

to the bed of the river, coupled with flow velocity measurements via an Acoustic Doppler Current Profiler (ADCP), enabling computation of the mean composition of the sedimentary flux.

12.3 Control of Organic Carbon Content by Sediment Properties

The simultaneous and monotonic evolution of organic carbon content and sediment properties from surface suspended sediments to bed sediments suggests that organic carbon content is (1) primarily controlled by sediment properties, and/or (2) affected by mixing and sorting processes in the same way as mineral particles. In G–B river sediments, organic carbon appears to be present under two different species: organo-mineral associations and free organic particles. Detailed observations of suspended sediments collected along depth profiles indicates that free organic particles tend to be segregated as a function of their size, in a similar way as minerals: coarse organic debris tend to concentrate in coarse sediments while fine grained sediments contain mostly tiny free organic particles. While we found several good correlations between sediment properties and TOC, the most robust relationship is obtained with Al/Si ratio (Fig. 12.3). This ratio represents the bulk mineralogical composition of the sediments with low values indicating high proportion of quartz and high values indicating high proportions of micas and clays. The positive linear relationship defined by TOC and Al/Si thus indicates a control of the mineralogy on the formation of organo-mineral

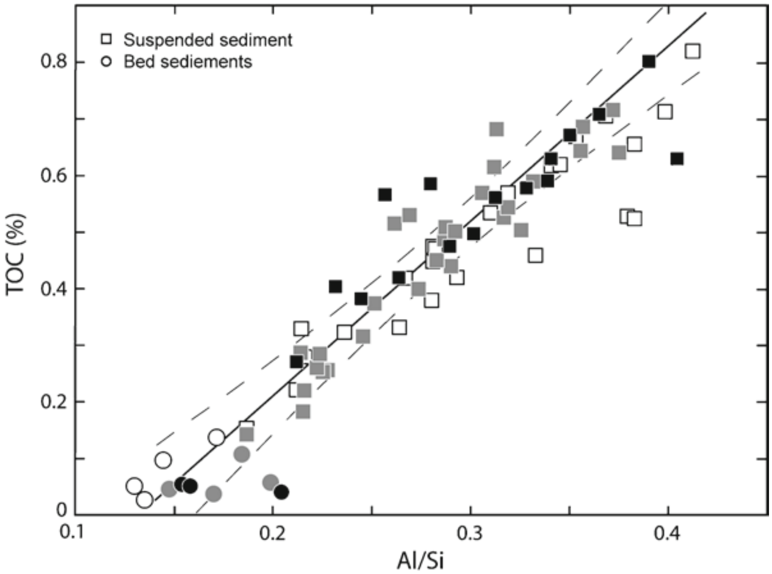

Fig. 12.3 TOC of the Brahmaputra (*grey symbols*), Ganga (*open symbols*) and Lower Meghna (*black symbols*) sediments as a function of Al/Si. Sediments from the three rivers define similar positive trend between TOC and Al/Si, indicative of similar OC loadings. Best fit and 95% confidence interval are shown for Lower Meghna sediments

associations. Microscopic observations of the sediments reveal the presence of organo-mineral aggregates. The formation of these aggregates is controlled by multiple physical parameters such as particle charge density, chemical composition (nature of exchangeable cation), crystalline structure, size and shape (e.g. Sollins et al. 1996). Specifically, our study indicates a greater affinity of organic carbon with clays and micas than with quartz, feldspar and dense minerals.

Al/Si ratio being dependent on both mineralogy and grain size it appears to adequately catch the processes controlling the repartition of both free organic particles and mineral bounded organic carbon. In the G–B system Al/Si ratio also has the advantage of being a conservative tracer because Si can be considered as an insoluble element (dissolved Si flux is three orders of magnitude lower than particulate Si flux). Al/Si ratio thus provides an efficient normalization parameter, allowing the definition of the organic carbon loading for each river and sampling location.

12.4 Evolution of Organic Carbon Loading During Transport

The comparison of different rivers and positions in the basin (high mountains, base of the range, delta) indicates that at the first order organic carbon loading varies little in the G–B system. Detailed study of the large Himalayan rivers at the base of the range however indicates some variability of the organic carbon loading.

This variability can be attributed to a complex combination of factors such as geomorphology, vegetation distribution, soil types and human activities. It is important to note that the main rivers in the plain – the Ganga and Brahmaputra – are characterized by very similar organic carbon loading (Fig. 12.3). The Lower Meghna – the mixing of Ganga and Brahmaputra in Bangladesh – also has very similar organic carbon loading (Fig. 12.3). Organic carbon loading in the delta furthermore corresponds to the average of the organic carbon loading of the large rivers at the base of the Himalayan range. Altogether these observations indicate that the exportation of organic carbon is primarily controlled by the capacity to export sediments out of the basin rather than by intrinsic parameters such as primary production.

12.5 Petrogenic Carbon: Detection and Characterization

The Himalayan range is almost exclusively composed of metamorphic rocks. The different Himalayan lithologies therefore contain some organic carbon that has been transformed – graphitized – during the metamorphic process. This graphitization consists in a chemical and structural transformation of the organic carbon leading to crystallized carbonaceous mater. With increasing temperature the graphitization is more intense and the final structure of carbonaceous mater closer to that of the graphite. Finally, when the metamorphic temperature reaches 550 degrees (or more) the graphitization process is complete and the organic carbon is transformed into graphite.

During erosion, this crystallized carbonaceous mater – hereafter referred to as petrogenic carbon – is liberated, transported by rivers and eventually oxidized or buried in marine sediments. Burial of petrogenic carbon in marine sediments does not represent a consumption of atmospheric CO_2 but a simple recycling of reduced carbon. On the other hand, oxidation of petrogenic carbon is a net source of CO_2 for the atmosphere. Evaluating the flux and fate of petrogenic carbon during erosion is therefore crucial to characterize the role of erosion in the global C cycle.

During erosion and fluvial transport, some biospheric organic carbon is admixed to the mineral matrix and petrogenic carbon. The total organic carbon content of river sediments hence account for both petrogenic and biospheric organic carbon. During the last decade or so several techniques have been developed to detect and quantify petrogenic carbon in river and marine sediments. However, these methods are based on the refractory character of the petrogenic carbon, which is not unique to petrogenic carbon. We therefore developed a new method allowing specifically detecting and characterizing the structure of petrogenic carbon (Galy et al. 2008a). This method consists in coupling Raman Micro-spectroscopy (RM) and High Resolution Transmitted Electron Microscopy (HRTEM). RM permits to characterize the microstructure of carbonaceous particles, while HRTEM allows the characterization of its nanostructure (Beyssac et al. 2002). Thanks to minimal sample preparation (hence bias) and great specificity for crystallized carbonaceous matter,

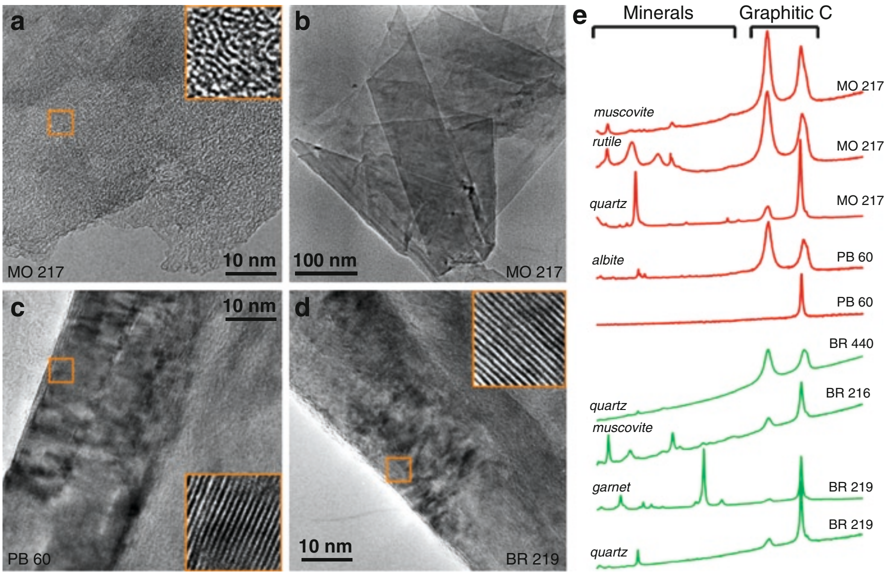

Fig. 12.4 Raman micro-spectroscopy and TEM characterization of petrogenic carbon in G–B river sediments. (**a**) TEM image of disordered and microporous petrogenic carbon in Narayani bed load. (**b**) TEM image of graphitic C in Narayani bed load. (**c**) Low magnification (LM) image of a graphite particle in Narayani suspended load. (**d**) TEM image of graphitic petrogenic carbon in Lower Meghna bed load. (**e**) Selection of representative Raman spectra from Himalayan rivers (*top panel*) and Lower Meghna (*lower panel*). These spectra were obtained from both individual petrogenic carbon particles (no mineral contribution in the spectrum) and petrogenic carbon inclusions/aggregates within minerals (mineral contribution in the spectrum as depicted)

these two methods allow the unambiguous detection and characterization of petrogenic carbon.

Using RM, petrogenic carbon was identified in various forms: (1) discrete “free” particles from a few to several tens of μm size, (2) inclusions within quartz, calcite and metamorphic minerals, (3) aggregates with minerals, mostly micas. RM shows a large structural variety of petrogenic carbon in bed and suspended loads from Himalayan rivers (Fig. 12.4). This is confirmed by TEM investigations, which reveal the presence of turbostratic disordered petrogenic carbon to perfectly crystalline graphite in these samples (Fig. 12.4). The structural variety of petrogenic carbon reflects the zoning of metamorphism in the source rocks of the Himalayan range (e.g. Beyssac et al. 2004) from low- to high-grade metamorphism. Similar structural variety is observed within the vertical depth profiles collected at the outflow of the range and in Bangladesh, although the less ordered petrogenic carbon is rarely observed. This is particularly true for the most distal sampling location in Bangladesh, where highly graphitic petrogenic carbon is largely dominant (Fig. 12.4). This implies that the less ordered petrogenic carbon is specifically oxidised during erosion and fluvial transport, while the most graphitised forms are selectively preserved and delivered to the Bay of Bengal.

12.6 Petrogenic Carbon: Quantification

Besides its detection and characterization, it is crucial to obtain a quantification of the petrogenic carbon in river sediments. We recently developed the use of vertical depth profile sampling to distinguish petrogenic and biospheric organic carbon components in river sediments on the basis of bulk ^{14}C measurements (Galy et al. 2008a). Our approach relies on a binary mixing model, which assumes the presence of two distinct populations of organic carbon in river sediments: (1) petrogenic carbon derived from rock erosion, and (2) biospheric organic carbon derived from vegetation, soil and autotrophic production in the river.

The petrogenic carbon is by definition ^{14}C free, while the biospheric organic carbon has a variable age but always contains some ^{14}C. Radiocarbon characterization of sediments along depth profiles that reflect the continuum created by sorting and mixing processes during fluvial transport yields values for the absolute concentration of petrogenic carbon in rivers sediments (Fig. 12.5).

Large Transhimalayan rivers sampled at the outflow of the range appear to carry variable amounts of petrogenic carbon. We estimate a petrogenic carbon content of

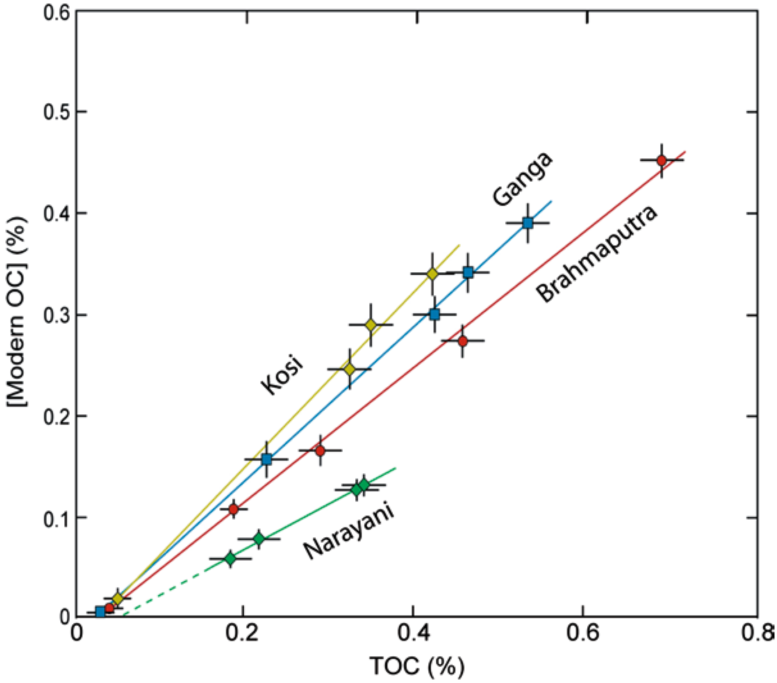

Fig. 12.5 Radiocarbon measurements in depth profile sediments collected in the Ganga–Brahmaputra system. This type of diagram shows the product of the radiocarbon composition by the TOC (or absolute modern organic carbon content) as a function of TOC. It allows calculating the absolute petrogenic carbon content for each depth profile, which is given by the intercept of the trends with the x axis

0.05% and 0.03% for the Narayani and Kosi, respectively (Fig. 12.5). This variability likely derives from intrinsic characteristics of the drainage basins. Our data consistently indicate a petrogenic carbon content of 0.02–0.03% in the sediments exported by the Brahmaputra and the Ganges sampled close to their mouth in the Bangladesh delta (Fig. 12.5).

To evaluate the fate of petrogenic carbon during erosion and fluvial transport we need to compare these concentrations to the initial mean petrogenic carbon content of the Himalayan rocks. The later has been estimated to be 0.05–0.08%, on the basis of (1) individual rock samples, and (2) composite gravels extracted from the bed of Himalayan rivers (France-Lanord and Derry 1997; Aucour et al. 2006; Galy et al. 2007b; Galy et al. 2008b). Based on these figures, at least 30% (40 ± 10) of the organic carbon contained in the Himalayan rocks appears to be preserved and delivered to the Indian Ocean.

12.7 Fate of Biospheric Organic Carbon During Fluvial Transport

Stable carbon isotopes ($\delta^{13}C$) have long been used as a biogeochemical tool to derive information on the source of organic carbon due to isotope contrasts resulting from photosynthetic C fixation mechanisms employed by different plant types (e.g. Deines 1980; Collister et al. 1994). In river sediments, the $\delta^{13}C$ of bulk organic carbon is a proxy for its provenance, because river algae, C3 and C4 plants have distinct isotope compositions. The geographic variations in proportions of C3 and C4 vegetation in the G–B drainage basin are substantial, rendering this a potentially valuable tracer, although petrogenic carbon contributions can muddy the waters, so as to speak, because of its variable and intermediate isotopic composition.

In large rivers at the outflow of the Himalayan Mountains, bulk organic carbon $\delta^{13}C$ values range between −21.2‰ and −25.7‰. Most of this variability is due to isotopic heterogeneity in organic carbon-poor bed sediments and reflects contributions from petrogenic carbon with variable $\delta^{13}C$ in the Himalayan bedrocks (Galy et al. 2008b). In suspended sediments, the $\delta^{13}C$ values display a narrower range with a mean value of ~−24‰. This isotope signature suggests only minor inputs of algal matter (which is typically significantly more ^{13}C-depleted), consistent with high sediment loads and very dynamic transport that inhibit primary production within the Himalayan rivers. In addition, this mean $\delta^{13}C$ value reveals that biospheric organic carbon is largely dominated by C3 plant inputs, consistent with vegetation patterns in the Himalayan region where forest and high altitude ecosystems dominate (e.g., Blasco et al. 1996; Dobremez et al. 1978). In summary, suspended sediments exiting the Himalayan range predominantly represent a binary mixture of organic carbon, with a portion of this comprised of petrogenic carbon from sedimentary rock erosion and the remainder from C3 vegetation that grows at lower elevations within the Himalayan range.

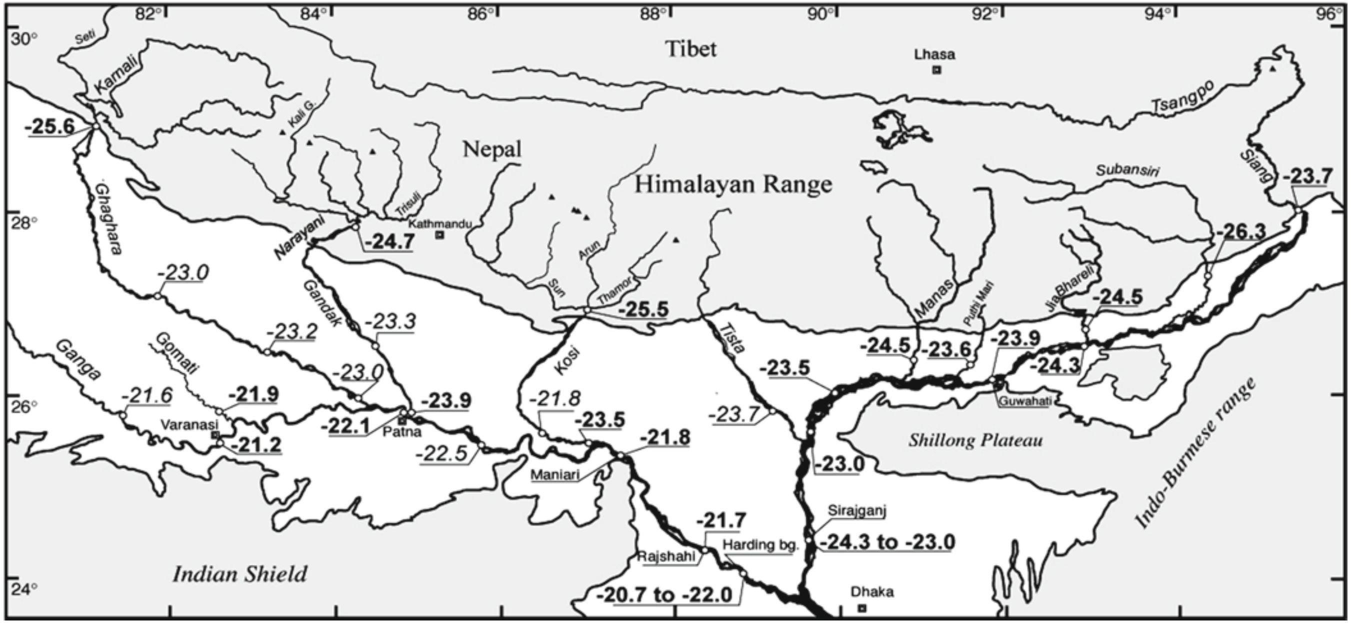

Fig. 12.6 Simplified map of the G–B system showing the evolution of bulk organic carbon δ^{13}C values from the Himalayan range to the delta. Bold numbers represent δ^{13}C values of surface suspended sediments; italic numbers represent δ^{13}C values of fine-grained bank sediments used as analogous of suspended sediments

In the floodplain, Ganga and Brahmaputra suspended sediments have distinct $\delta^{13}C$ values, ~−21‰ and −23.5‰ respectively (Fig. 12.6). The isotope composition of organic carbon in Brahmaputra suspended sediments is comparable to that of the Himalayan rivers at the outflow of the range implying that inputs are similarly dominated by C3 plants (Fig. 12.6). However, organic carbon in lower Ganga suspended sediments has $\delta^{13}C$ values that are on average 3‰ higher than that of Himalayan rivers suspended sediments (Fig. 12.6). This isotopic offset is interpreted as a consequence of significant contributions from ^{13}C-enriched C4-plant organic carbon to the Ganga suspended sediments. As the organic carbon loading in suspended sediments is similar at the outflow of the range and in the floodplain, the $\delta^{13}C$ shift is considered to reflect removal, and subsequent replacement of C3-derived organic carbon with C4 plant organic carbon during transit through the Ganga floodplain (Keil et al. 1997; Galy et al. 2008).

In the Brahmaputra floodplain, C3 plants dominate the vegetation. Hence, while this “loss-and-replacement” process may also be operative, there is insufficient isotope contrast in bulk $\delta^{13}C$ values between Himalayan and Brahmaputra floodplain vegetation to establish whether or not this is the case. While it is certainly plausible that similar processes occur along the course of the Brahmaputra River, there are differences other than vegetation type that may influence the efficacy of organic carbon turnover in the floodplain. Notably, the clay mineralogy of soils within the Ganga and Brahmaputra is quite distinct, with the former being dominated by smectite and the latter by illite. This difference manifests itself in mineral surface area measurements whereby smectite-rich sediments have high specific surface areas compared to those containing illite. The role of expandable clays as templates for organic matter attachment and transformation in soils and sediments is well known, and hence the higher proportion of these clays in the Ganga may be an important factor in dictating the exchange of organic carbon derived from different vegetation sources (e.g., Satterberg et al. 2003). Other parameters likely to limit organic carbon replacement in the Brahmaputra floodplain are the mode of fluvial transport and the size of the floodplain. While the Ganga in the plain is a meandering river and has a very long course, the Brahmaputra river is a braided river and has a much shorter course in its narrow floodplain. These geomorphologic differences further support a lower extent of organic carbon replacement in the Brahmaputra than in the Ganga floodplain.

12.8 Flux of Biospheric Carbon Delivered to the Ocean

A consequence of the huge variability of TOC along depth profiles is that estimates of organic carbon fluxes based on surface suspended sediment data are overestimated. Thus, assessing the organic carbon flux requires the mean sediment composition transported by the river to be calculated. Thanks to our sampling protocol coupling depth profiling and ADCP current profiling, the integrated suspended sediment TOC can be estimated by integrating TOC gradient, sediment concentration and flow velocity over the whole river depth. For the Lower Meghna prior to its discharge into the Bay of Bengal (Fig. 12.1) we calculated an integrated TOC of 0.41% ± 0.04%. In comparison, bed sediments have low TOC with an average value of 0.05%. Furthermore, based on radiocarbon measurements, we previously estimated that both bed and suspended sediments delivered to the Bay of Bengal contain 0.02–0.03% of petrogenic carbon. Hence the biospheric organic carbon content in mean suspended and bed sediments of the Lower Meghna is respectively 0.39% ± 0.04% and ca. 0.025%.

Suspended sediment fluxes have been measured for the Ganga and the Brahmaputra and the average total flux is around 1.15×10^9 t/year (RSP 1996). The flux of bed sediment is not directly measured but geochemical mass balance implies that bed sediment flux plus floodplain sequestration are almost equal to the suspended sediment flux (Galy and France-Lanord 2001). Taking into account these sediment fluxes, we estimate that the G–B system delivers $3.9 \pm 0.5 \times 10^{11}$ mol/year of biospheric organic carbon to the Bay of Bengal.

12.8.1 Organic Carbon Burial Efficiency in the Bengal Fan

The G–B river system supplies sediment to the Bengal Fan, Earth's largest active sedimentary system. Over the last glacial-interglacial cycle, the sediment source has remained stable and is largely dominated by Himalayan inputs (Pierson-Wickmann et al. 2001; Galy et al. 2008c). As in the rivers, characteristics of Fan sediments (grain size and mineralogy) are highly variable due to sorting during the transport within the depositional system. Nevertheless, while TOC contents are also variable, as for the river sediments they are tightly correlated with Al/Si, and thus a linear function of the proportion of clays and fine-grained minerals.

Importantly, the relationship between TOC and Al/Si defined by Bengal Fan sediments is statistically identical to that of the G–B river sediments (Fig. 12.7). This relationship implies an equivalent level of organic carbon loading in G–B river sediments and in modern Bengal Fan sediments. Several biomarker and isotope studies have shown that the organic carbon in both modern and ancient Bengal Fan sediments is overwhelmingly dominated by terrestrial inputs with negligible marine organic carbon (Cochran et al. 1989; Poynter and Eglinton 1990; Meyers and Dickens 1992; France-Lanord and Derry 1994; Freeman and Colarusso 2001; Galy et al. 2007; Galy et al. 2008c). Together, these observations imply that terrestrial organic carbon preservation in Bengal Fan sediments is exceptionally high, with the proportion of organic carbon exported by the river that is buried in fan sediments (the burial efficiency) approaching 100%! Although high terrestrial organic carbon export efficiencies have been reported for small mountainous rivers (e.g., Goni et al. 2006), this situation stands in sharp contrast with other large deltaic systems such as those of the Amazon and Mississippi rivers where terrestrial OC burial efficiencies typically do not exceed 30% (e.g. Burdige 2005; Burdige 2007; Hedges et al. 1997).

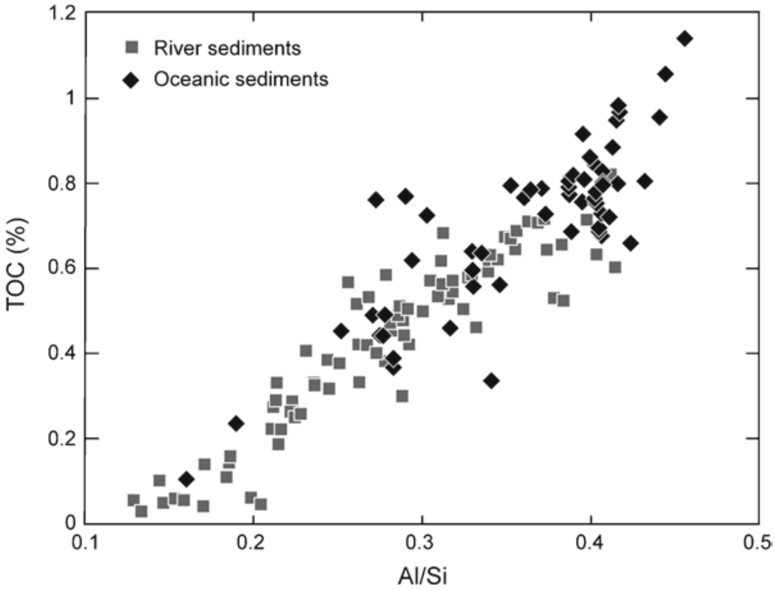

Fig. 12.7 TOC of the Bengal Fan sediments (*black diamond*) as a function of Al/Si with best fit and 95% confidence interval. Fan sediments define a trend comparable to that defined by river sediments (*grey squares*), suggesting they have similar organic carbon loadings

Very high organic carbon burial efficiency in the Bengal Fan likely derives from the transport dynamic, with rapid sediment accumulation on the delta shelf (up to 30 cm/year (Suckow et al. 2001). In shallow-water, where organic carbon oxidation is theoretically most efficient, organic carbon is protected from oxidation by quick burial under a thick layer of fresh sediments. Typical O_2 penetration depth in such sediments is only a few centimeters (Cai and Sayles 1996), i.e. the same order of magnitude as the Bengal shelf annual accumulation. Therefore, organic carbon exposure time to O_2 is only few years or so, insufficient for effective organic carbon oxidation. Sediments are finally transferred to the deep-water zone by turbiditic current and deposited in channel-levee systems. Identical organic carbon loading in the shelf, active channel-levee and mid-deep fan sediments indicates that organic carbon oxidation during sediment transfer from shelf to deep-ocean is negligible. In addition, river discharge and precipitation are responsible for a negative salinity anomaly and maintain stratified waters in the Bay of Bengal (Berner et al. 2003; Broecker et al. 1980). With high productivity in surface water sustained by high nutrient flux delivered by the G–B, the stratification of the Bay of Bengal waters favors an intense respiration of marine organic carbon in the surface waters. This process consumes O_2 and generates an extended O_2 minimum zone and generally low O_2 concentrations in the Bay of Bengal (Berner et al. 2003; Broecker et al. 1980). In Bengal Fan sediments, terrestrial organic carbon oxidation is thus limited by both short exposure to and low availability of O_2.

12.9 Role of Himalayan Erosion in the Global Carbon Cycle

We can finally evaluate the role of Himalayan erosion in the long term global carbon cycle by comparing the extent of the different process consuming or producing CO_2. We estimated that the G–B system delivers $3.9 \pm 0.5 \times 10^{11}$ mol/year of biospheric organic carbon to the Bay of Bengal. Because nearly 100% of the terrestrial organic carbon delivered to the Bay of Bengal is actually buried in Bengal fan sediments, this flux represents the atmospheric CO_2 consumption associated with biospheric organic carbon export and burial during Himalayan erosion.

On the other hand, according to the difference in petrogenic carbon between the Himalayan rocks and river sediments delivered to the Bengal fan, we estimate that Himalayan erosion generates a petrogenic carbon oxidation flux of $7 \pm 3 \times 10^{10}$ mol/year. The balance between biospheric organic carbon burial and petrogenic carbon oxidation finally indicates a net CO_2 consumption of $3.2 \pm 0.8 \times 10^{11}$ mol/year. Atmospheric CO_2 consumption through organic carbon cycling during Himalayan erosion is thus an order of magnitude higher than the CO_2 consumption through silicate weathering (coupled with subsequent carbonate precipitation) in Himalaya (6.4×10^{10} mol/year (Galy and France-Lanord 1999)). Although metamorphic outgassing represents a potentially significant source of CO_2 in Himalaya, the net effect of Himalayan erosion is to consume atmospheric CO_2, mostly through organic carbon export and burial. The efficiency of this process appears to be mostly determined by the extent of organic carbon preservation in the marine system, which is enhanced by intense orogenesis and subsequent rapid physical erosion and sediment export. The creation of new, tectonically active mountain ranges therefore acts as a driver of the global carbon cycle, hence long-term climate, through enhanced organic carbon cycling and corresponding atmospheric CO_2 consumption.

12.10 Conclusion

The Himalayan erosion generates one of the most intense physical erosion flux of the planet. The consequence is that the continental transfer to the ocean is remarkable by its particle flux. During transport in the floodplain, particle flux fixes and carries organic carbon derived from soil degradation. In spite of the relatively modest organic carbon loading of these sediments, the rapid accumulation in the ocean and relatively anoxic conditions in the Bay of Bengal concur to protect organic carbon from decay during transport. Comparatively, silicate-weathering uptake of CO_2 appears modest. This is in part linked to the lithological composition of the Himalaya that contains mostly metamorphosed recycled sediment and are therefore silicate crust already depleted in mobile elements such as Ca and Mg. As a consequence, the characteristic of the Himalayan orogeny is to promote an erosion cycle that impact the carbon cycle mostly through the fixation and burial of recent organic carbon rather than throughout the silicate weathering-biogenic carbonate precipitation pathway.

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