

Continental erosion and CO₂ uptake. Inferences from the Himalayan system

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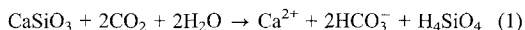
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Continental erosion via silicate weathering or organic carbon erosion/burial is considered has a first order control on long term changes in the level of CO₂ in the atmosphere and thereby on climatic changes. While the basic concepts of these processes are well-known, the effectiveness of the different reactions involved remains underconstrained, and recording their importance in the past or even on the modern system is difficult. The controls on erosion and weathering are tightly linked to climatic conditions such as temperature and precipitation leading to complex feedbacks (Walker *et al.*, 1981; Berner, 1995). Tectonic processes may also be important as orogenic belts are preferential places for erosion. At the global scale, attempts have been made to use the marine limestone record of Sr or C isotopic composition to decipher the fluxes of silicate weathering or organic carbon burial in the past. During the Cenozoic, the global cooling of climate roughly parallels the rise in seawater Sr isotopic ratio, leading to the hypothesis that enhanced silicate weathering increased both consumption of CO₂ and the riverine flux of Sr (Raymo and Ruddiman, 1992). By studying Himalayan erosion in both the modern river system and the erosion record in synorogenic sedimentary basins we can examine the role of several processes which affect the CO₂ budget, and their relationship with seawater tracers.

Silicate weathering and CO₂ uptake. The weathering of silicate rocks on the continental surface consumes atmospheric CO₂ to produce alkalinity as schematically represented by the classic 'Urey reactions':

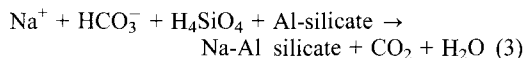


In order to withdraw CO₂ from the atmosphere-ocean system over the long term, the alkalinity transported by river must be precipitated as carbonate in the ocean. The reverse of reaction (1) will release half of the CO₂ balanced by silicate alkalinity. The other half will be stored in the sedimentary reservoir as

carbonate:



Weathering in the Himalayan is not a particularly efficient system for uptake of CO₂ for two reasons. First, Himalayan silicates are mostly alkaline, and in order to precipitate the alkalinity associated with Na⁺ and K⁺, these cations must be exchanged with Ca²⁺ prior to precipitation as calcite. The exchange of Na and K for Ca and Mg adsorbed on detrital clays can occur in estuarine zone or in the continental shelf but Na and K are also involved in reverse weathering reactions that produce secondary silicates (clays, feldspars or zeolites):



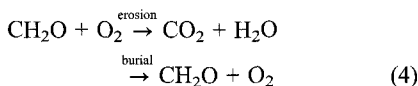
In this case all CO₂ consumed during the Na-silicate weathering reaction is finally returned to the atmosphere-ocean system. Because most Himalayan silicate alkalinity is in the form of Na and K, a large part of the reacted CO₂ ultimately returns to the atmosphere. Second, the intensity of silicate weathering in Himalaya is low. Despite creation of high surface area by physical processes such as glaciation or landsliding, detrital loads are transported fast enough to prevent significant alteration. This is illustrated by the fact that 5–8% of the detrital load in the modern Ganges is carbonate. While high levels of precipitation are usually considered to enhance weathering, one of the important effects of the monsoon regime is to flush out the disaggregated material very rapidly. This effect is particularly clear when comparing the Ganges, whose basin receives 1 to 3 m/yr precipitation, with the Brahmaputra basin which receives 3 to 6 m/yr. The smectite and kaolinite proportion of clays of the Ganges is *c.* 60% whereas for the Brahmaputra it is less than 20%. Similarly, the dissolved flux of the Ganges is *c.* 9% of the dissolved + particulate flux, while it is *c.* 3% for the Brahmaputra.

Based on the dissolved chemistry of the modern Ganges and Brahmaputra, the flux of silicate alkalinity is $c. 2.7 \times 10^{11}$ mol/yr. Assuming that 20% of K and 30% of Na are exchanged for Ca^{2+} , the modern effective CO_2 uptake by the Himalayan erosion would be around 6.4×10^{10} mol/yr which is rather modest at the global scale. The past silicate alkalinity flux can only be evaluated from the sedimentary record. The Bengal fan provides data on weathering intensity in detrital sediments from the Himalaya accumulated since the early Miocene. They show that weathering has been variable in the past with a period of more intense weathering between 7 and 1 Ma. This period is however likely one of lower total erosional flux, and Sr isotopic budget of seawater precludes any significant increase of the Himalayan silicate alkalinity flux of during that period.

Silicate weathering and seawater Sr record. The Sr oceanic budget is governed by both the riverine flux and the hydrothermal activity at ocean spreading sites. Assuming that one is able to constrain the hydrothermal flux of Sr in the ocean, the Sr isotope composition recorded in limestone can be used to monitor the past riverine flux of Sr, hence the intensity of silicate weathering and CO_2 consumption. However, both the riverine Sr flux and its isotopic composition are variable and influence the oceanic budget.

Himalayan rivers have remarkably high [Sr] and $^{87}\text{Sr}/^{86}\text{Sr}$ compared to other rivers in the world (Palmer and Edmond, 1992). Due to this unusual combination they have a very strong influence on the oceanic budget of Sr and it is likely that a large part of the rise of Sr isotopic composition of the ocean since 40 Ma is related to the Himalayan orogeny. The signature of dissolved riverine Sr results of the redistribution during recent metamorphism of radiogenic Sr, which is abundant in these old crustal formations, into easily weatherable minerals such as feldspars but also carbonates. The Himalayan riverine flux has a strong impact on the ^{87}Sr increase in the ocean, while its silicate alkalinity flux is modest. This illustrates that it is not possible to derive in a simple way weathering or erosion intensity from the marine Sr record.

Organic carbon burial. Continental erosion also affects the CO_2 budget by erosion and burial of organic carbon (C_{org}):



The effect of the Himalayan erosion can be estimated from the difference between Himalayan source rocks ($[\text{C}_{\text{org}}] = 0.1$ wt.%) and the final buried sediment in the deep Bengal fan ($[\text{C}_{\text{org}}] \approx 0.8$ wt.%). Compared to the budget of silicate weathering, the uptake of CO_2 by C_{org} burial is 2–5 times higher. During the 7 to 1 Ma interval of intense weathering and greatest CO_2 consumption the $[\text{C}_{\text{org}}]$ of Bengal sediment reaches 2 wt.% in smectite-rich material, and the effect of C_{org} burial is much larger than silicate weathering. The effect of Himalayan uplift on CO_2 uptake is primarily through the generation of a large particulate flux which leads to rapid C_{org} burial, not via enhanced silicate weathering.

The large flux of C_{org} burial in the Himalayan depositional system may appear at odds with the Neogene decrease of marine inorganic $\delta^{13}\text{C}$, since this record can be interpreted as a transfer of sedimentary carbon from the reduced organic reservoir to the carbonate reservoir (Shackleton, 1987). However the isotopic budget is strongly dependent on the fractionation between organic and inorganic carbon (Δ_B) which is governed by photosynthetic processes. Δ_B has decreased during the Cenozoic for marine organic carbon (Freeman and Hayes, 1992; Kump and Arthur, 1997). In terrestrial systems the expansion of C4 photosynthetic plants (Cerling *et al.*, 1993) also contributes to reduced average Δ_B . The Bengal Fan sediments show that C4 derived organic carbon is buried in high concentration since 7 Ma, demonstrating that a major zone of organic carbon burial can contain carbon with $\delta^{13}\text{C}$ as high as -15% . As a consequence, the Neogene decrease in marine $\delta^{13}\text{C}$ could result simply from reduced isotopic fractionation while the burial of organic carbon would continue to rise.

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