Organic carbon burial forcing of the carbon cycle from Himalayan erosion

Christian France-Lanord*† & Louis A. Derry†

* Centre de Recherches Pétrographiques et Géochimiques, CNRS, BP20 54501 Vandoeuvre-les-Nancy, France
† Cornell University, Department of Geological Sciences, Ithaca, New York 14853, USA

Weathering and erosion can affect the long-term ocean–atmosphere budget of carbon dioxide both through the consumption of carbonic acid during silicate weathering and through changes in the weathering and burial rates of organic carbon1–4. Recent attention has focused on increased silicate weathering of tectonically uplifted areas in the India–Asia collision zone as a possible cause for falling atmospheric CO2 levels in the Cenozoic era5–7. The chemistry of Neogene sediments from the main locus of sedimentary deposition for Himalayan detritus, the Bengal Fan, can be used to estimate the sinks of CO2 from silicate weathering and from the weathering and burial of organic carbon resulting from Himalayan uplift. Here we show that Neogene CO2 consumption from the net burial of organic carbon during Himalayan sediment deposition was 2–3 times that resulting from the weathering of Himalayan silicates. Thus the dominant effect of Neogene Himalayan erosion on the carbon cycle is an increase in the amount of organic carbon in the sedimentary reservoir, not an increase in silicate weathering fluxes.

Silicate weathering is typically incongruent, yielding both a solute and a secondary mineral phase, so direct evidence of chemical weathering can be found in the record of secondary minerals in sedimentary basins. The Bengal Fan and Ganges–Brahmaputra (GB) delta contain a huge volume of sediment derived from erosion of the India–Asia collision zone, with 6 × 10^6 km^3 deposited in the past 20 Myr (ref. 8). Isotopic data for Nd, Sr and O from Bengal Fan sediments show that the source for over 80% of the detritus since 20 Myr ago has been the high-grade metasedimentary rocks of the High Himalayan crystalline (HHC) sequence9. Clastic and carbonate sediments from the Precambrian Lesser Himalaya (LH) and Palaeozoic–Mesozoic Tethyan Himalaya (TH) are the important sources of sediment to the Bengal Fan during the Neogene.

Carbon dioxide consumption from silicate weathering can be represented schematically by:

CaSiO_3 + 2CO_2 + 2H_2O → Ca^{2+} + 2HCO_3^- + H_4SiO_4

where 1 mol of CO_2 is sequestered as marine carbonate for each mol Ca (or Mg) derived from silicate dissolution. Weathering of Na and K silicates contributes a smaller fraction to the weathering CO_2 sink because alkalis can exchange for Ca ± Mg adsorbed on detrital clays in estuarine zones, and during alteration of the oceanic crust10,11. We estimate the CO_2 consumption from silicate weathering by comparing the chemistry of the weathered sediments deposited in the Bengal Fan with the chemistry of their unaltered Himalayan source rocks. The comparison slightly overestimates CO_2 consumption because any base cations released by weathering with strong acids (such as H_2SO_4) are still included in this CO_2 consumption budget. To represent the source of Bengal Fan sediment we use a composite of 99 samples from outcrops in the HHHC (Table 1). Adding samples from the LH and TH strata to the average value for Himalayan source rocks does not change the estimated weathering fluxes significantly, because the combined contribution from these units to the sediment flux in the Bengal Fan is <20%, and all three (meta)sedimentary units are chemically similar. We analysed a subset of HHHC samples from Central Nepal for total organic carbon (C_{org}) contents. Metamorphic rocks of the HHHC average 0.05 ± 0.03% C_{org}. Sediments of the Lesser Himalaya also have low C_{org} contents, ≈0.10%, except for rare black shale beds12. Sediments of the Tethyan Himalaya include both carbonates and Palaeozoic clastic sediments with low C_{org} values, and some Mesozoic shales with up to 1.5% C_{org} (ref. 13). We estimate a volume-weighted mean C_{org} content of 0.10 ± 0.05% for the source rocks of Bengal Fan sediment.

We sampled Himalayan-derived sediments from late Pleistocene to mid-Miocene age recovered from the distal Bengal Fan on Leg 116 of the Ocean Drilling Program14. The sediments were chosen to represent a range of weathering intensities based on clay mineralogy15. Before 7 Myr and after 1 Myr ago the clay mineral assemblage (<2 µm size fraction) in the Bengal Fan is dominantly illite plus chlorite (the IC assemblage). From 7 to 1 Myr, clays in the Fan are dominantly pedogenic smectite and kaolinite (SK assemblage), reflecting more intense weathering in the GB floodplain16. The fine-grained, SK sediments from the Bengal Fan are the most intensely weathered Himalayan sediments, and are less abundant than the IC sediments. Before dissolution, whole rock samples were disaggregated in distilled H_2O, then leached with 10% acetic acid to remove minor carbonates (diagenetic, biogenic and detrital). Disaggregation and biostromal carbonate removes some Ca and Mg derived from alteration of detrital silicates, although Sr isotopic data on the carbonate fraction show that most cations are derived from sea water. Ion exchange of H^+ for adsorbed cations on clays may also release some silicate-derived cations. Thus our technique probably causes us to overestimate the silicate-derived alkalinity flux.

We normalized the major element concentrations of HHHC source material and Bengal Fan sediment to their Al_2O_3 contents, on the assumption that during low-intensity weathering characteristic of the Himalayan drainage, aluminium is conservative. The global mean transport of dissolved Al is estimated to be <0.1% of suspended load transport17, making this a reliable assumption. The differences in ratios of major cations to Al_2O_3 between the HHHC and Bengal Fan sediments can result from weathering losses,
mineral sorting or residual enrichment of insoluble cations. Dissolved silica transport in the modern Ganges (from all sources) is about 0.3% of suspended load transport, indicating that dissolution of quartz is minor. Low SiO₂/Al₂O₃ in the sediments results from mineral sorting, as quartz is mechanically resistant and is transported less readily than finer-grained aluminosilicate minerals. If fine-grained silicates are preferentially transported to the distal fan, with mean Corg of 0.90% (ref. 21), suggesting that any sorting effect on Corg contents is minor.

Consumption of CO₂ due to Himalayan silicate weathering was calculated assuming that all Mg²⁺ and Ca²⁺ lost from the silicates forms marine carbonates. The fraction of K and Na involved in cation exchange reactions with sediments or the oceanic crust remains poorly known. We conservatively estimate that 20% of K⁺ and 30% of Na⁺ in the global river flux exchanges for Ca²⁺. Consumption of CO₂ by silicate weathering and the modern discharge-weighted SiO₂ flux in the GB system are near the current world average. Despite the huge erosional flux from the Himalaya, the silicate weathering sink for CO₂ is modest on the global scale. The extreme relief of the Himalaya and the monsoon climate result in very rapid physical denudation and fast transport of sediment to the ocean. One result is a strongly weathering-limited system in which the kinetics of chemical weathering are slow relative to the transport time of eroded rock to the sea. Furthermore, Ca silicates are not abundant in the Himalaya, and the silicate-derived alkalinity flux is largely in the form of Na and K cations which are inefficient sinks of CO₂.

The data above yield an average Neogene rate of net growth (burial − weathering > 0) of the sedimentary Corg reservoir of 0.58 × 10¹² mol yr⁻¹ in the Himalayan–Bengal system. The net growth in the size of the global sedimentary Corg reservoir can be estimated from the marine carbon isotope mass balance. Our recent results from a δ¹³C model yield a global average net flux to the sedimentary Corg reservoir of about 1.1 × 10¹² mol yr over the past 15 Myr. The results are not directly comparable because one value represents a regional flux, whereas the other represents a global flux. However, they are consistent, and suggest that Corg burial in excess of weathering in the Himalayan–Bengal system can contribute significantly to changes in the global Corg reservoir. Together with the Indo–Gangetic plain, the Bengal Fan accounts for about 15% of the modern total burial flux of global Corg (ref. 20), so it is not surprising that any imbalance (burial − weathering ≠ 0) in the Himalayan–Bengal Corg budget could have had a global impact. Up to 90% of Corg burial takes place in continental margin sediments, so any process that increases continental margin sedimentation significantly, such as erosion of a major orogen, may be expected to increase Corg burial and possibly amplify imbalances in the Corg budget. Rapid erosion and the high suspended load of the GB system help drive Corg burial rates high enough to perturb the global carbon cycle significantly. Erosion of a major orogenic belt such as the Himalaya creates a large amount of mineral surface area, which is a strong control on organic carbon burial in continental margin settings.

<table>
<thead>
<tr>
<th>Table 1 Average chemical compositions of the High Himalaya Crystalline (HHC) and decarbonated Bengal Fan sediments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>HHC</td>
</tr>
<tr>
<td>Bengal IC</td>
</tr>
<tr>
<td>Bengal SK</td>
</tr>
</tbody>
</table>

Major element analyses were made by inductively coupled plasma optical emission spectroscopy on samples fused with lithium metaborate.
Recent work on the evolution of the global climate during the Cenozoic era has focused almost exclusively on the possible perturbation of atmospheric CO₂ levels resulting from weathering of silicates, especially in the Himalaya 1,2,29–32. But Himalayan erosion produces very large Corg fluxes 30,31,32. Although the hypothesized link between Himalayan silicate weathering and atmospheric CO₂ levels remains poorly quantified, our results indicate that increased sedimentary Corg storage resulting from Neogene Himalayan erosion and weathering has had a significantly larger effect on the carbon cycle than silicate weathering, by a factor of 2–3. Both models of the net change in the global sedimentary Corg reservoir 26 and data from the Himalayan–Bengal system are consistent with the hypothesis that an excess of Corg burial over weathering acted as a sink for atmospheric CO₂ during the Neogene.

Received 13 February; accepted 18 August 1997.


Acknowledgements. We thank Patrick Le Fort for providing part of the Himalayan samples and analyses. This study was supported by the CNRS-INSU program ‘Dynamique et Bilan de la Terre—Fleuve et Erosion’.

Correspondence should be addressed to C.-F.-L. at CRPG-CNRS (e-mail: clbf@cyrg.cnrs-nancy.fr).

Mechanical power output of bird flight

K. P. Dial†, A. A. Biewener†, B. W. Tobalske* & D. R. Warrick*†

* Division of Biological Sciences, University of Montana, Missoula, Montana 59812, USA
† Department of Organismal Biology and Anatomy, University of Chicago, 1025 East 57 Street, Chicago, Illinois 60637, USA

Aerodynamic theory predicts that the power required for an animal to fly over a range of speeds is represented by a ‘U’-shaped curve, with the greatest power required at the slowest and fastest speeds, and minimum power at an intermediate speed 1–6. Tests of these predictions, based on oxygen consumption measurements of metabolic power in birds 7–12 and insects 13, support a different interpretation, generating either flat or ‘J’-shaped power profiles, implying little additional demand between hovering and intermediate flight speeds 7. However, respirometric techniques represent only an indirect assessment of the mechanical power requirements of flight and no previous avian study has investigated an animal’s full range of attainable level flight speeds. Here we present data from in vivo bone-strain measurements of

Figure 1a. Illustration of a magpie pectoral girdle and forelimb showing the placement of a strain gauge on the deltopectoral crest (DPC; expanded in inset) and indwelling bipolar electromyographic (EMG) wires in the pectoralis muscle, all connected to a dorsal plug. b. Recordings of DPC strain calibrated to pectoralis force (arrows indicate kinematic upstroke and downstroke) and c, corresponding pectoralis (EMG) for three successive wingbeats of a magpie flying at 6 m s⁻¹. were synchronized to wing kinematics (obtained from 16 mm high-speed movie film at 150–200 f.p.s. in lateral and dorsal views) to estimate pectoralis fibre length change in relation to force development and to determine wingbeat cycle duration.