

Strontium isotope systematics of a Himalayan glacial chronosequence

A. D. Jacobson
J. D. Blum

Department of Earth Sciences, Dartmouth College, Hanover, NH
03755, USA

Chemical weathering of silicate minerals consumes atmospheric CO₂, and therefore, changes in global silicate weathering rates may act as a mechanism to drive major fluctuations in the Earth's climate and long-term global carbon cycle. Recent studies suggest that steep increases in the Cenozoic marine Sr isotope record correlate with periods of global cooling and enhanced silicate weathering rates, initiated by the onset of glaciation in the uplifting Himalayan mountains (Raymo and Ruddiman, 1992). However, due to the Himalaya's unique orogenic history, strontium with high ⁸⁷Sr/⁸⁶Sr ratios may reside in easily weathered carbonate minerals that do not act as a net sink for atmospheric CO₂ when undergoing chemical weathering (Edmond, 1992; Blum *et al.*, 1998). Thus, the dissolved flux of Sr from the Himalayan Mountains may not be an ideal proxy for silicate weathering and atmospheric CO₂ consumption. By studying the major element and Sr isotope chemistry of soils developed on a Himalayan glacial chronosequence, we are investigating how the dissolved flux of ions derived from carbonate versus silicate mineral weathering varies as a function of time following the exposure of fresh rock surfaces to the agents of chemical weathering.

Geologic setting and methods. The ~200 km² Raikhot Valley, located at an average elevation of ~4000 m on the northern slope of the Nanga Parbat-Harimosh Massif (NPHM) within the Pakistani Himalayas, contains both the ~50 km² Raikhot Glacier as well as a clearly visible glacial chronosequence. Four moraines, thought to be roughly Little Ice Age to neoglacial in age, are nested near the modern terminus of the glacier, while a fifth moraine, believed to be last glacial maximum in age, forms a bench about 200 m from the glacial terminus. The bedrock of the watershed, considered to be representative of the High Himalayan Crystalline Series (HHCS) which stretches for 2000 km across the length of the Himalayan Mountains, primarily consists of quartzofeldspathic biotite gneisses, biotite schists, leucogranite dikes, and granitic stocks, as well as minor amounts (~1%) of

interbedded amphibolite and calc-silicate schists. In order of increasing relative age, the sample numbers 96PK1, 96PK2, 96PK3, and 96PK4 refer to soil profiles collected from the four young nested moraines, while the sample numbers 96PK5 and 96PK5a refer to 2 separate soil profiles developed on the fifth moraine. This report presents results obtained from the analysis of the major element (Ca, Mg, Na, K, and Si) concentrations, minor element (Sr, Ti, and Zr) concentrations, and the Sr isotope ratios (⁸⁷Sr/⁸⁶Sr) contained in the bulk and exchangeable fractions of these soils.

Ca to Sr ratios. The analysis of Ca/(1000*Sr) ratios provides a useful mechanism for characterizing the mineral provenance of the bulk soil and exchangeable ions. The Ca/(1000*Sr) ratios of the bulk soil and exchangeable ions represent a mixture between the average calcium carbonate and silicate endmembers for the watershed, as determined by sequentially leaching and digesting modern riverbed sediment with 4N acetic acid and HF-HClO₄, respectively (Blum *et al.*, 1998). The average Ca/(1000*Sr) ratio of the exchangeable fraction in profiles 96PK1, 96PK2, 96PK3, and 96PK4 appears similar to the calcium carbonate endmember for the watershed (1.4), while the Ca/(1000*Sr) ratios contained in the entire suite of bulk soils as well as the exchangeable fraction in the C-horizons of profiles 96PK5 and 96PK5a appears more similar to the silicate endmember (0.19). These observations suggest that even though calcium carbonate represents only ~1% of the rock in the watershed, calcium carbonate is the primary source of Ca and Sr provided to the dissolved groundwater flux during the early stages of weathering. In addition, the Ca/(1000*Sr) ratios in the C-horizons of profiles 96PK5 and 96PK5a demonstrate that the calcium carbonate reservoir in the soils is nearly depleted within the ~15,000 to 20,000 years during which the soils have developed on the moraines. However, a reversal toward carbonate-like Ca/(1000*Sr) ratios in the uppermost horizons of the older profiles indicates that the continual addition of fresh weatherable material,

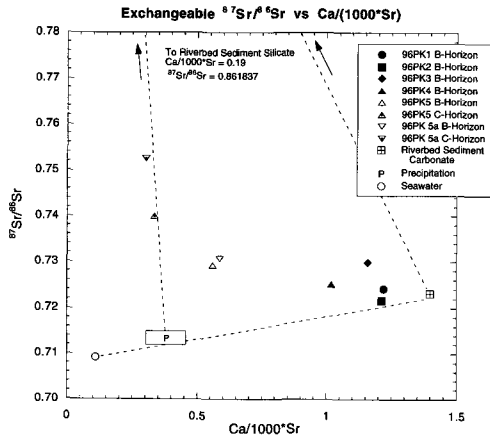


FIG. 1.

possibly via the atmospheric deposition of dust derived from within the watershed, buffers the system somewhat with respect to calcium carbonate weathering. This observation is not surprising given that the watershed is located in an area of pronounced tectonic activity where oversteepened slopes, frequent landslides, abundant rockfalls, and glacial silt provide an input of locally derived aeolian material.

$^{87}\text{Sr}/^{86}\text{Sr}$. The Sr isotope ratio of exchangeable Sr further reflects the dynamics of carbonate versus silicate weathering. Figure 1 shows the exchangeable Sr isotope and $\text{Ca}/(1000 \cdot \text{Sr})$ ratios obtained from the B-horizons of all moraines and the C-horizons of moraines PK965 and PK965a. Also plotted are the Sr isotope and $\text{Ca}/(1000 \cdot \text{Sr})$ ratios for seawater, the carbonate endmember for the watershed, and precipitation, which probably represents a mixture between seawater and locally derived carbonate material. If the exchangeable Sr isotope and $\text{Ca}/(1000 \cdot \text{Sr})$ ratios of the soils reflected simple two-component mixing between the carbonate and silicate endmembers for the watershed, all data points would plot on the mixing line connecting the two points. Young soils dominated by carbonate dissolution would plot close to the carbonate endmember for the watershed, while older soils would plot closer to the silicate endmember following the depletion of carbonate from the soil reservoir. However, Fig. 1 clearly shows that the analyses do not fall on this mixing line and suggests that an additional process is contributing to the chemical evolution of the soil chronosequence. We propose two possible mechanisms that may explain this observation: 1) the incongruent dissolution of carbonate minerals with

varying $\text{Ca}/(1000 \cdot \text{Sr})$ ratios, and 2) mixing with a third endmember, such as precipitation. The watershed contains carbonate minerals with a wide range of Sr isotope and $\text{Ca}/(1000 \cdot \text{Sr})$ ratios, and other studies have shown that even within single calcite veins, $\text{Ca}/(1000 \cdot \text{Sr})$ ratios can vary dramatically (Wogelius *et al.*, 1998). Thus, the $\text{Ca}/(1000 \cdot \text{Sr})$ ratio of the carbonate fraction in the moraine parent material could potentially be much lower than the average carbonate value shown in Fig. 1. The incongruent dissolution of impure calcium carbonate accompanied by the re-precipitation of calcite (e.g. Edmunds, 1982) could also contribute to a progressive lowering of the $\text{Ca}/(1000 \cdot \text{Sr})$ ratio released by carbonate dissolution as a function of time. Mass balance calculations suggest that the flux of Ca and Sr provided by precipitation is relatively low compared to the flux provided by carbonate dissolution during the early stages of weathering. Thus, the exchangeable cation chemistry of soils developed on young moraines is likely unaffected by precipitation and represents predominantly carbonate dissolution. Because the rate of carbonate dissolution probably decreases as a function of soil age, the exchangeable ions in the older profiles display a greater influence from silicate weathering as well as the possible accumulation of some Ca and Sr derived from precipitation. Our findings suggest that even though calcium carbonate represents only ~1% of the rock in the watershed, calcium carbonate is the primary source of Ca and Sr provided to the dissolved groundwater flux for at least 20,000 years following the exposure of fresh rock surfaces. These results support other studies (e.g. Quade *et al.*, 1997) which also demonstrate that the dissolved flux of radiogenic Sr from the Himalayas is largely controlled by carbonate weathering and therefore is not an ideal proxy for silicate weathering and atmospheric CO_2 consumption.

References

- Blum, J.D., Gazis, C.A., Jacobson, A.D., and Chamberlain, C.P. (1998) *Geol.*
- Edmond, J.M. (1992) *Science*, **258**, 1594–7.
- Edmunds, W.M., Bath, A.H., and Miles, D.L. (1982) *Geochim. Cosmochim. Acta*, **46**, 2069–81.
- Raymo, M.E. and Ruddiman, W.F. (1992) *Nature*, **359**, 117–22.
- Quade, J., Roe, L., DeCelles, P.G., and Ojha, T.P. (1997) *Science*, **276**, 1828–31.
- Wogelius, R.A., Fraser, D.G., Wall, G.R.T., and Grime, G.W. (1997) *Geochim. Cosmochim. Acta*, **61**, 2037–51.