Relationship between mechanical erosion and atmospheric CO₂ consumption in the New Zealand Southern Alps

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ABSTRACT

To examine the influence of mountain uplift on the long-term carbon cycle, we used geochemical, hydrologic, and suspended-load data for 12 streams draining the New Zealand Southern Alps to quantify rates of erosion, weathering, and atmospheric CO₂ consumption. Rapid uplift in the western Southern Alps elevates mechanical erosion rates by a factor of ~13 relative to those on the tectonically stable eastern side [125 × 10⁸ vs. 9.4 × 10⁸ g/(km²·yr), respectively]. Similarly, the average chemical weathering rate is ~5 times higher on the western compared to eastern side of the mountain range [9.8 × 10⁸ vs. 2.0 × 10⁷ g/(km²·yr), respectively]. However, because the proportion of stream-water Ca²⁺ and Mg²⁺ from carbonate weathering increases as the rate of mechanical erosion increases, the long-term atmospheric CO₂ consumption rate on the western side is ~2 times higher than that on the eastern side [14 × 10^4 vs. 6.9 × 10^4 mol/(km²·yr), respectively] and only ~1.5 times higher than the global mean value [~9 × 10^4 mol/(km²·yr)]. Data for major world rivers (including Himalayan rivers) provide a consistent interpretation regarding the relationship between mechanical erosion intensity and the ratio of silicate to carbonate weathering. Thus, we conclude that mountain building increases atmospheric CO₂ consumption rates by only a factor of ~2, which is much lower than previous estimates.

Keywords: New Zealand Southern Alps, mountain uplift, chemical weathering, mechanical erosion, carbon dioxide.

INTRODUCTION

Mountain uplift is known to greatly enhance rates of physical erosion and chemical weathering compared to the rates in tectonically stable regions (e.g., Stallard and Edmond, 1983; Milliman and Syvitski, 1992; Derry and France-Lanord, 1997). These observations have been used to argue that orogenic events lead to global cooling over geologic time scales by accelerating the rate of atmospheric CO₂ consumption by silicate weathering (e.g., Raymo et al., 1988; Raymo and Ruddiman, 1992; Edmond and Huh, 1997; Wallmann, 2001). However, recent studies have shown that much of the chemical weathering flux from uplifting mountain basins is due to increased carbonate dissolution, which does not influence long-term atmospheric CO₂ levels (Blum et al., 1998; Galy and France-Lanord, 1999; English et al., 2000; Karim and Veizer, 2000; Jacobson et al., 2002b, 2003). To examine this problem in more detail, we quantified rates of mechanical erosion and both silicate and carbonate weathering across a gradient of variable uplift rates but constant bedrock composition in the New Zealand Southern Alps, which we previously demonstrated to be well suited for conducting experiments designed to isolate the effects of uplift on chemical weathering (see Jacobson et al., 2003, for a review of the geochemical and hydrologic setting). To interpret the global-scale significance of weathering processes occurring within the Southern Alps, we compared our findings to global mean values as well as to data for major world rivers in various tectonic and climatic settings.

METHODS

The calculation of mechanical erosion, chemical weathering, and atmospheric CO₂ consumption rates for the 12 streams examined required knowledge of hydrologic parameters, stream-water concentration data, and criteria for apportioning solutes between silicate and carbonate weathering. Unless indicated otherwise in Table 1, all hydrologic information was provided by the National Institute of Water and Atmospheric Research Limited in Christchurch, New Zealand. This data set contained watershed areas, mean annual rainfall, and mean annual runoff for sampling periods ranging from 6 to 42 yr.

Concentration data were reported in Jacobson et al. (2003). These samples were collected during a single time period and do not account for possible seasonal variations in solute concentrations. Following methodology discussed in Jacobson et al. (2003), we apportioned dissolved Ca²⁺ between silicate (Caᵢsil) and carbonate (Caᵢcarb) weathering with the equations

\[ Caᵢsil = (Ca/Na)_{plag} \times Naᵢsil \] (1)

and

\[ Caᵢcarb = Caᵢsil - Caᵢsil, \] (2)

where (Ca/Na)_{plag} is the molar ratio of calcium to sodium inferred to exist in Southern Alps plagioclase (~0.32), Naᵢsil is the concentration of dissolved sodium corrected for atmospheric inputs, and Caᵢsil is the total dissolved calcium concentration. Because biotite (the most common Mg-bearing silicate mineral in the Southern Alps) is primarily weathering to vermiculite (which retains Mg²⁺), small amounts of dissolved Mg₅₂₆ (only ~9% of the cationic charge) were attributed to carbonate weathering.

Total chemical weathering rates \(W_{\text{chem}} = \text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^{+} + \text{K}^{+} + \text{Si}\), silicate weathering rates \(W_{\text{sil}} = \text{Ca}^{2+} + \text{Na}^{+} + \text{K}^{+} + \text{Si}\), and carbonate weathering rates \(W_{\text{carb}} = \text{Ca}^{2+} + \text{Mg}^{2+}\) were calculated with the equation

\[ W_i = \sum C_i \times R, \] (3)

where \(W_i\) resolves to units of g/(km²·yr) when the sum of the respective solute concentrations corrected for atmospheric inputs \((2C_i)\) has units of µg/L and runoff \((R)\) has units of mm/yr. Long-term atmospheric CO₂ consumption rates attributed to silicate weathering \(W_{\text{sil-CO}_2}\) were calculated with the equation

\[ W_{\text{sil-CO}_2} = 2 \times Caᵢsil \times R, \] (4)

where \(W_{\text{sil-CO}_2}\) has units of mol/(km²·yr) when Caᵢsil has units of µmol/L and \(R\) has units of mm/yr. The factor of 2 arises from the stoichiometry of the reaction between carbonic acid and plagioclase. Atmospheric CO₂ consumption rates attributed to carbonate weathering \(W_{\text{carb-CO}_2}\) were calculated with the equation

\[ W_{\text{carb-CO}_2} = (\text{Ca}^{2+} + \text{Mg}^{2+}) \times R, \] (5)

where \(W_{\text{carb-CO}_2}\) has units of mol/(km²·yr) when the quantity (Caᵢcarb + Mgᵢcarb)
Mg^{2+}) has units of μmol/L and R has units of mm/yr. In the case of \( W_{\text{carb-CO}_2} \), the factor of 2 is not included because only half of the alkalinity derived from the reaction between carbonic acid and carbonate-bearing minerals is from hydrated atmospheric CO₂. Mechanical erosion rates (\( W_{\text{mech}} \)) were assumed to equal suspended sediment fluxes, which are generally considered to represent ~90% of the total sediment transported by rivers (Stallard, 1995). However, we point out that this assumption may underestimate actual erosion rates due to both natural and anthropogenic factors that inhibit sediment transport (Milliman and Syvitski, 1992).

RESULTS

Average \( W_{\text{chem}} \) and \( W_{\text{mech}} \) values (weighted by watershed areas) in the tectonically stable and low-rainfall eastern Southern Alps are 2.0 \( \times 10^7 \) and 9.4 \( \times 10^8 \) g/(km²·yr), respectively (Table 1). The average \( W_{\text{chem}} \) in the rapidly uplifting and high-rainfall western Southern Alps is ~5 times higher at 9.8 \( \times 10^7 \) g/(km²·yr), and the average \( W_{\text{mech}} \) is ~13 times higher at 125 \( \times 10^8 \) g/(km²·yr). On the eastern side, the average \( W_{\text{sil}} \) is 8.1 \( \times 10^7 \) g/(km²·yr), and the average \( W_{\text{carb}} \) is 1.2 \( \times 10^9 \) g/(km²·yr). On the western side, the average \( W_{\text{sil}} \) is 3.0 \( \times 10^7 \) g/(km²·yr), and the average \( W_{\text{carb}} \) is 7.0 \( \times 10^8 \) g/(km²·yr). The average long-term atmospheric CO₂ consumption rate attributed to silicate weathering (\( W_{\text{sil-CO}_2} \)) is 6.9 \( \times 10^5 \) mol/(km²·yr) on the eastern side and 14 \( \times 10^5 \) mol/(km²·yr) on the western side. The average atmospheric CO₂ consumption rate attributed to carbonate weathering (\( W_{\text{carb-CO}_2} \)) is 3.2 \( \times 10^7 \) mol/(km²·yr) on the eastern side and 18 \( \times 10^5 \) mol/(km²·yr) on the western side. Chemical weathering and mechanical erosion rates are statistically different between the eastern and western sides of the mountain range, with \( p < 0.002 \) for \( W_{\text{chem}}, W_{\text{mech}}, W_{\text{sil}}, W_{\text{carb}} \), and \( W_{\text{carb-CO}_2} \) and \( p < 0.04 \) for \( W_{\text{sil-CO}_2} \).

DISCUSSION

To address how stable versus rapidly uplifting landscapes in the Southern Alps influence weathering rates, we compared streams with variable ratios of \( W_{\text{chem}} \) to \( W_{\text{mech}} \) which reflect the relative dominance of chemical versus mechanical weathering. Streams draining the eastern Southern Alps have an average \( W_{\text{chem}}/W_{\text{mech}} \) ratio of 22 \( \times 10^{-3} \), whereas streams draining the western Southern Alps have an average \( W_{\text{chem}}/W_{\text{mech}} \) ratio of 7.9 \( \times 10^{-3} \). When \( W_{\text{chem}} \) is plotted versus \( W_{\text{chem}}/W_{\text{mech}} \), the data display an inverse correlation, demonstrating that the tectonically active western Southern Alps is dominated by mechanical weathering but possesses high chemical weathering rates relative to the stable eastern side (Fig. 1). In the eastern Southern Alps, \( W_{\text{chem}} \) is nearly equivalent to the global mean value of ~2.0 \( \times 10^7 \) g/(km²·yr), and \( W_{\text{chem}}/W_{\text{mech}} \) is ~4 times lower than the global mean value of 82 \( \times 10^{-3} \) (Gaillardet et al., 1999). On the western side, \( W_{\text{chem}} \) is ~5 times higher than the global mean, and \( W_{\text{chem}}/W_{\text{mech}} \) is ~10 times lower (Fig. 1).

An inverse correlation is also observed when \( W_{\text{sil}} \) and \( W_{\text{carb}} \) values are compared to \( W_{\text{chem}}/W_{\text{mech}} \) (Table 1), which suggests that intense mechanical erosion and high runoff inherent to uplifting mountain ranges elevate both silicate and carbonate weathering rates relative to more stable landscapes. However, the carbonate Ca-Mg weathering flux...
increases fivefold from east to west across the mountain range, whereas
the silicate Ca-Mg weathering flux only increases twofold. This finding
is consistent with the observation that the continuous exhumation and
erosion of metamorphic bedrock on the western Southern Alps maintains
a fresh supply of trace hydrothermal calcite, which has been esti-
mated to dissolve ~350 times faster than plagioclase in this environ-
ment (Jacobson et al., 2003). The consequence of this observation is
that \( W_{\text{sil-CO}_2} \) in the most tectonically active landscapes is only elevated
by a factor of ~2 over \( W_{\text{sil-CO}_2} \) in regions subject to lower uplift rates
and less pervasive mechanical erosion (Fig. 2). If the data are compared
to the global long-term atmospheric \( \text{CO}_2 \) consumption rate attributed
solely to Ca-Mg silicate weathering \( \sim 9.0 \times 10^4 \text{ mol/(km}^2\text{-yr)} \); Gaill-
lardet et al., 1999), it is observed that \( W_{\text{sil-CO}_2} \) in the eastern Southern Alps is slightly lower than the global value and that \( W_{\text{sil-CO}_2} \) on the western side is only ~1.5 times higher.

To examine whether the previous interpretations relating mechanical
erosion to chemical weathering are relevant for understanding
global-scale processes, we compared our findings to published geo-
chemical data for the world’s largest rivers, including the Amazon,
Congo-Zaïre, Orinoco, Yangtze, Brahmaputra, Mississippi, Yenisei,
Lena, Mekong, Ganges, St. Lawrence, Paraná, Irrawady, Mackenzie,
Columbia, and Indus Rivers (Milliman and Syvitski, 1992; Pande et
al., 1994; Gaillardet et al., 1999; Galy and France-Lanord, 1999). Geo-
chemical studies of small watersheds are numerous, but few include
all of the parameters necessary for conducting comparisons to the present
data set, i.e., mechanical and chemical weathering rates as well as a
discernible criterion for apportioning solutes between silicate and
chemical weathering. In contrast, large river basins have been studied
extensively with regard to these parameters; however, we recognize that
many of these rivers have been modified physically and chemically by
human activities (Milliman and Syvitski, 1992; Gaillardet et al., 1999).

Consistent with the trend observed for New Zealand streams, \( W_{\text{chem}} \) for large rivers decreases as \( W_{\text{chem}}/W_{\text{mech}} \) increases (Fig. 1).
Major rivers generally have lower \( W_{\text{chem}} \) values and higher \( W_{\text{chem}}/W_{\text{mech}} \) ratios compared to New Zealand streams; this likely reflects
lower runoff and less efficient sediment transport correlated with in-
creasing drainage-basin size (e.g., Milliman and Syvitski, 1992). Rivers
draining the tectonically active Himalaya Mountains have relatively
high \( W_{\text{chem}} \) but the lowest \( W_{\text{chem}}/W_{\text{mech}} \) ratios of all major rivers. Hi-
malayan rivers appear most similar to streams draining the eastern
Southern Alps. When examined as \( W_{\text{sil-CO}_2} \) versus \( W_{\text{chem}}/W_{\text{mech}} \), the
correlation between intense mechanical erosion and the dominance of
carbonate weathering in uplifting mountain belts is further emphasized
by the position of \( W_{\text{sil-CO}_2} \) for the Indus and Ganges-Brahmaputra,
which are ~2.5 times lower than the global mean value.

Geomorphic patterns of landscape evolution appear to exert a
strong control on the ratio of silicate to carbonate weathering. Figure 3
shows the relationship between the \( W_{\text{chem}}/W_{\text{mech}} \) ratio and \( W_{\text{sil-CO}_2}/(W_{\text{sil-CO}_2} + W_{\text{carb-CO}_2}) \), the percentage of consumed atmos-
pheric \( \text{CO}_2 \) attributed to silicate weathering. In the Southern Alps, the
most pronounced enhancement of silicate versus carbonate weathering
accompanies landscape destabilization, which we attribute to the fact that
landscape stabilization leads to the depletion of carbonate from develop-
ing soil profiles (Jacobson et al., 2002a). Streams draining the eastern
Southern Alps have an average value of \( w_{\text{sil-CO}_2} \) that is ~2 times lower than the global mean value of ~30 (Gaillardet et al., 1999),
whereas streams draining the western side have an average value that
is ~4 times lower than the global mean. We also point out that in
terms of Figure 3, appropriate data are available for the small and well-
studied Raikhot watershed, which drains the uplifting Nanga Parbat
massif in the northern Pakistan Himalaya (Gardner and Jones, 1993;
Blum et al., 1998). Similar to the Southern Alps, the predominantly
silicate Nanga Parbat massif contains small amounts of hydrothermal
calcite and high mechanical erosion rates. Accordingly, the Raikhot
watershed plots in the same domain as streams draining the western
Southern Alps.

The analysis of large rivers indicates that \( w_{\text{sil-CO}_2} \) shows no clear
correlation with \( W_{\text{chem}}/W_{\text{mech}} \). However, rivers draining the eastern
Southern Alps are subject to a temperate climate, and therefore a com-
parison to temperate major rivers suggests that the trend of increasing
\( w_{\text{sil-CO}_2} \) with increasing landscape stabilization is maintained. It is also
interesting to note the general pattern that large rivers subject to high
\( W_{\text{chem}}/W_{\text{mech}} \) ratios and relatively cool climates have \( w_{\text{sil-CO}_2} \) values
similar to those of rivers draining orogenic environments with very
low \( W_{\text{chem}}/W_{\text{mech}} \) ratios. This finding demonstrates that carbonate
weathering dominates in landscapes subject to either intense mechanical erosion or cool temperatures. By comparison, large rivers subject to high $W_{chem}/W_{mech}$ and relatively warm climates have $w_{sil-CO_2}$ values significantly elevated above the global mean. This observation indicates that an optimum range of mechanical erosion and climate may exist where the dominance of silicate over carbonate weathering is maximized.

CONCLUSION

Our findings demonstrate that tectonic uplift in the New Zealand Southern Alps accelerates chemical weathering and mechanical erosion rates but does not greatly enhance the rate of long-term atmospheric CO$_2$ consumption, because intense mechanical erosion maintains low ratios of silicate to carbonate weathering. The similarity between stream-water chemistry in the Southern Alps and the Himalaya Mountains suggests that these findings may be generally applicable to understanding chemical weathering in orogenic belts. We further propose that stable landscapes with overall lower chemical weathering rates but high ratios of silicate to carbonate weathering may exert more significant influence on long-term atmospheric CO$_2$ levels. This statement is particularly true if it is considered that a twofold increase in CO$_2$ consumption rates during mountain building likely has only a modest impact on the global-scale drawdown of atmospheric CO$_2$ by silicate weathering, because the area of uplifting mountain ranges is small relative to the total area of the continents. Modeling studies have provided evidence for this assertion by demonstrating a limited impact of Himalayan uplift on the Cenozoic carbon cycle, even when CO$_2$ consumption rates were estimated to be ~8 times higher than the findings presented here (Godderis and François, 1995). Similar models have suggested that uplift-driven changes in chemical weathering may affect atmospheric CO$_2$ levels, but only if considered in conjunction with climatically modulated feedbacks (Kump and Arthur, 1997). Given that landmasses subject to warm climates and moderate erosion rates appear to have the highest ratios of silicate to carbonate weathering, our findings support the contention that factors such as temperature (Berner et al., 1983; White and Blum, 1995) or the latitudinal position of large stable continents (Worsley and Kidder, 1991) may be more important variables for modulating silicate weathering controls on atmospheric CO$_2$ levels. We suggest that future attempts to model the impact of mountain uplift on the long-term carbon cycle take these findings into consideration.

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