

# Relationship between mechanical erosion and atmospheric CO<sub>2</sub> 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 CO<sub>2</sub> 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 × 10<sup>8</sup> vs. 9.4 × 10<sup>8</sup> g/(km<sup>2</sup>-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 × 10<sup>7</sup> vs. 2.0 × 10<sup>7</sup> g/(km<sup>2</sup>-yr), respectively]. However, because the proportion of stream-water Ca<sup>2+</sup> and Mg<sup>2+</sup> from carbonate weathering increases as the rate of mechanical erosion increases, the long-term atmospheric CO<sub>2</sub> consumption rate on the western side is ~2 times higher than that on the eastern side [14 × 10<sup>4</sup> vs. 6.9 × 10<sup>4</sup> mol/(km<sup>2</sup>-yr), respectively] and only ~1.5 times higher than the global mean value [~9 × 10<sup>4</sup> mol/(km<sup>2</sup>-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 CO<sub>2</sub> 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 CO<sub>2</sub> 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 belts is due to increased carbonate dissolution, which does not influence long-term atmospheric CO<sub>2</sub> 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 geologic 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.

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## METHODS

The calculation of mechanical erosion, chemical weathering, and atmospheric CO<sub>2</sub> 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 Ca<sup>2+</sup> between silicate (Ca<sub>sil</sub><sup>2+</sup>) and carbonate (Ca<sub>carb</sub><sup>2+</sup>) weathering with the equations

$$\text{Ca}_{\text{sil}}^{2+} = (\text{Ca/Na})_{\text{plag}} \times \text{Na}_{\text{sil}}^{+} \quad (1)$$

and

$$\text{Ca}_{\text{carb}}^{2+} = \text{Ca}_{\text{tot}}^{2+} - \text{Ca}_{\text{sil}}^{2+}, \quad (2)$$

where (Ca/Na)<sub>plag</sub> is the molar ratio of calcium to sodium inferred to exist in Southern Alps plagioclase (~0.32), Na<sub>sil</sub><sup>+</sup> is the concentration of dissolved sodium corrected for atmospheric inputs, and Ca<sub>tot</sub><sup>2+</sup> 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 Mg<sup>2+</sup>), small amounts of dissolved Mg<sub>tot</sub><sup>2+</sup> (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 ( $W_{\text{sil}} = \text{Ca}_{\text{sil}}^{2+} + \text{Na}^{+} + \text{K}^{+} + \text{Si}$ ), and carbonate weathering rates ( $W_{\text{carb}} = \text{Ca}_{\text{carb}}^{2+} + \text{Mg}^{2+}$ ) were calculated with the equation

$$W_i = \sum C_i \times R, \quad (3)$$

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

$$W_{\text{sil-CO}_2} = 2 \times \text{Ca}_{\text{sil}}^{2+} \times R, \quad (4)$$

where  $W_{\text{sil-CO}_2}$  has units of mol/(km<sup>2</sup>-yr) when Ca<sub>sil</sub><sup>2+</sup> 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 CO<sub>2</sub> consumption rates attributed to carbonate weathering ( $W_{\text{carb-CO}_2}$ ) were calculated with the equation

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

where  $W_{\text{carb-CO}_2}$  has units of mol/(km<sup>2</sup>-yr) when the quantity (Ca<sub>carb</sub><sup>2+</sup> +

TABLE 1. HYDROLOGIC PARAMETERS AND WEATHERING RATES FOR WATERSHEDS DRAINING THE NEW ZEALAND SOUTHERN ALPS

| River               | A*<br>(km <sup>2</sup> ) | R <sup>††</sup><br>(mm/yr) | W <sub>mech</sub> <sup>#</sup><br>(×10 <sup>8</sup> g·km <sup>-2</sup> ·yr <sup>-1</sup> ) | W <sub>chem</sub><br>(×10 <sup>7</sup> g·km <sup>-2</sup> ·yr <sup>-1</sup> ) | W <sub>sil</sub><br>(×10 <sup>7</sup> g·km <sup>-2</sup> ·yr <sup>-1</sup> ) | W <sub>carb</sub><br>(×10 <sup>7</sup> g·km <sup>-2</sup> ·yr <sup>-1</sup> ) | W <sub>sil-CO<sub>2</sub></sub><br>(×10 <sup>4</sup> mol·km <sup>-2</sup> ·yr <sup>-1</sup> ) | W <sub>carb-CO<sub>2</sub></sub><br>(×10 <sup>5</sup> mol·km <sup>-2</sup> ·yr <sup>-1</sup> ) |
|---------------------|--------------------------|----------------------------|--|---|--|---|---|--|
| <b>Eastern side</b> |                          |                            |  |   |  |   |   |  |
| Waitaki             | 9760                     | 1245                       | 1.4  | 1.5   | 0.62   | 0.85  | 5.3   | 2.3  |
| Jollie              | 139                      | 1852                       | 2.0  | 1.5   | 0.75   | 0.80  | 5.3   | 2.1  |
| Rangitata           | 1461                     | 2042                       | 9.5  | 2.4   | 1.1  | 1.4   | 9.5   | 3.6  |
| Rangitata           | 1461                     | 2042                       | 9.5  | 2.3   | 1.0  | 1.3   | 8.7   | 3.4  |
| Ashburton, S.       | 539                      | 701                        | 2.2**  | 0.94  | 0.49   | 0.45  | 3.5   | 1.3  |
| Ashburton, N.       | 276                      | 1145                       | 3.6**  | 1.4   | 0.60   | 0.80  | 3.5   | 2.1  |
| Rakai               | 2560                     | 2723                       | 16   | 3.6   | 1.3  | 2.3   | 13  | 5.9  |
| Rakai               | 2560                     | 2723                       | 16   | 3.6   | 1.3  | 2.4   | 10  | 6.1  |
| Waimakariri         | 3210                     | 1193                       | 17   | 1.7   | 0.69   | 1.1   | 5.8   | 2.8  |
| Waimakariri         | 3210                     | 1193                       | 17   | 1.5   | 0.58   | 0.91  | 4.6   | 2.4  |
| <b>Western side</b> |                          |                            |  |   |  |   |   |  |
| Hokitika            | 352                      | 8920                       | 171  | 11  | 4.0  | 7.2   | 15  | 19   |
| Waitaha             | 223                      | 9152                       | 149 <sup>††</sup>  | 15  | 4.5  | 10  | 19  | 26   |
| Whataroa            | 445                      | 9526                       | 149 <sup>††</sup>  | 12  | 3.5  | 8.8   | 31  | 22   |
| Waiho               | 185                      | 5900 <sup>§</sup>          | 53 <sup>§§</sup>   | 10  | 3.4  | 6.4   | 12  | 17   |
| Paringa             | 230                      | 4982 <sup>§</sup>          | 29 <sup>§§</sup>   | 5.9   | 2.2  | 3.8   | 10  | 10   |
| Haaast              | 1020                     | 5787                       | 127  | 8.1   | 2.2  | 6.0   | 7.4   | 15   |

\*Data from National Institute of Water and Atmospheric Research Limited (NIWA), Christchurch, New Zealand.

<sup>†</sup>Mean annual runoff; sampling period ranges from 6 to 42 yr.

<sup>§</sup>Estimated from rainfall assuming 10% evapotranspiration reported for the nearby Taramakau river (Griffiths and Glasby, 1985).

<sup>#</sup>W<sub>mech</sub> assumed to equal suspended sediment flux; from Griffiths (1981) and Griffiths and Glasby (1985) unless indicated otherwise.

\*\*Estimated by using R to apportion W<sub>mech</sub>, reported for the Ashburton main stem.

<sup>††</sup>Average value for watersheds between Kapitea and Mackenzie reported in Griffiths and Glasby (1985).

<sup>§§</sup>Estimated by using empirical relations in Griffiths and Glasby (1985).

Mg<sup>2+</sup>) has units of μmol/L and R has units of mm/yr. In the case of W<sub>carb-CO<sub>2</sub></sub>, 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 CO<sub>2</sub>. Mechanical erosion rates (W<sub>mech</sub>) 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<sub>chem</sub> and W<sub>mech</sub> values (weighted by watershed areas) in the tectonically stable and low-rainfall eastern Southern Alps are 2.0

× 10<sup>7</sup> and 9.4 × 10<sup>8</sup> g/(km<sup>2</sup>·yr), respectively (Table 1). The average W<sub>chem</sub> in the rapidly uplifting and high-rainfall western Southern Alps is ~5 times higher at 9.8 × 10<sup>7</sup> g/(km<sup>2</sup>·yr), and the average W<sub>mech</sub> is ~13 times higher at 125 × 10<sup>8</sup> g/(km<sup>2</sup>·yr). On the eastern side, the average W<sub>sil</sub> is 0.81 × 10<sup>7</sup> g/(km<sup>2</sup>·yr), and the average W<sub>carb</sub> is 1.2 × 10<sup>7</sup> g/(km<sup>2</sup>·yr). On the western side, the average W<sub>sil</sub> is 3.0 × 10<sup>7</sup> g/(km<sup>2</sup>·yr), and the average W<sub>carb</sub> is 7.0 × 10<sup>7</sup> g/(km<sup>2</sup>·yr). The average long-term atmospheric CO<sub>2</sub> consumption rate attributed to silicate weathering (W<sub>sil-CO<sub>2</sub></sub>) is 6.9 × 10<sup>4</sup> mol/(km<sup>2</sup>·yr) on the eastern side and 14 × 10<sup>4</sup> mol/(km<sup>2</sup>·yr) on the western side. The average atmospheric CO<sub>2</sub> consumption rate attributed to carbonate weathering (W<sub>carb-CO<sub>2</sub></sub>) is 3.2 × 10<sup>5</sup> mol/(km<sup>2</sup>·yr) on the eastern side and 18 × 10<sup>5</sup> mol/(km<sup>2</sup>·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<sub>chem</sub>, W<sub>mech</sub>, W<sub>sil</sub>, W<sub>carb</sub>, and W<sub>carb-CO<sub>2</sub></sub> and p < 0.04 for W<sub>sil-CO<sub>2</sub></sub>.

**DISCUSSION**

To address how stable versus rapidly uplifting landscapes in the Southern Alps influence weathering rates, we compared streams with variable ratios of W<sub>chem</sub> to W<sub>mech</sub>, which reflect the relative dominance of chemical versus mechanical weathering. Streams draining the eastern Southern Alps have an average W<sub>chem</sub>/W<sub>mech</sub> ratio of 22 × 10<sup>-3</sup>, whereas streams draining the western Southern Alps have an average W<sub>chem</sub>/W<sub>mech</sub> ratio of 7.9 × 10<sup>-3</sup>. When W<sub>chem</sub> is plotted versus W<sub>chem</sub>/W<sub>mech</sub>, 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<sub>chem</sub> is nearly equivalent to the global mean value of ~2.0 × 10<sup>7</sup> g/(km<sup>2</sup>·yr), and W<sub>chem</sub>/W<sub>mech</sub> is ~4 times lower than the global mean value of 82 × 10<sup>-3</sup> (Gaillardet et al., 1999). On the western side, W<sub>chem</sub> is ~5 times higher than the global mean, and W<sub>chem</sub>/W<sub>mech</sub> is ~10 times lower (Fig. 1).

An inverse correlation is also observed when W<sub>sil</sub> and W<sub>carb</sub> values are compared to W<sub>chem</sub>/W<sub>mech</sub> (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

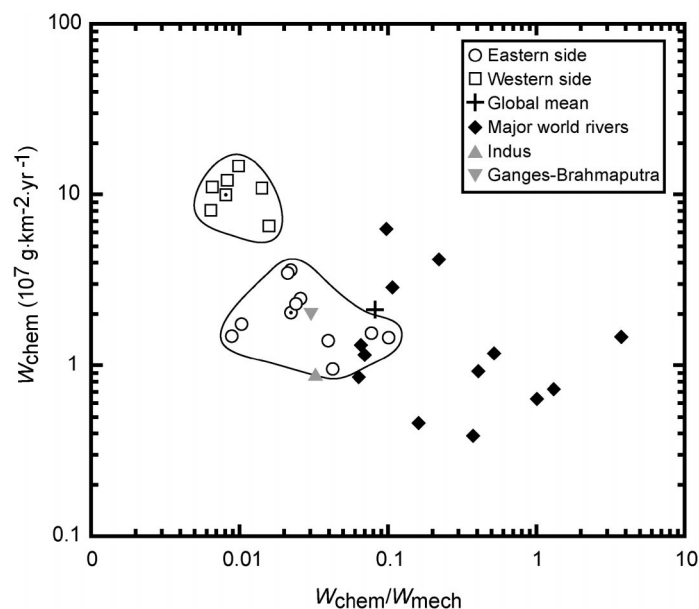


Figure 1. W<sub>chem</sub>/W<sub>mech</sub> vs. W<sub>chem</sub> (see text). Average values (weighted by watershed areas) for New Zealand streams shown as symbols with dot.

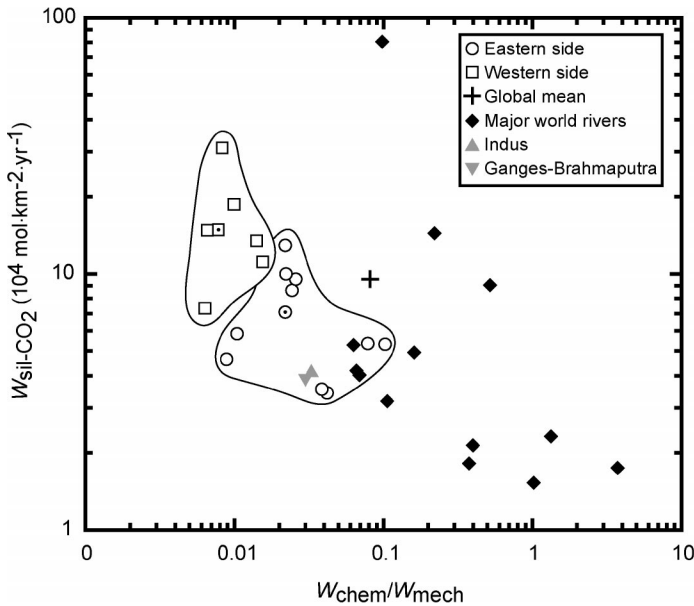


Figure 2.  $W_{\text{chem}}/W_{\text{mech}}$  vs.  $W_{\text{sil-CO}_2}$  (see text). Average values for New Zealand streams same as Figure 1.

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 estimated to dissolve  $\sim 350$  times faster than plagioclase in this environment (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  $\sim 2$  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 [ $\sim 9.0 \times 10^4 \text{ mol}/(\text{km}^2 \cdot \text{yr})$ ; Gaillardet 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  $\sim 1.5$  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 geochemical data for the world's largest rivers, including the Amazon, Congo-Zaire, 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). Geochemical 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 carbonate 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 increasing 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-

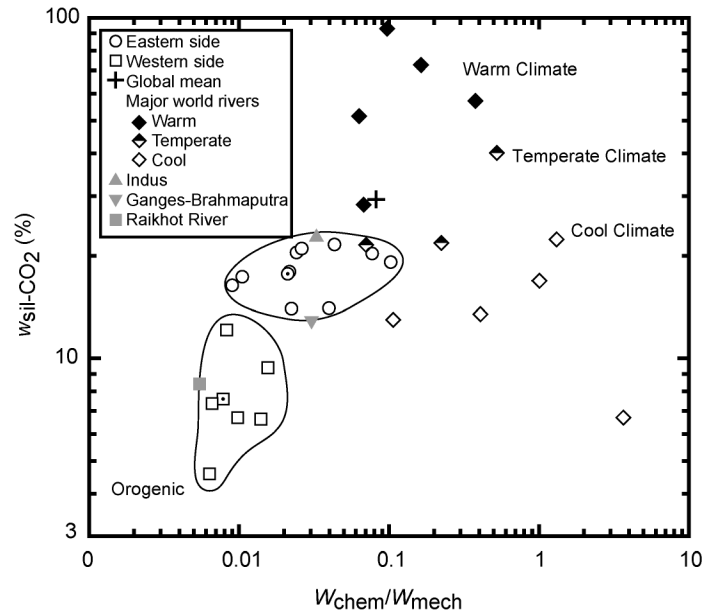


Figure 3.  $W_{\text{chem}}/W_{\text{mech}}$  vs.  $W_{\text{sil-CO}_2}$  (see text). Average values for New Zealand streams same as Figure 1. Field labels: orogenic—streams and rivers draining Southern Alps and Himalaya Mountains; warm climate—Amazon, Congo-Zaire, Irrawady, Orinoco, and Paraná; temperate climate—Columbia, Mekong, and Mississippi; cool climate—Lena, Mackenzie, St. Lawrence, Yenisei, and Yangtze.

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  $\sim 2.5$  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  $W_{\text{sil-CO}_2}/(W_{\text{sil-CO}_2} + W_{\text{carb-CO}_2}) = w_{\text{sil-CO}_2}$ , the percentage of consumed atmospheric  $\text{CO}_2$  attributed to silicate weathering. In the Southern Alps, the most pronounced enhancement of silicate versus carbonate weathering accompanies landscape stabilization, which we attribute to the fact that landscape stabilization leads to the depletion of carbonate from developing soil profiles (Jacobson et al., 2002a). Streams draining the eastern Southern Alps have an average value of  $w_{\text{sil-CO}_2}$  that is  $\sim 2$  times lower than the global mean value of  $\sim 30\%$  (Gaillardet et al., 1999), whereas streams draining the western side have an average value that is  $\sim 4$  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 comparison 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  $W_{\text{chem}}/W_{\text{mech}}$  and relatively warm climates have  $w_{\text{sil-CO}_2}$  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  $\text{CO}_2$  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  $\text{CO}_2$  levels. This statement is particularly true if it is considered that a twofold increase in  $\text{CO}_2$  consumption rates during mountain building likely has only a modest impact on the global-scale drawdown of atmospheric  $\text{CO}_2$  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  $\text{CO}_2$  consumption rates were estimated to be  $\sim 8$  times higher than the findings presented here (Godd ris and Fran ois, 1995). Similar models have suggested that uplift-driven changes in chemical weathering may affect atmospheric  $\text{CO}_2$  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  $\text{CO}_2$  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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