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Silicate weathering of soil-mantled slopes in an active Alpine landscape

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Abstract

Despite being located on high, steep, actively uplifting, and formerly glaciated slopes of the Swiss Central Alps, soils in the upper Rhone Valley are depleted by up to 50% in cations relative to their parent bedrock. This depletion was determined by a mass loss balance based on Zr as a refractory element. Both Holocene weathering rates and physical erosion rates of these slopes are unexpectedly low, as measured by cosmogenic ^{10}Be-derived denudation rates. Chemical depletion fractions, CDF, range from 0.12 to 0.48, while the average soil chemical weathering rate is 33 ± 15 t km^{-2} yr^{-1}. Both the cosmogenic nuclide-derived denudation rates and model calculations suggest that these soils have reached a weathering steady-state since deglaciation 15 ky ago. The weathering signal varies with elevation and hillslope morphology. In addition, the chemical weathering rates decrease with elevation indicating that temperature may be a dominant controlling factor on weathering in these high Alpine basins. Model calculations suggest that chemical weathering rates are limited by reaction kinetics and not the supply rate of fresh material. We compare hillslope and catchment-wide weathering fluxes with modern stream cation flux, and show that high relief, bare-rock slopes exhibit much lower chemical weathering rates despite higher physical erosion rates. The low weathering fluxes from rocky, rapidly eroding slopes allow for the broader implication that mountain building, while elevating overall denudation rates, may not cause increased chemical weathering rates on hillslopes. In order for this sediment to be weathered, intermediate storage, for instance in floodplains, is required.

1. INTRODUCTION

Much recent work has pointed towards physical erosion rates as a first order control on chemical weathering rates (Riebe et al., 2001a,b, 2004b). One consequence of these studies is that the concept of limits has to be applied to hillslope weathering. At very low erosion rates, the rate of supply of fresh material into the weathering zone is lower than the rate of mineral dissolution. In this case, termed supply-limited, all easily weatherable minerals are dissolved (Stallard, 1995; Riebe et al., 2004b; West et al., 2005). In contrast, at very high erosion rates, rock is moved through the weathering zone at a rate faster than that required for mineral dissolution. In this case, termed kinetically limited, the degree of chemical weathering is dependent on the rate at which individual minerals can be dissolved. To quantify these relationships, the chemical depletion fraction CDF has been introduced as the total fractional mass loss by weathering relative to the composition of the original bedrock (Riebe et al., 2001a). In the supply-limited case, CDF should remain constant with variable erosion rates as all weatherable minerals are dissolved. The CDF for the kinetically limited systems will scale inversely with physical erosion rates since faster erosion rates result in shorter residence time in the soil and therefore less intense chemical weathering. If physical erosion rates increase even further, soil cover thins, residence times become shorter and weathering rates decrease (Gabet, 2007; Ferrier and Kirchner, 2008; Gabet and Mudd, 2009).

Identification of these controls is important because removal of atmospheric CO_2 by chemical weathering represents

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a mechanism that is essential to balancing volcanic emissions, thereby maintaining CO_2 levels over geologic time scales at levels that favor a habitable climate on Earth (Berner, 1990). A common hypothesis suggests that the formation of mountain ranges should facilitate an increase in silicate weathering rates and consequently a reduction in atmospheric CO_2 and global temperatures (Raymo and Ruddiman, 1992; Berner and Kothaval, 2001). These hypotheses rely on the assumption that the increased relief generated in active orogens causes an increase in silicate weathering by providing abundant fresh rock to the surface. This hypothesis seems to be supported by stream cation fluxes, which are higher for mountainous regions than for stable cratons (Stallard, 1995). However, the global acceleration of this process in the last 10 My by an increase in global mountain erosion rates was recently challenged (Willenbring and von Blanckenburg, 2010).

The last decade has seen advances in the ability to accurately quantify weathering over varying timescales. Basin-averaged denudation rates can be calculated from cosmogenic nuclide concentrations in stream sediment (Brown et al., 1995; Granger et al., 1996; Kirchner et al., 2001; Schaller et al., 2001; von Blanckenburg, 2005). Bedrock denudation rates can be similarly determined from the concentration of cosmogenic nuclides in weathered regolith (Riebe et al., 2004a). When used in conjunction with the CDF derived from solute loss mass balance based on concentrations of refractory elements, the chemical and physical components of total denudation rate can be calculated separately. Riebe et al. (2004a) have used the combination of CDF and cosmogenic nuclide-derived denudation rates to demonstrate variation in chemical weathering rate with altitude in the Santa Rosa Mountains, California. In other studies, Riebe et al. (2001a,b, 2004b) show a strong correlation between physical erosion and chemical weathering rates. While both CDF and cosmogenic nuclide-derived denudation rates average over the time of soil formation, which is typically 10^2–10^4 yrs, modern chemical weathering rates can be calculated using stream cation flux if stream discharge is known (e.g. Gaillardet et al., 1999). Cation flux has been used extensively in the European Alps in order to characterize chemical weathering in proglacial and post-glacial environments (Sharp et al., 1995; Hosein et al., 2004; Georg et al., 2006). Modern chemical weathering rates in formerly glaciated watersheds are often many times smaller than the long-term rates in the same regions (Taylor and Blum, 1995). Fine-grained glacial sediments undergo rapid weathering of carbonate and biotite (Anderson et al., 2000), leaving behind the less reactive minerals, leading to reduced total weathering rates as soils develop on the glacial substrate. Chemical weathering rates have also been shown to vary over small spatial scales. Green et al. (2006) and Burke et al. (2007), investigating well-studied soils in California and Australia (Heimsath et al., 2000, 2005) suggest that chemical weathering rates and CDF can either increase or decrease with distance from ridge-tops due to varying soil depth and mass transport processes. Yoo et al. (2007) noted that down-slope movement of soil material in the dissolved or solid state leads to a systematic redistribution of elements in these soils, with most of the solutes produced high on the ridge, some of which are reprecipitated at lower elevation. Finally, Dixon et al. (2009a,b) separated chemical weathering in regolith from that of the underlying saprolite, finding an inverse correlation. These authors show that considerable weathering can take place below the soil when saprolite is present. They also showed that total denudation rates are higher for higher rates of saprolite weathering.

Here we attempt to address the question of the driving forces and rates of chemical weathering in the high Central Swiss Alps. A thorough analysis of the geomorphic processes sculpting this landscape including their denudation rates was recently published by Norton et al. (2010). We use Zr-derived CDF in conjunction with cosmogenic nuclide-derived denudation rates of amalgamated soil samples to calculate chemical and physical weathering rates in the upper Rhone Valley. We are specifically interested in the relationships between position on the hillslope and chemical weathering rates in the steep, high relief settings of the Central Alps and if the correlation between chemical weathering and physical erosion rates hold in areas undergoing transient response to Pleistocene glaciations. We apply a chemical weathering concept (Ferrier and Kirchner, 2008) to our data in order to model the degree of chemical weathering in terms of supply- vs. kinetically-limited weathering. Since, however, this model is based on the assumption that all weathering takes place in the soil layer and that the thickness of this layer is a function of denudation rate, we have also compared this model to the empirical law of West et al. (2005). This model takes into account that weathering can take place beneath the soil and that rates continuously increase with physical erosion rate. Finally, by comparing soil-based and stream cation-based fluxes, we investigate the temporal evolution of chemical weathering rates in these partially glaciated basins and discuss the implications with reference to orogen-scale weathering in general and the consequences for withdrawal of atmospheric CO_2.

1.1. Geomorphic setting

The upper Rhone Valley, or the Goms (Fig. 1), is located in the high central Swiss Alps. The northern and southern sides of the valley are underlain by the crystalline Aar and Gotthard Massifs respectively, with the meta-sedimentary Furka-Useren-Garvera Zone and Gomser Zwischenmassif inbetween. The study area includes portions of six watersheds on the northern side of the Rhone River. All sampling locations are underlain exclusively by the Aar Massif, which consists predominantly of gneiss (mineral modes calculated from bedrock elemental data: 23% quartz, 53% plagioclase, 17% orthoclase, ~4% biotite, and 3% muscovite), with granite (34% quartz, 35% plagioclase, 27% orthoclase and 4% biotite) found only in the upper most sections of the northern lateral valleys. These rocks dip steeply north northwest to vertical, striking roughly parallel to the main Rhone Valley with the result that the bedrock is homogeneous between the basins. Shear zones and large-scale sackungen are abundant in the Aar Massif, and are parallel the dominant foliation (Ustaszewski and Pfiffner, 2008). A Swiss Meteo weather station at Ulrichen, in the Goms, 1345 m, records