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Combining cosmogenic nuclides and major elements from moraine soil profiles to improve weathering rate estimates

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Previous studies of chemical weathering rates for soil developed on glacial moraines generally assumed little or no physical erosion of the soil surface. In this study, we investigate the influence of physical erosion on soil profile weathering rate calculations. The calculation of chemical weathering rates is based on the assumption that soil profiles represent the integrated amount of weathering since the time of moraine deposition. The weathering rate of a surface subjected to denudation is the sum of the weathering loss from the existing soil profile added to the weathering loss in the material removed by denudation, divided by the deposition age. In this study, the amount of weathered material removed since moraine deposition is calculated using the denudation rate estimated from cosmogenic nuclide data and the deposition age of the moraine. Weathering rates accounting for denudation since moraine deposition are compared to weathering rates based on the assumption of no physical erosion and on the assumption of steady-state denudation for the Type Pinedale moraine (~21 ka) and the Bull Lake-age moraine (~140 ka) in the Fremont Lake Area (Wind River Mountains, Wyoming, USA). The total weathering rates accounting for denudation are 8.15 ± 1.05 $g_{(oxide)}$ m^{-2} y^{-1} for the Type Pinedale moraine and 4.78 ± 0.89 $g_{(oxide)}$ m^{-2} y^{-1} for the Bull Lake-age moraine, which are ~2 to 4 times higher, respectively, than weathering rates based on the assumption of no physical erosion. The weathering rates based on denudation since moraine deposition are comparable or smaller than weathering rates assuming steady-state denudation. We find the assumption of steady-state denudation is not valid in depositional landscapes with young deposition ages or slow denudation rates. The decrease in weathering rates over time between the Type Pinedale and Bull Lake-age soils that is observed in the case of no physical erosion is decreased when the influence of denudation on the total weathering rates is taken into account. Fresh unweathered material with high reactive mineral surface area is continuously provided to the surface layer by denudation diminishing the effect of decreasing weathering rate over time.

1. Introduction

Quantification of weathering rates is important for the understanding of landscape evolution. Chemical weathering rates are influenced by many factors such as climate, vegetation, physical erosion, parent material composition, and soil age. Long-term chemical weathering rates have been determined from glacial deposits and river terraces of known age (e.g., April et al., 1986; Bain et al., 1993; Taylor and Blum, 1995; White et al., 1996) and hillslopes assumed to be in steady-state (e.g., Riebe et al., 2001; Green et al., 2006; Granger and Riebe, 2007). The analysis of soil chronosequences is the only direct method for determining changes of long-term chemical weathering rates over time, but this method is subject to several sources of uncertainty including differences in vegetation, climate, or heterogeneous soil parent material. Furthermore, the calculation of chemical weathering rates is sensitive to denudation of the soil surface, dust input, and the assumption of immobility of a reference element.

In this study, we specifically address the uncertainty introduced to chemical weathering rate calculations by denudation of the soil surface. In the past, the calculation of long-term chemical weathering rates from soil chronosequences was based on the assumption that the surfaces chosen for study were subjected to little or no physical erosion. However, soil chronosequences from glacial moraines are commonly sampled from moraine crests that are most likely subjected to significant physical erosion (e.g., Hallet and Putkonen, 1994; Putkonen and Swanson, 2003). Hence, the amount of weathering loss by removal of weathered material since moraine deposition needs to be added to the weathering loss calculated from the present soil profile. The quantity of the weathering loss since the time of moraine deposition from physical erosion depends on the denudation rate, the age of the moraine, and the depletion in major elements of the weathered material over time. The denudation of the soil can be quantified using cosmogenic nuclide concentrations (e.g., Wolkowinsky and Granger, 2004; Lal and Chen, 2005, 2006).

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In this study, we combine the analysis of major elements and cosmogenic nuclides from depth profiles situated on terminal moraines to better constrain the effect of denudation on long-term chemical weathering rates. Soil profiles from the ~21-ka-old Type Pinedale moraine and the ~140-ka-old Bull Lake-age moraine in the Fremont Lake Area (Wind River Mountains, Wyoming, USA) were investigated. We present a comparison of long-term chemical weathering rates based on the assumption of (i) no physical erosion (e.g., April et al., 1986; Brimhall and Dietrich, 1987; Bain et al., 1993; Taylor and Blum, 1995), (ii) denudation since moraine deposition (this study), and (iii) steady-state denudation (e.g., Granger and Riebe, 2007). Furthermore, we address the influence of denudation on the change of weathering rate with increasing surface exposure age.

2. Study area and characteristics of soil profiles

2.1. Study area

Soil profiles from the Type Pinedale (~21 ka) and Bull Lake-age (~140 ka) terminal moraines were sampled in the Fremont Lake Area (Wind River Mountains, Wyoming, USA). The moraines were formed during glaciations by large valley glaciers extending from the highland ice-caps covering the mountain range. The Type Pinedale, the Bull Lake-age, and potentially the Sacagawea glaciations have been recognized in the Fremont Lake Area (Richmond, 1973). Detailed mapping distinguished seven Pinedale (1–7) and five Bull Lake (I–V) moraines (Richmond, 1987) with “1” and “I” designating the terminal moraines. The steep-sided Type Pinedale moraine surfaces contain more boulders than the more gently sloping Bull Lake-age moraine surfaces. The climate is characterized by a mean annual temperature and precipitation of 1.8 °C and 231 mm, respectively (Zimmerman et al., 1994: United States Department of Commerce, 1965). The predominant vegetation has been big mountain sagebrush (*Artemisia tridentata*) since at least 11.5 ky as determined by ^{14}C (Barnosky et al., 1987). Some soil studies in the Fremont Lake Area indicate that loess or reworked loess is locally present in the soils of the Fremont Lake Area (Shroba, 1989; Sorenson, 1987), whereas other studies suggest that there is little or no loess in these soils (Hall and Shroba, 1993). Volcanic heavy minerals have been used to demonstrate the existence of loess in A and B horizons of soils developed on Type Pinedale and Holocene moraines in the Fremont Lake Area (Dahms, 1993). However, Sr isotope analysis showed no signal of significant eolian material in the depth profiles of the Type Pinedale and Bull Lake-age moraines used for chemical weathering rate calculations by Taylor and Blum (Blum and Erel, 1997; Taylor and Blum, 1997).

Ages for the Type Pinedale and Bull Lake-age moraines are derived from boulder exposure age dating. The Type Pinedale terminal moraine is attributed an age of 21.7 ± 0.7 ka (Gosse et al., 1995) based on surface exposure age dating of boulders. Recalculation of the ages based on different production rates results in a mean age of 19.6 ka (Benson et al., 2004). Cosmogenic nuclide exposure ages from boulders of the Bull Lake-age moraine in the Fremont Lake Area range from 115 to 160 ka with a mean age of 140 ka (Easterbrook et al., 2003). Combining surface exposure ages of moraines and ^{230}Th/U age constraints of fluvial terraces in the east of the Wind River Mountains yields best age estimates of 21 and 140 ka for the Type Pinedale and Bull Lake-age moraines, respectively, in the Fremont Lake Area. Denudation rates of the moraine crests were determined with cosmogenic nuclide depth profiles to be 0.025 and 0.012 mm y^{-1} for the Type Pinedale termfinal moraine and the Bull Lake-age terminal moraine, respectively (Schaller et al., in press).

2.2. Characteristics of soil profiles

Depth profiles for weathering rate studies were collected from the Type Pinedale terminal moraine (2262 m asl, 42° 53' 26" N., 109° 49' 34" W.) and the Bull Lake-age terminal moraine (2285 m asl, 42° 52' 39" N., 109° 51' 00" W.) in the Fremont Lake Area, Wyoming (Fig. 1). The soil profiles of this study were sampled in close proximity to other well-studied soil profiles (e.g., Hall and Shroba, 1995). The tills sampled for this study are a mixture of Archean granite, granodiorite, and dioritic gneiss. The primary minerals observed in the unweathered samples are

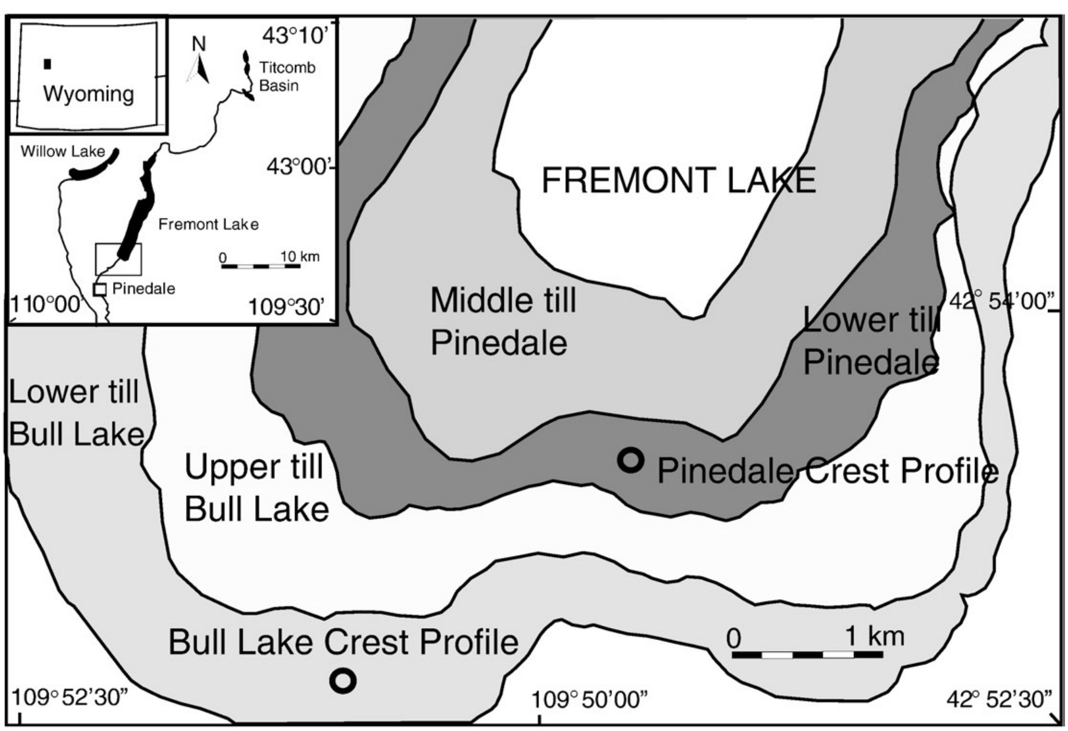

Fig. 1. Location overview of depth profiles from the Fremont Lake Area (Wind River Mountains, Wyoming, USA) used for weathering rate studies. The depth profiles were taken from the terminal Type Pinedale (~21 ka) and Bull Lake-age (~140 ka) moraines (see Richmond, 1973, 1987).