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Potential of in situ-produced cosmogenic nuclides for quantifying strength reduction of bedrock in soil-mantled hillslopes

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Abstract

This study presents a semi-empirical model for quantifying the reduction in the mechanical strength of bedrock beneath actively eroding soil-mantled hillslopes. The strength reduction of bedrock controls the rate of physical disintegration of saprolite, which supplies fresh minerals that are then exposed to intense chemical weathering in soil sections. To determine the values of parameters employed in the model requires knowledge of the denudation rate of the hillslope, the thickness of the soil and saprolite layers, the strength of fresh bedrock, and the threshold strength for physical erosion at the uppermost face of the saprolite. These parameters can be obtained from cosmogenic nuclide analyses for quartz samples from the soil–saprolite boundary and basic field- and laboratory-based investigations. Further testing of the model within a diverse range of climatic, tectonic, and lithologic environments is likely to provide clues to the mechanisms responsible for local and regional variations in the rates of soil production and chemical weathering upon hillslopes.

Keywords: Cosmogenic nuclides; Weathering; Soil production; Saprolite; Rock strength

1. Introduction

Analyses of in situ-produced cosmogenic nuclides, especially ^{10}Be ($T_{1/2} = 1.36 \times 10^6$ yr) and ^{26}Al ($T_{1/2} = 7.05 \times 10^5$ yr) produced in quartz, have revolutionized our approach to the dating of landforms and determining the rates of earth surface processes (Gosse and Phillips, 2001). The application of the cosmogenic nuclide methods in geomorphology has altered our understanding of the ages of landforms and the timescales of landscape change (Bierman et al., 2002; Bierman and Nichols, 2004; Cockburn and Summerfield, 2004; Von Blanckenburg, 2006). Such nuclides can be used as a chronometer that provides the exposure age of an 'event surface', where both of pre-exposure nuclide accumulation under the depths of shielding and post-exposure erosion are negligible. The nuclide concentration at an actively eroding surface or in sediment eroded from its source area acts as an indicator of denudation. This is because the nuclide concentration reflects the residence time of the material near the land surface, where it is subject to cosmic ray irradiation (Lal, 1991). The shorter the residence time, the lower the steady-state equilibrium concentrations of nuclides will be in minerals within the rock, implying rapid denudation of the landform.

The application of the cosmogenic nuclide method was initially confined to areas of bare rock at high latitudes or in arid environments, but has rapidly spread to humid and temperate mid-latitude areas where soils cover most of the land surface. Although the soil thickness in a given region generally ranges from only several decimeters to several meters, the soil layer provides the key to understanding ongoing geomorphic and geochemical processes in mountainous terrain. The conversion of bedrock to soil leads to the accumulation of unstable material on hillslopes, thereby controlling the sediment yield within watersheds, which in turn affects natural ecosystems in the catchments of mountain streams and the lifetimes of civil engineering structures in the lower reaches of rivers. At a longer

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timescale, the soil layer functions as a geochemical subsystem that consumes atmospheric CO_2 via silicate weathering; this process possibly acted as a buffer to fluctuations in paleoclimate, having a negative feedback in terms of weakening the greenhouse effect (Walker et al., 1981; Berner, 1995).

The present paper highlights recent advances and future potential of the cosmogenic nuclide approach in studies of hillslope denudation. Several recent studies have developed the methodology for quantifying long-term chemical weathering in soil-mantled hillslopes by combining measurements of cosmogenic nuclides with a conservative element mass-balance approach (Riebe et al., 2001, 2003, 2004; Green et al., 2006; Burke et al., 2007; Yoo et al., 2007). These studies have demonstrated the strong coupling of physical and chemical processes in hillslope denudation. The present study focuses on the saprolite zone, a chemically decomposed layer that occurs beneath the mobile soil mantle, where the bedrock is set to be physically disintegrated into the overlying soil layer. The susceptibility of bedrock to chemical decomposition, especially in terms of the resulting reduction in mechanical strength, is a crucial factor in determining the rates of physical soil production and transport, and hence subsequent chemical weathering in soil sections.

We propose a semi-empirical model that describes the reduction in mechanical strength of bedrock and captures a steady-state depth–strength profile in the saprolite zone. The term 'strength' is here defined as the mechanical resistance of landform materials to physical geomorphic agents, including shearing by gravity or water flow, freeze–thaw action, bioturbation, and wetting–drying processes. The proposed model provides a means of evaluating the controlling mechanisms of soil production functions, linking geologic, climatic, and tectonic factors with the rates of physical and chemical denudation of soil-mantled hilly landscapes.

2. Methods for quantifying physical and chemical processes on hillslopes

The denudation of hillslopes progresses via two types of mass loss: (1) chemical weathering (mineral dissolution by water–rock reactions), and (2) physical erosion (the mechanical breakdown of bedrock and the downslope removal of the resulting mineral fragments). These processes act together in developing soil-mantled hillslopes. The chemical weathering rates were typically measured by solute fluxes from watersheds (e.g., White and Blum, 1995), or by chemical composition of non-eroding soils with known age (e.g., Brimhall and Dietrich, 1987). For a physically eroding soil on a sloping terrain, quantification of the chemical weathering rate requires the mean residence time of the soil that correlates inversely with the rate of rock-to-soil conversion, which in turn is equivalent to the long-term rate of total denudation of the hillslope (White et al., 1998; Anderson et al., 2002).

The concentration of cosmogenic nuclides in rock minerals is a function of the total denudation on a given hillslope (sum of the chemical and physical mass losses). Denudation rates determined from cosmogenic nuclides are typically averaged over a timescale of 10^3–10^5 yr that is relevant to the timescales for soil generation and alternation on hillslopes under a wide range of climate regimes. Riebe et al. (2001, 2003) proposed a methodology for separately quantifying the rates of chemical weathering and physical erosion by combining the cosmogenically determined denudation rate with the geochemical mass-balance for a hillslope.

Fig. 1 shows denudation processes in a soil-mantled mountainous watershed. Immobile parent material (saprolite on fresh bedrock) is converted to mobile soil on a hillslope at the rate of D, and the soil is subject to physical erosion E and chemical weathering W (each of these terms are given in mass flux: $\mathrm{g\,m^{-2}\,yr^{-1}}$). Under steady-state soil production and denudation, implying a constant soil thickness on the hillslope over time, the rate of saprolite conversion to soil is equal to the total denudation (Riebe et al., 2001):

$$D = E + W. \quad (1)$$

Because bedrock subject to denudation contains both soluble and insoluble components, chemical depletion of the rock-forming minerals should lead to an enrichment in insoluble elements within soil sections (Fig. 1). Focusing on an insoluble element such as zirconium, the mass

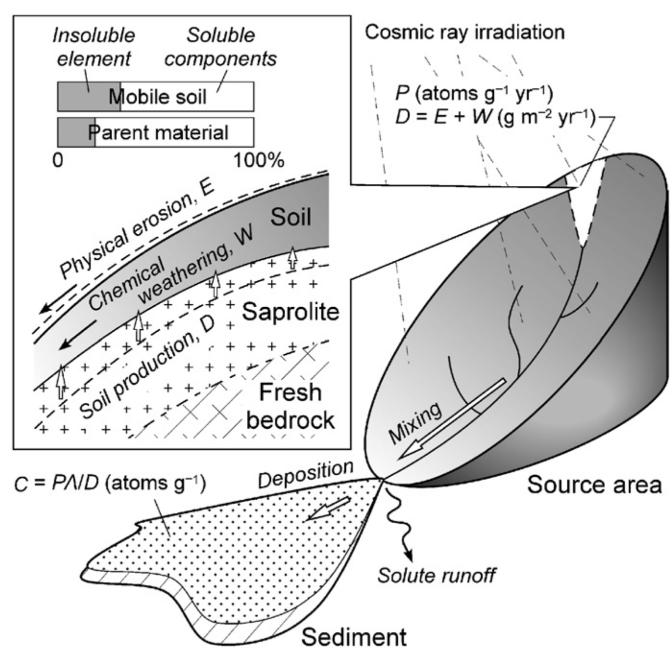

Fig. 1. Schematic illustration of denudation processes within a soil-mantled watershed (D, rate of conversion of bedrock to soil; E, rate of physical erosion; W, rate of chemical weathering; P, production rate of cosmogenic nuclides; C, cosmogenic nuclide concentration; Λ, cosmic ray attenuation length).