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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 of 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 ($T_{1/2}$ = 1.36×10^6 yr) and ^{26}Al ($T_{1/2} = 7.05\times10^5$ 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 is 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 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.

Figure 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: 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):

$$D = E + W \,. \qquad (1)$$

Fig. 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 conservation equation can be rewritten as

$$D[\mathrm{Zr}]_{\mathrm{rock}} = E[\mathrm{Zr}]_{\mathrm{soil}}\,, \qquad (2)$$

where $[\mathrm{Zr}]_{\mathrm{rock}}$ and $[\mathrm{Zr}]_{\mathrm{soil}}$ are the concentrations of zirconium in the rock and soil, respectively (Riebe et al., 2001). Equation (2) states that the zirconium budget during the conversion of rock to soil is balanced solely with physical erosion, under conditions of no chemical dissolution. Substitution of Eq. (2) into Eq. (1) yields

$$\frac{W}{D} = \left(1 - \frac{[\mathrm{Zr}]_{\mathrm{rock}}}{[\mathrm{Zr}]_{\mathrm{soil}}}\right), \qquad (3)$$

indicating that we are able to quantify the contribution of chemical weathering to total denudation based on the enrichment of conservative elements in soil sections. The ratio (W/D) was termed the chemical depletion fraction (CDF) by Riebe et al. (2003).

At a catchment-averaged scale, the total denudation rate D can be determined from the cosmogenic nuclide concentration C in well-mixed sediment washed out from the source area (Fig. 1). The nuclide concentration C (atoms g^{-1}) in the sediment can be written as

$$C = \frac{P\Lambda}{D}, \qquad (4)$$

where P is the nuclide production rate (atoms g^{-1} yr^{-1}) at the land surface in the source area and Λ is the cosmic ray attenuation length (g m^{-2}) (Granger et al., 1996). Equation (4) is based on the three main assumptions: 1) the hillslopes are eroded continuous processes, 2) the time required to remove materials with a thickness equivalent to Λ from the hillslopes is much shorter than the radioactive mean life (10^6 yr timescale for ^{10}Be and ^{26}Al), and 3) hillslopes in the source area contribute sediment to the channel in proportion to their local erosion rate.

Combining Eqs. (3) and (4), we can deduce the chemical weathering rate:

$$W = \frac{P\Lambda}{C}\left(1 - \frac{[\mathrm{Zr}]_{\mathrm{rock}}}{[\mathrm{Zr}]_{\mathrm{soil}}}\right). \qquad (5)$$

Riebe et al. (2004) applied this methodology to several granitic sites in Central and North America and New Zealand under various climatic and tectonic settings. They empirically formulated the rates of chemical weathering with the product of an Arrhenius-like function of mean annual temperature and power functions of the rates of precipitation and total denudation. The empirical function was successful in explaining regional variations in the rates of chemical weathering of bulk soils (from close to 0 to 2×10^2 g m^{-2} yr^{-1}).

3. Importance of reductions in bedrock strength

Riebe et al. (2004) concluded that the most crucial factor in controlling the rate of chemical weathering is the total denudation rate, which in turn is regulated mainly by tectonic forcing leading toward a local base-level lowering (Riebe et al., 2000); while the climatic factors appear to affect the relative contribution of chemical weathering (CDF: W/D). Under a given climate, they found that the rate of chemical weathering is almost proportional to the total denudation rate (rate of rock-to-soil conversion on hillslopes). This situation is termed 'supply-limited weathering', whereby chemical depletion occurs only if attackable mineral surfaces are made available as a consequence of the mechanical disintegration of bedrock (Riebe et al., 2004).

Riebe et al.'s (2001, 2003, 2004) method enables us to make rough comparisons of the rates of chemical weathering under different conditions of physical erosion rates, and suggests a large-scale coupling of chemical and physical processes. This spatially averaged estimate of the rate of chemical weathering is only valid if the soil chemistry is homogeneous within the hillslope of interest, implying uniform mineral supply, soil transport, and subsurface water dynamics regardless of topographic location. However, most recent studies suggest that CDFs and chemical weathering rates vary at the hillslope scale because of spatial variations in soil production rates, soil particle dwell time, and fluid flux (Green et al., 2006; Burke et al., 2007). Point-specific CDFs and chemical weathering rates have been modeled by integrating physical soil production and transport along a hillslope transect (Yoo et al., 2007).

Soil production is one of the most crucial factors in modeling local variations in the values of CDF and the rates of chemical weathering (Yoo et al., 2007). Heimsath et al. (1997) determined the first empirical soil production function from measurements of cosmogenic nuclides at the soil–saprolite boundary, assuming the steady-state production and transport of soil on the hillslope. Heimsath et al. (1997, 1999, 2000, 2001a, b, 2005, 2006) deduced the soil production functions at several sites in northern California, U.S., and Southeast Australia, and demonstrated that the soil production rate decreases exponentially with increasing local soil depth (Fig. 2). The intercept of the soil production function showed marked differences among the sites analyzed, varying between 50 and 300 mm kyr^{-1} (Fig. 2).

Fig. 2

The balance between mechanical strength and the physical processes acting on a hillslope determines whether a block of bedrock disintegrates into loose mineral fragments; consequently, differences in the soil production functions should be considered with respect to the strength reduction behavior of bedrock and the threshold of physical erosion. A reduction in strength occurs within the saprolite zone: a decomposed layer between soil and fresh bedrock. In the present study, we suggest the potential of combining analyses of cosmogenic nuclides at the soil–saprolite boundary and determining a strength profile for the saprolite zone in terms of quantifying the sensitivity of bedrock to strength reduction, as this sensitivity is a crucial factor in determining the physical erodibility of saprolite and hence the rates of soil production and soil chemical weathering on a hillslope.

4. Model for quantifying the reduction in rock strength

In this section, we present a semi-empirical model that describes the reduction in the mechanical strength of bedrock during weathering. Three subsurface layers are defined within a hillslope (Fig. 3): the mobile soil layer above the depth of the soil–saprolite boundary Z_{SSB} [L], the zone of fresh bedrock below the depth of the weathering front Z_{WF} [L], and the layer of saprolite between Z_{SSB} and Z_{WF}. The depth Z [L] is defined normal to the land surface, being equal to zero at the land surface at an arbitrary point in time. The depth Z_{SSB} is the boundary between the mobile and immobile layers. No strength reduction occurs below Z_{WF}, beyond the extent of weathering.

Fig. 3

Under conditions of steady-state denudation on a hillslope, the soil–saprolite boundary and the weathering front migrate downward at the same rate. Assuming that the total denudation rate in the soil section is D [M L^{-2} T^{-1}], the rate of downward migration of the soil–saprolite boundary is D/ρ_{sp} [L T^{-1}], where ρ_{sp} [M L^{-3}] is the density of saprolite. The rate D/ρ_{sp} is the same for downward penetration of the weathering front, fulfilling the condition that the hillslope maintains a constant thickness of soil and saprolite layers over time (Fig. 3).

The strength of fresh bedrock S_{FB} [M L^{-1} T^{-2}] decreases to the erosion threshold S_{ET} [M L^{-1} T^{-2}] within the saprolite zone, leading to mechanical disintegration and the removal of material at the uppermost face of the saprolite. The reduction in rock strength S [M L^{-1} T^{-2}] with time t [T] has been modeled previously by Sunamura (1996):

$$\frac{\mathrm{d}S}{\mathrm{d}t} = -kS \qquad (6)$$

where k [T^{-1}] is the strength reduction coefficient ($k > 0$). The equation's prediction of an exponential decrease in rock strength with time has been verified by measurements of the compressive and tensile strength of rhyolite lavas with eruption ages of 40, 20, 2.6, and 1.1 ka (Oguchi, 1999).

This study assumes that the strength reduction coefficient k decreases with increasing depth within the saprolite zone, as an inward decrease in the degree of weathering is commonly observed in subsurface hillslope profiles. The rate of strength reduction must be zero below the weathering front. Accordingly, the coefficient k should be a depth-dependent value that decreases with increasing depth below Z_{SSB} and diminishes to zero at $Z \rightarrow Z_{\mathrm{WF}}$:

$$k = f(Z) = m\left(1 - \frac{Z}{Z_{WF}}\right)^{n-1} \qquad (Z_{\mathrm{SSB}} \leq Z < Z_{\mathrm{WF}}), \qquad (7)$$

where m [T^{-1}] and n [–] are parameters ($m > 0$; $n \geq 1$) that represent the sensitivity of bedrock to strength reductions with time and depth, respectively.

The apparent profile of subsurface strength should be time-independent under steady-state denudation, characterized by a constant thickness of soil and saprolite. Thus, the strength reduction with time at depth Z should be zero (note that Z is the depth from the eroding land surface at an arbitrary point in time):

$$\frac{\partial S}{\partial t} = -m\left(1 - \frac{Z}{Z_{\mathrm{WF}}}\right)^{n-1} S + \frac{D}{\rho_{\mathrm{sp}}}\frac{\partial S}{\partial Z} = 0\,. \qquad (8)$$

The solution of the differential equation is

$$S = S_{\mathrm{FB}} \exp\left[-\frac{m}{n}\frac{\rho_{\mathrm{sp}}}{D} Z_{\mathrm{WF}}\left(1 - \frac{Z}{Z_{\mathrm{WF}}}\right)^{n}\right] \qquad (Z_{\mathrm{SSB}} \leq Z < Z_{\mathrm{WF}}), \qquad (9)$$

with the initial condition that $\lim_{Z \rightarrow Z_{\mathrm{WF}}} S = S_{\mathrm{FB}}$.

The three curves shown in Fig. 3 represent schematic strength profiles in the cases of n = 1, 2, and 3. A depth–strength profile for a given saprolite zone, along with values of S_{FB}, Z_{WF}, and ρ_{sp}, can be determined from field- and laboratory-based investigations, and the denudation rate D can be deduced from cosmogenic nuclide analyses at Z_{SSB}. Thus, fitting Eq. (9) to the measured depth–strength profile provides the optimal values of m and n in the strength reduction function.

The strength S decreases to the erosion threshold S_{ET} at $Z = Z_{SSB}$ (Fig. 3); that is,

$$S_{ET} = S_{FB} \exp\left[-\frac{m}{n} \frac{\rho_{sp}}{D} Z_{WF} \left(1 - \frac{Z_{SSB}}{Z_{WF}} \right)^n \right]. \qquad (10)$$

Solving Eq. (10) for D gives

$$D = \rho_{sp} \frac{m}{n} \frac{H_{sp}{}^n}{Z_{WF}{}^{n-1}} \left[\ln\left(\frac{S_{FB}}{S_{ET}} \right) \right]^{-1}, \qquad (11)$$

where H_{sp} [L] is the steady-state thickness of saprolite ($H_{sp} = Z_{WF} - Z_{SSB}$). The value of H_{sp} can be obtained via observations of drill core from the hillslope of interest or outcrop exposed within a large quarry if present, while S_{ET} can be deduced from strength measurements at the soil–saprolite boundary. Consequently, we can test the strength reduction model using Eq. (11), provided that denudation rates D are available at several points on a hillslope with contrasting H_{sp} and S_{ET}.

It is possible to use various measures of material strength (e.g., compressive or tensile strength, cohesion) and proxies (e.g., dynamic cone penetrating resistance, static cone or needle penetration hardness, vane shearing strength, rebound values of an impact test hammer) in this approach. An appropriate strength measure or proxy should be analyzed to understand geomorphic processes with respect to the type of driving forces operating on the landform material subject to erosion; however, a single measure or proxy is seldom able to cover the wide range in strength of diverse landform materials that vary from fresh, hard bedrock to soft, loose saprolite and soil. Although practical difficulties remain in terms of measuring material strength, the proposed model provides a conceptual framework in which to quantify the strength reduction function of bedrock.

Lithologic, climatic, and topographic factors act to regulate the values of parameters employed in the proposed model. The strength of fresh bedrock S_{FB} varies for different rock types, and the parameters m, n, and H_{sp} are controlled by the solubility of bedrock (which varies with mineral composition) and slope hydrology or climate conditions. The erosion threshold S_{ET} is influenced by the local hillslope gradient, thickness of the soil mantle, and the intensity and type of physical processes that operate at the soil–saprolite boundary. Testing of the strength reduction model using Eqs. (9) and (11) under diverse environments would provide clues to the controlling mechanisms of the rates of soil production and transport, and hence the rate of chemical weathering on hillslopes.

5. Concluding remarks

The concentration of cosmogenic nuclides at the soil–saprolite boundary reflects the duration over which the fresh bedrock converts to a mobile soil layer, and therefore the time required for the bedrock strength to decrease to the threshold of physical erosion within the saprolite zone. The model proposed in this study can be used to evaluate the susceptibility of bedrock to strength reduction with time and depth, providing crucial data for understanding the rate of rock-to-soil conversion on hillslopes and hence the rate of chemical weathering in soil sections. Although the proposed model is semi-empirical and based on the assumption of steady-state conditions, it provides a new theoretically motivated soil-production function, expressed as Eq. (11). The model requires cosmogenically determined denudation rates and several other parameters that are readily obtainable from field- and laboratory-based investigations. Future testing of the model within various climatic, tectonic, and lithologic settings is likely to reveal the mechanisms that control the rates of soil production and chemical weathering on hillslopes, as well as those factors that influence landscape diversity such as the development of soil-mantled or bare-rock-dominated hilly terrains.

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Figure captions

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.

Fig. 2. Plot showing the exponential decrease in soil production rates with increasing soil thickness, as reported in Heimsath et al. (1997, 1999: Marin County, CA, US; 2001a: Coos Bay, OR, US; 2005: Point Reyes, CA, US; 2000, 2001b, 2006: Bega Basin, Southeast Australia). The soil production functions were determined based on analyses of cosmogenic nuclides at the soil–saprolite boundary, assuming steady-state conditions of the formation and transport of soil upon each of the analyzed hillslopes. The shaded regions in the figure indicate the range of uncertainty based on variance-weighted regressions for datasets of local soil thickness and cosmogenically determined rates of soil production.

Fig. 3. Subsurface layers and model strength profiles for a soil-mantled hillslope. The strength of fresh bedrock S_{FB} decreases to the erosion threshold S_{ET} within the saprolite zone. Both the soil–saprolite boundary and the weathering front migrate downward at the rate of D/ρ_{sp} (where ρ_{sp} is the density of saprolite), thereby fulfilling the condition that the hillslope maintains soil and saprolite layers of constant thickness over time, as well as a constant apparent strength profile. The strength reduction functions are modeled as Eqs. (6) to (9) in the text.

Figures

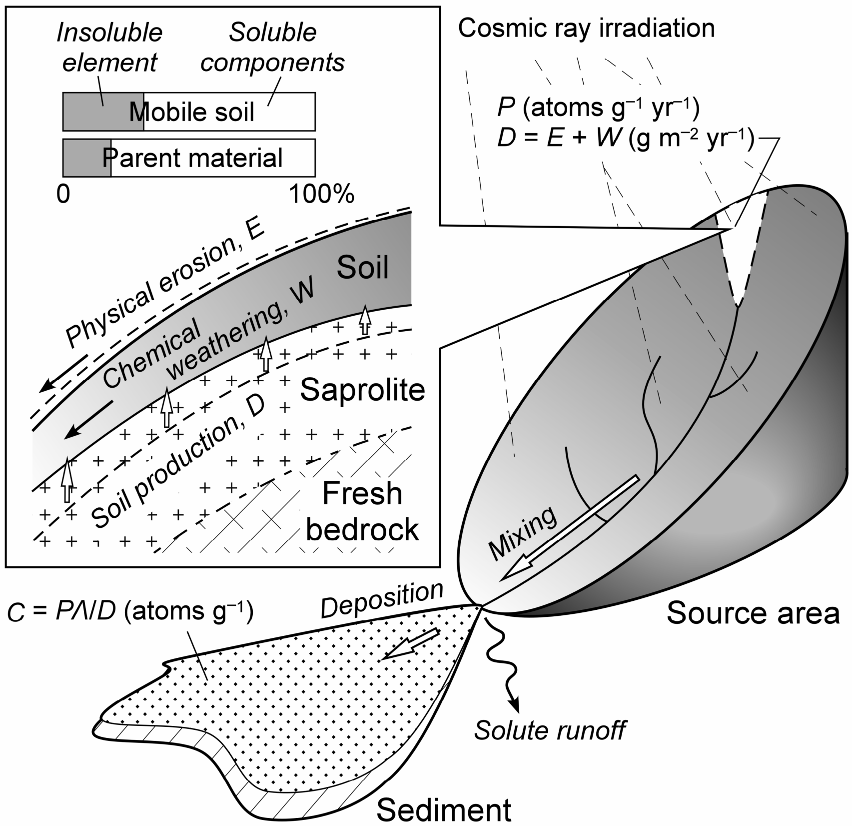


Fig. 1

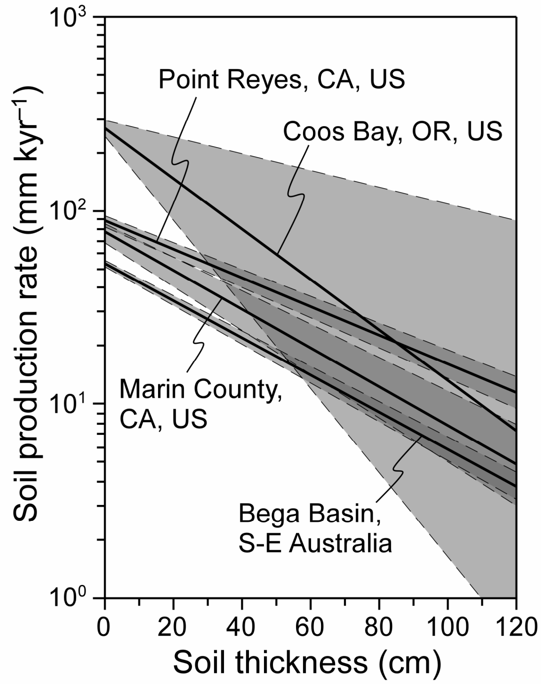
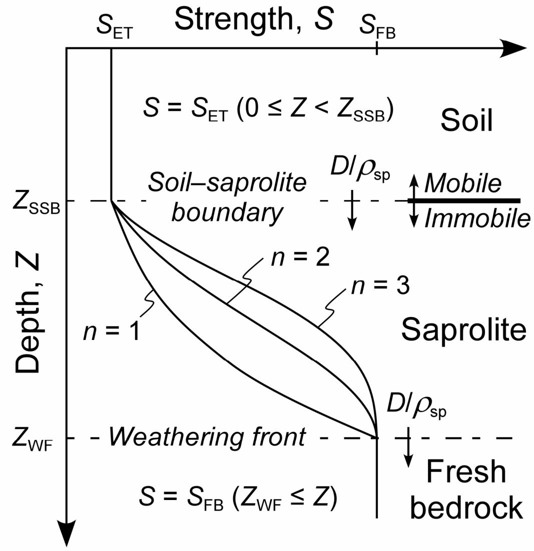

Point Reyes, CA, US
Coos Bay, OR, US
Marin County, CA, US
Bega Basin, S-E Australia
Soil production rate (mm kyr^{-1})
Soil thickness (cm)
10^3
10^2
10^1
10^0
0
20
40
60
80
100
120

Fig. 2



$$S = S_{FB} \cdot \exp[-(m\rho_{sp} Z_{WF}/nD) \cdot (1 - Z/Z_{WF})^n]$$
$$(Z_{SSB} \le Z < Z_{WF})$$

Fig. 3