Quantification of soil production and downslope creep rates from cosmogenic ^{10}Be accumulations on a hillslope profile

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ABSTRACT

Average soil transport rates over a period of ~3500 yr on a convex soil-mantled hillslope have been quantified using a mass-balance model that incorporates the soil concentration of the cosmogenic isotope ^{10}Be. The ^{10}Be model results support the assumption used in most geomorphic models that the soil creep rate is proportional to surface gradient. The predicted diffusion coefficient is 360 ±55 $cm^3 \cdot yr^{-1} \cdot cm^{-1}$ contour length and the average rate of soil production is 0.026 ±0.007 cm/yr. Within the uncertainty of this technique, the data do not reject G. K. Gilbert's hypothesis that some hillslopes may exist in a condition of dynamic equilibrium with a uniform soil production rate. However, the model does not require an assumption of dynamic equilibrium and may be an approach that uniquely allows the quantification of a local soil-production rate law.

INTRODUCTION

Geomorphic modeling of long-term hillslope evolution is commonly done by imposing conservation of mass and using transport algorithms to describe the movement of material on slopes (e.g., Ahnert, 1967; Kirkby, 1971). However, there are few field data to either evaluate the validity of proposed transport laws or quantify any of the transport rates.

It has been suggested frequently that gravity-driven soil creep is an important transport process on many soil-mantled hillslopes. Gilbert (1877, 1909) proposed that the rate of soil creep is proportional to slope gradient and that slopes may achieve a condition of dynamic equilibrium. On such slopes both the soil thickness and rate of soil production by rock weathering are uniform and the soil creep flux increases with distance from the top of the slope. It then followed (Gilbert, 1909) that the slope must steepen with distance from the divide; i.e., the slope profile must be convex upward to provide the necessary transport capacity. This hypothesis is the basis for many models that use slope-dependent soil-transport laws to investigate the evolution of soil-mantled hillslopes.

However, soil-creep rates are slow enough that precise measurements over long time periods are required to quantify creep movement patterns by direct observations. Most of the published soil-creep data from in situ measurements made over periods of only a few years display large variability and show little evidence for a slope dependence of downslope creep rate (e.g., Kirkby, 1967; Fleming and Johnson, 1975). Soil production rates are even more difficult to measure, and there are few data published on this critical process (Ahnert, 1967).

Here we use a mass-balance model (Monaghan et al., 1992) that incorporates the rate of production of the cosmogenic isotope beryllium-10 (^{10}Be) to evaluate directly with field data the Gilbert (1877, 1909) hypothesis of dynamic equilibrium on soil-mantled hillslopes. The model effectively allows measurement of soil creep and soil production rates integrated over periods of thousands of years, thereby avoiding the uncertainty of short-term in situ measurements.

ONE-DIMENSIONAL, STEADY-STATE, MASS-BALANCE MODEL

^{10}Be ($t_{1/2}$ = 1.5 m.y.) is produced in the atmosphere from spallation reactions (Lal and Peters, 1967). The ^{10}Be attaches to aerosols and is delivered to the ground by precipitation. The atmospheric production rate varies with latitude, and the delivery rate to a site depends on both the atmospheric production and local precipitation rates. In situ production of ^{10}Be in soils is approximately five orders of magnitude slower and is ignored here. Previous studies have shown that in clay-rich soils, infiltrating cosmogenic ^{10}Be cations are quickly adsorbed, and that over short time scales little ^{10}Be migration in ground water occurs (e.g., Pavich et al., 1986). In some coarse-grained, low-pH soils, the ^{10}Be residence time in the soil may be short because the isotope is not efficiently adsorbed and is leached by ground water (e.g., Monaghan et al., 1983). This mass-balance model is not appropriate if the ^{10}Be is mobile in the ground water.

On a hillslope in dynamic equilibrium, the soil-creep rate at any position may be considered to be relatively steady over periods of a few thousand years. If the atmospheric delivery rate of ^{10}Be is also approximately constant, and the isotope is adsorbed in the soil horizon, a mass balance of ^{10}Be is developed in the soil between the steady atmospheric input and the steady downslope creep flux (Fig. 1A). If the bedrock contains no ^{10}Be, then in one dimension the soil ^{10}Be mass balance over some slope distance may be expressed (after Monaghan et al., 1992) as

$$\int_0^x P_{Be}(x)\,dx = \int_0^h \rho_s(x, z)V_s(x, z)\varepsilon_{Be}(x, z)\,dz. \tag{1}$$

Here ε_{Be} is the concentration of ^{10}Be in the soil (atoms/g), P_{Be} is the atmospheric delivery rate of ^{10}Be (atoms$\cdot cm^{-2} \cdot yr^{-1}$), ρ_s is the soil density (g/cm^3), V_s is the soil creep velocity (cm/yr), and h is the soil thickness (cm) (Fig. 1A).

It may reasonably be assumed that $P_{Be}(x)$ is uniform over any slope and that $\rho_s(x, z)$ and h are uniform over some slope distance. If the soil creep is assumed to occur as simple plug flow, then the creep velocity is only a function of x and a vertically averaged concentration of ^{10}Be (C_{Be}) may be evaluated at any x. Equation 1 then reduces to $P_{Be}x = \rho_s V_s(x) C_{Be}(x) h$, and noting that the volume flux of soil $Q_s(x) = V_s(x)h$ gives

$$Q_s(x) = \frac{P_{Be}x}{\rho_s C_{Be}(x)}. \tag{2}$$

The assumption of plug flow is not necessary, and any vertical velocity profile function may be substituted into equation 1. In fact, no assumptions are required about the mechanics of soil creep (e.g., that creep rate is proportional to slope angle). Monaghan et al. (1992) evaluated soil production rates using two extremes of velocity profiles (plug flow and pure shear flow) and found little change in the predicted result. Therefore, the simpler case of plug flow is used here.

The presumed linear dependence of soil volume creep on slope steepness has been expressed as $Q_s(x) = k(x)S(x)$, where S is the tangent of the slope angle, and k is a diffusion coefficient. Then, substituting into equation 2 yields

$$k(x) = \frac{P_{Be}x}{\rho_s C_{Be}(x)S(x)}. \qquad (3)$$

Under steady-state conditions there is also a soil mass balance wherein the downslope soil flux away from some point must exactly balance the mass arriving from upslope plus that mass produced by bedrock conversion to soil (Fig. 1A). In one dimension, this may be expressed (following Kirkby, 1971) as

$$\frac{\partial \rho_s Q_s}{\partial x} = \rho_r C_o(x), \qquad (4)$$

where ρ_r is the uniform weathered-rock density (g/cm^3) and C_o is the steady rate of production of soil by rock weathering. Then by substitution of $Q_s(x)$ from equation 2 into equation 4, the soil ^{10}Be concentration pattern may be used to evaluate $C_o(x)$.

STUDY SITE AND METHODOLOGY

The model was evaluated on a hillslope in the Black Diamond Mines Regional Preserve, East Bay Regional Park District, ~60 km east of San Francisco, California. The slope is convex in profile (Fig. 1A) and straight in plan view (Fig. 1B). The site bedrock is an overconsolidated Eocene marine shale (Sullivan, 1987) that weathers to a high-plasticity clay soil. The slope faces south and is obsequent to the bedrock, which dips north at ~30°. Vegetation on the slope consists of grasses. The mean annual precipitation is ~45 cm and occurs as rain (Contra Costa County Flood Control District, 1992, personal commun.).

The slope is extremely smooth, suggesting that the dominant transport processes are slope dependent. Over a 3-yr period, no overland flow or surface features such as rills have been observed, indicating little or no surface erosion by sheet wash. No evidence of past mass movement is visible on the slope. Soil transport on the convex slope appears to be by mechanical creep and/or biological mixing. The soil layer is uniform, with only a slight downslope thickening (Fig. 1A). Thus, the assumptions in the mass-balance model appear to be met on this slope.

Three test pits were excavated on a slope profile (Fig. 1, A and B; CLTP1, CLTP2, and CLTP3). Details of the sampling from the pits and the ^{10}Be extraction and measurement processes are in J. McKean (unpublished).

RESULTS

The ^{10}Be concentration depth profiles for each test pit are shown in Figure 2. Each data point represents the average of two duplicate measurements from a single homogenized block sample taken from a given depth interval. The relevant depth interval is shown by the vertical line through the point. The upper and lower error bars are the maximum and minimum of the accelerator mass spectrometer (AMS) 1 σ uncertainty values for the two duplicate samples. These error bars thus depict the combined uncertainty due to both natural differences within the block sample and the AMS measurement errors.

The majority of the ^{10}Be resides in the soil layer at each test pit (Fig. 2). The unweathered-rock ^{10}Be concentrations are virtually identical to the background level of ^{10}Be in the AMS control blank samples. This indicates that the ^{10}Be probably does not migrate with ground water from the soil into the rock. Furthermore, the porosity and typical field capacity for this clay soil suggest that ~15 cm of rain can be stored in the soil layer. Over a 15-yr period, the maximum 5-day rainfall was 8.6 cm at a gauge 4 km from the site (Contra Costa County Flood Control District, 1992, personal commun.). Thus, little infiltration into the rock probably occurs at this ridge-line site.

In the test pits, a weathered-rock horizon was exposed that consists of intact bleached blocks of shale that are slightly separated from their neighbors by open joints (<0.5 cm wide) orthogonal to the bedding surfaces. Some soil material has fallen into the open joints, carrying with it only a small amount of ^{10}Be, as seen by the slight increase in ^{10}Be concentration in the weathered rock (~3 to 5 × 10^6 atoms/g) (Fig. 3). This small leakage of soil ^{10}Be is neglected at present, although this ^{10}Be mass could be included in the soil values if desired.

The decrease in ^{10}Be concentration with depth in each soil horizon profile may reflect the rapid adsorption of ^{10}Be onto soil particles during infiltration and a decrease with depth in the intensity of mixing of the soil due to creep and bioturbation. As noted, a plug flow approximation assuming uniform mixing of the soil is used in this model because this assumption introduces no additional uncertainty in the result. The profiles also suggest that the ^{10}Be is not

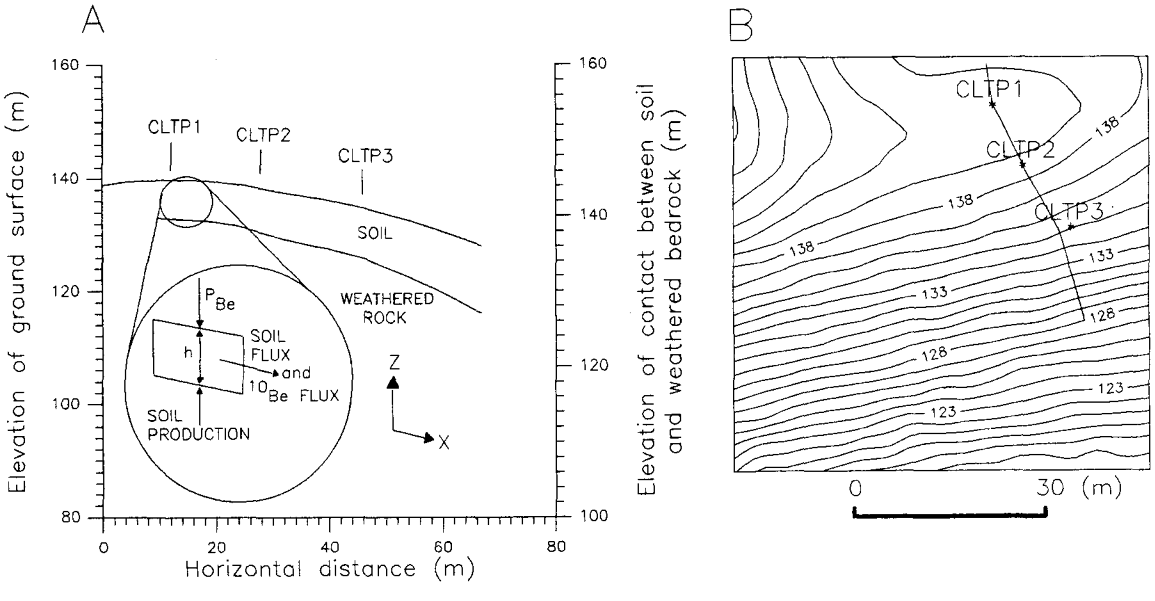

Figure 1. A: Hillslope profile (see B for location) with soil horizon defined on vertically exaggerated right-hand depth scale. Inset figure shows ^{10}Be and soil mass balance over some slope profile length interval x. P_{Be} = hillslope ^{10}Be deposition rate; soil creep mass flux = $\rho_s V_s h$; ^{10}Be mass flux = $C_{Be}\rho_s V_s h$; and soil production rate = $\rho_r C_o$. B: Black Diamond site topography. CLTP1, CLTP2, and CLTP3 are ^{10}Be sample locations on slope profile. Contour interval = 1 m. Scale bar = 30 m.

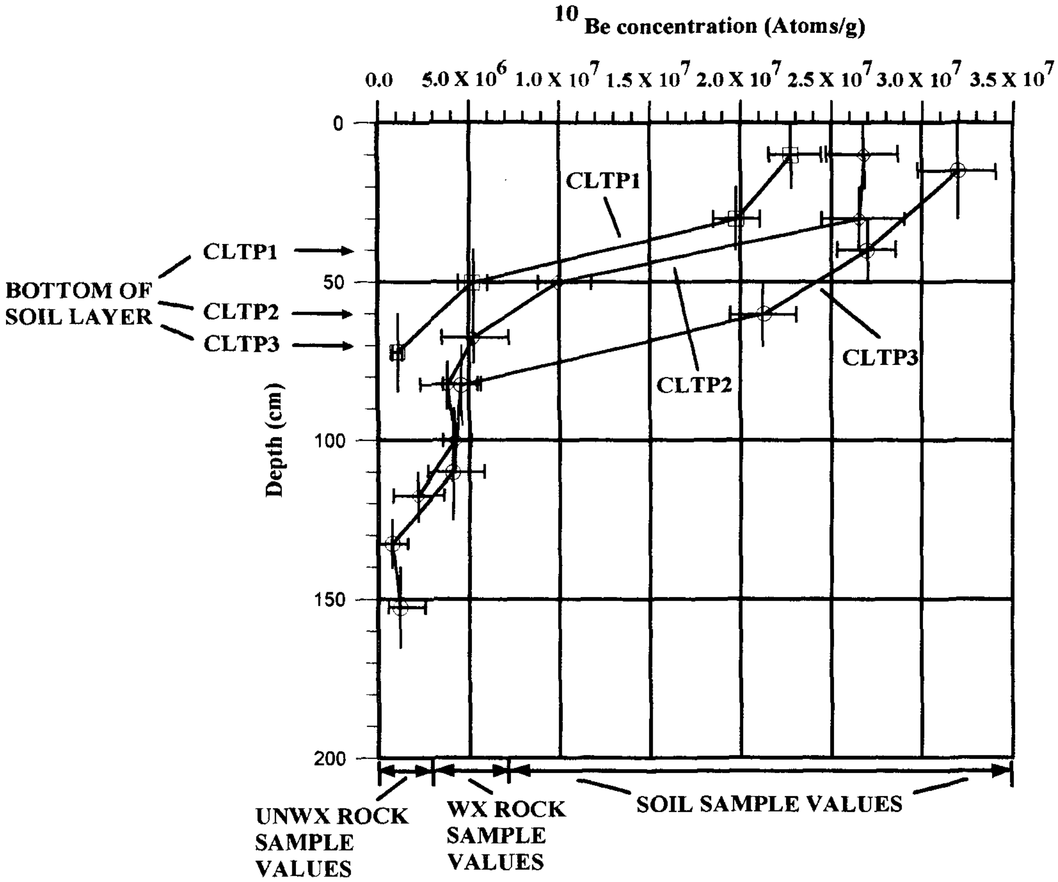

Figure 2. Profiles of ^{10}Be concentration in test pits, Black Diamond Mines Regional Preserve. Vertical lines through data points represent sample depth intervals. Each data point is average of two duplicate measurements. Error bars represent maximum and minimum AMS 1 σ uncertainty values for two duplicate samples. WX = weathered bedrock and UNWX = unweathered bedrock. Bottom of soil horizon in each test pit noted on vertical axis.

TABLE 1. RATE CALCULATIONS

Sample site	Slope distance from ridge (cm)	Depth averaged soil ^{10}Be concentration (10^7 atoms/g)	Depth averaged soil density (g/cm^3)	Depth averaged weathered rock density (g/cm^3)	Soil mass production rate (g•cm^{-2}•yr^{-1})	Soil volume production rate (cm/yr)	Soil mass flux rate (g•yr^{-1}•cm^{-1})	Soil volume flux rate (cm^3•yr^{-1}•cm^{-1})	Tangent of slope angle	Slope mass transport coefficient (g•yr^{-1}•cm^{-1})	Slope diffusion coefficient (cm^3•yr^{-1}•cm^{-1})
CLTP1	0	2.13	1.4	1.3			0	0	0		
					0.041	0.033					
CLTP2	1600	2.13	1.25	1.2			65	52	0.15	430	345
					0.024	0.019					
CLTP3	3500	2.75	1.35	1.3			111	82	0.22	505	375

mobile in the ground water. If leaching and secondary deposition of ^{10}Be were occurring, concentration peaks would be seen in the lower parts of the soil horizon.

The local ^{10}Be delivery rate was estimated for this area by Monaghan et al. (1992) as 0.87×10^6 atoms$\cdot$cm$^{-2}\cdot$yr^{-1}. Using this value of P_{Be} and measured values of C_{Be} and the average ρ_s for each sample site, equations 2 and 3 predict $Q_s(x)$ and $k(x)$ (Table 1). The flux rates convert to downslope soil velocities of ~1 cm/yr. Fleming and Johnson (1975) reported vertically averaged creep rates of ~0.4 cm/yr in a 1–2-m-thick silty-clay soil on a 12% to 14% slope, located 65 km southwest of Black Diamond, that was monitored for 1 yr. Reneau (1988) reported average volume transport rates during the Holocene in granular soils in the San Francisco Bay area of ~25 cm$^3\cdot$yr$^{-1}\cdot$cm^{-1}. As expected, the clay-rich soils at the Black Diamond site appear to move at a faster rate than these stronger granular soils.

Assuming an average downslope velocity of 1 cm/yr, the total transit time from the ridge top downslope to CLTP3 is ~3500 yr. Uncertainties in the model include long-term local precipitation variations (~10% over the past 3500 yr from analysis of pollen samples in the northern California Coast Range; Adam and West, 1983), soil density variability (~10%), AMS 1 σ error (~5%), and soil ^{10}Be concentration variability between duplicate samples (~5%). The overall standard error in the predicted soil flux rates is estimated to be ~15%.

Figure 3 and the diffusion coefficients in Table 1 show that, just as suggested by Gilbert (1877, 1909), the creep flux rate is directly proportional to slope steepness, and the diffusion coefficient (k) is calculated to average 360 cm$^3\cdot$yr$^{-1}\cdot$cm^{-1} contour length. The transport rates reported by Reneau (1988) for granular soils in the Pacific coastal mountains can be used to estimate k if it is assumed that transport is proportional to the average contributing hillslope gradient. For 34 such sites in California, Oregon, and Washington, the average k is 49 ±37 cm$^3\cdot$yr$^{-1}\cdot$cm^{-1}. The diffusion coefficient obtained from the ^{10}Be model for the weak, plastic, clay soils at Black Diamond is much greater than that for sites that contain relatively strong granular soils. An advantage of the ^{10}Be model is that it does not require the assumption that the soil flux rate is proportional to slope gradient, as does the method used by Reneau (1988).

Equation 4 predicts the average soil-production rate over the

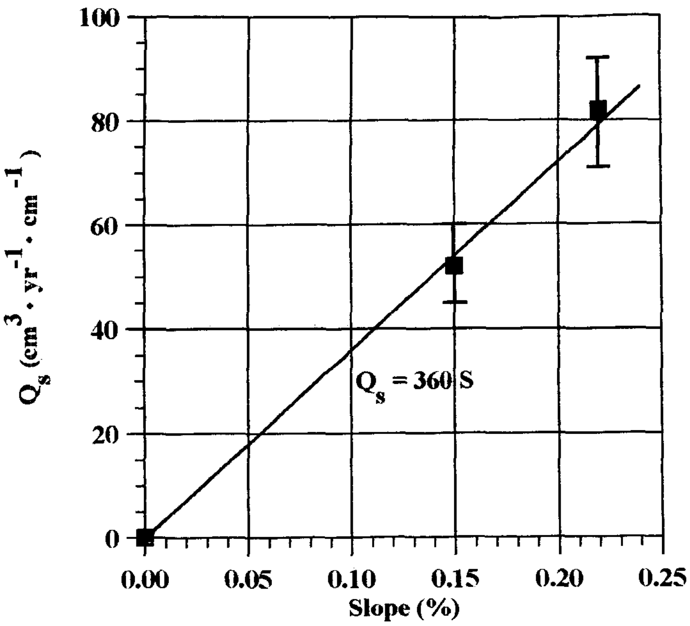

Figure 3. Slope vs. soil-creep flux rate (Q_s). S = ground surface percent slope. Error bars indicate ~15% uncertainty in technique.

slope intervals between CLTP1 and CLTP2 and between CLTP2 and CLTP3 (Table 1). These rates are comparable to those measured by Monaghan et al. (1992) in similar shales at another hillslope in the Black Diamond Mine Regional Preserve (average of 2.5×10^{-2} cm/yr). Reneau and Dietrich (1990) reported average rates of ~2 to 7×10^{-3} cm/yr in sandstones that should be much more resistant than the overconsolidated shales at Black Diamond.

The hypothesis of Gilbert (1877, 1909) of slopes in dynamic equilibrium assumes a uniform k and C_o. The Black Diamond ^{10}Be data suggest that k may increase slightly and C_o decrease in a downslope direction (Table 1). This would imply that the slope is not in dynamic equilibrium. However, on the convex part of this slope it appears mechanically unlikely that k or C_o would vary greatly because material composition and soil moisture conditions are very uniform. Calculations show that small (~15%) differences in C_{Be} at CLTP2 and CLTP3 would yield spatially uniform k and C_o. Such small variations in C_{Be} are within the estimated error of this technique; therefore, the Gilbert hypothesis of hillslopes in dynamic equilibrium cannot be rejected using these ^{10}Be data.

CONCLUSIONS

A simple mass-balance model that incorporates fluxes of both cosmogenic ^{10}Be and soil has been used to quantify material transport rates and to examine the dependence of the soil-creep rate on slope gradient. The predicted soil-creep flux rates and soil-production rates are reasonably higher than rates published for stronger, granular soils. Over the convex part of the test hillslope, the observed ^{10}Be concentration pattern predicts a linear increase in creep flux with slope gradient with a diffusion coefficient of 360 ±55 $cm^3 \cdot yr^{-1} \cdot cm^{-1}$. Within the 15% uncertainty of the method, the possibility of dynamic equilibrium on this slope cannot be rejected.

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Reviewer's comment

The first direct test of the applicability of a long-revered analysis of Gilbert's.

Robert Anderson