Earth and Planetary Science Letters, 111 (1992) 483–492
Elsevier Science Publishers B.V., Amsterdam

[MK]

^{10}Be chronometry of bedrock-to-soil conversion rates

Marc C. Monaghan [a], James McKean [b], William Dietrich [b] and Jeffrey Klein [c]

[a] *Department of The Geophysical Sciences, The University of Chicago, 5734 South Ellis Avenue, Chicago, IL 60637, USA*
[b] *Department of Geology and Geophysics, The University of California at Berkeley, Berkeley, CA, USA*
[c] *Department of Physics, The University of Pennsylvania, Philadelphia, PA, USA*

Received June 27, 1991; revision accepted April 14, 1992

ABSTRACT

We report concentrations of cosmogenic ^{10}Be ($t_{1/2} = 1.5 \times 10^6$ yrs) in soil excavated from a soil-mantled hillslope in Black Diamond Mines Regional Park, Contra Costa County, California. The most striking features of the data are: (1) the similarity in the downward decreasing trends of ^{10}Be concentrations in two soil profiles collected 75 m apart, (2) the coincidence in each soil profile of the soil/bedrock interface (as defined by visual inspection of soil pits) and the level at which ^{10}Be concentrations attain very low values ($\sim 4 \times 10^6$ atoms/g), and (3) the extremely low ^{10}Be concentrations in the underlying regolith (0.5×10^6 atoms/gram). The inventory of ^{10}Be in these soils is low, equivalent to about 6000 yrs of ^{10}Be accumulation in a soil initially containing no ^{10}Be. On the basis of these measurements, and with the aid of simple models of soil (^{10}Be) motions on the hillslope, we conclude that ^{10}Be loss from the surface is dominated by its removal in soil by creep. We calculate local rates of bedrock-to-soil conversion of between 0.15 and 0.27 km/10^6 yrs. Comparing these with uplift rates determined for coastal regions of California indicates that soil creep alone is capable of removing soil from the local geomorphic system at a rate equivalent to the rate of uplift of much of the coast.

1. Introduction

Gilbert [1,2] was the first to develop a theory of hillslope evolution linking the morphological character of the landscape with the rate of production of erodible materials by weathering, the thickness of the weathered mantle, and the rate of surface erosion. Subsequent efforts elaborating on Gilbert's general paradigm resulted in more complex and more quantitative models of hillslope evolution [3–6]. These studies made it clear that the geomorphic character of a landscape reflects the overall balance between the rate of uplift of the crust, the rate of bedrock-to-soil conversion, and the carrying capacity of the soil transporting agent. In part they did so by recognizing that the rate of production of erodible soil can limit the rate of erosion of the surface. Thus the presence or lack of a thick soil mantle on a landscape might seem to reflect a low or high rate of soil erosion, but actually it reflects the overall balance between the rates of soil production (bedrock-to-soil conversion) and removal (carrying capacity of the soil transporting agent). Despite the long-standing realization that measuring these rates is important to the study of landscape evolution, and perhaps even to the study of the geochemical evolution of the oceans and crust, they have yet to be determined either widely or with much confidence.

Earlier efforts to determine soil production rates were based on measurements of sediment accumulation rates and sediment transport rates at locales downstream from the site of soil production. In ground-breaking studies, Reneau et al. [7] and Reneau and Dietrich [8] estimated rates of production of erodible material for small hillslope catchment areas of the coastal mountains of the western United States from ^{14}C ages of charcoal deposited in colluvium-filled hollows. We take a different approach; we estimate the

Correspondence to: M.C. Monaghan, Department of The Geophysical Sciences, The University of Chicago, 5734 South Ellis Avenue, Chicago, IL 60637, USA.

rate of soil production at the site of production—the hillslope. We measure cosmogenic ^{10}Be ($t_{1/2} = 1.5 \times 10^6$ yrs) concentrations in vertical profiles of soil pits excavated in the hillslope and then estimate rates of bedrock-to-soil conversion from the measured profiles with the aid of simple models of soil (^{10}Be) motions on the hillslope. We concern ourselves only with ^{10}Be produced in the atmosphere and subsequently delivered to the soil by dry- and wet-fallout, because ^{10}Be produced in situ by cosmic ray spallation of atomic nuclei in soil minerals accounts for less than 1% of the total.

Previous studies of ^{10}Be in soils yielded estimates of ^{10}Be's mean residence time in the solum before removal downward by percolation [9], of long-term erosion rates from relatively stable surfaces [10–13], and of recent deviations from those long-term rates [14,15]. These studies indicate that ^{10}Be resides within the top meter of the solum for periods of the order of 2×10^4 yrs to 5×10^5 yrs, before it percolates to deeper parts of the regolith or leaves the system. They also indicate that the retentivity of ^{10}Be within the top few meters of the regolith depends on regolith chemistry and mineralogy, with clay-rich soils being the most retentive of ^{10}Be [11,12,16], while other soil types do not retain ^{10}Be so tenaciously [9,10].

In the light of these results, we focused our study on a landscape underlain by smectite clay-rich bedrock, where creep processes actively remove soil from hillslopes. We shall demonstrate that the residence time of soil on one of these hillslopes is short compared to both the half-life of ^{10}Be and the residence time of ^{10}Be in geochemically similar but mechanically stable soils. Thus the conversion rate of bedrock to soil (g cm^{-2} yr^{-1}) in our study area should be equal to the ratio of the ^{10}Be delivery rate (atoms cm^{-2} yr^{-1}) divided by the average concentration of ^{10}Be (atoms/g) in the soil leaving the system.

2. The study site and soil sampling methods

The study site is situated in the rolling hills north of Mt. Diablo in Black Diamond Mines Regional Park, Contra Costa County, California. The area is underlain by the Eocene Sidney Flat Shale, comprising intercalated layers of sand, shale, and a few organic-carbon-rich horizons. The hills are vegetated by a continuous cover of grass and by scattered oaks. The present climate of the area is Mediterranean with about 44.5 cm of rainfall occurring on average during the winter months (October to May), followed by a summer drought with no precipitation [personal communication from the Contra Costa County Flood Control and Water Conservation District]. The clay-rich soil is a few tens of centimeters thick at the tops of divides and increases within a few tens of meters down slope of the divides to about one to two meters thick; whereafter the soil exhibits a relatively constant thickness. Soil movement occurs predominantly by creep in the middle and upper slopes, while creep and landslides both are active in the lower slopes. Due to the continuous grass cover, erosion by overland flow is not expected to play a significant role in the mass balance of soil on the hillslopes; the absence of erosional features on the surface indicates this is the case.

In profile and plan view the specific hillslope we studied is broadly convex. Its slope gradient varies from 10° to about 15°. Three soil pits were excavated in the slope. Test Pit 5 (TP-5) was located in an area with no evidence of past instability, about 125 m below a point of maximum divergence on the convex drainage divide. Test Pits 2 and 6 (TP-2 and TP-6) were situated immediately uphill of the head scarp of a shallow earthflow about 200 m below the same point of maximum divergence on the divide. The soil pits were dug through the soil into the shale bedrock. A contiguous set of undisturbed samples was taken by trowel from the uphill side of each pit, so that complete profiles of material bulk density and ^{10}Be content could be made. In addition, a single undisturbed sample of unweathered bedrock was cut from 2.2 to 2.4 m below the surface of Test Pit 2, to determine whether significant amounts of ^{10}Be had penetrated to those depths.

Densities for the Test Pits 2 and 5 samples were determined by weighing and waxing the raw samples prior to immersing them in water to determine their volumes, and by subsequently dewaxing and drying the soils at 40°C for 24 h before reweighing. The bulk dry densities of several samples, for which waxed volumes were not

determined, were calculated from their water contents using empirical relationships between the weight percent water and the bulk dry and wet densities of the other samples. These bulk dry densities are listed in Table 1.

3. ^{10}Be measurement methods and results

For each ^{10}Be analysis between 2 g and 3 g of dry soil were dissolved by sequential treatments with concentrated reagent grade hydrofluoric, nitric and hydrochloric acids. To each dissolved sample between 1.0 mg and 2.0 mg of ^{9}Be (extracted from a pegmatite beryl recovered from depth, crushed in a porcelain mortar and pestle and containing $\leqslant 3 \times 10^{-15}$ ^{10}Be atoms/^{9}Be atom) was added as a yield tracer and as a carrier for the determination of ^{10}Be concentrations by isotope-dilution accelerator mass spectrometry.

In preparation for the ^{10}Be determinations, beryllium was separated from the solutions using two 150 ml 0.7 normal hydrochloric acid saturated Dowex 50/100 cation exchange columns. The separated beryllium was precipitated in hydroxide form with anhydrous ammonia gas and subsequently dissolved in concentrated hydrofluoric acid. In an effort to remove boron, which interferes with the mass spectrometric analysis, the dissolved beryllium was sequentially and repeatedly dried and re-dissolved in concentrated hydrofluoric acid and double-distilled nitric acid. The clean beryllium was re-precipitated as the hydroxide with anhydrous ammonia gas and oxidized to beryllium oxide in a platinum crucible by a hot flame. The ^{10}Be/^{9}Be ratio of the beryllium oxide powder was then determined by accelerator mass spectrometry on the tandem accelerator at the University of Pennsylvania [17]. Blank ^{10}Be concentrations were determined by subjecting the ^{9}Be carrier to the entire separation and purification process. Blanks processed at the same time as the soil samples had ^{10}Be/^{9}Be atom ratios of 3×10^{-15} and 5×10^{-15}, small compared to the soil sample ^{10}Be/^{9}Be atom ratios which ranged

TABLE 1

^{10}Be concentration and soil density data

	Mid-depth of sampled interval below surface (cm)	Interval thickness (cm)	Dry soil density (g/cm^3)	^{10}Be concentration (10^7 atoms/g)	AMS 1σ uncertainty ^{10}Be concentr. [a] (%)
Test Pit 5 samples					
TP5-1 (0–23)	11.5	23.0	1.3	2.8	3.2
TP5-1 (23–46)	34.5	23.0	1.4	2.7	3.2
TP5-1 (46–65)	55.5	19.0	1.8	3.9	3.5
TP5-1 (65–87)	76.0	22.0	1.8	2.5	4.2
TP5-1 (87–99)	93.0	12.0	1.8	1.2	4.2
TP5-1 (99–110)	104.5	11.0	1.6	0.94	4.1
TP5-1 (110–125)	117.5	15.0	1.5	0.75	3.9
Test Pit 2 samples					
TP2-1 (0–46b)	10.2	20.4	1.1	4.0	2.2
TP2-1 (0–46a)	33.2	25.6	1.1	4.8	1.9
TP2-1 (50–60)	55.0	10.0	1.7	3.9	2.1
TP2-1 (60–80)	70.0	20.0	1.7	3.9	1.8
TP2-1 (80–93)	86.5	13.0	1.7	2.3	2.7
TP2-1 (93–105)	99.0	1.0	1.5	1.6	3.5
TP2-1 (105–120)	112.5	15.0	1.3	0.36	3.4
TP2-1 (120–140)	130.0	20.0	1.3	0.40	6.0
Test Pit 2 deep sample					
TP2-9 (219–223)	221.0	4.0	1.4	0.05	13.4

[a] The reported uncertainties include uncertainties in normalization, standard reproducibility, background corrections and counting statistics.

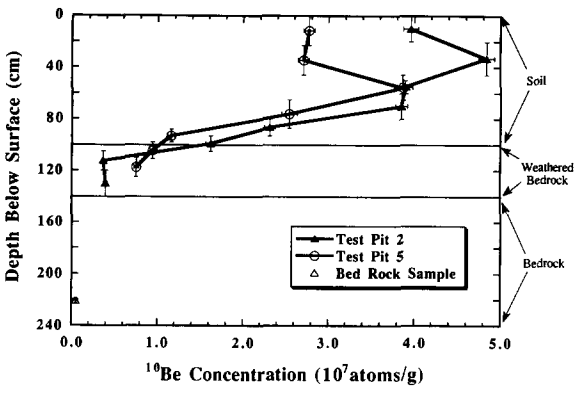

Fig. 1. ^{10}Be concentrations in soil samples taken from two soil pits excavated in a hillslope in Black Diamond Mines Regional Park, Contra Costa County, California.

between 5×10^{-14} and 1×10^{-12}. The results of the ^{10}Be analyses are listed in Table 1.

Profiles of ^{10}Be concentrations in Test Pits 2 and 5 are plotted in Fig. 1. The most striking features of these profiles are: (1) the similarity in the downward decreasing trends of ^{10}Be concentrations in the two soil profiles collected 75 m apart, (2) the coincidence in each soil pit of the soil/bedrock interface (as defined by visual inspection of the soil pits) and the level at which ^{10}Be concentrations attain very low values, and (3) the extremely low ^{10}Be concentrations in the underlying bedrock.

4. The rate of ^{10}Be delivery to and ^{137}Cs and ^{7}Be inventories in the soils

In order to accurately interpret the ^{10}Be concentration profiles, the delivery rate of ^{10}Be to the surface from the atmosphere must be known. Yearly ^{10}Be deposition rates have been measured at a number of sites in the United States [18,19]. These measurements indicate that within limited regions, annual-average ^{10}Be deposition fluxes covary linearly with annual-average precipitation fluxes. Thus if the ^{10}Be deposition flux at one locality is known, its deposition flux at another nearby locality can be determined by scaling, using the ratio of the precipitation rates at the two localities as the scaling factor.

In an effort to assess whether this method would yield accurate estimates of the ^{10}Be flux at the study site, we determined total inventories (dpm/cm^2) of bomb-derived ^{137}Cs (which has a 30.2 year half-life) in soil profiles TP-2, TP-5 and TP-6 and of cosmogenic ^{7}Be (which has a 53.3 day half-life) in soil profile TP-6. ^{137}Cs and ^{7}Be are useful for this purpose because: (i) they are transported by the same size-class of aerosol as is ^{10}Be [20,21]; and (ii) their total deposition can be determined easily by measuring their inventories in soils [9,22]. Furthermore, ^{137}Cs is derived from the stratosphere, as is most of the ^{10}Be deposited at mid-latitudes [23]. Specific activities (dpm/g) of ^{137}Cs and of ^{7}Be in the oven-dried soil samples and in above-soil vegetation samples were determined by gamma ray spectrometry of ^{137}Cs (661.7 keV) and of ^{7}Be (477.6 keV) on a planar, intrinsic germanium, gamma ray detector. Detector efficiencies were determined using National Institute of Standards and Technology mixed radionuclide standards [River Sediment and Rocky Flats Soil]. Blank ^{137}Cs and ^{7}Be activities were below the limit of detection of the counting system. These measurements yielded total soil-column ^{137}Cs inventories of 7.5 ± 0.2 dpm/cm^2 for Test Pit 2, 7.1 ± 0.8 dpm/cm^2 for Test Pit 5, and 6.0 ± 1.2 for Test Pit 6. (These inventories are corrected for decay to 1/1/80 for comparison with other west coast data; the reported uncertainties include uncertainties in counter efficiencies, background corrections and counting statistics.) As shown in Fig. 2, these ^{137}Cs inventories are consistent with the those determined for or calculated for other near-coast northern California sites, if the differences in the ^{137}Cs inventories between the sites are due to differences in precipitation rates alone. The ^{7}Be inventory in TP-6 on the sample collection date was 1.9 ± 0.4 dpm/cm^2, about what one would expect from measurements of ^{7}Be inventories in Mendocino county soils, 4.0 dpm/cm^2 [9], and the average annual rainfalls at the two sites, 44.5 cm/yr at the study locality and 100.3 cm/yr at the Mendocino locality [24].

Therefore, as Black Diamond Mines Regional Park is located near Berkeley, California, one of the sites for which Monaghan et al. [18] determined the annual ^{10}Be flux, we use the ratio of the mean-annual precipitation rate at the study site, 44.5 cm/yr, divided by the precipitation rate reported by Monaghan et al. [18] for Berkeley, 62.5 cm/yr, multiplied by the measured ^{10}Be

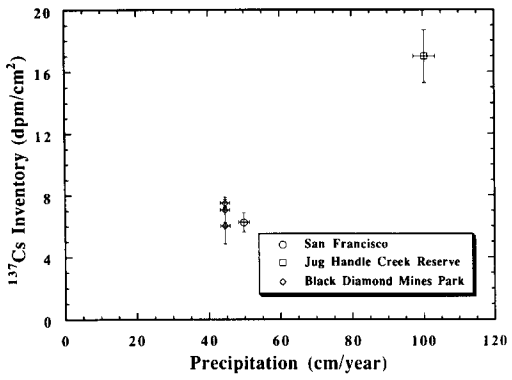

Fig. 2. ^{137}Cs inventories (total activity per unit area of soil–atmosphere interface [dpm/cm^2]) in California soils determined by measurement for both Black Diamond Mines Regional Park, Contra Costa County (this study) and Jug Handle Creek Reserve, Mendocino County [22], and by calculation for San Francisco. The San Francisco ^{137}Cs inventory was calculated using the record of ^{90}Sr deposition to San Francisco, accounting for the missing years in the incomplete San Francisco record by appropriate scaling with the complete record of ^{90}Sr deposition to New York, and using a decay-corrected deposition-flux-weighted ^{137}Cs/^{90}Sr flux ratio of 1.5 [27]. All data have been corrected to 1/1/80 for comparison.

deposition rate at Berkeley (1.22×10^6 atoms cm^{-2} yr^{-1}) to yield a ^{10}Be delivery rate for the study site of 0.87×10^6 atoms cm^{-2} yr^{-1}.

5. What accounts for the low inventory of ^{10}Be in the soils?

Using this ^{10}Be delivery rate, the inventories of ^{10}Be in the soils could be accounted for by 5300 yrs (Test Pit 5) and 6300 yrs (Test Pit 2) of ^{10}Be accumulation, if the soils contained no ^{10}Be initially and lost none subsequently. As it is obvious that the hills have been present for a longer period of time, the relatively low inventories of ^{10}Be in the soils must be accounted for by: (i) removal of ^{10}Be from the soil in groundwaters, (ii) episodic removal of soil and ^{10}Be from the hillslope, and/or (iii) continuous removal of soil and ^{10}Be from the hillslope.

As has been observed at other locations [9], the entire inventory of ^{7}Be at the study site was found in the above-soil vegetation (grass and other herbs). In addition, the ^{7}Be inventory is what one would expect from regional ^{7}Be deposition data and from regional precipitation data. Thus, the ^{7}Be measurements indicate that during and immediately after deposition, cosmogenic beryllium is efficiently retained by the soil–grassland system.

^{10}Be adsorbs strongly (partition coefficients of 10^6) onto the solid phase in soils which contain a large fraction of high cation exchange capacity clays, and which are characterized by near-neutral pH conditions [16]. The soils at this site are smectite-rich [P. Gaines, pers. commun.], with measured pH values ranging from 6.0 to 6.3. These soils, therefore, should efficiently sequester ^{10}Be. Various characteristics of the measured ^{10}Be profiles indicate in fact that ^{10}Be has been efficiently sequestered by the soils. These include: (i) the shapes of the ^{10}Be profiles, which seem to be controlled by the bedrock/soil interface, which is a textural interface and not a compositional interface, and (ii) the low concentrations of ^{10}Be in the soil near the bedrock–soil interface, which indicate that groundwaters carrying appreciable amounts of ^{10}Be have not passed through these levels of the soil (groundwaters would most likely flow through the soils along the bedrock–soil interface). The low ^{10}Be concentrations in the bedrock indicate as well that an extremely insignificant amount of ^{10}Be has penetrated this interface to the underlying bedrock in groundwaters. Observations of a well excavated in bedrock on a ridge line of a nearby hillslope, which also is underlain by the Sidney Flat Shale, revealed that after approximately 7 cm of rain over a 5-day period, groundwater did not seep into the well from the bedrock. Thus it appears unlikely in most years that sufficient rainfall occurs to cause bedrock groundwater flow in the upper portions of the hillslope.

Episodic removal of soil by landslides would be patchy and thus result in dissimilar ^{10}Be profiles from one location to another on the hillslope. The great similarity between the measured ^{10}Be profiles in TP-2 and TP-5 indicates that it is likely that this mechanism of soil and ^{10}Be removal is not active in the upper portions of the hillslope.

As creep at present removes soil from the hillslope, it is likely therefore that the low inventory of ^{10}Be in the soils is due to removal from the slope of ^{10}Be adsorbed onto the creeping soil. On the basis of these observations and arguments, we now discuss the ^{10}Be profiles using

models of continuous ^{10}Be and soil removal from the hillslope by creep alone.

6. Determination of bedrock-to-soil conversion rates on the hillslope

To make sense out of the ^{10}Be data we use simple, steady-state models to describe mass- and ^{10}Be-conservation on the hillslope. Once we have derived the apparent bedrock-to-soil conversion rates for the hillslope, we can test the validity of our thesis' critical presumptions, namely that ^{10}Be is removed by creep alone and the system is at steady state. The transit time of soil on the hillslope must be short compared to the residence time of ^{10}Be in geochemically and compositionally similar but mechanically stable soils, and the transit time must be such that while soil moves down the hillslope, the general characteristics of soil motions on the hillslope and the delivery rate of ^{10}Be do not change significantly, particularly in response to climate.

A steady state of ^{10}Be abundances on the hillslope is characterized by a balance between its input by precipitation on the surface and its removal by soil creep down slope. Similarly, a steady state of soil mass on the hillslope is characterized by a balance between its input from below through bedrock-to-soil conversion and its removal down slope by soil creep. Figure 3 shows a schematic conceptualization of these processes. In order to formalize this conceptual model, we characterize soil creep by a time-invariant velocity field, $W(x,z)$ [cm/yr], which varies both down slope

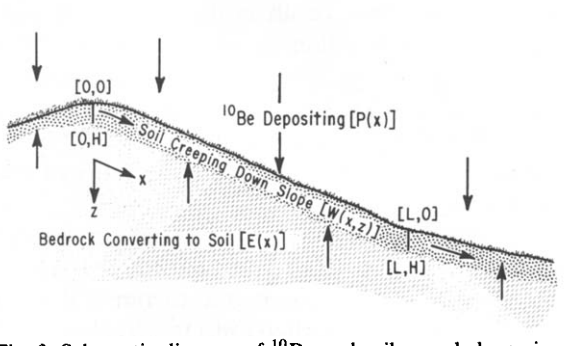

Fig. 3. Schematic diagram of ^{10}Be and soil mass balance in a hillslope from which soil is removed predominantly by soil creep.

(x) [cm] and with depth in the soil (z) [cm]. The integral relationships that define soil mass and ^{10}Be balances on a hillslope from its symmetrical crest ($x = 0$ and $W(0,z) = 0$) to any point down slope ($x = L$) yield the following conservation equations:

Soil mass balance

$$\int_0^L E(x)\,\mathrm{d}x = \int_0^H \rho(L,z)W(L,z)\,\mathrm{d}z \tag{1}$$

^{10}Be balance

$$\int_0^L P(x)\,\mathrm{d}x = \int_0^H \rho(L,z)C(L,z)W(L,z)\,\mathrm{d}z \tag{2}$$

in which $E(x)$ [g cm^{-2} yr^{-1}] is the bedrock-to-soil conversion rate at the base of the soil, i.e. where $z = H$, $P(x)$ [atoms cm^{-2} yr^{-1}] is the ^{10}Be input rate at the surface, i.e. where $z = 0$, and, at $x = L$, $r(L,z)$ [g/cm^3] is the soil density, $W(L,z)$ is the down slope velocity field, and $C(L,z)$ [atoms/g] is the ^{10}Be concentration field. Using these equations, we can now determine bedrock-to-soil conversion rates on the hillslope.

The average bedrock-to-soil conversion rate up slope of any particular position on the hillslope, e.g. where $x = L$, is given by:

$$\bar{E}(L) = \left(\frac{1}{L}\right)\int_0^L E(x)\,\mathrm{d}x \tag{3}$$

Once we know the ^{10}Be input rate $P(x)$ [atoms cm^{-2} yr^{-1}], which should not vary with position on the hillslope, i.e. $P(x) = P$, the ^{10}Be- and soil-mass-balance equations can be combined to yield the average bedrock-to-soil conversion rate:

$$\bar{E}(L) = P\frac{\int_0^H \rho(L,z)W(L,z)\,\mathrm{d}z}{\int_0^H \rho(L,z)C(L,z)W(L,z)\,\mathrm{d}z} \tag{4}$$

The function $W(L,z)$ is not known, but, based on field observations [e.g., 25], may be characterized by two end-member forms:

(i) plug-flow where the velocity is invariant with depth from the surface ($z = 0$) to the soil–bedrock interface ($z = H$):

$$W(L,z) = W(L) \tag{5}$$

(ii) and shear-flow where the horizontal velocity is a simple linear decreasing function of depth

from the surface ($z = 0$) to the soil–bedrock interface ($z = H$):

$$W(L,z) = \left(1 - \frac{z}{H}\right) W(L,0) \tag{6}$$

In the case of plug-flow, eq. 4 reduces to:

$$\bar{E}(L) = \frac{P}{\bar{C}(L)} \tag{7}$$

where $\bar{C}(L)$ is the integrated average ^{10}Be concentration in the soil profile:

$$\bar{C}(L) = \frac{\int_0^H \rho(L,z) C(L,z)\, \mathrm{d}z}{\int_0^H \rho(L,z)\, \mathrm{d}z} \tag{8}$$

In the case of shear-flow, eq. 4 becomes

$$\bar{E}(L) = P \frac{\int_0^H \rho(L,z)\left(1 - \frac{z}{H}\right) \mathrm{d}z}{\int_0^H \rho(L,z) C(L,z)\left(1 - \frac{z}{H}\right) \mathrm{d}z} \tag{9}$$

The integrals in eqs. 8 and 9 can be estimated using the trapezoidal approximations:

$$\bar{C}(L) = \frac{\sum_{i=1}^{n} \rho_m C_m \Delta z_m}{\sum_{i=1}^{n} \rho_m \Delta z_m} \tag{10}$$

and:

$$\bar{E}(L) = P \frac{\sum_{i=1}^{n} \rho_m \left(1 - \frac{z_m}{H}\right) \Delta z_m}{\sum_{i=1}^{n} \rho_m C_m \left(1 - \frac{z_m}{H}\right) \Delta z_m} \tag{11}$$

in which ρ_m is the measured soil density, C_m is the measured ^{10}Be concentration in each sampled interval, z_m is the midpoint depth of each sampled interval, Δz_m is the interval thickness, and n is the number of sampled intervals from the soil surface to the soil–bedrock interface.

Estimates of $\bar{E}(L)$ calculated using the ^{10}Be delivery rate to the study site estimated earlier, $P = 0.87 \times 10^6$ atoms cm^{-2} yr^{-1}, and assuming either plug-flow or shear-flow are given in Table 2. These bedrock-to-soil conversion rates are rather remarkable in that the presumptions of shear-flow and plug-flow yield similar estimates of $\bar{E}(L)$. As it is likely that the actual $W(L,z)$ field has a form intermediate between shear- and plug-flow, we conclude that it is also likely that the actual bedrock-to-soil conversion rate is intermediate between the calculated values.

7. Soil transit times on the hillslope: the mechanism of ^{10}Be removal and steady state

The validity of our earlier presumptions, namely that ^{10}Be is removed by creep alone and the system is at steady state, can now be assessed by determining the average transit time of soil on the hillslope using the calculated bedrock-to-soil conversion rates. To determine this transit time we must first determine the vertical average of the down slope velocity of soil at all positions on the hillslope, and then integrate and average these vertical averages over the hill from its crest to its base to yield the average velocity of soil moving down the hillslope. From this average velocity we can calculate the transit time of soil on the hillslope.

TABLE 2

Bedrock-to-soil conversion rates

	Integrated average ^{10}Be concentration (10^7 atoms/g)	Integrated average soil density (g/cm^3)	Bedrock-to-soil conversion rates [a]			
			plug flow		shear flow	
			(10^{-2} g cm^{-2} yr^{-1})	(km/10^6 yr)	(10^{-2} g cm^{-2} yr^{-1})	(km/10^6 yr)
Test Pit 5	2.34	1.49	3.72	0.27	3.21	0.22
Test Pit 2 [b]	2.82	1.38	3.08	0.22	2.38	0.15

[a] Calculated using soil depths defined by the weathered bedrock/bedrock interface (see Fig. 1) and a bedrock density of 1.4 g/cm^3.

[b] Results for Test Pit 2 include interpolated estimates of soil density, 1.4 g/cm^3, and ^{10}Be concentration, 4.35×10^7 atoms/g, in the depth interval 46–50 cm below the surface.

The vertical average of the horizontal velocity $\bar{W}(L)$ at any distance L (now a variable) from the divide can be determined by assuming a constant soil density and combining eqs. 1 and 3 to yield:

$$\bar{W}(L) = \frac{L}{H\rho}\bar{E}(L) \tag{12}$$

where:

$$\bar{W}(L) = \frac{1}{H}\int_0^H W(L,z)\,dz \tag{13}$$

The average down slope velocity $\hat{W}(D)$ of soil transiting a hillslope of total length D can be determined by integrating and averaging eq. 12 over the hill from its crest, where $L = 0$, to its base, where $L = D$:

$$\hat{W}(D) = \frac{1}{D}\int_0^D \bar{W}(L)\,dL = \frac{1}{D}\int_0^D \frac{L}{H\rho}\bar{E}(L)\,dL \tag{14}$$

Assuming a constant bedrock-to-soil conversion rate $\bar{E}(L)$ and soil thickness H (which approximates conditions on the hillslope), eq. 14 can be integrated easily to yield:

$$\hat{W}(D) = \frac{D}{2H\rho}\bar{E}(L) \tag{15}$$

The average transit time T of soil on the hillslope is then:

$$T = \frac{D}{\hat{W}} = \frac{2H\rho}{\bar{E}(L)} \tag{16}$$

Using a soil density of 1.44 g/cm^3, a bedrock-to-soil conversion rate of 3.1×10^{-2} g cm^{-2} yr^{-1} (an average of the rates listed in Table 2), and an average thickness of mobile soil on the hillslope of 135 cm yields an average down-slope transit time for soil on the hillslope of about 12,500 yrs. As this transit time is much shorter than the residence time, circa 100,000 yrs, of ^{10}Be in the top meter of compositionally and geochemically similar but mechanically stable soils (from which ^{10}Be is removed predominantly by groundwaters) [9,12], our presumption that ^{10}Be is removed from the hillslope predominantly by creep appears justified.

With respect to climate change, the weakness of the steady-state presumption is based on the fact that a past change of climate could have caused a change either in the ^{10}Be delivery rate to the surface or in soil motions on the hillslope. Presuming that the production rate of ^{10}Be has remained constant, significant changes in the local ^{10}Be deposition rate could have been effected either by atmospheric motions distributing ^{10}Be differently in the atmosphere or by the local-average of the precipitation rate changing in a manner disproportionate to or of opposite sign to changes in zonal- or global-average precipitation rates. The rheological characteristics of the soil could have changed as well, either because a different biological community came to occupy the landscape or because the shrink/swell behavior of the soils changed in response to a different abundance or seasonal distribution of precipitation. At the present time, neither the facts nor the consequences of these suppositions about climate change can be accurately assessed. Nevertheless, support for the presumption that ^{10}Be- and soil-motions on the hillslope are at steady state is provided by the similarity of ^{10}Be profiles in the two soil pits, the general convexity of the hilltops, and the uniformity of soil thicknesses.

Overall steady state, in which the uplift, soil production and removal rates are in balance, is possible but not yet confirmed in the study area. Uplift affects a hillslope only through its influence on the channel at the base of the hillslope. If channel incision keeps pace with uplift, then a sediment removal rate will be imposed at the hillslope base which, through propagation of topographic change up the hillslope, will cause a slope morphology to develop that supports this steady rate of sediment discharge. To assess the tendency toward this steady state we would need to know not only the local rate of uplift but also the rate of channel incision. These rates are not known.

A comparison of the rates of bedrock-to-soil conversion we have determined (about 0.22 km/10^6 yrs) with rates of uplift reported in McLaughlin et al. [26] for the coast of California (about 0.3 km/10^6 yrs for much of the coast; up to 1.0 km/10^6 yrs to 2.0 km/10^6 yrs for regions undergoing active deformation) indicates that soil is removed from the study area at about the same rate that much of coastal California is uplifted. Thus the possibility of overall geomorphic steady state in the study area is not disproved by our

measured bedrock-to-soil conversion rates. Furthermore, the similarity of the rates of soil removal and uplift also indicates that overall geomorphic steady state is a possibility for those parts of the California coastal landscape where creep processes dominate the erosion of soil developed in shale bedrock. We cannot confirm or deny, however, whether steady state is a possibility for those portions of the coast undergoing extremely high rates of uplift or underlain by different bedrock lithologies.

Our bedrock-to-soil conversion rates are three to four times higher than those (about 0.06 km/10^6 yrs) determined by Reneau et al. [7] and Reneau and Dietrich [8] for hillslopes developed on sandstone in Oregon. The large difference between the rates of sandstone-to-soil conversion and shale-to-soil conversion is not surprising (it is practically a maxim of earth sciences that hard rocks weather more slowly than soft rocks). Nevertheless, the magnitude of the difference indicates that the character of the transporting agent dominating the removal of soil from a landscape underlain by sandstone would very likely be different than that dominating the removal of soil from a landscape underlain by shale. In a landscape underlain by mixed bedrock lithologies, different soil-removing processes thus might dominate in different parts of the landscape. In our study area, interbedded sandstones and shales clearly have exerted a strong influence on landscape development. Slopes underlain by shale are more gentle and mantled by thicker soils than those underlain by sandstone.

8. Conclusions

^{10}Be can be applied as an accurate chronometer of bedrock-to-soil conversion rates only when its loss from a surface is dominated by its removal in soil by creep or by other mechanical processes, and not by its removal by groundwater or through decay. This requirement is tantamount to requiring that the residence time of a soil on a hillslope is short compared to the residence time of ^{10}Be in the soil. Even when this condition is met, estimates of bedrock-to-soil conversion rates based on ^{10}Be still depend on assumptions about the delivery rate of ^{10}Be to the surface and on the nature of soil removal, assumptions that are intimately dependent on climate.

As we don't know how soil motions and the ^{10}Be delivery rate might have responded to past climate change, we cannot be absolutely sure that the ^{10}Be profiles we measured are steady-state profiles. Nevertheless, the similarity of the ^{10}Be profiles in the two soil pits, the general convexity of the hilltops, and the uniformity of soil thicknesses are consistent with the geomorphic system being at a steady state. In this region of Mediterranean climate, our measurements indicate that it takes about 12,500 yrs for creep to move soil down a hillslope developed in smectite clay-rich bedrock. This is much shorter than the residence time, circa 100,000 yrs, of ^{10}Be in the top meter of geochemically similar but mechanically stable soils (from which ^{10}Be is removed predominantly by groundwaters) [9,12]. At this site, therefore, it is likely that ^{10}Be loss from the surface is dominated by its removal in soil by creep. Thus, the most important condition for the use of ^{10}Be as an accurate chronometer of bedrock-to-soil conversion rates has been met.

Acknowledgements

We would like to thank the East Bay Regional Park District for its help and cooperation. This work was funded by grants from the National Science Foundation.

References

1 G.K. Gilbert, Report on the geology of the Henry Mountains, U.S. Geogr. Geol. Surv., Washington, 1877.
2 G.K. Gilbert, The convexity of hilltops, J. Geol. 17, 344–351, 1909.
3 J.T. Hack, Interpretation of erosional topography in humid temperate climates, Am. J. Sci. 258-A, 80–97, 1960.
4 F. Ahnert, The role of the equilibrium concept in the interpretation of landforms of fluvial erosion and deposition, Symp. Int. Geomorphologie, Congr. Colloq. Univ. Liège, 40, pp. 22–41, 1967.
5 F. Ahnert, Approaches to dynamic equilibrium in theoretical simulations of slope development, Earth Surface Processes Landforms 12, 3–15, 1987.
6 M.A. Carson and M.J. Kirkby, Hillslope Form and Process, Cambridge Univ. Press, London, 475 pp., 1972.
7 S.L. Reneau, W.E. Dietrich, M. Rubin, D.J. Donahue and A.J.T. Jull, Analysis of hillslope erosion rates using dated colluvial deposits, J. Geol. 97, 45–63, 1989.

8 S.L. Reneau and W.E. Dietrich, Depositional history of hollows on steep hillslopes, coastal Oregon and Washington, Natl. Geogr. Res. 6, 220–230, 1990.
9 M.C. Monaghan, S. Krishnaswami and J.H.Thomas, ^{10}Be concentrations and the long-term fate of particle-reactive nuclides in five soil profiles from California, Earth Planet. Sci. Lett. 65, 51–60, 1983.
10 M.J. Pavich, L. Brown, J. Klein and R. Middleton, ^{10}Be accumulation in a soil chronosequence, Earth Planet. Sci. Lett. 68, 198–204, 1984.
11 M.J. Pavich, L. Brown, J.N. Valette-Silver, J. Klein and R. Middleton, ^{10}Be analysis of a Quaternary weathering profile in the Virginia Piedmont, Geology 13, 39–41, 1985.
12 M.J. Pavich, L. Brown, J. Harden, J. Klein and R. Middleton, ^{10}Be distribution in soils from Merced River terraces, California, Geochim. Cosmochim. Acta 50, 1727–1735, 1986.
13 L. Brown, M.J. Pavich, R.E. Hickman, J. Klein and R. Middleton, Erosion of the Eastern United States observed with ^{10}Be, Earth Surface Processes Landforms 13, 1988.
14 J.N. Valette-Silver, L. Brown, M.J. Pavich, J. Klein and R. Middleton, Detection of erosion events using ^{10}Be profiles: example of the impact of agriculture on soil erosion in the Chesapeake Bay Area, Earth Planet. Sci. Lett. 80, 82–90, 1986.
15 C.-F. You, T. Lee, L. Brown, J.J. Shen and J.-C. Chen, ^{10}Be study of rapid erosion in Taiwan, Geochim. Cosmochim. Acta 52, 2687–2691, 1988.
16 C.-F. You, T. Lee and Y.H. Li, The partition of Be between soil and water, Chem. Geol. 77, 105–118, 1989.
17 J. Klein, R. Middleton and H. Tang, Modifications of an FN Tandem for quantitative ^{10}Be measurement, Nucl. Inst. Meth. 193, 601–616, 1982.
18 M.C. Monaghan, S. Krishnaswami and K.K. Turekian, The global-average production rate of ^{10}Be, Earth Planet. Sci. Lett. 65, 279–287, 1985/86.
19 L. Brown, G.J. Stensland, J. Klein and R. Middleton, Atmospheric deposition of ^{7}Be and ^{10}Be, Geochim. Cosmochim. Acta 53, 135–142, 1989.
20 J.A. Young and W.B. Silker, The determination of air sea exchange and oceanic mixing rates using ^{7}Be during the BOMEX experiment, J. Geophys. Res. 79, 4481–4489, 1974.
21 E.A. Bondietti, C. Papastefanou and C. Rangarajan, Aerodynamic size associations of natural radioactivity with ambient aerosols, in: Radon and its Decay Products: Occurrence, Properties, and Health Effects, ACS Symp. Vol. 331, P.K. Hopke, ed., pp. 377–397, Am. Chem. Soc., New York, 1988.
22 M.C. Monaghan, Lead 210 in surface air and soils from California: implications for the behavior of trace constituents in the planetary boundary layer, J. Geophys. Res. 94, D5, 6449–6456, 1989.
23 D. Lal and B. Peters, Cosmic ray produced radioactivity on the Earth, in: Handbuch der Physik, Vol. XLVI/2, pp. 551–612, Springer, New York, 1967.
24 Climatological Data California, Vol. 93, 1 to 12, Environmental Data and Information Service, NOAA, Dep. Comm., 1989.
25 R.W. Fleming and A.M. Johnson, Rates of seasonal creep of silty clay soil, Q.J. Eng. Geol. 8, 1–29, 1975.
26 R.J. McLaughlin, K.R. Lajoie, D.H. Sorg, S.D. Morrison and J.A. Wolfe, Tectonic uplift of a middle Wisconsin marine platform near the Mendocino triple junction, California, Geology 11, 35–29, 1983.
27 H.W. Feely, L. Toonkel and R. Larsen, Environmental quarterly report EML-395, Appendix, U.S. Dep. Energy, New York, 1981.