ABSTRACT

The functional dependence of bedrock conversion to soil on the overlying soil depth (the soil production function) has been widely recognized as essential to understanding landscape evolution, but was quantified only recently. Here we report soil production rates for the first time at the base of a retreating escarpment, on the soil-mantled hilly slopes in the upper Bega Valley, southeastern Australia. Concentrations of \(^{10}\)Be and \(^{26}\)Al in bedrock from the base of the soil column show that soil production rates decline exponentially with increasing depth. These data define a soil production function with a maximum soil production rate of 53 m/m.y. under no soil mantle and a minimum of 7 m/m.y. under 100 cm of soil, thus constraining landscape evolution rates subsequent to escarpment retreat. The form of this function is supported by an inverse linear relationship between topographic curvature and soil depth that also suggests that simple creep does not adequately characterize the hillslope processes. Spatial variation of soil production shows a landscape out of dynamic equilibrium, possibly in response to the propagation of the escarpment through the field area within the past few million years. In addition, we present a method that tests the assumption of locally constant soil depth and lowering rates using concentrations of \(^{10}\)Be and \(^{26}\)Al on the surfaces of emergent tors.

Keywords: erosion, cosmogenic nuclides, landscape evolution, geomorphology, tors.

INTRODUCTION

Rates of bedrock conversion to soil were recently shown to decline with increasing local soil thickness on a hilly landscape in northern California, thus defining empirically the soil production function (Heimsath et al., 1997, 1999). However, the dependence of soil production on soil depth has not been measured extensively. Here we examine a soil-mantled landscape at the base of a passive margin escarpment in the Bega Valley, southeastern Australia, to quantify the relationship between soil production and depth. We also use concentrations of \(^{10}\)Be and \(^{26}\)Al from the surfaces of emergent bedrock outcrops, or tors, to test whether soil thickness has remained constant while the ground surface has been lowering.

Recent modeling studies have suggested that the pace of escarpment retreat on passive margins depends on the rate of conversion of bedrock to erodible material (e.g., Kooi and Beaumont, 1994; Tucker and Slingerland, 1994; van der Beek and Braun, 1999). Maximum rates of soil production, occurring where soil is thinnest or absent (Heimsath et al., 1997), set the limiting lowering rates for soil mantled landscapes. This study constrains the retreat rates and sediment transport processes of an erosional escarpment, thus furthering our understanding of a largely unsolved problem for tectonic geomorphology.

THEORY

Soil production in coastal California was determined from soil depth-topographic curvature relationships and cosmogenic nuclides (Heimsath et al., 1997, 1999). The first method rests on a simple mass balance, neglecting mass loss in solution, between the change in mass of the soil column and the balance between soil produced from the underlying bedrock and the divergence of the sediment transport flux, \(\vec{q}_s\) (Fig. 1A),

\[
\rho_s \frac{\partial h}{\partial t} = - \rho_r \frac{\partial z_b}{\partial t} - \nabla \cdot \vec{q}_s, \tag{1}
\]

where \(h\) is soil thickness, \(z_b\) is the elevation of the soil-bedrock boundary, \(\rho_s\) and \(\rho_r\) are the bulk densities of soil and rock, respectively, and \(t\) is time. Heimsath et al. (1997, 1999) assumed linear soil creep (\(\vec{q}_s = -\rho_s K \nabla z\)) and also assumed steady-state local soil depth (\(\partial h/\partial t = 0\)), to show

\[
\varepsilon(h) = -\frac{\rho_r}{\rho_s} K V^2 z_b, \tag{2}
\]

where \(V\) is the elevation, \(z = z_b + H\) (Fig. 1B). The functional dependence of bedrock conversion to soil on the overlying soil depth (the soil production function) has been widely recognized as essential to understanding landscape evolution, but was quantified only recently. Here we report soil production rates for the first time at the base of a retreating escarpment, on the soil-mantled hilly slopes in the upper Bega Valley, southeastern Australia. Concentrations of \(^{10}\)Be and \(^{26}\)Al in bedrock from the base of the soil column show that soil production rates decline exponentially with increasing depth. These data define a soil production function with a maximum soil production rate of 53 m/m.y. under no soil mantle and a minimum of 7 m/m.y. under 100 cm of soil, thus constraining landscape evolution rates subsequent to escarpment retreat. The form of this function is supported by an inverse linear relationship between topographic curvature and soil depth that also suggests that simple creep does not adequately characterize the hillslope processes. Spatial variation of soil production shows a landscape out of dynamic equilibrium, possibly in response to the propagation of the escarpment through the field area within the past few million years. In addition, we present a method that tests the assumption of locally constant soil depth and lowering rates using concentrations of \(^{10}\)Be and \(^{26}\)Al on the surfaces of emergent tors.

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where $K$ is a diffusion coefficient with dimensions $L^2T^{-1}$, $z$ is the ground surface elevation, and $\varepsilon(h)$ is the soil production rate. This formula neglects the difference between vertical and slope-normal soil depth, $H$ (Fig. 1A). Equation 2 led Heimsath et al. (1997) to regard topographic curvature as a proxy for soil production. Measurements of soil depth and slope curvature in northern California indicated that soil production declined exponentially with normal depth,

$$\varepsilon(H) = \varepsilon_0e^{-(\alpha H)},$$  

(3)

where $\varepsilon_0$ is the production rate with zero soil cover (m m.y.$^{-1}$), and $\alpha$ is a rate constant. Without a known diffusivity, $K$, however, the rates cannot be quantified.

Soil production also can be evaluated using cosmogenic nuclides, produced by cosmic ray interaction with common nuclei in rock and soil minerals. The concentration, $C$, of a nuclide depends on its production rate, which depends on depth, $z_x$, and its radioactive decay (e.g., Lal, 1991),

$$\frac{dC}{dt} = P_0e^{-\mu z_x} - \lambda C,$$  

(4)

where $P_0$ is the nuclide production rate at a flat surface, $\mu$ is the absorption coefficient (material density divided by the mean attenuation length for cosmic rays, $\Lambda \sim 165 \pm 10$ g cm$^{-2}$), and $\lambda$ is the nuclide decay constant ($\lambda = \ln2/t_{1/2}$, where $t_{1/2} = 1.5 \times 10^6$ yr for $^{10}$Be and $t_{1/2} = 7.01 \times 10^5$ yr for $^{26}$Al). Under steady state, when $t >> (\lambda + \mu')^{-1}$ with constant erosion and constant soil depth, the nuclide concentration is

$$C = C_0e^{-\lambda t} + P[H, \theta] \left( \frac{1}{\lambda + \mu'} \right).$$  

(5)

where $P[H, \theta]$ is the nuclide production rate (atom g$^{-1}$yr$^{-1}$) at the soil-bedrock boundary on a slope, $\theta$, and $C_0$ is the initial concentration of the nuclide (Lal, 1991). $P(H, \theta)$ is calculated as a factor of surface production: $6 \times 10^{10}$Be and 36.8 $^{26}$Al atoms g$^{-1}$yr$^{-1}$ for sea level and high latitude (>60°) (Nishizumi et al., 1989; Lal, 1991; Dunne et al., 1999). Under steady state, the soil production rate equals the erosion rate and is determined from measured $^{10}$Be and $^{26}$Al, with $C_0$ assumed to be zero.

Equation 5 depends on a local steady-state assumption. Here we propose an independent test of this, based on emergent tors. Tors are corestones from within the weathering zone that emerge as the surrounding saprolite is eroded; the concentrations of nuclides on the tor surfaces thus depend on the subsurface exhumation history as well as the subsaerial, bare-rock erosion rate, $\varepsilon_r$.

We consider two patterns of tor exposure history: (I) a steady-state model with constant soil thickness and constant soil production and erosion rates (Fig. 1B); and (II) a model where steady-state erosion is followed by an episode of accelerated erosion (stripping) leading to tor emergence, after which the tor surface erodes at a rate $\varepsilon_r$. We integrated equation 4 numerically using standard Runge-Kutta methods to determine nuclide concentrations on a tor surface for both models instead of using Lal’s (1991) steady-state solution. The program was checked with the constant erosion case and replicated exactly results from Lal’s solution. As shown in Figure 1C, the profile of predicted nuclide concentrations under steady-state (model I) conditions is quite different from model II profiles.

**STUDY AREA**

Nunnock River is a tributary to the Bega River that descends from steep granitic slopes of the eastern Australian escarpment and drains into the Pacific Ocean, through Late Silurian to Early Devonian granite and granodiorite of the Bega batholith (Lewis and Glen, 1995) (Fig. 2). The high-relief, steep-faced escarpment, which probably has retreated inland from a rift-initiated margin (Ollier, 1982; Seidl et al., 1996; Weissel and Seidl, 1997), separates a highland region of gentle topography, low relief, and slow erosion rates (e.g., Young, 1983; Bishop, 1985; Wellman, 1987; Nott, 1992) from a coastal belt with higher denudation rates (O’Sullivan et al., 1996). Relief is about 200 m between the study area and the coast and increases to the escarpment, which rises to about 950 m and is covered with intermediate to wet sclerophyll forest with patches of dense understory in the valley bottoms. Rain falls throughout the year, ~910 mm yr$^{-1}$ (Bureau of Meteorology, Australia, 1999). The southeastern highlands above about 700 m were affected episodically by periglacial processes in the Pleistocene (e.g., Galloway, 1965; Caine and Jennings, 1968; Costin, 1972) and sediment transport processes and rates may have fluctuated (e.g., Butler, 1967). These effects appear to have been negligible at our low-elevation site, where there is no evidence for the episodic sedimentation and denudation (e.g., Butler, 1967; Prosser et al., 1994). The absence of texture contrast or stratified soils further supports this, but we test it explicitly with our tor model.

Soil production and transport appeared to be primarily due to biogenic processes, although there was some evidence of overland flow. Burrowing wombats (*Vombatus ursinus*) were the most obvious agents of soil disturbance and their burrows, ~30 cm, occur widely across the landscape. Burrowing echidnas (*Tachyglossus aculeatus*), scraping lyre birds (*Menura novatehollandiae*), and worms are also important in southeastern Australia (Paton et al., 1995). Tree throw also uproots bedrock and distributes sediment, but at our site such features were shallow and there was little evidence of pit-mound topography. A well-defined, thin (<1 m) soil mantled the underlying saprolite and bedrock. Soils showed no horizonation beyond a thin
(<15 cm), organic-rich A horizon and a relatively homogeneous B horizon. Tors protruded on nearby ridge crests, and erode by grain-by-grain spallation and by thin (1–2 cm) exfoliation sheets.

RESULTS

Soil production rates determined from 26Al and 10Be concentrations in 14 bedrock or saprolite samples from the soil-bedrock interface are in Table 1. Figure 3 plots the soil production rates, calculated with equation 5, against observed soil depth. A variance-weighted best-fit regression defines the following soil production function,

$$\varepsilon(H) = (53 \pm 3) \cdot e^{-(0.020 \pm 0.001)H},$$

(6)

where the soil production rate is in meters per million years and the soil depth is in centimeters. Scatter around the regression line shown in Figure 3 is small and is significantly less than for the California data of Heimsath et al. (1997). Analytical uncertainties from the relatively clean granitic quartz were small and the soil-bedrock boundary was clearly defined. The lack of scatter also suggests that no episodes of major disturbance occurred during the time required to generate the soil (i.e., 20–100 k.y.) and that bioturbation, highly variable in space and introducing scatter, may have less effect on the soil production depth dependence here than at the California sites. A catchment average erosion rate of 51.5 ± 4.8 m m.y.–1, determined from a stream sediment sample, is plotted to the right of the soil depth axis. We measured 10Be and 26Al concentrations from seven samples from two tors (Table 1). Results plotted against height above ground level match well a theoretical concentration profile, calculated for steady-state conditions, with \(\varepsilon_s = 25\) m m.y.–1 and \(\varepsilon_r = 8\) m m.y.–1 (Fig. 4). The observed profile shows increasing nuclide concentrations with height above ground, leading to apparently decreasing erosion rates, where \(9\) m m.y.–1 from the top sample is least likely to show any legacy. Similarly, the best-fit value for \(\varepsilon_s\) fits well the soil production rate of 26 m m.y.–1 obtained by equation 6 for observed soil depths around the tors of 35 cm. The good fit of the observed with the theoretical profile supports the steady-state lowering assumption.

The soil production function compares closely with nuclide-based results from California, but the soil depth curvature data highlight a complexity in process. A plot of topographic curvature versus soil depth shows a well-defined linear relationship (Fig. 5). There is no relationship between soil depth and slope, nor do the modest slopes (<25°) suggest nonlinear sediment transport processes. For the divergent areas of the site the soil production function, equation 6, can be substituted for \(\varepsilon(h)\) in equation 2, using the data in Figure 5.

---

**Table 1. Soil Production Rates from Cosmogenic Nuclide Concentrations**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (cm)</th>
<th>Slope factor</th>
<th>10Be (mg)</th>
<th>26Al (mg)</th>
<th>(\varepsilon(H)) (m m.y.–1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR1</td>
<td>90</td>
<td>17</td>
<td>0.30</td>
<td>389.564</td>
<td>0.457</td>
</tr>
<tr>
<td>NR2</td>
<td>10</td>
<td>12</td>
<td>0.37</td>
<td>395.526</td>
<td>0.442</td>
</tr>
<tr>
<td>NR3</td>
<td>12</td>
<td>15</td>
<td>0.55</td>
<td>388.506</td>
<td>0.459</td>
</tr>
<tr>
<td>NR4</td>
<td>17</td>
<td>9</td>
<td>0.45</td>
<td>386.508</td>
<td>0.459</td>
</tr>
<tr>
<td>NR5</td>
<td>12</td>
<td>4</td>
<td>0.56</td>
<td>378.507</td>
<td>0.458</td>
</tr>
<tr>
<td>NR6</td>
<td>30</td>
<td>12</td>
<td>0.68</td>
<td>404.504</td>
<td>0.458</td>
</tr>
<tr>
<td>NR7</td>
<td>28</td>
<td>9</td>
<td>0.72</td>
<td>404.520</td>
<td>0.450</td>
</tr>
<tr>
<td>NR8</td>
<td>40</td>
<td>15</td>
<td>0.64</td>
<td>385.523</td>
<td>0.458</td>
</tr>
<tr>
<td>NR9</td>
<td>47</td>
<td>24</td>
<td>0.50</td>
<td>377.535</td>
<td>0.450</td>
</tr>
<tr>
<td>NR11</td>
<td>22</td>
<td>7</td>
<td>0.71</td>
<td>383.518</td>
<td>0.461</td>
</tr>
<tr>
<td>NR12</td>
<td>0</td>
<td>1.00</td>
<td>0.00</td>
<td>381.426</td>
<td>0.458</td>
</tr>
<tr>
<td>NR13</td>
<td>52</td>
<td>20</td>
<td>0.49</td>
<td>389.507</td>
<td>0.490</td>
</tr>
<tr>
<td>NR14</td>
<td>15</td>
<td>8.2</td>
<td>0.49</td>
<td>399.504</td>
<td>0.490</td>
</tr>
<tr>
<td>NR15</td>
<td>66</td>
<td>21</td>
<td>0.39</td>
<td>389.506</td>
<td>0.463</td>
</tr>
<tr>
<td>NR20</td>
<td>0</td>
<td>1.00</td>
<td>0.00</td>
<td>412.507</td>
<td>0.462</td>
</tr>
<tr>
<td>NR23</td>
<td>40</td>
<td>15</td>
<td>0.64</td>
<td>420.557</td>
<td>0.404</td>
</tr>
</tbody>
</table>

---

**Figure 3. Soil production function (see text equation 6). Solid black circles are averages of rates from both 10Be and 26Al (Table 1), and error bars represent all errors propagated through nuclide calculations, i.e., uncertainty in atomic absorption, accelerator mass spectrometry, bulk density and soil depth measurements, and attenuation length of cosmic rays. Black triangles are erosion rates from two highest tors samples, NR-21 and NR-18.**

**Figure 4. Predicted and observed concentrations of 10Be for tor profile (26Al results are equivalent).** 10Be is plotted with height above present ground surface, with measured nuclide concentrations normalized to sea level (Table 1) and error bars as in Figure 3.

---

**Note:** All errors are propagated to the soil production or erosion rate, \(E\), and \(26\)Al and \(10\)Be concentrations are normalized to sea-level, high-latitude production rates of 36.8 and 6 atoms g\(^{-1}\) yr\(^{-1}\) (Lal, 1991; Nishizumi et al., 1989).

*The average soil density is 1.2 g/cm\(^3\) and the site location is lat 36.62 degrees S, long 149.5 degrees E.

*The H-slope factor corrects for soil depth and slope yielding for all samples (Dunne et al., 1999).

**Samples** are from the sides and top of one tor (2.5 m), top of an adjacent one (1.6 m), and top of an emergent tor (0 m).
to solve for $K$ that yields the best-fit overlay of the curvature and nuclide data. The bulk density ratio between rock and soil was 2.0, and solving for $K$ yielded 40 cm$^2$ yr$^{-1}$. This is similar to the average $K$ for 34 sites in California, Oregon, and Washington: 49 ± 37 cm$^2$ yr$^{-1}$ (McKean et al., 1993).

**DISCUSSION AND CONCLUSIONS**

The nuclide-based soil production function reported here supports the form of equation 3, as defined by Heimsath et al. (1997). Furthermore, the spatial variation of soil production rates suggests a landscape out of morphologic equilibrium, similar to northern California. Here this disequilibrium may be in response to the propagation of the escarpment through the field area. Other studies determined slow rates of erosion (~10 m m.y.$^{-1}$) for the southeastern highlands, west of the escarpment (e.g., Wellman and McDougall, 1974; Young, 1983; Bishop, 1985; O’Sullivan et al., 1996).

In stark contrast to such slow rates, Seidl et al. (1996) and Weissel and Seidl (1997) inferred a long-term average rate of 2 km m.y.$^{-1}$ for escarpment retreat by assuming that the scarpt retreated 200 km from the margin since rifting, 100 m.y. ago. This rate is 10 times higher than their bedrock erosion rates and they suggested that hillslope processes control escarpment retreat rates (Weissel and Seidl, 1998). On similar grounds, the head of the Bega Valley has retreated ~500 m m.y.$^{-1}$ (50 km to the rift margin). Our maximum soil production rate of 53 ± 3 m m.y.$^{-1}$ is only one-tenth of this value.

**REFERENCES CITED**


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