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Exploring pedogenesis via nuclide-based soil production rates and OSL-based bioturbation rates

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Abstract. New dating techniques are available for soil scientists to test fundamental pedogenic ideas. Recent developments in applications of terrestrial *in situ* cosmogenic nuclides (TCN) from bedrock and saprolite allow the derivation of soil production rates, at scales ranging from local (sub-hillslope) to catchment wide, generally averaged over timescales of 10^4–10^5 years. Where soil depths are relatively constant over time, soil production rates equal transport rates and are thus essential to establishing sustainable erosion rates. TCN also allow the form of the soil production function to be compared to theoretical models—a difficult task previously. Furthermore, parameterised soil production functions can now be incorporated into numerical surface process models to test landscape evolution ideas.

Bedrock and saprolite conversion to soil is demonstrably dependent on the overlying soil depth, and there is general agreement that weathering declines exponentially beyond maximum soil production, consistent with theory. Whether maximum soil production occurs under a finite or non-existent soil cover at particular sites remains unresolved. We suggest that, in general, soil production from saprolite declines exponentially with increasing depth, while production from bedrock follows a humped function.

Estimates of the role of flora, fauna and processes such as freeze–thaw that mix soil mantles to depth, have been limited prior to optically stimulated luminescence (OSL) dating techniques. Recently derived OSL mixing rates extend the magnitude of previous partial, short-term bioturbation rates. In fact, bioturbation appears to be the most active pedogenic process operating in many soils, with freeze–thaw environments a noted exception. Although bioturbation far outweighs soil production, it does not always lead to homogenisation as is often reported. We maintain that the above-ground component of bioturbation, i.e. mounding, may alone, or particularly when combined with particle sorting via rainwash processes, lead to horizonisation and texture contrast soils in those materials that can be sorted such as mixtures of sand and clay. Together, TCN- and OSL-based estimates of hillslope soil transport and bioturbation, suggest significant rates of downslope soil mantle movement coupled with rapid mixing, contrary to *in situ* soil development models.

Additional keywords: soil formation, soil mixing, horizonisation, geochronology.

Introduction

The rate at which saprolite is altered to soil is known as *soil production*, and its quantification is vital to assessing sustainable erosion rates in areas where soil loss, enhanced by overgrazing and deforestation, threatens productivity (e.g. McNeill and Winiwarter 2004) and carbon sequestration (e.g. Lal 2004). When erosion outpaces soil production, soil thickness declines, which may eventually result in exposed bedrock. This definition of soil production conforms to recent literature (e.g. Heimsath *et al*. 2000) even though the word *bedrock* is often employed rather than *saprolite*. In this context, *soil* is the material that overlies saprolite as per convention in soil production studies. A key feature of soil formation is the development of horizons, but it also includes a continuation of mineral alteration that began during the development of saprolite.

A number of dating techniques are becoming increasingly accessible that can be used to estimate soil age and quantify pedogenic processes within soil profiles. Until recently, this exercise was largely restricted to evaluating soil formation rates in deposits (e.g. Birkeland 1999) and less commonly in *in situ* soil focusing on extrusive rocks such as basalts (e.g. Pillans 1997). Recent advances in optically stimulated luminescence dating of grains and cosmogenic nuclide dating of surfaces and sediment allow the testing and quantification of a number of long-held pedogenic ideas. The new techniques allow soil production and soil formation to be assessed from a greater range of lithologies.

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The conversion rate of bedrock/saprolite into soil, has long been thought to depend on overlying soil depth, and is often referred to as the soil production function. Gilbert (1877) first proposed this idea, reasoning that soil production was greatest under a thin soil mantle. His conceptual model remained difficult to constrain and assess until the advent of measuring terrestrial *in situ* cosmogenic nuclide (TCN) concentrations in bedrock and saprolite in order to derive soil production rates. Estimates for several sites by a small group of authors are now available.

In a general sense, soil production rates must match the rate in which landscape surfaces are lowering or denuding. The fact that soil mantles on hillslopes are often shallow, $<$1–2 m, provides empirical evidence of a type of dynamic equilibrium between soil production and surface denudation, first identified by Nikiforoff (1949), since the conversion of bedrock to soil and subsequent denudation involves very little storage of soil material. Where soil transport removes all soil, slope sediment transport is considered *weathering limited*, resulting in slopes dominated by outcrop; whereas the retention of soil or other weathering products indicates the slope is *transport limited* (Jahn 1968; Carson and Kirkby 1972).

Similarly, the role of bioturbation (mixing by biota) within soil profiles has proved difficult to quantify, and hence its role in pedogenesis has yet to be fully established. Preliminary estimates, however, suggest it may be very important (Johnson 1990; Paton *et al*. 1995; Johnson *et al*. 2005). Optically stimulated luminescence (OSL) dating has developed to a stage where the time elapsed since individual quartz and feldspar grains were last exposed to sunlight can be determined (Murray and Roberts 1997). Hence vertical mixing within soil profiles can now be evaluated over long time scales.

In this paper we give a general introduction to TCN and OSL applications with regard to their use in determining soil production and mixing rates. The measurement of OSL and TCN allows these processes to be constrained more precisely than before, both spatially and temporally, and thus provides improved age estimates of not only the soil mineral material itself, but also the horizons and fabrics (i.e. pedogenic features) within. Both these techniques display great potential for evaluating soil systems, and are a welcome addition to pedologists' 'toolkits' to complement more traditional approaches and emerging pedometric techniques (e.g. McBratney *et al*. 2000). Data from TCN and OSL suggest soils in upland settings are composed of considerable amounts of soil transported from upslope, and that soils are continually mixed while moving downslope. The rate of movement of soil particles is such as to encourage further research and to consider soil development with these processes in mind.

Terrestrial *in situ* cosmogenic nuclides (TCN)

Cosmic rays penetrating the Earth's atmosphere bombard elements in the atmosphere and geosphere where they alter atomic structures, thereby producing cosmogenic nuclides. Meteoric or atmospheric cosmogenic nuclides are produced in the atmosphere, while TCN are produced within soil and rocks at the Earth's surface (for reviews, see Nishiizumi *et al*. 1993; Bierman 1994; Gosse and Phillips 2001). For instance, Si and O within quartz are typically converted to ^{26}Al (half life 7.05×10^5 years) and ^{10}Be (half life 1.5×10^6 years), respectively, by nucleon spallation (Gosse and Phillips 2001). Commonly used TCN include ^{3}He, ^{14}C, ^{21}Ne, and ^{36}Cl and a wide variety of minerals are possible targets, such as quartz, plagioclase, pyroxene, amphibole, and olivine (Gosse and Phillips 2001). Since mineral exposure time to cosmic radiation flux is proportional to TCN concentration, the latter can be measured to quantify exposure, e.g. that of glacially polished surfaces. TCN production within minerals is typically very slow, e.g. $\sim$5 and 31 atoms per gram of quartz per year for ^{10}Be and ^{26}Al, respectively, standardised for sea level and high latitudes (Stone 2000); thus accelerator mass spectrometry (AMS) is used to measure the low nuclide concentrations in sample surfaces. A numerical model is applied to derive an estimate of the surface age, based on appropriate assumptions, such as the simplest case—targeted by many investigators—where it can be assumed that no erosion has occurred since exposure. TCN production decreases exponentially with depth in rock due to attenuation. Consequently, surface lowering (denudation) exposes previously shielded minerals whose nuclide concentrations are inversely proportional to the erosion rate. The TCN concentration of such samples can be used to derive an erosion or surface lowering rate provided erosion has been constant over time and exposure is comparatively longer than the nuclide half life (Lal 1991). Any radiation shielding by overlying snow, soil, or surrounding topography must be accounted for (e.g. Dunne *et al*. 1999). In soil production studies, the lowering rate of the surface underlying the soil mantle, usually saprolite but sometimes bedrock, is equated to the soil production rate. It is assumed that soil cover shielding remains constant for the time period that the TCN are produced in the sampled surface, which is the time required to convert Λ/E to soil (where the cosmic ray attenuation length, Λ, is $\sim$60 cm in rock, and $E =$ the local soil production rate) and is typically $\sim 10^4$ to 10^5 years. This is also the time period over which the soil production rate is averaged.

Soil production has been estimated in a small number of studies. Early studies used ^{14}C chronologies of colluvial fills (Reneau *et al*. 1989; Reneau and Dietrich 1990), and mass-balance approaches for atmospheric ^{10}Be (Monaghan *et al*. 1992; McKean *et al*. 1993) to estimate average production for small catchments and hillslopes, respectively. Granger *et al.* (1996) used TCN-based erosion rates of small catchments, which may be taken as catchment-averaged soil production rates; while local soil production rates from TCN were first derived by Heimsath *et al.* (1997, 1999) and Small *et al.* (1999), with the former detailing the functional response of soil production to soil depth.

Time-invariable soil depths imply local soil production rates equal local erosion or denudation rates i.e. both the soil surface and saprolite–soil interface lower at the same rate. In upland settings where soil production studies have been performed, soil removal from the hillslope is thought to be largely via biogenic soil creep (e.g. Heimsath *et al.* 2002; Roering *et al.* 2002) and rainwash (e.g. Paton *et al.* 1995; Prosser and Williams 1998) resulting in the net downslope transport of soil extending to the soil-saprolite interface. Figure 1 demonstrates that local (sub-hillslope) soil production estimates are generally similar in magnitude to denudation estimates derived using a variety of techniques over a range of spatial scales, and thus provide a first order validation of the TCN technique where soil production and transport are thought to be balanced. The data in Fig. 1 illustrate that ~1–250 m of soil is produced per million years (m/My = mm/1000 years) on hillslopes in a variety of settings, and most of the data occupy a range an order of magnitude wide, between 10 and 100 m/My. The

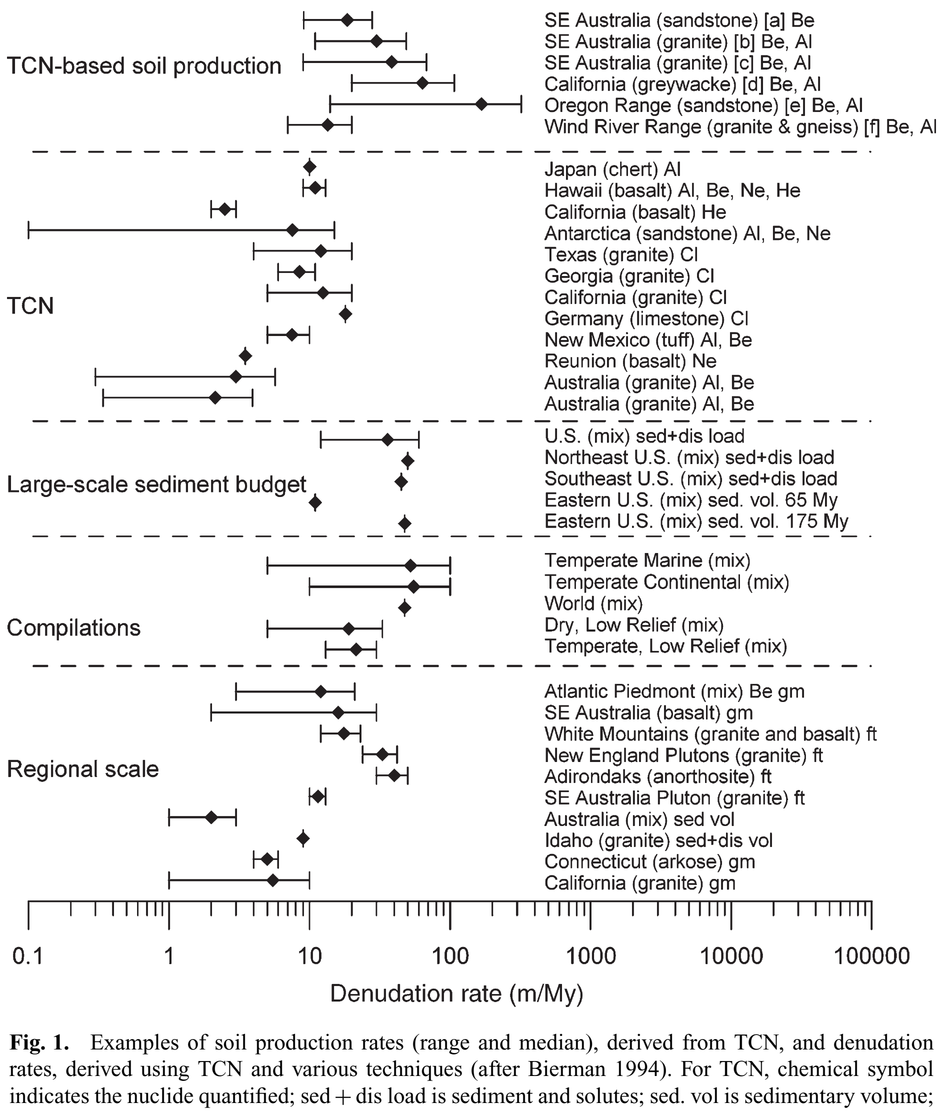

Fig. 1. Examples of soil production rates (range and median), derived from TCN, and denudation rates, derived using TCN and various techniques (after Bierman 1994). For TCN, chemical symbol indicates the nuclide quantified; sed + dis load is sediment and solutes; sed. vol is sedimentary volume; gm is a geomorphic basis, using dated surfaces, etc; ft is fission tracks. Additional references to Bierman (1994); a, Wilkinson *et al.* (2005); b, Heimsath *et al.* (2001*a*); c, Heimsath *et al.* (2000); d, Heimsath *et al.* (1999); e, Heimsath *et al.* (2001*b*); f, Small *et al.* (1999); g, Bierman and Caffee (2002); h, Belton *et al.* (2004).

concordance of soil generation rates, considering differing climates, lithologies, and tectonic settings, is rather striking. These data are also consistent with local erosion rates from outcrops or weathering-limited slope segments (TCN, Fig. 1), which are generally lower than erosion rates of weathered bedrock (saprolite) actively being converted to soil, as intuition would suggest. Erosion rates derived from sediment budgets and compilations show similar averages to soil production rates, suggesting soil production is a major (subsoil) surface lowering process, but because these average erosion over large spatial scales, there is less variation compared to local rates. Such comparisons are reliant on the assumptions of steady-state over a great range of spatial and temporal scales.

Optically stimulated luminescence (OSL)

Optically stimulated luminescence dating uses a beam of light to release a luminescence signal within particular mineral grains (generally quartz or feldspar), which is measured using a photomultiplier (see reviews in Aitken 1994, 1998; Duller 2004). OSL dating differs from thermoluminescence dating in that the latter uses heat to stimulate the luminescence, but otherwise the two techniques measure the same phenomenon. The OSL signal, which is proportional to the time elapsed since the grain was last exposed to sunlight, accumulates in the crystal structure of quartz and feldspar minerals as a result of exposure to cosmic rays and ionising radiation from radionuclides (Th, U, K) in adjacent soil. This radiation flux is measured and termed the dose rate. The maximum measurable or 'saturation' age, depends on the dose rate and the crystal characteristics of the target mineral which determine how much energy can be stored, and generally ranges from 10^1 to 10^6 years (Pillans 1998; Yoshida *et al.* 2000). Thus grains derived from bedrock with no exposure history to sunlight will be dose saturated i.e. not datable by this technique. In natural settings, when a grain is exposed to sunlight (bleached), the OSL signal is released (i.e. age reset to zero) and electrons only begin to re-accumulate within the crystal lattice when the grain is buried. Hence, OSL has been used to measure the burial age of fluvial, colluvial, and aeolian sediments in a variety of settings and the technique can be used to estimate vertical mixing in a soil profile if exposure to sunlight and subsequent reburial occurs. While OSL analysis has traditionally been carried out on samples or aliquots with multiple grains, the technique has developed to the stage where luminescence dating can be performed on individual grains (Murray and Roberts 1997).

Soil production and TCN

The 'humped' model

Gilbert (1877) suggested that the physical and chemical weathering of bedrock into soil at a point on a hillslope varies systematically with overlying soil depth. Importantly, he inferred that soil production is maximised under a shallow soil cover, d_m (Fig. 2*a*, curve A). This function is generally referred to as a 'humped' function (Cox 1980; Dietrich *et al.* 1995). There are several reasons to support Gilbert's notion (e.g. Carson and Kirkby (1972). Physical disruption of bedrock can result from biota, freeze–thaw and other processes. Animals and plants require at least a moderate mantle to exploit as habitat, and in doing so, assist soil production (e.g. Dietrich *et al.* 1995). Plant roots and burrowing mesofauna at the base of the soil column disturb the soil–saprolite interface, thereby altering saprolitic fabric (e.g. Humphreys 1994). This disturbance creates voids which may be filled by water, gases or soil, enabling further access into the profile by weathering agents. Furthermore, the disturbance increases the surface area of bedrock exposed to chemical weathering (Gabet *et al.* 2003, their fig. 6). Plants and animals also penetrate beyond saprolite into unweathered bedrock (e.g. Lee and Wood 1971). However under thicker soil mantles, biota will reach bedrock less frequently. The action of freeze–thaw is similarly limited under shallow and deep soil covers, since water runs off bare rock, and under increasingly deeper cover the frequency of freeze–thaw

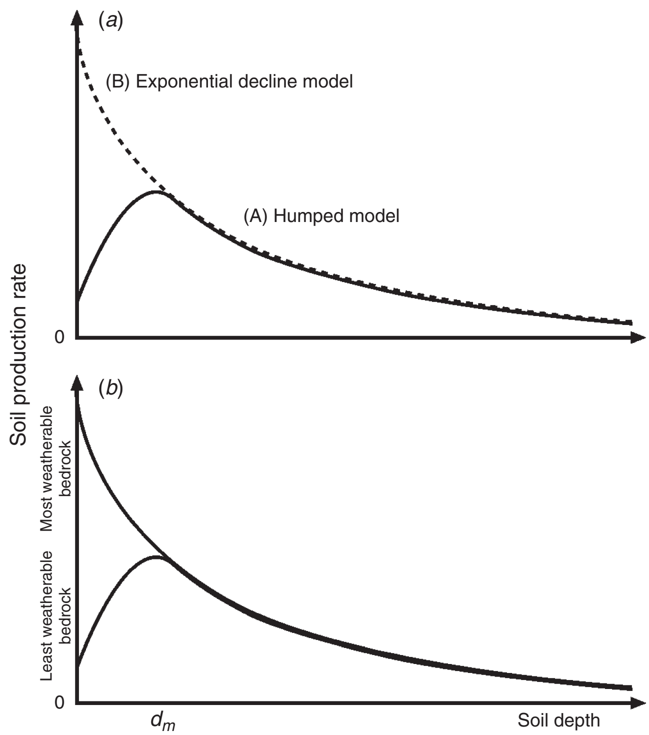

Fig. 2. (*a*) Two schematic soil production models discussed in the text; d_m, is the soil depth at which soil production is maximised. (*b*) A possible resolution of the two known soil production functions, where data from saprolite (most weathered bedrock) plots high on the *y*-axis, whereas bedrock erosion rates (least weathered bedrock) are low. This interpretation is supported by the datasets of various authors.

decreases exponentially (Ahnert 1988). Anderson's (2002) modelling of soil production by frost cracking on gentle alpine slopes cut into granite and gneiss in the western USA supports this viewpoint. Frost cracking is thought to be very low on bare rock, increasing to a maximum under 0.2 m of soil cover, whereby cracking efficacy decreases exponentially to almost zero under 2.0 m of soil. A similar soil production function in steeper, non-periglacial greywacke terrain, was considered but subsequently rejected by Dietrich *et al*. (1995, see their fig. 2).

Chemical weathering by water is also thought to be similarly depth-dependent since it relies upon the contact of bedrock with water, and water circulation to replenish saturated solutions (e.g. Ahnert 1976; Stallard 1992). Thus water displacement from non-concave rock outcrops will limit chemical reactions such as hydrolysis, while very deep soils will buffer underlying bedrock from water penetration. Therefore chemical weathering also appears to be most effective under a shallow to moderately deep mantle. Of course there are exceptions to these generalised notions such as karst landscapes in limestones, where solutional weathering can take place effectively at great depths. However, based on the apparent conditions most suitable for rock weathering, it appears intuitive that soil production is maximised under a finite cover of soil.

The exponential decline model

An alternative to the humped soil production model has been examined by a number of authors (e.g. Ahnert 1967 for purely mechanical weathering; Dietrich *et al*. 1995; Heimsath *et al*. 1999), who suggest a monotonic exponential decline in soil production with increasing soil depth (Fig. 2*a*, curve B). Similarly, hyperbolic relationships between production and depth have also been suggested (see Cox 1980 for a review). The inverse exponential relationship between soil production and depth may be thought of as a humped model with the peak in weathering occurring under zero soil cover. Support comes from two main sources which form the backbone of papers by Heimsath *et al*. (1999, 2000, 2001*a*, 2001*b*). The first uses TCN-based soil production estimates as detailed above. The second approach also relies on the assumption of constant soil depth, since it allows a simplification of the soil mass balance equation, such that local soil production is proportional to local topographic curvature with the caveats that mass solution is negligible and soil flux is linearly proportional to surface gradient. Therefore, mapping soil depth and curvature (morphometry) is thought to reveal the relationship between soil production and soil depth. Constant soil depth is reasoned to be likely on particular landforms where soil loss equals soil gain from soil production and colluvial deposition. Therefore the distal end of spurs—termed 'noses' in geomorphic literature—convex in both plan and profile curvature, have been targeted for investigation by both techniques. On this type of landform chemical weathering is likely to be minimal since water is generally dispersed.

Features and problems

A number of authors have suggested that should soil production behave as depicted by the humped model (Fig. 2*a*, curve A), then the hillslope will exhibit segments where soil transport is weathering-limited (i.e. non-existent soil cover) and others that are transport-limited (i.e. finite depth soils) (e.g. Carson and Kirkby 1972; Dietrich *et al*. 1995; Furbish and Fagherazzi 2001). If soil production is maximised under a non-zero soil depth, d_m, the function is unstable when local mantle thickness is between zero and d_m. Within this depth range, should a decrease in soil depth occur, such as via treefall excavation, it will result in lower soil production, accompanied by a decrease in soil depth, thereby decreasing soil production, and so on, eventually leading to total local soil loss. Similarly, positive feedback results from an increase in soil cover thickness—perhaps due to mounding by fauna—for local soil depths to the left hand side of d_m, until d_m is exceeded. In contrast, soil mantles that are thicker than d_m are inherently stable under such a model because of negative feedback between mantle depth and soil production. Therefore sites with humped soil production functions that are in equilibrium with the underlying slope transport and soil production rates, are thought to exhibit a 'morphologic signature' (Dietrich *et al*. 1995; Heimsath *et al*. 2001*b*) of rock outcrop and/or no soil depths between zero and d_m.

At present a humped soil production on saprolite and the hypothesised attendant morphologic signature have not been unambiguously identified in the field, although sharp changes in soil depth, reported by Wilkinson *et al*. (2003, 2005) on sandstone spurs in the Blue Mountains, Australia, may be an exception. Furthermore, this morphologic signature may in fact be less precise than as noted above. Dietrich *et al*. (1995) modelled soil depth patterns and outcrop resulting from a humped soil production function, using a generic diffusivity parameter applied equally to each cell. However, if the diffusivity parameter is non-uniform over the slope, as Anderson (2002) noted elsewhere, the morphologic signature of a humped soil production function may not include as much outcrop as indicated in the simulation by Dietrich *et al*. (1995).

The TCN results of Small *et al*. (1999), in concert with detailed hillslope evolution modelling by Anderson (2002), support a humped soil production function. TCN data illustrate that soil production under 0.90 m soil cover on these alpine slopes is at least slightly faster, and up to twice as fast as the erosion of bare rock from tors. This is contrary to Heimsath *et al*.'s (1997, 1999, 2000, 2001*a*, 2001*b*) datasets where soil production is thought to decline exponentially with increasing soil thickness, and surface lowering of outcrops is similar to that of bedrock under thick cover. Unfortunately Small *et al.*'s (1999) soil production estimates cannot directly support the hypothesised soil production function of Anderson (2002) since the broad slope exhibits near uniform soil depth, as it appears to be close to morphologic equilibrium. To confirm the operation of a humped soil production function, there must be evidence for both maximum weathering under soil cover and slower bedrock/saprolite weathering under thinner cover. However this is difficult to find on equilibrium slopes as soils depths $<d_m$ are thought to be absent. Currently only one dataset displays this feature (Heimsath *et al.* 2001*b*).

Implicit in the methods of Heimsath *et al.* (1997, 1999, 2000, 2001*a*, 2001*b*) is that unmantled samples must be saprolitic to be included in the soil production function, whereas TCN-based bedrock outcrop lowering rates are considered as hard rock erosion rates, even though they are often plotted with lowering rates of saprolite. Thus, the definition commonly cited that soil production is the conversion of bedrock to soil (e.g. Heimsath *et al.* 1999) is slightly misleading, because in application it is the conversion of saprolite to soil; i.e. their data show that soil production is maximised on bare saprolite, not bare bedrock.

Soil age, bioturbation, and OSL

There are several processes to consider when estimating soil age indirectly. In upland settings, soil is produced at the base of the soil column via soil production, and for hillslopes, colluvium is also transported, generally close to the surface (e.g. Paton *et al.* 1995; Roering *et al.* 2002). If soil transportation leads to net soil loss (erosion), surficial material is replaced in position by material beneath, and this, in turn, is the case for all positions down the soil column, with soil input via bedrock weathering lowermost. In this schema (which ignores chemical dissolution), a soil profile may be considered similar to an elevator, whereby disaggregated rock (soil material) enters the mantle at the bedrock–saprolite interface, and leaves at the surface via downslope transport, keeping in mind that the overall effect is the altitudinal lowering of all components of the soil column at the same rate when soil depths are time-invariable (i.e. hillslope denudation, Johnson 2002). This model suggests that soil particles are youngest at the base near bedrock, and that age increases linearly towards the soil surface if soil erosion and production remain constant over the time taken to produce the profile. In this situation the turnover time or residence time of the local soil column is the soil production rate divided by the soil depth. For instance, sandstone soil production inferred from TCN in the Blue Mountains, yields ~15 m/My (Wilkinson *et al.* 2003, 2005). In this case, soil particles in a typical 1-m soil profile reside for ~67 ky on average, before being transported downslope.

However, soil mantles are mixed by flora and fauna e.g. worms, termites, ants, wombats, treefall (Johnson 1990, Paton *et al.* 1995). This may modify or even totally disrupt the simple elevator-like progression of soil from bedrock up to the surface, depending on the rates and processes of bioturbation at various depths. Thus, while the average residence time of soil grains is as described above, bioturbation may bury some grains to a depth beyond the reach of surface erosion processes, so that they reside longer than average; and conversely, some soil will be elevated in the profile faster than the background elevator rate and thus leave the surface prematurely in this context.

Quantification of these processes can be achieved using OSL. If the elevator model of soil movement in a soil column is the only process taking place, only surface soil grains would return an unsaturated (i.e. datable) luminescence age since exposure to light is a prerequisite for dating, whereas all other grains away from the immediate surface would be saturated with radiation (i.e. not datable) This is depicted in Fig. 3*a* (curve A); the immediate surface is affected by rainsplash and scour via wash, such that we suggest soil grains in the upper 50–100 mm of most profiles are frequently bleached. Unsaturated luminescence ages from soil grains deeper in the profile would indicate these grains have been to the surface and subsequently buried (Fig. 3*a*, curve B). This phenomenon has been reported from stable soil profiles in several hillslope-focused studies (Heimsath *et al.* 2002; Pillans *et al.* 2002; G. S. Humphreys, J. M. Olley, R. G. Roberts, J. Campbell, I. Webster, B. L. Smith, and P. P. Hesse, unpublished data). Aside from the near-surface bleaching processes mentioned above, the most likely process that exposes soil to sunlight is mounding by bioturbators, e.g. worm castings, termitaria, and ant mounds. Since mounding involves mining of grains or aggregates, subsidence also takes place, leading to burial of grains formerly exposed to sunlight.

Data in Heimsath *et al.* (2002), from a granite catchment at the base of the Great Escarpment in south-eastern Australia, provide a useful example. The luminescence profile shows that the number of quartz grains that have not been exposed to sunlight, increases with depth. Also, the authors find grains with a luminescence signal in the saprolite of a shallow profile, which is consistent with soil mixing from the surface to within the saprolite, in places. Vertical velocities of particles from the surface to depth can thus be calculated by dividing the burial depth by OSL age. Furthermore, if the residence time of the soil column is known, then one can compare the rate of bioturbation with the inferred erosion rate, providing soils are in steady-state. At present, the only dataset that allows this is also from Heimsath *et al.* (2002). It indicates mixing agents move soil grains at least 5–20 times faster than the liberation of those grains from underlying bedrock.

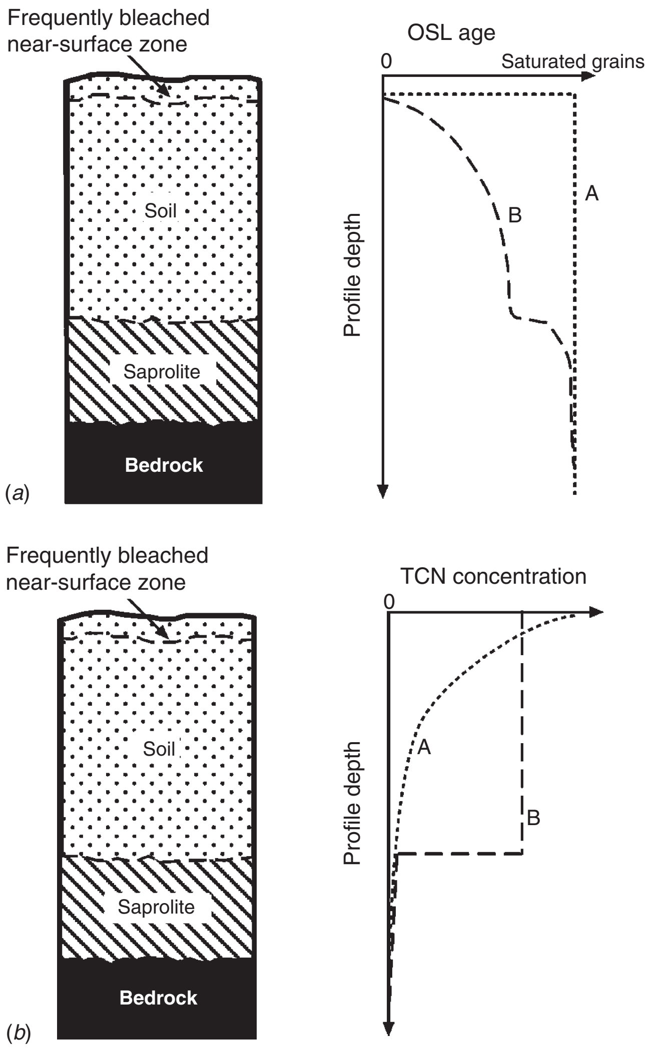

Fig. 3. (*a*) Schematic OSL age profiles and soil profiles, based on 2 models of pedogenesis. Curve A is based on the traditional explanation of soil formation whereby soil is thought to be derived primarily from *in situ* weathering of underlying bedrock. By comparison, Curve B can only be explained by considerable mixing that involves the transport of soil grains to and from the surface. The frequently bleached near-surface zone is a result of rainsplash and rainwash processes, see text (*b*) TCN profiles, as for Fig. 3*a*. Curve A is based on the traditional model of soil formation, while Curve B is a result of mixing, similar to that of Small *et al*. (1999). Mixing in alpine settings is attributed to freeze–thaw. The presence or absence of processes operating in the frequently bleached near-surface zone are unlikely to affect the TCN concentration significantly.

Soil mixing has also been demonstrated using TCN data too. In a periglacial setting Small *et al*. (1999) report constant TCN concentrations with depth in a 1-m soil profile (Fig. 3*b*, curve B), which they attribute to soil mixing by the growth of ice crystals within the profile, i.e. cryoturbation. If no mixing had taken place, the profile would exhibit declining TCN concentrations with increasing soil depth (Fig. 3*b*, curve A) due to cosmic ray attenuation.

Other estimates of bioturbation are available but these depend on extrapolating short term (up to a few years at best) process results over thousands of years. These results are considered in the following section. Nevertheless, based on the limited but realistic appraisals provided by the OSL and TCN examples, it appears that the elevator concept in pedogenesis must be significantly augmented by other processes that move soil grains within the soil.

Pedogenesis

While it is now possible to estimate rates of soil production and bioturbation, rates of pedogenesis (horizonisation) in upland soils have received little direct attention. OSL datasets indicate considerable soil mixing, especially within the topsoil. TCN soil production rates and limited hillslope soil storage suggest significant rates of soil transport, which is unlikely to involve aeolian activity in humid areas. If mixing is coupled with soil transport, it is evident that upper soil horizons in upland settings on hillslopes are unlikely to be derived solely from *in situ* alteration of local bedrock, as has often been assumed (e.g. Stace *et al*. 1968, and most accounts of soil formation). Rather, mineral soil is likely to be a combination of material derived from local saprolite and saprolite upslope, the latter delivered by downslope transport within the soil mantle via bioturbators and/or surface wash.

With the exception of periglacial sites, many studies identify bioturbation as a key component in driving soil production and this leaves open the role of bioturbation in contributing to pedogenesis as in the development of horizons. Paton *et al*. (1995) summarise considerable data on mounding rates—the above-ground component of bioturbation—and this compares favourably with other processes (Fig. 4) whereby mounding rates often exceed estimates of solution and weathering, soil creep and solifluction and slope wash as summarised by Young and Saunders (1986). At 2 sites in south-eastern Australia, mounding was greatest by ants with variable input by earthworms, termites and cicadas. Combined local mounding rates of 600–1000 g/m^2.year were recorded (Humphreys and Mitchell 1983). Using a soil density of 1.4 g/m^3, this equates to $\sim$428–714 m/My, and is 6–80 times local soil production estimates for parts of the region (Heimsath *et al*. 2000; Wilkinson *et al.* 2005).

Though rates of mounding are impressive they are possibly less than the subsurface component of bioturbation viz. mixing or biomixing. There are, however, very few estimates of this (Humphreys and Field 1998) and all but one study is based on rates of soil ingestion by earthworms. In the UK mixing and casting rates are similar (Evans 1948; Satchell 1967) whereas a study in the Ivory Coast indicated a mixing rate of a staggering 70 000–110 000 m/My, which was 25–50 times the casting rate (Lavelle 1978). A dyed soil column emplaced in the soil for 17 years

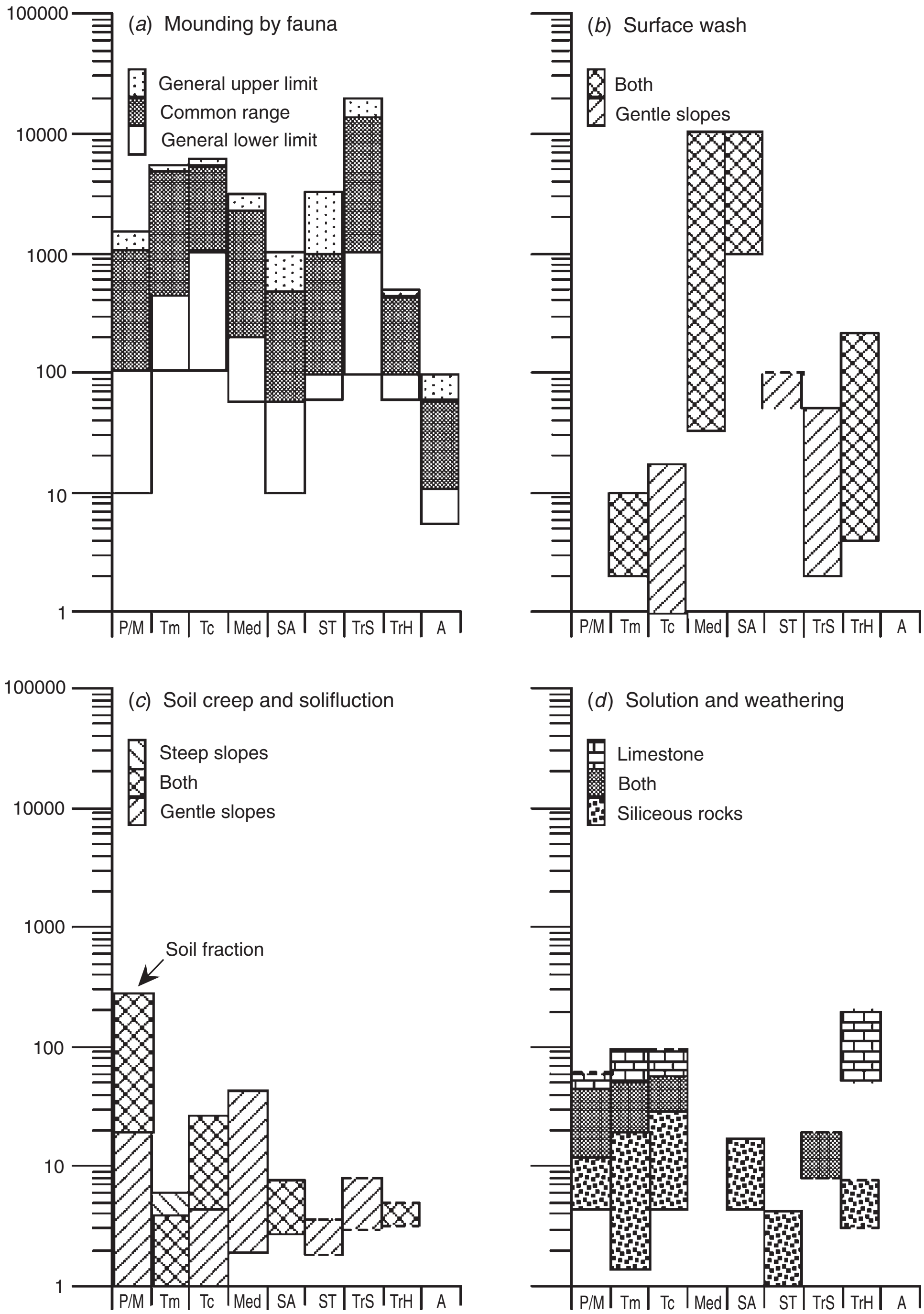

Fig. 4. Generalised ranges of observed mounding rates (*a*) compared to other relevant processes including (*b*) surface wash, (*c*) soil creep and solifluction, and (*d*) solution and weathering, plotted in m/My (log-scale, vertical axis) and expressed on an environmental basis. Environmental codes (horizontal axis) follow Young and Saunders (1986): P/M, polar/montane; Tm, temperate maritime; Tc, temperate continental; Med, mediterranean; SA, semi-arid; ST, humid subtropics; TrS, tropical wet and dry; TrH, humid tropics; A, arid. A continuous line at the upper or lower limit of a range in (*b*), (*c*) or (*d*) indicates that three or more records exist, of which the single most extreme value has been excluded from the range; a broken line indicates that the boundary is based on one record only. Data on mounding obtained from Paton *et al*. (1995, their fig. 3.8) and data from other processes after Young and Saunders (1986, their fig. 1.1).

was used by Humphreys and Field (1998) to estimate mixing at Cattai, near Sydney. The replacement biofabrics attributed mostly to ants and earthworms indicated mixing (10 600 m/My) was 21–26 times the mounding rate which is probably 2–3 orders of magnitude greater than the soil production rate.

This analysis reveals that bioturbation is operating significantly faster than soil production, and possibly many other processes known to affect soil (Fig. 4). As such bioturbation, if dominant, might be expected to homogenise the soil. However, where bioturbation is coupled to other soil movement processes such as rainwash, and/or where the biomixing depth function varies with depth and/or where the incorporation of other constituents such as organic matter also varies with depth, horizonisation is expected (e.g. Humphreys and Mitchell 1983; Paton *et al*. 1995). This is a theme that demands much more attention than is afforded at present.

Discussion

Although it is possible that soil production rates may vary widely over the surface of the Earth, preliminary evidence suggests considerable consistency between landscapes that *a priori* appear disparate (Fig. 1). Furthermore, the TCN-based soil production estimates appear robust in the context of other erosion estimate methods. There is consensus between field evidence and ideas that soil production rates decline exponentially beyond the maximum. However whether maximum soil production occurs under soil cover at some study sites remains unresolved. For instance a TCN dataset that appears to define a Gilbert-type soil production function was obtained at the Oregon Coast Range, USA, by Heimsath *et al*. (2001*b*), however the authors interpret the data differently. At this site, bedrock under 0.15 m or less cover is producing soil more slowly than bedrock with slightly greater cover. Although this is consistent with a humped soil production function, the authors separate the shallow samples, and interpret these as hard rock erosion rates rather than saprolite soil production rates. These samples appear consistently less weathered than saprolite under deeper soil cover which is fractured, and although soil production is largely attributed to bioturbation by animals and large trees which probably require a moderate amount of soil cover to maximise their impact, the absence of extensive bedrock outcrop and few sites with shallow soils—i.e. the morphologic signature for a humped soil production function—guided the authors' interpretation. A second example comes from a granite catchment in the south-eastern Australian highlands, where Heimsath *et al*. (2001*a*) observed an absence of soil depths less than 0.25 m, consistent with a humped production function. However the data gap prevents complete verification.

If the distinction between bedrock and saprolite were relaxed and bedrock lowering rates determined from TCN in all outcrop samples (both bedrock and saprolite) are included in existing soil production plots, the function would bifurcate at shallow depths to incorporate exposed saprolite and bedrock (Fig. 2*b*) in which the bedrock samples plot below the *y*-intercept of the proposed monotonic exponential decline function. Not only does this accommodate the TCN datasets produced by various authors, but it also is possible conceptually. Soil transport is typically stochastic (e.g. Heimsath *et al*. 2001*b*; Roering *et al*. 2002), and therefore, saprolite may be unmantled temporarily. However this is unlikely to persist because of the ease with which it is physically weathered. If soil and saprolite are stripped by an extreme event or series of events, thereby exposing fresh bedrock, it appears there is little to aid weathering. This is consistent with the very low soil production rates on fresh basalts in semi-arid tropical Australia, reported by Pillans (1997), and the higher rates from catchments underlain by saprolite (e.g. Heimsath *et al*. 2000). In view of this dichotomy, Wilkinson *et al.* (2005) interpret TCN data as a humped soil production function where soil overlies hard bedrock but an exponential decline for soil derived from saprolite, at their Blue Mountains site.

Defining the soil production function for shallow soil mantles is important for soil recovery on hillslopes where most, if not all, mineral soil is derived from the weathering of underlying bedrock (local and upslope). If a humped soil production function is operating, soil mantles thinner than d_m are particularly sensitive to erosion and hence severe degradation. If soil can accumulate, however, it will do so rapidly until cover thickness equals d_m. Thus, an understanding of the production function, for the particular environmental setting may assist in devising appropriate land management strategies.

A critical assumption, when using TCN to estimate soil production rates, is that of constant soil depth over the time taken to accumulate the TCN population i.e. 'local equilibrium' (Dietrich *et al*. 1995) or 'steady state' (Heimsath *et al*. 1997). This may be difficult to test at some sites but has been accomplished using TCN to examine tor emergence from surrounding regolith (Heimsath *et al*. 2000, 2001*a*). The effects of episodic erosion on TCN concentrations can be modelled, thus limiting the range of soil–landscape history possibilities (Lal 1991; Nishiizumi *et al*. 1991; Bierman and Steig 1996; Heimsath *et al*. 2001*a*). Uranium-series dating has recently been applied to derive an estimate of the onset of catchment-scale weathering (Vigier *et al*. 2001) and this technique could be used to assess steady-state conditions for TCN-based erosion rates. In particular, various ratios of uranium daughter products allow steady-state to be assessed over periods of 10^3–10^5 years.

If a hillslope is in morphological equilibrium, i.e. adjusted in form to current base level and climate, and soil transport is proportional to slope inclination, soil depth and curvature are likely to be constant over the slope (e.g. Anderson 2002). Such a site is not useful for defining the soil production function using TCN. Instead morphologic disequilibrium is required, so that a range of soil depths is encountered, however the TCN method necessitates local equilibrium, to be accurate. Sites like these have generally been the focus of soil production function investigations, however they are unlikely to display soil depths $<d_m$ should a humped soil production apply, which results in a data gap between 0 and d_m. Perhaps the onus of proof, in distinguishing between an exponential decline and a humped soil production function, rests with the former, because one cannot rule out a humped function without shallow or exposed saprolite erosion rates depicting an exponential decline in soil production.

There are suggestions, also, that the soil production models examined here may be too simplistic on a hillslope scale. For instance, Furbish and Fagherazzi (2001) have proposed that soil production may increase downslope for any given soil thickness if an increase in the water content of the soil profile occurs, which probably enhances chemical weathering especially via hydrolysis.

OSL data suggest that great rates of soil mixing is taking place in soils traditionally interpreted as developing *in situ*. However difficulties in obtaining an accurate time interval since a grain or aliquot of grains last visited the surface arise due to incomplete bleaching or resetting of the OSL clock (Murray and Olley 2002), which is likely to be a problem in some bioturbation studies (Bateman *et al*. 2003) but not all (Bush and Feathers 2003). Various aliquot sizes (Roberts *et al*. 1999) and statistical analysis techniques (e.g. Spencer *et al*. 2003) may be able to resolve this matter and other problems associated with aliquots containing grains with mixed exposure histories (Roberts *et al*. 2000). Importantly, the comparison of multiple-grain aliquot ages with sub-sample single grain ages reveals that grains at any depth in a soil profile have individual exposure histories (Roberts *et al*. 1998; G. S. Humphreys, J. M. Olley, R. G. Roberts, J. Campbell, I. Webster, B. L. Smith, and P. P. Hesse, unpublished data); this is consistent with grain-by-grain bioturbation by soil mesofauna (Paton *et al*. 1995).

While soil mixing may be thought of homogenising process, the combination of mounding with surface transport leads to sorting of that soil profile. Sorting is limited by the mining depth of biota, and the soil must consist of material capable of being sorted, e.g. a mix of sand- and clay-sized particles (Humphreys and Mitchell 1983). Thus, bioturbation and texture contrast soil genesis appear to be closely linked and hence well-sorted layers may overlie less sorted horizons, eventually grading into unsorted saprolite. Bioturbation-depth profiles demonstrate both gradual (Humphreys and Field 1998; Heimsath *et al*. 2002) and abrupt (Roering *et al*. 2002) declines in mixing with depth. Additionally and/or alternatively, bioturbation may be dominated by agents that cannot move coarse soil fractions such as pebbles and cobbles, e.g. worms, in which case these latter components sink as the soil around them is moved. Darwin (1881) noted this process, and Johnson (1990) and Paton *et al*. (1995) explain stonelayers and texture contrast soil genesis in the same manner. Both slopewash sorting and selective mining by bioturbators suggest sorting and horizonisation rather than homogenisation via bioturbation. The pedogenic model outlined here is consistent with observations of soil horizons that are parallel to the bedrock-soil interface at the hillslope scale.

The homogenisation of well mixed soils or soil components has been illustrated by Roering *et al*. (2002) who report a mixing depth of $\sim$0.40 m for a site where a tephra layer is thought to have been bioturbated largely by root growth from successions of *Nothofagus* and podocarps in New Zealand. This depth is coincident with the trees' rooting depth, and mixing has led to homogenisation of the topsoil here, because surface sorting by rainwash is inhibited by persistent vegetation cover, and tree turnover is capable of exhuming a large range of particle sizes.

The soils that mantle many of Australia's landscapes are generally regarded as old, and while there are only a few well constrained accounts of soil antiquity, it is often not clear whether the age refers to the soil material or the pedogenic features within (e.g. peds, pedogenic horizons). TCN-based soil production rates can be used to constrain the residence time of slope soils, providing soil thickness is in steady-state. Furthermore, bioturbation rates, derived from both OSL and rates of mounding, suggest soil profiles may be organised into horizons much faster than their production from underlying bedrock. The latter can be viewed in another way; if a soil mantle can be maintained through the vicissitudes of environmental change it may form several horizons in which features from past environments may or may not be preserved. Examples of relict features are widely discussed in the palaeosol literature (e.g. Birkeland 1999). Bioturbation rates suggest a topsoil can be produced from a partially stripped profile much faster than the absolute soil production rate. This is not to suggest that erosion rates faster than underlying soil production are sustainable in the long term, for not only are shallow topsoils of limited value for plant growth, but more importantly, this level of erosion will reduce soil cover irrespective of any pedogenic features within. The coupling of soil production and horizonisation offers exciting new areas of inquiry as we seek to understand the development and maintenance of soils during the late Quaternary and seek to manage soils at a variety of spatial scales for differing purposes (McBratney *et al*. 2000). Furthermore, the fact that TCN and OSL quantify pedogenic processes allows the input of soil production, soil transport, and bioturbation into quantitative catena-scale models of soil development (McBratney *et al*. 2003).

Conclusion

The use of TCN and OSL allows fundamental ideas of pedogenesis to be examined. TCN applications have lead to considerable advances in understanding soil production at local, hillslope and catchment scales. Preliminary data are now available to quantify soil production rates under varying mantle depths in a range of landscapes. Furthermore, field evidence from a number of authors supports the theory for the exponential decline in bedrock lowering at depths greater than that where soil production is maximised. Whether maximum production occurs under soil cover at some sites is unresolved, however there is evidence to suggest maximum production from saprolite occurs when saprolite is unmantled, while maximum bedrock weathering requires a finite soil cover. While these dating techniques are indeed powerful, their application requires judicious consideration, and interpretations of the datasets generated must be consistent with field observations. These challenges are to be expected when studying complex natural processes such as those under consideration.

Quantifying the extent of mixing, such as that by soil organisms, was hampered until the advent of OSL. This technique integrates soil mixing, typically over several millennia, whereas previous measurements, derived from surface mounding were short-term and partial (Humphreys and Mitchell 1983). Only by extrapolating short term measurements could longer term effects be evaluated (e.g. Williams 1968), however this approach is not without its problems (e.g. Ahnert 1970, Kirchner *et al*. 2001). The small OSL dataset that has been produced on soil mixing is consistent with early work by many authors. Importantly, soil bioturbation appears to be operating significantly faster than soil production via rock weathering, and probably faster than many other pedogenic process, with the obvious exception of landslide impacted terrain and where freeze–thaw is common. Nevertheless mounding-derived bioturbation estimates are likely to be minimum estimates of mixing—this can be tested by OSL data. Together, TCN- and OSL-based process estimates, suggest significant rates of soil transport coupled with rapid mixing is a central component of pedogenesis. This conclusion challenges the long held view that soil development is primarily by the *in situ* alteration of parent material.

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