Bioturbation and erosion rates along the soil-hillslope conveyor belt, part 1: Insights from single-grain feldspar luminescence

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ABSTRACT: The interplay of bioturbation, soil production and long-term erosion–deposition in soil and landscape co-evolution is poorly understood. Single-grain post-infrared infrared stimulated luminescence (post-IR IRSL) measurements on sand-sized grains of feldspar from the soil matrix can provide direct information on all three processes. To explore the potential of this novel method, we propose a conceptual model of how post-IR IRSL-derived burial age and fraction of surface-visiting grains change with soil depth and along a hillslope catena. We then tested this conceptual model by comparison with post-IR IRSL results for 15 samples taken at different depths within four soil profiles along a hillslope catena in the Santa Clotilde Critical Zone Observatory (southern Spain).

In our work, we observed clear differences in apparent post-IR IRSL burial age distributions with depth along the catena, with younger ages and more linear age–depth structure for the hill-base profile, indicating the influence of lateral deposition processes. We noted shallower soils and truncated burial age–depth functions for the two erosional mid-slope profiles, and an exponential decline of burial age with depth for the hill-top profile. We suggest that the downslope increase in the fraction of surface-visiting grains at intermediate depths (20 cm) indicates creep to be the dominant erosion process.

Our study demonstrates that single-grain feldspar luminescence signature-depth profiles provide a new way of tracing vertical and lateral soil mixing and transport processes. In addition, we propose a new objective luminescence-based criterion for mapping the soil-bedrock boundary, thus producing soil depths in better agreement with geomorphological process considerations. Our work highlights the possibilities of feldspar single grain techniques to provide quantitative insights into soil production, bioturbation and erosion–deposition. © 2019 The Authors. Earth Surface Processes and Landforms Published by John Wiley & Sons Ltd.

KEYWORDS: bioturbation; erosion; soil formation; feldspar luminescence; Critical Zone

Introduction

The top layer of soil or mobile regolith forms the heart of the Critical Zone, the heterogeneous, near-surface environment, in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources (National Research Council, 2001). Soil production is driven by the rate at which bedrock or saprolite is converted into soil or mobile regolith. Much progress has been made over the past years in quantifying these soil production rates in different environments; for example by using terrestrial cosmogenic nuclide (TCN) inventories (Heimsath et al., 1997, 2000; Stockmann et al., 2014), which provide average rates of soil production over millennial timescales (> 10³ years). The empirical exponential or humped soil thickness-dependent soil production function, derived from these data, is now widely accepted (Heimsath et al., 1997; Wilkinson and Humphreys, 2005). However, the exact processes and controlling factors giving rise to this empirical soil production function are not well characterized, presumably due to being related to the precluding temporal resolution of the corresponding TCN inventories. In general, soil production rates are believed to be dependent on local site characteristics such as climate, geology, vegetation and erosion rates (e.g. Gabet and Mudd, 2010; Larsen et al., 2014; Norton et al., 2014). Yet Stockmann et al. (2014), in their global review of TCN-based soil production rates (n = 226), found no significant difference in TCN-based soil production rates as a function of parent geology or climate conditions. Apart from the coarse temporal resolution, TCN-based soil production rates have two other important limitations for studying soil landscape relationships: (i) they are bound to steady-state conditions assuming soil production equals soil erosion (e.g. Stockmann et al., 2014), and (ii) they are insensitive to soil fluxes related to
biological soil mixing (bioturbation) typically affecting soil formation on shorter timescales.

Recent work by Amundson et al. (2015) compiled existing field, experimental and modelling observations on the development of hillslope soils to conclude that vegetation has a crucial role in soil production in a way that is currently not well quantified. These authors found that, on hillslopes, plants exert a vital control on maximum soil thickness due to tree throw mechanisms, and they were able to show that, in the absence of plants, no soil would exist on hillslopes. However, partly contrasting information from the compiled studies highlights the need for further research to elucidate the different biological processes contributing to soil production and its evolution. Similarly, to the bioturbation effect of vegetation on soils, the influence of animals (e.g. earthworms, ants, etc.) on soil production and evolution is only poorly understood and quantitative information is scarce (Wilkinson et al., 2009).

In contrast to biological soil mixing, physical and especially chemical weathering have received abundant attention in recent years (e.g. Sklar et al., 2017). To be specific, different studies have reported a clear feedback between chemical weathering and physical erosion rates (Riebe et al., 2003; Larsen et al., 2014). Although bioturbation is increasingly recognized as being a key process in soil formation and landscape evolution (Wilkinson and Humphreys, 2005; Wilkinson et al., 2009; Wackett et al., 2018) as it significantly influences the disintegration of the saprolite and bedrock and actively mixes the soil or mobile regolith layer, current reconstruction methods are unsuitable for quantitatively comprehending these key process relationships. Thus, there is an urgent need in soil geomorphology for complementary reconstruction methods to: (i) quantify soil fluxes related to bioturbation, (ii) elucidate soil process rates at a higher temporal resolution than is currently possible with TCN and (iii) study soil–landscape processes under non-steady-state conditions.

Heimsath et al. (2002) have shown that single-grain optically stimulated luminescence (OSL) dating offers an efficient solution for quantifying pedogenic processes such as soil mixing, erosion or deposition rates at a centennial to millennial resolution, and the approach was adopted in a number of studies in different environments (Stockmann et al., 2013; Johnson et al., 2014; Kristensen et al., 2015; Gliganic et al., 2016). However, due to the actual time and labour-intensive nature of single-grain quartz OSL analyses and their limited applicability for settings in close proximity to plutonic or metamorphic bedrock (e.g. Guralnik et al., 2015), the method was not widely embraced for studying soil-related processes.

Reimann et al. (2017) showed that using feldspar rather than quartz single-grain luminescence techniques has important advantages when studying the mixing of soils. Feldspar single-grain luminescence measurements are more time-efficient, and this technique is more widely applicable in terms of soil parent material and provides more reliable soil reworking rates, especially in settings close to the boundary with the saprolite (Reimann et al., 2017). So far, nearly all luminescence-based soil mixing studies focus on individual soil profiles to derive vertical mixing rates, with no, or a limited, consideration of lateral particle movements along the hillslope. Yet, such lateral processes are highly important in areas with relief, and can only be elucidated by investigating multiple soil profiles along a hillslope catena, including erosional and depositional areas.

Similarly, to biological soil mixing, it is astonishingly difficult to accurately identify soil thickness, i.e. the thickness of the mobile regolith layer, using objective and thus reproducible criteria (Patton et al., 2018). Soil thickness is a parameter that is not included in current soil surveys, and cannot easily be correlated with horizon descriptions, despite being crucial for landscape evolution modelling (Yoo and Mudd, 2008). Mudd and Yoo (2010) call this mobile regolith ‘the physically disturbed zone’, as opposed to the definition of soil in the soil science community that extends to the chemically altered but physically undisturbed zone (generally designated as C horizon). Recently, Foster et al. (2015) stress the importance of consistent terminology and of the correct identification of the mobile regolith–saprolite boundary being vital for obtaining accurate TCN-based soil production rates.

In Reimann et al. (2017) we demonstrate that the fraction of surface-visiting grains can be traced down the profile through the non-saturation factor (NSF) derived from feldspar single-grain luminescence measurements. This important NSF parameter cannot be reliably extracted from quartz OSL single-grain data, at least not for a close to granitic bedrock setting (Reimann et al., 2017). Close to the mobile regolith–saprolite boundary, NSF drops to zero, indicating that no grain has been surfaced. However, the suitability of this luminescence-based signature to objectively map the mobile regolith–saprolite boundary and thus the soil thickness has not yet been tested.

The objective of this article is to use the feldspar single-grain luminescence method recently proposed by Reimann et al. (2017) to simultaneously trace vertical and lateral soil mixing and transport processes along a hillslope catena. With this research, we aim to explore the potential of luminescence-based signatures derived from feldspar single-grain analyses to provide insights into:

- Soil mixing/reworking rates
- Interplay of bioturbation and erosion–deposition processes
- Lateral displacement of soil material along a hillslope catena
- Soil thickness
- Alternative ways to reconstruct soil production

Study Area, Cardeña and Montoro Natural Park, Spain

The catena sampled in this study is located in a granitic rock catchment in Cardeña and Montoro Natural Park (latitude 38° 12’ N, longitude 4° 17’ W), Cordoba province, southwest Spain (Figure 1). The area is influenced by a Mediterranean climate, where the annual average rainfall is 600 mm, concentrated during the winter wet season, and the minimum and maximum temperatures vary between 5 and 40°C, with average values of 15°C. The climate could be classified as Bsk, (cold semi-continental) within the Köppen–Geiger system (Peel et al., 2007). This climate has allowed the development of Mediterranean sclerophyllous forests in areas with slopes higher than 5%. Generally, flatter areas are covered by oak-woodland savannah (‘dehesa’), which is used for extensive grazing with very low stocking densities, i.e. below 0.10 LSU ha⁻¹ (livestock units per hectare). The main vegetation is represented by different oak tree species (Quercus ilex subsp. ballota, Quercus iber, Quercus tina). In geological terms, the study site is part of the Pedroches Batholith, in Sierra Morena, which is a mountain range in southern Spain that separates the Central Plateau from the Baetica Depression. The soil parent material is dominated by granitoids. The mineralogy group is porphyric microdiorite with a fine-grained matrix formed by quartz, K-feldspar, plagioclase, biotite and apatite (Larraza et al., 2013). Soil types are Regosols, Cambisols and Phaeozems with disturbed zone under the FAO-Unesco World Reference Base (IUSS Working Group, 2014).
The sampling area is located along a catena on the north-facing hillslope of a steep valley with a permanent creek, covered by natural Mediterranean forest outside the area, that is extensively grazed (Figure 1). The slope range is of between 10 and 58% along this catena. The land use of this steep valley is a natural Mediterranean forest and it has never been ploughed. Wild fires are endemic to Mediterranean forest conditions, but there are no records of wildfire occurrence in recent history. The samples were taken from four soil profiles (SC-7, SC-8, SC-9, SC-10), located in distinct landscape positions. The first profile, SC-7, is located at the hill-base, but away from fluvial influence. Profiles SC-8 and SC-9 are located near the lower and upper end of the linear hillslope and SC-10 is situated on the hilltop.

Figure 1. (a) Location of the study area in Spain and in the Cardeña and Montoro Natural Park. (b) Slope distribution in the study area with indications about the sampling points. (c) View of the study site with indications about the location of the soil profiles. (d) Transect showing the distribution of the soil profiles sampled along the catena and their slope gradient. The greyed-out area indicates the mobile regolith thickness (not indicated for the valley bottom and opposite slope). [Colour figure can be viewed at wileyonlinelibrary.com]
Experiment Details

Sample preparation and luminescence analysis

Fifteen samples for luminescence analysis were obtained from the four soil profiles along the catena described earlier. Within each soil profile, samples were taken from near the surface to the bottom of the mobile regolith layer, as visually identified in the field (Table I). Samples were taken at regular intervals, allowing for some flexibility to avoid large rocks or tree roots. The samples were obtained by hammering metal tubes with dimensions of 25 cm × 5 cm horizontally into the exposure. The material contained in the centre of the tube was not exposed to light during sampling, and was therefore suitable for luminescence analysis (equivalent dose estimation). Material from the outer end of the tubes was used to determine the environmental dose rate. Samples were prepared at the Netherlands Centre for Luminescence Dating (NCL) at Wageningen University under subdued amber light. Details on sample preparation and the experimental set-up are specified in Reimann et al. (2017), our previous study containing the methodological groundwork of this contribution. In summary, for equivalent dose determination, the material was sieved to 212–250 μm and K-rich feldspar extracts were retrieved using standard laboratory procedures. For environmental dose rate determination, the material was first dried at 105°C to measure the moisture content, and subsequently ashed at 500°C to measure the organic matter content. Afterwards, this material was ground and homogenized to produce pucks, which were used to determine the dose rate.

Equivalent dose and dose rate measurements

For calculating a luminescence age two quantities need to be determined for each sample: (i) the palaeodose, which is the best estimate of the radiation dose received during burial, i.e. since the last daylight exposure of the grains, and it is obtained by the interpretation of feldspar single-grain equivalent dose \((D_e)\) distributions. The individual \(D_e\) values are obtained by comparing the natural luminescence signals, with luminescence signals responding to laboratory irradiation of the same grains (details later). (ii) The environmental dose rate, which is the amount of ionizing radiation absorbed by the sample per year.

To determine the palaeodose of our samples, we made use of single-grain feldspar luminescence measurements applied to the 212–250 μm sand fraction. We applied the feldspar single-grain measurement protocol developed by Reimann et al. (2012), which was recently extended by Reimann et al. (2017) to study soil reworking rates. This measurement protocol measures two feldspar luminescence signals: (i) the infrared stimulated luminescence at 50°C (IRSL50, Hütt et al., 1988) and (ii) the post-infrared infrared stimulated luminescence at 175°C (pIRIR175, Thomsen et al., 2008). In the previous study both feldspar luminescence signals produced largely consistent results (Reimann et al., 2017). Here we focus solely on results obtained using the pIRIR175 signal, as it is less affected by anomalous fading (Thomsen et al., 2008) and thus less dependent on fading correction procedures. More detailed information on the experimental set-up, data analysis, performance of the measurement protocol (e.g. dose recovery), as well as pIRIR175 signal resetting upon surface exposure, is provided in Reimann et al. (2017).

The dose rate was assessed from measurements of the activity concentration of isotopes in the thorium-232 \((232\text{Th})\) and uranium-238 \((238\text{U})\) decay chains as well as potassium-40 \((40\text{K})\) employing high-resolution gamma spectrometry. The conversion factors of Guérin et al. (2011) were used to transfer activity concentrations to gamma and beta dose rates. Attenuation due to grain size (Mejdahl, 1979) and moisture and organic matter (Aitken, 1985; Madsen, 2005) were taken into account, and contributions from cosmic radiation (Prescott and Hutton, 1994), and the internal radiation (Smedley et al., 2005) were included (see Supporting Information Table S1).

Luminescence ages and reworking rates

To obtain insight into single-grain \(D_e\) distributions, the pIRIR175 \(D_e\) measurements were repeated on 300 to 1300 feldspar grains for each sample. For the calculation of the palaeodose, only grains with suitable luminescence characteristics were used. We used the interpretation of single-grain equivalent dose \((D_e)\) distributions. The individual \(D_e\) values are obtained by comparing the natural luminescence signals, with luminescence signals responding to laboratory irradiation of the same grains (details later). (ii) The environmental dose rate, which is the amount of ionizing radiation absorbed by the sample per year.

Table I. Representative soil properties and topographic variables in the soil profiles along the catena analysed

| Soil profile and sample code | Depth (cm) | Horizon and soil type | Mobile regolith depth (m) | Slope (%) | Curvature\(^a\) | Bulk density (kg m\(^{-3}\)) | Clay (%) | Sand (%)\(^b\) | Organic carbon (%) |
|-----------------------------|-----------|----------------------|--------------------------|-----------|-------------|-----------------------------|----------|--------------|------------------|
| SC-7                        |           | Phaeozems            | 0.97                     | 13.08     | –0.25       | 1355                        | 6.8      | 74.6         | 2.91             |
| 1214082                     | 5         | Hill-base-A          |                          |           |             | 1514                        | 9.3      | 73.4         | 1.97             |
| 1214083                     | 20        | Hill-base-A          |                          |           |             | 1466                        | 9.3      | 73.2         | 0.91             |
| 1214084                     | 37        | Hill-base-A          |                          |           |             | 1753                        | 7.6      | 79.7         | 0.63             |
| 1214085                     | 55        | Hill-base-B          |                          |           |             | 1468                        | 6.3      | 75.7         | 2.76             |
| SC-8                        |           | Cambisol             | 0.47                     | 38.68     | 0.048       | 1382                        | 10.9     | 57.3         | 0.59             |
| 1214086                     | 5         | Lower hillslope-A    |                          |           |             | 1422                        | 11.3     | 49.8         | 0.57             |
| 1214087                     | 20        | Lower hillslope-B    |                          |           |             | 1284                        | 5        | 70.5         | 3.37             |
| 1214088                     | 35        | Lower hillslope-B    |                          |           |             | 1473                        | 6.8      | 70.9         | 1.83             |
| SC-9                        |           | Cambisol             | 0.57                     | 36.68     | –0.03       | 1512                        | 5        | 78.3         | 0.37             |
| 1214089                     | 5         | Upper hillslope-A    |                          |           |             | 1628                        | 6.3      | 73.4         | 0.27             |
| 1214090                     | 18        | Upper hillslope-A    |                          |           |             | 1505                        | 6.6      | 68.5         | 4.73             |
| 1214091                     | 35        | Upper hillslope-B    |                          |           |             | 1771                        | 4.5      | 83.8         | 0.59             |
| SC-10                       |           | Regosol              | 0.51                     | 1.58      | –0.19       | 1903                        | 3.3      | 86.3         | 0.42             |
| 1214093                     | 5         | Hilltop-C            |                          |           |             | 1764                        | 3.3      | 86.4         | 0.35             |

\(^a\)A negative value indicates that the surface is convex upward in that cell. A positive value indicates that the surface is concave upward in that cell.

\(^b\)Taken as a fraction 200–2000 μm.
(i.e. passing rejection criteria), and below the saturation threshold (described later), were taken into account (Reimann et al., 2017). From the distribution of the remaining \( D_b \) estimates, the unweighted average and its 1-sigma standard error were assigned as the sample palaedose. The sample palaedose was divided by the corresponding dose rate to obtain the uncorrected apparent luminescence age of the sample. A fading correction (Huntley and Lamotte, 2001) was applied to all uncorrected pIRIR\(^{75} \) ages to obtain the corresponding fading corrected apparent luminescence ages, hereafter referred to as apparent luminescence age. More details regarding age determination are provided in Reimann et al. (2017).

Following previous luminescence studies on soil reworking (Heimsath et al., 2002; Wilkinson and Humphreys, 2005; Stockmann et al., 2013), the apparent soil reworking rate (\( S_{R\text{app}} \) in mm\(^a\)) was calculated by dividing the sample depth by the apparent luminescence age. This rate indicates the displacement rate, or more specifically, the mean rate of re-burial of individual sand grains relative to the soil surface. The disadvantage of this simple measure is that it only provides a linear or average rate of burial. In Reimann et al. (2017) we contend that the apparent soil reworking rate assumes that all grains are participating in the mixing process, as ‘out of competition’ grains (with luminescence signals above the signal saturation) are not taken into account.

The calculation of meaningful soil reworking rates requires the accurate determination of the fraction of grains in the soil matrix that never reached the surface as shown in Reimann et al. (2017). These ‘out of competition’ grains have geological luminescence signals close to saturation, and for identification we employed the two times \( D_b \) saturation threshold (equivalent to \(-5\%\) full saturation) suggested by Wintle and Murray (2006). More details about fitting the dose response curve, including examples, are provided in Reimann et al. (2017, section 2.3). From the fraction of grains below this saturation threshold we established the NSF, which measures the fraction of surface exposed or finite age grains. If all the grains have been exposed to light at least once (due to soil mixing or erosion), we expect an NSF of one. For a sample from the upper saprolite, where no grains have been light-exposed, we expect all grains to be above the saturation threshold, yielding an NSF of zero. This NSF is censored at the upper end by the corresponding luminescence saturation age, in our case of at least 300 ka.

This NSF can be used to calculate more realistic measurements of soil mixing and to obtain an effective soil reworking rate (\( S_{R\text{eff}} \) in mm\(^a\)) (Reimann et al., 2017). This measurement takes into account the fraction of grains that participate in the soil mixing process, i.e. grains with an exposure history, and, thus, the intensity of the mixing. This mixing intensity is incorporated, in the form of the NSF described earlier, into the calculation of the effective soil reworking rate (Equation (1)).

\[
S_{R\text{eff}} = \left( \frac{\text{sample depth (mm)}}{\text{apparent burial age (years)}} \right) \times \text{NSF}
\]  

The processes responsible for soil particle exhumation and re-burial can be two-fold. If bioturbation is dominant, \( S_{R\text{eff}} \) provides process rates due to vertical soil mixing. Where lateral surface erosion and deposition is dominant, the process rate will be dominated by sedimentation. Lateral movement due to the creep process should not have any influence on particle age as particle trajectories are parallel to the slope surface, as shown by Anderson (2015). However, when these different soil geomorphological processes act simultaneously and are interconnected, the resulting burial age–depth as well as NSF–depth functions becomes more complex. In the next section, a conceptual model is proposed to evaluate the effect of these interconnected processes.

The Effect of Soil Transport and Mixing on the Luminescence Age–Depth Profiles Along a Hillslope – a Conceptual Model

The effect of different interconnected soil geomorphological processes on single-grain luminescence tracers along a hillslope catena is conceptually compiled in Figure 2. We can distinguish between two populations of grains tracing different grain motions in the soil (also see Furbish et al., 2018b): (i) those that have not yet reached the surface and therefore yield infinite ages (‘out of competition’ grains according to Reimann et al., 2017) and (ii) grains with finite luminescence burial ages referring to their most recent surface exposure. While the fraction of ‘out of competition’ grains increases with increasing proximity to the mobile regolith–saprolite interface resulting in decreasing NSF down the profile (Figure 2), the fraction of grains yielding finite luminescence burial ages (A in Figure 2) increases with a closer proximity to the surface (Reimann et al., 2017).

In our conceptual model we consider three soil geomorphological processes: bioturbation, soil production, erosion–deposition. First, we will briefly introduce the individual impact of each of the three processes on the single-grain luminescence signatures (NSF and burial age), and then infer their combined effect on three geomorphological units along a hillslope catena (cases I, II, and III in Figure 2).

All profiles are subject to vertical mixing of the soil column through bioturbation. It is generally assumed that bioturbation activity declines non-linearly with depth, often assuming an exponential decline (e.g. Wilkinson et al., 2009; Johnson et al., 2014). As a result, the average time grains, being shielded from daylight, will increase with depth within the bioturbated layer. This dependency gives rise to an increasing average burial age with depth, which was for example demonstrated by Madsen et al. (2011) for lugworm bioturbation in a tidal flat. However, it is fair to assume that the same type of age–depth profile also results from soil mixing by other mounding bioturbators (e.g. ants, earthworms, termites, etc.).

As all profiles are affected by vertical soil mixing, soil production will also affect all the profiles under consideration as it feeds fresh ‘out of competition’ grains from the mobile regolith–saprolite boundary into the vertically mixed soil matrix. Thus, soil production is manifested by an increasing fraction of ‘out of competition’ grains with an increasing proximity to the mobile regolith–saprolite boundary, resulting in a decreasing NSF down the soil profile (Figure 2). Soil production has no impact on the luminescence burial age.

Besides soil production and vertical biological soil mixing, lateral displacement of grains may occur, especially in cases with topographic relief. Here we focus on superficial erosional processes like surface or overland flow (moving particles at the top of the profile), and creep (moving a shallow layer of the profile) as these are the most relevant for our study site. This would imply that creep does not expose grains to light during lateral transport and thus particles will age on their downslope pathway along a catena. In practice, the age–depth trend does not vary along the hillslope as long as profiles are in steady-state. Anderson (2015) demonstrated this nicely with a numerical model: if creep is the dominant process, the particle ages only depend on the depth in the soil reflecting bioturbation and not on their position on the catena. However, in our study area, creep movement is likely to occur as a disturbance-like
motion. While particle trajectories are more complex in such cases, Furbish et al. (2018a) were able to show, with a numerical model based on random walk, that statistical mean particle trajectories are also parallel to the surface. They reported that the age–depth characteristics depend largely on the balance between soil mixing rates, soil production at the mobile regolith–saprolite interface and erosion rates, as will be explained in detail later.

Three situations, each being associated with a typical geomorphological unit along a hillslope catena (Figure 2), can now be considered, and the combined effect of the three processes outlined earlier can be investigated: (case I) a steady-state case, and two transient cases either (case II) erosional or (case III) depositional. To simplify this conceptual model, bioturbation rates will be assumed to be homogeneous along the catena.

In the reference or steady-state situation, erosion is compensated for by soil production and the profile thickness remains constant over time (case I). Hence, in this steady-state case, there is no net soil loss or gain. The soil erosion–soil production nexus will create a clear upward motion within the profile (shown by grey arrows in Figure 2, Ia and Ib), where eroded particles are replenished by soil formation. This would be typically expected on plateaux, or hillcrests. The shape of the luminescence burial age–depth and NSF–depth profiles will now depend on the balance between mixing the rates and residence time of the grains in the soil. As explained earlier, bioturbation will result in a low NSF and old particle ages at depth, and a high NSF and younger particle ages closer to the surface. However, for the same mixing rate, soils with lower soil production–erosion rates will have longer residence

**Figure 2.** Conceptual model for the variation in age \((A)\) and non-saturated fraction \((\text{NSF})\) with depth \((z)\) under the influence of overland flow erosion (left panel a, c, e) and creep (right panel b, d, f), under three different situations: (case I) steady-state, (case II) erosional and (case III) depositional. See text for detailed explanation. Dotted lines and black arrows represent the comparison with the reference situation under steady-state. Grey arrows represent fluxes due to soil erosion, creep or soil formation.
times with a longer time period between particle detachment at the mobile regolith–saprolite interface, and either their outcropping (in the case of overland flow erosion, Figure 2, la) or their appearance at the downslope face (in the case of creep, Figure 2, lb). While the burial age is not a direct measurement of the soil residence time because it is controlled by the last surface exposure appearance, the two are obviously related. The age particles can reach will be older for a longer residence time of the profile, i.e. with a lower upward flux; and vice versa.

Higher soil production–erosion rates will reduce grain residence time in the soil matrix resulting in a lesser cumulative bioturbation activity steepening the NSF function down the soil profile. Lesser soil production and erosion rates, in turn, will allow more grains to participate in the bioturbation process, leading to more grains with finite luminescence burial ages and thus increasing NSF values down the profile. At the same time, those grains remain longer in the bioturbation zone leading to older luminescence burial ages down the profile. The extreme end member would be a situation in which soil erosion and production rates are both zero. Under this condition, with an infinite residence time, only bioturbation processes will act on the soil profile, burying and resurfacing them. This situation leads to the same exponentially declining age with depth, shown in Figures 2 la and lb. However, eventually, the whole soil profile is turned over, leading to NSF = 1 throughout the profile, if the total turnover time is shorter than the luminescence saturation age censoring NSF at the upper end (~300 ka for feldspar and ~150 ka for quartz grains). We postulate, however, that this ‘bioturbation only’ case is not relevant for the hillslope profile under investigation, thus, we will not elaborate any further on it.

In case II, an erosional profile is considered. In this case, production rates cannot keep up with erosion rates and soil thickness will decrease over time. Erosion can be due to overland flow or to creep, as both processes generate similar luminescence burial age–depth profiles. So, the upward particle flux is still present, but it is sufficient enough to compensate for the loss of particles. The direct consequence is a descent of the reference frame. If erosion is caused by overland flow (Figure 2, Ilc), the reference age–depth profile is truncated at the surface by a depth Δz, hereby exhuming older soil particles (see Supporting Information Figure S1). As a result, the mobile regolith–saprolite border (dotted line) appears at a shallower depth. At each depth the burial age (A) is increased with respect to the reference profile shown by a dotted line. The ‘apparent’ age increase observed at each depth z in the eroded hillslope profile simply corresponds to that of z + Δz in the un-eroded reference profile (case I). The trend for NSF with depth is expected to decrease for the same reason. If erosion is caused by creep (Figure 2, subcase IId), soil will not be lost at the surface but over the face of the entire vertical profile. Influx of material from upslope into this profile is lesser than the downslope outflux. This loss of matter over the entire soil profile leads again to surface lowering. The effect of lowering the reference frame will be the same as in the subcase Ilc.

It is important to point out again that the lateral movement itself of soil grains due to creep does not have any impact on the burial age–depth structure. This is because grains of the same age are moved laterally in and out of a particular infinite soil layer at depth z. As age is an average measurement for the corresponding sample at a certain depth, adding more grains of the same age will not change the luminescence age of that depth layer. However, the situation is different for the NSF, i.e. the fraction of ‘out of competition’ grains or grains of an infinite age. Here, lateral transport by creep does have an impact. While in the reference steady-state profile (subcase Ib in Figure 2) NSF at a particular depth depends on the balance between bioturbation and upward flux through soil production and erosion, this balance is ‘broken’ for subcase IId. Due to the lateral creep transport, the equilibrium between the upward movement of saturated particles and the downward incorporation of new finite burial age grains by bioturbation is interrupted. Indeed, this lateral flow will add finite age grains of the same age laterally to the eroding profile that is on a hillslope. As NSF is not an average measurement, but is directly dependent on the fraction of finite age grains, it can be expected to increase downslope. This downslope increase in NSF can be expected to be more pronounced near the surface, where the creep velocities are higher. Close to the mobile regolith–saprolite interface, this effect should be negligible as creep velocities approach zero (Figure 2, IId). Overland flow erosion will not induce a change in NSF curve down the profile, as particles only move over the surface, although the reference frame will be lowered. This would imply that creep and overland flow erosion cannot be distinguished through their burial age–depth profile, but that their NSF–depth profile should be different.

The third geomorphological situation considered is that of a depositional profile (case III, Figure 2). In this case, the profile is accreting due to the addition of upslope sediment. If erosion is caused by overland flow, then, this process resets surface grains during transport (Fuchs and Lang, 2009) and freshly deposited hillside sediments add young, newly bleached grains to the surface. This new layer of non-saturated, zero age grains at the surface will start to build up a luminescence signal as soon as it is buried by a new layer of sediment following hillslope erosion. For this scenario, the age of the buried sediment would increase with depth and reflect the deposition rate. This scenario describes the conventional application of OSL in dating hillslope sediments (reviewed in Fuchs and Lang, 2009). However, in our case, this deposition is moderated by bioturbation, which decreases exponentially down the profile. Thus, the curvature of the burial age–depth function in subcase IId is dependent on the relationship between sedimentation and bioturbation. If the former is dominant it would be manifested in a higher linearity. In addition, these new sediments also induce a change in the reference frame, ‘pushing it down’ along the depth axis. This results in an apparent ‘rejuvenation’ of the burial age–depth profile, i.e. with respect to the reference profile (Figure 2, case I) shown by a dotted line (Figure 2, subcase IId). In addition, the layer(s) of newly added sediment are finite aged grains, i.e. all grains have a surface exposure history (NSF = 1).

If deposition results from creep, the same observations are expected. The burial age of the material flowing in and out is the same as that of the material in the control volume, and the average age does not change. However, as material flux in the control volume exceeds the downslope outward flux, there is an excess of material. Assuming a rigid lower boundary condition with a bedrock or saprolite layer at the bottom of the mobile regolith, this material is ‘pushed upward’. The profile as a whole will be ‘pushed up’ by Δz. This changes the reference level of the burial age–depth graph, i.e. age at depth z corresponds to the age previously at z – Δz. This leads again to an apparent ‘rejuvenation’ of the burial age–depth profile. In addition, NSF will change as well. As in subcase IId for the erosional profile, the additional lateral flux adds relatively more non-saturated or finite age grains to a layer at a particular depth. NSF is therefore also expected to increase in this situation for the part of the profile that is affected by creep. In conclusion, the difference between a depositional profile due to overland flow and one due to creep would not be reflected in the luminescence signals.
Results

Soil profile characteristics

The four profiles along the catena sampled, reveal significant differences, as shown in Figure 3. The main soil properties are summarized in Table I. Mobile regolith thickness observed in the field is similar for the hilltop and hillslope profiles (SC-10 to SC-8), varying between 0.47 and 0.57 m. It is almost twice as thick, however, in the hill-base profile (SC-7), with a depth of 0.97 m. This gives a first indication of the accumulation of sediment at the bottom of the hillslope. Soil properties indicate that the hilltop profile SC-10 is the one least weathered, as it is characterized by an A horizon directly overlying a less weathered C1 horizon, and it has a higher sand fraction throughout. All other profiles are characterized by a more advanced soil weathering, as they have an A and B horizon overlying the saprolite. The hill-base profile SC-7 and lower hillslope profile SC-8, especially, have a noticeably higher clay content, almost double that of the top two profiles. In the hilltop profile SC-10, the C layer is not necessarily undisturbed parent material. It is weathered parent material that has been little affected by pedogenetic processes such as clay illuviation or formation of structure. The hilltop profile is classified as Regosol (IUSS Working Group, 2014), the two hillslope profiles as Cambisols and the hill-base profile as Phaeozem, due to the presence of a dark, organic-rich, surface horizon. Bulk density increases linearly with depth in all soil profiles, due to the proximity of the saprolite border and a higher stone fragment content with increasing depth. Organic carbon content decreases exponentially with depth (Román-Sánchez et al., 2016).

Fraction of finite age feldspar grains or the non-saturation factor (NSF)

Table II and Figure 4 show the NSF, i.e. the fraction of finite age grains, for each sample and reveal important patterns both for the individual profiles as well as along the hillslope catena. The data show how NSF is close to one (i.e. most grains visited the surface at least once) for the surface sample at 5 cm depth and rapidly declines with depth. In the two profiles where the bottom sample was taken closest to the saprolite, SC-9 and SC-10 (respectively at 55 and 50 cm), the corresponding NSF values approach zero, i.e. only a very few or no grains visited the surface.

Exploring the lateral trends along the catena, a clear downslope increase in NSF can be seen for 20 cm soil depths (Table II, Figure 4). The NSF increases from 0.12 to 0.94 for the hilltop profile SC-10 to the hill-base profile SC-7, respectively. At 35 cm, the hill-base profile clearly differs from the other profiles with a very high NSF value of 0.93. The NSF in the profiles SC-9 and SC-10 is similar and very low (0.08 and 0.12, respectively), and for SC-8 a value of zero is observed. For the surface samples at 5 cm, no clear trend is apparent and all NSF values are above 0.9.

The boundary between the mobile regolith and the underlying saprolite as observed in the field (see earlier), is shown by a continuous line in Figure 5. According to our luminescence NSF results, the actual boundary is closer to the surface for SC-8 and SC-9. The NSF-derived transition zone is represented by the shaded areas in Figure 5. This transition zone marks the depth below the last sample with NSF > 0 and above the following sample with NSF = 0. For SC-9 the boundary would be somewhere between 35 and 55 cm and for SC-8 between 20 and 35 cm.

Equivalent dose ($D_e$), palaeodoses and luminescence ages

The feldspar pIRIR175 $D_e$ distributions and the corresponding palaeodoses (see Experiment Details section) for each individual soil profile increase with depth (Figures 5 and S2, Table II). At 5 cm depth the vast majority of individual feldspar grains yield a $D_e$ near zero, and resulting palaeodoses for the four soil locations are relatively low (< 10 Gy). Furthermore, $D_e$ analyses along the catena, at constant depth, reveal a lateral effect with a downslope decrease in the palaeodose, similar to the previously observed increase in NSF in the downslope direction. The palaeodose error is higher for the profiles located at the top of the hillslope, due to larger scatter in the corresponding $D_e$ distribution.
Table II. A summary of the main luminescence results

| Soil profile and sample ID | Depth (cm) | NSF a (a.u.) | Dose rate (Gy ka⁻¹) | Palaeodose (Gy) | Uncorr. age (ka) | Apparent fading corr. ageb (ka) | SScpe (mm a⁻¹) | SScde (mm a⁻¹) |
|----------------------------|------------|--------------|----------------------|----------------|-----------------|-------------------------------|----------------|----------------|
| SC-7                       | 5          | 0.990        | 5.71 ± 0.26          | 2.70 ± 0.56     | 0.47 ± 0.10     | 0.54 ± 0.2                   | 0.093 ± 0.034 | 0.092 ± 0.023  |
| NCL-1214082                | 20         | 0.938        | 5.59 ± 0.24          | 20.2 ± 1.21     | 3.61 ± 0.27     | 4.00 ± 0.35                   | 0.050 ± 0.004 | 0.047 ± 0.004  |
| NCL-1214084                | 37         | 0.922        | 5.87 ± 0.25          | 29.0 ± 1.14     | 4.94 ± 0.29     | 5.51 ± 0.41                   | 0.067 ± 0.005 | 0.062 ± 0.005  |
| NCL-1214085                | 55         | 0.353        | 6.58 ± 0.30          | 54.4 ± 3.08     | 8.26 ± 0.60     | 9.24 ± 0.76                   | 0.060 ± 0.005 | 0.021 ± 0.002  |
| SC-8                       | 5          | 0.913        | 6.16 ± 0.28          | 9.08 ± 1.95     | 1.47 ± 0.32     | 1.60 ± 0.30                   | 0.031 ± 0.006 | 0.029 ± 0.005  |
| NCL-1214087                | 20         | 0.690        | 6.16 ± 0.24          | 109.3 ± 19.8    | 17.74 ± 3.29    | 19.9 ± 4.00                   | 0.010 ± 0.002 | 0.007 ± 0.001  |
| NCL-1214088                | 35         | 0.000        | 5.85 ± 0.22          | —               | —               | —                             | —              | —              |
| SC-9                       | 5          | 0.912        | 5.50 ± 0.29          | 6.37 ± 0.62     | 1.16 ± 0.13     | 1.30 ± 0.10                   | 0.038 ± 0.003 | 0.035 ± 0.003  |
| NCL-1214090                | 18         | 0.420        | 5.08 ± 0.26          | 21.2 ± 2.80     | 4.17 ± 0.59     | 4.70 ± 0.70                   | 0.038 ± 0.006 | 0.019 ± 0.003  |
| NCL-1214091                | 35         | 0.077        | 5.64 ± 0.29          | 25.9 ± 4.20     | 4.59 ± 0.78     | 5.10 ± 0.90                   | 0.069 ± 0.012 | 0.008 ± 0.001  |
| NCL-1214092                | 55         | 0.000        | 5.12 ± 0.26          | —               | —               | —                             | —              | —              |
| SC-10                      | 5          | 0.968        | 5.19 ± 0.28          | 8.26 ± 1.40     | 1.59 ± 0.28     | 1.76 ± 0.32                   | 0.028 ± 0.005 | 0.028 ± 0.005  |
| NCL-1214094                | 20         | 0.121        | 4.10 ± 0.21          | 76.1 ± 21.8     | 18.57 ± 5.41    | 20.9 ± 5.7                    | 0.010 ± 0.003 | 0.001 ± 0.000  |
| NCL-1214095                | 35         | 0.122        | 4.21 ± 0.21          | 108.6 ± 59.4    | 25.80 ± 14.16   | 29.1 ± 18.2                   | 0.012 ± 0.008 | 0.001 ± 0.001  |
| NCL-1214096                | 50         | 0.062        | 4.54 ± 0.17          | 203.4 ± 40.4    | 44.81 ± 9.06    | 50.7 ± 10.9                   | 0.010 ± 0.002 | 0.0006 ± 0.000 |

aNon-saturation factor (NSF). The fraction of grains below the saturation threshold with respect to the total number of luminescence grains accepted.
bApparent fading corrected feldspar ages. Details are provided in the section for experiment details and in Reimann et al., 2017. Note that all the results are from feldspar single grain post-infrared infrared stimulated luminescence at 175°C (pIRIR175) analyses.

Figure 4. Non-saturated factor (NSF) as a function of the distance from the hill-base for different depths. The NSF indicates the ubiquity of grains that have surfaced after being weathered from bedrock. [Colour figure can be viewed at wileyonlinelibrary.com]
profile yields the oldest age, with an apparent age of 50.7 ± 10.9 ka at 50 cm depth. The apparent ages of the deepest samples in the soil profiles seem to decrease downslope (Figure 6a). For the hill-base profile SC-7 an age of 9.24 ± 0.76 ka at a depth of 55 cm was obtained.

Apparent and effective soil reworking rates

Figures 6b and 6d show the apparent soil reworking rates (SR_{app}, in mm a\(^{-1}\)) and the effective soil reworking rate (SR_{eff}, in mm a\(^{-1}\)) for the four profiles along the hillslope catena (also listed in Table II). The SR_{eff} is calculated by applying NSF to SR_{app} (see Equation (1)), as proposed by Reimann et al. (2017). As NSF is an important input for the calculation of the SR_{eff}, Figure 6c shows the variation in all the NSF values for all four soil profiles with depth. There is a clear vertical trend in each soil profile with NSF ≈ 1 at the surface approaching zero to the bottom of the profiles. The lateral NSF trend at 20 cm depth of the four soil profiles is also clearly visible in this graph.

In Figure 6d vertical SR_{eff}–depth trends are shown with SR_{eff} decreasing with depth for all four soil profiles. Apart from the hill-base profile SC-7, the SR_{eff} decrease seems to follow an exponential downturn. The resulting lateral trends of the effective reworking rates (SR_{eff}) are shown in Figure 7. For all soil depths SR_{eff} decreases with increasing proximity to the hilltop (from SC-7 to SC-10). The highest SR_{eff} values are obtained for the hill-base profile SC-7 at 5 cm with a rate of 0.092 ± 0.023 mm a\(^{-1}\). The lowest SR_{eff} value is observed for the hilltop profile SC-10 at 50 cm soil depth with rates as low as 0.0006 ±0.0001 mm a\(^{-1}\). For approximately the same soil depth (55 cm), the SR_{eff} in the hill-base profile SC-7 is 0.021 ± 0.002 mm a\(^{-1}\), and thus significantly higher.

Discussion

Vertical and lateral soil transport and mixing processes along a hillslope catena

We have shown important variations in age and NSF for the soil profiles analysed, both vertically and laterally (Figures 6a and 6c). Within each soil profile, apparent luminescence ages increase exponentially with depth from the surface. At the surface, all profiles show relatively young burial ages and a high fraction of finite age grains (high NSF), indicating that the majority of grains recently visited the surface. The fraction of these grains then decreases with depth from the soil surface (Figure 6c). This is consistent with our current understanding of bioturbation processes, Wilkinson et al. (2009) review data on surface mounding, burial and mixing rates. They conclude that local mounding rates outweigh burial ones by one order of magnitude. Very often, a large proportion of the soil is mixed
from shallow depths, hence, much greater bioturbation activities are observed at the surface. Bioturbation studies generally observe an exponential downturn in activity with depth below the surface (Roering, 2004; Wilkinson et al., 2009; Johnson et al., 2014). Furbish et al. (2018b) re-analyse the data by Johnson et al. (2014) and report that their results are also compatible with a linear trend. However, our observations of the variation in $S_{Reff}$ with depth confirm an exponential decline for our study site.

As a consequence of taking into account the fraction of finite age grains as a measurement of soil reworking intensity (Reimann et al., 2017), our effective soil reworking rates ($S_{Reff}$) are lower compared to apparent values ($S_{Rapp}$) obtained in other studies (discussed later), especially for samples in close proximity to the mobile regolith–saprolite interface. Considering the hilltop profile, the $S_{Reff}$ is 0.028 mm a$^{-1}$ for the surface sample at 5 cm. Our values are comparable to the vertical mixing values obtained by Stockmann et al. (2013) in Werrimah National Park [New South Wales (NSW), Australia] of 0.031 and 0.085 mm a$^{-1}$ at 4 cm depth in a similar topographic position. During their study, they concluded that the main bioturbator was the forest and understory vegetation with an abundance of root channels in the top 30–50 cm, while earthworms did not seem to be active. From our field observations and descriptions of our soil profiles, we anticipate that ants are the main bioturbator in the study area. The earthworm densities are low, the same as those of the root channels in the soil profiles, and although tree throws were observed, they are not frequent, and the root ball volume moved is typically small (< 0.5 m$^3$). Furthermore, uprooting of trees is likely to result in a complete mixing of soil for the total rooting depth, with the light exposing a large fraction of the grains deep down the profile. This would presumably result in steeper burial age–depth functions and higher NSF values deep in the soil profile than those seen for our study area. The bioturbation age–depth and NSF profiles observed could indeed be better explained by ant bioturbation. Ants move grains to the surface generating superficial mounds and bury them through their underground nest network down to a maximum of 1 m below the surface (Richards, 2009). Gabet et al. (2003) compiled bioturbation rates from other authors (Michell, 1988; Whitford, 2000) and state that ants mix the soil at rates of between 0.0045 and 1.8 mm a$^{-1}$, while earthworm bioturbation is characterized by higher rates ranging between 0.54 and 10 mm a$^{-1}$. Note that these data refer to soil displaced per unit area, but not to a specific depth.

The vertical mixing value reported by Heimsath et al. (2002) observed at Nunnock River (NSW Australia) at 10 cm depth for a similar topographic position was 0.26 mm a$^{-1}$, presumably caused by burrowing wombats and tree throw as principal bioturbation agents. Our rates are again smaller by one order of magnitude suggesting different bioturbating agents to be mainly responsible for soil mixing. The $S_{Reff}$ rates observed for our study area are in good agreement with typical ant bioturbation rates as mentioned earlier, and we have concluded that ants are likely to be the main bioturbation agent on the investigated hillslope.
Laterally, the age at the same depth decreases downslope from SC-10 to SC-9, increases from SC-9 to SC-8 and, finally, decreases from SC-8 to SC-7. The lateral trends in the fraction of non-saturated or finite age grains (NSF) are depth-dependent. Close to the surface, all profiles have high NSF values due to the dominating bioturbation. Deep in the soil profile, the inter-profile differences in NSF depend mostly on the relative proximity of the sample to the actual mobile regolith–saprolite interface. For example, for SC-7 this boundary is much deeper and corresponding NSF values are relatively high (Figure 4). However, at 20 cm depth, there is a clear increase in NSF downslope from SC-10 > SC-9 > SC-8 > SC-7 (Figures 4 and 6c). This can be explained by hillslope erosion due to creep. As illustrated in our conceptual model (Figure 2), creep processes lead to longer cumulative soil transport times for upper and intermediate soil depth resulting in higher NSF values, in particular on erosional hillslope positions (Figure 2, Ile versus Ild). Creep in our study area is either associated with biological mixing or drying–wetting processes. Note that freeze–thaw conditions are not likely to have ever occurred in the study area during the whole quaternary. We will now elaborate further on this trend by comparing NSF and burial age–depth functions of the different soil profiles with each other.

Profile SC-10 is assumed to be closest to steady-state conditions because of its position on the hill-top (case I in Figure 2), so that it can be used as a reference to evaluate the processes in the other profiles. Profile SC-9 appears to be moderately erosional, with younger ages at similar depths (Figure 6a) compared to profile SC-10. While the burial age–depth distribution does not allow one to distinguish between erosion due to overland flow or creep (Figure 2, case II), the higher NSF at 20 cm soil depth points to creep as being the dominating process (corresponding to sub-scenario shown in Figure 2, IId). The NSF values of this soil profile also seem to indicate that the mobile regolith–saprolite boundary, i.e. transition of NSF = 0 to NSF > 0 indicated by the grey bar in Figure 5 and NSF trend in Figure 6c, is at a lower soil depth compared to the steady-state profile SC-10, which would agree with net erosion > net soil production for profile SC-9. While this NSF-based boundary would be in line with the soil depth trend expected from the geomorphological position of this profile, the boundary as observed in the field cannot sufficiently reflect this trend.

Profile SC-8 is strongly erosional, presumably resulting in a truncation of the burial age–depth profile and a very shallow soil depth (NSF transition zone between 20 and 35 cm, Figure 5). As a result, only two samples could be analysed for palaeodose impeding a more elaborate interpretation (e.g. regarding NSF trends) of this soil profile. However, it again seems that the NSF-based soil depth agrees better with the geomorphological position of this soil profile than the soil depth based on field observation, which was recognized as being ~50 cm (Figure 5).

Potential of feldspar luminescence tracers to monitor soil transport and mixing

Furbish et al. (2018b) recently discussed the performance of TCN versus conventional quartz OSL tracers to study soil transport and mixing. Effective soil reworking rate (SR_{eff}) as a function of distance from the hill-base for four different depths. [Colour figure can be viewed at wileyonlinelibrary.com]
particle transport and mixing. They point out that while TCN tracers track grain trajectories and history bottom-up, quartz OSL tracers do so top-down. In this study, we have applied, for the first time, feldspar single-grain luminescence as a soil transport and mixing tracer, and we were able to clearly distinguish between two luminescence signatures in our data: (i) the burial age–depth information and (ii) the NSF–depth information (i.e. tracing the fraction of grains with a surface exposure history). While signature (i) provides a top-down tracer of soil transport and mixing similar to conventional quartz OSL (Figure 6a), signature (ii) provides a bottom-up tracer of soil transport and mixing (Figure 6c), potentially providing an alternative to TCN tracers. We show that NSF luminescence signatures down the soil profile can reflect soil production. Under steady-state soil thickness and constant bioturbation, an increase in soil production will result in an excess of ‘out of competition’ (or infinitely old) grains, resulting in a steeper NSF decline down the soil profile. A decrease in soil production, in turn, will lead to a flattening of the NSF curve. For the steady-state profile SC-10, an exponential downturn of NSF down the profile is observed (Figure 6c). The latter effect is also observed for the moderately eroding profile SC-9. These observations are in line with soil production under steady-state (SC-10), or close to steady-state (for SC-9), conditions, and an exponential decrease in bioturbation intensity with soil depth. Thus, our data support the hypothesis that NSF functions down the soil profile derived from single-grain feldspar luminescence analyses are able to detect soil production. This implies a significant extension and refinement of luminescence-based methods to trace soil transport and mixing. Our findings need further testing and the full potential of NSF-based soil production rates should be thoroughly explored in future research. One interesting issue remaining is whether we can use NSF to determine soil production for profiles that clearly violate the steady-state assumptions. Figure 6c suggests that, for those soil profiles (e.g. SC-7), NSF–depth decline clearly deviates from simple exponential behaviour.

Our results also demonstrate the importance of taking into account the NSF to translate burial age–depth information into measurements of soil reworking/mixing. We observed a marked difference between the apparent soil reworking rate (SRapp), as adopted in previous quartz OSL-based soil reworking investigations (Heimsath et al., 2002; Wilkinson and Humphreys, 2005; Stockmann et al., 2013), and the effective soil reworking rate, which incorporates NSF to factorize the soil reworking intensity (Reimann et al., 2017). This study confirms our previous finding that SReff better reflects the exponential decrease of biological soil mixing with soil depth than SRapp (Figure 6b versus Figure 6d). Accurate quantification of NSF is problematical for single-grain quartz OSL due to OSL signal sensitization of plutonic or metamorphic bedrock-derived quartz (Reimann et al., 2017). However, this might not be the case in sedimentary bedrock settings (either consolidated or unconsolidated) as soil parent material. For those settings, we would expect a less problematical quartz OSL signal sensitization, and NSF, or similar approaches could be applicable.

It needs to be noted, however, that both SRapp and SReff are still simple soil reworking measurements that only provide a linear measurement of the burial rate, which in fact is affected by both bioturbation and erosion processes. A follow-up study will analyse bioturbation rates by calculating the diffusivity constant using this same dataset and comparing this to the linear soil reworking measurements presented here (see companion paper Román-Sánchez et al., 2019, https://doi.org/10.1002/esg.4626). Furthermore, feldspar single-grain luminescence analyses can be used to objectively map the boundary between the mobile regolith and the saprolite through keeping track of the fraction of finite age grains, i.e. grains with an exposure history (NSF, see Figure 5). The basal transition to the underlying granitic saprolite, as observed in the field, is clear (Schoeninger et al., 2012). Our luminescence data suggest that the field identification of the depth of the border between the mobile regolith and the saprolite might have been overestimated, at least for the two hillslope profiles (Figure 5). In fact, we are able to demonstrate that NSF-based soil depth measurements are able to capture the correlation between decreasing soil depth with increasing erosion (SC-8 and SC-9, Figure 5) much better than field observations (see discussion earlier). This has important consequences for accurately estimating soil depth, that is especially important for calculating soil production rates by TCN, which are vitally dependent on the correct identification of this boundary. Luminescence could therefore be important for complementing measurements of soil production rates using cosmogenic nuclides or other methods.

Conclusions

In this study we have explored the potential of two luminescence signatures derived from feldspar single-grain analyses to clarify soil transport and mixing processes along a hillslope catena. From our study, we have drawn the following conclusions:

(i) Effective soil reworking rates (SRapp) yield a greater explanatory power than simple apparent soil reworking rates (SRapp) adopted in other luminescence soil mixing studies. SRapp accounts for the fact that not all grains participate in the mixing process by including the NSF as a measurement of reworking intensity. SRapp rates obtained for our study area point to ants as being the main bioturbating agents.

(ii) By analysing four luminescence burial age–depth and luminescence NSF–depth profiles along a hillslope catena in combination with our conceptual model, we were able to disentangle bioturbation, soil production and erosion–deposition processes.

(iii) We identified soil creep to be the dominant process of lateral soil displacement. This is reflected in increasing NSF values at intermediate depths (~20 cm) along our hillslope catena.

(iv) For the erosional part of our hillslope catena, NSF-based soil thicknesses align better with the geomorphological position of the corresponding soil profile than soil thickness measurements based on field observations.

(v) Finally, our study suggests that NSF–depth profiles reflect soil production, potentially providing an alternative to TCN-based soil production rates (Heimsath et al., 1997).

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. Central age model (CAM) equivalent dose values and corresponding over-dispersions (ODs)

Figure S1. Illustration of the effect of lowering the reference level due to erosion on the observed age–depth trends.

Figure S2. Equivalent dose distributions for the four soil profiles (SC-7, SC-8, SC-9, SC-10) at different depths for the single-grain feldspar pIRIR175 luminescence signal. We have specified the arithmetic mean and its 1-sigma standard error as the palaeodose of the sample and the fraction of saturated grains, i.e. grains above the 2*D0 saturation threshold (see Experiment Details section). Note that the fraction of saturated grains is the inverse of the non-saturation factor (NSF).