

Investigating processes of pedogenesis in the Werrikimbe National Park, NSW, Australia

Uta Stockmann^A, Budiman Minasny^A, Alex. McBratney^A, David Fink^B and Tim Pietsch^C

^AFaculty of Agriculture, Food and Natural Resources, The University of Sydney, NSW, Australia, Email u.stockmann@usyd.edu.au; b.minasny@usyd.edu.au; A.Mcbratney@usyd.edu.au

^BAustralian Nuclear Science and Technology Organization (ANSTO), Menai, NSW, Australia, Email fink@ansto.gov.au

^CAustralian Rivers Institute, Griffith School of Environment, Griffith University, QLD, Australia, Email t.pietsch@griffith.edu.au

Abstract

The significance in analysing pedogenesis quantitatively has become apparent as a response to increasing environmental problems. Recently there has been a movement of interest towards quantifying the rate of soil formation in situ to better understand the dynamics of soil systems. Work on quantifying the processes that form a soil profile is still minimal in soil science, but with laboratory techniques available now to address this demand, this research aim is achievable. Therefore, we conducted a field study along three principal toposequences in the Werrikimbe National Park situated in northeastern NSW, Australia. To investigate soil formation processes we used terrestrial cosmogenic nuclides (TCN) to derive production rates of soil (SPR) in mm/kyr and optically stimulated luminescence (OSL) to examine vertical mixing rates of soil and also to estimate relative dates of soil horizons. SPR calculated at Werrikimbe National Park are relatively low ranging between 3 and 18 mm/kyr underneath soil depths of 40 to 120 cm. Looking at each toposequence individually, the SPR has the tendency to decrease with increasing soil thickness, which supports the concept of exponential decrease of soil production with increasing soil depth. Results of our study in a warm-temperate to subtropical environment with high annual rainfall show the lowest TCN-derived SPR so far when compared to published SPR of different climate regimes. However, with a value for a potential weathering rate, P_0 , of 10 ± 4 mm/kyr, our data fit very well within those previously derived data.

Key Words

Pedogenesis, soil production rate (SPR), soil mixing rates, dating, terrestrial cosmogenic nuclides, optically stimulated luminescence.

Introduction

Quantifying soil formation is important to understand the dynamics of soil systems. The significance to investigate pedogenesis quantitatively has become apparent as a response to increasing environmental problems (Hoosbeek and Bryant 1992). In pedology the focus has been directed towards the prediction of soil properties from landscape attributes at specific sites based on empirical quantitative relationships (McBratney *et al.* 2003). However, recently there has been a movement of interest towards quantifying the rate of soil formation and improving the understanding of pedogenesis (Minasny, McBratney *et al.* 2008). With laboratory techniques available now to address this demand, this research aim can be achieved and is necessary since work on quantifying the processes that form a soil profile is still minimal in soil science (Bockheim and Gennadiyev 2009).

This paper aims to present the application and findings of using terrestrial cosmogenic nuclides (TCN) and optically stimulated luminescence (OSL) to investigate soil formation processes.

Methods

Study site

We conducted a field study in a subcatchment with significant relief of the Werrikimbe National Park in northeastern NSW, Australia. The National Park belongs to the warm-temperate to sub-tropical climate zone with an annual rainfall of up to 2000 mm. Werrikimbe National Park lies within the New England Fold Belt of Eastern Australia. Parent materials of the sampling sites at Spokes Mountain, Plateau Beech and Mount Boss comprise of sedimentary and metamorphic rocks of Devonian, Carboniferous and Permian age, consisting of mudstones, siltstones and fine lithic sandstones (Atkinson 1999).

Within Werrikimbe National Park we ensured to choose sampling sites with minimal disturbance by human activities. Hence, sampling took place in old growth forest areas along three principal toposequences,

following a sampling scheme by Odgers *et al.* (2008). This sampling scheme combines the concepts of catenas, random sampling and stream order.

Three soil profiles along each toposequence were dug to the soil-bedrock or soil-saprolite interface with soil pits varying between 40 and 120 cm in depth. A total of nine soil pits were located at the top, midslope and the base of the hillslope. Each horizon of the soil profiles has been fully analysed in terms of physical and chemical properties including bulk density, particle size distribution, organic carbon content and mineralogy suite of the soil.

TCN Analysis

About 1500 g of parent material, sampled beneath different soil depths, was analysed for concentrations of the TCN ^{10}Be via Accelerator Mass Spectrometry (AMS), a very mass-sensitive, precise technique that can detect radioisotope atoms as low as 10^6 for ^{10}Be . TCN preparations and TCN laboratory analysis was carried out at the ANTARES AMS facility at the Australian Nuclear Science and Technology Organisation (ANSTO) in Sydney, Australia (Child, Elliott *et al.* 2000). TCN are formed via the interaction of secondary cosmic rays with earth materials. The higher the measured concentration of TCN in the sample, the longer the exposure to cosmic rays has been. Concentrations of ^{10}Be in parent materials of soils were used to derive soil production rates (SPR) following equations in Nishiizumi *et al.* (1991) and Heimsath *et al.* (1997). SPR were normalized to sea level and high latitude (Stone 2000), and corrected for shielding, slope and depth below the soil surface (Dunne, Elmore *et al.* 1999; Granger and Muzikar 2001). Here, SPR are defined as the conversion from parent material to soil combining the effect of physical and chemical processes whereas the physical conversion of the parent material is the dominant process in thickening the soil profile.

OSL Analysis

Undisturbed soil samples were taken with soil cores of 26 cm in length and 5 cm in diameter to ensure that the soil in the middle part of the soil core was not exposed to daylight at any time during sampling. This sampling procedure was necessary, because the OSL dating technique is based on the exposure of mineral grains to daylight. Hence, all sample preparations and analysis was carried out in the darkroom environment. OSL samples were analysed at CSIRO Land and Water in Canberra, Australia, using the single-aliquot regenerative-dose (SAR) protocol of Olley, Pietsch *et al.* (2004). The OSL dating technique uses a beam of light to release a luminescence signal within a particular mineral grain (quartz), which is measured by a photomultiplier. The measured OSL signal (dose, D_e in Gy) is proportional to the time elapsed since individual mineral grains were last exposed to daylight. However, to estimate a burial age for individual quartz grains, we also need to know the annual radiation dose (Gy/yr) the grains received over time. Therefore, the annual radiation dose rate has been calculated in using high resolution gamma spectrometry measurements of the radionuclide content of the samples. Burial ages of quartz grains have been calculated using the following equation:

$$\text{Burial age (yr)} = \frac{\text{Dose (Gy)}}{\text{Annual radiation dose (Gy/yr)}} \quad (1)$$

Results

Physical and chemical soil properties

The vegetation at the field sites consists of cool temperate rainforest, wet sclerophyll forest and dry sclerophyll forest. At our sampling sites at Werrikimbe National Park soil types belong to the soil group of Kandosols under the Australian soil taxonomy nomenclature (belonging to Acrisols and Luvisols under the FAO-Unesco World Reference Base).

Topsoils are characterized by stony silty loams to silty clay loams whereas subsoils are characterised by silty loams, silty clay loams and silty clays with a significant amount of stones. For all sampling sites, the clay contents were moderate to high (>40 %) throughout the soil profile. The organic carbon content of the forest soils was approximately 10% in the topsoils, decreasing to 1 % with depth.

Results of the soil mineralogy suite, obtained from X-Ray diffraction spectroscopy are shown in Figure 1. At all three toposequences, the clay mineral Kaolinite (basal spacing (d) = 0.718 nm) and the aluminium-oxide Gibbsite (d = 0.356 nm) were found. The iron-oxide Goethite was also present in each horizon of the nine soil profiles. Chlorite (d = 1.408 nm) was present in two of the three toposequences (at Spokes Mountain and Plateau Beech). Kaolinite, Gibbsite and Chlorite are all indicators of extensive soil weathering.

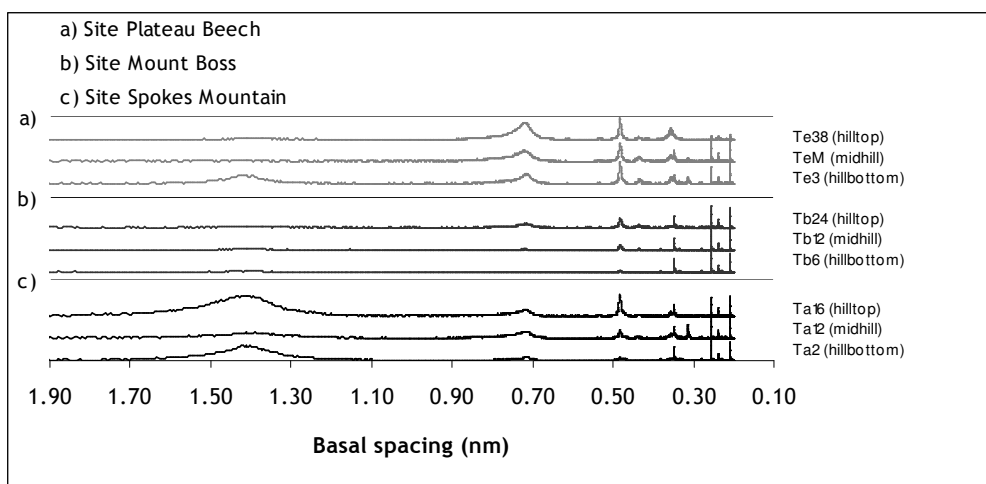


Figure 1. Diffractograms obtained from clay tile preparations, from 10-20 cm depths, for all study sites at Werrikimbe National Park

TCN-derived SPR

Normalized concentrations of ¹⁰Be, analysed from parent materials below different soil depths and one outcrop sample, range between 0.103 to 0.450 x 10⁶ atoms/g-quartz and are shown in Figure 2.

At Werrikimbe National Park, calculated soil production rates vary between 3 and 18 mm/kyr, with a maximum of soil production occurring between 0 and 50 cm of soil depth. The SPR of each individual toposequence tends to decrease with increasing soil depth. Hence, under steady-state conditions, the production of soil (SPR) follows an exponential decline of the weathering of bedrock with increasing soil thickness: $SPR = P_0 \exp(-bh)$ where P_0 is the potential physical and chemical weathering rate of the parent material at depth $h=0$, and b is an empirical constant (Minasny and McBratney 1999). With a value of 10 ± 4 mm/kyr ($b=0.125 \pm 0.617$), the potential weathering rate (P_0) is relatively low for this warm-temperate to subtropical environment.

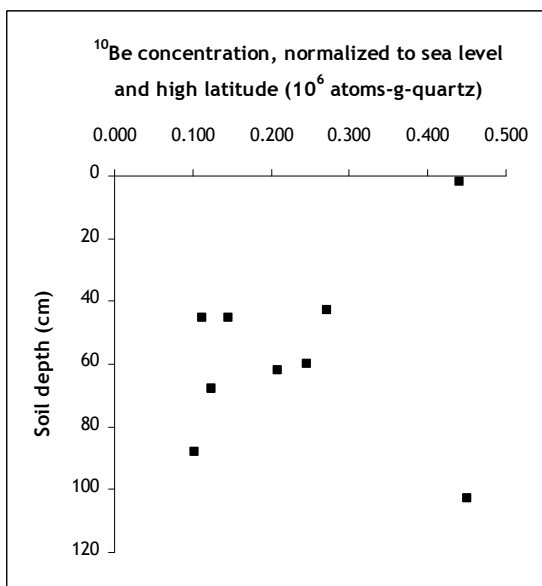


Figure 2. In situ produced ¹⁰Be concentrations versus measured soil depths, normalized to sea level and high latitude (Stone 2000)

OSL

Results show that the amount of quartz grains responsive to the OSL dating technique decreases down the soil profile. Median ages of quartz grains range between 100 and 5000 years, calculated using dose (in Gy) and annual dose rate (in Gy/yr) values, following equation (1). For the toposequence at Mount Boss, median ages of quartz grains are generally younger (up to 500 years) in the top 15 cm of the soil profile than quartz grains deeper down the profile (with median ages of up to 1500 years). This tendency is also present in the data from the topo-sequence at Plateau Beech, but here median ages are significantly higher, with up to 1500

years in the top 15 cm of the soil profile and up to 5000 years deeper down the profile. However a few younger grains can also be found deeper down the profile and older grains near the soil surface.

Conclusions

Interpreting the results of the semi-quantitative analysis of clay minerals and oxides implies that the soils at our field site of Werrikimbe National Park are highly weathered.

TCN-derived SPR at our study site are the lowest so far compared to previously published data with a P_0 value of 10 ± 4 mm/kyr. SPR at Werrikimbe National Park follow an exponential decline with increasing soil thickness, and therefore support the conceptual work of an exponential decrease of soil formation with increasing soil thickness (Ahnert 1977).

Results of the OSL data show that grains near the surface of the soil profile are younger and are getting much older down the profile. However a few younger grains can also be found deeper down the profile and older grains near the soil surface. These results imply some kind of mixing in the first 50 cm of the soil profiles. TCN and OSL data will be used to refine parameters of a quantitative model to simulate soil profile development in the landscape and to predict the function and the response of the soil to a changing environment. This work is ongoing...

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