# NEW DETERMINATIONS OF THE LONG-TERM PRODUCTION AND MIGRATION OF SOIL, OUR LARGEST MINERAL DEPOSIT

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Soil is the most widely used and most valuable form of regolith. It also is prone to loss and degradation under most modern agricultural practices. International and Australian data indicate that at present soil-loss rates, agricultural and pastoral hillslope soils could be gone in less than 1000 years, and in even less than 200 years in some situations.

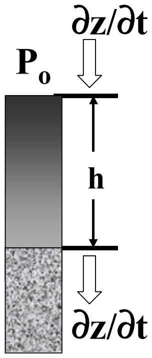
Sustainability requires that soil loss is matched by soil production. While soil production can be accelerated by tillage and related methods, application of these techniques is restricted to certain styles of land use such as cropping. Elsewhere, soil production is the consequence of natural processes dominated by weathering and bioturbation in the regolith. In contrast with soil loss, which is estimated by a variety of techniques, the determination of natural rates of soil production has been problematic.

Measurements of soil properties on dated landforms such as alluvial terraces and volcanic deposits (chronosequences) give rates of net soil accumulation, which can be converted to primary soil production rates provided that soil transport rates are also known. Measurement of long-term transport rates, especially soil creep, also has been problematic.

This paper describes the determination of rates of both soil production and transport, using measurements of isotopes produced in situ by cosmic rays. Results are presented from granite-based agricultural landscapes in southeastern New South Wales, and in the Western Australian wheat belt.

## METHODS

Rare isotopes of a number of elements are produced in rocks at the earth's surface by cosmic rays, which react with nuclei of elements in the rock itself. Products include radionuclides $^{10}$Be, $^{26}$Al and $^{36}$Cl (half-lives 1.5, 0.7 and 0.35 Myr, respectively). Their concentration near the rock surface depends on cosmic ray flux and, more importantly for our purposes, on the exposure history of the rock. Where long-term erosion has been uniform, the cosmogenic nuclide concentration varies inversely with erosion rate. Thus, the long-term erosion rate can be determined. Furthermore, where soil loss (by soil creep and surface wash) is matched by production of soil by rock weathering, the soil production rate can be determined by measuring cosmogenic nuclides at the soil base. For measuring rates of soil production and erosion in terrain comprised of quartz-bearing rock, $^{10}$Be is the most useful nuclide. Figure 1 outlines these principles.



At soil base, lowering

$$\partial z/\partial t = (P_o\, e^{(-\mu h)}/N - \lambda)/\mu$$

If soil thickness h remains constant through time, soil production $S_p = \partial z/\partial t$

where $P_o$ is production rate of a given cosmogenic nuclide at the ground surface, at the site (a.g$^{-1}$ y$^{-1}$), $N_b$ is concentration (a.g$^{-1}$) of nuclide b in sample at soil base, depth h (b = $^{10}$Be, $^{26}$Al etc), and $\mu$ is density-adjusted cosmic ray absorption coefficient.

**Figure 1:** determination of soil production using cosmogenic radionuclides.

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These cosmogenic nuclides are produced at very low rates in rock surfaces (~6 atoms/year in a gram of quartz at sea level). As their resulting concentrations are very low, their measurement involves the specialised technique of accelerator mass spectrometry (AMS). Results reviewed below are from measurements made at ANU and at Lawrence-Livermore Laboratories.

## RESULTS

### Bega Valley, Southeast NSW

Cosmogenic determination of soil production was pioneered in Australia at a hillsope site in the upper Bega Valley, NSW, in a study reported by Heimsath *et al.* (2000). The site is a soil-mantled, forested composite ridge in granite terrain, near the base of the Great Escarpment. The soil is produced from the underlying granitic saprolite and its depth varies with slope curvature, from about 5 cm at the crest where the ridge is strongly convex, to about 90 cm where the slope is straight or passes into a swale. Palaeoclimate studies in the region indicate that the site was forested throughout the Quaternary climatic cycles; hence, it is assumed that the soil-forming processes and soil thicknesses have remained much as they are today.

A second site was subsequently selected, in pastured downland of the upper Bega Valley. As at the spur site, the slopes are soil mantled and soil thickness decreases with increasing convexity.

Soil production at a number of points at both sites was determined from concentrations of $^{10}$Be and $^{26}$Al in quartz particles sampled at the top of the saprolite. Surface lowering $\partial z/\partial t$ was evaluated from concentration N of a given nuclide, and the soil production rate was equated to surface lowering rate, as shown in Figure 1. It was found that the soil production rate decreases as soil thickness increases, varying from about 55 mm kyr$^{-1}$ under very thin soil (<10 cm), down to ~10 mm kyr$^{-1}$ where soil thickness approaches 1 m. Results from both sites are very similar, although production rates at the downland site are a little lower than at the ridge site. Figure 2 shows that the data fit the relationship

(1) $S_p = 55e^{-0.2h}$

Heimsath et al. (2000) refer to formula (1) as the soil production function, and note that quantitatively similar relationships between soil production and soil thickness, determined by the same method, have been reported from coastal California.

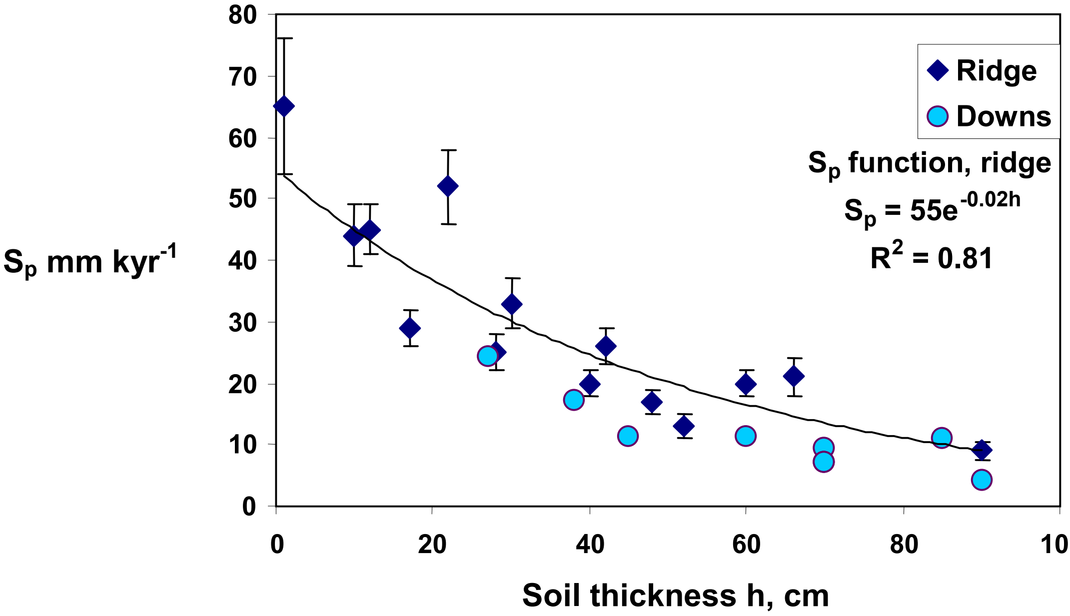

**Figure 2:** soil production rates, Bega Valley

### Miling region, Western Australia

The West Australian wheat-belt in the Moora-Miling area north of Perth includes soil-mantled granite downs resembling the Bega Valley farmland site, although the climate is somewhat drier and warmer. Significantly, the relationships between soil, saprolite and bedrock differ between the two regions. Whereas texture and composition show that the Bega Valley granitic soil is derived from saprolite, which in turn is 10-20 m thick, a similar derivation is not obvious at Miling. Moreover, in many parts of the latter region, hard granite underlies the soil with little or no intervening saprolite. Thus, soil production processes and rates at Miling may differ from those in the Bega Valley; and, to examine this, a pilot study using cosmogenic methods was initiated in July 2001. For comparative purposes, samples also were collected for determination of long-term erosion rates on rocky terrain devoid of soil, in the goldfields region east of the wheat belt.

Erosion rates at Miling were determined from concentrations of $^{10}$Be in saprolite and bedrock samples from at or near the ground surface, near hill crests and on middle slopes. As at the Bega Valley sites, soil production on the soil-mantled slopes at Miling was equated with long-term lowering rate, making the steady-state assumption that the long-term balance between soil production and removal has remained constant. As an unknown amount of soil has been lost through cultivation, samples were from residual woodland and uncultivated areas.

Results are listed in Table 1, in three groups: Miling granite and saprolite sites, Miling palaeosol and precursor sand, and Goldfields rocky hillslope sites. In summary, $^{10}$Be measurements from the Miling granite and saprolite sites indicate long-term erosion rates of 1.7 - 2.4 mm kyr$^{-1}$, with a mean of 2.1 mm kyr$^{-1}$. If this figure correctly represents the mean rate of soil production, the result is surprisingly low in comparison with the determinations at Bega Valley, particularly as the differences of rock-type and climate are slight. However, several considerations weigh against this interpretation, and suggest that the balance between erosion and soil production has not remained constant:

1. Texture and composition of the soil particles indicate that a substantial fraction is not derived from the underlying granite but comes from allochthonous quartzose sand. Moreover, the Miling soil commonly rests directly on bedrock or on thin, residual saprolite, and does not show the type of thick, graded passage from bedrock through saprolite to soil, seen at the Bega Valley sites.
2. Long-term erosion rates at Miling match those of bare bedrock slopes in the goldfields region, implying that long-term erosion processes in the two regions have been similar (Table 1). Given the measured concentrations of cosmogenic $^{10}$Be, it follows that soil may have mantled the Miling landscape for only a fraction of the last million years or so.
3. Very high levels of cosmogenic $^{10}$Be were measured in quartz grains from a residual palaeosol at Miling and from 4.25 m depth in local sand deposits within the regional soil mantle (Table 1). Both results indicate that ancestral soil materials have remained in the region, moving slowly to and fro in the landscape, for perhaps a million years.

Together, these factors appear to invalidate the assumption that pre-agricultural soil production and erosion at Miling were in steady-state. Instead, it is inferred that present soils in this region have been generated largely from former sand sheets, partly aeolian, and residual palaeosols, under a climate that has prevailed for the last 10,000 - 12,000 years, i.e., during the Holocene global interglacial period. The rate of soil formation in this disaggregated sediment during the Holocene was much more rapid than occurs by steady-state conversion of granitic saprolite to soil. Similar situations probably arose in previous interglacials, only for the resultant soils to be dispersed during intervening semi-arid periods. The parent soil materials were mobile in the landscape under semi-arid conditions, which in terms of total time may have amounted to about 80% of the last few million years. This will be tested by sampling other types of regolith, including surface lag and aeolian deposits, which are likely to record semi-arid processes that were operative between sub-humid interglacial phases.

## REFERENCES

HEIMSATH A., CHAPPELL J., DIETRICH W.E., NISHIIZUMI K. & FINKEL R.C. 2000. Soil production on a retreating escarpment in southeastern Australia. *Geology* **28**, 787-790.

**Table 1:** Soil-production study, western Yilgarn.

| **Miling sites, Po = 6.258 a/g/yr**<br>**Granite & saprolite sites** | | **Depth cm** | **$^{10}$Br $10^3$ ag$^{-1}$** | **Erosion mm ka$^{-1}$** |
|---|---|---|---|---|
| MilSap | Saprolite 0.0 m | 0 | 1842 | 1.68 |
| WA-21 | Saprolite 0.0 m | 0 | 1659 | 1.89 |
| WA-14 | Granite 0.0 m | 0 | 1563 | 2.02 |
| WA-20 | Granite 0.0 m | 0 | 1531 | 2.07 |
| WA-22 | Quartz 0.0 m | 0 | 1350 | 2.38 |
| WA-19 | Gr under 0.4 m sap. | 40 | 7.13 | 2.42 |
| MilQ | Qtz under o.3 m sap. | 30 | 894 | 2.24 |
| | **Mean, Miling granite & saprolite** | | | **2.10** |
| **Palaeosol & precursor sand** | | | | |
| WA-34 | Palaoesol, 0.9 m | 90 | 2356 | 0.11 |
| WA-29 | Sand quarry 4.25m | 425 | 2097 | -0.26 |
| **Comparative data: Goldfields regional erosion study**<br>**PO, Lav – 7.05, Kam = 7.041, Mt Holl = 7.0** | | | | |
| WA-1 | Lancefield east ridge | 0 | 3664 | 0.84 |
| WA-4 | Laverton SE ridge | 0 | 3328 | 0.95 |
| WA-7 | Laverton SE ridge | 0 | 1683 | 2.13 |
| WA-9 | Laverton SE ridge | 0 | 1211 | 3.06 |
| WA-11 | Mt Holland crest | 0 | 2032 | 1.70 |
| WA-12 | Mt Holland crest | 0 | 1572 | 2.28 |
| WA-51A | Kambalda N granite | 0 | 1492 | 2.43 |
| WA-51B | Kambalda N granite | 0 | 1356 | 2.68 |
| | **Mean, Goldfields rocky slopes & crests** | | | **2.01** |