Delineating Regolith Materials Using Multi-Scaled Terrain Attributes and Gamma-Ray Imagery - Applications for Updating Soil-Landscape Maps and Managing Dryland Salinity

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EXTENDED ABSTRACT

Many automated digital terrain analysis techniques have been developed to map regolith (including soils) due to the close spatial and genetic relationship between landforms, geomorphic processes and regolith materials. Complementary information reflecting the mineralogy and geochemistry of surface materials to a depth of approximately 30cm can be derived from the analysis of airborne gamma-ray imagery. Gamma-ray surveys measure the naturally occurring concentrations of three radioelements including potassium, thorium and uranium. In this paper we combine an objective digital landform delineation technique with regolith information, specifically, weathering intensity/depth. Weathering intensity/depth was derived from the multiple-regression analysis using gamma-ray channels and a digital elevation model derived relief map. These terrain and weathering components were then combined with an existing soil-landscape map to predict the spatial distribution of both specific soil types and more general regolith information. The new soil-landscape map has the potential to support a range of improved modelling (e.g. salinity) and management applications.

1. INTRODUCTION

An understanding of landscape function and in particular the nature and distribution of regolith is critical in developing more effective and sustainable environmental management approaches. Regolith includes all materials above fresh bedrock and can be broadly divided into *in-situ* materials (e.g. saprolite) and transported materials (e.g. colluvial/alluvial sediments). Soil forms the upper part of a regolith profile that may extend a hundred metres or more below the surface and can form on both *in situ* and transported materials. Australia is well endowed with regolith due in the main to the continents overall low relief and corresponding relatively low erosion rates, geological stability, and absence of extensive Cainozoic. Regolith materials are typically discontinuous and highly variable, and invariably to explain their nature and origin requires a long term landscape perspective.

Although soil and regolith form part of the one system, they are typically mapped separately in Australia. Soil maps focus on the upper one to two metres of the regolith profile and are based on an extensive heritage of pedology research. In contrast, regolith mapping has been largely directed at assisting the mineral industry in exploring in complex highly weathered terrains. For example, many regolith maps to date commonly include information about the nature and distribution of geochemical sample media (Craig, 2001) for mineral explorers. Because regolith maps examine the whole weathering profile the soil component is usually not described in any great detail.

However, both regolith-landform and soil-landscape mapping approaches are very similar. The mapping systems largely rely on the well established spatial and genetic correlation between regolith/soil type and topography (e.g. exemplified by the catena concept – Milne 1935). Topography or landforms, and to a lesser extent, lithology, are used as the principle surrogates for mapping both soils and regolith. Other important factors include climate and time. These similarities reflect a common origin – both approaches are largely based on the lands system mapping described by Christian and Stewart (1952). In their definition, a land system is an area or group of areas throughout which a recurring pattern of topography, soils and vegetation can be recognised. Hence the mapping approaches are fundamentally similar, the main difference is on which part of the profile is emphasised. For example, the same landform boundaries can be used to provide detailed descriptions for soil and regolith materials (Wilford et al., 2006), the former focussing on detailed analysis of the soil and the latter describing the regolith in its entirety, often in conjunction with associated landforms. Fitzpatrick *et al*. (1996) demonstrated how a long term landscape evolution perspective combined with more recent soil processes were used to better understand saline-sulfidic seepage zones.

This paper demonstrates a rapid mapping approach that combines regolith attributes, in particular, weathering intensity/depth with digital elevation model (DEM) - derived landform facets to improve the existing soil-landscape maps. The value-added soil-landscape map can then be used to support more robust environmental modelling (e.g. salinity modelling) and management approaches.

2. STUDY AREA

The study area is located approximately 45km east of Cowra in Central New South Wales (Figure 1). The region lies within the Lachlan Fold Belt and includes Ordovician-Silurian meta-volcanics and Silurian-Devonian metasediments and granites (Raymond *et al*., 1998) (Figure 2). These rocks have undergone multiple episodes of regional deformation and hydrothermal alteration leading to a high degree of structural and lithological complexity. Cainozoic basalt flows are also scattered throughout the region. Steep, highly dissected landforms occur over the southern part of the study area and more subdued, lower relief landforms occur to the north (Figure 2).

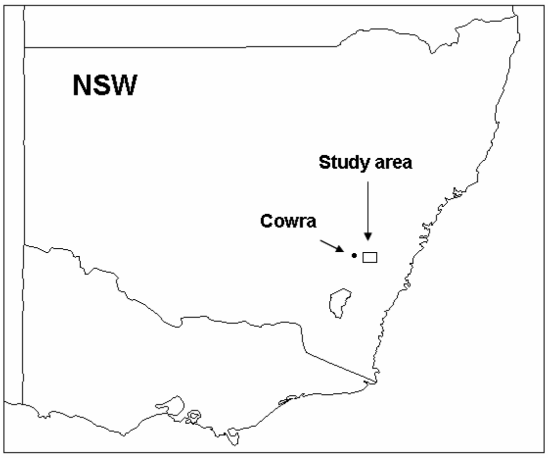

Figure 1. Location of the study area.

3. METHOD

The methodology is divided into three main components – 1) modelling gamma-ray grids and terrain attributes to derive a weathering intensity layer, 2) delineating landscape facets using an automated digital terrain modelling approach, and 3) integrating the above attributes within an existing soil-landscape mapping framework.

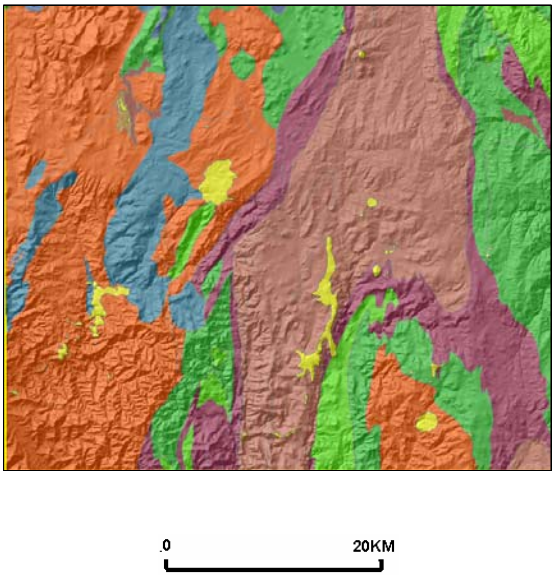

Figure 2. Major lithological units draped over a hillshaded digital elevation model. Tertiary basalt – yellow; Devonian sandstones – brown; Felsic volcanics – green; Mafic volcanics – dark green; Granites blue; Ordovician meta-sandstone and siltstone.

3.1. Gamma-ray spectrometry

Airborne gamma spectrometry measures the natural radiation from potassium (K), thorium (Th) and uranium (U) in the upper 30 centimetres of the Earth's surface. Potassium is measured directly from the radio-element decay of ^{40}K. Thorium and U are inferred from daughter elements associated with distinctive isotopic emissions from ^{208}Tl and ^{214}Bi in their respective decay chains. Part of the Bathurst 1:250 000 map sheet gamma-ray survey with 200m flightline spacing (resampled to a 70m cell size) was used in the investigation.

Emissions of gamma-rays from the Earths surface will largely reflect its geochemistry and mineralogy. Weathering or regolith formation typically alters the concentration of these radioelement from the primary bedrock source. In general K is usually leached during weathering whereas Th and U tend to increase due to their affinity with iron oxides and clays (Dickson and Scott, 1997).

A multiple regression approach was used to explore the relationships between weathering and

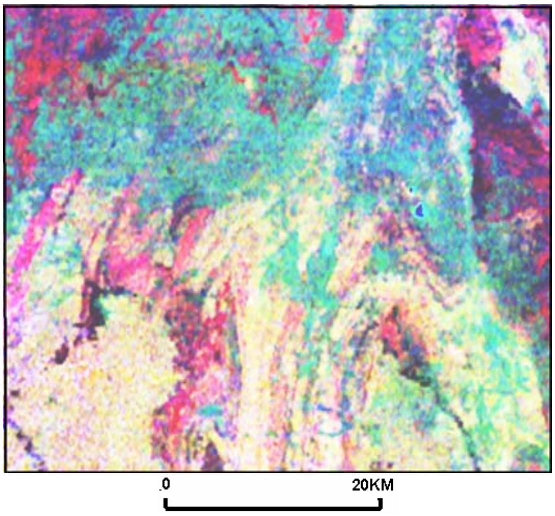

Figure 3. Ternary gamma-ray image. Potassium in red, thorium in green and uranium in blue.

gamma-ray responses and for the prediction of variations in weathering intensity and possible weathering depth. The dependant variable describing weathering intensity/depth was classified into three classes including slightly, moderately and highly weathered regolith. Data sampling points that reflected each of the three classes were based on field relationships observed in road cuttings and erosion gullies. Criteria included the degree of outcrop, composition (e.g. preservation of primary mineralogy) and thickness. The environmental variables (predictors) include airborne K, Th/K ratio, total gamma-ray flux (total count) and relief. Relief was calculated from the DEM by determining the relative elevation differences with a 150m radius window.

3.2. Automated landform mapping

A 25m resolution DEM was constructed from spot heights and contours from 1:25 000 – 1:50 000 topographic maps to model the landforms (NSW LIC 1999). Landform facets were delineated using an objective terrain analysis based method described by Summerell *et al.* (2005). This uses the UPNESS index from the Fuzzy landscape Analysis Geographic Information System (FLAG) model of Roberts *et al.* (1997). UPNESS is a predictor of surface and groundwater accumulation strongly related to landscape position. Inflection points on a cumulative frequency plot of the UPNESS index is used to identify major landform facets as these inflection points represent concave and convex breaks of slope. The method of Summerell *et al.* (2005) uses these points to delineate four major landform types. These landforms include (a) the ridge tops and upper slopes, (b) mid slopes, (c) lower slopes and (d) infilled valleys and alluvial plains. However the valley bottoms and alluvial plains were often under-represented by this method (Summerell *et al.*, 2004). To improve the classification of depositional landforms, the FLAG derived landforms were combined with a multi-resolution index of valley bottom flatness (MRVBF) (Gallant and Dowling, 2003; Summerell *et al.*, 2005). This integrated approach generated seven landform categories which represented (1) ridge tops (2) upper slopes, (3) mid slopes, (4) lower slopes, (5) valley fill in upland landscapes, (6) rises in lowland alluvial fill or long gentle sloping foot slopes and (7) large expanses of infilled valleys and alluvial depositions. The seven unit landform classification is used in this paper.

3.3. Soil –landscape map

A portion of the Bathurst soil landscape map (Kovac *et al.*, 1990) that covered the study area was used in the investigation. Soil-landscape units are coded according to the dominant soil present and are based on Great Soil Groups (Stace *et al.*, 1968). Soil-landscape boundaries were largely compiled on aerial photograph delineated landform boundaries and geology units (Packham, 1968) (Figure 4).

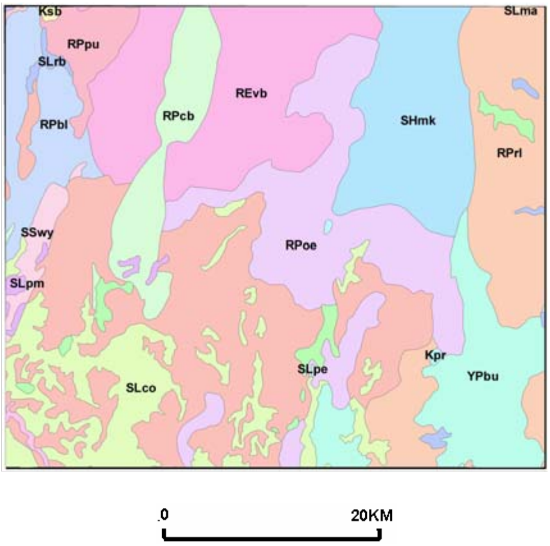

Figure 4. Soil-landscape units.

4. RESULTS AND DISCUSSION

4.1. Weathering index and landscape processes

The multiple-regression analysis approach used to generate a weathering intensity index showed a good correlation ($R^2 = 0.89$) between the environmental variables (airborne K, total count, Th/K ratio and local relief) and relative estimates of the degree of regolith development based on reconnaissance field investigations. In general decreasing concentrations of K, total count, relief and increasing Th/K are observed from slightly weathered to highly weathered regolith. This is reflecting weathering of primary bedrock minerals and the corresponding loss and reorganisation of K and Th in the weathering profile. K is largely lost in solution as K-bearing minerals like K-mica and K-feldspar weather to clay. Thorium, in contrast, accumulates in the weathering profile because of its tendency to be scavenged by iron oxides and incorporation in clays. Thorium is also associated with resistate minerals such as zircon. Variations in these radioelements will also reflect differences in bedrock type. For example, weathering responses will, in places, relate to primary bedrock responses. However, the weathering index is not solely reliant on radioelement patterns as the relief component adds further constraints to the model. Based on ground checking of the modelled predictions, we concluded that as a first pass, the weathering index provides a good separation of regolith and bedrock materials (Figure 5A.).

The model for spatial prediction of weathering intensity is presented below and in Figures 5 and 6.

Weathering index = *0.405443 + 0.007304 X relief + -0.069814 X Th/K + 0.017819 * Total count*

As shown by the weathering index, highly weathered regolith occurs predominantly over the northern half of the study area (Figure 5A) where it is associated with elevated, low relief landforms. These landscapes are associated with a partially preserved Cainozoic palaeosurface that is currently being removed by headwater erosion and scarp retreat (Chan, 1998). Overall geomorphic activity is low with weathering rates exceeding erosion rates leading to the formation of a thick regolith. In this scenario, hill slopes are transport limited. High weathering rates are not necessarily required to form deep regolith as long as the removal rates are low. Therefore, it is the relative rates of weathering and erosion that are important. In contrast, dissected terrain over the southern part of the study area (Figure 5A) is only slightly weathered as a result of higher erosion rates relative to weathering rates, leading to the development of thin regolith. Under these conditions, the slope development is said to be weathering limited.

The weathering index is more likely to show gross and relative differences in weathering that is indicative of an average weathering depth rather than any specific depth measurement. At local scales, weathering depth is likely to be highly irregular reflecting lithological and bedrock structures (e.g. preferential weathering along faults).

4.2. Soil-regolith integration

The geological and geomorphological character of the soil landscape units is demonstrated more clearly by the DEM derived landform facets and weathering intensity attributes (Figure 5A and B). When these are added to soil-landscape unit boundaries it is possible to build a more spatially explicit map that incorporates 'whole of profile' weathering characteristics within a detailed landform framework. These integrated soil/regolith units are similar conceptually to regolith-catenary units described by Thwaites (2007). The weathering index grid was simplified into two groups that separate highly from moderately to slightly weathered regolith. Class thresholds for these groups were based on field observations and relationships with major erosional scarps in the area that typically marked the boundary between different degrees of bedrock weathering.

The soil landscape units are allocated to three separate groups: those on the Cainozoic palaeosurface, those on the high relief landforms and those which are a mixture of the palaeosurface and high relief landforms. These three groups can be distinguished by the weathering index as shown in Figure 6. The weathering index is scaled from values around 1 for highly weathered soil/bedrock to values around 2-3 for slightly weathered soil/bedrock. The soil landscapes on the palaeosurface have a lower weathering index value than those on landforms with higher relief. The mixed soil landscapes have an intermediate response (Figure 6).

The potential use of the regolith information to improve the soil landscape map can be demonstrated by investigating the Carcoar-Barry soil landscape. This is formed on granodiorite. This soil landscape is astride the highly weathered and slightly weathered boundary as shown in Figure 5A. The northern portion is on the highly weathered regolith and the southern portion on the slightly weathered regolith

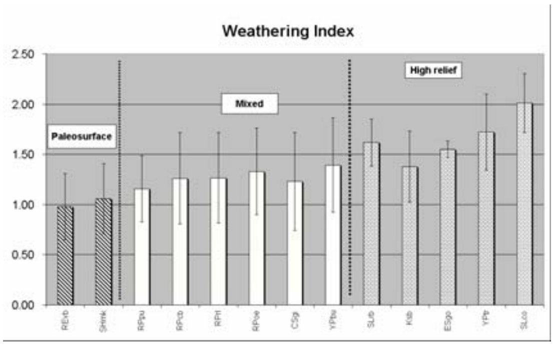

Figure 6. Calculated weathering indices for the groupings of soil landscapes showing means and standard deviations

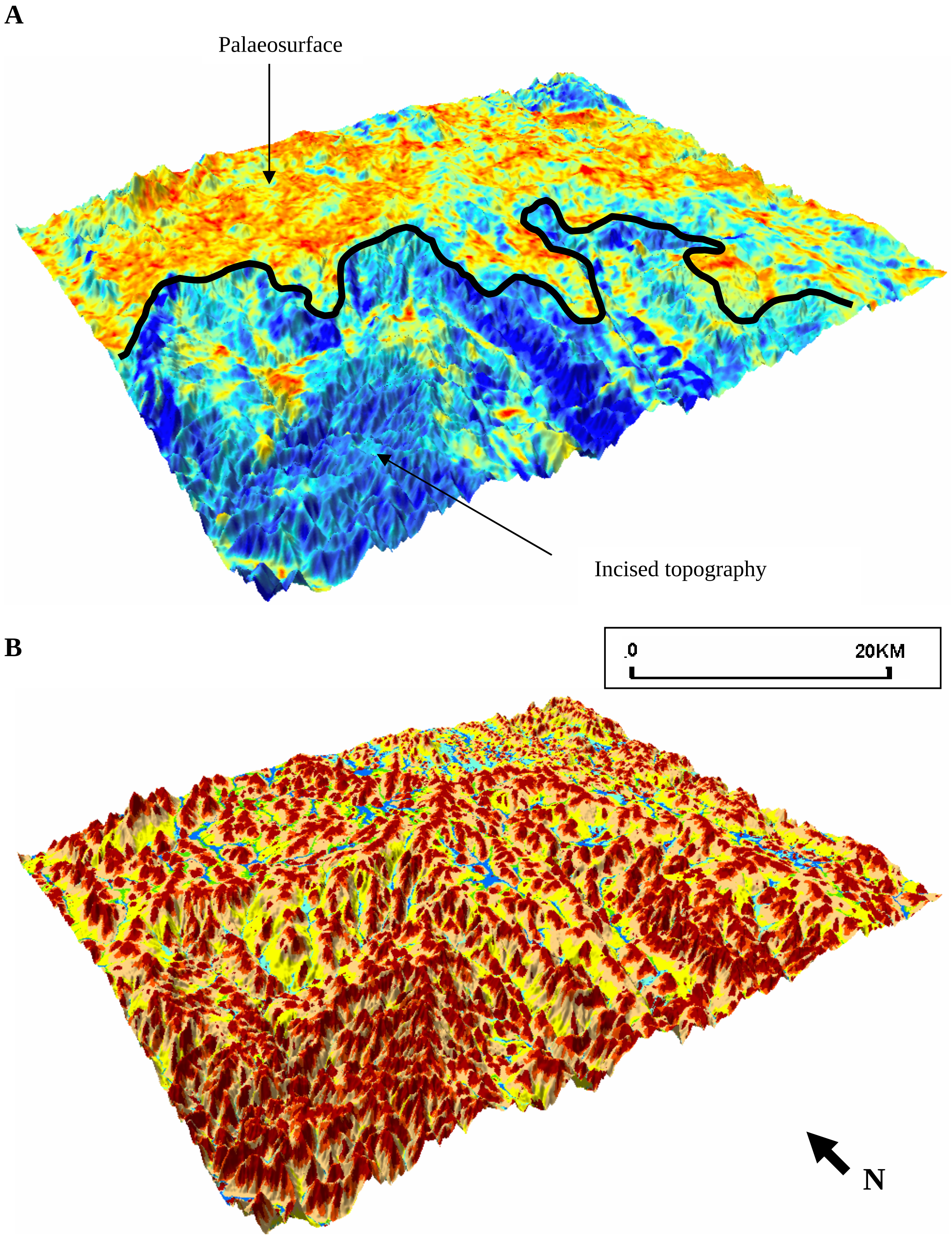

Figure 5A. Weathering index draped over a hillshaded DEM. Highly weathered landscapes in red hues and slightly weathered (bedrock dominated) landscape in blue hues. Erosional scarp in black. **5B**. LF7 landform classes draped over the DEM. Hill crests and upper slopes in reddish brown hues; mid-lower colluvial slopes in yellow hues and valley floors and alluvial plains in green and blue hues.

The terrain analysis shows that the northern and southern parts have very different distributions of landform elements (Figures 7 and 8). The northern palaeosurface part of the Carcoar-Barry soil landscape has a much higher proportion of crests and upper slopes than the southern portion of the soil landscape. The southern portion of the soil landscape has a large area of lower slopes.

These landform and weathering differences have significant implications for the distribution of soil/regolith types. Table 1 indicates that it is likely that more red podzolic and siliceous sand soils occur in the northern portion of the soil landscape, while the southern portion is likely to have more yellow solodic soils. Also, the deeper regolith over the northern part of the Carcoar-Barry soil-landscape has a much high capacity to store water and salts. This has implications for land management and especially for salinity management.

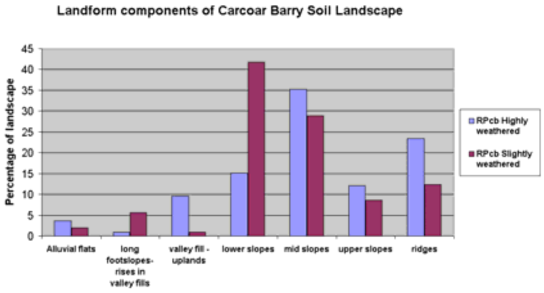

Figure 7. Distribution of landform elements in the Carcoar-Barry soil landscape based on LF7 terrain analysis.

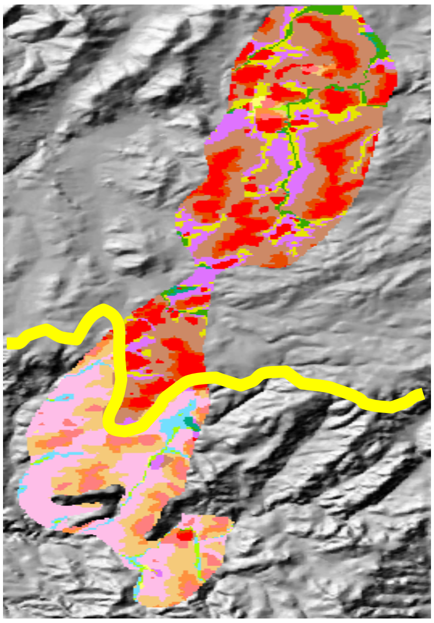

Figure 8. Distribution of soil/regolith facets within the Carcoar-Barry soil landscape. The erosional scarp (yellow line) marks the boundary between the more weathered palaeosurface to the north from shallow regolith associated with incised topography to the south.

Table 1. Soil/regolith distribution within the Carcoar-Barry Soil Landscape.

Slightly weathered landforms	**Major soils/regolith expected**
ridge tops	Siliceous sands overlie slightly weathered granite. Granite tors common.
upper slopes,	Red podzolic soils overlie slightly weathered granite. Outcrop common.
mid slopes	Red podzolic soils developed in sand/clay colluvium. Moderately weathered granite.
lower slopes	Yellow solodic soils developed in colluvial sands/clays. Moderately weathered granite
valley fill in upland landscapes	Yellow solodic soils developed in colluvial/alluvial sands and clays. Underlying granite variably weathered
rises in lowland alluvial fill or long gentle sloping foot slopes	Yellow solodic soils and sands developed in colluvial/alluvial sands and clays. Underlying granite variably weathered.
large expanses of infilled valleys and alluvial depositions	Alluvial soils, sands developed in colluvial/alluvial sands and clays. Sediments typically >4m thick. Moderately to highly weathered granite
Highly weathered landforms	**Major soils/regolith expected**
ridge tops	Siliceous sands overlie moderately weathered granite. Minor outcrop
upper slopes,	Red podzolic soils overlie moderately weathered granite. Minor outcrop
mid slopes	Red podzolic soils developed in sand/clay colluvium, overlying highly weathered/mottled granite.
lower slopes	Yellow solodic soils developed in sand/clay colluvium, overlying highly weathered/mottled granite.
valley fill in upland landscapes	Yellow solodic soils developed in colluvial/alluvial sands and clays. Sediments typically >3m thick. Very highly weathered granite
rises in lowland alluvial fill or long gentle sloping foot slopes	Yellow solodic soils and sands developed in colluvial/alluvial sands and clays. Sediments typically >3m thick. Very highly weathered granite
large expanses of infilled valleys and alluvial depositions	Alluvial soils, developed in colluvial/alluvial sands and clays. Sediments typically >6m thick. Moderately to highly weathered granite.

5. CONCLUSION

A methodology that incorporates regolith (specifically weathering intensity/depth) and DEM-derived landforms with an existing soil-landscape framework has been developed and applied to an upland region in central NSW. The approach enables multi-scaled prediction of the 'whole profile' soil-regolith properties. This is achieved by integrating broad scale relief attributes and weathering intensity characteristics with locally derived landform facets (e.g. FLAG model). However the technique is still largely experimental and further refinements and validation with ground truth observations are required to assess the accuracy of the predictions.

The benefits of producing regolith maps and soil landscape maps as a joint exercise are clearly demonstrated in this paper.

Multiple-regression analyses using local relief, ratio of Th/K, total count and K were useful in explaining the relative distribution of the degree and depth of weathering in the study area. Improvements to the model are in train to accommodate shallow regolith on low relief landforms (e.g. pediments) and landscapes with low gamma-ray emitting lithologies (e.g. siliceous sandstones, ultramafic bedrock).

6. ACKNOWLEDGMENTS

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