Developments and New Approaches in Regolith Mapping

Proceedings of a two day seminar and workshop organised by
the Centre for Australian Regolith Studies
at the University of Canberra
20-21 June 1995

Edited by

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PREFACE

This publication arose from a two day seminar-workshop organised by the Centre for Australian Regolith Studies and held at the University of Canberra on 20-21 June 1995. The seminar-workshop was the second in an annual series designed to explore issues related to Cainozoic geology, regolith and other topics relevant to landscape evolution and geomorphology. Thirty six scientists and students attended the seminar-workshop, representing eight organisations in the ACT and local area with interests in regolith mapping. The main aim of the seminar was to present an overview and information on new developments in regolith mapping techniques and their applicability to a range of clients. The workshop addressed issues concerned with regolith nomenclature and terminology and outlined some possible future directions for the further development of regolith characterisation and mapping.

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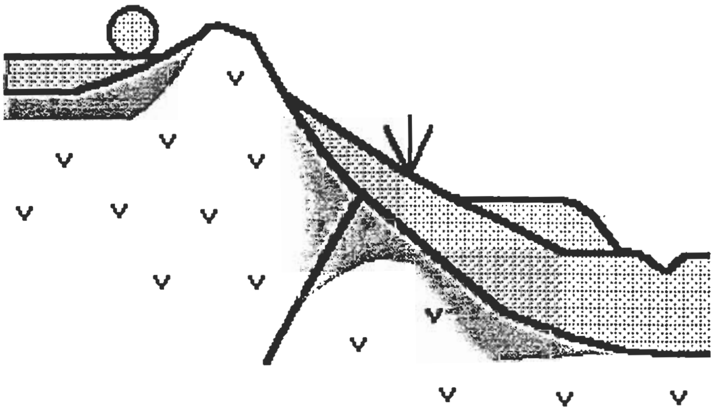

LITHOS

An Unreliable History of Regolith Mapping

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Introduction

The study of regolith is modern. Geologists studied rocks and soil scientists studied soil. The idea that there may be something in between was not usually interesting, so usually the regolith was, and is, ignored.

A simple definition of regolith might be "all surficial materials above fresh bedrock." More formally:

> "Regolith (reg'-o-lith) A general term for the layer or mantle of fragmental and unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface of the land and overlies or covers the bedrock. It includes rock debris of all kinds, volcanic ash, glacial drift, alluvium, loess and aeolian deposits, vegetal accumulations, and soil. The term was originated by Merrill (1897, p. 299). Etymol: Greek *rhegos*, "blanket", + *lithos*, stone." (Bates and Jackson, 1987, Glossary of Geology).

Although this definition is almost 100 years old, the study of "regolith", meaning something more than surficial sediments is fairly young - fifty years covers most of it. But what is meant by 'more than surficial sediments'? To most people it means the addition of soil, some specific feature such as duricrusts, and perhaps weathering profiles, though most earth scientists seem remarkably ignorant about weathering profiles and saprolite. Maps of soils and sediments have been around for quite a long time, but these are only partial or surrogate regolith maps, and the history of true regolith mapping is much shorter.

The first maps that showed regolith were devised in the first place to show other things. Soil maps are of great antiquity, but usually only refer to the top metre or less of regolith. The oldest I have found is one of Suffolk produced in 1797 (Fig. 1), and it is a rough map of the texture of the topsoil (sand, rich loam, fen, etc.). Perhaps we should have a prize for the oldest regolith map yet discovered. Graham Taylor (pers. comm.) told us of regolith (soil) maps used by tax collectors in ancient China, and there may have been equivalents in ancient Egypt or Mesopotamia.

We shall now consider various maps that are in some way 'regolith maps.'

Depth of Weathering

At the simplest, one might expect maps of regolith thickness to be produced, but they are rare. Thomas (1966) produced one which is of considerable interest, for a small area of Nigeria, but I have not found any others. Engineers have sometimes collected information but usually are content with sections, and do not produce maps. Moye (pers. comm.) told me of vast amounts of drilling information obtained by the Snowy Mountain Authority during its exploration. This was not produced in map form, and years later it was not even possible to find the raw borehole data.

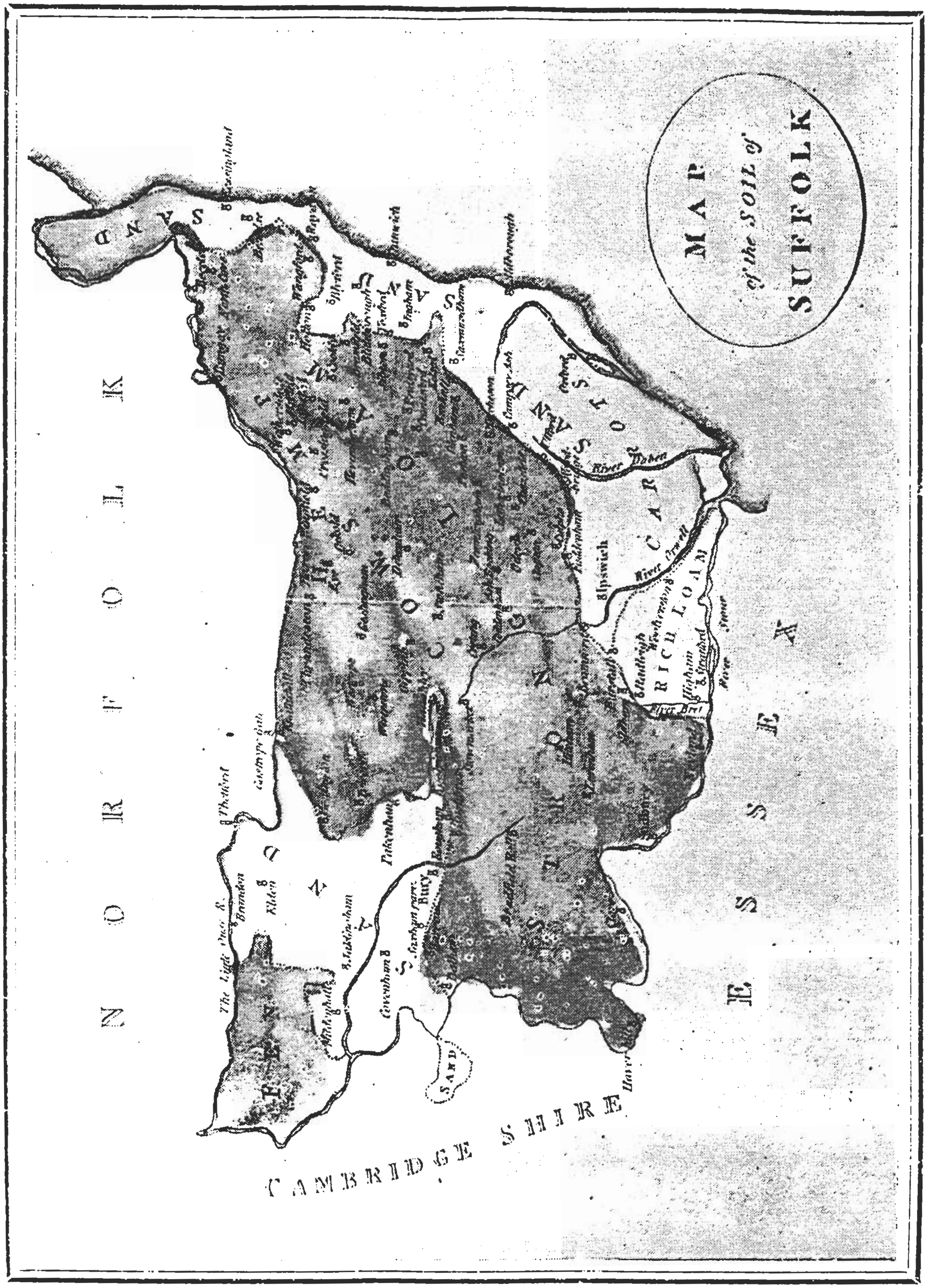

Fig. 1. Map of the soil of Suffolk, England, produced by the Board of Agriculture in 1797.

One of the saddest 'regolith' maps (Fig. 2) is that showing the distribution of deep weathering profiles, a very rough attempt by Roy Woodall (1981) produced in the hope of inducing CSIRO to take up regolith studies for the benefit of the mining industry.

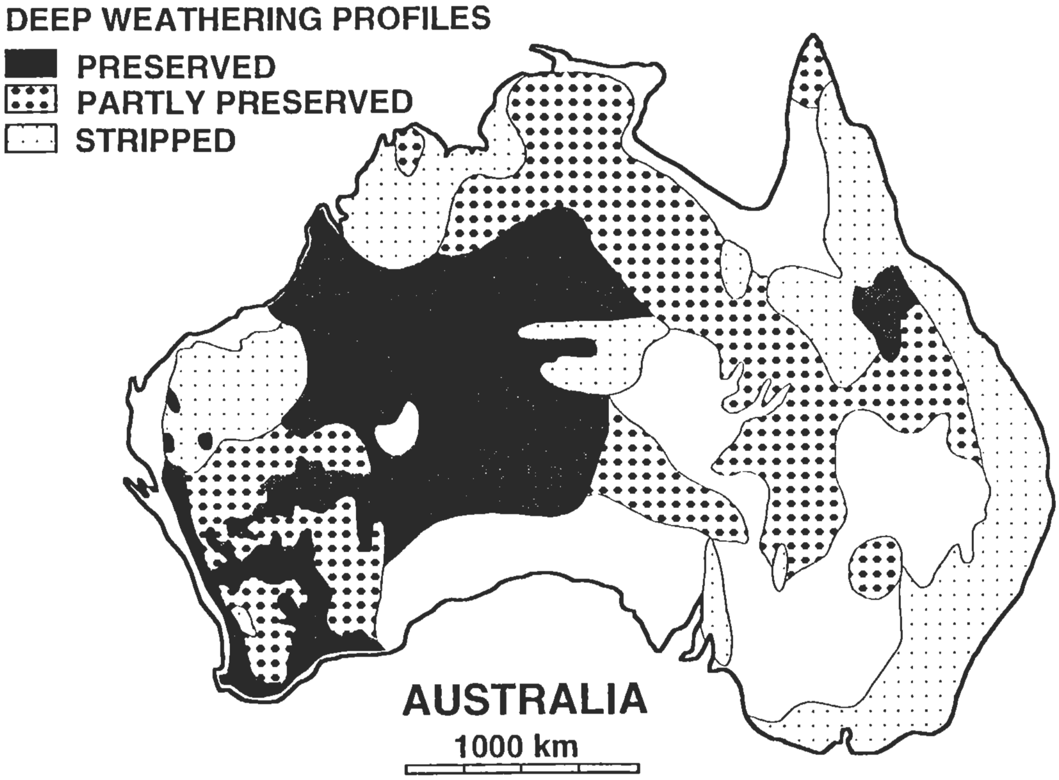

Fig. 2. The distribution of deep weathering profiles in Australia, after Woodall (1981).

Surface Deposits

Hunt was an American interested in the geology of soils. He produced a small-scale map of surface deposits of the United States that included various kinds of surface deposits, and three categories of weathered rock (Hunt, 1967). This is perhaps the nearest thing to a regolith map of the United States.

The inclusion of surficial sediments in regolith means that some maps, such as maps of flood plains, have been with us since the early days of geomorphology. An example is the Geomorphic Map of the Riverine Plains (Butler *et al.*, 1973).

Drift Maps

Maps of glacial and periglacial deposits are a specific type of regolith or geomorphic map that have been around a long time. In Britain the bedrock geology is obscured in many areas by regolith, much of which is glacial 'drift', and the Geological Survey produced maps of both solid geology and 'drift maps.' The drift was not only glacial, but any surficial material. However, there was no interest in deep weathering, and drift maps are only part way to being regolith maps.

Soil Maps

Soil maps usually only show the top metre or so of material, and if the maps are based on conventional soil profiles they may be somewhat limited. In Britain the concept of the Soil Series was used. These were more 'natural' units, and often reflected genuine regolith units. In the Chalk country of the Chiltern Hills, the distribution of soil series really brought out the distribution of regolith - Plateau drift, hillslope creep materials, footslope debris, decalcified footslope debris and alluvium, and enabled some detailed geomorphic interpretations to be made (Ollier and Thomasson, 1957). The Batcombe Soil Series, for instance, was not simply a soil, but had a profile consisting of Tertiary sedimentary clay with rolled flints (Reading Beds), underlain by a decimetres-thick layer of clay with unrolled flints derived from Chalk solution beneath the Reading Beds, with an addition at the surface of Quaternary windblown silt (brickearth), the whole bearing a brown earth type of soil.

In Scotland the concept of soil association was used. Although based on soil hydrology, the mapped units were significant regolith units. In some areas the soil boundaries were roughly like the geological boundaries but about 2 km further south, indicating the average movement of glacial bedload.

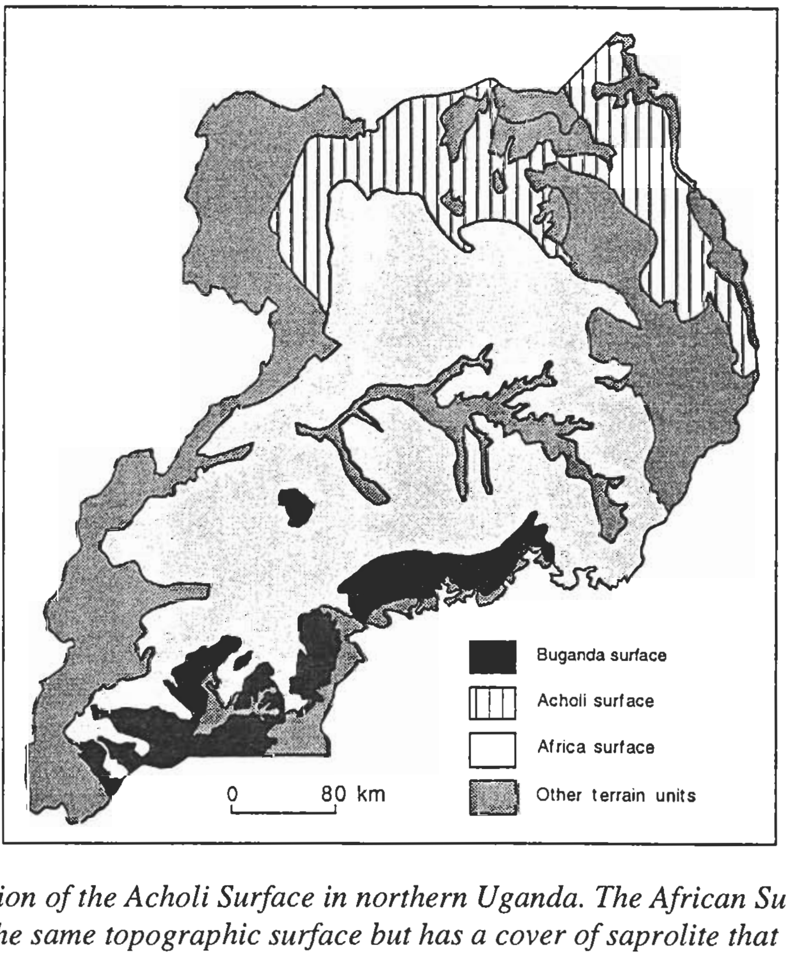

Fig. 3. The location of the Acholi Surface in northern Uganda. The African Surface to the south is the same topographic surface but has a cover of saprolite that has been stripped from the Acholi Surface. A few "pendants" of saprolite occur within the Acholi Surface. (after Ollier, 1992).

In Uganda a reconnaissance soil map was prepared in the years 1956-60. The soils were mainly variants of tropical red earths, but the soil maps could be simplified into "geomorphic maps" which purported to show `erosion surfaces.' In reality, in northern Uganda the map separated those areas with deep saprolite from those with soils formed on fresh bedrock (Fig. 3). The significance of old saprolite was recognised at the time: "The African surface is largely cut across rotted or pre-weathered rock, and such areas are shown on the geomorphic map. The so-called Acholi surface is cut across fresh rock. The two surfaces are not separated by any fundamental change in base level, and there is no erosion scarp between them, and it is probable that they are parts of one and the same erosion surface; the Acholi being part of the African surface where all the regolith has been stripped off by erosion. As the presence or absence of a regolith is of fundamental importance to soil formation the term Acholi surface has been retained as a useful name for the lowest parts of the African surface."(Ollier, 1959, p 2.). The story of the regolith map was published in more accessible form in the *Israeli Journal of Earth Science* (Ollier, 1992).

The Soils Atlas of Australia is another regolith map disguised as a soil map: it is described later.

Geomorphology Maps

Geomorphologists have concentrated on landform in their maps, which is right and proper in view of the etymology. A few have included aspects of weathering, but generally only in passing. In areas of glacial deposition some geomorphology maps are regolith maps in the sense that they depict surficial deposits.

Hays (1967) produced a map of erosion surfaces in the Northern Territory, which, in conjunction with his text that described the regolith in some detail, came close to a small scale regolith map. In the same book (Mulcahy, 1967) published a map of soils and land surfaces in part of Western Australia, which was based on an earlier survey by Mulcahy and Kingston (1961), again very close to a regolith map.

Duricrust Maps

Duricrusts have attracted attention quite disproportionate to their area, or perhaps importance, and maps purporting to show the distribution of laterite and silcrete have been around for a long time. Prescott and Pendleton (1952) presented a laterite map for Australia and Litchfield and Mabbutt (1962) a silcrete map (Fig. 4). Mabbutt (1974) produced a map of silcrete and laterite cappings; as did Dury (1968) and Stephens (1971; Fig. 5); Twidale (1983); Twidale and Campbell (1995; Fig. 6), and others. Many duricrust maps were devised to illustrate a theory - most often an alleged relationship to some climatic parameter such as the 10 inch isohyet. The maps are all quite wrong, and silcretes are now known in Victoria, eastern New South Wales and Queensland - well outside the areas indicated on the 'distribution' maps.

Terrain Classification

Some terrain classification maps also come close to being regolith maps. Terrain classification arose after the second world war in various guises. As Mabbut wrote in 1968: "Tired of fitting boundaries which did not exist around areas which did not matter, regional geographers abandoned the search for the elusive 'natural region' and sought real objects of study in distinctive parts of the observed environment."

The basic idea is that there are areas (mapping units, land systems) with repetitive landscape units that differ from other areas with their own, different repetitive landforms. When the land

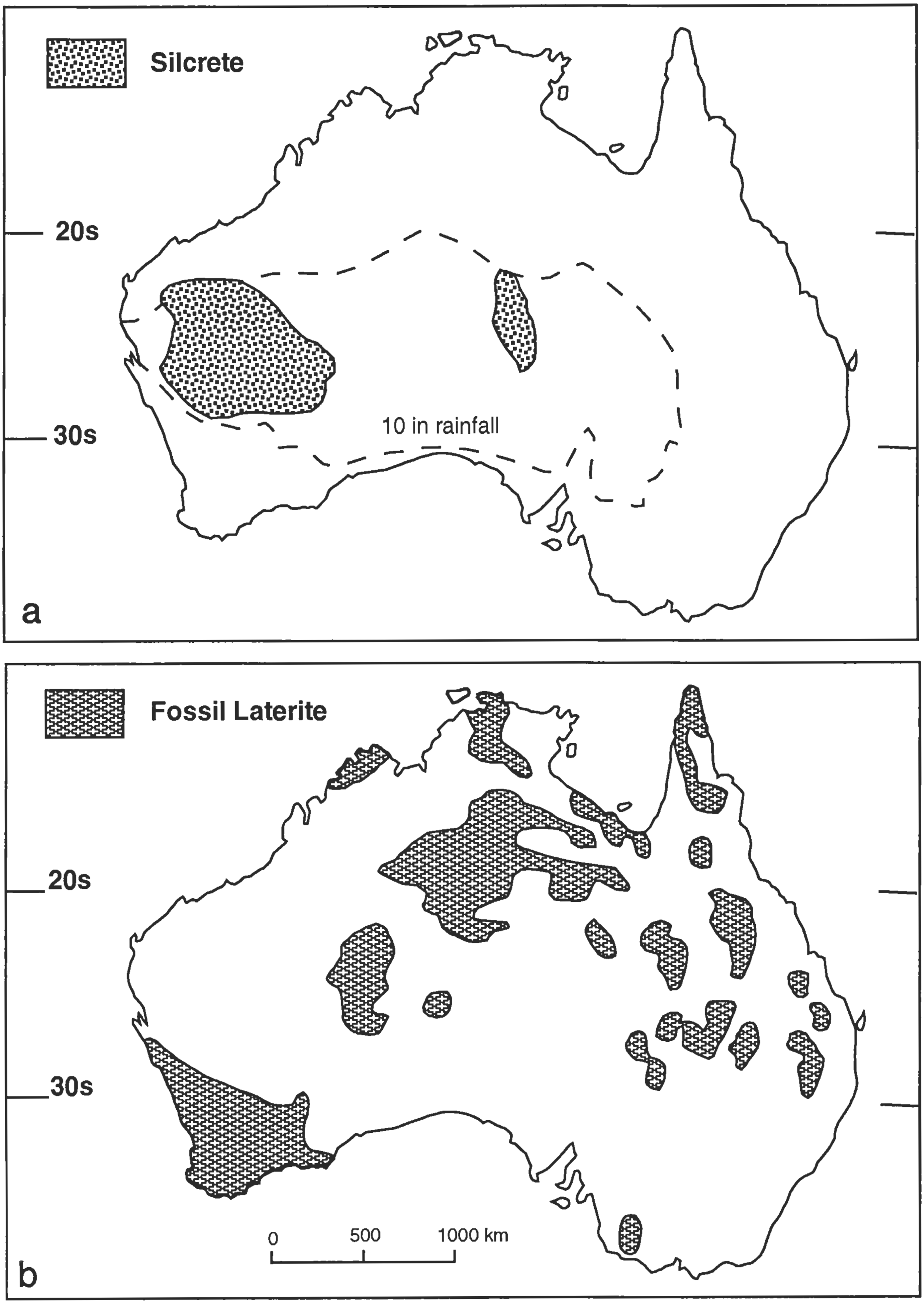

Fig. 4. The distribution of silcrete (a) (after Litchfield and Mabbutt, 1962) and ferricrete/laterite (b) (after Prescott and Pendleton, 1952). According to Cruickshank (1972) "The distributions are partly complimentary, indicating different formative conditions on opposite sides of the present 10 in (250 mm) isohyet."

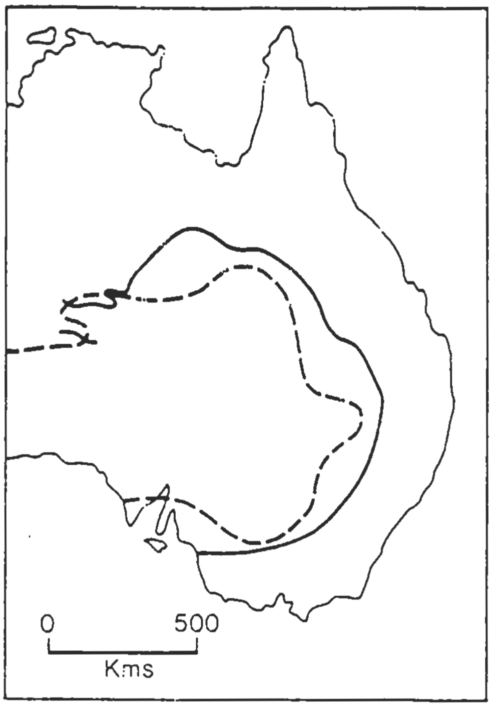

Fig. 5. The distribution of ferricrete (outside) and silcrete (inside) after Dury, 1968 (solid line) and Stephens, 1971 (dashed line)

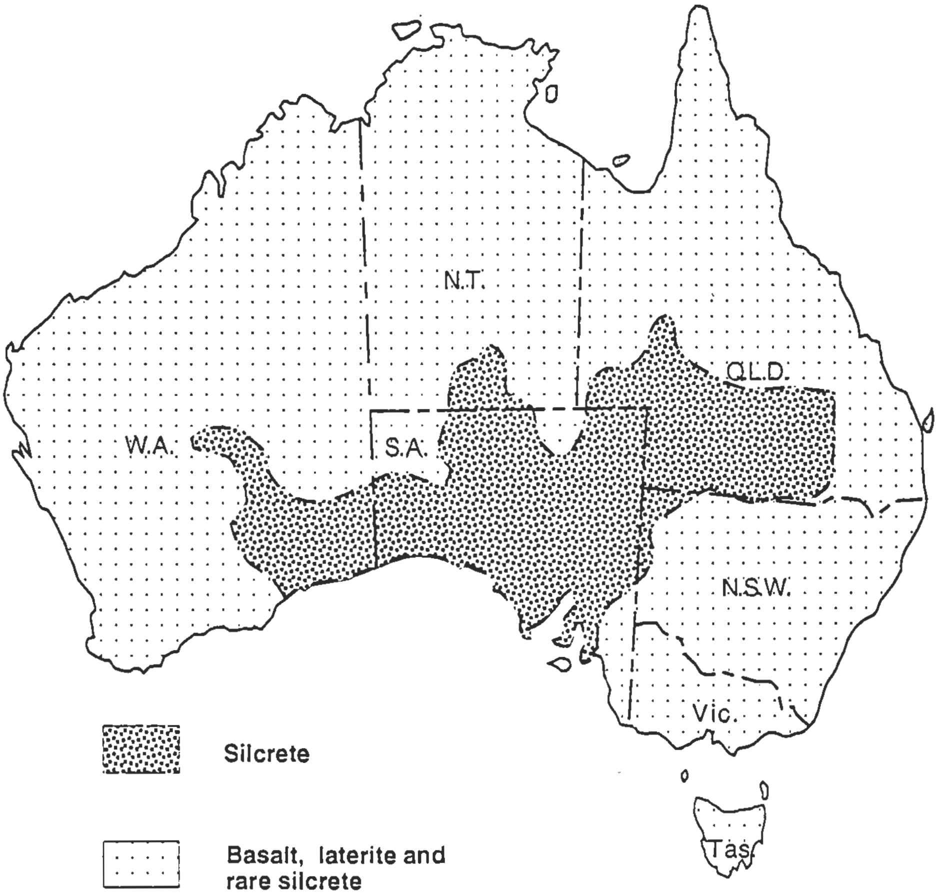

Fig. 6. The distribution of silcrete and ferricrete according to Twidale and Campbell (1995).

was subdivided, each land system (terminology varies) was described in terms of topography, vegetation, soils, and so on, and incidentally the regolith was often included. The first CSIRO Land Research maps were on the way to being regolith maps. The method was used by others, in many parts of the world, summarised by Ollier (1977). In Nigeria terrain maps were made for road making and other engineering purposes (Dowling, 1968). In Britain the lead was taken by the military who wanted "going maps" - essentially maps that showed where you could go with infantry, tanks, camels or whatever - which could be prepared for enemy territory, in advance (from air photos at the time). Again these maps showed a lot of topography, vegetation and other features, but inevitably described the geology and soils, and became a sort of surrogate regolith map.

The British system, known as the Oxford/MEXE System, was tried out in Uganda, Swaziland, and part of Kenya. The Uganda map (Ollier *et al.*, 1969) proved to be potentially very useful. Had it preceded the Soil Survey of Uganda instead of coming years later it could have made the Soil Survey quicker, cheaper and more accurate. It also provided a better objective base map for geomorphology map when compared with a straightforward geomorphology map (De Swart and Trendall, 1970).

The terrain classification approach was adopted by the BMR for its first maps. These included:
The Hamilton Regolith Map at 1:1 000 000 (Ollier and Joyce, 1986);
The Regolith Map of Australia at 1: 5 000 000 (Chan *et al.*, 1986);
The Kalgoorlie Regolith Map at 1:1 000 000. (Chan *et al.*, 1992).

It was, of course, premature to try to make a map of the regolith of all Australia, but there is a basic tenet amongst surveyors - "Always work from the whole to the part." and it was thought that an overview, however skimpy, would help to relate later work in different parts of the country. This would overcome the problem of the CSIRO Land Research maps, which were scattered here and there but had no relationship to each other.

This situation contrasts with Papua New Guinea, where the Land System mapping was completed for the whole country. It provides a superb basic document for research into regolith or geomorphology. Unfortunately the documentation that goes with the maps is not especially helpful, and it is best to use these maps in conjunction with the book by Loffler (1979).

Other people were also mapping regolith in Australia. Victoria led the way. The Soil Conservation Authority of Victoria produced a series of volumes on terrain classification in various parts of the state (e.g. Gibbons and Downes, 1964). Some of the work was published in learned journals, such as the paper by Gibbons and Gill (1964) who proposed units still used much later in the BMR Regolith Map of the Hamilton Sheet (Ollier and Joyce, 1986). The CSIRO Division of Applied Geomechanics also produced a series of volumes on terrain classification of specific areas (e.g. Grant, 1972). They had an engineering approach, and when they described 'soil' they were not thinking of pedological or agricultural soil. A typical description might be: "Duplex light grey clay over silt to 10 in, over yellow heavy-textured clay, over decomposed rock at variable depth." Generally they worked on a detailed scale, but they also produced a map of all Australia at 1:2 500 000 (Grant *et al.*, 1984). This used a great soil group classification of soils (e.g. podzols, soloths, but also alluvial soils, siliceous sands) and also had a class of Superficial Lithology which included duricrusts and sand dunes.

The Soils Atlas of Australia (Northcote, 1968) is essentially a terrain classification map, and a very good one too. By a complex system of keys you can find the soil at a given place (in the

Northcote Classification), but it is also possible to get a rough idea of the topography and regolith for each unit. Much of this information was used in the BMR Regolith Map of Australia.

Much more detailed maps are desirable for specific purposes. In particular engineers want details for foundations and other structural information, and mineral explorers want to home in on their targets. There is here a conflict: you need a regolith map to give an overview, but detailed site investigation for a specific damsite, tunnel, gold prospect or mine. If you concentrate all your work on specific sites you can cover little territory, so a decision has to be made on just what is required. In general small companies will work on detailed scales; government agencies (and major companies that want to cover a lot of ground) will work on small scales. CSIRO Division of Exploration and Mining, getting much of its funding from mining companies, works on small areas, but the information remains in private hands. On the other hand, AGSO in the National Geoscience Mapping Accord, works on large areas, but the work is ultimately published.

A very interesting series of terrain classification maps are produced on large scales in Hong Kong, basically for geotechnical purposes associated with engineering in this densely populated area, but allied to excellent regolith studies, so these are close to being regolith maps.

The Impact of Theory on Mapping

Theory has a very significant impact on regolith maps, though it is usually more implicit than specifically stated. One set of theories comes from climate, and the usually unstated idea that soils and regolith are in equilibrium with the present climate. In Prescott's early soil maps of Western Australia he used rainfall patterns as surrogate boundaries for soil types. These diagonal boundaries in the Perth corner of the State are lingering on still. I once asked C.G. Stephens why such boundaries still appeared on his soil map, though he knew it was inaccurate. He replied that they were 'political boundaries' (meaning that Prescott was still the boss!).

Another neat example comes from volcanic Western Samoa (Fig. 7). A soil map had been made by Wright (1963) who assumed that climate controlled soil types and his 'soil map' had boundaries that followed rainfall (assuming further that rainfall followed altitude). A later survey based in the first place on terrain classification, showed that the age of the lava flow was the dominant factor, not climate (Ollier, 1988). The regolith/soil divisions were very simple. On the youngest lava flows a bushknife could make a ringing note as it hit the rock; on middle-aged flows a bushknife could penetrate about 20 cm; on older flows a bushknife could be plunged to the hilt in the stone-free deeply weathered basalt.

Geomorphic theory also has its place. Throughout much of this century geomorphology has been based on the idea of cycles, with successive erosion surfaces. Davisian peneplains are all that most geologists have ever heard of, but the successive pediplains of Lester King are also widely known amongst geomorphologists. Some workers, such as Wooldridge and Linton (1939) in England, mapped specific erosion surfaces and examined their regolith, giving some factual authority to the concept. They recognised a Plio-Pleistocene marine platform on the dipslope of the Chalk, and identified deposits by mineralogy, gravels, and fossils. Detailed re-examination of the same area cast grave doubts on that interpretation (Moffat *et al.*, 1986). In similar style, Sparks (1949) found a whole suite of surfaces on the South Downs of southern England. Naturally the older surfaces should bear a more weathered regolith than younger ones. Unfortunately, later workers (Hodgson *et al.*, 1974) who studied the regolith in detail

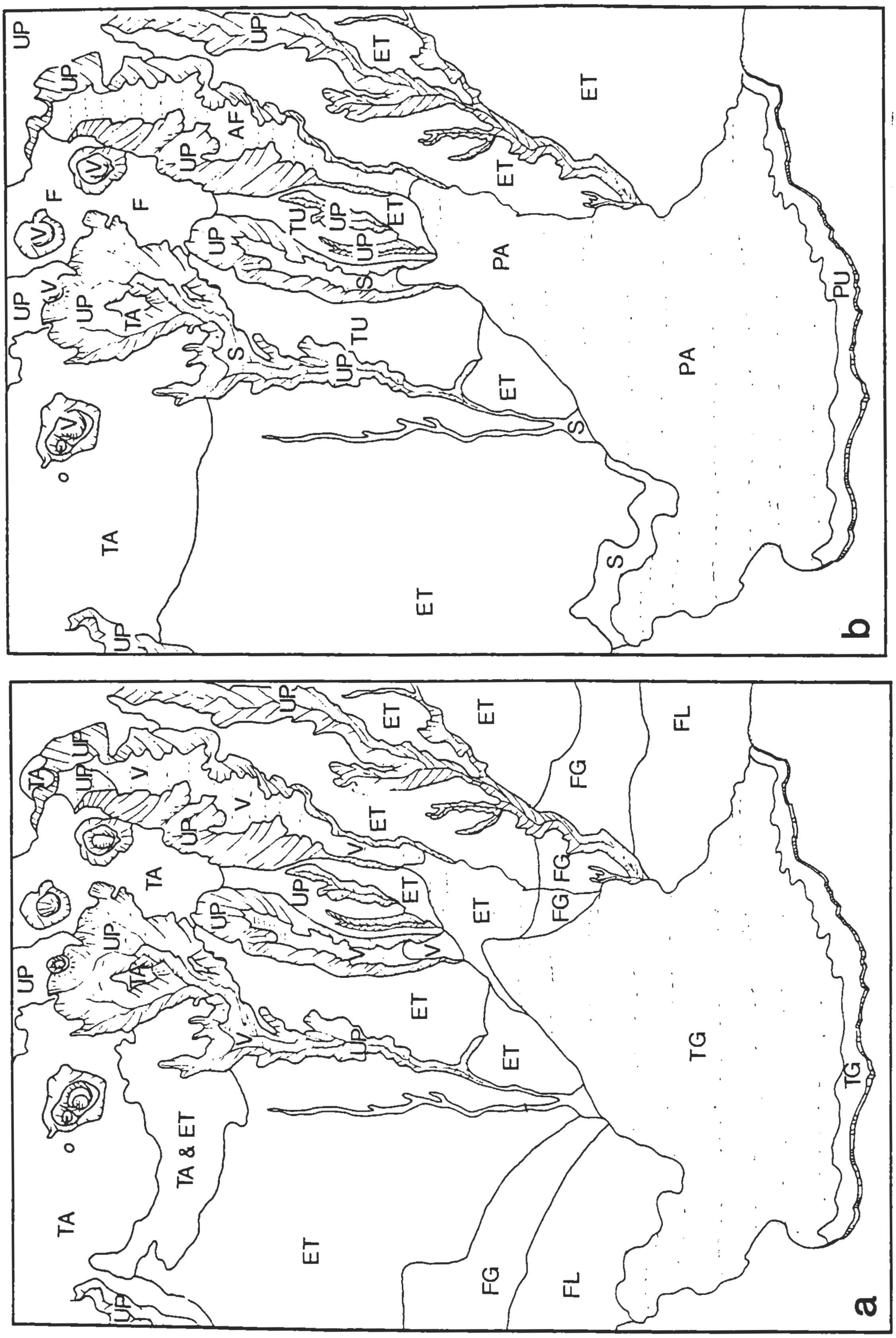

Fig. 7. A soil map of part of Western Samoa by Wright, 1963 (a), with climatic boundaries acting as surrogate soil boundaries, and by Ollier, 1988 (b) based on terrain classification and field checking.

found it was not so, and even the surfaces themselves proved spurious. The re-assessment arose from the regolith work of the Soil Survey of Great Britain.

In Western Australia the first systematic account of the physiography (geomorphology) was given by Jutson (1914). He envisaged an ancient peneplain (the Old Plateau) which was covered in laterite - a deep weathered profile with an ironstone (ferricrete) crust. This was dissected by valleys which then widened to form a Young or New Plateau, leaving only remnants of the Old Plateau (Fig. 8). The model was continued by Mabbutt (1974; 1988) and no doubt goes on to the present day. It is the basis of the RED (residual, erosional, depositional) scheme of regolith mapping used by CSIRO Division of Exploration and Mining,

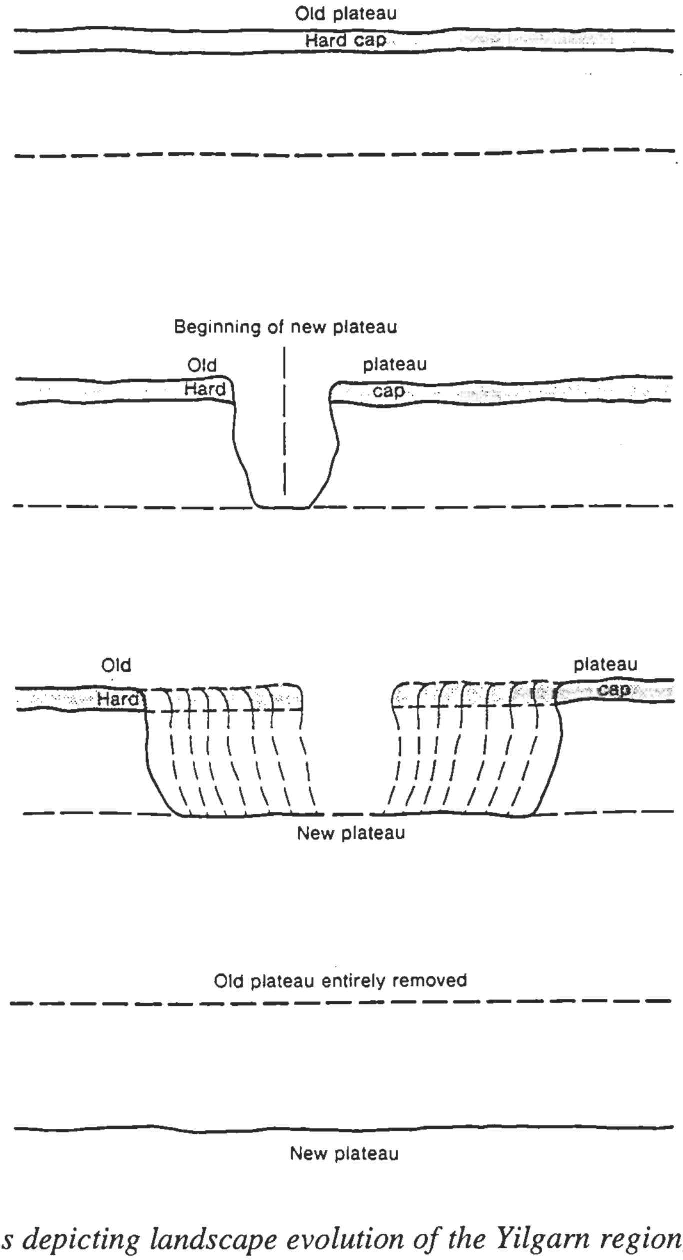

Fig. 8. Cross sections depicting landscape evolution of the Yilgarn region, Western Australia, according to Jutson (1914). This implies (1) formation of the "old plateau" and development of a "hard cap" (ferricrete) across the entire landscape. (2) incision of valleys (apparently to the base of the saprolite). (3) valley widening (or scarp retreat) to the level of a "new plateau" leaving remnants of the "old plateau" as duricrusted hills in the present landscape.

the residual corresponding to the old plateau, the erosional to the slopes, and depositional to those parts covered in younger sediments. Formally the three 'regimes' are defined as follows (Craig, 1993):

> *Residual Regimes*
>
> Residual regimes are mappable areas characterised by widespread preservation of lateritic residuum. Conceptually, they are relics of an ancient weathered land surface.
>
> *Erosional Regimes*
>
> Erosional regimes are characterised by erosion and removal of the lateritic residuum to a level where the mottled zone, clay zone, saprolite, or fresh bedrock are either exposed, concealed beneath soil, or beneath thin locally-derived, associated sediments.
>
> *Depositional regimes*
>
> These regimes are characterised by widespread sediments which can be many metres thick. The boundary between residual and depositional regimes can be gradational or sharp. The substrate can range from stripped surfaces to complete weathering profiles.

The definition of the Erosional Regime in particular conveys the idea that the entire landscape was once covered in laterite, as in the Jutson model. In the Kalgoorlie region the BMR mapping suggested an alternative hypothesis of inversion of relief, and the "old plateaus" are interpreted as old valley floors. In fact it is doubtful if there was ever enough iron to form a sheet of ferricrete across the entire landscape, but if iron is concentrated in drainage lines - perhaps five percent of the landscape - there is no problem.

The same story has been found in North Queensland on the Cape York Peninsula (Pain and Ollier, 1992), and the Charters Towers region provides a modern example. Rivers and Eggleton (1994) wrote that "The older (Tertiary?) ferricretes have developed *in situ* on the granodiorite." but Henderson and Nind (1994) wrote of the Charters Towers region "Deep weathering is ubiquitous and ferricrete duricrust is commonly developed in its upper horizons. The upland association of the formation is the product of topographic inversion resulting from the duricrust development."

Another, classic example of inversion of relief is at Robe River, Western Australia, a huge economic iron ore deposit. This points out another problem encountered in regolith mapping - the tendency to map a specific attribute rather than all the regolith. There are many maps of the iron ore deposits, but little attempt to map the regional regolith.

Some confusion occurs because of the distinction between soil and regolith. In some areas there is a simple story of soil formation on fresh rock; in others there is inheritance of deep weathered profiles from former times, and saprolite, not fresh rock, is the parent material. In the Ballarat area there is hardly any exposure of fresh rock (Ollier and Joyce, 1986), and in east Gippsland there is extensive deep weathering, even on steep slopes. In contrast, on the Monaro Plateau, despite prolonged erosional stability and a parent material of basalt, the soils are thin and related to the present conditions (Pillans and Walker, 1995). No geomorphic theory that I know of could predict these distributions, which demonstrate the importance of field observation.

Partial, Surrogate and Real Maps

Mapping regolith is difficult because it cannot be seen without digging it all up. So how can it be mapped? As we have seen, some maps devised for other purposes are partial regolith maps.

Soil maps at a small scale may be regolith maps if there is no inherited deep weathering, or if the soil surveyors have genuinely concerned themselves with the total weathering/soil profile. Terrain classification maps may also be regolith maps.

Alternatively, soil may be mapped as a surrogate for regolith, and it gives lots of clues. So does topography, but topography alone is a poor surrogate map. Workers with a strong biological or ecological bent often use vegetation as a surrogate for regolith mapping. This is generally dubious, even positively misleading, in my experience, especially if the mapping is done using remote sensing. Basically most remote sensing sees the top few microns of what is beneath. You may see the tree canopy, but if that is penetrated there is bush, grass, or moss to reflect and it is rare to see the earth at all. That is why the success stories of remote sensing come from Death Valley and the Simpson Desert. Only radiometrics really 'sees' through vegetation and into the top metre of regolith. Lastly there are various 'black-box' techniques for making surrogate regolith maps. I have yet to be convinced that they have anything to offer. At the moment regolith mapping is more an art than a science, but in view of the real advances that have been made over the past fifty years I think a generation of 'real' regolith maps is close.

One thing that has held back regolith mapping so far is the fact that the maps are hard to interpret. We should remember that a geology student probably spends a year learning the basics of interpreting geology maps, a geomorphologist can spend a long time learning how to interpret contour maps properly, but people still expect to understand a regolith map on first inspection. For 'real' regolith maps it is probably advisable to have a "How To Use This Map" box included on the map, or a chapter on the same in the accompanying account.

The Need for Mapping

"During the Second Australian Conference in Soil Science held in Melbourne in August 1957 it was stressed that the collection of systematic information about the various geomorphic features of the continent would contribute greatly to the understanding of the origin and development of Australian soils and thereby facilitate their mapping and help to explain their fertility characteristics." This quote from a Symposium held in Adelaide in 1961 was, I think, the first clear call for geomorphic maps of Australia. At the Symposium, E.S. Hills (1962) said "In the long run, the results of your work will be expressed in cartographic form. We are certainly very far from being able to show soils, geomorphology, Quaternary geology and current earth movement on maps, even for southeast. Australia where a good deal of work has been done. But it is clear that a beginning should be made, and I do hope that out of this symposium may come suggestions for the preparation of such maps." It seems to me that a beginning has been made and we now hope for a successful continuation.

Mapping regolith is difficult, because most of it cannot be seen. Furthermore there may be disagreement on what is seen even when it is exposed. The interpretation usually depends upon a burden of prior knowledge and theoretical concepts. Even if you know what you are mapping there are problems of scale. Above all there is the problem of purpose - who is going to use the map and for what end? For these, and other reasons the history of regolith mapping has been a stuttering and unsatisfactory affair. But I believe it is now showing its value in such diverse fields as mineral exploration, highway engineering, hydrology and soil erosion control that it must consolidate.

In the past a great deal of regolith research has concentrated on the study of single profiles, or on sections, or on catenas. A full three-dimensional approach has been generally lacking, but will be provided by regolith maps. We can expect that a burgeoning of regolith mapping will lead to greater understanding and new concepts. As the great geologist Lapworth wrote: "Map it, and it will all come out right."

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Regolith Mapping: What Do We Think We Are Doing? (and are We Really Doing It?)

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Introduction

The origins of regolith mapping largely come from an incorporation of many different approaches to representing the distribution of the Earth's surface and near surface features and materials. Approaches to mapping in these related fields have a long history of development, however regolith mapping (*sensu stricto*) is a relatively recent development and as a result many of its conceptual approaches are still being developed. This paper will raise some questions concerning the development of regolith mapping strategies and philosophies and as a result issues such as mapping constraints and surrogacy as well as circular arguments, assumptions and subjectivity will be identified and discussed. These issues need to be appreciated when either compiling or utilising regolith maps.

What Are We Trying To Do?

Regolith mapping is generally concerned with representing the distribution and location of the mantle of materials, including weathered rocks, sediments and soils, altered or formed by land surface processes (the mantle of material overlying the bedrock). This involves more than just adding detail to the Cainozoic, or even the "yellow shaded" and "soft rock" areas of geological maps, and requires a specific approach and philosophy to its mapping.

A number of different regolith maps and mapping schemes can be applied to regolith mapping projects. Many of these schemes are designed for specific purposes and therefore may not always be generally applicable, however a scheme that fulfils most general needs should have the following features:

(i) *Flexibility and robustness* - allowing for application in a variety of terrain and regolith types.

(ii) *Simplicity and clarity* - it is important that the map is readily interpretable, and this is often dependent upon the production of a logical and easy to comprehend presentation scheme.

(iii) *Scale independence* - the scheme should be able to be used at a variety of scales, allowing for the ready transfer of information from one scale to another.

(iv) *Time independence* - regolith materials cover a broad age span, so therefore age specific limitations should not restrict the use of the scheme. This may be a limiting factor for mapping philosophies developed in regions dominated by a specific age of regolith, such as in a Quaternary landscape (e.g. Thornbury, 1954, p. 26, and the limitations of his "Concept 6", when applied to areas of more ancient regolith).

(v) *3-dimensional representation* - the distribution of regolith materials and features varies both in the horizontal and also the vertical dimensions. Ideally a regolith map should give some feel for this.

(vi) *Compatibility with special purpose maps* - regolith maps may be utilised for a variety of objectives in a variety of fields. The regolith mapping schemes and maps must be compatible with these.

In reality a number of different regolith maps and mapping schemes can be applied to regolith mapping projects. Many of these schemes have strengths and weaknesses, often dependent upon the requirements and specific purposes of the work, and they may not always be generally applicable. Regolith mappers therefore need to determine whether the scheme they are going to use fulfils their needs.

More specific requirements and map types may be related to many different applications, including:

- mineral exploration;
- land use;
- landscape research;
- hydrology;
- ecology;
- soil sciences;
- engineering;
- military.

Regolith mapping has the potential to provide general landscape information as well as information for specific fields of interest. The development of these maps to provide information about a wide range of features and also to cater to a wide user base is one of the great strengths of regolith mapping, however it is a very large task and in reality frequently encounters various constraints. Some of the constraints and issues that require consideration are outlined in the following discussion.

What Do We Actually Do?

Do all regolith maps really represent the distribution and location of the mantle of materials overlying the bedrock?

Regolith mapping projects and the nature of the map produced may be influenced and constrained by a variety of things including time, money, as well as the general mapping philosophies and concepts. Constraints relating to regolith mapping philosophy and concepts include: the scale of mapping, surrogacy employed in mapping, subjectivity and inbuilt genetic connotations. These constraints may not necessarily be detrimental, however their presence and influence should be appreciated when compiling and using regolith maps.

Scale of Mapping

There have been various approaches to regolith mapping related to scale. It is important to decide from the outset whether the map information needs to be represented in detail or as a broad regional view. For instance an alluvial fan may be considered as a single unit in the regional context or as a series of smaller lobes and associated depositional facies on a detailed scale. There is also a limit to the amount of information that can be shown on a map face, therefore mapping units at regional scales tend to be more general and have more internal variation than units shown at more detailed scales. For a given map scale, units that are narrower than about 3 mm on the map cannot be easily read.

Cartographic precision will also vary with map scale. For example, a 0.3 mm line thickness at 1 : 100,000 scale is equivalent to 30 m on the ground. This distance will be more significant for smaller scale maps, and highlights a potential problem with using regional scale maps for local scale applications. Related to this is the problem of distinguishing between gradual and sharp unit boundaries in a detailed scale map presentation. In the case of gradual unit boundaries a dividing line often represents the site of intermediate characteristics or where maximum change occurs. Some boundaries may be difficult to precisely ascertain in the field and map users need be aware of the criteria used for developing map polygon boundaries. Consistent use of particular criteria is important and an hierarchy of polygon boundary lines to represent the differences in boundary precision may help alleviate some of these problems (i.e. the use of solid, dashed and dotted lines).

Internal variation within mapped regolith unit polygons will usually be greater for regional scale maps than for detailed maps. At regional scales either the dominant regolith type or a characteristic assemblage of regolith types is shown. Regional scale mapping also tends to employ a greater level of surrogacy than detailed scale mapping.

Surrogacy

Surrogacy, in the context of regolith mapping, is the employment of a mappable feature the distribution of which can be related to the regolith features that we intend to map. It may be employed at various scales and different types of surrogacy may be used, even within a single hierarchical level of classification. Different types of surrogacy used in regolith mapping include: landsurface morphology (geomorphology and landforms), lithology (materials), geology, chronology, soils, remotely sensed features and vegetation.

It is important to remember that with surrogacy we are indirectly mapping the regolith. The success of a particular surrogate is dependent upon how well the relationship between the regolith and the surrogate is known. This usually requires some detailed investigation of this relationship at selected sites within the mapping area. Extrapolating from one area to another without investigating the relationship of the surrogate to the regolith in different areas is potentially dangerous. For example in one terrain ferruginous duricrusts may be intimately associated with mesas however that does not mean that mesas in another region will necessarily correspond with ferruginous duricrusts. This highlights the need to critically test the value of surrogates for regolith mapping on an area to area basis, before they are put to use.

An appreciation of the type of surrogate used is also important when making correlations between regolith map polygons and the distribution of other features in an area. Without this appreciation there is a danger of becoming locked in circular arguments where the distribution of regolith features may only be found to correlate with the surrogate that was used to map the regolith in the first instance. Examples include correlations between regolith and possible surrogates such as vegetation and geology. There is also the danger of correlating regolith distribution with another feature that was mapped using the same surrogate. For instance correlations between soils and regolith that have both been mapped using landform as a surrogate, or regolith and geology that have both been mapped using a vegetation surrogate.

Morphological, geomorphological and landform based maps

Land-surface morphology is a traditional surrogate for regolith mapping. Its use relies on the generally intimate relationship between regolith and landforms (not only can the type of regolith influence land-surface morphology, but the land-surface morphology commonly determines the type of regolith that occurs in a given area). Advantages with this surrogate include:

- greater speed and efficiency of mapping than for regolith at every point in the landscape;
- continuos coverage of the landscape by landforms;
- generally good suitability for representing spatial relationships between regolith units;
- the potential to allow extrapolation beyond the study area (although beware of some of the previously discussed dangers).

There are, however potential problems that should be considered:

- the success of the surrogate is dependent upon how well surface morphology correlates with regolith profiles (this relationship usually needs to be established on an area to area basis);
- the surrogate is good for widespread and thin depositional units, but subsurface information is more difficult to consider;
- schemes based on landforms may sometimes be confronted with problems of in-built interpretation, whereby they assign subdivisions and connotations of genesis and/or age (morphogenetic and morphochronological maps).

Landform units are often grouped hierarchically on the basis of genesis. The recognition, emphasis and classification of landforms also commonly involves a degree of subjectivity. This will depend on the compiler's previous experience and also their landscape evolution philosophical standing. One person's etchplain may be another's peneplain or pediplain, depending on their recognition and emphasis of particular genetic processes. Compilations of standard landform classification units, such as those in Speight (1990) and Pain *et al.* (1991) help to overcome this problem, although their success is still dependent to some degree on the user's interpretation.

Lithological and materials based maps

This surrogate is usually less subjective than the others listed here. Unit descriptions are typically based on such features as grain size, type of induration, and colour, although the criteria that may be used is limitless. Lithology can be used to show differences in regolith both horizontally and vertically and may be used in conjunction with other approaches (e.g. regionally mapped morphological features may be subdivided on the basis of constituent materials at the detailed scale). A major limitation with this approach is that it is very time demanding especially at the regional scale. Subjectivity and surrogacy problems may also arise due to specific lithological features being used to delineate regolith mapping units. For example a single feature such as textural properties or chemistry may alone be used as a mapping surrogate.

Geology based maps

The main objective of geological mapping is to represent the surface distribution and geometry of bedrock geology. Geological maps may also directly and indirectly provide some regolith information. Direct information such as the occurrence of significant areas of unconsolidated relatively young deposits or duricrust outcrops are usually rather simplistically presented. Other, more indirect information may include regolith parent materials, sediment provenance and morpho-tectonic features.

Regolith maps, particularly at a regional scale, may use geology as a parent material surrogate. Mapping units classified as "weathered granite", "granitic debris", "deeply weathered basalt flow" are invariably associated with the use of a geological surrogate. It is foreseeable that an unjustified reliance on this approach could present a misleading regolith distribution pattern, where map polygons more closely reflect the underlying geology rather than regolith units in the purest sense. While regolith maps do have a lot of potential for making associations between regolith and bedrock geology, care needs to be taken that such correlations are not entrenched in circular arguments, where regolith mapping units derived from geological surrogates are found to have a perfect correlation with geological maps.

Chronology based maps

These maps define regolith mapping units based on their age. They are most successfully applied to younger depositional units that may be absolutely or relatively dated. Their application to older deposits and deeply weathered and erosional features is more difficult. For instance a polygenetic weathered landsurface that has undergone several periods of weathering and erosion is not only difficult to obtain a single age for, but any age that is obtained is open to many interpretations. There is also the problem of deciding what age the map should represent (e.g. for saprolitic areas, should the map show the age of weathering profile development or of the erosion that defines the landsurface?).

Soil based maps

Soil maps essentially show the pattern of soils in the landscape. Soil mapping units are generally related to variations in parent material, time, climate, topography and living organisms (Ollier, 1984), aspects that also affect regolith development. Thus the soil units will be similar to the polygons on a regolith map. Polygons will also be closely related because regolith is the parent material for many soils. The association between soils (which is usually taken as being the near surface regolith that is influenced by biological activity) and the deeper parts of regolith profiles is usually less diagnostic. The relationships between soil and regolith maps is an area that needs more investigation and is discussed further in other papers in this publication.

Vegetation based maps

Vegetation is frequently used as a regolith surrogate, either directly or indirectly. This surrogate exploits relationships between vegetation and the supporting regolith substrate. The relationships between regolith mapping units and vegetation are discussed further in Hill (1995), although it is stressed that the same cautions that apply to the other surrogates also apply to vegetation.

Remotely sensed features

Remotely sensed features such as patterns, colours and tones derived from aerial photographs, satellite imagery and geophysical responses are a major tool used by regolith mappers to determine entire polygon boundaries or to close mapping polygons where other information is scant. The surrogate nature of this information is frequently overlooked and users need to be cautious about having absolute faith that this data is always showing regolith information in the purest sense. Remotely sensed responses are also frequently a reflection of other regolith surrogates such as vegetation or surface lithology or morphology. The relationship between regolith and its remotely sensed attributes needs to be understood for a given region before the potential advantages of this surrogate can be utilised.

Genetic Models

Genetic models as applied in regolith mapping are usually based upon regolith-landform models. The value of these schemes is therefore dependent upon the model's ability to account for the features of a given area. Many models, are limited in their success, because there is insufficient information available to understand the processes that influence the regolith and associated features such as landforms. Robust models are therefore needed if a mapping approach is to have a suitable genetic basis. In reality these maps are perhaps best considered a means of conveying interpretative results, rather than a source of raw data.

Examples of genetic model schemes include those based on climatic, geomorphological and pedological models, continent scale maps based on plate tectonics theory and the classification of mapping units based on models of landscape evolution. Map compilers and users of these schemes should be cautious of subjectivity in support of a particular model. For example in the Yilgarn Craton of Western Australia the identification of a regionally mapped dendritic lateritic duricrust pattern may be seen as supporting evidence for regolith-landscape models invoking inversion of relief (Ollier *et al.*, 1988). However, critics of this model are unable to map a similar pattern at the local scale (Anand, 1995). This is a concern to users who require a map that objectively shows the distribution of regolith types, and has major implications for the understanding of these landscapes.

The CSIRO/AMIRA's regolith mapping scheme is an example of a genetic-model based scheme. This scheme broadly subdivides regolith into three main types (Anand and Smith, 1993):

- *Residual regimes* - where near complete laterite profiles are preserved;
- *Erosional regimes* - where the lateritic profile is assumed to have been truncated to the level of saprolite/bedrock; and
- *Depositional regimes* - characterised by units of sedimentary origin.

This scheme (generally referred to as the RED scheme) has been developed mainly to serve the practical requirements of mineral exploration programs in lateritic terrains, such as the Yilgarn Craton of Western Australia. The underlying genetic model here is one of a former deeply weathered landscape covered with a lateritic duricrust, that has since undergone erosion and subsequent deposition in some areas.

This model may appear to be satisfactory for the requirements of the mineral exploration industry although it also raises many questions about the widespread validity of the underlying regolith-landscape model. For instance:

- Is it valid to assume that "erosional" regimes were formerly covered by a lateritic duricrust that has since been removed (i.e. was the lateritic duricrust a single continuous cover)? This argument is often based on negative evidence, and in most cases is a gross over-simplification. It is probable that many erosional areas never had a lateritic duricrust cover.
- What about the possible existence of "residual" landscape features that are comprised of materials other than lateritic duricrust?

- How applicable is the scheme to polygenetic, diachronous, laterally variable and reworked lateritic material? For example lateritic duricrust developed in transported material may have attributes that are similar to both depositional and residual regimes (the induration may be consistent with residual regimes, whereas the framework material is essentially depositional, and is actually derived from former landscape materials).
- How applicable is the scheme to non-lateritic terrains? The scheme was developed for the Yilgarn Craton, but is this landscape and its evolutionary models similar to landscapes elsewhere?

The success of the RED scheme in assisting exploration programs and discovering concealed ore bodies in deeply weathered terrains is most likely due to its inherent mapping of the regolith material types, rather than the classification of this material according to regimes within this regolith-landscape model. Parts of the model are likely to be applicable to some parts of other landscapes. However, many other areas may not be this way. The long-term and widespread success of this scheme will be dependent upon how well it is able to deal with many of the issues discussed here.

Where Does This Leave Us?

Hopefully this discussion has left us in a position where we can ask meaningful questions and make better assessments of approaches to regolith mapping. This should reduce the possible disappointment resulting from having false expectations of what regolith maps are showing. An important point to consider is whether or not what is called a "regolith map" is in reality showing us regolith information in the purest sense. As has been discussed, many "regolith maps" may be more closely related to mapping surrogates or derivative mapping philosophies. By considering many of these issues better interpretations and assessments can be made of the features shown in regolith maps. It is hoped that regolith mapping schemes are able to develop to the point where they can satisfactorily deal with many of these issues and maybe even come to a universal or at least compatible and communicable approach to mapping the regolith.

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New Developments in Regolith Mapping:
The Bathurst Experience

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Recent regolith-landform mapping of the Bathurst 1:250 000 sheet area in central eastern NSW by AGSO's Division of Regional Geology and Minerals has provided some helpful insights into new developments in regolith mapping.

The resultant Bathurst Regolith Maps Portfolio is a product of the National Geoscience Mapping Accord. It consists of six 1:100 000 scale preliminary hardcopy regolith-landform maps and digital geographic information system (GIS) data sets (ArcInfo 7 coverage), and two 1:250 000 scale preliminary hardcopy maps (a regolith-landforms map, and a derivative landforms map). Figures 1, 2 and 3 show portions of these products. RTMAP, an Oracle database, will store field site data and mapping unit attribute data and be linked to the GIS.

Relevant Mapping Tools

These maps present a systematic analysis and interpretation of 1:89 000 scale RC9 aerial photography, 1:100 000 scale topographic maps (Australian Land Information Group), and field mapping data. High resolution (250 m line spacing) airborne gamma-ray spectrometry and magnetics (Geoterrex Pty Ltd) were used where applicable.

Photo interpretation was the prime method of defining mapping unit boundaries, thereby retaining consistency in the landform mapping approach. The palate of other useful mapping tools is area dependant. In the Bathurst region widespread cultural influences (e.g. farming, forestry, urbanisation, lakes) effectively negate geobotanical signatures in most areas, other than the most rugged parts. Landsat Thematic Mapper imagery is thus of little use. Airborne magnetic imagery was useful in identifying lava flows and vents. Fieldwork was an essential component in defining various imagery signatures, and in characterising the regolith toposequences for each regolith-landform mapping unit.

Gamma-ray spectrometric imagery was of limited use for regolith-landform mapping in the Bathurst region. Erosional landforms predominate and in areas where the rate of erosion exceeds the rate of weathering the imagery reflects mainly the variable bedrock lithologies. This effectively masks regolith-landform commonality across lithologies, and often swamps regolith-landform variability within lithologies. There is a better correlation between regolith-landform units and the gamma-ray spectrometric depiction of the more weatherable granites that form erosion bowls (e.g. Bathurst Granite) than with the regional sedimentary and volcanic bedrocks.

In areas of deep weathering where the rate of weathering exceeds the rate of erosion, highly weathered *in situ* and transported regolith is commonly associated with ferruginous clay hardpans. The resulting strong and ubiquitous uranium signal swamps internal differentiation of regolith-landform units.

In depositional areas in the west of the Bathurst region, gamma-ray spectrometric imagery was of use in delineating regolith changes on subtle relief with low regolith visibility, and in determining the provenance of sediments, especially where the signal of the sediments contrasted with that of the surrounding regolith. High level sediments were recognised and delineated by the gamma-ray spectrometric imagery: quartzose sediments were low in potassium, uranium, thorium; and ferruginous sediments gave a strong uranium signal.

Gamma-ray spectrometric imagery was also useful in depicting volcanic areas, especially when used in conjunction with airborne magnetic imagery to delineate lava flows. These lava flows commonly occur as sinuous lava plateaus which have been inverted in relief; the less weathered flows have a signal which is low in all three channels, whereas the more weathered flows have a high thorium signal. Similarly, the extensively weathered lava plains south of Orange, which are generally clayey and swampy, have a high thorium signal interrupted in places by a signal low in all three channels where the lava is less weathered. It should be noted that some peripheral areas to this lava plain still have a strong thorium signal even though there is no obvious basalt: presumably these areas were previously covered with basalt and only a remnant soil signature now remains.

Scale of Mapping and Map Presentation

The scale and variability of the landforms in the Bathurst region determined the minimum detail required to adequately depict and understand the regolith distribution within its geomorphic context. Differentiation of regolith materials within landforms may also be a mapping scale determinant in low relief areas: for example, differentiating proximal and distal components of colluvial fans. Data on hardcopy maps must be presented clearly and so are scale dependant. The decision to produce maps at 1:100 000 scale was an outcome of the need to portray all relevant information clearly on a hardcopy map, whereas the 1:250 000 scale maps provide the regional integration. The information on the 1:250 000 scale maps is a subset of that contained on the combined 1:100 000 scale maps: some information was dissolved (regolith-landform units with the same dominant regolith-landform associations) and some information was selectively left off (some geomorphic features). These limitations do not apply to the digital data.

The Bathurst regolith-landform maps portray the type and distribution of dominant regolith-landform associations using new AGSO colour, letter symbol and geomorphic symbol schemes. These schemes will allow easy comparison of regolith-landform mapping units across the continent. The extended legends on the 1:100 000 scale maps provide succinct statements of major attributes. The complexities of the regolith-landform associations within each mapping unit are defined by relevant attributes in the "unit" fields of the RTMAP database. Mineral deposit types are shown on the 1:100 000 scale maps for potential use by mineral industry clients.

Geomorphic Context

Geomorphology underpins elucidation of regolith distribution and evolution. Regolith-landform mapping integrates geomorphology and regolith. Regolith-landform units are distinct patterns of recurring landform elements with characteristic regolith associations, and may be typified by one or more regolith toposequences. Geomorphic features indicate the location and type of regolith-landform activity, as well as the status (active, passive), degree and direction of this activity. Variable denudation and incision rates can then be understood in this context. A regolith-landform map without geomorphic features is like a solid geological map without structure.

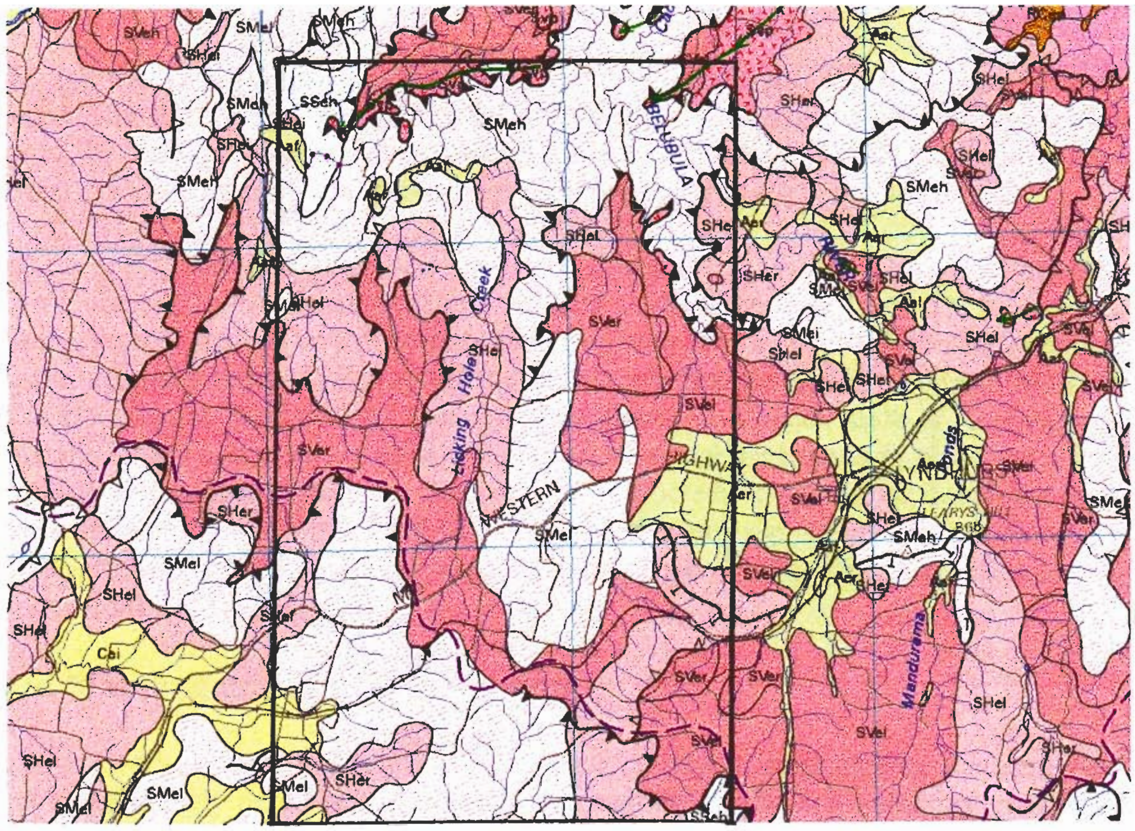

Fig. 1. Portion of 1:250 000 scale Regolith-Landform map, coloured by dominant regolith type, showing outline of the 1:100 000 scale inset shown in Fig. 3.

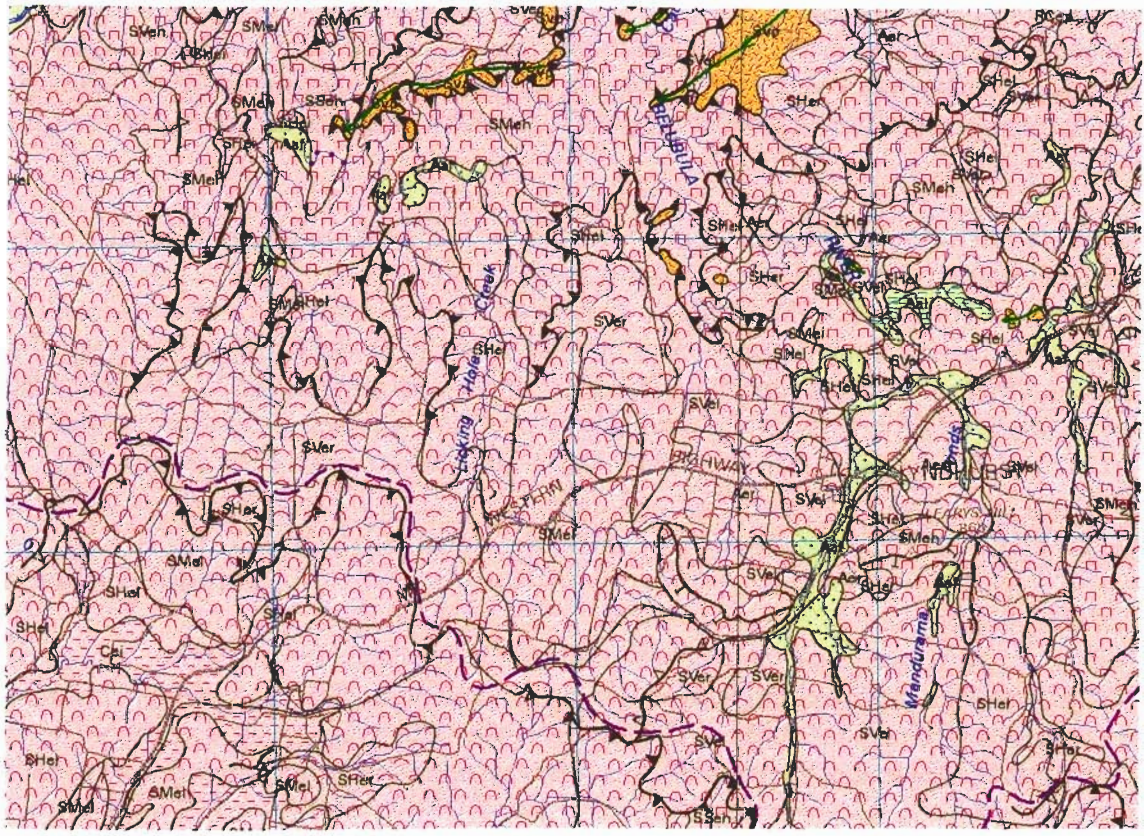

Fig. 2. Portion of 1:250 000 scale derivative Landform map, coloured and patterned by dominant landform type, of same area as in Fig. 1.

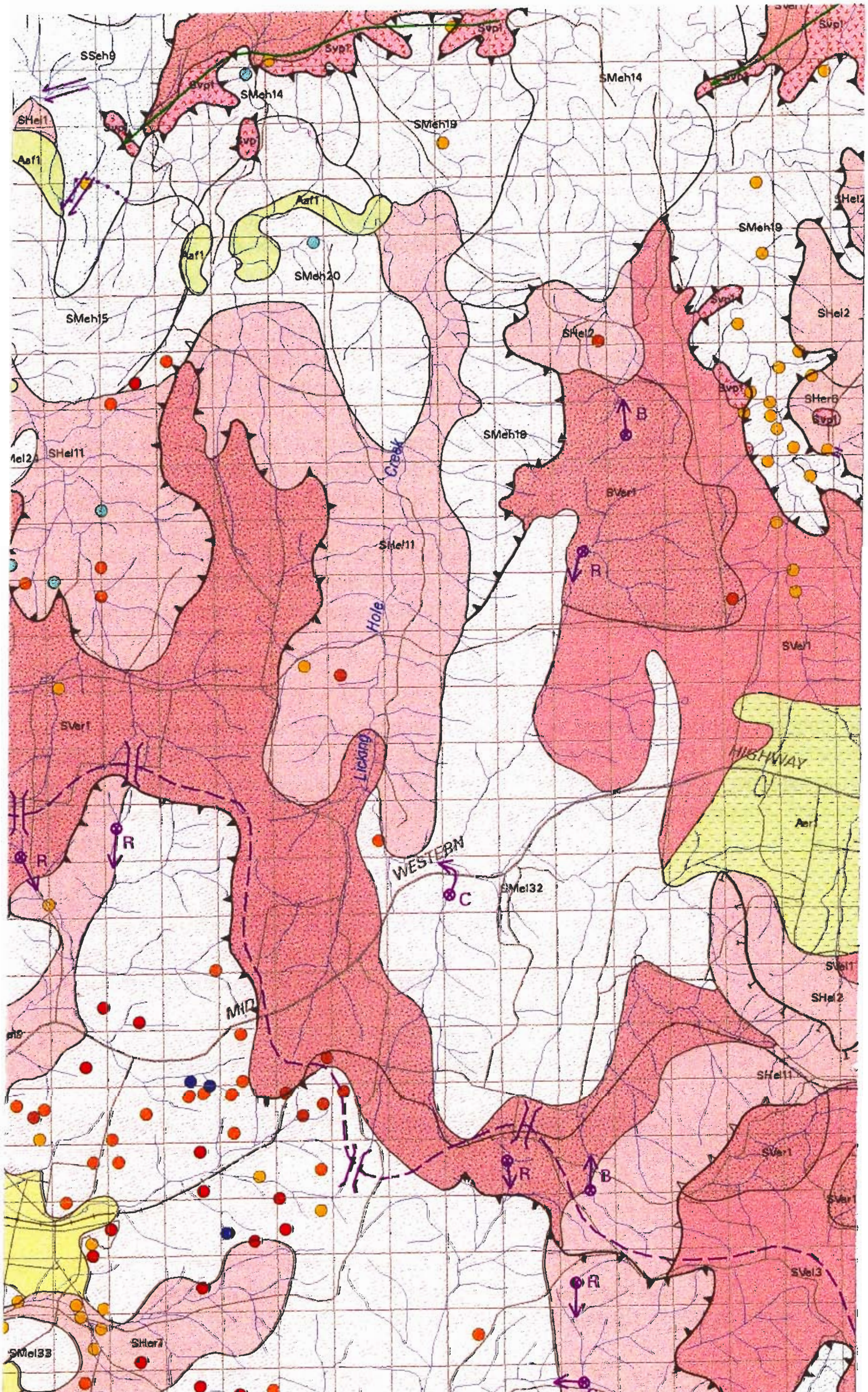

Fig. 3. 1:100 000 scale inset, coloured by dominant regolith type, showing geomorphic features in black, purple and green line symbols, mineral deposits as coloured circles, indurated areas by grey patterns, and lava flows by red patterns.

Regolith-landform mapping units, in conjunction with database attributes, geomorphic features and dating (whether relative or absolute), depict aspects of all four dimensions of regolith formation: areal distribution with depth over time. This integrated information contains the building blocks for determining the regolith and associated geomorphic evolution of the Bathurst region. The present distribution of regolith materials, landforms and drainage patterns is the outcome of the interplay of geomorphic, lithologic, structural and tectonic influences. Palaeodrainage evolution in the Bathurst region, as determined from the preservation of such features as channel migration, superimposition of drainage, wind gaps, high level gravels and sub-lava gravels, records this interplay through time. Some examples of geomorphic influences are:

- scarps define limits to more deeply and highly weathered regolith;
- greater preservation of regolith and landforms along present old drainage divides, for example, Mt Canobolas Divide;
- inversion of relief;
- relative activity of drainage basins (for example, the direction of drainage capture and reversal, denudation and incision rates);
- base level control, for example, Bathurst Granite erosion bowl and the Murray Basin.

Potential Applications

There is much potential for application of this style of regolith-landform mapping in the Bathurst region and beyond. The same mapping basis is used whatever the application, but additional application specific attributes may need to be determined (e.g. parameters for the Universal Soil Loss Equation). Diverse applications include mineral exploration, land use and environmental strategies.

Mineral exploration strategies for targeting prospective areas could include:

- determining *in situ* versus transported regolith;
- determining sediment provenance;
- determining palaeodrainage implications;
- correlating regolith terrain units with mineralisation occurrences;
- developing models of orebody modification;
- directing geochemical sampling and drilling programmes.

Land use applications specific to the Bathurst region could include:

- urban expansion;
- agriculture;
- forestry.

Environmental applications could include:

- land degradation, for example, soil erosion, acidity and salinity;
- groundwater modelling (e.g. to locate and qualify/quantify recharge areas for Murray and Darling Basins);
- biodiversity programs.

Future Challenges

A more holistic integrated approach to regolith studies is required. There is a need to integrate the related disciplines of geochemistry (regolith materials and water chemistry) and hydrology (surface, subsurface and groundwater) and apply these perspectives interactively with geomorphology to regolith studies. Where possible, more quantitative aspects should be incorporated into the present, mainly descriptive, framework. There is a continual need to liaise with clients to sharpen focus on their problems and to determine how regolith studies can address their needs.

It is only when recognising and issuing such future challenges that progress is accelerated.

The Mapping of Granitic Regolith and Landform Features at Wilsons Promontory, Victoria

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Introduction

The granite regolith and landscape evolution at Wilsons Promontory, southeastern Victoria have been studied using a variety of regolith and landscape mapping approaches. Regolith-landform maps of the study area at 1:50 000 scale, as well as at more detailed scales for key areas, and for individual weathering profile sections, have been produced. This paper discusses some of this mapping and the approaches developed specifically for this project.

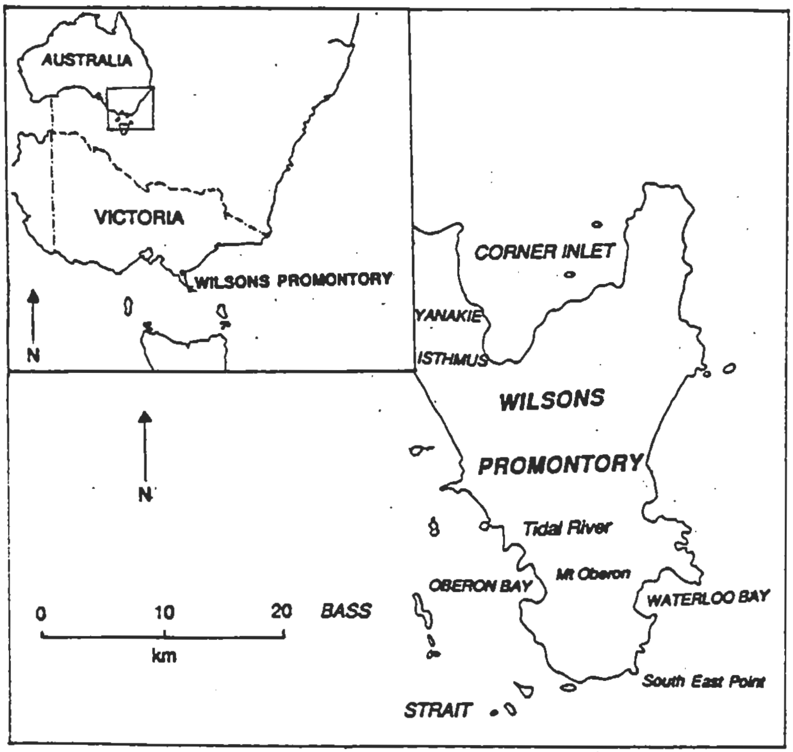

Fig. 1. Location of the Wilsons Promontory mapping area and localities mentioned in the text

The Study Area

Wilsons Promontory, the most southerly point of the Australian mainland, lies approximately 230 km southeast of Melbourne. The mapping area is shown in Figure 1 and includes all of Wilsons Promontory and adjacent offshore islands as well as the southern portion of the Yanakie Isthmus. The Promontory consists of Devonian granites, overlain and abutted in parts by Cainozoic sediments. An outline of the geology of the Wilsons Promontory Batholith is given by Wallis (1980; 1981; 1988) and the Cainozoic sedimentation by Tuddenham (1970), Oyston (1988) and Hill and Bowler (in press). The geomorphology and aspects of the landscape evolution of the study area are outlined in Hill (1994), Hill *et al.* (1995), and Hill and Joyce (1995).

Regolith-Landform Mapping

The regolith-landform features of the Wilsons Promontory study area have been presented in Hill (1992) as a 1:50 000 scale map derived from detailed field mapping compiled at 1:25 000 scale, and interpretation of 1:50 000 aerial photography provided by the Victorian Department of Conservation and Natural Resources. A landform (geomorphology) based mapping scheme that could be related to the general regolith material types and features was needed to provide general landscape information for the project. Emphasis was given to the granitic weathering and landform features that were the major concern of this research project and also a major component of the mapping area. The tor morphology and weathering profile scheme given below was therefore developed specifically for the granitic areas considered in this project, complimenting a basic lithology/geomorphology based scheme for the areas of Cainozoic sediments.

Mapping Units

The regolith polygons on the 1:50 000 map are essentially regolith material based, with specific morphological features shown as a separate layer of information. Granitic regolith material was broadly subdivided into two main types; (i) weathered and fresh material that is essentially *in situ*, and, (ii) material that has experienced a significant amount of physical transportation. *In situ* material was further subdivided at the 1:50 000 scale according to the generalised zones of a granitic weathering profile (Fig. 2) largely on the basis of the presence of corestones and their roundness. The zones mapped were: granitic saprolite, rounded granitic corestones (tors) and angular granitic corestones (tors), and fresh granitic material.

Cainozoic sediments in the mapping area consisted of either siliceous or calcareous sediments and were mapped on the basis of their lithological composition. Individual geomorphological features (such as individual dunes, alluvial fans and debris flows) were shown as a separate layer of information, within the regolith material based polygons. A brief description of the polygon units follows.

Granitic saprolite:
This material is characterised by an abundance of residual and secondary minerals, with very little fresh granitic material. The original volume and structures of the parent rock are retained. It is characterised by minimal fresh rock outcrop and subdued topographic relief (mostly associated with palaeosurface remnants). This unit generally overlies corestone or fresh granite units, although irregularities in the distribution of weathering profile zones also occur.

Rounded and angular corestones:
The most prominent feature of this material is the presence of cores of fresh granite that have been or are surrounded by granitic saprolite. These corestones are typically expressed at the land surface as tors, after the less consolidated saprolite material that once surrounded the corestones has been eroded away. The use of tor morphology as a general reflection of original corestone morphology is based on the assumption that tors predominantly form from subsurface weathering, and experience only minor modifications once exposed at the surface (as has been established by other studies including Linton, 1955; Ollier, 1965; Thomas, 1965; Hill *et al.*, 1995).

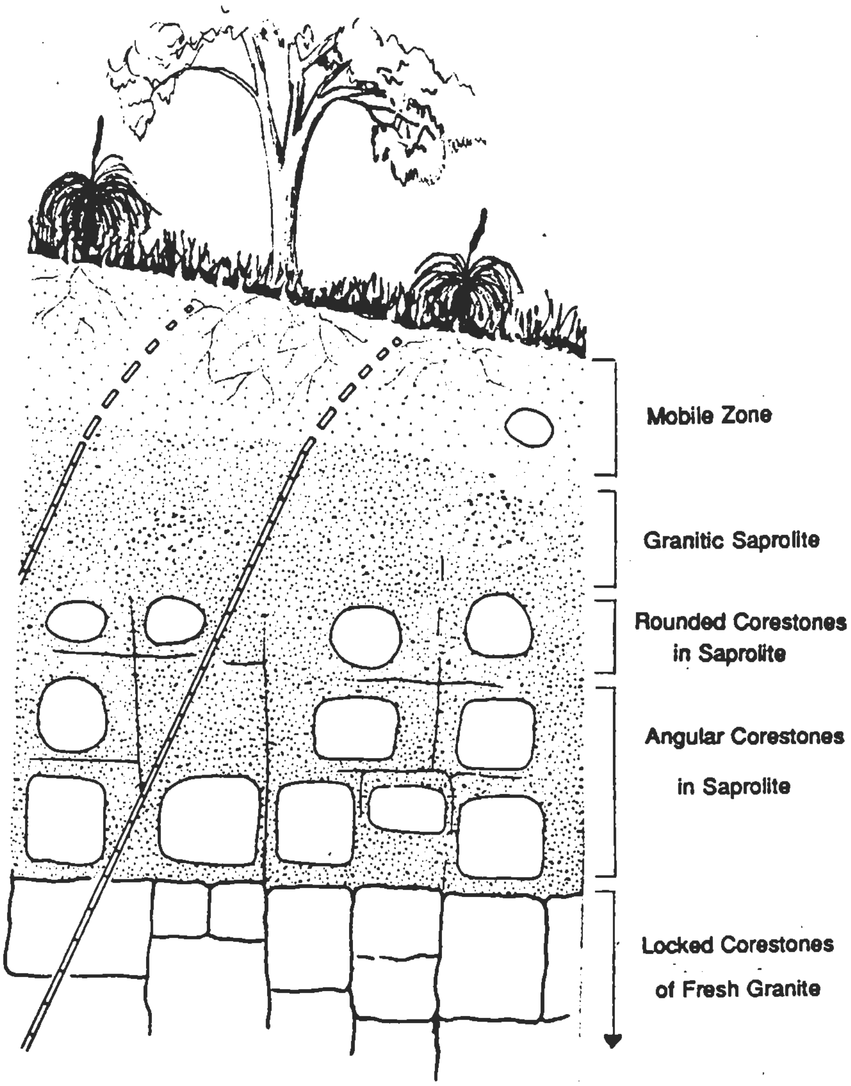

Fig. 2. A generalised granite weathering profile (after Ollier, 1984).

This zone of material has been subdivided on the basis of the roundness of the corestones (or tors), using the roundness visual comparison chart of Powers (1982). Corestones and tors with roundness values greater than 3.5 rho ("rounded" and "well rounded") are classed as rounded, and corestones with rho values of less than or equal to 3.5 ("sub rounded" to "angular") are classed as angular. The zone of corestone material typically contains 5-90% fresh rock with areas of rounded corestone material generally associated with greater amounts of saprolite.

Zones of angular corestones may grade into zones of rounded corestones or saprolite material. This is in accord with the typical granite weathering profile (Fig. 2), although irregularities, such as fresh granite grading directly into saprolite material without any intermediate corestone zones also occur.

Fresh granite:
Areas of fresh rock were defined as being mostly unaltered granite containing less than 10% weathered material. This unit represents the parent material of the granitic weathering profile. It is frequently found grading both upwards and laterally into more weathered zones of the profile, although in many cases this material has been removed by erosion, leaving the fresh rock exposed.

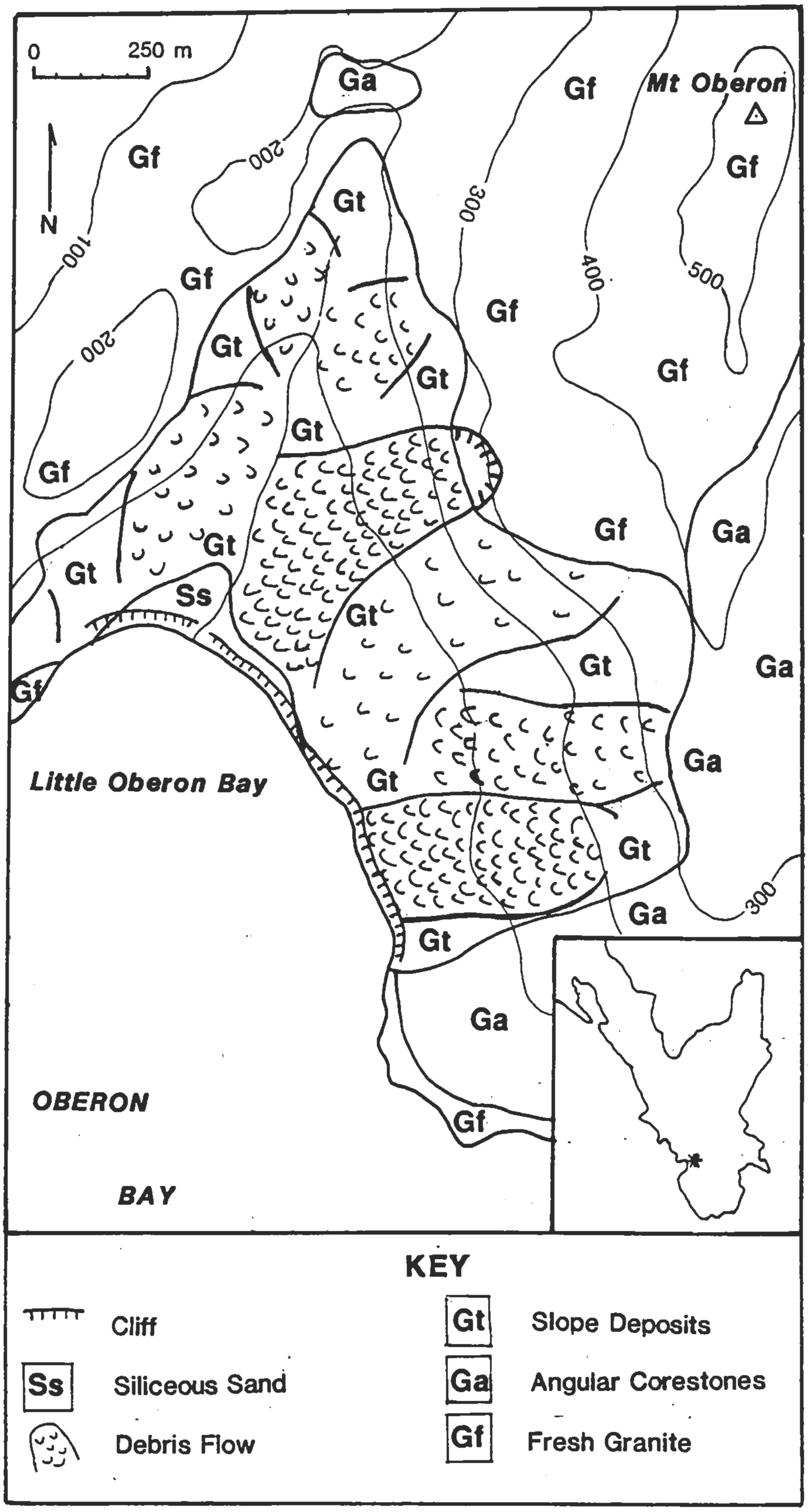

Fig. 3. A portion of the regolith-landform map showing the Little Oberon Bay area.

Transported granitic material:
This mainly consists of deposits associated with the downslope movement of granitic detritus. It is made up of a mixture of unconsolidated gravels, sands and clays, composed of both fresh and weathered granitic material. This unit flanks the highland areas, extending into adjacent valley systems and lowlands. Surface morphology is typically of a series of coalesced fans or debris cones with a general concave slope profile, commonly with a surface expression featuring an irregular distribution of tors. This unit is material that has lost its original granitic fabric and structures due to colluvial and alluvial mobilisation and subsequent reorganisation.

Subdivision of this unit into discrete fans and lithological subunits was carried out as a part of local scale mapping in the Oberon Bay area (Fig. 3). The detailed scale of this mapping enabled more morphological and lithological subdivisions to be represented than on the 1:50 000 scale study area map.

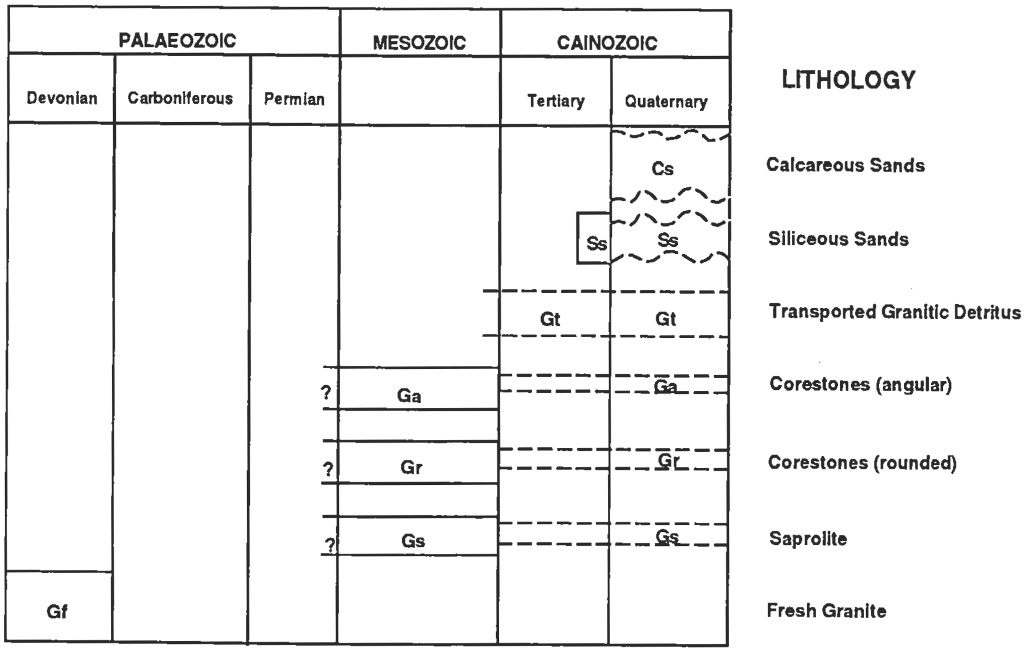

Fig. 4. The legend developed for the lithological units on the 1:50 000 scale regolith landform map.

Cainozoic sediments:
These sediments mostly consist of sands, subdivided on the basis of their lithological content into siliceous and calcareous sands. Finer grained lithologies were not represented on the regional map as they are only a minor component of these sediments, being deposited in localised swampy areas and also off-shore in areas such as Corner Inlet. The sands occur as alluvial, marine, and aeolian deposits. Surface morphological features such as dune crests and beach ridges were shown on the map as a morphological layer of information.

Map Legend

The map legend presents both lithology polygon and morphology overlay information (Fig. 4). The lithologies and their chronological ranges are shown in graphical form. This provides the map with some chronological interpretative information. The thickness of the legend block is proportional to active periods of development or deposition of the material in the unit.

The legend blocks for weathering features such as saprolite and corestone units are thickest for the Mesozoic era when these profiles experienced their most significant period of formation (Hill *et al.,* 1995; Hill and Joyce, 1995). Weathering continued during later times, although erosion generally predominated over weathering rates. This is represented by the thinner block for later time periods up to the present. Dashed lines are used to represent the block outlines for time periods when information has not been able to be obtained. With further information it is possible that "peaks" and "troughs" in block thickness could be used to represent greater and lesser periods of development of a regolith type (Fig. 4). The graphic nature of this legend enables some regolith chronology interpretations to be shown without influencing the nature of the raw polygon data shown on the map, and also has the potential to represent complex polygenetic, multi-stage and continuous events.

Morphological features are shown in tabular form with a corresponding interpretative classification of their mode or modes of origin. The 1:50 000 scale of mapping did not lend itself to showing the full details of morphological features and only major or specific features could be represented, often in a generalised form.

Other Related Maps

A series of related maps were derived to complement the regional regolith mapping. These assisted in the compilation of the regional map and are also a source of further landscape data for the region. These additional maps include a 1:25 000 scale slope map of the area (derived from field survey and classifying of contour spacing on the 1:25 000 topographic sheets), a series of 100 m spaced east-west topographic cross sections (presented at 1:50 000 scale), a 1:50 000 scale drainage system map, a 1:50 000 scale map of major granite outcrops, and a lineament and morpho-tectonic map.

Assessment of the Value and Philosophies of this Regolith-Landform Mapping

This 1:50 000 scale regolith-landform mapping is essentially a material based scheme, with additional morphological information, provided as a separate layer of information. It is largely based on observations related to the identification of distinct zones within the weathering profile developed from the granite parent rock. It must be remembered however, that the commonly shown "text-book" examples of weathering profiles, such as those shown in Figure 2, are a generalised amalgam of observations. Variations of this profile are observed more often than not. Although the rationale behind the mapping of subdivisions in this profile is based on this "typical" profile, the actual classification of mapping units is not so much dependent upon the existence of this profile but rather on the identification of related characteristics observed in the field. Genetic connotations concerning the nature of the weathering profile are only considered in later interpretations.

Surrogacy and assumptions have been kept to a minimum. The use of surface tor outcrops to represent corestone material is an example of an underlying assumption within this mapping philosophy. In this case this relationship has been well established by previous studies and it was also important to demonstrate the *in situ* nature of these tors and thereby their spatial relationship to former zones of corestone material.

The scheme was found to be easily adapted to larger, more detailed scales with the advantage that at these scales the information presented was less generalised and more precise than the regional map. Mapping unit heterogeneity and simplification is most apparent within the slope deposits where detailed mapping is able to represent individual morphological and lithological subdivisions. The weathered granite material units were also simplified for the study area map, and more detailed mapping (even up to scales where individual tors could be shown) should be able to identify further complexity and irregularities within these units. Local variation in tor morphology due to variations in parent rock lithology and jointing would be best identified with this detailed mapping. The Cainozoic sedimentary units were also generalised partly due to scale constraints but also because they were not the major emphasis in this project. These differences in the complexity of information presented are typical for most comparisons between detailed and regional scales of mapping (Hill, 1995).

The maps presented some chronological information, but this was restricted to an interpretative level within the map key. Its presence on the map sheet is to provide a sense of relative chronologies between the units as a source of further information, rather than as an inbuilt aspect of the mapping scheme. In other words the basic ability of the map to represent the regolith-landform features of the areas is not dependent upon this chronology. The wider application of this form of presentation is limited by the quality and the amount of chronological information available for the units within a given area. Unfortunately even the limited amount of chronological information that could be determined for this area is not possible for many other sites.

This approach to mapping was a valuable aid in achieving the objectives of this project. It was an efficient approach in this rugged and densely vegetated terrain, where tor and corestone morphology had to be mapped both in the field and from aerial photographs. It enabled the identification and characterisation of many landscape features that would otherwise have been difficult to demonstrate, including:

- the irregular nature of the weathering profile (unlike that presented in many "ideal", "textbook" examples, such as in Fig. 2);
- the former existence of a deep weathering profile that has since been etched by subsequent erosion (Hill *et al.*, 1995);
- possible tectonic displacement of weathering zones (many regional boundaries in granitic weathering units correspond to regional lineaments and faults (e.g. downthrown areas, such as near Corner Inlet, are characterised by surface expressions of saprolite and rounded corestone material, whereas the upthrown highlands are mainly characterised by fresh and angular corestone granite exposures - the boundary between these terrains corresponds to a major regional fault);
- differential weathering of different granites (granites with larger quantities of biotite and to a lesser extent plagioclase tend to be more weathered and develop more rounded tors and corestones than other granites).

Detailed Weathering Grade Mapping

Over ten metres of weathering profile is exposed and was mapped within an abandoned quarry on the north-eastern lower slopes of Mt Oberon. Weathering profiles developed on the two compositional extremes of the Wilsons Promontory Batholith can be seen in the southern face of the quarry. The Promontory Leucogranite is the main weathered rock type in the quarry. It is a coarse-grained granite with low plagioclase and biotite and high K-feldspar and quartz contents. The Xenolith Biotite Adamellite occurs sporadically throughout the quarry and a completely weathered contact with the Promontory Leucogranite can be seen on the southern face of the quarry. It has high plagioclase, moderate biotite and low K-feldspar and quartz contents (Wallis, 1981). The progressive weathering of these two granite types was studied in detail (Hill, 1992), however before samples were collected, the quarry face was mapped at

Table 1. Weathering grade classification criteria used to map weathering profile sections at Wilsons Promontory.

WEATHERING GRADE	Features adopted after Ollier (1965)	Features adopted from Lee & de Freitas (1989)	Density (from Hill, 1992).
Fresh (F)	A hammer tends to bounce off the rock	All mineral constituents are sound. No evidence of microfracturing using 10x magnification. Feldspars cannot be scratched with a knife.	>2.6 g/cm^3
Slightly Weathered (SW)	Easily broken with a hammer	Some plagioclase grains are slightly decomposed. Biotites are slightly decomposed and are beginning to stain some of the surrounding minerals. Slightly microfractured. Feldspars cannot be easily scratched with a knife.	2.5 - 2.6 g/cm^3
Moderately Weathered (MW)	Broken by a kick, but not by hand	Most of the plagioclase and some K-feldspars are moderately decomposed. Biotites are moderately decomposed, staining many of the surrounding minerals. Microfractured. Feldspars noticeably scratched with a knife	2.4 - 2.5 g/cm^3
Highly Weathered (HW)	Broken by hand, but does not disintegrate in water	All plagioclase and some K-feldspars are highly decomposed. Biotites are highly decomposed. Highly microfractured and slightly open grain boundaries. Some feldspars can be peeled with a knife.	2.0 - 2.4 g/cm^3
Completely Weathered (CW)	Disintegrates when immersed in water	All plagioclase, most K-feldspars and biotites are completely decomposed. Microfractures and grain boundaries tend to be open. Feldspars can be peeled by a knife.	< 2.0 g/cm^3

approximately 1:100 scale, onto a colour photograph mosaic base (Fig. 5). This detailed mapping was based on assigning weathering grades to the *in situ* weathered granitic regolith. The scheme utilised aspects of the engineering geology approaches outlined in Ollier (1965) and Lee and de Freitas (1989).

The five point scale of Ollier (1965) based on friability gave a general indication of weathering. However, the classifying criteria alone were too subjective and also varied markedly depending on the time elapsed since rain events (i.e. with variations in water content in the saprolite). Aspects of the scale proposed by Lee and de Freitas (1989) proved to give the most objective and repeatable results. The aspects used from this scheme were easily determined with the aid of a hand lens and could also be directly related to the detailed examination of the weathering of these granites using thin section, X-ray diffraction and scanning electron microscope techniques (Hill, 1992). The scheme used and the aspects of previous schemes adopted are shown in Table 1.

This general scheme gave a good general overview of the distribution of weathering grades within the quarry faces and also in other road cuttings in weathered granites in the region. It would not be practical to try to apply this scheme to a regional mapping project, being too time consuming and reliant upon good exposure. This approach is specifically designed for applications to weathered crystalline rocks (in this case granites, but possibly also to some high grade metamorphic rocks). In sedimentary and low-grade metamorphic rocks assessments with this scheme would be less successful due to the inheritance of earlier weathering products in sediments (e.g. clays and iron oxides). These rock types are also commonly finer grained, making some details, such as mineralogical changes, difficult to see in hand specimen. Other geo-mechanical properties were not used in this exercise, however for engineering based projects properties such as permeability, porosity, shear strength, texture and liquid and plastic limits may also lend themselves to incorporation into the scheme (e.g. Lee and de Freitas, 1989). These would provide a more quantitative data base to the exercise.

Conclusion

Adaptations of a simple regolith-landform and detailed weathering profile mapping scheme have been able to provide further regolith and landscape information for an area of deeply weathered and partially-stripped granite. This mapping technique provided an important basis to a study of landscape evolution and weathering at Wilsons Promontory, and could be of similar value in other areas where regolith developed from granitic parent material is being examined and mapped.

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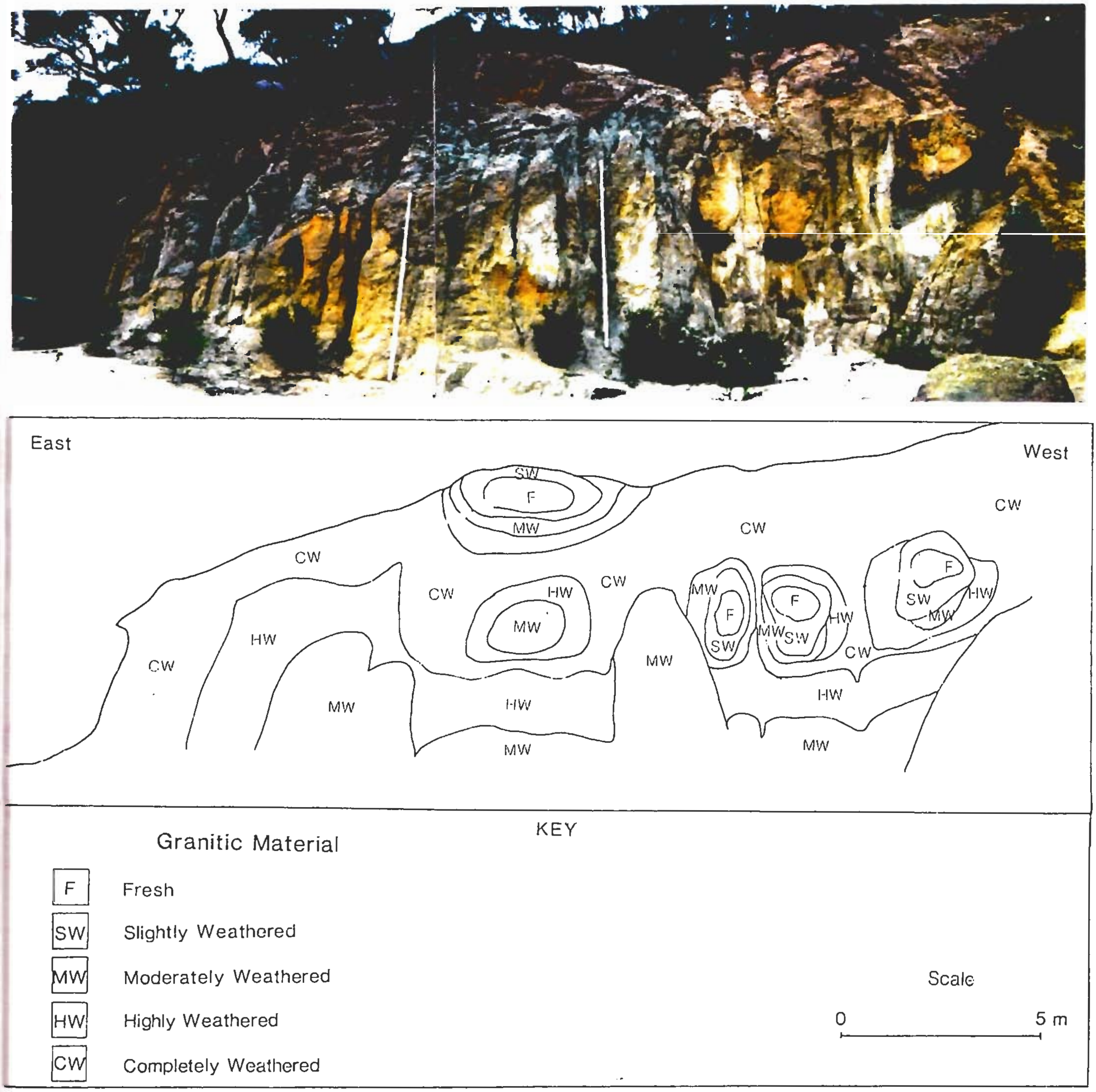

Fig. 5. Detailed weathering grade mapping of the granitic regolith in the south face of the Mt Oberon Quarry. a) Photograph of the quarry wall, b) weathering grade map.

New South Wales Soil Landscape Mapping and Regolith Studies

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In the current soil mapping of NSW, the mapping unit is a soil landscape, an area of land with identifiable features and characteristic soil types. The methodology of the mapping is highly geomorphic-oriented and soils are described and presented by a layered approach.

Soil Material - a layered approach for soil description

Instead of soil type, the soil description is based on *soil material*, defined (Atkinson, 1993) as "three dimensional soil entities which have a degree of homogeneity and lateral continuity". A soil material is usually, but not always, a soil horizon. For each mapping unit (soil landscape), several soil materials are identified and described, and their occurrence is shown by a diagram (Fig. 1). The soil types at a particular landform position are determined by the combination of the soil materials. For example, the **pu1, pu2** and **pu4** at the drainage depression (Fig. 1) form a sodsol (solodic soil).

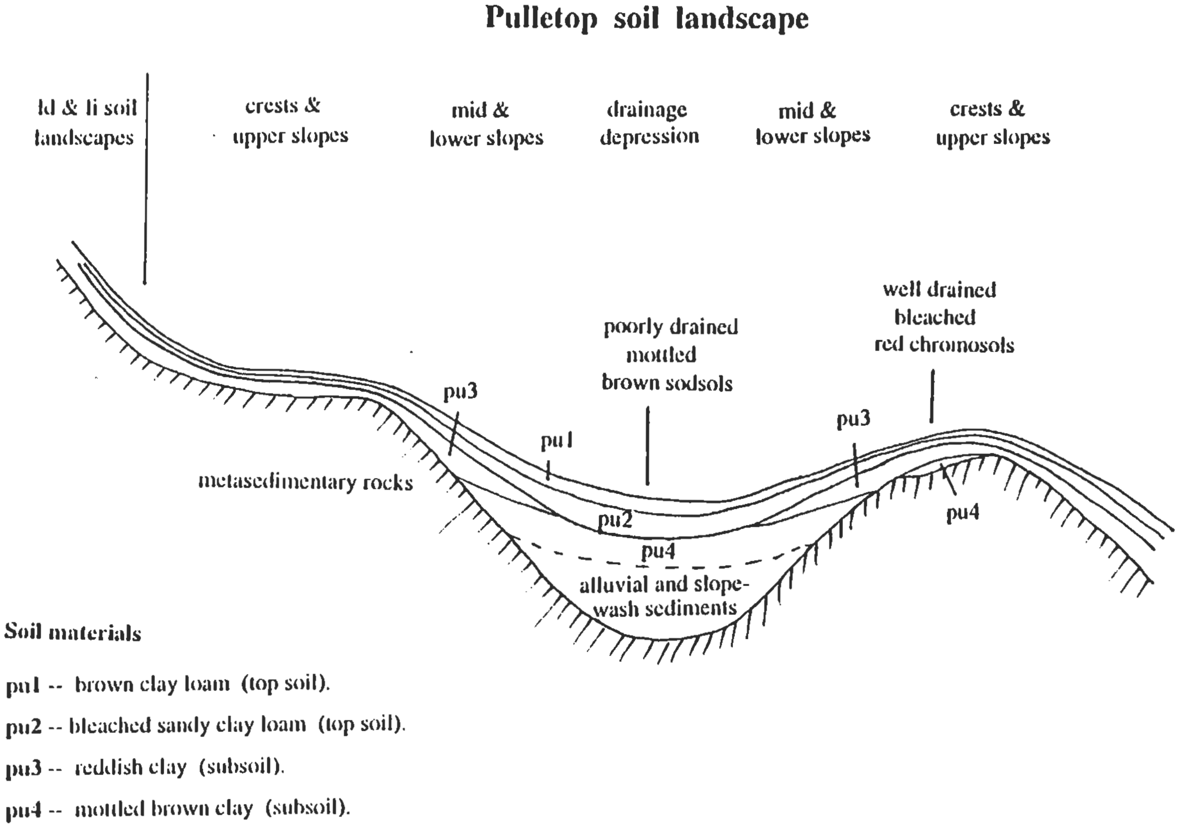

*Fig. 1. Distribution of four soil materials in the soil landscape Pulletop (**pu**) of 1:100 000 Wagga Wagga soil landscape map (Chen and McKane, 1996).*

This layered approach presents data more objectively and avoids problems arising from soil classification practice. Moreover, this has significantly narrowed the gap between soil scientists and regolith geologists. The formation of soils or the top 1-2 m of regolith may involve both sedimentary processes (erosion/deposition) and pedogenic processes (e.g. leaching). Some soil scientists tend to interpret the different layers in a profile only by pedogenesis, but regolith geologists may explain the same layers by transportation and deposition. In some cases (e.g. Nott *et al*, 1994), the top soils (A horizons) are indeed brought to the profiles much later than the subsoils (B horizons). Some soil scientists are unaware of this significant time break within a soil profile. On the other hand, regolith geologists need to know that although time breaks exist between some layers, they can be regarded as soil horizons of one soil profile. The principle is that soil horizons are determined by their present functions no matter when and how they are originally brought into position. By using soil material, soil or regolith profiles can be described objectively no matter how the profiles are interpreted.

Prediction Models Based on Landform Evolution

During mapping, many prediction models are generated, tested and used. This is essential because the field sampling is so limited (at 1:100 000 scale, only about one soil profile per km^2) and the relationship between soils and landscapes must be used.

However, the relationship between soils and topography is complex because of the influence from other soil forming factors. A simple descriptive model, relating topographic parameters with soils, is sometimes inadequate. More comprehensive (or interpretive) models are needed which relate soil features to landscape evolution and sedimentation history. For example, in the 1:100 000 Wagga Wagga landscape map (Chen and McKane, 1996), an eroded piedmont plain (soil landscape **bl**) has similar topography as some bedrock rises (soil landscape **pu**). However, the soils of the soil landscape **bl** is much thicker and less stony than those of the **pu**. Before subsequent erosion, the piedmont plain was formed by deposition of alluvial/colluvial sediments derived from a relatively large hilly catchment area, but erosion has remained a prevailing process on the residual bedrock rises.

Another example is the various alluvial soil landscapes in the Wagga Wagga sheet. Although all the relatively young alluvial sediments are mapped as Qa in the geological map, the soils are highly variable, which may be explained by some other controlling factors:

- *Type of sediment* - as the parent material, this determines some basic soil features (e.g. soil texture). The long-distance transported fine sediments form clayey soils uniform across a large area. In small valley plains, locally derived sediments are more variable resulting in more variable soils.
- *Hydrological conditions* - the flooding frequency determines the water and sediment inflows which influence the drainage and the thickness of the soils.
- *Time of soil development* - the longer the soils develop, the more soil organisations develop (e.g. more differentiated soil horizons).

Several alluvial soil landscapes of the Wagga Wagga sheet are listed in Table 1, showing the soil features in relation to the controlling factors.

Table 1. Soil features and controlling factors on some alluvial soil landscapes of the Wagga Wagga sheet area.

Soil landscape	Distance of sediment features transport (km)	Sediments	Hydrologic condition	Soil age (yrs)	Soil
kp	hundreds	suspended load (silt & clay)	occasional flooding	tens to hundreds	thick, uniform silty clay soils, no A2
ma	tens	clay, silt & sand	no flooding for hundred to thousands of years	thousands to tens of thousands	duplex soil dominant, with red clay subsoil and bleached A2
bu	tens	suspended load, clay	frequent flooding dominant	up to tens	uniform brown & grey clays, with surface cracks and gilgai
ob	from <1 to tens	sand, silt, clay & gravels	rare flooding but commonly water-logging	thousands	duplex to gradational soils with yellow & brown clay subsoil and bleached A2

Conclusion

In summary, the quality of the NSW soil landscape maps largely depends on how well the soil surveyors understand the landform evolution and the regolith formation. The 'interpretive' models used in the mapping are highly relevant and very useful for mapping the regolith of the same area. Moreover, the layered approach (soil material) in the soil description provides more objective data to regolith geologists.

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Soil Landscape Mapping

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Abstract

The NSW Department of Land and Water Conservation (formerly Department of Conservation and Land Management and Soil Conservation Service) has developed a soil landscape mapping program to provide soil and land resource information which can be used as a tool for land management and in the prevention and remediation of land degradation.

Soil landscapes are areas of land that "have recognisable and specifiable topographies and soils, that are capable of presentation on maps, and can be described by concise statements" (Northcote, 1978). The soil landscape concept integrates both soil and topographical constraints into one unit for the purpose of land management (Hazelton, 1992).

Soil is a component of regolith and as such an understanding of the regolith in its entirety is essential to the understanding of soil landscapes. The traditional approach of soil mappers to regolith has been dictated by the purpose driving the mapping.

Background

The soil landscape mapping program arose from the then Soil Conservation Service of New South Wales charter to "advocate and assist land conservation (and) to sustain the land resource base...". The Service developed three goals from this charter, the first relating to an understanding of the land, the second to engage community support for the principles of land conservation and sustainable land use and the third to maintain the Service as an organisation with the skills, knowledge and energy to deal with land resource management problems.

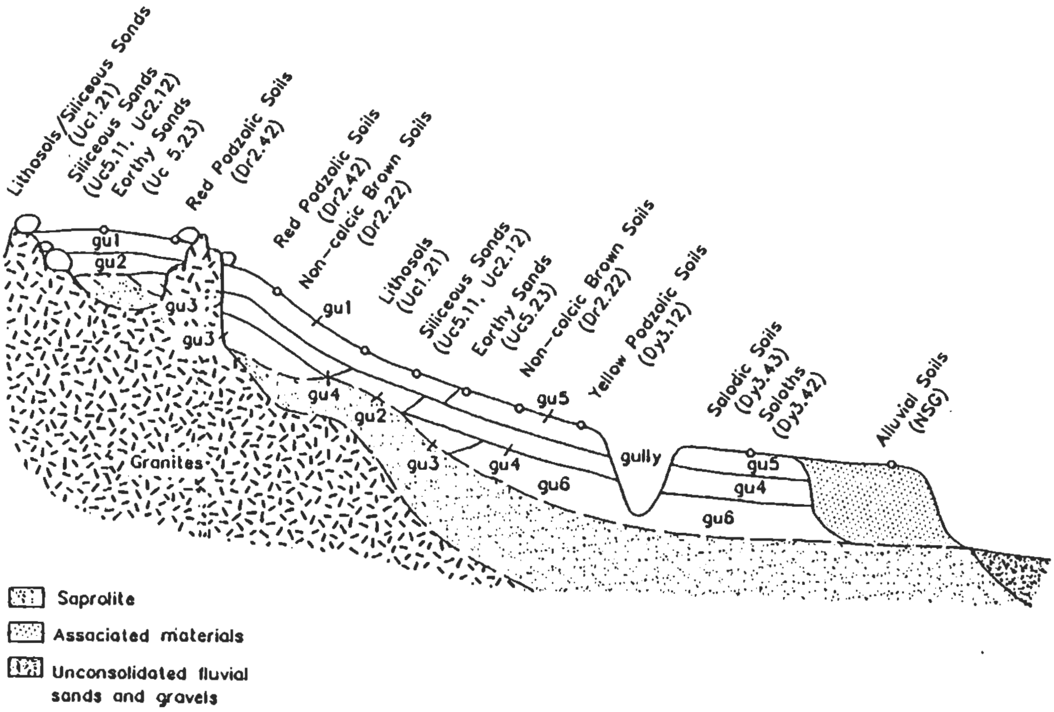
A knowledge of the distribution and attributes of soil and land resources is essential for achieving ecologically sustainable development. As part of its land management strategy the Service recognised the need for quality soils information and in 1980 established a program to map the state's soil resources.

Soil Landscapes

Soil landscape mapping was the preferred method of collecting resource information applicable to the management of the state's soil resources. It is a style of mapping suited to the broad scale of mapping necessary to cover an area as large as NSW. It allows for soils information to be incorporated in greater detail than for other styles of mapping at the same scale. Within soil landscapes, soil distribution is further defined by, amongst other things, occurrence and relationship diagrams (see Fig. 1).

Landscapes can be used to distinguish mappable areas of soils because the formation of landscapes and soils is interrelated. The soil landscape concept merges soil and landscape qualities into a single mapping unit. It is a recognition that land management constraints relate to both land and soil limitations.

Soil landscapes may be defined as areas of land with readily identifiable geomorphic features and soil characteristics. They are comparable to land systems in that landform and geology are important factors in determining unit boundaries but soil landscapes usually place greater emphasis on the soils and less on the vegetation. Soil landscapes also differ from soil associations mapping in that greater significance is assigned to geomorphic processes.



■ ***Schematic cross-section of Gudgenby soil landscape illustrating the occurrence and relationship of the dominant soil materials.***

Fig. 1. Schematic cross section of the Gugenby soil landscape.

Soil Landscape Reports

Soil landscape reports include information for each soil landscape on:

- geology/rock types;
- regolith;
- landforms and slopes;
- native vegetation;
- severity and types of erosion/land degradation;
- detailed soil descriptions and locations where typical soils can be seen;
- diagrams of soil occurrence patterns;
- listings of soils and landscape properties which can affect development;
- soil fertility assessments and tables of soil test results and interpretations;
- soil erodibility;
- severity of erosion hazards;
- likely hazards for foundations;
- urban capability;
- rural capability.

Soil Materials

Soils are described in terms of *soil layers* in addition to the more traditional *soil profile*. These layers are termed *soil materials* and are defined by Atkinson (1993) as "...three dimensional soil entities which have a degree of homogeneity and lateral continuity". Each soil material is defined and described in terms of its readily recognised and characteristic morphological properties. The definitive attributes may vary from one soil material to another, depending on what is recognisably characteristic of the material. In most cases each soil material has a consistent set of properties and limitations. This is because soil materials are not necessarily defined by soil formation processes or position within a soil profile. Introduced fill, weathered rock or unconsolidated alluvium may be included. However, soil materials usually correspond with soil boundaries (Chapman and Murphy, 1989). The vertical association of soil materials in a soil profile can be classified using traditional soil taxonomic systems such as Great Soil Groups (Stace *et al.*, 1968), Principal Profile Forms (Northcote, 1979) or the recently released Classification System for Australian Soils (Isbell, 1994). Soil materials often cross traditional taxonomic boundaries.

Methodology

Soil landscape maps are based on the Land Information Centre 1:100 000 and 1:250 000 topographic map series.

Provisional landscapes are delineated by stereoscopic interpretation of aerial photographs and the examination of other available remotely sensed data such as Landsat and radiometric images. They are defined by recurring patterns in the underlying lithology, relief, landscape and slope. Land use, erosion, native vegetation and drainage may also be used to delineate landscape units.

For the 1:100 000 mapping program the provisional landscapes are transferred to 1:25 000 topographic maps. Field sheets are digitised at the 1:25 000 scale but the final product is published at 1:100 000. Soil landscape polygons are generally greater than 30 hectares unless they are considered to be locally significant.

Each soil landscape is given a name based on the locality where a typical example occurs. On the map this is represented by a two-letter alphabetic code. For example, the Gudgenby soil landscape occurs on Clear Range granodiorite and adamellite in the Murrumbidgee River Valley, south of Canberra (Jenkins, 1993). It is represented on the map by the code letters **"gu"**.

Soils are examined and described in detail at over 250 sites and inspected at over 1000 other sites. At each described site, soil morphological data and site information is recorded on Soil Data Cards (Abraham and Abraham, 1992). Landscape boundaries and descriptions are checked at each site inspection. Soil descriptions are made from road batters, building sites, trenches, backhoe pits and hand-augured holes. Sufficient field sampling is undertaken within each soil landscape to identify and describe the range of soil materials present to enable individual descriptions of their occurrence and relationships. At least one sample is collected of each soil material for laboratory analysis.

Each soil material is given a unique code consisting of two letters and one number. The letters are taken from the soil landscape in which the material is found and the number distinguishes it from other soil materials in the same soil landscape. For example, **gu2** is the second soil material described in the Gudgenby soil landscape. Terminology used follows McDonald *et al.* (1990) and Abraham and Abraham (1992).

Laboratory Testing

In addition to the field attributes described, type profiles within each landscape have laboratory tests conducted on each soil material. Tests undertaken include:

- particle size analysis;
- bulk density;
- dispersion;
- unified soil classification system (USCS);
- volume expansion;
- linear shrinkage;
- pH (1:5 water)/(1:5 $CaCl_2$);
- electrical conductivity;
- organic carbon;
- phosphorus, phosphorus sorption;
- cation exchange capacity.

Soil test data have been analysed and interpreted using the INTERP program (cf. Chapman *et al*, 1993). The interpretations are taken from the available literature and provide general rankings for each attribute tested.

Product

Soil landscape maps and reports have been produced at scales of 1:100 000 for the coast and tablelands and 1:250 000 to the west of the tablelands. The Soil Landscapes of the Sydney 1:100 000 map sheet was the first in the series to be published. It was released in 1989. The following maps and reports have been published thus far:-

Cooma	1:100 000
Curlewis	1:100 000
Gosford-Lake Macquarie	1:100 000
Katoomba	1:100 000
Kiama	1:100 000
Lismore-Ballina	1:100 000
Michelago	1:100 000
Port Stephens	1:100 000
Penrith	1:100 000
Sydney	1:100 000
Wallerawang	1:100 000
Wollongong-Port Hacking	1:100 000

Bathurst	1:250 000
Goulburn	1:250 000
Singleton	1:250 000

A number of map sheets are due for release by the end of 1995 or mid 1996. They include:-

Bega-Goalen Point	1:100 000
Braidwood	1:100 000
Dorrigo	1:100 000
Kempsey-Korogoro Point	1:100 000
Murwillumbah-Tweed Heads	1:100 000
Newcastle	1:100 000
Wagga Wagga	1:100 000
Dubbo	1:250 000

Numerous other map sheets are in various stages of completion.

The soil and landscape information has been extended much further than the traditional published map and report. A series of derivative maps has been produced for each map sheet. For example, the Cooma map sheet (Tulau, 1994) has derived map sheets for the following attributes:

- topsoil acidity;
- phosphorus sorption;
- capability for septic absorption fields;
- suitability for *Pinus radiata* plantations;
- native vegetation;
- calcium, deep subsoil and regolith;
- soil depth.

Any number of derivative maps can be produced using the soil and landscape data and/ or importing additional data sets. For example the Cooma "Suitability for *Pinus radiata* plantations" derivative map was constructed from soil and slope data collected as part of the soil landscape survey and imported climate and soil boron data.

A number of programs which are closely linked to soil landscape mapping have or are being undertaken. This includes the recently completed Acid Sulphate Soils risk mapping at a scale of 1:25 000 which has been done for the entire NSW coast.

Future Challenges

The major challenge to soil surveyors in the future is to extend soil data past the traditional soil map and bound report outputs to a range of more flexible and user friendly products whilst maintaining the quality of the information collected. The production of derivative maps is a good start but the process of disseminating information to user groups must be continued and expanded upon.

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Value Adding To Radiometrics

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Introduction

The full value of airborne radiometric or gamma-ray data has not been exploited for mineral exploration or land management purposes. Research and development undertaken by ERIC has demonstrated that radiometrics can yield significant information about the land surface relevant to geochemical and structural analysis, soil and surface hydrology mapping. ERIC has developed techniques using TNTmips^{TM} Map, Image Processing and GIS software to spatially map the similarities and differences in surface patterns, including lineament mapping.

Soil Mapping for Land Management

Soil mapping is traditionally undertaken by subdividing the area into broad geological categories and further subdividing the geological categories according to position in the landscape (catenary position) The result is a soil landscape map where the mapped areas contain poorly defined mixtures of soils. One of the reasons ERIC has persued the use of radiometrics for mapping soil *properties* is to overcome the major limitations embedded in soil landscape maps which map soil *types*. Soil landscape maps are confounded with geophysical and landscape interpretations, although the quality of these maps has improved where radiometric data have been used as a base for soil field survey design. However, these soil landscape maps are only useful in a land use planning context and have little use in land use management. Also, the soil landscape map approach is not practicable on low or flat terrain which covers a major portion of Australia's agricultural land.

The question of independence of data becomes important where soil maps are to be used in subsequent analyses in a GIS. The geological maps used to derive the soils maps usually incorporate an interpretation of the landform, geology and hydrogeology and may depend in part on vegetation patterns. The soils maps can also incorporate a further interpretation of the landscape, soil measurements and vegetation patterns. In this context, the maps are seldom independent of geology, landform, hydrogeology, soils and vegetation and therefore of limited use in a GIS.

The airborne radiometric data reflect parent material and weathering and provide an opportunity to derive soils mappings that are independent of the data sources used to map terrain and vegetation. Consequently, radiometrics provide the best means available to date for stratifying field sampling for the purposes of soil description, simply through identifying areas that are homogeneous with regard to parent material and weathering The degree to which the radiometric data meets this requirement depends on the detail necessary. High quality reconnaissance grade data at 1.5 km spacings are probably most suitable for broad regional mapping of soils at say 1:250 000 scale. However, high resolution data at 400, 250 or 100 m spacings would generally be required to map the finer patterns relevant to paddock management or crop selection, say 1:25 000 scale.

Comparisons between soil landscape maps and radiometric maps were undertaken as early as 1964 by Foote (1964) and more recently by Tunstall and Gourlay (1994) where correlations were poor. The ERIC objective in using radiometrics to map soils is not to emulate existing soil mapping practices, but to provide improvements for land management. Existing methods of mapping soils have been shown to contain innumerable deficiencies and these can be related to the basic precepts and technologies. Besides, any suggestion that one method of describing soils will meet all land use requirements is untenable.

ERIC makes no claim to a capability to map soil types (as often described or defined in literature) for reasons which include:

- there can be no definition of soil types that meets all requirements;
- most classifications of soil type are based on judgements as to the processes of soil development and therefore depend on interpretation. They do not solely represent all the soil characteristics (or how soils are spatially related) and therefore do not provide a reliable basis for testing other measures; and
- there is no logical reason for there to be a relationship between radiometric signals and soil types (Foote, 1964; Tunstall and Gourlay, 1994).

A limitation in the radiometric data for classification is that they do not always differentiate different soils where they have similar radiometric signals. This limitation applies with any analysis of radiometric data. Indeed, it applies to any data where a given result can arise for a number of different reasons. The resulting confounding of effects can only be removed through appropriate stratification of field sampling which requires that differences in parent material be taken into account. However, spectrally similar signals can often be separated using spatial algorithms prior to field sampling. Also, finer levels of differentiation may be required prior to final data processing where the results of pilot soil survey demonstrate a statistically significant variation within a soil class.

The major differences in the ERIC approach to that used by others relate to the stratification and measurements used in sampling, and the techniques used to spectrally and spatially classify the radiometrics. The stratification is based on the premise that parent material is a greater determinant of soil properties than terrain, both in regional and local analyses. This can readily be demonstrated and is supported by field observations. The radiometrics provide a means of stratifying sampling according to patterns of parent material and, where the resolution is adequate (e.g. 100 m spacings), of indicating terrain/local related patterns. Radiometrics alone do not uniquely map soils. No method uniquely maps soils without reference to additional information, but the radiometrics appear to provide a better basis for mapping soils than current soil landscape map approaches.

Classification provides a means of deriving higher resolution maps from the radiometrics than any other means, provided the characteristics of the data and nature of the required results are appreciated. Classification can be readily performed by anyone but considerable knowledge and skill (expertise) are required to obtain the best results.

The main benefits in using airborne radiometrics in mapping soils are:

- the mappings relate directly to factors important in soil development;
- mappings are independent of other variables and interpretations;
- classifications define the limits to areas that can be regarded as homogeneous;
- classifications provide indications of similarities in soil characteristics within the mapped area;
- mappings provide a basis for the stratification of field sampling; and
- the technique is highly efficient compared with traditional soil mapping techniques.

Soil mapping results achieved by ERIC indicate that soils can be discriminated in a statistically significant manner for soil structure and chemistry (e.g. profile thickness, texture, pH, Eh and pe). The soils maps derived from the radiometric data would be particularly relevant to any industry involved in soils management or site selection/characterisation for agriculture, mining, forestry, road construction/ quarries, hydrological and ecological studies.

This procedure has been used by ERIC to map the soils of the Jemalong/Wyldes Plains (70 km x 50 km) for NSW Agriculture, from 400 m spacing airborne radiometric data provided by the Australian Geological Survey Organisation (Gourlay, 1995). The Plains are a complex mix of soils formed on flood plains, prior streams, and prior lake beds; and including colluvial, aeolian and fluvial materials of different ages. The classified radiometrics provided the spatial and spectral separation of these materials into 22 soil classes and the basis for field survey design. Soil samples were collected for each class and statistically interpreted for profile thickness, texture, colour, pH, pe, EC, bulk density and dispersability. Labels were then attached to each class to provide a soils map based on significant differences (mainly for texture, thickness, pH, pe and EC). These field data for the soil classes also enabled soil property patterns to be mapped (e.g. texture, pH and salinity) at each of the soil horizons; which highlights the value of maintaining independence of data within a GIS. Other maps derived from the radiometric data included surface hydrology, landscape evolution and surface structure (basement fractures or lineaments) information.

The Jemalong/Wyldes Plains project has clearly demonstrated the efficiency and effectiveness of this approach to soil mapping, at a cost of less than 20 cents per hectare within 50 work days. This cost could increase to $2.00 per hectare where the data are not available and has to be specially flown (i.e. at 400 m spacings).

Conclusion

The use of radiometrics for the mapping of geochemical, structural, surface hydrology and soils information has not been fully exploited but provides significant opportunities to reduce the cost of field survey, and better understand surface processes and materials. The cost savings and economic benefits derived from using radiometrics for soil mapping could be enormous, and the benefits to a wide industry/resource management and research base should be considered in airborne data acquisition plans.

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Incorporating Landscape Descriptions in Land Degradation Management: A Role for Regolith Mapping?

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Australian society now demands that our natural resources are used in a sustainable fashion. This position emphasises management over development. As well, governments have themselves emphasised "beneficiary pays" ideals when deciding who should pay for actions. Together, this leads to a certain amount of confusion when large natural systems are to be managed. Fundamental to understanding how to manage these systems is knowledge of both the distribution of landscape units and the temporal nature of the land and water processes operation within those landscapes. How best do we describe these entities in terms of a minimum data-set? Is that minimum data set a regolith map?

One of the major problems, if not natural resource disasters, currently facing people of southern Australia is that of dryland salinity. Current estimates suggest that about 2.5 million hectares are affected, likely to grow to about 4 million hectares by 2010. In some areas the problem is growing rapidly; rates of increase of 30% per year have been mapped since 1990. With each hectare of salinised dryland giving up about 800 kg per year the mass of salt to be mobilised out of these landscapes is astronomical.

In trying to respond to this issue a number of questions arise.

- With the problem seemingly randomly spread across the landscape, how do managers predict where the problem will arise next?

- The problem is based in the interaction of hydrology and plant-water use. What are the minimum data sets needed to characterise the problem and hence define the most appropriate solutions to be used?

- Intuitively, spatial analysis of landscapes will be involved in any catchment based approach to managing the problem. How do we describe unique mapping areas within that catchment, recognising the time frame for meaningful action?

The EGG (Environmental Geoscience and Groundwater) Program at the Australian Geological Survey Organisation is embarking on a major program of Land Management Mapping in Degraded Catchments as an earth-science based response to these issues. The program involves integrating airborne geophysical datasets (primarily gamma-ray spectrometry), geological and regolith attributes and groundwater dynamics, rapidly at a catchment scale. This information is then combined with economic models as a basis for building catchment decision support systems. A key element of this work is the close integration with the demands of local communities.

Future issues that will need to be answered in the process of undertaking this work will be:

- some quantitative measure of the within and between mapping unit variability in the key parameters involved in the decision support process;

- value for money and timely mapping techniques; and

- a methodology robust enough to be able to be applied in a variety of terrains.

The Impact of the Scale of Mapping on Soil Map Quality

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Abstract

It is generally assumed that increased precision (i.e. map unit homogeneity) and accuracy should result from increasing the scale of mapping, since it should enable a more intricate breakdown of the landscapes into landform facet based units. This study compared the success of a 1:10 000 scale soil association map with a 1:25 000 and 1:100 000 scale soil landscape maps for the Birrigai area within the Paddys River catchment, south west of Canberra, A.C.T. The study found that, although there was little reduction in the soil variability of the map units with increased scale, significant gains were achieved in terms of eliminating map unit impurities. In terms of soil map predictive success, the 1:10 000 and the 1:100 000 scale maps both performed well, although the 1:10 000 map was considered superior on the basis of its lesser reliance on landform interpretation. This study also brings to light the need to accept soil spatial variability as a natural landscape attribute that does not always show apparent order within the landscape. If it cannot be delineated into map units, it at least needs to be accurately quantified. Some anecdotal evidence from the surveying of the 1:100 000 scale Paddys River soil landscape map is also cited to emphasise the importance of the ground truthing and field checking phase of soil survey, especially for the small scale soil mapping.

Introduction

Only a few overseas studies (e.g. Marsman and de Gruijter, 1986; Leendhardt *et al.*, 1994) have looked at the effect of the scale of mapping on map quality and these studies found that for free surveyed soil maps, the purity (accuracy) and precision (homogeneity) of the more detailed 1:10 000 scale soil maps was only slightly higher than that achieved by the smaller 1:25 000 and 1:50 000 scale soil maps. This apparent lack of differentiation was attributed to the presence of short range variability in the soils and their properties at these locations.

This study has attempted to investigate such effects of the scale of mapping in relation to soil maps produced by the more common Australian soil survey procedures, and as such should be of more relevance to the Australian situation.

How the Scale of Mapping Effects Map Quality

The scale of mapping affects the soil map quality in two main ways. Firstly, it limits the minimum area on the ground which can be represented on the map, which in effect limits the minimum size of the soil units and therefore the degree of detail in the soil distribution which can be portrayed. Secondly, it determines the intensity of field investigations, as a consequence of adhering to a standard observation site density/cm^2 for the published map. For example, the Australian Standard observation site density of 0.25 observations/cm^2 of published map (Reid, 1988), would represent 1 observation site per 4 hectares on the ground for a 1:10 000 scale map, but only 1 observation site per 400 hectares on the ground for a 1:100 000 scale map.

It is generally assumed that increased precision (i.e. map unit homogeneity) should result from increasing the scale of mapping, since it should enable a more intricate breakdown of the landscapes into landform facet based units. But this of course depends on the strength of the soil landscape relationships and the extent of short range soil variation within the landscape. One would certainly expect decreases in the extent of impurities in the form of alien facets due to poor air photo and published map resolution, with increased mapping scale.

Research Methods

This study was centred on the Paddys River catchment, south west of Canberra in the ACT, and involved the production of a 1:100 000 scale integrated soil landscape map of the Paddy`s river catchment, as well as a 1:10 000 scale soil association map of the Birrigai sub-catchment within this catchment. The 1:100 000 scale soil landscape map used standard NSW Department of CALM methodology, while the 1:10 000 scale soil association map used observable land facet based mapping units delineated by air photo interpretation and field investigations as described in Gunn *et al.* (1988). In addition to these two maps, a 1:25 000 consultancy soil landscape map of this area which had been completed earlier by another author for the ACT Government (Hird, 1988) was also evaluated. Thus the Birrigai sub-catchment was the focus of this evaluation, where upon the boundaries of the 1:25 000 and 1:100 000 scale soil maps were overlayed over the more detailed 1:10 000 scale soil map for evaluation purposes.

It was thus in this setting that 42 randomly located evaluation sites (3 in each of the 14 major 1:10 000 scale soil units) were used to evaluate the utility of each of these maps in terms of their purity (accuracy) and their map unit precision (homogeneity) for selected soil properties using Marsman and de Gruijter (1986) measures. An ANOVA evaluation of the ratio scale soil property data was carried out in respect of the 1:10 000 soil units to determine whether the grouping of soil properties by these landform facet based units was considered statistically significant. In addition to these investigations, the detailed 1:10 000 scale soil boundaries were used to determine the extent of area occupied by impurities within the 1:100 000 scale soil landscape map.

Some Results of this Study

The accuracy of the soil maps

Table 1 shows the accuracy of the three scales of soil map in predicting the selected soil descriptors (i.e. Partial Purities) at the randomly located evaluation sites within the Birrigai sub-catchment. It also shows the average of all of these accuracy ratings (Average Purity) as well as the 'Strict Purity' which is defined as the proportion of the evaluation profiles which satisfy the soil maps defined criteria for all of these soil descriptors (Marsman and de Gruijter, 1986).

If one looks only at the first 3 result columns in Table 1 it appears as though the smaller 1:100 000 scale soil landscape map was more successful in predicting most of the soil descriptors, than either the 1:25 000 or the 1:10 000 scale soil maps. However, this first 100 000 result column, includes the use of the 'Included Landscape' concept. This concept was applied where the soil map report mentioned inclusions of other soil landscapes too small in area to have been mapped out separately. In these cases evaluation sites located in such included landscape areas were allowed to use the predictive model of the included landscape to predict the soils of that site. Thus this result, is heavily dependent on individual interpretations of what landform facets actually fit the central concept of the included landscapes at the site. For this reason the final column of results which reflects the success of the central basic soil landscape models was included. The calculations of this column treat all included landscapes as impurities, and as such these sites are designated as being incorrect for all soil descriptors. This approach is considered to be a more realistic appraisal of the 1:100 000 scale soil map since land use planners away from any given site would assume that the central soil landscape models would be the dominant situation within the delineated soil landscape areas on the map. This is especially the case when one considers that a central role of soil survey is to provide "a means or a tool with which the problem solver can inform himself about the relative soil conditions at all sites in the area without having to go there and see" (Butler, 1980, p. 2).

Table 1. The purity values (i.e. predictive success) of the three scaled soil maps evaluated for the Birrigai area.

SOIL DESCRIPTORS	**PARTIAL PURITY VALUES (% OF SITES CORRECT)**			
	1:10K SCALE SOIL MAP.	1:25K SCALE SOIL MAP.	1:100K SCALE SOIL MAP. (+ I.L)	1:100K SCALE SOIL MAP. (Basic Model)
(i) SOIL CLASSIFICATION;	*	*	*	*
Great Soil Group.	79	39	**90**	67
Northcote Factual Key.	40	21	**55**	48
Australian 3rd Approximation.	**69**	absent	69	50
(ii) A Horizon Properties.	*	*	*	*
Depth of A_1 Horizon.	79	67	**81**	69
Depth of Total A Horizon.	**81**	52	76	67
pH.	83	32	**90**	71
Texture Grade.	**88**	34	**88**	74
Total Gravel (%).	**88**	absent	66	51
Grade of Pedality (Structure).	88	absent	**95**	73
Emerson Aggregate Class.	86	absent	**90**	73
(iii) B_2 Horizon Properties.	*	*	*	*
Soil Colour.	87	32	**91**	67
Mottles Present (yes or no).	91	37	**96**	70
pH.	74	37	**91**	67
Texture Grade.	87	21	**91**	67
Total Gravel (%).	**74**	absent	55	37
Grade of Pedality.	83	20	**95**	67
Emerson Aggregate Class.	70	absent	**77**	53
*	*	*	*	*
AVERAGE PURITY.	79	36	**82**	63
*	*	*	*	*
STRICT PURITY.	10	0	**19**	19

The predictive success of the 1:100 000 basic soil landscape model is thus shown to be somewhat less than the 1:10 000 soil map, but is still substantially better than the 1:25 000 consultancy soil landscape map. The poor predictive performance of the 1:25 000 scale soil landscape map and the moderately good performance of the 1:100 000 scale soil landscape map, are both related to the range of values catered for in the predictive models, and this is in turn related to the extent to which the apparent soil landscape relationship is backed up by replicate soil profile observations. Thus the low soil property ranges of the 1:25 000 scale soil predictive model were found not to be the case on the ground. The superior performance of the 1:100 000 scale map in terms of strict purity is again probably a consequence of the larger range of property values of these models. The fact that the models with the larger ranges have out performed the more homogeneous soil unit models bares testimony to the extent of soil variability within this area.

The extent of area occupied by impurities within the 1:100 000 scale soil landscape units

Table 2 reveals that the presence of included landscape impurities within this evaluation area is quite extensive for the 1:100 000 scale map, ranging from 14 to 56% of the area of these map units.

Table 2. The proportion of the area of each 1:100 000 scale soil landscape unit present in the Birrigai sub-catchment, accounted for by landscape impurities.

1:100K SCALE MAP LANDSCAPE	Total Area in Birrigai (Ha)	1. Area(Ha) Occupied By Included Landscape Category	2. Area (Ha) Occupied By Outright Impurities.	Total Area (Ha) Occupied by Impurities (1+2)	% of Landscape occupied by Impurities.
GIBRALTAR	210.7	27.6	2.6	30.2	14.3
NATURE RES`	27.3	6.0	9.3	15.3	56.0
PADDYS RIVER	61.2	9.9	5.5	15.4	25.2
SWAMP	6.0	.92	0.08	1.0	16.7
PADDYS RIVER ALLUVIUM	5.3	2.4	----	2.4	45.3

For the above table the Gibraltar soil landscape consists of steep granite hills and mountains, the Nature Reserve soil landscape refers to the footslope areas at the base of these steep hills, the Paddys River soil landscape refers to the low undulating granite rises, and the Swamp soil landscape refers to the swamp areas on the flats and in the drainage lines. The Paddys River Alluvium soil landscape consists of the alluvial flats and terraces along the Paddys River and its tributaries.

The dominant impurities take the form of small areas of alluvial flats and swamp units within the hills, although smaller areas of steeper hills and alluvial fans were also present within some of these landscapes. Since these soil map impurities carry with them there own set of land use hazards such as soil erosion, mass movement, flooding and drainage risks, they have very important implications for land management planning.

Statistical differences in the soil properties of each map unit

Table 3 shows that there is an adequate degree of overall variability in most of the soil properties in the Birrigai area to allow meaningful evaluations of mapping success to be carried out.

A Fixed One-Way Analysis of Variance (ANOVA) was carried out on the discrete soil data from the random evaluation sites, in respect of the 1:10 000 scale map unit groupings, which in effect represent the most detailed and accurately delineated landform based map units for this area. This analysis revealed that the only soil properties considered to have been separated out into significantly different populations by the map units were the clay % and the gravel % of the A1 horizons ($P<0.05$). Further investigations of this variance, by Tukey multi-comparisons, revealed that for both of these soil properties the Swamp unit (SW) differed significantly from all the other units. These significant differences are obvious, if one looks at the graphs of the means and standard deviations of the clay % and gravel % in each map unit in Figures 3 and 4, respectively.

Table 3. Overall Birrigai evaluation area variability (from the 42 random evaluation sites).

Soil Property	EVALUATION AREA I - BIRRIGAI (Random Data)						
	STATISTICS FOR AREA AS A WHOLE.						
	X	**SD**	**V**	**CV**	**Min.**	**Max.**	**Range.**
Depth of A_1	11.6	6.8	46.4	58.6	2	40	38
Depth of Total A	39.5	46.6	2171.3	118	4	300	296
% Clay - A_1	17.8	5.9	34.9	33	12.3	37.3	25
% gravel - A_1	19.8	11.9	140.8	60	0	45	45
pH - A_1	5.75	0.39	0.15	7	5.5	7.0	1.5
% Clay B_2	28.9	10.1	102.3	35	18.5	51.7	33.2
% Gravel B_2	30.5	15.6	242.2	51	2	55	53
pH -B_2	5.87	0.41	0.16	7	5.5	7.0	1.5

This inability to delineate statistically significant areas of soil properties using the most detailed breakdown of the landscape into soil map units, reflects some lack of order in the soil-landscape relationships of this area. This is a consequence of short range variability in the soil properties. This should not be considered in any way a mapping failure, but merely a reflection of the soil-landscape relationships of this particular location. Even though these units have not delineated out areas of distinct soil property populations, they have accurately outlined areas with unique combinations of natural hazard risks to land management unique to their landscape position, and within this framework have estimated successfully the values of the soil properties and their variability.

To assist the comprehension of Figures 1 to 5, it is necessary to now define the 1:10 000 soil association map units:

- **Sb** and **Sbf** denote the steep bouldery slopes and the steep boulder free slopes of the granite hills respectively;
- **M** denotes the moderately inclined slopes of the low granite hills;
- **Cr**, **Rs**, and **D** denote the crests, convex slopes, and drainage lines respectively of the low undulating granite rises;
- **R** denotes areas of rocky outcrop and boulders within the low granite hills and rises;
- **Wfs** denotes areas of waning footslopes;
- **Cfs** denotes convex footslope deposits;
- **Af** denotes alluvial fans;
- **Cf** denotes colluvial fan deposits;
- **AA** denotes young alluvial flats;
- **AP** denotes alluvial flats with Minimal Prairie soils; and
- **Sw** denotes areas of swamp within the low lying flats and drainage lines.

Even though the above ANOVA procedure revealed few soil landscape relationships, a less strict graphical review of the standard deviations and means reveals some further apparent relationships. A review of Figure 4 reveals that all of the low to moderately inclined hillslope units and the alluvial elements within them (i.e. M, Cr , R, Wfs, Af, AA, AP) are consistently slightly variable with clay percentages in the range of sandy loam to loam texture grades, while the steeper hillslope units(i.e. Sb , Sbf), the steeper footslope units (i.e. Cfs, Cf) and the rock outcrop units have consistently low clay content in their topsoils with very little variability. The drainage line unit (D) within the low granite rises was found to have no variability in its A horizon clay % with all three of its evaluation sites having clay loam texture grades reflecting its depositional setting in the landscape.

Figure 2 shows the estimated clay % of the B2 horizons of these sites and reveals that most of these units are highly variable with the exception of steeper hillslope units (Sb), the colluvial fan unit (Cf), and the crests of the low granite rises unit (Cr). This reflects the erosional/transportational nature of the Sb unit, the lack of sorting of the Cf unit subsoil materials, and the residual nature of the hillcrests (Cr), respectively.

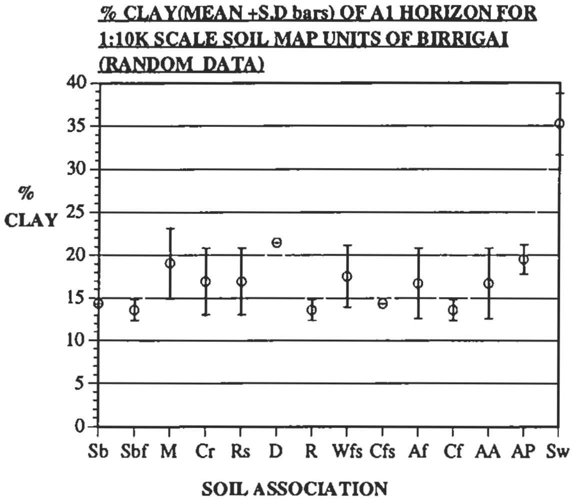

Fig. 1.

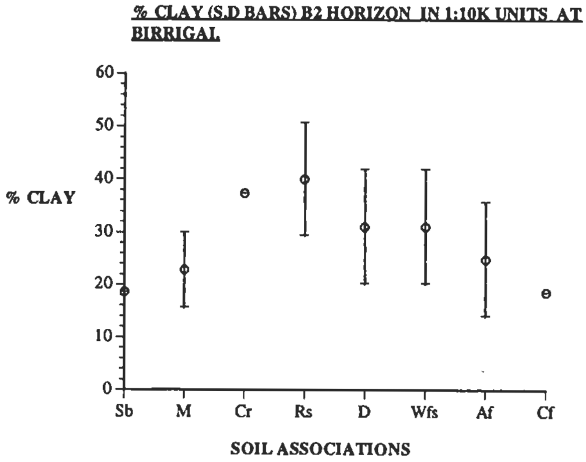

Fig. 2.

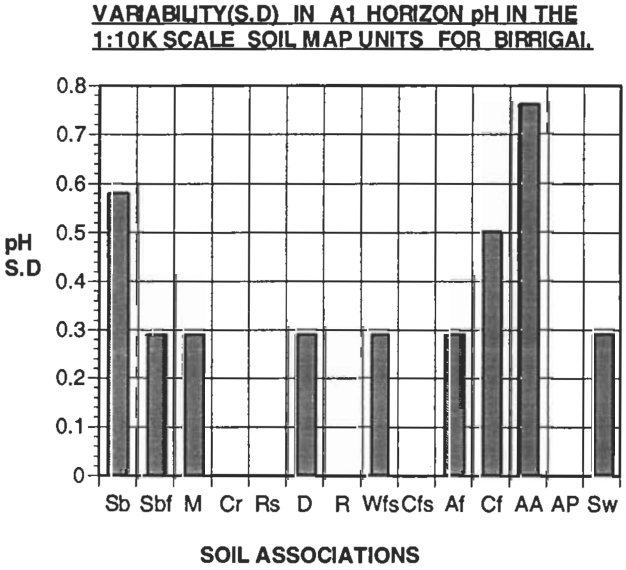

Fig. 3.

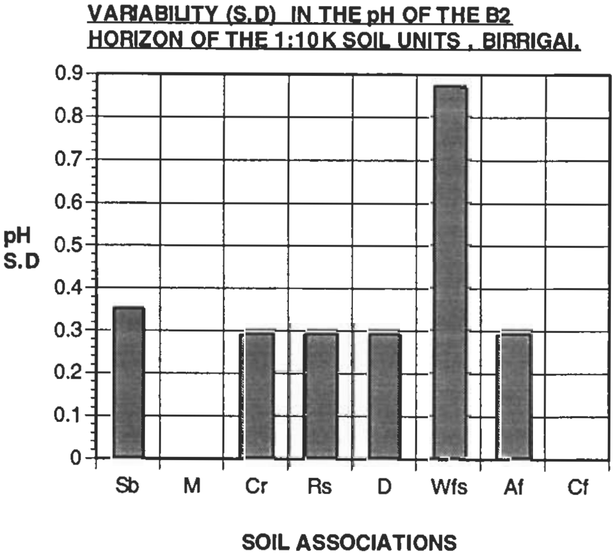

Fig. 4.

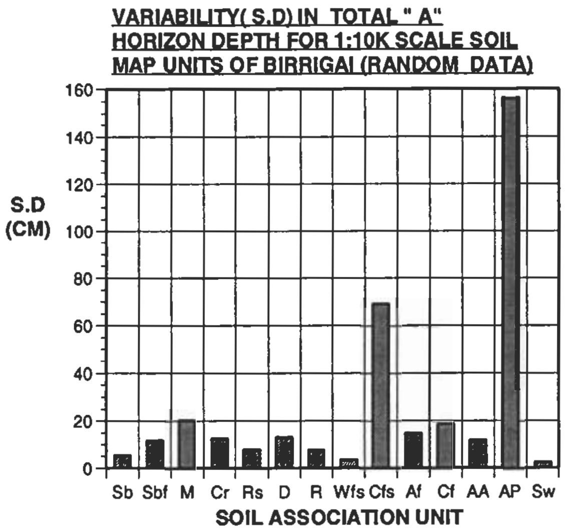

Fig. 5.

Figure 3 reveals that the pH of the A1 horizon for some of the units is quite uniform, while in other units it is slightly variable, but it is hard to see any obvious trends. It is interesting to note the dramatic difference in the variability in pH between the two alluvial soil units (AA and AP). This may be a consequence of the fact that the AA unit receives regular depositions of alluvial sediment with frequent flooding, while the AP unit with its Minimal Prairie soils experiences more stable conditions, thus contributing to less heterogeneous soil materials.

An outstanding feature in Figure 4 is the higher variability of the subsoil pH of the waning footslope unit (Wfs) compared to the other units. This could be a consequence of variable inputs of materials from the higher slopes to the parent materials of the soil profiles of this landscape zone.

Figure 5 reveals how the variability in the depth of the total A horizon is low for most of the soil units except for the convex footslope unit (Cfs) and the Minimal Prairie soil alluvial unit (AT). The higher variability of these two units results from a combination of the typically deep A horizons of these soils with areas of shallow soils associated with the sporadic presence of boulders and rock outcrops near the ground surface.

Thus, even though the soil populations delineated by the landform based mapping unit boundaries were not considered to be statistically significantly different for the majority of the discrete soil properties examined, trends were apparent between these units in terms of the extent of within unit variability of certain soil properties.

There is very little reduction in the variation in soil properties within units with increasing mapping scale in this area, as revealed when the predictive models of the 1:100 000 scale soil landscape map, are examined landform facet by facet and then compared with the 1:10 000 scale soil unit predictive models. This is a consequence of the inability of the 1:10 000 scale soil association map to further subdivide the basic landform facets of the 1:100 000 scale soil landscape predictive models on the basis of observable landscape features, with the increased resolution.

A need for thorough on the ground reconnaissance in small scale soil survey

Ground truthing should involve utilizing most of the accessible roads in the mapping area, and is important for the following reasons;
(i) It allows the map unit boundaries determined from air photo interpretation to be checked for accuracy, and consequently to be modified if found wanting. A number of the Paddys River soil landscape boundaries were subsequently adjusted following quick field checks.
(ii) It allows detection of any subtle changes in parent material or landscape pattern, not apparent in the typical small scale geology survey maps and the medium scale air photos available. The Gibraltar Creek Forest (GF) soil landscape in the Paddys River catchment, with its very porous earthy well drained Red Kandosol (red earth) soils, was only discovered as a result of field checking. These soils are associated with an area of biotite-rich granite not delineated on the geology map, .
(iii) It enables the testing of extrapolations of apparent soil-landscape relationships from the initial soil traverse to other areas of that unit across the entire map area, and as such indicates whether there is a need to modify the initial model.

Thus a rapid, on the ground coverage of an area in a vehicle can help reduce the extent of mapping error usually associated with small scale soil resource mapping.

A need for thorough on the ground reconnaissance in small scale soil survey

Ground reconnaissance is needed to help accurately ascertain the degree of variability in designated soil materials. The dominant subsoil material (Bc4) of the alluvial terrace Blue Gum Creek soil landscape within the Paddys River catchment was found to be highly variable from 3 sites 20 m apart (see Table 4).

Table 4. Variability within the Bc4 subsoil material

SOIL PROPERTY.	PROPERTY RANGE (Modal condition in brackets)
SOIL COLOUR	Light grey to bright yellow brown.
TEXTURE	Fine sandy clay to heavy clay [light -medium clay]
STRUCTURE	Massive to strongly pedal [massive]
GRAVEL %	0 to 20 [0]
pH	4.5 to 7.0 [5.5]
Emerson Aggregate class	1 to 5/6 [5/6] ie very dispersible to slaking soil aggregates.

A need for quality control in regolith mapping

The Marsman and de Gruijter (1986) measures of map accuracy (purity) and homogeneity (precision), some of which were used in this study, have been recommended as appropriate map quality measures for soil maps in two recent reviews by McKenzie (1991) and East (1994). These reviews have suggested that somewhere between 100 and 150 independent evaluation sites per map sheet should be allocated to give an independent assessment of the quality and reliability of the soil map produced. It would seem logical that such an independent assessment of map quality would be equally applicable to other varieties of regolith maps.

Conclusion

The scale of mapping was found to have had very little effect in reducing the variation in the soil properties within the landform facets. This is due mainly to short range variation in the soil properties, and a general lack of order in the soil-landscape relationships for many soil properties within this area. However, significant gains were achieved in eradicating map impurities, in the form of included landscapes and alien landform facets, by increasing the scale of mapping and hence the resolution that comes with it.

Even though the strict ANOVA procedure revealed few statistically significant soil - landscape relationships, a graphical review of the statistics revealed some further apparent soil - landscape relationships in regard to some important A and B horizon properties.

In terms of map predictive success, both the 1:100 000 scale soil landscape map and the 1:10 000 scale soil association map performed well, but the 1:10 000 scale soil map was considered superior because it had less map unit impurities and relied less on landform interpretation for its success. This was despite the fact that there was no obvious reduction in the interpretive map unit homogeneity ratings, with increased mapping scale .

This study has confirmed that soil spatial variability is a real landscape attribute which does not always exhibit apparent order in the landscape. This variability has to be taken into account in soil survey procedure, with adequate field reconnaissance checking and site replication to enable its extent to be adequately estimated and incorporated into the predictive models of the soil map units.

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THE REGOLITH

The regolith is a mass of weathered material that is charged with salts and biota ..... it is a suppurating mass that gradually consumes any blocks enclosed within it, and is gradually gnawing away at ..... the bedrock. In general, the regolith is a discontinuous, festering veneer .....

Twidale, 1990

Biological Applications of Regolith Mapping

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Introduction

Regolith mapping applications in the fields of mineral exploration and to a lesser extent landuse management have been widely documented and appreciated. However, the value of regolith mapping to biology has unfortunately been comparatively overlooked. The interaction between biology and regolith substrate is the basis for many of these biological applications. They have long been recognised (perhaps even taken for granted) in many of the biological disciplines (e.g. botany, zoology and ecology), however collaborative work between these disciplines and geology (including regolith studies) has been limited. This paper briefly highlights some of the areas where there is potential for collaborative work between the regolith mappers and biologists.

Biology and Regolith Interactions

Regolith may be a major ecological constraint. Many flora and fauna species require particular landscape settings or regolith substrates to survive. Therefore the distribution of flora and fauna species may be restricted to areas with particular regolith characteristics. Symbiotic relationships between living organisms and the regolith commonly occur and may influence the development and subsequent distribution of many regolith features (Ollier, 1984; Taylor, 1994). The spatial aspects of these relationships may be mapped and subsequently delineated using a regolith map.

Geobotany

Geobotany is the visual association of flora species and communities with the geological substrate. These observations have been well known since ancient times. Philosophers such as Vitruvius in 10 BC observed that certain species are restricted to marshy ground and the 6th Century AD Indian philosopher Varahamahira identified many relationships between plants, minerals and groundwater (Dunn, 1995). In 1841, Karpinsky made the significant conclusion that in most cases a *whole* plant community should be considered rather than just a single species.

Geobotanical relationships tend to be most obvious in environments that are harshest on plants. Examples include arid or waterlogged areas where extremes in water availability is a major factor influencing plant life, and also in areas with elemental deficiencies and toxicities such as may be associated with geological substrates with extreme geochemical compositions such as calcareous materials, serpentinites (Brooks, 1987) and ore bodies (e.g. Cole, 1973; Gough, 1986). These relationships may be very obvious, such as in riparian and swamp communities, however in many cases they may also be more subtle, requiring detailed vegetation surveys.

Biogeochemistry is a field that is still developing its potential as a geochemical exploration tool. It involves the chemical analysis of trace elements in plant tissues. It is important that the substrate in which the plant is growing, and from which it obtains its chemical signature, is considered when interpreting these surveys. Regolith maps used in conjunction with biogeochemical surveys have the potential to do this. For instance biogeochemical thresholds may differ for plant samples taken from different landscape settings and substrates. This is similar to the philosophy behind using regolith maps to provide the context and the means to compare results from more traditional regolith geochemical surveys (Anand and Smith, 1993).

Geozoology

The occurrence of many fauna species may also be intimately related to substrate characteristics. This may occur indirectly as a result of fauna being influenced by geobotantical associations but may also occur through the fauna species' direct interaction with the substrate. Examples include, aquatic species that have particular water quality and bedload requirements which ultimately will be controlled by the regolith substrate. Many fauna species are dependent upon the nature of the regolith substrate to determine the provision of homesites. Burrowing organisms (such as rabbits, termites) are obvious examples of this, but the same is also true for many other fauna types, particularly reptiles. The importance of interactions between micro-organisms and the regolith substrate is also becoming increasingly recognised (e.g. McFarlane, 1987; Phillips *et al.*, 1987), and is a research area that has great potential to increase our knowledge of regolith processes and in turn contribute to our understanding of genetic and spatial aspects of the regolith. Biogeochemical applications using fauna species may also have potential as a geochemical exploration tool.

Geoecology

Underlying much of this discussion is the philosophy that animals, plants (the biosphere) and the terrestrial spheres (the atmosphere, hydrosphere, toposphere and lithosphere) all interact with one another. This philosophy is embraced in the discipline of geoecology. In other words regolith and associated landscapes are the substrate upon which ecosystems are developed. Ecological processes and features can all, even if only indirectly, be related to the regolith substrate upon which they occur and interact. An excellent example of the application of this philosophy, even up to a continental scale, can be seen in the work of Bell (1982) where he emphasises this relationship between soil nutrients (and thereby part of the regolith substrate) to ecosystem biomass in Africa. There are numerous other examples of these types of relationships at all scales, many of which are outlined in Huggett (1995).

Implications for Regolith Mapping

Besides the specific interactions between biology and the regolith substrate that are of significance to regolith mapping, there are several related direct applications.

Biological Regolith Mapping Surrogacy

Vegetation is a commonly used surrogate in regolith mapping. The philosophy behind this comes from geobotanical observations where the occurrence of certain plant species and communities may be intimately related to the soils and in turn the geological or regolith substrate and landscape setting in which they live. With some understanding of the substrate requirements of the plants being used as a surrogate, their distribution patterns may even be directly related to specific attributes of the regolith, such as a sandy substrate (e.g. Parsons, 1966) or calcrete (e.g. Hill *et al.*, 1994). As with the use of all regolith mapping surrogates some precautions need to be taken (Hill, 1995). Other factors besides regolith substrate will commonly influence plant communities. Factors such as climate, fire history and anthropogenic influences may also be related to the nature of the regolith, however they potentially can give erroneous impressions if they are not considered.

Regolith Maps for Biological Surveys and Management

Regolith maps have the potential to provide assistance in areas of biological habitat characterisation and management. Land management applications of the geobotanical associations with regolith substrate could also be utilised. For instance the recognition of groundwater discharge and recharge regolith-landform settings and their corresponding vegetation features could be important for dryland salinity management.

The incorporation of this type of broad scope information at a regional scale was a major feature of Land System mapping developed by the CSIRO. The collaborative use of regolith maps and biological surveys has the potential to provide more detailed and specific information than the Land System approach. For example the pink-tailed legless lizard is an endangered species in the Canberra region that has a distribution potentially related to the regolith-landform characteristics of its homesites. This lizard lives in shallow burrows beneath partly buried rocks. If the regolith-landform characteristics of the preferred homesite rocks are identified, then the distribution of areas with these characteristics can be delineated on a regolith landform map. Preliminary observations in association with S. Jones from the University of Canberra Applied Ecology Research Group suggest that the lizard has a preference for hill slopes with partially buried, angular rhyodacitic rocks with a large surface area to volume ratio. A regolith map based on rock float morphology and slope facets can identify possible lizard habitats, providing additional information about the variables that influence its habitat selection and also assisting in its conservation management. The further understanding of the ecological requirements of other species could be identified in a similar manner (e.g. Vaughan, 1978). Further research into related issues such as correlations between regolith-landform diversity and species diversity could also be valuable to these types of applications.

Conclusion

Regolith mapping has much to offer the biological sciences. As has been identified by geoecologists and workers in related fields, it is the regolith that provides the substrate and interface upon which life on Earth is dependent. Without considering the nature and distribution of regolith types, biological researchers could be overlooking a fundamental basis of their study (Barsch, 1990). This relationship may also be exploited by regolith workers where a greater appreciation of biological interactions with the regolith may assist in the understanding and recognition of distribution patterns of the regolith.

Acknowledgments

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Data, What Data?

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Introduction

Methods of presenting data, be they by academics for their own use or professionals for clients, are being rapidly overhauled with the advent of new computer technology. Discussions during the Regolith Mapping Workshop at the University of Canberra saw division on how to present data to their best advantage in the future. Some participants still regard paper maps as the best way to present data. Others (including myself) believe that data should be presented in a way that allows manipulation by the client (i.e. digitally) rather than in a fixed format which may not totally suit the client's needs (i.e. as paper maps).

The advent of cost-recovery and rapid developments in the technology of data presentation have changed the range and quality of presentation methods, although the actual quality of the data is still subject to human intervention and may not have improved. Professional and semi-professional database and GIS programs now allow an operator with average skills to produce high-quality digital and paper output from their desktop computer in formats that suit the end user, not the purveyor. However, some individuals and organisations are still producing output which was satisfactory decades ago in the belief that it should still be satisfactory today.

This short paper discusses the likely future trends in data presentation. What will be the needs of your future clients? How will they want to purchase their data and how should you be prepared to present it to them?

What Data?

Data, in the sense of this discussion, are any facts or interpretations which can be presented in a digital format, including data currently in an analogue format which is capable of being digitised or otherwise entered into a computer database. It makes sense to handle data by computer in a digital format because computers operate at speeds many thousands of times faster than humans in a relatively error-free fashion (never forgetting that a computer is only as good as its programming). Geographic Information Systems are now regarded as the bottom-line method of computerised data manipulation and this data most often takes the form of map data: points, lines (vectors), polygons (regions) and their associated attributes; and raster data (an average of the characteristics of a small, usually square, area or pixel). GIS data is predominantly spatial in that it depicts the spatial relationships between data items. Newer, faster systems can store temporal data (showing the change through time of spatial data) and allow data augmentation by linking GIS systems to relational databases, allowing much more attribute data to be stored and cross-matched.

How are Data Currently Presented?

A large amount of the data presented during the Regolith Mapping Workshop was presented as images, the rest as maps. The images were composed of digital data either in the form of rasters (pixels), as GIS data consisting of points, lines and polygons depicting various attributes within the field of view, or as a combination of both. All of the images depicted what their creators thought end-users should see.

Some of the maps and images were obviously professionally typeset and printed using offset printers or photo-lithography. Others were the products of smaller, personal computer-based GIS and image processing systems which were printed on ink-jet printers at or near the authors desk. In the case of the professionally typeset maps and images, the time between completing the mapping and producing the finished product could be more than two years (I am not suggesting that maps drawn by professional cartographers are obsolete, just that they are very slow to produce). In the case of the desk-top published maps production times could be as little as two days. In either case, the presentation method was as a fixed format on paper.

How Should Data be Presented?

Some of the presentations were, in my opinion, approaching the style expected by future data users. Mitch Tulau from CALM presented a series of soil landscape maps from the Cooma-Monaro region which he had produced on a desktop-mapping system and printed on an ink-jet printer. While I can not comment on the quality of the maps and the information which was contained on them, the *way* he produced them impressed me. Mitch produced his maps from a small computer and printed them on an ink-jet printer using a system which allowed the end-user (or client) to define what was necessary on the final output. The system then allowed the operator to quickly alter the data or map parameters to produce a final copy of what the user (client) actually wanted.

The system allowed the operator to quickly produce a product and just as quickly alter it to make it more suitable. In the interim, I believe that this method of presentation is superior to professionally drawn maps because of the speed of production and the ability to alter the product at short notice without great expense. Incorrect data can be updated quickly and re-issued without the need for expensive typesetting and reprinting. Some of the other advantages in going the digital route are summarised in Fig. 1.

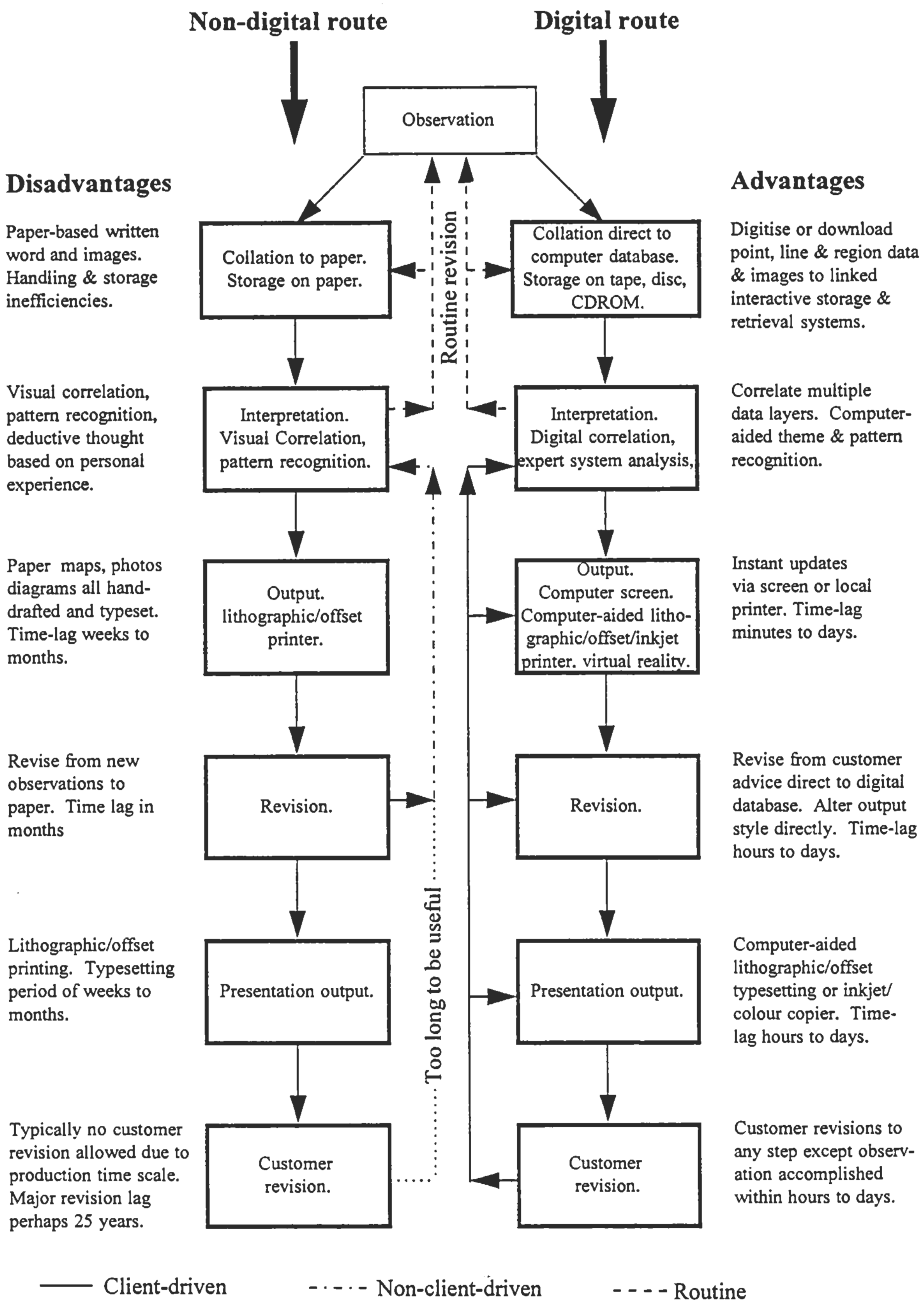
What Will Be the Needs of Future Users?

We can now produce a map or image from the desktop and alter it to suit the needs of out clients, what of the future? The future is digital. I believe that users and clients of the future will expect to be given their data in a purely digital form to create maps and databases at their whim. They should be able to manipulate it on their own desktop computer to create the products they want when they want them. Users will carry the digital data with them in the field (as some do already) and will be able to update the data *in situ.*

The point is that data need to be presented on some form of high-density storage medium (CD-ROM, DAT tape, magneto-optical disc) in a form that can be manipulated to suit the user's needs, not the purveyor's. Instead of providing a paper map, the purveyor should supply a disc or tape containing raw data that the user can manipulate themselves, allowing greater flexibility. The user should not have to revert to paper at all during the process.

Are These Needs Being Met at Present?

Two organisations which come to mind (AgRecon and AGSO) are already following this course to some extent. AgRecon is a joint venture between the University of Canberra and Dr Brian Button (also of the University of Canberra) which specialises in remote sensing for



Disadvantages

Paper-based written word and images. Handling & storage inefficiencies.

Visual correlation, pattern recognition, deductive thought based on personal experience.

Paper maps, photos diagrams all hand-drafted and typeset. Time-lag weeks to months.

Revise from new observations to paper. Time lag in months

Lithographic/offset printing. Typesetting period of weeks to months.

Typically no customer revision allowed due to production time scale. Major revision lag perhaps 25 years.

Advantages

Digitise or download point, line & region data & images to linked interactive storage & retrieval systems.

Correlate multiple data layers. Computer-aided theme & pattern recognition.

Instant updates via screen or local printer. Time-lag minutes to days.

Revise from customer advice direct to digital database. Alter output style directly. Time-lag hours to days.

Computer-aided lithographic/offset typesetting or inkjet/ colour copier. Time-lag hours to days.

Customer revisions to any step except observ-ation accomplished within hours to days.

Fig. 1. Summary flow chart showing the typical processing of digital and non digital data and the advantages of the digital route.

agricultural purposes. AgRecon takes Landsat and SPOT satellite data it purchases from the Australian Centre for Remote Sensing (ACRES), reprocesses it and sells it on to agriculturalists who use it to assess crop health. While many companies and government organisations already do this, AgRecon has gone one step further and has had inexpensive image processing software written to allow the purchaser to manipulate the images themselves to produce the product they want, not what the supplier thinks they want. In this case, the data are sold on mass-storage media (floppy disk or more usually CD-ROM) and kept permanently in a digital format. Unless the end-user wants to take a hardcopy out into the paddock, the data need never be printed on paper.

The Australian Geological Survey Organisation (AGSO) will sell you anything. Data products range from satellite images to sets of geochemical data and can be purchased in a range of formats (floppy disk, exabyte tape, DAT tape, round computer tape, square computer tape, the list is endless) to suit the user. The key to AGSO's policy is that the user can purchase raw data and manipulate the information themselves to create a product to suit their own purposes. Unfortunately, the raw data comes at great expense because of the advent of cost recovery by most government agencies.

Conclusion

There will always be people who want to read paper maps. I do not think that there will ever be a time when they are not used for something. However, many users want to be able to manipulate their own data to suit their own individual needs and hardcopy paper maps do not give them this flexibility. By providing digital data in the first place, users can create their own datasets and eventually their own hardcopy paper maps. This offers users the flexibility that the large-scale cartographical map making methods deny and serves to make eventual final products more meaningful. I hope the arguments presented here will add even a little support to the idea of moving towards producing more digital data and less paper data to support the needs of future users.

The Nature and Importance of Regolith Mapping: Workshop Outcomes

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Introduction

Systematic regolith mapping is still in an early stage of development. In many ways the situation is similar to that faced by geologists in the early part of the 19th century when they started to produce the first small scale, largely bedrock, geological maps. Problems of nomenclature, material versus genetic classifications, competing theories of material origin and difficulties with correlation and dating are still to be overcome or resolved in regolith mapping. Lessons and approaches pioneered by 170 years of bedrock geological mapping may well be relevant to regolith mapping. Some problems may require special solutions. In a way it is ironic that although regolith is the most visible and accessible material of the earth's crust, systematic continent and global scale mapping was first developed for the underlying and commonly regolith-obscured bedrock. It is also a curious fact that interest in regolith materials by geologists was first brought to focus by studies of another planet, the Moon (all samples collected on the Moon by the Apollo program were from the lunar regolith).

One of the main aims of this workshop was to discuss issues relevant to the improvement and development of regolith mapping. Discussion revolved around four questions:

1. What are we mapping when we map "regolith"?
2. Why are we mapping it?
3. How do we map it?
4. How do we present the data?

What are we mapping when we map "regolith"?

Most people would agree about the definition of regolith. According to Bates and Jackson:

> "Regolith (reg'-o-lith) A general term for the layer or mantle of fragmental and unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface of the land and overlies or covers the bedrock. It includes rock debris of all kinds, volcanic ash, glacial drift, alluvium, loess and aeolian deposits, vegetal accumulations, and soil. The term was originated by Merrill (1897, p. 299). Etymol: Greek *rhegos*, "blanket", + *lithos*, stone." (Bates and Jackson, 1987, Glossary of Geology).

Presumably this is what we are trying to map? However, as Roslyn Chan pointed out, because of its complex nature, we often use a surrogate for the regolith. Usually this is landform, and this works because of the close correlation between landscape position and regolith type in most landscapes. Cliff Ollier notes that it is often difficult to map regolith without a model, or a theory of how the regolith sits in the landscape. This is fraught with difficulties, and if pushed too far, we may end up, to use Cliff's words, mapping our state of mind rather than what is actually there. Steve Hill notes that there are in fact a number of surrogates that can be used - lithology, geology, soil, vegetation. One thing is quite clear, regolith mapping units are very different in concept from geological mapping units.

Why are we mapping it?

The reasons for mapping regolith can be to provide a data base on regolith nature and distribution, or to help in the production of derivative maps. A knowledge of the nature and distribution of different types of regolith can have direct application in understanding soil types and distribution (and hence agricultural production), groundwater hydrology and geochemical dispersion. Knowledge of the physical and chemical characteristics, thickness and source of regolith is also useful to geotechnical engineering, mineral exploration and studies of landscape evolution, palaeoclimates and land degradation.

It is also clear from Ray Evans' paper that regolith information may turn out to be critical for the management decisions that will affect landuse in Australia. Ray stressed the fact that environmental degradation is at a critical level in Australia, and that it should be a catalyst for regolith mapping.

Regolith mapping can also assist in bedrock mapping and soil-landscape mapping. In the former there has, and still is, a tendency to regard most of the regolith as Quaternary. A consequence of this is to see the "yellow wash" on the geology map as the province of the regolith specialists. This underlines the confusion between the time-stratigraphic concept of geological mapping and the materials/landform concept behind most regolith mapping. Soil-landscape mapping on the other hand is clearly landscape based, and regolith maps provide a background against which to compile soil-landscape maps.

Another issue here is whether we produce general or special purpose maps. Several people at the workshop argued strongly that regolith maps should be "fact" maps that can be interpreted by the user for their own application. This means that the mapping basis should be the same whatever the application.

How do we map it?

This question generated the most discussion. There is a wide range of data sources, from drill core to Landsat images. The main issue in "how" is probably the scale of mapping, and whether it is for general or specific purposes. Some organisations have already adopted a standardised approach in the collection of regolith data and the spatial representation of the information and interpretation. As an example, the approach to regolith mapping currently employed by the Australian Geological Survey Organisation (AGSO) is to:

- compile an initial map at suitable scale from aerial photographs;
- supplement this with Landsat TM data;
- collect information in the field at suitable and key sites;
- construct a data base of: - site information;
  - attributes assigned to polygons;
- incorporate data from other sources such as radiometrics, radar, aeromagnetics.

The basic units of mapping are regolith terrain units (RTU's), which for all practical purposes are land units rather than units of material. Minimum attributes for polygons include regolith type and landform type, but other attributes are also included (up to 8) such as drainage, toposequence etc.

The detail of these procedures for regolith description and mapping is provided in the "Red Book" (Pain *et al.*, 1991). A similar guide for soil-landscape mapping has been prepared by workers at CSIRO and is referred to as the "Yellow Book" (McDonald *et al.*, 1990). The Department of Exploration and Mining, CSIRO have also developed less formalised procedures for mapping and describing regolith materials (e.g. Butt and Zeegers, 1992; Anand and Smith, 1993).

The greatest need stressed by the workshop participants was for some form of consistency, in mapping methodology, but more particularly in terminology. There was a general feeling that both the terms "ferricrete" and "laterite" should be tossed out the window!

How do we present the data?

There are many ways to present data collected during regolith mapping exercises.

- Hardcopy maps are currently the most common option. The main problem is deciding what to show on a hard copy map. Moreover, most people need to be taught how to read a regolith map.

- Digital data, perhaps on CDROM, are becoming much more important. Most if not all organisations producing regolith maps do so through a geographic information system. This allows the inclusion of layered data, not only of regolith information, but also images, scanned photos, and site data.

- Digital data will become increasingly available on the Internet via a World Wide Web browser, or anonymous FTP (e.g. check the WWW sites http://cars1.canberra.edu.au and http://geology.anu.edu.au/leme/).

Future Developments

Probably the most critical requirement for the further development of regolith mapping is a standardised terminology of regolith materials. One of the key tasks of the new Cooperative Research Centre for Landscape Evolution and Mineral Exploration (CRC LEME) will be to address this issue of regolith nomenclature. Various suggestions were made at the workshop as to how this might be approached. It might be possible to combine the existing AGSO and CSIRO schemes. But would this be too specific to the minerals exploration industry? It was generally agreed that any scheme should, as far as possible, retain existing common-usage terms. It was also felt that the nomenclature should be developed for Australia but as far as possible be compatible with a global coverage. The definition and nomenclature of regolith units also requires consideration. Most participants at the workshop agreed that they would have little trouble defining and naming regolith units of sedimentary origin but how do we define and name weathering profiles?

The practice of regolith mapping will need improvement and refinement. It was pointed out that there is a need to ensure accurate overlap of regolith and bedrock types. Regolith data base layers need to incorporate a time layer to help describe age and stratigraphy of the regolith. There needs to be a consistent, or at a least a correlatable, approach to mapping at particular scales. This will require a standard set of polygon attributes, possibly with an additional set for specific client use.

In the future there will be greater need for quantitative measures of within and between unit variability of regolith features. We will also need to further develop rapid and low cost mapping techniques. Remote sensing techniques such as aerial photography, Landsat TM and increasingly airborne magnetics and radiometrics, have been successfully applied to assist rapid regolith mapping. The minerals exploration industry has also successfully applied geochemical assessment techniques in defining element dispersion and material types in the regolith. Understanding and mapping mineralogical variation in the regolith will become increasingly important and rapid low cost techniques such as PIMA (portable infrared mineral analyser) and field-based XRD will be important tools for the regolith mapper of the future.

Concern for environmental degradation will undoubtedly become a greater catalyst for regolith mapping. This concern already drives soil-landscape mapping in Australia. A challenge will be to determine the most appropriate regolith attributes to use in environmental degradation studies. Aspects currently under consideration include:

- possible correlations between salinity and deep weathering profiles;
- the control of hydrology by particular regolith materials;
- relationships between erosion and the degree, distribution and depth of weathering in the landscape;
- the possibilities for artificial or natural modification of regolith to combat degradation.

What additional regolith attributes should be collected to monitor degradation? How do we cope with the variance in scale of these problems in relation to our regolith mapping? It was suggested at the workshop that the new CRC LEME should attempt to forge bonds with the National Geoscience Mapping Accord and land degradation mapping groups to begin cooperative research and education programs in this area.

Undoubtedly in the future there will be new methods of data collection and handling beyond our imagination and current capabilities. Regolith mapping is still in its infancy.

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