BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1983/27

RECORD

Regolith in Australia: Genesis and Economic Significance

Summary papers presented at a symposium held in
Canberra, November 1983

Sponsored by the Bureau of Mineral Resources, Geology and Geophysics
and the CSIRO Institute of Energy & Earth Resources

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PREFACE

The summaries in this volume are those of papers presented at the symposium on Regolith in Australia: Genesis and Economic Significance, held at the Australian Academy of Science in Canberra from 15 to 18 November 1983. The Symposium was sponsored by the Bureau of Mineral Resources, Geology and Geophysics and CSIRO Institute of Energy and Earth Resources.

The initial stimulus for the meeting came from the realisation that both the BMR and CSIRO were involved in regolith research, and it was felt that a meeting in which each could discover what the other was doing would help to avoid overlap and assist in co-operative work. These two organisations are not the only ones interested in the regolith, so it was decided to widen the scope of the symposium to include other interested groups, especially universities and colleges, and companies in the mining industry. It is a disappointment that no papers were offered from companies, and the symposium is more academic than we had intended.

In a way this symposium is a successor to the 1981 symposium on the Cainozoic Evolution of Continental Southeast Australia, and recent workshops on Geochemical Exploration in Deeply Weathered Terrain. This time the entire continent is included, and techniques are by no means limited to geochemistry.

By chance our symposium comes at a time when Regolith seems to be a fashionable topic for symposia. In March 1982 the Geological Society of London held a two-day symposium on Residual Deposits: Surface Related Weathering Processes and Materials: an International Colloquium on Petrology of Weathering and Soils was held by CNRS in Paris in July, 1983: one of the themes of the forthcoming International Geological Congress in Moscow, August 1984, is Regoliths and Mineral Resources.

The deep weathering of rocks is developed to an exceptional extent in Australia, and is of considerable significance to mining and mineral exploration. Some weathered material is itself of economic value; more often the weathered zone is a barrier between explorers and their target.

The symposium includes papers ranging from the continental scale through regional to quite local studies. Techniques include geomorphology, geochemistry, isotope studies, remote sensing and palaeomagnetism. Most studies deal with weathering but some are concerned with surficial sediments. The very long time scale of Australian surficial geology is evident in many contributions. There is no ruling theory in regolith studies, and it is clear that the authors of these papers often differ not only in details of such topics as geomorphic evolution, climatic history and geochemical mechanisms, but even in basic concepts. This is inevitable in a lively, growing field of study. We hope the exchange of views at the symposium will help all who work on regolith problems and bring together to some extent the many workers in Australia who are separated by barriers of geography and discipline.

The papers reproduced here are essentially as they were submitted by authors: only a few minor changes have been made in a few contributions to meet the needs and standards required for camera-ready reproduction. The organising committee wishes to thank the speakers, chairmen and field excursion leaders, and CRA Exploration for assistance.

C.D. Ollier (BMR) and G.F. Taylor (CSIRO) Convenors

R.W. Galloway (CSIRO)
G.E. Wilford (BMR)

G. Taylor (CCAE)
B. Murrell, J.B. Field (CRAE)

Organising Committee 1983

CONTENTS

Pb AND S ISOTOPE SIGNATURES IN WEATHERED TERRAINS

A.S. ANDREW and B.L. GULSON

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Pb isotopes are a relatively new tool in exploration, applicable both in the early phases of surface-based target evaluation and later at the drilling stage. Using Pb isotope ratios, Gulson and Mizon (1979) successfully distinguished fertile gossans, representing the weathered exposure of outcropping base-metal sulfide mineralization, and barren gossans.

S isotopes have not been used in mineral exploration apart from genesis-related studies. Their behaviour during gossan formation and weathering is not well understood and the data presented here are, as far as the authors are aware, the first to be published. There is some suggestion from the work of Smith and Batts (1974) on S isotope values in coals, that the sulfate found in coal seams has the same value as the total S and is formed by weathering of the coal during recent times.

The main emphasis of this paper is the behaviour of Pb and S isotopes during weathering and gossan formation. The Elura Zn-Pb-Ag deposit, western NSW, has been selected as an example of a massive sulfide deposit with homogeneous Pb and S isotope values. Although isotope values play a significant role in ore genesis investigations, which are of great importance in the development of conceptual models for exploration, they are not considered in this paper.

VARIATIONS IN Pb AND S ISOTOPE VALUES

In broad terms, the Pb isotope technique relies on the different isotopic signatures expected in country rocks, iron sulfides and base-metal mineralization. They are not influenced by comparatively recent processes such as weathering and oxidation. Variations in Pb isotopes arise mainly by radioactive decay (age dependent), from the differences in U/Pb and Th/Pb ratios and by mixing of Pb evolved from different environments.

The lithosphere contains varying amounts of U, Th and Pb. Separation of Pb from U and Th to form an orebody at a particular time after the formation of the Earth 4.55 Ga ago endowed that orebody with a unique set of Pb isotope ratios (the isotope "fingerprint" or "signature"). Pb-rich orebodies, known as "massive stratiform" sulfide types, are thought to be derived from a well-mixed Pb isotope reservoir such as the continental crust, as their Pb isotope ratios are usually homogeneous within the deposit and lie on, or very close to, a set of single reference growth curves (Figure 1). This updated concept derives from the pioneering work of Stanton and Russell (1959).

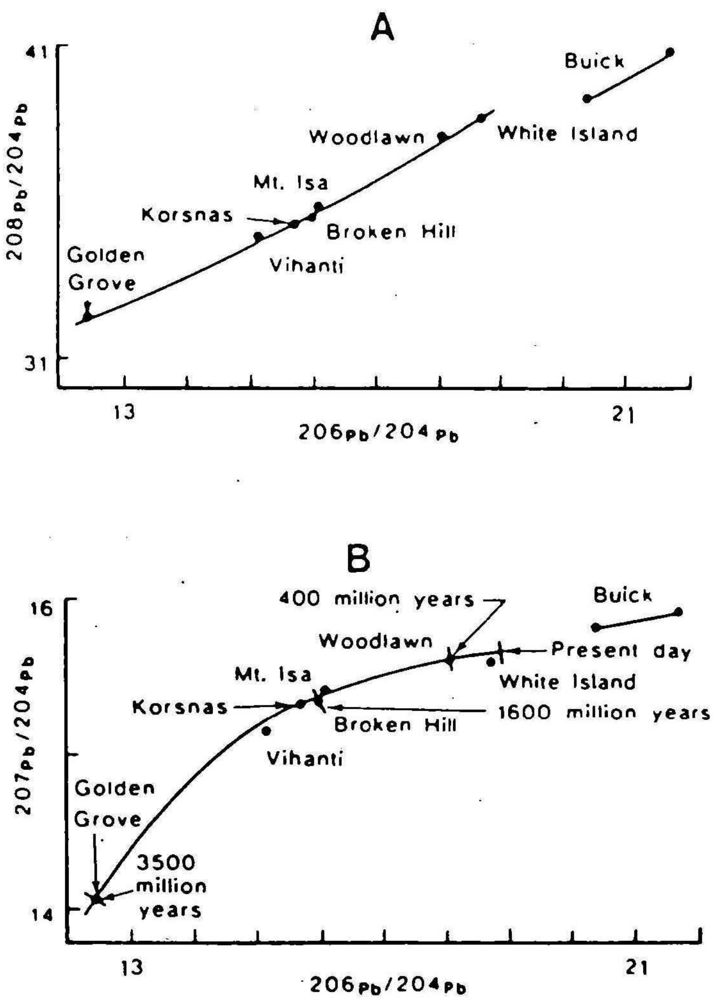

Figure 1 Pb isotopic ratio plots for the thorogenic (A) and uranogenic (B) isotopes illustrating the closeness of fit of major "massive" sulfide orebodies to the reference curves and their time dependence. "Buick" refers to a Mississippi Valley deposit in south-east Missouri, "White Island" is a massive sulfide occurrence in New Zealand.

The S isotope values found in ores depend on the isotopic fractionation that accompanies physical and chemical processes. Once "set" by a reaction, S isotope values do not change with geological time. However, subsequent weathering, metamorphism and hydrothermal alteration may change the isotopic values of some, and perhaps all, of the S-bearing minerals which make up the orebody. Variations in S isotope values within an orebody are related to changes in the mineralizing fluid (e.g. temperature, oxidation state), biological activity and the mixing of different S sources.

ISOTOPIC SIGNATURE

In order to apply isotope techniques to exploration it is necessary to establish the isotopic signatures of known mineralization. Systematic studies of various styles of mineralization (including barren iron sulfides) have established a series of Pb "target" isotopic signatures for use in exploration in Australia. For example, major orebodies such as Captains Flat, Woodlawn, Elura and Cobar in the Lachlan Fold Belt have similar isotopic signatures (Gulson, 1983), whereas those in the Mt Isa-McArthur belt (Mt Isa, Lady Loretta, Dugald River, McArthur, Coxco) have another distinctive signature (Gulson and Mizon, 1979). These signatures are quite different from those of other styles of mineralization (B.L. Gulson and M. Vaasjoki, unpublished data). Unlike Pb isotope values, S isotopes commonly have a large range of values within a single deposit and target "signatures" are not uniform within a metallogenic province. If no known mineralization exists, it is still possible to make an estimate of the "target" isotopic signatures using knowledge of the ore type sought, models for its genesis, host rocks and approximate age.

THE ELURA Zn-Pb-Ag DEPOSIT

Gossan

The Elura gossan has been divided into two types (G.F. Taylor, Y. Togashi, J.R. Wilmshurst and A.S. Andrew, in prep.):

(1) direct gossan formed in situ directly from sulfide, with the development of boxworks or pseudomorphic iron oxides; and

(2) solution-deposited gossan with a matrix of iron oxides precipitated at a distance from the site of oxidation.

The oxidation profile at Elura is deep (approximately 80 m) and well-developed, with an extensive ironstone zone. A narrow (3 m) oxidate zone of groundwater control (higher pH) extends from the ironstone to fresh sulfides and it has been suggested that a significant change has occurred recently in the rate and nature of the weathering (G.F. Taylor, Y. Togashi, J.R. Wilmshurst and A.S. Andrew, in prep.).

Pb isotopic ratios for eight gossan samples are homogeneous and similar to those in the massive sulfides. Ratios for gossans (and sulfides) are as follows: $^{208}Pb/^{206}Pb$ 2.1120 (2.1117) $^{207}Pb/^{206}Pb$ 0.8627 (0.8626) and $^{206}Pb/^{204}Pb$ 18.139 (18.126).

S isotope values for the ore at Elura are uniform, with values for pyrites of 8 to 12^{o}/oo CDT (Sun, 1983). Three grab samples, including both direct and solution-deposited gossans, were selected from gossans studied by G.F. Taylor, Y. Togashi, J.R. Wilmshurst and A.S. Andrew (in prep.). A sample from the oxidate zone containing secondary Pb minerals was also analysed. Gossan analyses (Table 1) were well within the range of S isotope values for the orebody which suggests that in gossan formation neither oxidation nor precipitation results in significant fractionation of S isotopes.

There is no recognizable isotopic difference between direct or solution-deposited gossans. The $\delta^{34}S$ value for the oxidate zone is significantly enriched in ^{34}S relative to both the ore and the gossan. The increase in $\delta^{34}S$ value may reflect fractionation during gossan formation, but in the light of mineralogical evidence (G.F. Taylor, Y. Togashi, J.R. Wilmshurst and A. Andrew, in prep.) it probably reflects a recent influx of ^{34}S-rich groundwaters.

Table 1: S isotope data for Elura gossans and weathered bedrock

Gossans CSIRO	DDH	Depth (m)	Type	S(wt%)	$\delta^{34}S$ (°/oo CDT)
63455	25	77.8	soln-deposited	0.67	8.6
63459	25	81.5	mixed	0.48	8.7
63462	25	89.3	direct	1.60	9.1
63466	25	101.8	oxidate	2.00	17.2

Weathered bedrock CSIRO	DDH	Depth (m)	S(wt%)	$\delta^{34}S$ (°/oo CDT)
101168	75	1.0-2.0	0.14	13.7
101171	75	4.0-5.0	0.25	12.5
101172	75	5.0-6.0	0.30	12.4
101178	100	5.0-6.0	0.20	11.4
101196	200	5.0-6.0	0.29	14.8

Weathered Bedrock

Soil and weathered bedrock samples were taken along traverses across the Elura deposit to test the application of isotope ratios in finding concealed orebodies. Samples from soil profiles to 45 cm depth have been analysed for Pb isotopic ratios in two traverses at Elura (Figure 2). Traverse A is over "blind" mineralization of the northern apophysis, whereas Traverse B is across a gossan formed by weathering of the massive sulfides of the southern apophysis (Figure 3). Soils from Traverse A have relatively uniform isotopic ratios and differ from the ore by more than 2%. These samples are taken to be background soil isotopic ratios for the Elura area. Soils from Traverse B (Figure 3) demonstrate the potential of Pb isotopes in exploration for concealed massive sulfides and may assist in defining the limits of the orebody.

Samples of weathered bedrock studied by G.F. Taylor, Y. Togashi, J.R. Wilmshurst and A.S. Andrew (in prep.) were used for a profile of S isotope values around the Elura orebody (Traverse C; Figure 2). Traverse C runs along a palaeodrainage channel and

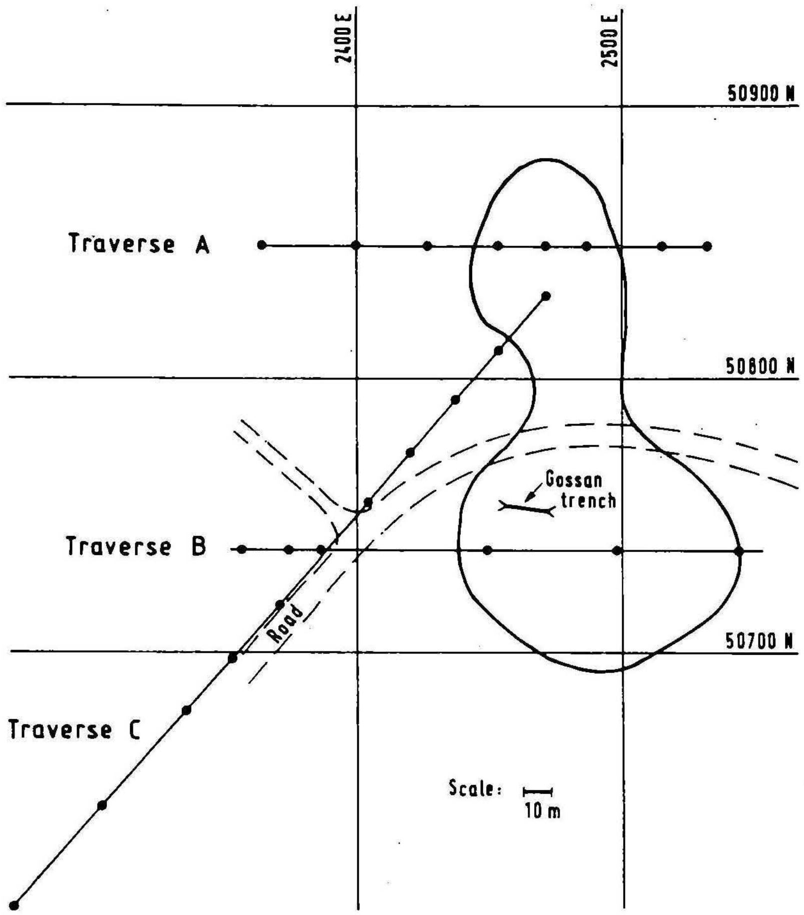

Figure 2 Plan of Elura mine site showing soil (Traverses A and B) and weathered bedrock (Traverse C) sampling sites. The surface projection of the orebody for a depth of about 100 m is outlined.

dispersion of elements is expected to be greatest along this trend. Sample selection was limited to samples with S contents $\geqslant$ 0.1 wt% S. At site 4 (75 m) samples were analysed 0-1, 4-5 and 5-6 m from the surface; at all other sites samples were from 5-6 m. The S isotope value of the surface sample from site 4 is enriched in ^{34}S relative to the deeper samples and the higher $\delta^{34}S$ values probably reflect contamination from recent events. The values from Traverse C (Figure 3) suggest that although S contents are uniformly low, S isotope variations may outline a meaningful halo around the orebody.

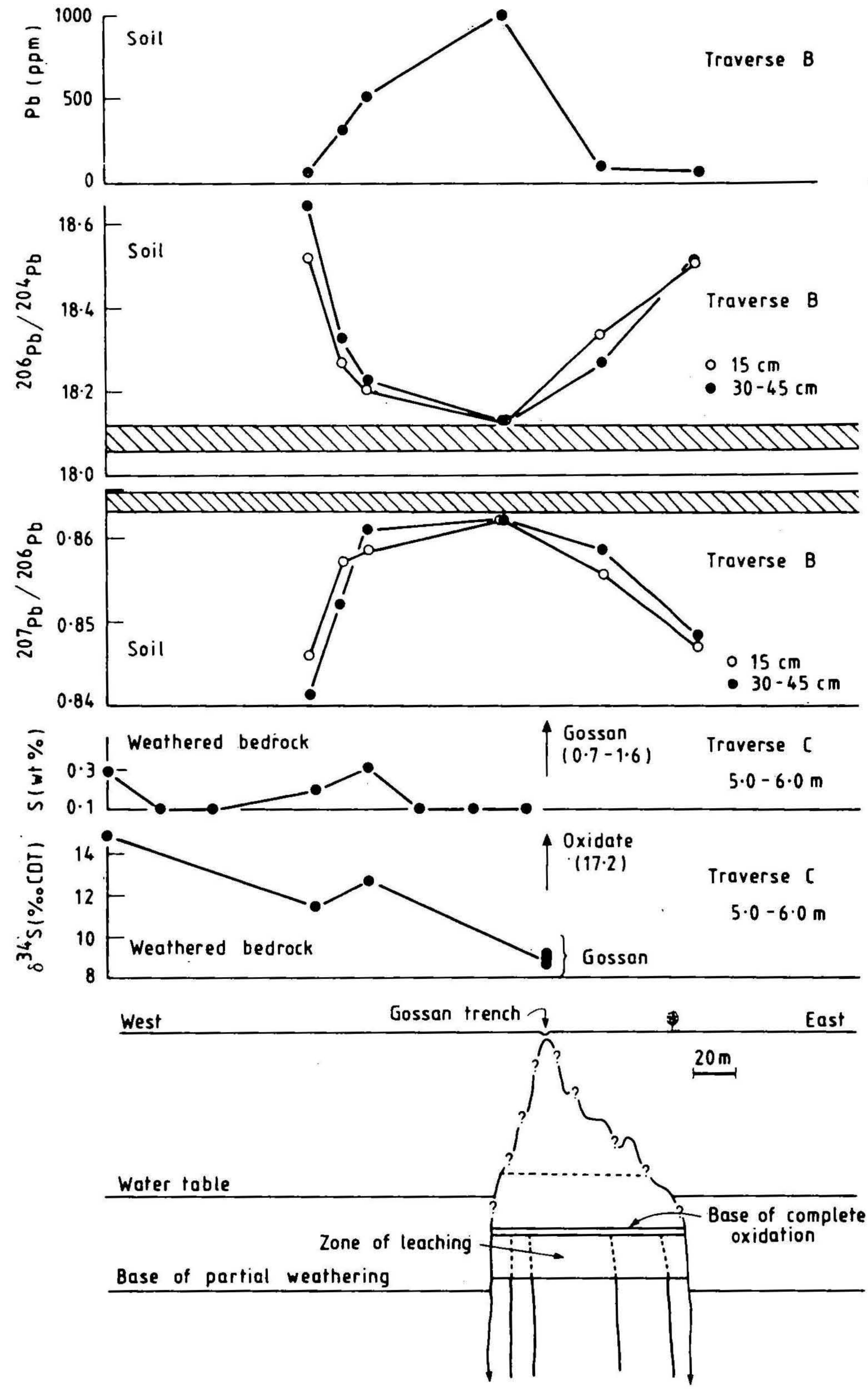

Figure 3 Variations in Pb and S contents and isotope values over the Elura orebody. The shaded bands denote the known ranges in Pb isotopic ratios for orebodies in this province.

FUTURE DEVELOPMENTS

Future exploration must place increasing emphasis on the location of concealed mineralization. In many potential exploration situations the concealing cover will be weathered. As an extension of the gossan project, the CSIRO Division of Mineralogy is undertaking an evaluation of isotopic methods in exploration for concealed orebodies. Both under the auspices of the AMIRA programme and concurrent investigations, Pb isotope research is involved in the analysis of soils, plants and waters associated with low-Pb deposits, the establishment of drilling vectors, and the analysis of soils and sulfides in the transition from massive iron sulfides to disseminated base metal sulfides to viable mineralization.

The potential usefulness of S isotope values in exploration needs to be evaluated further, particularly in soils. S isotopes provide a chemical system whose behaviour is independent of the Pb system. As such they may provide a further check of mineralization potential. Compared with Pb isotope analyses, the analysis of S isotopes is inexpensive.

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Stratigraphic framework of Tertiary duricrusts and weathering profiles, east margin of the Eucla Basin, southern Australia.

by

M.C. Benbow*

Debate continues on the genetic relationships between, and the exact timing and duration of, the various components of the weathered mantle covering much of Australia. (Langford-Smith, 1978). Research currently in progress on the east margin of the Eucla Basin, (Fig. 1) is providing rewarding evidence bearing on such problems. The basin was a major area of shallow marine sedimentation during the Eocene and Miocene. More localised, dominantly terrestrial sedimentation occurred on the margins in basin-ward draining palaeorivers that had their head-waters in the more central parts of the continent (Fig. 1). That the palaeorivers flowed into an area where marine sedimentation took place, provides the chance of determining better age constraints on both periods of terrestrial sedimentation and weathering. Although the general character and outline of these ancient rivers has been described (Bunting et al., 1974; van de Graaff et al., 1977; Barnes and Pitt, 1976; Pitt, 1980); little has been documented of their sediment infill and related weathered rocks.

Deeply weathered rocks are evident on the east margin of the Eucla Basin, seen in the Precambrian basement of the Gawler Craton and in the cover rocks as young as Early Cretaceous (Aptian) of the SW margin of the Great Artesian Basin. The oldest sedimentary unit unaffected by this weathering event is the carbonaceous Middle-Late Eocene Pidinga Formation (Harris, 1966; Lindsay and Harris, 1975). Such sediments as were deposited in palaeorivers, sharply overlie deeply weathered basement and in the upper-most part at least, contain clasts of weathered basement. Deep weathering thus occurred sometime during the

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Late Cretaceous to (late) Middle Eocene.

These deeply weathered rocks (i.e. the weathering) may be correlated with the Morney Profile (Senior and Mabbutt, 1979) in SW Queensland. The Morney Profile has similar age constraints indicating probable continent-wide deep weathering. Whether the Late Palaeocene lower part of the Eyre Formation was deposited after or before (or even during) deep weathering, is unknown.

Sedimentation ceased about the Eocene-Oligocene boundary (Benbow in prep.; Benbow et. al., 1982) and did not recommence until the Late Oligocene and on the basin's margins, not until about the Early-Middle Miocene boundary (Lindsay and Harris, 1975; cf. Firman, 1983) marked there by deposition of the marine Nullarbor Limestone. During that interval of some 22 million years, there were two major periods of duricrust formation. Massive quartzose silcrete up to 2-3 metres thick formed in (predominantly) non-carbonaceous sands at the top of the Pidinga Formation. Such silcretes are generally pale grey to brown and lack any conspicuous pedogenic structures. This last feature and their occurrence at present day lake level or their relatively low position in the landscape suggests their formation was a result of groundwater movement of silica.

Silicification was followed by a major phase of ferruginisation. Brecciated silcretes and regolith formed within and on these silcretes, have been cemented by iron oxides, resulting in the formation of ferricrete (Yapinga Ferricrete of Benbow (in prep.)). Iron concentration preferentially took place in sands at the top of the Pidinga Formation, especially where silicification was less intense or absent, leading to the formation of massive friable to very hard ferricrete. Dark to black ironstone mottling and concentration of iron, parallel foliation and layering is conspicuous in places, in already weathered Precambrian basement. These ferricretes may be up to 3-4 metres thick and occur, as do the earlier silcretes, about the east margin of the basin.

A subsequent period of extensive silcrete formation took place after deposition of the Nullarbor Limestone and also after deposition of a fluvial sequence and younger lacustrine sequence (Munjena Formation and Garford Formation* respectively of Benbow (in prep.); Benbow and Pitt, (1978)) found in the ancient drainage lines. This silcrete is of two main types. In sands which intertongue with both the Nullarbor Limestone and Garford Formation, silicification has resulted in structureless massive sheet-like silcretes similar to those already described. They are especially prominent on the northern margin of the basin, outcropping in a topographic low marked by a series of playa lakes where silicification probably occurred in a groundwater environment. Here they formed in the Colville Sandstone (Lowry, 1970), a nearshore to beach facies which intertongues with the Nullarbor Limestone.

The second form of silicification resulted in "grey billy" silcrete which often displays typical pedogenic features such as vertically oriented rodding and tear drop structures. Also commonly associated are vertically oriented and interconnecting burrows which may have formed as the result of ant or termite activity. Such silcretes formed in pale grey to white fluvial sands of the Munjena Formation (older than the Garford Formation, Fig. 2).

These pedogenic silcretes often occur high in the landscape capping mesas or gently undulating hills. Such silcretes have not been observed much further south and west of 30°S and $133^{\circ}30'$E but this may principally be a function of the distribution of the Munjena Formation. A Pliocene age for silicification is suggested.

No extensive or pervasive kaolinisation or deep weathering profile is seen in these silcrete-capped sands or associated with those silcretes interpreted to form in a groundwater environment.

*Equivalent to the Etadunna Formation of Stirton *et al*. (1961).

There is minor kaolinisation associated with the pedogenic silcrete. The association sometimes seen of silcrete overlying deeply weathered pre-Tertiary sediments, is fortuitous and does not imply a genetic relationship.

Iron-staining of silcrete capping the Munjena Formation is commonly observed. Less common is iron oxide-cemented regolith formed especially in the lower part of the silcrete profile. Regolith has also been cemented by brick red jasper silcrete but the relationship of iron and silica cementation is presently unknown. There is also limited evidence for iron accumulation preceding the pedogenic "grey billy" silcrete.

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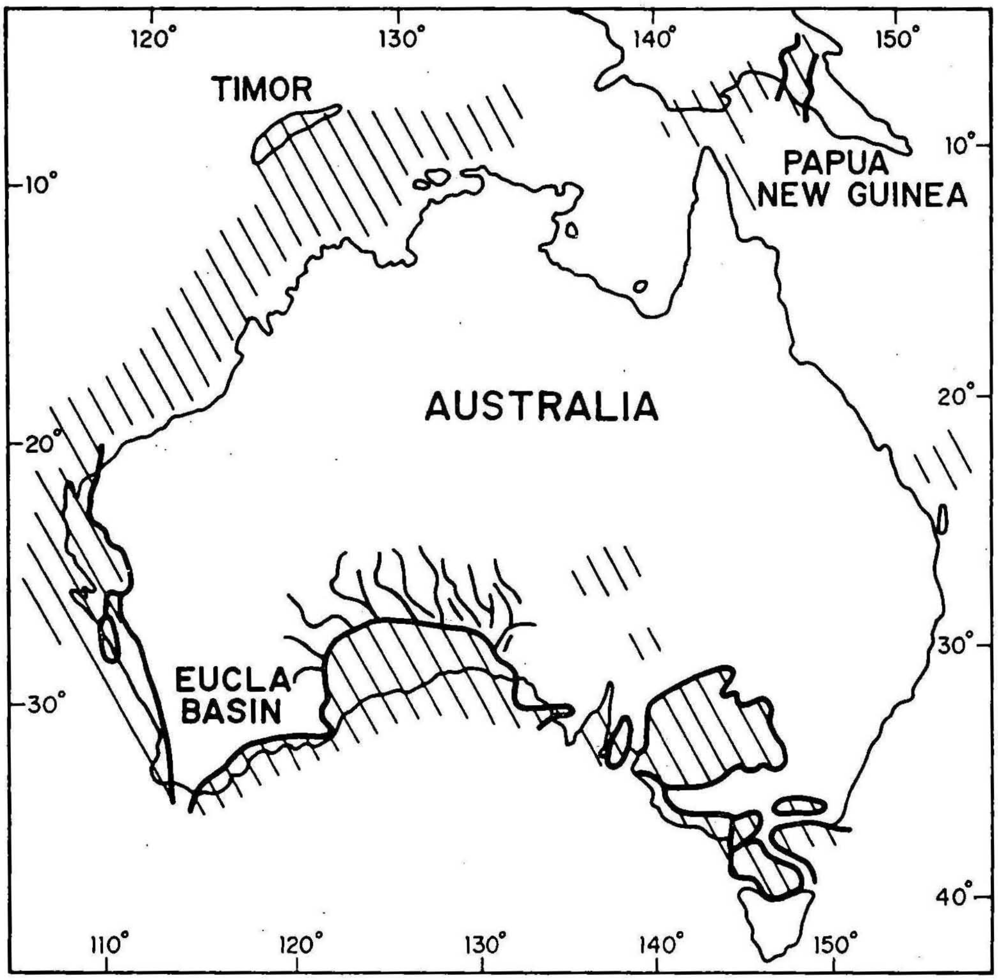

Fig. 1 Major Tertiary basins of the continental margin of Australia adapted from McGowran, (1979). Circum-drainage pattern of Eucla Basin taken from Pitt, (1980) and van de Graff et al. (1977).

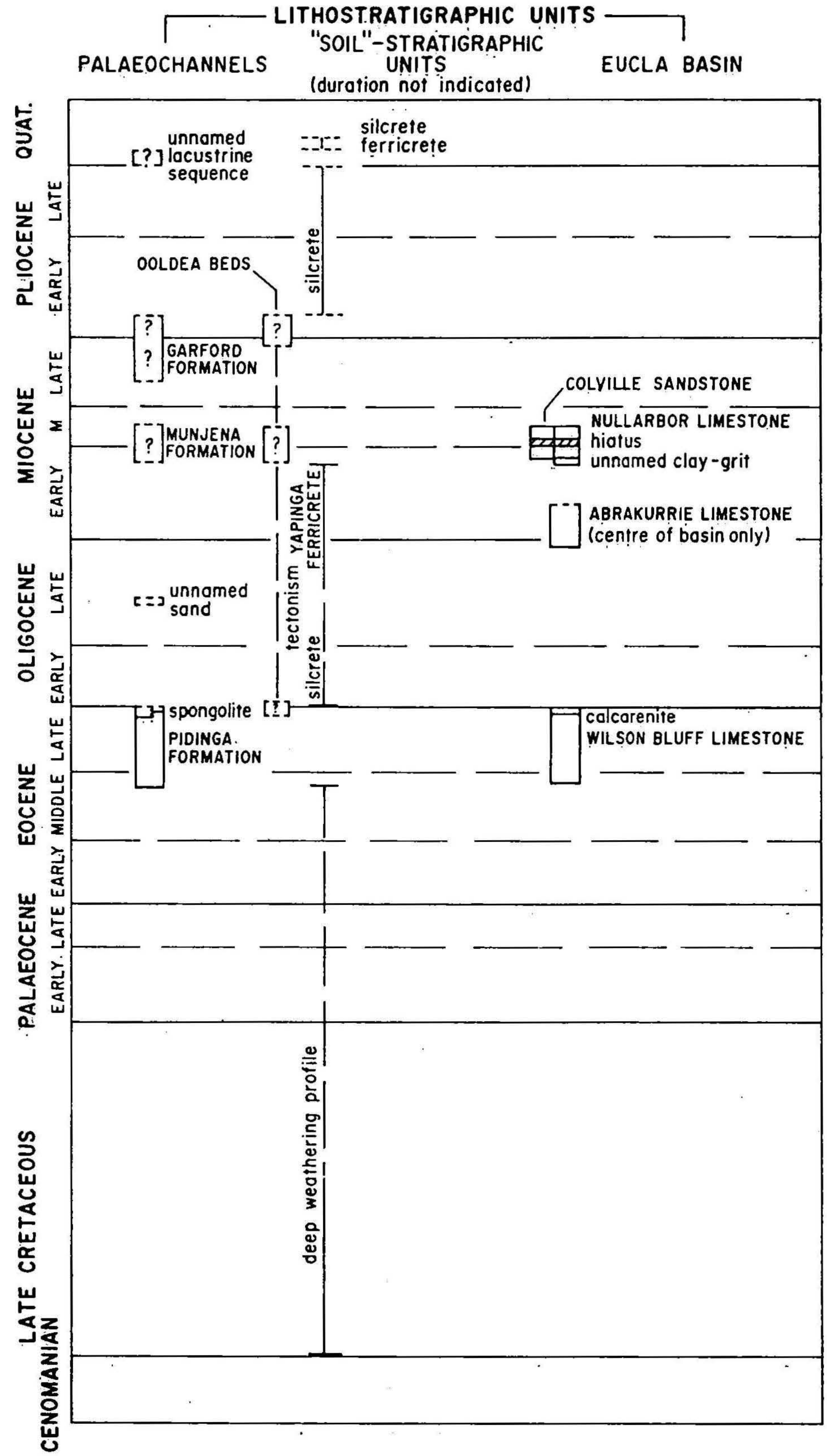

Fig. 2 Stratigraphic framework east margin of the Eucla Basin

REGOLITH STUDIES IN WESTERN AUSTRALIA

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INTRODUCTION

Much of Australia, and in particular Western Australia, has a long history of stability in that it has escaped the effects of recent tectonism, and of glaciations during the Pleistocene. This has led to the development of an extensive and well preserved regolith, consisting of a zone of deep chemical weathering of both crystalline and sedimentary rocks, more or less _in situ_, and of superficial deposits of an aeolian, alluvial or colluvial nature. These materials have both scientific and economic importance since they are the parent materials of soils which are frequently poor in most essential plant and animal nutrients, thus affecting wild life, forestry and agriculture. Additionally they may form a considerable barrier between mineral explorers and their target, as well as themselves providing economic deposits of, for example, sands, clays and gypsum, and iron, aluminium and manganese ores.

This paper describes briefly some work relating to the nature of the regolith of the western one third of Australia, and is largely based on field and laboratory studies with which the author has been associated. A further paper at this symposium by Churchward, will deal with regolith distribution on the Great Plateau of Western Australia.

FACTORS INFLUENCING REGOLITH CHARACTERISTICS

The main factors influencing regolith characteristics are provenance, weathering history and subsequent rejuvenation, and current climate. These will be discussed briefly below.

The provenance determines the basic particle size distribution (percentage of clay, silt and sand size particles) since regoliths may be derived from acid, or basic, igneous, metamorphic, or sedimentary rocks. The regolith may be formed by _in situ_ breakdown of the country rocks, and/or from aeolian, riverine, or colluvial sediments. In the latter cases further sorting occurs resulting in changes in grain size and in regolith chemistry as will be illustrated later.

Weathering history also plays a large part in determining grain size and regolith chemistry. With increased weathering primary rock minerals are altered to clays, with only the most resistant, such as quartz, being preserved as a skeletal framework. Where drainage is adequate the end products of weathering are extensive deep saprolites overlain by ferruginous and aluminous duricrusts. Figure 1 (taken from Bettenay et al (1980)) shows the weathering sequence which takes place in both acid and

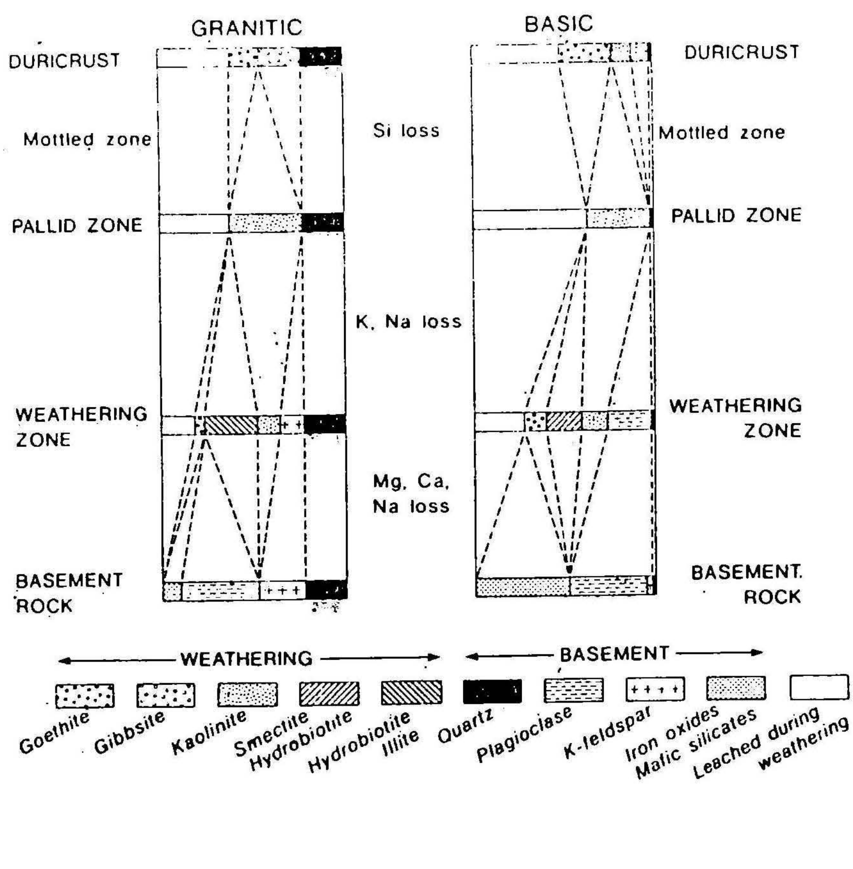

Figure 1 Diagram of typical profiles showing the major mineralogical and chemical changes that occur during weathering (from Bettenay et al. 1980).

basic rocks and results in progressive changes in the basement rock to form weathering zones, pallid zones, mottled zones and duricrust. In sump areas, where bases accumulate and weathering is minimal, there is a very different mineral assemblage with the formation of authigenic clay minerals, such as smectites, and the accumulation of soluble salts such as halite and gypsum, and carbonates. While deeply weathered lateritic profiles and their associated groundwaters are frequently acid, with pH as low as 3.5, sump areas are often alkaline with pH in excess of 8.5.

Subsequent landscape rejuvenation, due to incision, bevelling, or additional deposition, may greatly alter the nature of the regolith. These processes have been discussed by Stephens (1946). In extreme cases the deep saprolite zone may be completely removed with the exposure of fresh rocks, and elsewhere additions of alluvial, colluvial or aeolian materials may result in major changes in grain size and chemistry of the surface of the regolith.

Current climate too has been shown to have an influence on the soils which characterise the upper regolith (Bettenay 1968). In those soils whose morphology indicates a lengthy exposure to the present leaching environment, there is a gradation, relating to current rainfall, from acid reaction trends (Northcote 1960) near the coast, through neutral to alkaline in the semi-arid interior. Additionally the extensive sand sheets of south-western Australia change from yellow, through orange to red with decreasing and less reliable rainfall.

Regolith characteristics are also influenced by man's activities such as strip mining, and extensive clearing which, in places, has led to accelerated sheet, gully, and wind erosion, and to extensive salinisation at the soil surface.

MAIN REGOLITH TYPES

In this section some of the main regolith types present in Western Australia are briefly described, and, in some cases, illustrated by type sections from areas of more detailed study. In any one region many regolith types may occur, each of which occupies a different type of landscape situation depending on geomorphic history. These are frequently given place names and may be recognized regionally across wide areas.

Because of its extent, the deeply weathered or lateritic landscape is of major importance (see also paper by Churchward, this conference). The saprolite mantle, developed over both crystalline and sedimentary rocks, with its attendant ferruginous and aluminous crusts and extensive sandplain sheets, has been mapped and described in detail by, for example, Mulcahy and Hingston (1961), Bettenay and Hingston (1964) and Churchward (1970).

The Merredin area (Bettenay and Hingston loc cit) is taken as a type example (see figure 2).

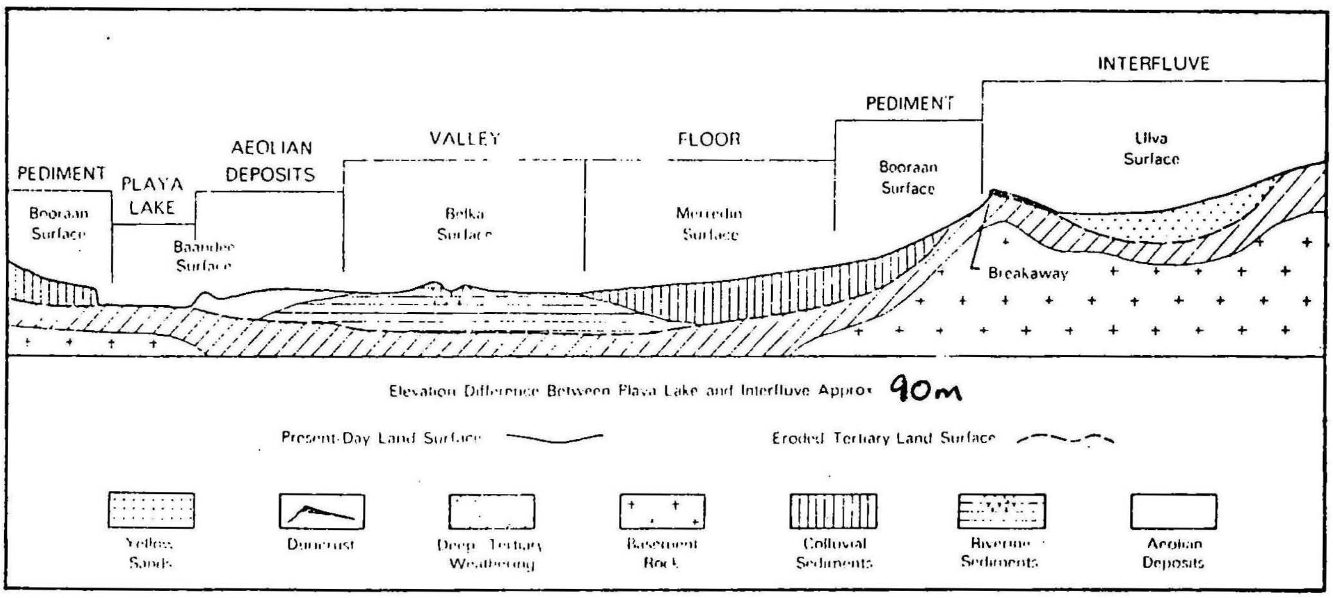

Figure 2 Modification of the lateritised Tertiary landscape at Merredin showing surfaces of erosion and deposition associated with the main landscape elements (from Bettenay and Hingston 1964).

It is evident that extensive weathering and duricrust formation took place on a landscape which was undulating, and in which drainage was competent to remove the products of chemical weathering - the bases - leaving a weathered zone up to 50 m deep. The accumulation of soluble salts, particularly NaCl, in the deep saprolites and in sump areas was evidently a later phenomenon resulting from a change to greater aridity and the disruption of the drainage systems. Dissection resulting from instability due to more arid conditions, has resulted in the exposure of the various lateritic horizons including mottled zones, pallid zones, weathering zones, and underlying basement rock. Much of this material, of mixed weathered and fresh origin, has been retained in the landscape in the form of shallow colluvial sheets extending both over pediment slopes below breakaway scarps and out onto valley floors, and as sandplains derived from indurated mottled and pallid zones which form deposits up to several metres thick in the lower parts of the undulating uplands.

Colluvial sediments are also extensive in the Murchison district where they occupy broad plains which have calcreted valley fills in the drainage axes. One such area is shown in figure 3 which is taken from Brewer et

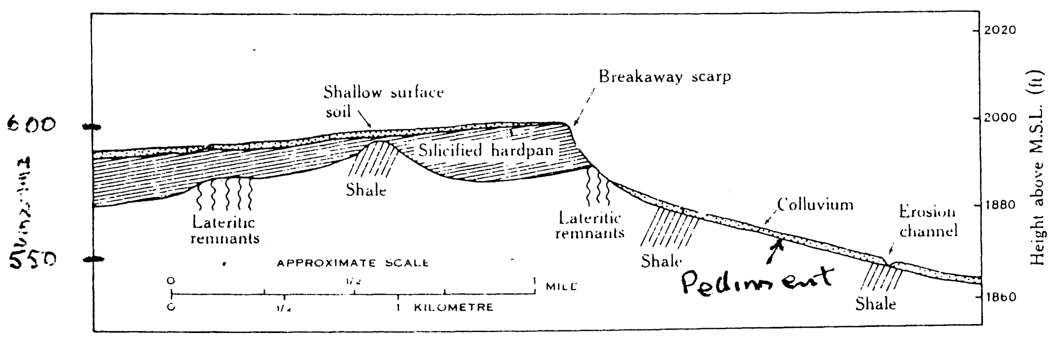

Figure 3 Diagramatic section showing relationship of silicified Wiluna Hardpan with lateritic remnants and country rock (after Brewer et al. 1972).

al. (1972). The silicified colluvial deposits, or Wiluna Hardpan (Bettenay and Churchward 1974), are up to 30 m thick and variously overlie both weathered lateritic remnants and relatively unweathered country rock. Here the Wiluna Hardpan is currently being destroyed by headward erosion of the Ashburton River with the formation of breakaways below which thin and uncemented pedisediments overlie relatively fresh shale.

Alluvial sediments both in the Merredin and Murchison area are shallow and confined to the major trunk valleys. Elsewhere on the Swan Coastal Plain near Perth (McArthur and Bettenay 1960), and in the flood plains of major rivers they may be developed as multiple deposits in which grain size and geochemical characteristics vary in an orderly fashion with distance from the deposition stream. Figure 4 taken from Bettenay et al

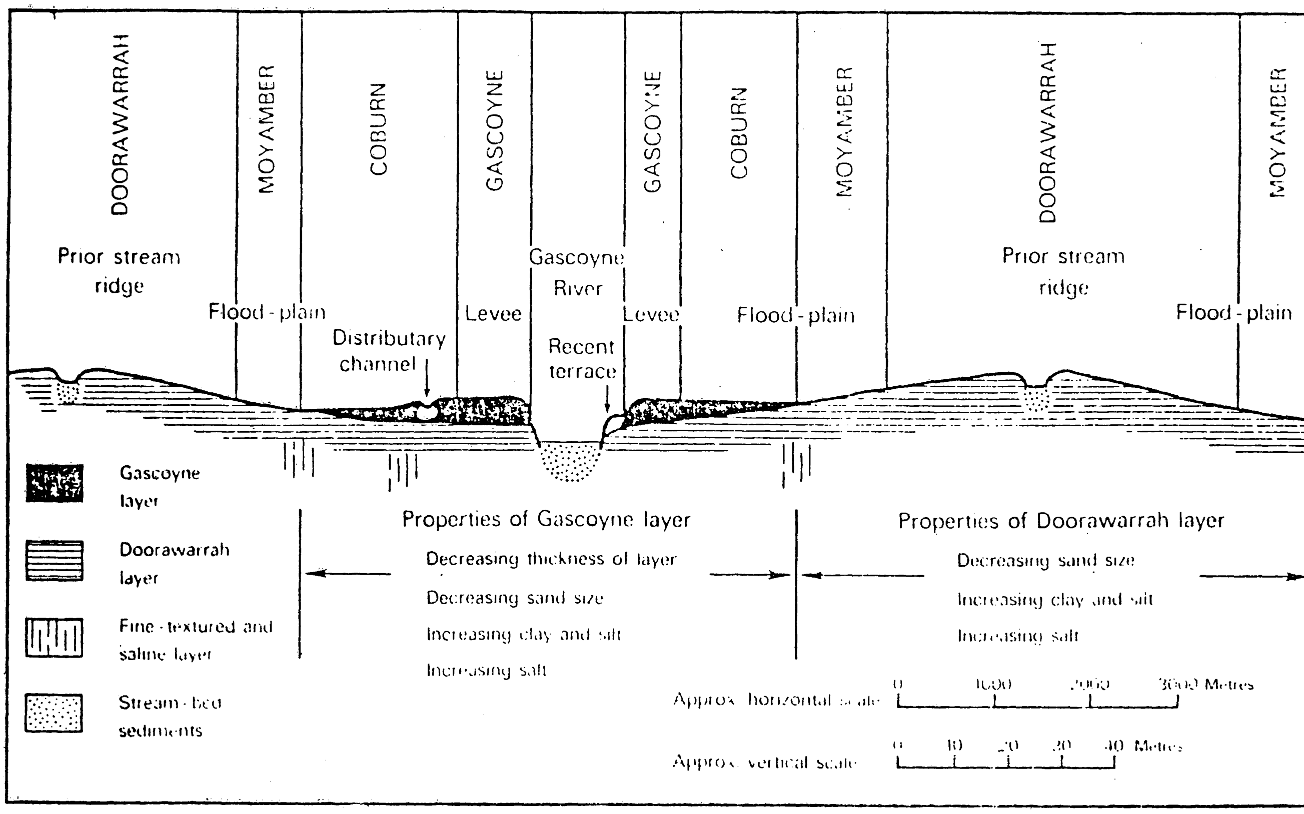

Figure 4 Generalized section of the Gascoyne Delta showing major topographical features and general layer relationship (from Bettenay et al. 1971).

(1971) shows the multiple deposits of the Gascoyne River near Carnarvon. Here older courses of the Gascoyne may be recognized overlying a fine textured and saline layer, which may be estuarine, and are themselves overlain by deposits from the present river. Properties of these layers vary with coarse bed-load materials on prior stream ridges and in the present bed of the Gascoyne, and with a decreasing thickness of levee and flood-plain deposits away from the depositing stream. With distance there is also a sorting resulting in decreased sand size, an increase in total silt plus clay content, and an increase in salt concentration.

Aeolian deposits are also common in Western Australia. Areas with old, saline drainage lines and salt pans have a sequence of dunes and silt or clay sheets (lake parnas) which have been described in some detail by Bettenay (1962) (see also figure 2). Close to the source there is an accumulation of gypsum in low dunes, and these are succeeded by sandy and clayey lunettes. Further downwind are the parna sheets which may blanket extensive areas, or form shallow sheets which are incorporated with time with the surface of the prior regolith. Thus it is common to find saline and alkaline silts and clays mixed with, or blanketing acid materials characteristic of the lateritic profile.

In addition to the above there are extensive linear dunes characteristic of the arid interior and dunes of varying age flanking the coast. These latter have perhaps been best studied on the seaward side of the Swan Coastal Plain (McArthur and Bettenay _loc cit_). Three major dune systems are recognized each with characteristic soil profiles. The youngest, or Quindalup dunes, are shelly sands in which different ages represented by different degrees of profile organisation can be recognized (McArthur and Bartle 1980). With increasing age there is a removal of carbonate, this being leached downwards so that in the middle, or Spearwood, dunes there are several metres of yellow brown iron stained quartz sand, with a neutral reaction, which overlies cemented-aeolianite-limestone. The oldest, or Bassendean dunes have a variety of soil profiles with most of the iron being leached out of the surface with the progressive development of leached acid sands with iron and/or organic pans developed at depth. This sequence is shown in a graphic form in figure 5 taken from McArthur and Bettenay (_loc cit_).

In situ soils whose properties closely reflect the nature of the underlying rock are not wide-spread in south-western Australia. Such soils are characteristic of areas of major stripping of the regolith, and of areas such as steep faced scarps where lateritic deep weathering has not taken place.

DISCUSSION

In Western Australia field pedologists (Soil Scientists) have studied the regolith both on a broad scale, as reflected in the various sheets of the Atlas of Australian Soils (Northcote Ed. 1967, 1968), and in greater detail as illustrated by the figures in this paper.

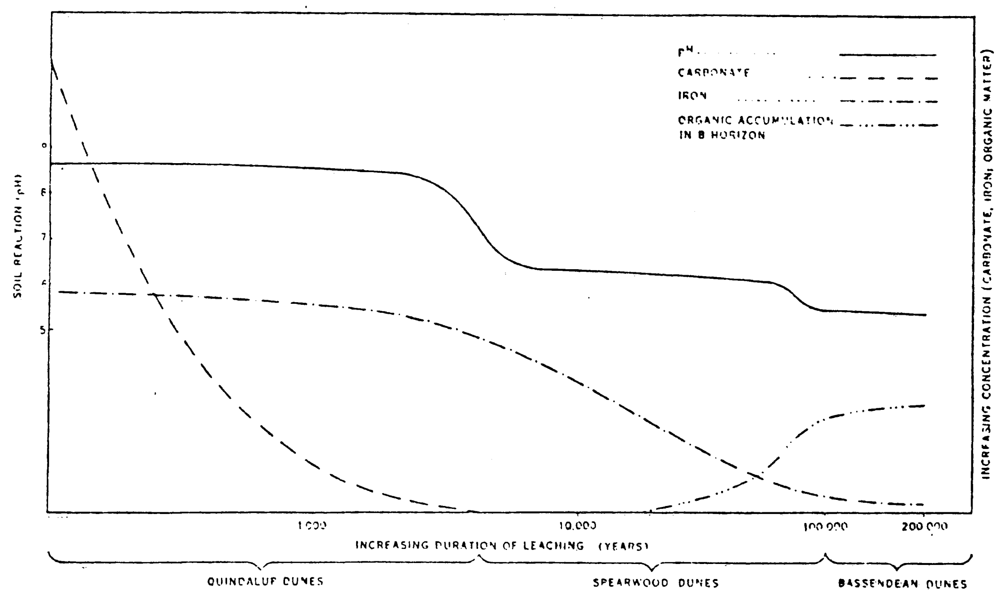

Figure 5 Age sequence on the Swan Coastal Plain as shown by the surface soils of the dune systems. The line representing pH is real, but the others are relative (after McArthur and Bettenay 1960).

As pointed out by Bettenay (1968) an understanding of soil-geomorphological relationships provides a major tool for broad scale soil mapping and consequently in an understanding of the nature of the regolith. Such studies have made wide use of the K-cycle concept developed by Butler (1959) which uses soil-stratigraphic observations as a means of deciding the relative age of multiple deposits. These have been supplemented by physical, micromorphological, and chemical studies of the various regolith layers. In many areas the record is not complete due to destruction by erosion, but there is sufficient evidence of widespread deep weathering, and of cyclic deposition of aeolian, alluvial and colluvial materials, followed by soil formation, to encourage their study and mapping on an Australia-wide basis.

The Australian regolith has been studied extensively in various States and regions, but so far little attempt has been made to correlate superficial deposits and weathered mantles across the continent. Such correlations could provide a basic framework within which regional methodologies for land management and mineral exploration might be developed, as well as providing a sound basis for information exchange across wider areas.

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THE GEOCHEMISTRY OF MERCURY IN THE SECONDARY ENVIRONMENT

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Although Hg has been used as a pathfinder element in mineral exploration for over a quarter of a century, its behaviour in the weathered zone of mineral deposits is not well understood. Environmental studies have to some extent defined the important geochemical processes involving Hg in lakes, rivers and the oceans (overviewed by Nriagu, 1979), but these have only limited application to exploration. Geologists have for many years relied on the pioneering work of the Russians (especially Saukov, 1946; Ozerova, 1962) in their attempts to interpret Hg surveys in soils and weathered rock. However, the applicability of the Russian work has not been determined because the relatively few published case history studies have been inadequately documented. The Russians contend that because of its high volatility, Hg forms broad, relatively easily detected primary (hypogene) and secondary (weathering) haloes around Hg-containing ore bodies. Such dispersion has generally been considered to be via vapour transport.

In 1979 a project was initiated within the CSIRO Division of Mineralogy under the sponsorship of fourteen AMIRA companies to study the behaviour of Hg in the weathering environment. The project required case history documentation of a wide variety of prospects and ore deposits in various climatic and geomorphic terrains. Work on base metal deposits was completed in 1982 but study of Au and other precious metal deposits is continuing.

On the basis of the completed case histories, it was concluded that there are five important factors which define the distribution of Hg about a weathering ore body.

1. PRIMARY MERCURY CONTENT AND DISTRIBUTION

The Hg content of the primary mineralization ultimately determines the levels in the weathered media. Table 1 shows that significant levels of Hg occur in Australian ore deposits which vary widely in both commodity elements and style of mineralization.

2. NATURE OF THE HOST ROCKS

Chemical and physical factors such as rock permeability and the distribution of the sulfides within the host rocks also affect Hg dispersion. In addition, it appears that the chemical relationships of Hg with elements within the host rocks or in the sulfides themselves are an important control, although unfortunately little is known of the partitioning of trace Hg into the oxidate minerals. The Fe oxide-Hg association is a likely one however, both because of the effects observed in soils and the persistence of Hg in leached gossanous ironstone. It is likely that Hg, as some other trace elements, can be incorporated into the oxide structure during deposition and recrystallization, thereby becoming more resistant to the effects of further weathering.

3. NATURE AND THICKNESS OF THE OVERBURDEN

The thickness, mineralogical makeup, permeability and saturation of the overburden are important factors in determining the dispersion of Hg both as a vapour and in aqueous solution. These factors are discussed with reference to case histories in the following sections.

4. SOIL CHARACTERISTICS

The principal factors influencing the retention and accumulation of Hg in soil are (1) the presence of organic matter,

Table 1: Mercury contents of some Australian ore deposits

Deposit	Mineralization style and commodity		Host rocks	Mercury contents (ppb) Range	Geom. mean	N
HYC	stratiform	Pb-Zn-Ag	shale	450-2000	1300	42
Mount Isa	stratiform	Pb-Zn-Ag	shale	1500-70000	8300	48
Lady Loretta	stratiform	Zn-Pb-Ag	shale	8500-33000	22000	27
Dugald River	stratiform	Zn-Pb-Ag	shale	1000-2200	1500	6
Elura	?stratiform	Zn-Pb-Ag	shale	1000-200000	53000	30
Broken Hill	stratiform	Zn-Pb-Ag	?acid volcanics	1000-37000	8200	35
Woodlawn	stratiform	Pb-Zn-Cu	acid volcanics	100-18000	3600	64
Currawang	stratiform	Pb-Zn-Cu	andesitic volcanics	1700-5600	4000	4
Que River	stratiform	Pb-Zn-Cu	andesitic volcanics	800-7200	3500	21
Pinnacles	stratiform	Pb-Zn-Cu	acid volcanics	2400-16000	8300	9
Yarroloola	stratiform	Cu	basalt	15000	-	1
Gossan Hill	stratiform	Zn-Cu	basalt	12500-5000	3000	4
Scuddles	stratiform	Zn-Cu	basalt	120-18000	6500	11
Woodcutters	stratabound	Pb-Zn	carbonates	65-7000	2400	3
Mount Black	stratabound	Pb-Zn	carbonates	700-4000	1700	9
Mammoth	stratabound	Cu	sandstone	100-14000	3000	53
Morning Star (Walhalla, Vic)	vein	Au	shale	2500	-	1
Nine Mine (Drake NSW)	vein	Au	volcanoclastic	23000	-	1
Hill End (NSW)	vein	Au	shale	700	-	1
Big Bell (Yilgarn WA)	vein	Au	dolerite	7000	-	1
Mt Charlotte (Eastern Goldfields, WA)	vein	Au	dolerite	1400	-	1
Jabiluka Two (NT)	unconformity	U-Au	schist	660-11200	-	10

especially humic substances, (2) the presence of Fe oxides and clays, (3) the salinity of the soils and (4) the presence of discrete Hg-bearing (oxidate) minerals. Although the association of Hg with organic detritus has been described as adsorption, it is probable that direct chemical bonding is involved, either via chelating groups or by virtue of S-Hg bonding (Jonasson, 1980). Data presented by Andersson (1979) show that Hg can be accumulated by soil humic substances even at low pH, which in itself suggests strong chemical bonding. Case history studies in western Tasmania show that on a regional scale Hg levels in the organic-rich A_0 and A_1 horizons are much higher than in the underlying organic-poor C horizon (Figure 1). The source of such Hg enrichment is consid-

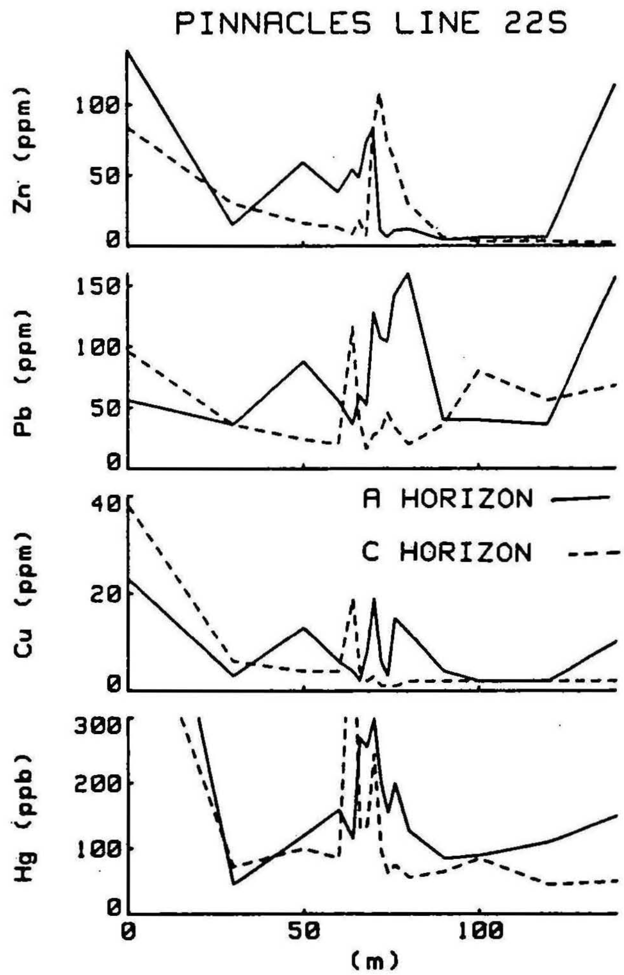

Figure 1. Hg, Cu, Pb and Zn contents of A and C horizon soils at the Pinnacles prospect, western Tasmania. The sample line crosses a small outcropping massive sulfide lens at 60 m E.

ered to be the atmosphere (both of natural occurrence and as pollution from smelting operations) as well as from weathering of underlying rocks. However, where the underlying rocks are themselves enriched in Hg, such as over Pb-Zn mineralization, this pattern is most likely reversed and soil Hg levels are higher in the B/C horizons than in the A, resulting in relatively enhanced peak/background contrasts.

Apart from organic material, two major groups of adsorbents are identifiable in the secondary regime: the clays and the hydrous oxides of Fe, Al and Mn (sometimes grouped as the "sesquioxides"). Although laboratory studies have detailed their sorptive properties, there are, necessarily, no data on the fate of adsorbed mercury as the adsorbents age and recrystallize. It may be reasonably assumed, however, that Hg can and does enter the structure of such substances to varying degrees and thereby becomes a "residual" element removed from the dynamic cycle.

The salinity of the soil is also important because of the effect of Cl^- which reduces the capacity of the soil components to adsorb Hg. At the Salt Creek deposit, where the water table is shallow (7 to 8 m) and the groundwaters are highly saline, Hg has been leached from the residual soils overlying a massive-sulfide lens (Figure 2) leaving only a one-point anomaly. The same effect is not as apparent with respect to Zn, Pb and Cu.

By far the majority of our case histories show anomalous soil Hg contents which can be ascribed to the presence of residual oxidate phases derived from the erosion of gossanous outcrops. In these situations Hg anomalies are generally coincident or almost coicident with other residual base-metal anomalies.

5. NATURE OF WEATHERING: PAST AND PRESENT

During active weathering, any Hg released during oxidation is incorporated into the existing dynamic cycle. Such Hg may be

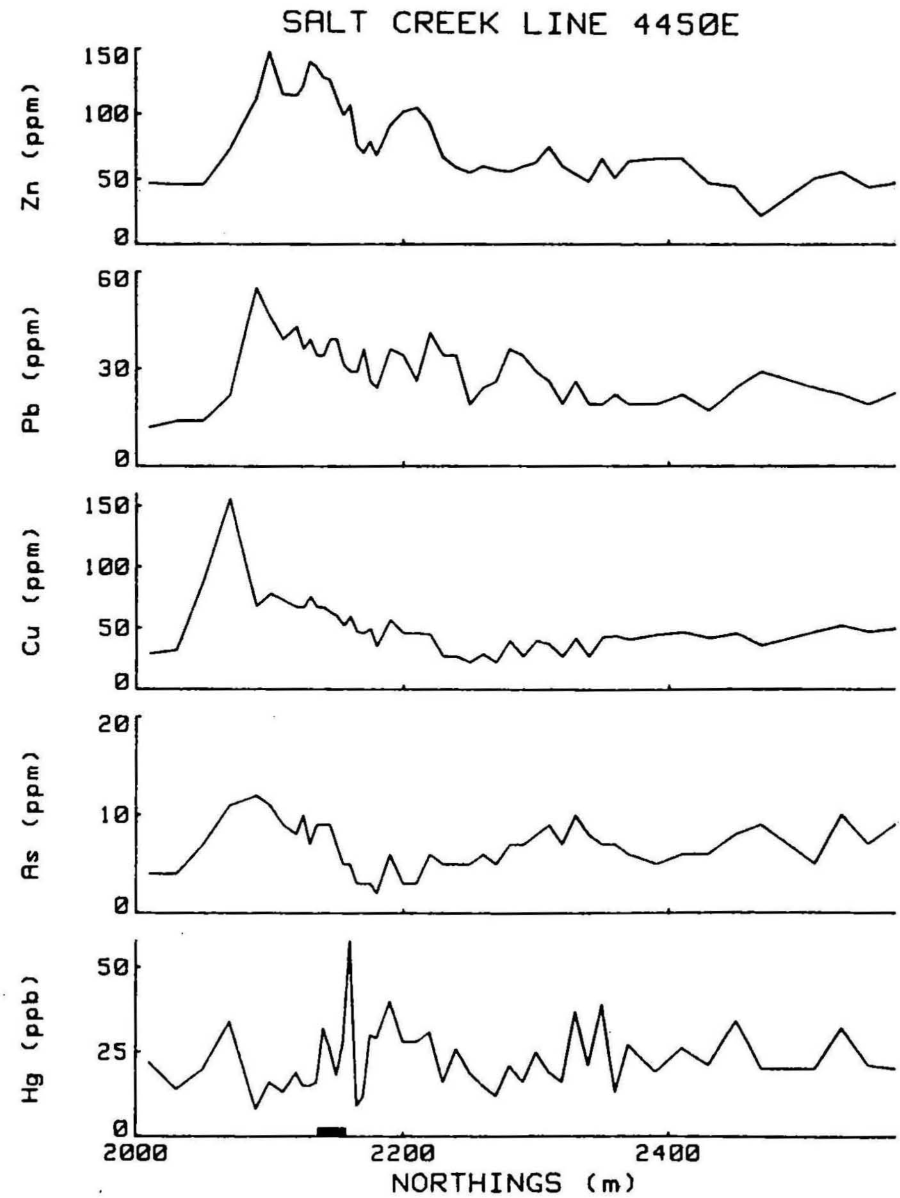

Figure 2. Hg, As, Cu, Pb and Zn contents of lithosols from the Salt Creek massive sulfide deposit in the Pilbara of Western Australia. The sample line crosses the outcropping sulfide lines at 2140 m.

transported from the site of weathering either in solution or as a vapour, thus forming hydromorphic or vapour-generated haloes. In any particular situation, the relative importance of these two mechanisms of dispersion will depend inter alia on climatic conditions. In wet regimes no measurable vapour-generated haloes occur because of the strong partitioning of Hg into the aqueous phase. This was observed in a number of cases in Tasmania where only hydromorphic dispersion patterns were recognised in association with actively weathering sulfides beneath transported fluvio-glacial sediments. However, where climates are at least seasonally dry, vapour phase transport through the overburden is possible. Such movement is limited by both the overburden thickness and its adsorptive capacity. Whereas clays, Fe oxides and organic matter strongly absorb Hg, quartz (sand) has a low sorptive capacity. At Jabiluka Two, where the overburden is principally a permeable quartz sand, a narrow Hg soil-gas anomaly was observed over a fault which intersects the buried Hg-rich U-Au mineralization (Figure 3). No anomalous values were measured in the sand itself.

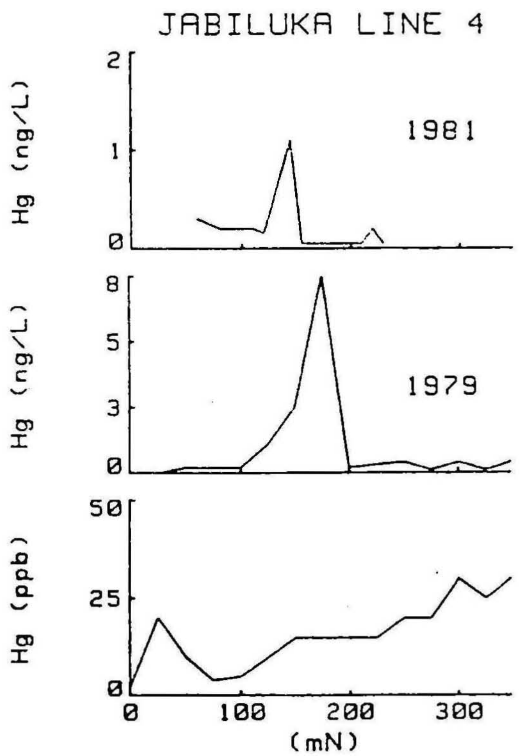

Figure 3. Hg content of sand and soil gas over a fault which intersects the Jabiluka Two U-Au mineralization. The soil gas was sampled in 1979 and again in 1981 at the same time of year.

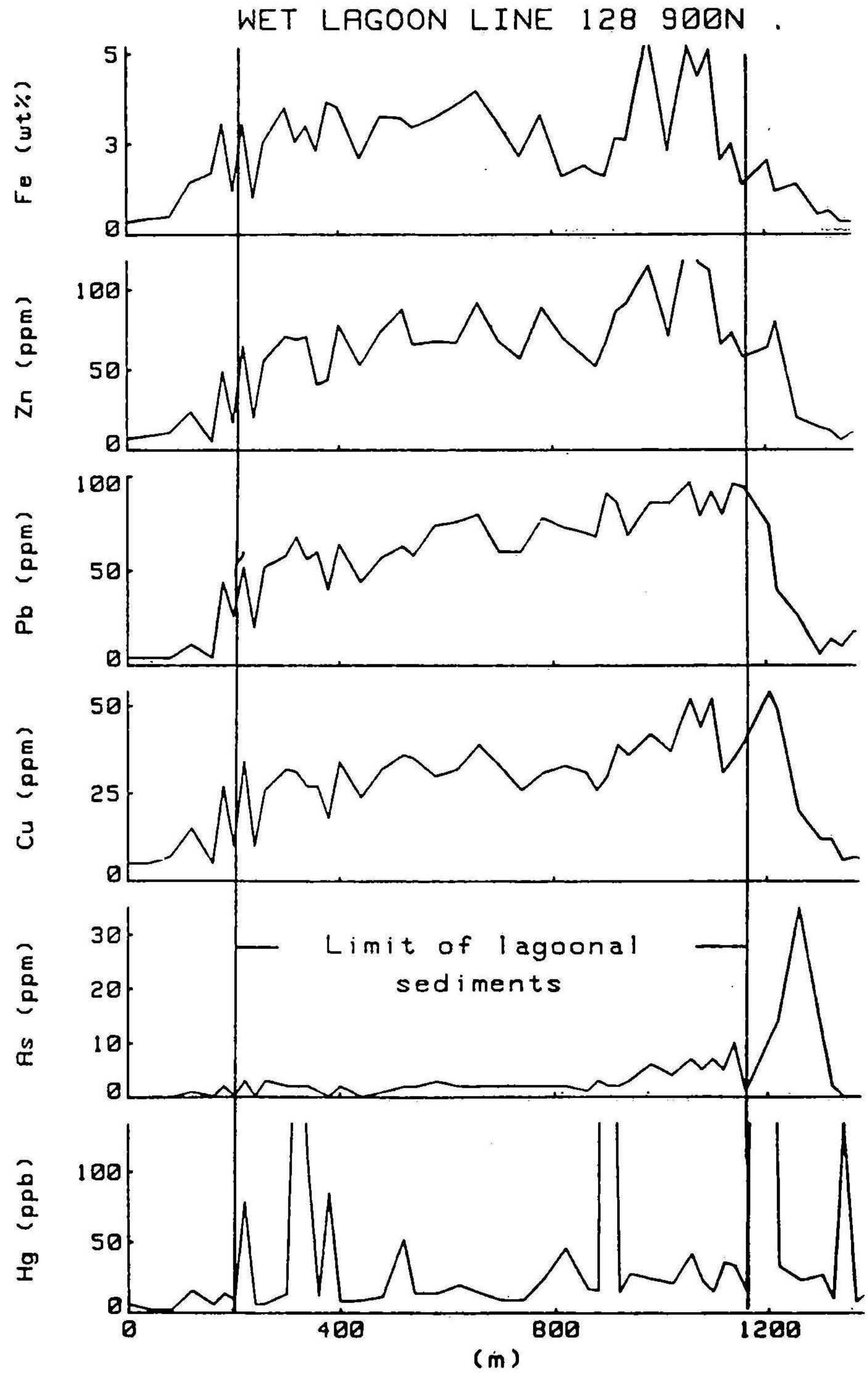

Figure 4. Hg, As, Cu, Pb, Zn and Fe contents of soils at the Wet Lagoon prospect in the Southern Tablelands of NSW. Outcropping pyritic volcanics occur to the east of the lagoonal sediments.

In large areas of Australia it is questionable whether sulfide oxidation is continuing because climatic changes have resulted in re-equilibration of the water table. In these situations no measurable soil-gas anomalies are possible as there is no significant Hg flux. This could possibly explain the lack of anomalies over such dry-climate deposits as Pegmont in northwest Queensland. However, fossil hydromorphic and vapour-generated soil anomalies may be preserved. One such example is at Wet Lagoon in the Southern Tablelands of NSW where discrete Hg anomalies occur in waterlogged swamp soils over a small buried massive-sulfide lens (Figure 4). No such anomalies were found for the elements, Pb, Zn, Ag, Cu or As. It is postulated that at some time in the past the climate was dry enough to produce cracking and permeability in the organic and clay-rich sediments allowing the movement and adsorption of the Hg released by the directly underlying weathering sulfides. This adsorbed Hg remained tightly bound during the ensuring wet-climate cycle.

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Parna in north west New South Wales

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INTRODUCTION

Desert loams and associated clays occur extensively across wide tracts of north west New South Wales. Mapping completed by the Soil Conservation Service of New South Wales has demonstrated that 4436 km^2 out of a total area of 64,000 km^2 on the Milparinka, Urisino, Cobham Lake and White Cliffs mapping sheets (1:250,000 scale) are covered by desert loams, whilst a further c.13000 km are mapped as complexes of desert loams and associated clays. In this paper, the properties of these soils are used to demonstrate that much of the parent material of desert loams and similar soils is aeolian in origin and forms part of the widespread mantle of parna (Butler, 1956, 1982) that blankets much of western New South Wales and adjacent parts of Queensland and South Australia.

DISTRIBUTION OF DESERT LOAM AND ASSOCIATED SOILS

The work of Jessup (1960) and more recently Chartres (1982) has demonstrated that desert loam and associated soils occur on a wide range of geological substrates varying from quartzites and silcretes to shales and alluvium. Similarly, such soils are found on plateau surfaces, sloping sites, river terraces and alluvial fans, though, in general, the heavier clay soils occur in low-lying sites.

PHYSICAL AND CHEMICAL PROPERTIES OF DESERT LOAM AND ASSOCIATED SOILS

The modal concept of a desert loam (Northcote: Dr 1.43) has an apedal stony A horizon of sandy loam to sandy clay loam overlying reddish, pedal, clayey stone-free B_1 and B_2 horizons. Although the B_2 horizon is often strongly saline (the maximum E.C. values are often 8-10 mS cm^{-1}) carbonate and gypsum contents are usually only a few per cent (Table 1). Underlying the B_2 horizon, however, highly gypsiferous and sometimes calcareous materials are often found.

These are paler in colour, and less clayey than the overlying B_1/B_2 horizons and frequently stony and are designated Bcs or Bca horizons. In some areas, however, the latter horizons are absent and the clayey B_2 lies abruptly on silica hardpan or rock. Further details of physical and chemical analyses are shown in Table 1.

SILT (63-20 μm) MINERALOGY

Studies at Fowlers Gap in the Barrier Ranges have indicated that there is a mineralogical discontinuity between the upper profile A and B_1/B_2 horizons and the underlying material. (Chartres, 1982). In the upper material heavy fraction there is a relatively rich suite of minerals including zircon, tourmaline, biotite, chlorite, amphiboles, garnet, epidotes and titanium minerals. In the lower horizons (Bcs and underlying shales and siltstones) tourmaline and chlorite are predominant, with very few of the other minerals listed above, except zircon.

CLAY MINERALOGY

Results (Figs 2 and 3) again from Fowlers Gap (Chartres, 1983a) indicate the presence of illite, kaolinite and mixed layer clays in the A horizons, montmorillonite and kaolinite and illite in the B_1/B_2 horizons and kaolinite, illite, mixed layer clays and chlorite in the Bcs horizons of several profiles investigated. In contrast soils developed entirely in shale and siltstone tend to be dominated throughout the profile by chlorite.

TOTAL CHEMICAL ANALYSES

TiO_2/ZrO_2, Al_2O_3/K_2O and Al_2O_3/Na_2O ratios of the entire less than 2mm fraction made on desert loam soils from Fowlers Gap (Chartres, 1983a) indicate changes between A and B_1 horizons, B_2 and Bcs horizons and the Bcs horizon and underlying rock (Fig. 4).

MICROMORPHOLOGY

Micromorphologically the A horizons of the desert loams have asepic to insepic plasmic fabric and contain pedological features such as pedorelicts and lithorelicts indicative of colluvial depositionary processes. In the B_1/B_2 horizons stress features are prominent in the B_1 horizon, whereas with increasing depth small sub-round to rounded clay pellets (median size c.100 μm) become more apparent. Such clayey pellets are also observed in the Bcs horizons. The latter horizons also contain fine-earth calcium carbonate and commonly large (2 mm) gypsum crystals in the voids and channels.

DISCUSSION

The distribution of desert loam and similar soil over a wide range of topography and substrates is itself indicative of an aeolian origin of some of the soil parent material. The differences in mineralogy between A and B_1/B_2 horizons and the Bcs horizon and underlying rocks coupled with occurrence of clayey pellets presumed to be derived from lacustrine sources and then wind transported prior to deposition (Chartres, 1983b), further indicates aeolian accessions to the soils. As has been pointed out, however, by Chartres (1983a) the soils themselves are composed of several layers of material. These are:-i) the Bcs/C horizons which themselves are probably the truncated remnants of older soil profiles.

ii) the B_1/B_2 horizons considered to be predominantly aeolian silts and clays.

iii) the A horizons considered to be primarily colluvially transported material.

Pedological processes have only made a very minor contribution to the development of the present soil profiles, possibly including the redistribution of soluble salts in the A, B_1 and B_2 horizons, and some translocation of clay and iron oxides from A to B_1 horizons.

In many areas the desert loam and associated soils are economically very significant because they provide a deep soil cover and,therefore,rooting medium, where none would normally occur under arid conditions. Similarly, the aeolian deposits mantle the underlying geology with mineralogically exotic material, thus indicating that geochemical soil surveys could be very misleading. Although the aeolian mantles of north west N.S.W. and other parts of arid Australia are usually only 0.5-2.0 m deep, it is, however, important that parna and like deposits are recognised as such and not interpreted as simply the uppermost member of an *in-situ* weathered regolith.

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TABLE 1 Some physical and chemical properties of a desert loam soil

Profile No: FG 15.

Location: Fowlers Gap, 110 km north of Broken Hill

Topography: Gently sloping (2°), footslope

Geology: Precambrian shales

Vegetation: Shrub steppe of Atriplex vesicaria (saltbush)

		Particle-size distribution (µm)									
		2000-500	500-250	250-263	63-20	20-2	<2	pH (water) 1:5	E.C.	$CaCO_3$	$CaSO_4$
Depth (cm)	Horizon	%	%	%	%	%	%		$mScm^{-1}$	%	%
0 - 5	A	2.1	2.0	27.0	29.8	11.7	27.4	9.1	0.12	0.0	0.05
10 - 20	B_2	1.4	1.2	11.7	9.1	11.1	65.5	8.1	1.15	ND	ND
40 - 50	B_2	0.8	0.7	12.9	12.1	10.0	63.5	8.3	4.30	1.40	0.23
60 - 70	B_2	0.6	0.6	12.1	18.1	6.5	61.1	8.0	8.89	1.42	0.20
120 -130	Bcs	2.1	1.3	17.9	8.0	21.2	49.5	8.0	8.06	2.31	28.76
140 -150	Bcs/C	1.1	0.5	11.2	30.3	18.2	38.7	7.6	5.90	0.0	16.36
Rock		ND	ND	ND	ND	ND	ND	ND	ND	0.0	0.05

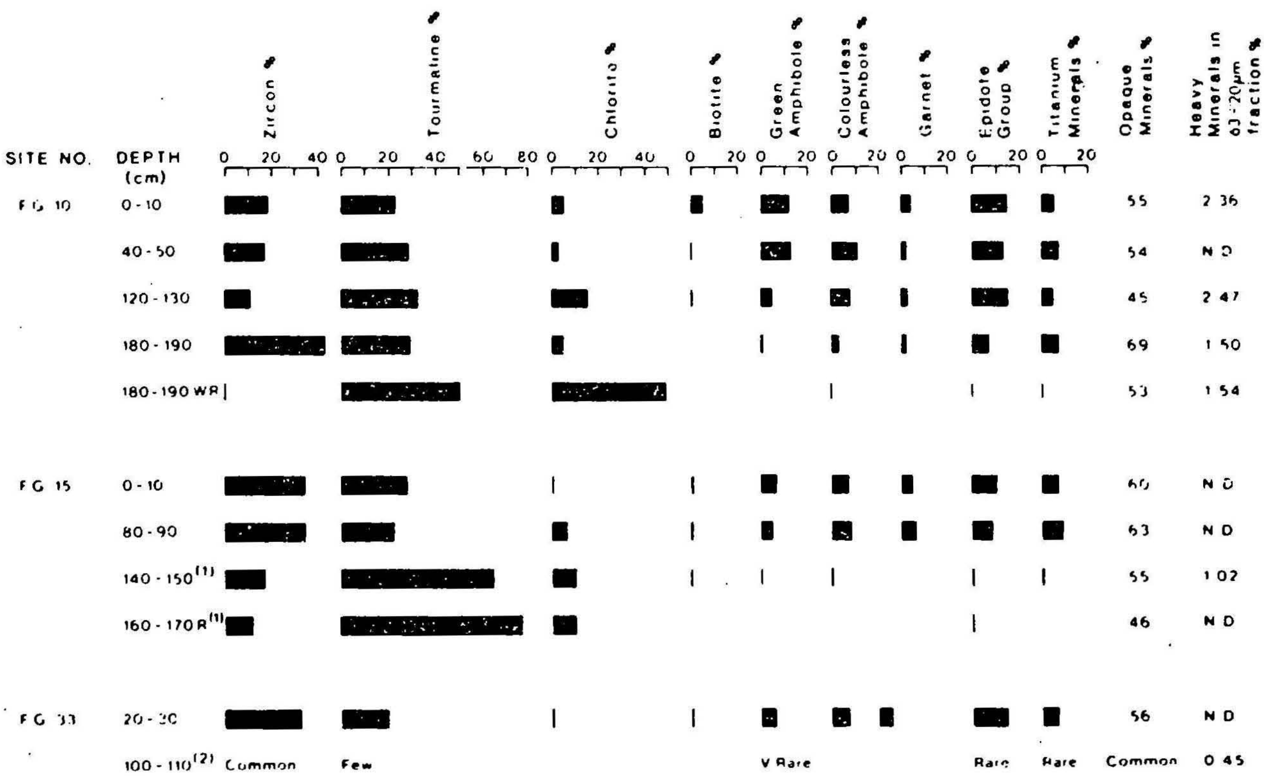

Fig. 1. Heavy mineral analyses of the coarse silt (63-20 µm) fractions from desert loam soils at Fowlers Gap. Percentages based on counts of *c*. 1200 grains and recorded as per cent of the non-opaque fraction (1) Based on a count of *c*. 400 grains. (2) Relative abundance only because of paucity of non-opaque fraction in this sample. N.D., Not determined; R, rock; WR, weathered rock.

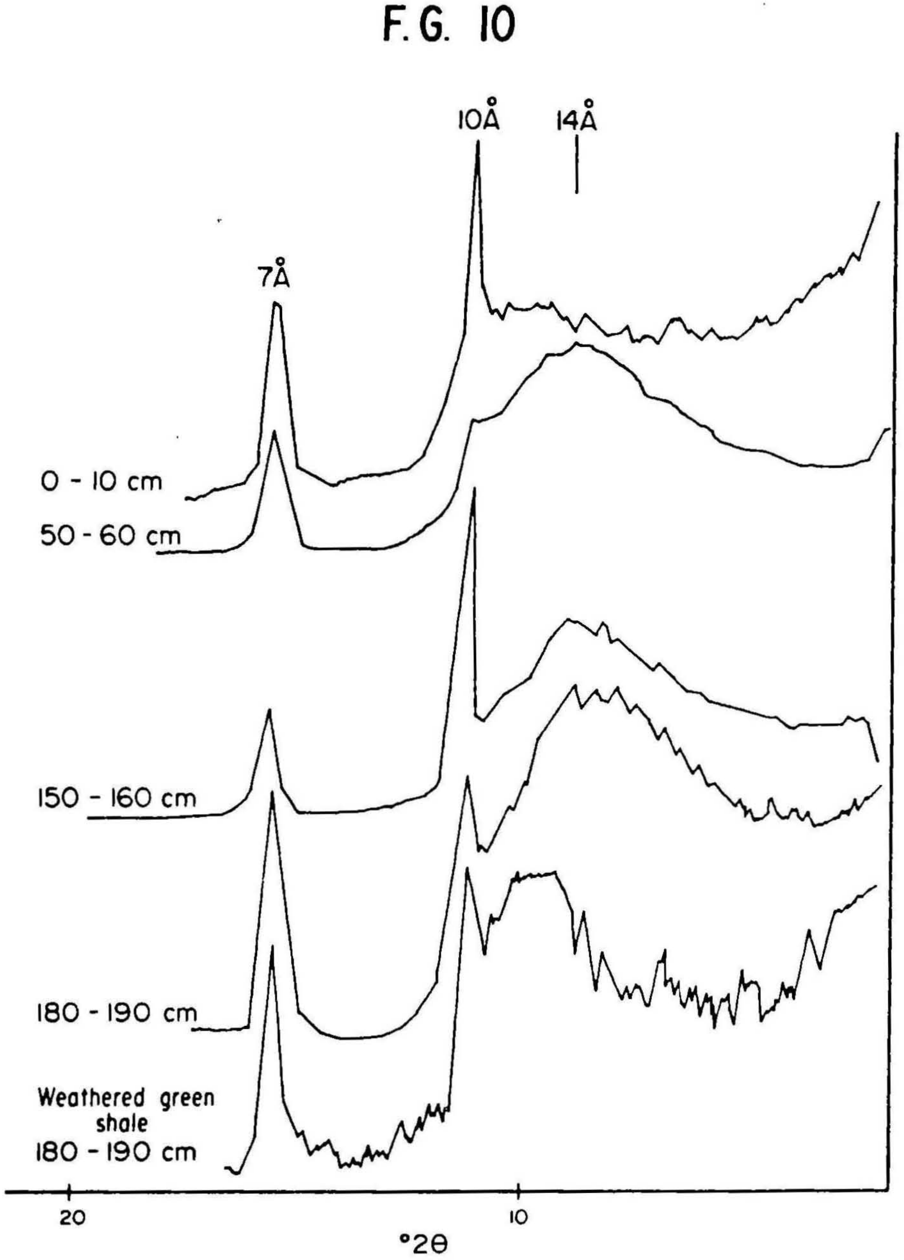

Figure 2. X-ray diffraction traces from profile F.G. 10. Fe Kα radiation; air-dried, oriented, (<2 μm) samples.

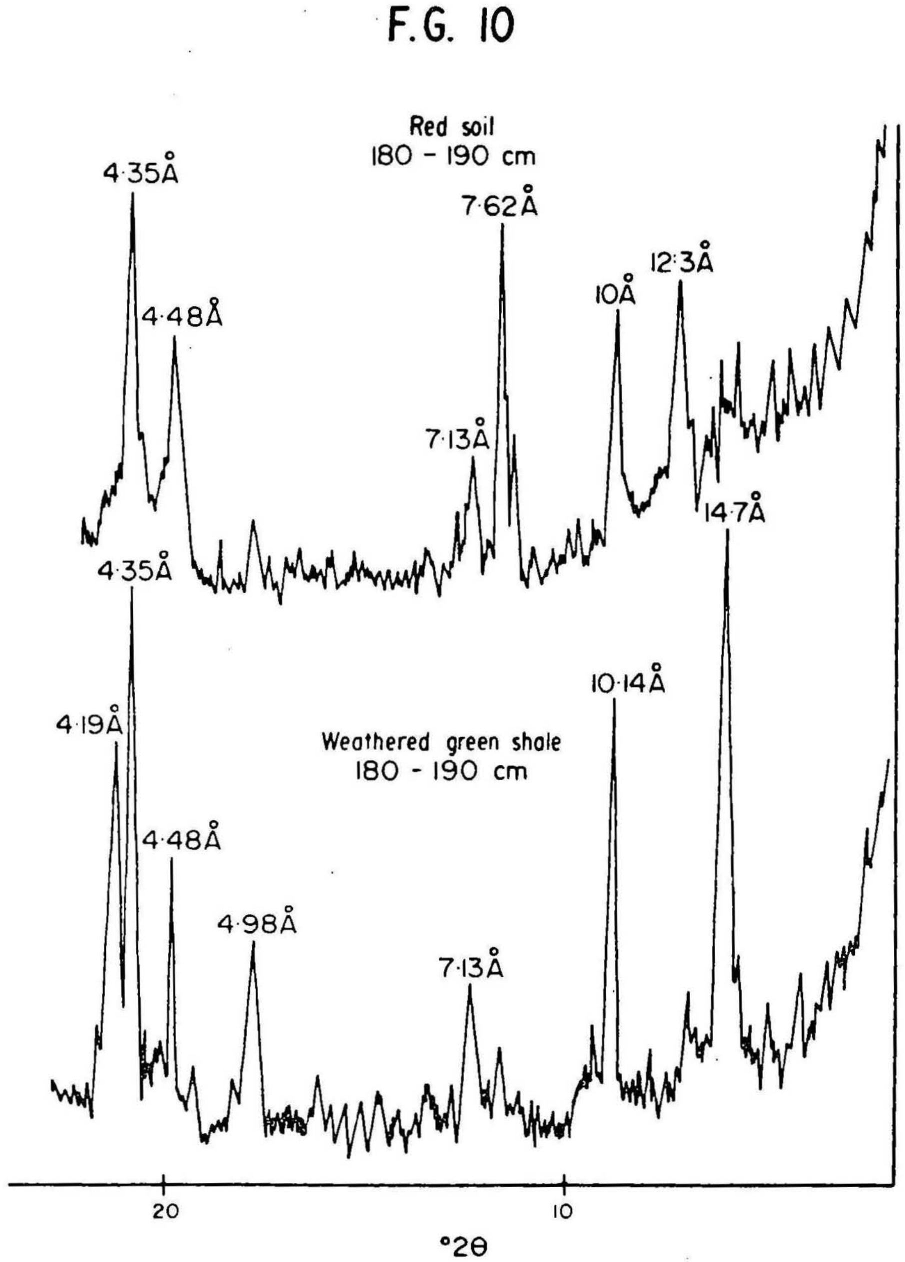

Figure 3. X-ray diffraction traces of powder samples (< 50 μm fraction crushed to a fine powder) from profile F.G. 10. Cu Kα radiation; samples collected approximately 10 cm apart at 180-190 cm depth.

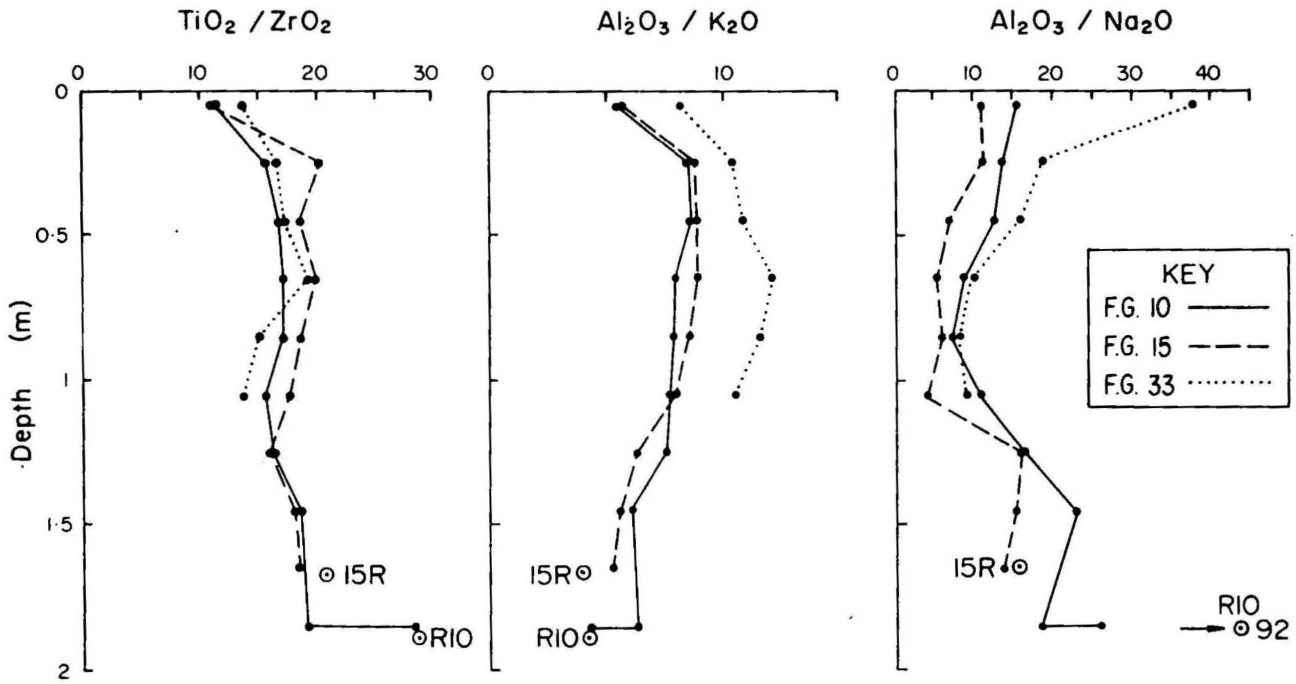

Figure 4 Some elemental oxide ratios of the ignited, less than 2mm fraction from desert loam soils at Fowlers Gap. R10 and 15R refer to rock samples.

THE CLIMATIC CONDITIONS DURING REGOLITH FORMATION: OXYGEN- AND HYDROGEN-ISOTOPE EVIDENCE

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ABSTRACT

The isotopic composition of modern meteoric waters vary as a function of atmospheric temperatures near the earth's surface. Several minerals that develop during regolith formation preserve a record of the composition of past meteoric waters and thus a record of past environmental conditions. Observed isotopic variations in clay minerals are due to global climatic variations and/or tectonism (uplift or continental drift).

No stable-isotope data are available for the Australian regolith. Calculations using the present and inferred past isotopic compositions of meteoric water and Tertiary drift history of Australia indicate stable-isotope analyses are likely to provide information bearing on the timing of uplift of the Eastern Highlands. If an isotopic 'apparent drift curve' can be produced for Western Australia, indirect dating of Tertiary weathering profiles may be possible.

INTRODUCTION

The oxygen- and hydrogen-isotope compositions of modern meteoric waters are a function of the earth's surface temperature, or more specifically, of the temperature of condensation of water vapour from clouds at the site of precipitation. Unless groundwater has migrated large distances and/or has been heated, its isotopic composition is similar to that of rainfall from the same region and also reflects the climate of a given site. The main factors affecting the temperature of condensation of rainfall (or air temperature) are variations in latitude and elevation (Dansgaard 1964).

The isotopic systematics of some clay minerals, notably kaolin and montmorillonite (Savin and Epstein 1970) and oxide minerals, for example gibbsite (Lawrence and Taylor 1971, 1972) and silica are adequately understood. At the temperatures of the earth's surface, these minerals fractionate oxygen- and hydrogen isotopes by a constant amount. Thus, the isotopic composition of minerals and meteoric waters that were present during 'weathering' are related. The equilibrium isotope fractionation factors for clays-water are insensitive to variations in temperature at near-surface temperatures. Therefore, the isotopic composition of clay minerals may be used to calculate the composition of meteoric water at the time of clay formation and, in turn, to infer the air temperature at this time.

Nomenclature

The isotopic composition of waters and minerals are reported in the δ-notation, whereby values are given in parts per thousand (permill, ‰) with respect to Vienna-Standard Mean Ocean Water (V-SMOW) which has a δ-value of zero. This scale applies to both oxygen- and hydrogen isotopes. For modern meteoric waters from tropical and temperate regions, variations in the isotopes of both elements are coupled, and obey the relationship $\delta D = 8\delta^{18}O + 10$ (Craig 1961). In areas of high evaporation, meteoric waters may develop with compositions that fulfill equations with slopes of less than 8 (commonly between 3 and 5).

Using the more general equation, $\delta D = 8\delta^{18}O + d$, Merlivat and Jouzel (1979) indicate the 'deuterium excess' d varies as a function of wind speed, relative humidity and evaporation temperature. This is a powerful tool to study ice cores, but it seems unlikely that the isotopic composition of clays can be related sufficiently precisely to their palaeowaters to enable use of the 'deuterium excess' factor.

Clays of supergene or hypogene origin?

Extensive zones of kaolinitized granite are commonly associated with mineralization (e.g. Cornwall, Malay Peninsula).

Similar altered zones are known from barren granites (e.g. Pittong, Victoria). Isotopic data readily distinguish between several possible modes of formation for this kaolin, and indicate unequivocally that kaolinitization was accompanied by water of meteoric composition, typically at near-surface ($\sim$25°C) temperatures.

CLIMATIC CHANGES THAT ARE VERIFIABLE BY STABLE-ISOTOPE STUDIES

Major variations of climatic changes at given sites during the past can be attributed to global changes (either secular or glacial/interglacial cycles) and/or changes of elevation and/or continental drift. The relative importance of these processes at a given site can be examined by choosing localities where one or more of these variables are constrained.

From a stable-isotope investigation of supergene and hydrothermal clays and fluid inclusions from late Tertiary ore deposits of the western Cordillera of North America, uplift of the Sierra Nevada is shown to be largely restricted to the last 8 Ma (O'Neil and Silberman 1974). In this case the effect of continental drift is negligible. The stable-isotope variations indicate specifically uplift of the Sierra Nevada rather than down-warping of the area to the east, a result that cannot be deduced independently by structural geology.

Uplift of the ore deposits at Yandera and Ok Tedi in Papua New Guinea is also indicated from an isotopic study of their clay minerals (Chivas et al. 1983). For this case the variables of continental drift and glacial/interglacial climatic fluctuations are constrained. The latter is so, because the change in the isotopic composition of the oceans during glacial compared to interglacial periods is towards slightly more positive values, whereas the rainfall condensed from this reservoir at near-equatorial regions becomes relatively more negative. The net result leads to meteoric waters with similar isotopic compositions during both glacial and interglacial regimes. Even for temperate regions, there should be only slight differences in the isotopic composition of meteoric waters during glacial and interglacial periods.

STRATEGY FOR THE ISOTOPIC INVESTIGATION OF THE AUSTRALIAN REGOLITH

Investigation of the regolith of the Eastern Highlands and the western portion of the continent present different problems and require separate strategies. In Western Australia, uplift during the Tertiary is of little significance and the main isotopic variations that can be expected to be preserved from this interval are the result of continental drift and global or continental gross changes in climate. Dating of individual regolith profiles is difficult and depends on geomorphic mapping, which produces only relative age sequences or palaeomagnetic dating. The latter depends on 'fitting' the apparent pole position for a given site to the Tertiary apparent polar wandering path. Likely age estimates by this technique have associated errors of ±5 to 10 Ma.

Since the late Cretaceous, Australia has drifted northwards across approximately 30 degrees of latitude. The anticipated changes in the composition (δD) of meteoric waters during this time vary from -150 (90 Ma ago) to -55 (present) for Tasmania; from -135 to -20 for the site of Perth; and from -55 to -20 for Cape York. For the southern parts of the continent these changes have been large. If studies on dated Tertiary regoliths indicate a regular change of δD of clays as a function of time, regoliths of unknown age might be dated by fitting the isotopic compositions of their palaeowaters to an 'apparent drift curve' in a similar manner to the fitting of palaeomagnetic data to apparent polar-wandering curves. As a corollary, the range of isotopic compositions in profiles from given sites would indicate the duration of regolith formation, or superposition of several periods of regolith formation.

Comparisons need to be made with isotopic results from the regolith of southern Africa, which had negligible continental drift during the Tertiary. In this case, isotopic differences would largely reflect global-scale effects. By contrast, India underwent rapid drift during the Palaeogene within tropical latitudes, on either side of the equator, where the isotopic compositions of meteoric waters vary little.

Large areas of regolith surface such as the 'breakaway' terrain of the Yilgarn Block or the profiles of southern Queensland could be mapped isotopically. If there were a relatively short period of development for a given surface, these isotopic maps would represent palaeoclimate maps.

Studies of laterites, palaeosols and silcretes from the Eastern Highlands are facilitated by the presence in several areas of multiple weathering surfaces and basaltic flows of numerous ages, many of which are already dated by the K-Ar method (e.g. Wellman and McDougall 1974). Interpretation of the isotopic data for clay minerals from the Eastern Highlands might seem to involve too many variables to explain satisfactorily. Contributions due to global climatic change, continental drift and uplift and/or subsidence are likely to be present. However, it should be possible to consider, at least, the problem of the timing of uplift of the Eastern Highlands. For example, two proposals for the timing of uplift anticipate isotopic results of completely opposing trends. Wellman (1980) proposed that the highlands have risen steadily over the past 60 Ma, whereas Jones and Veevers (1982) consider the highlands first came into existence, and were probably at their greatest extent between 50 and 60 Ma ago.

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LANDFORMS AND REGOLITHS OF THE GREAT PLATEAU, WEST AUSTRALIA

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INTRODUCTION

The western quarter of Australia comprises a plateau of generally low relief developed largely on the Precambrian Shield as well as on elements of younger sedimentary basins peripheral to it. Granitic rocks form extensive, relatively uniform lithological terrains sandwiching frequently fine-grained Proterozoic sediments of the Hamersley and Bangemall basins. The western limits of the plateau are marked by scarps, while to the east the plateau is dominated by rocks of the Officer and Eucla Basins and here lithologies, regoliths and landforms are sufficiently different to be excluded from this study.

Long continued weathering of the plateau surface has yielded a thick regolith dominated by clayey kaolinitic saprolites with varying amounts of quartz depending on local lithologies. The erosional modification of this deep mantle of chemical weathering is a central theme in the development of landscapes in this region. The twin process of deep weathering and the erosion of the products of this chemical alteration has analogy with the etch process. Wayland (1933) and Thomas (1965) applied it to dissected weathered plateaux in Africa while Finkl and Churchward (1973) see it as a unifying concept in the classification of landscapes on weathered plateaux in south-west Australia. Some of the detritus derived from this process has been emplaced on the plateau as alluvial and colluvial trains which have been partly indurated by chemical precipitates and modified by subsequent stream incision.

The extensive weathered plateau of low relief having large tracts of similar lithologies and comparable saprolites is seen as a useful common basis on which to examine broad trends of landforms and regoliths in this region.

Trends in stripping pattern have been clearly demonstrated by a number of soil-landform studies in south west Australia (Mulcahy et al. 1972; Bettenay and Mulcahy 1972; Churchward and McArthur 1980). Broad scale maps have been developed for stripped landscapes in south west Australia based on information in "A description of Australian soils" (Northcote et al. (1975)), in the Atlas of Australian Soils (Northcote et al. 1960-68) and in papers by Finkl and Churchward (1973) and Mulcahy (1973). Other background information include papers by Mabbutt (1961), Bettenay and Churchward (1974) and Churchward (1977) and the 1:250,000 geological series.

REGIONAL TRENDS IN LANDFORMS AND REGOLITHS

A common trend in the regolith pattern is that associated with down-drainage change in relief and valley side declivity in individual catchments. The pattern of regoliths shows gross changes between catchments and a consideration of these could highlight regional trends.

A generalized landscape model is presented showing trends down an idealized basin. The variation of the elements of this model is considered across the suite of drainage basins arrayed along the flanks of the plateau. Much of the information is presented schematically in figure 1 and as a generalized map of the region in figure 2.

In the model the idealized catchment has been viewed as comprising upper, mid and lower reaches. The upper reaches comprise areas with minimal stripping. Much of the deep weathered mantle appears to be intact and on these upland situations there is an extensive overlay of gravelly and sandy detritus. There may be scattered zones of stripping or it may be on a broad front in the lower parts of the reach. The broad valley floors may be

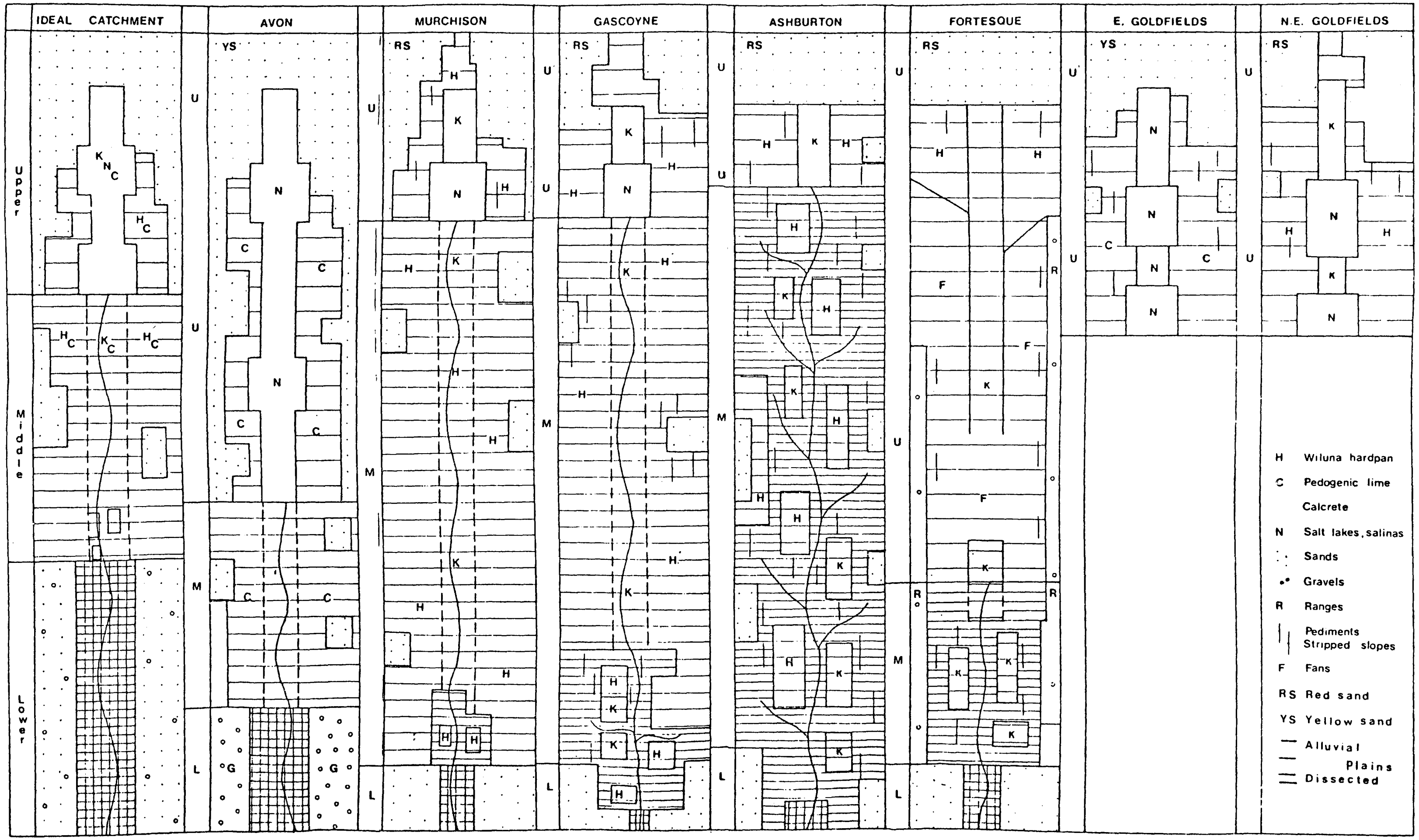

Fig. 1. Idealized catchments

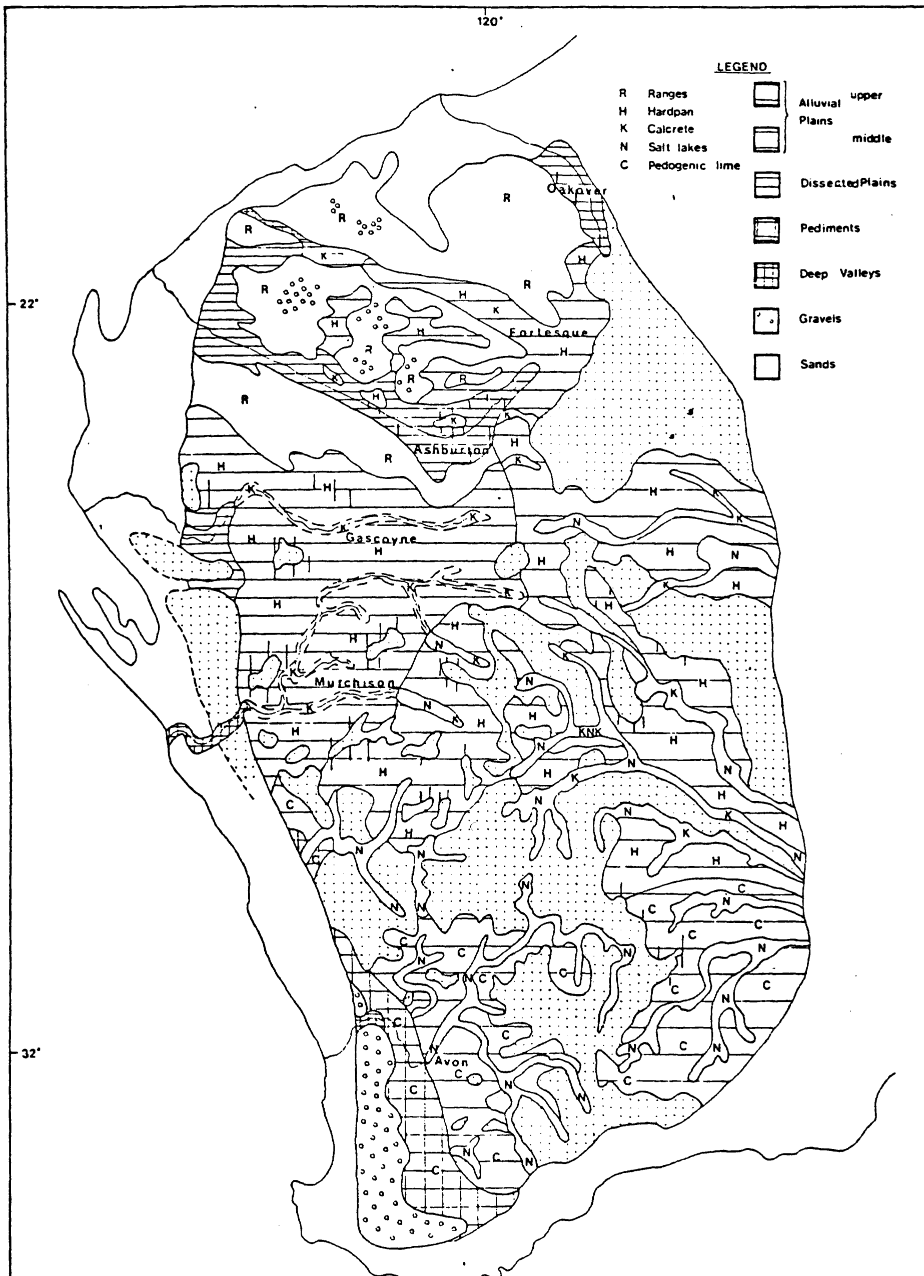

Fig. 2. Regional trends in regoliths and landforms.

mantled by alluvium in which chemical precipitates occur, particularly concentrated along the drainage axis. Drainage is not integrated and salt lakes are a feature of this reach.

The middle reach is the most extensively stripped part of the idealized catchment. Scattered upland residuals capped by laterite duricrust or by silcrete (billy) and flanked by breakaway scarps and pediment slopes, are a common feature. Alluvial fans and plains may be extensive. An essential feature is the channeled drainage axis flanked by terraces. These replace the salt lakes. Siliceous and calcareous precipitates, as calcrete, pedogenic lime and as siliceous hardpan, are common. Dismemberment of the alluvium by stream incision may be a feature as the lower reach is approached.

The lower reaches feature streams occupying clearly defined valleys. Stripping of the regolith is limited to the steep valley sides. Here the upland tracts often show minimal stripping of the weathered mantle, and sands and lateritic gravels are common.

We may now consider the major variations in this model between catchments. In the upper reach of the Avon drainage deep yellow sand occurs extensively on a gently undulating surface. There may be some stripping and breakaway development in the lower parts of this reach. Drainage axes are dominated by saline evaporites. Alluvial valley floors, flanking these salt lakes, have pedogenic lime. Deep kaolinized saprolite is a common substrate in the valleys, and on the uplands as well. Northward into the Murchison, Gascoyne, Ashburton and the Fortescue the sand plains are red in colour and considerably fragmented and are replaced by extensive alluvial plains. These latter are partially cemented to a dull earthy red-brown siliceous hardpan (the Wiluna hardpan, Bettenay and Churchward 1974) and by calcrete along drainage axes. There are some large salt lakes. The upper reach of these catchments occupy much less of the catchment than in the Avon.

The middle reaches of the Avon are characterized by low angle pediments, cut in saprolite, and mantled by shallow colluvium. Alluvial tracts are usually limited to terraces flanking the stream channels and these have replaced the salt lakes. Mulcahy (Mulcahy and Hingston 1961) has referred to this point as the Meckering line. Pedogenic lime is common in soils on the alluvium and pediments but there are no calcretes or evaporites. There appears to be some mottled siliceous hardpan (not the Wiluna hardpan) but distribution of this is not well documented. The middle reaches of the Murchison and Gascoyne are much more extensive than the Avon and are dominated by plains of alluvium cemented by the red brown siliceous hardpan. There is little pedogenic lime but calcretes are common along the stream channels. There are no salt lakes. As the drainage channels approach the lower reaches they are deeply incised into the alluvium with its consequent fragmentation into mesaforms. Though this condition is well expressed in the Gascoyne it is more extensive in the Ashburton and here it occupies the entire middle reaches of the catchment. Here extensive relics of the alluvial plain, capped by calcrete and hardpan, are interspersed with tracts of exposed country rock and younger alluvium. Such is also the case of the Oakover in the northernmost sector of the shield. However in the intervening Fortescue catchment the alluvial plains extend well down stream flanked by fans and scarps. The Fortescue River has incised and partly fragmented the alluvial plains downstream for a short distance before entering its lower reach as a gorge set in the Chichester Ranges.

In the lower reaches of most of the main catchments streams occupy open, V-shaped valleys clearly defined from flanking uplands in the Avon which are here mantled by thick gibbsitic laterite and gravelly sands. In contrast the uplands adjacent to the lower reaches of the Murchison are red sand plain related to sedimentary rocks. A similar though more fragmented situation exists for the lower reach of the Gascoyne. Ferruginous duricrusts on summits flanking the Ashburton and Fortescue rivers have some comparability to the laterite-mantled local divides in the lower reaches of the Avon system.

The eastward-trending catchments blend into dune fields beyond the shield so only elements of the upper reaches of the model are represented. Across the extensive sand plain divide of the Avon the catchments in the eastern goldfields (at the latitude of Kalgoorlie) are dominated by extensive stripping of yellow sand plains. Drainage axes are of the upper reach type, unincised and dominated by salt lakes. Lime is only present as the pedogenic form, in the extensive alluvial plains. There is no calcrete. Northward of Kalgoorlie by some 200 km, the catchments are more akin to the upper reaches of the Murchison and the Gascoyne. The red sand plains are very fragmented and red-brown hardpan is extensive on the alluvial plains below. Calcretes and salinas are along the drainage axes. Pedogenic lime is not usually present.

Regional trends in the nature of duricrusts on upland residuals should be briefly reiterated. The thick gibbsitic duricrust contrasts with thin mottled kaolinitic duricrusts capping low breakaways in the upper reach on the Avon. Duricrusts capping mesaform residuals, in the other catchments, are often indurated pallid saprolite. In these more inland parts thick ferruginous duricrusts relate to more basic lithologies, banded iron formations and such like. Northward of the Avon the divides of the lower reaches are often mantled by red sands.

DISCUSSION

The increased stripping of regoliths and the increased channel development and drainage integration, as well as the change in nature of chemical precipitates, show a parallel with present climatic trends. Northward of the Avon (wet winters, dry summers) rainfall decreases and becomes increasingly variable and episodic (summer cyclones). These conditions may be viewed as being conducive to stripping, alluviation and at times, to the development of braided streams. The broad regional pattern should not be taken as being the result of the present climate. Rather, it is suggested that this parallel between landscape patterns and climate might indicate that climate has played a significant, if not major, role in its development. Relic landforms at various levels clearly indicate periodicity in landscape history. Thus we have extensive alluvial plains established following the stripping of a deep weathered older land surface. The alluvial plains themselves have been partly removed by an integrated stream system which also contains terraces.

The dominance of on-shore winds could have contributed to the considerable extent of saline tracts in the southern latitudes. Northward the catchments are more subjected to off-shore winds for much of the year. The situation is however not clear, made complex by increased stream integration and apparently associated with restriction of salt lakes in these catchments.

Certain anomalies in the broad picture may be related to lithology. Thus sandy tracts flanking the lower reaches of the Murchison and Gascoyne overlie coarse sedimentary rocks while a large lobe of sand plains, east of the Ashburton appears to be underlain by extensive beds of Calyie sandstones. The gibbsitic duricrust of the lower reaches of the Avon has yet to be satisfactorily explained. Physiography and past climatic patterns, as well as lithology, have probably all contributed to this phenomenon. However this crust appears to have had a significant effect on the stripping pattern in a zone of relatively high relief and drainage. This thick crust could provide a protective capping, constraining the lateral extension of stripping whereas the thinner and less bauxitic and ferruginous duricrust in the middle and upper reaches may have been less effective in limiting the stripping process.

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PETROGRAPHY, DISTRIBUTION, ORIGIN AND AGE OF FERRICRETE AND SILCRETE IN THE ARMIDALE AREA, NEW SOUTH WALES

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1.1 Ferricrete Petrography

The term 'ferricrete' is used here to refer to cohesive material, rich in weathered iron minerals. In the Armidale area this iron-rich material is found in a variety of slope and soil contexts. It is commonly nodular, with 1-13 mm nodules, though the usual size range is 1-7 mm. Nodules are usually ferruginously cemented sediments, often rich in quartz, and are commonly orange to red-brown in colour. Concentric laminations are rare.

Where quartz sand is present it is usually moderately to well rounded, with a size range of 0.1-1.0 mm. Ferricrete sometimes also contains fragments of basalt, silcrete, chert and jasper.

Nodular ferricrete usually contains cavities which can be vesicular (tube-like), cellular (spheroidal) or intermediate between the two. Some cavities are simply spaces between nodules, while others apprar to be the result of weathering within the ferricrete.

1.2 Ferricrete Distribution

Although ferricrete is found at all elevations in the Armidale landscape, the main deposits are in low relief, poorly drained areas along the valley floor of Saumarez Creek, 10 km southwest of Armidale. Here ferricrete is underlain by basalt, and this close field relationship is characteristic, with other ferricrete frequently developing immediately downslope of basalt.

Massive, highly weathered ferricrete horizons at Bald Knobs and Arthurs Seat (7 km south of Armidale), and at Mount Butler (15 km west of Armidale), are overlain by relatively unweathered 32-21 my basalt that has only a 2 mm rind of surface weathering. At other sites, such as The Sugarloaf (3 km north of Uralla), and Uralla Trig. (3 km east of Uralla), massive, highly weathered ferricrete forms topographic highs, emerging through valley-fill basalt.

1.3 Ferricrete Origin

The close field relationship between ferricrete and basalt, and the propensity of basalt to produce hydroxides of aluminium and iron as end products of weathering, suggest that basalt has been an important source of the iron minerals now concentrated as ferricrete. Ferricrete profiles frequently lack a pallid zone, and therefore cannot be adequately explained in terms of the upward movement and concentration of iron minerals. Thus lateral and downward transport is likely, and the characteristic development of ferricrete downslope from basalt suggests that iron minerals in the weathering basalt have been transported downslope and down profile, by throughflow water and/or groundwater, before being reprecipitated within the soil profile on lower slopes.

2.1 Silcrete Petrography

There are three main types of silcrete in the Armidale area.

1. Silica-cemented sorted sediments, consisting of moderately to well-sorted quartz clasts of sand to pebble size in silica cement. Clasts are often well-rounded, and fracture varies from conchoidal to uneven.

2. Silica-cemented poorly sorted sediments, consisting of unsorted to poorly sorted quartz clasts of sand to pebble size, in silica cement. Rounding is more variable than that of silica-cemented sorted sediments, as is to be expected since clasts are both sorted and rounded during transport in streams.

3. Replacement silcrete, in which unsorted, angular clasts of quartz and chert are cemented by cryptocrystalline silica that infills voids and fractures between and within clasts. The texture and appearance of the host rock is usually preserved, and where weathering prior to silicification was further advanced, replacement silcrete grades into siliceous breccia or silica-cemented poorly sorted sediments.

2.2 Silcrete Distribution

Silcrete is more common on upper slopes and interfluves than on valley floors, and most deposits either adjoin or lie near Tertiary basalt. Mining records and bore logs, and inspection of waste heaps of disused deep lead mineshafts in the Uralla area, show that at least some silcrete is sub-basaltic. Surface outcrops vary from less than 10 m across, to elongate deposits 2 km by 1 km.

2.3 Silcrete Origin

Much of the silcrete in the Armidale area is silicified fluvial sediments that occupied streams inundated by valley-fill basalt. As these sediments occupied low parts of the pre-basalt and immediate post-basalt landscape, they were well situated for infiltration by groundwater. Many clasts in silcrete show etching and solutional embayment, indicating that at least some of the silica cement was dissolved and reprecipitated *in situ* by percolating groundwater.

3.1 Age of Ferricrete and Silcrete

Both ferricrete and silcrete are found at all elevations in the Armidale area, suggesting that neither was formed as a result of one particular phase of climate or stage of landscape evolution. On the assumption that much of the iron in ferricrete is derived from weathered basalt, the ferricrete must post-date at least the oldest basalt. Some ferricrete occupies soil profiles on contemporary floodplains and lower slopes, indicating it is much younger. On this evidence ferricrete probably formed over an extended period, from soon after the earliest dated basalt extrusions, 32 my ago, possibly to Recent times.

Attempts to calculate palaeomagnetic ages for the massive, highly weathered ferricrete deposits have been inconclusive, though a Jurassic age calculated for The Sugarloaf, and its present position in the landscape, suggest that it formed a pre-Tertiary topographic high that stood above the ensuing Tertiary lava flows. These flows covered alluvial sediments in a valley at the base of The Sugarloaf. On this evidence the massive, highly weathered ferricretes are substantially older than even the oldest post-basaltic nodular ferricretes.

The relative dating of silcrete is complicated by the fact that at some sites silcrete is found as inclusions in ferricrete, while at other sites ferricrete nodules are found as inclusions in silcrete, indicating that there was at least partial overlap in the periods of development of the two materials. As much silcrete is developed on fluvial sediments in or near streams that were active until disrupted by Tertiary basalt extrusions, silicification is probably post-basaltic, and may have followed each phase of basalt extrusion, as valley floor sediments became confined and subject to groundwater percolation beneath valley-fill basalts. On this basis silcrete in the Armidale area is early to mid-Miocene in age. The relationship between silcrete and basalt is one of physical proximity of relief-inverted basalt remnants and sub-basaltic sediments; there is no evidence of a genetic link.

IMPLICATIONS OF SECOND GENERATION REMOTE SENSING SYSTEMS FOR AUSTRALIAN GEOLOGY

A.R. Gabell and A.A. Green

INTRODUCTION

The development of remote sensing has been extremely rapid in the past ten years and it has been stimulated to a very large extent by the huge success of the Landsat Multispectral Scanner system (MSS). The MSS is in a sense a first generation remote sensing system. For although it was designed to be primarily an agricultural satellite it is able to provide valuable new information in many other disciplines. The second generation of sensors which are now becoming available have been designed for much more specific applications. In particular, it is clear that it is possible to design systems which will be sensitive to certain types of mineralogy.

The range of minerals which can be sensed is of course limited to those which have diagnostic optical properties in the atmospheric windows. Information is available in three wavelength regions and is summarized below:

Region	Minerals Detected	
Visible - near infrared (0.4 - 1.0 μm)	Iron Oxides	(Haematite (Goethite (Limonite
Near infrared (1.6 - 2.5 μm)	Phyllosilicates and Carbonates	
Thermal infrared (8 - 14 μm)	Silicates and Carbonates	

Although the number of minerals which can be detected is limited, it is possible that some quite subtle descriminations can be made within each group.

Mineral exploration in Australia faces a number of severe and almost unique problems. One of the most important is the effect of our Tertiary weathering history. This has resulted in the development, at the surface of mineral assemblages rich in iron oxides and clays. The very same minerals which will be detected by the new remote sensing techniques.

We shall now examine the interaction of electromagnetic radiation with geologic materials in more detail. Firstly, radiation from the visible and near infrared (from about 0.4 μm to 1.1 μm), where spectral reflectance of minerals is influenced mainly by the wings of charge transfer bands in the ultraviolet and electronic transitions at longer wavelengths, caused by transition elements. Iron is by far the most important of the transition elements for remote sensing purposes. Figure 1 shows the reflectance spectra of a number of iron oxides and hydrous iron oxides, with a characteristic steep fall-off reflectance in the visible towards the ultraviolet and an absorption band between 0.85 and 0.92 μm. In contrast the major variation in rocks containing no iron is in the magnitude of the reflectance (or the overall brightness) of the rock.

The second interval of interest is the short-wavelength infrared region, between 1 and 3 μm, which provides more diagnostic spectral information about the composition of minerals and rocks than the visible and near infrared region. Of particular interest is the region between 2 and 2.5 μm where sharp, highly diagnostic spectral absorption bands are caused by lattice overtone bending-stretching vibrations of -OH bands in amphiboles and phyllosilicates and by C-O bands in carbonates. Figure 2 shows the spectra of a number of these minerals, with the position of the major absorption feature being dependent on the nature of the atoms to which the -OH groups are bonded. In general an -OH group bonded to aluminium will have its major absorption feature in the 2.2 μm region, while a group bonded to magnesium will produce a feature closer to 2.3 um. Some minerals (for instance kaolinite in Figure 2) have a doublet structure caused by -OH groups occupying two different bonding sites in the lattice, and therefore vibrating at slightly different frequencies. Thus there is an enormous amount of information in this portion of the electromagnetic spectrum if it can be measured in sufficient detail.

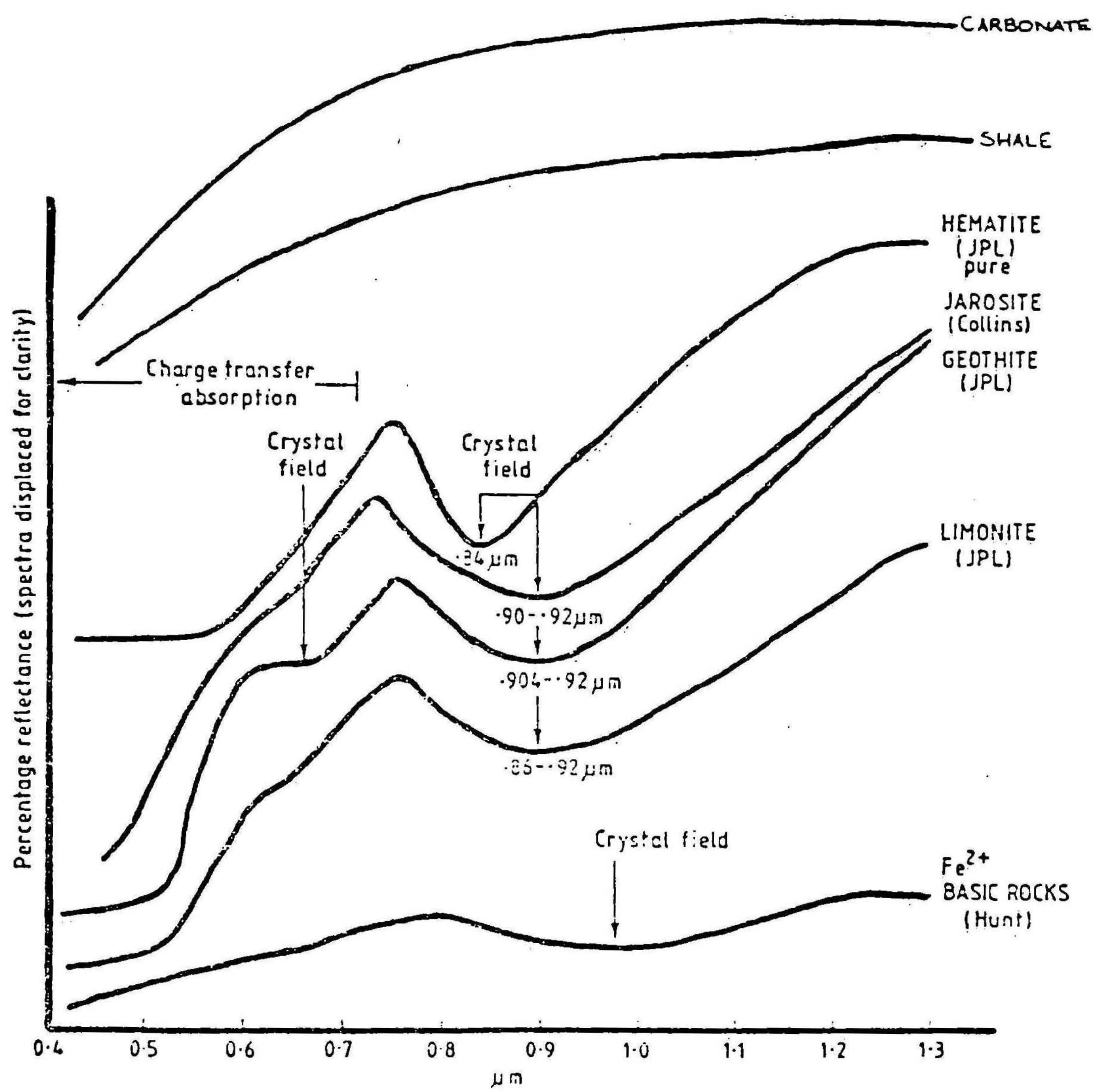

Figure 1 Typical visible and near infrared spectra of the iron oxides

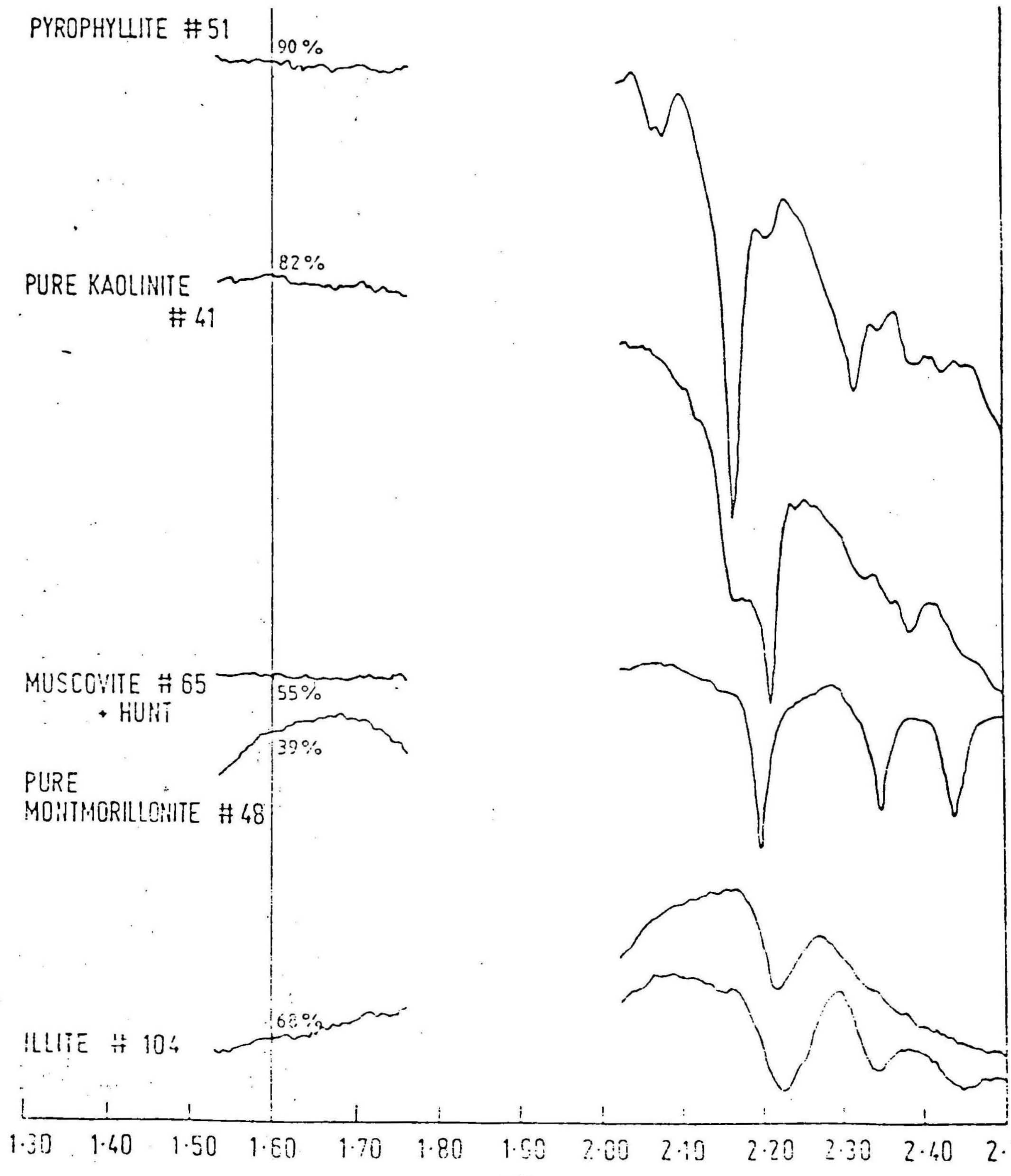

Figure 2. Reflectance spectra of clay minerals. Pyrophylite is an alteration mineral, while the others can form by either weathering or alteration processes.

Second generation remote sensing systems for Australia will be one of two types. The first is a "profiling" system where extremely detailed spectral measurements will be made along a traverse producing a single line of pixels. The second type of instrument will be a scanning system which will produce much less detail spectrally, but an array of pixels which can be presented in an image form. Data will be collected from a number of carefully chosen narrow bands centred on specific absorption features in order to maximise the information from such a system.

The majority of the research in remote sensing to date has been done in the United States. MSS data have been used for the identification and mapping of limonitic alteration zones that are important surface indicators used in exploration for precious and base metals. However, in addition to these significant areas, other areas containing concentrations of iron oxides in a form which are not geologically as important are also mapped. Because of this the information in the short-wavelength infrared region becomes extremely important. A Thematic Mapper Simulater (TMS) was used to collect broad band data in the 1.6 μm and 2.2 μm portions of the spectrum, in addition to a number of bands similar to, but narrower than, those on the Landsat MSS. This resulted in the detection of clay alteration minerals in addition to limonitic alteration, thereby enabling areas of alteration to be separated from areas where iron oxides had accumulated for different reasons. Examination of similar data in other areas has also led to the ability to detect non-limonitic hydrothermally altered rocks.

Australia has had a significantly different weathering history to the U.S. Widespread Quaternary glaciation in much of North America virtually scraped the landscape clean, exposing fresh bedrock. In Australia the last glacial event was in the Permian, and since that time the widespread lateritic weathering has produced extremely complex assemblages of weathered material, many areas having little outcrop. Figure 3 is a schematic presentation of the lateritic weathering process, showing the types of mineral assemblages produced. Notable features of this diagram are the prominence of iron oxides, and the type of clays produced by weathering, which are often the same as those produced by hydrothermal alteration. It should also be noted that all of the minerals in Figure 3 can be detected by detailed spectral measurement.

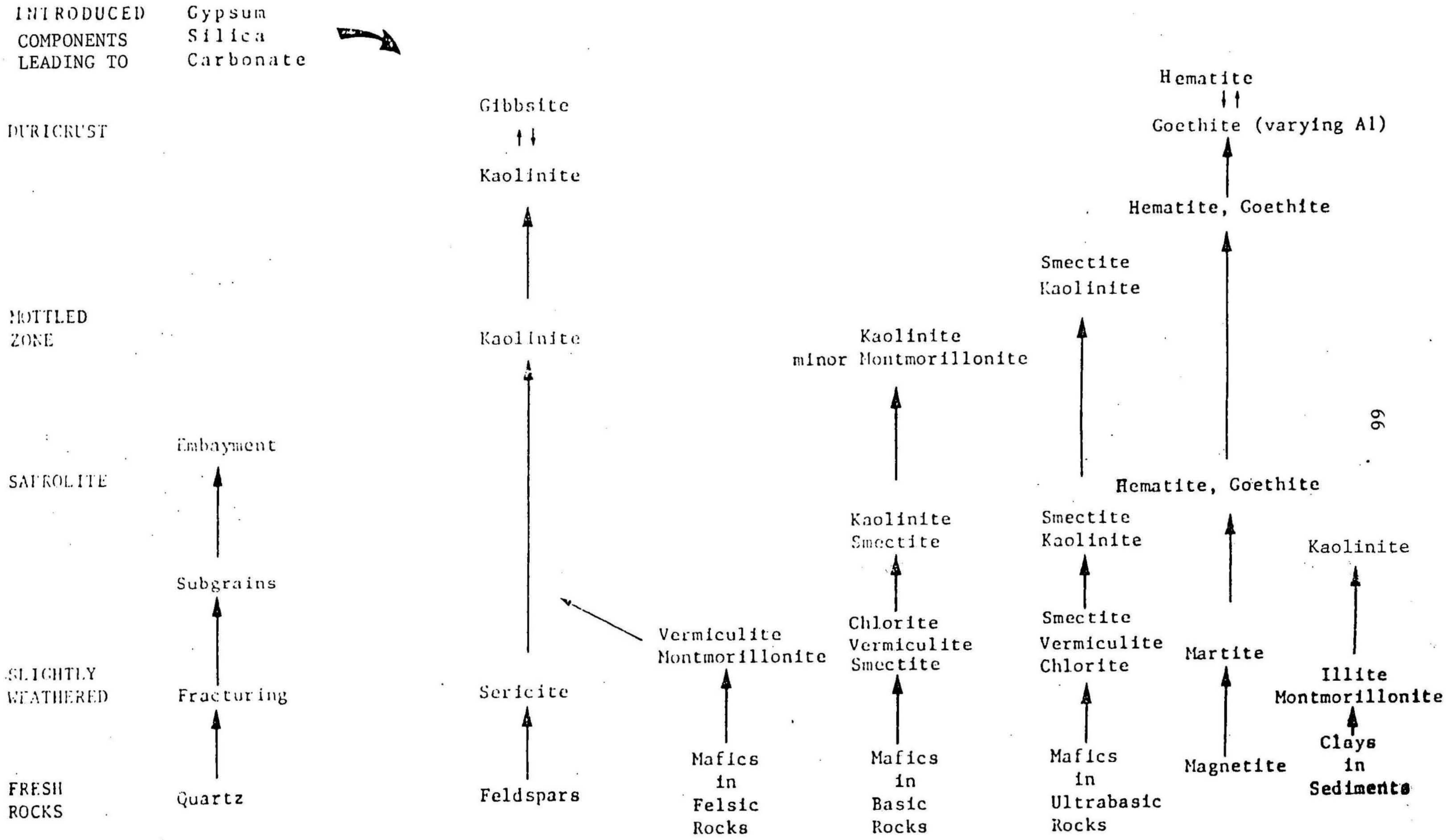

Figure 3. Generalized representation of the lateritic weathering process

DEEP WEATHERING EVENTS IN QUEENSLAND

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Most of Queensland's deep weathered surfaces are of Cainozoic age. However, some earlier weathering events are known. A ferruginous weathering event of pre-Mid-Cambrian age has been recorded in the Georgina Basin, and karst surfaces are also known within that sequence (Shergold & Druce, 1980). Devonian red beds are recorded in northern and western Queensland, though their origin is not known. In the southern Bowen Basin the red mudstones of the Late Permian to Early Triassic Rewan and Clematis Groups may have been derived from humid temperate soils (Jensen, 1975). In the same area a Late Triassic leached and silicified surface is preserved beneath the overlying Surat Basin sequence (Dickins & Malone, 1973).

Early in the Late Cretaceous, deposition of Mesozoic sediments ceased and left a broad depositional plain over most of the northwest and southwest of the State. Deep weathering of this surface commenced in the Late Cretaceous, and continued through much of the Paleocene. This formed the kaolinised, ferruginised, mottled, and silicified Morney Profile which has been palaeomagnetically dated at 60 $\pm$ 10 Ma (Idnurm & Senior, 1978). The profile is now preserved only in the Inland Region (Fig. 1), but it could have extended northwards into parts of the Carpentaria Region, and a possible laterite of pre mid-Eocene age is developed on Early Cretaceous sediments in the TAI Anchor Cay 1 well in the Papuan Basin. Earth movements and erosion may have prevented extensive deep weathering further to the east. Some silcretes in the eastern regions may date back to this period, though many of these underlie mid-Tertiary basalts and may be due to the later weathering of the volcanic rock (Gunn & Galloway, 1978).

Three cycles of Tertiary geological activity can be recognised, together with several subsidiary cycles (Grimes, 1980). Each of the first two cycles comprised an initial active phase with earth movements, erosion and deposition, followed by a stable phase in which planation surfaces were commonly formed, and deep weathering was the main process. Ferruginous, siliceous, or other types of duricrust formed during these stable phases. The third cycle is still in its active phase.

The first Cainozoic cycle (Figs 2 & 3)

The first Tertiary active phase began in the late Paleocene and had begun to die down by the end of the Eocene. Erosional and depositional planation surfaces developed in many areas. During the Oligocene these surfaces were deeply weathered to form siliceous and ferruginous duricrusts over much of the State (Fig. 3). The main surfaces and profiles include: the ferruginous Canaway Profile and the Curalle Silcrete Profile (Senior & Mabbutt, 1979), developed on the Cordillo Surface in the Inland Region; the silicified and ferruginised Tennant Creek Surface of Hays (1967), which extends from the Northern Territory into the Isa Highlands; the lateritised and bauxitic Aurukun Surface in the Carpentaria Region (Grimes, 1979); the ferruginised Featherby Surface of the Burdekin Region, previously thought to be younger (Grimes (1979, 1980); and the main, unnamed, lateritised surface of the Fitzroy Region (Dickins & Malone, 1973). The Canaway Profile has been palaeomagnetically dated at 30 $\pm$ 15 Ma (Idnurm & Senior, 1978).

The second Cainozoic cycle (Figs 4, 5 & 6)

The second cycle started in the late Oligocene with epeirogenic movements in eastern Queensland and eruption of plateau basalts. A second period of erosion and deposition was initiated - in the late Oligocene in the east, and in the mid-Miocene in the west (Figs 4 and 5).

Idnurm & others (1980) have reported a preliminary palaeomagnetic date of about 15 Ma or younger (mid-Miocene) from a laterite profile on a post-basalt erosion surface in the eastern part of the Inland Region. In the Brisbane Region the lateritised, post-basalt Woodford Surface of Beckman & Stevens (1978) might be contemporaneous (Fig. 5). In the Burnett Region, two dated basalt flows at Dundowran appear to bracket a mid-Miocene weathering event (Barnbaum, 1976).

CAINOZOIC GEOLOGICAL EVOLUTION

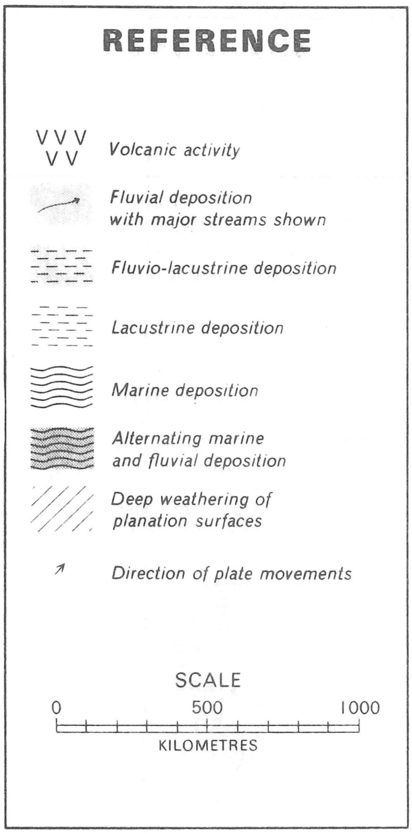


FIG. 1

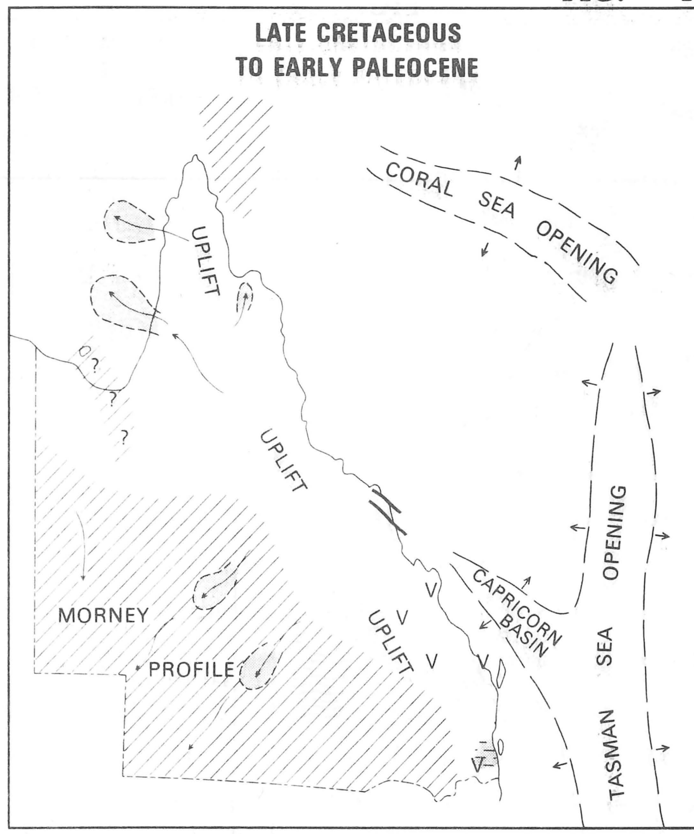


FIG. 2

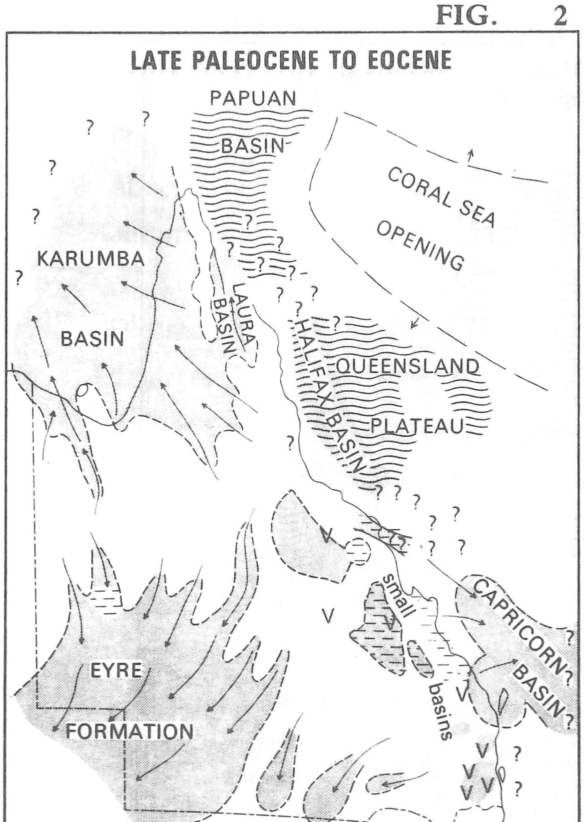


FIG. 3

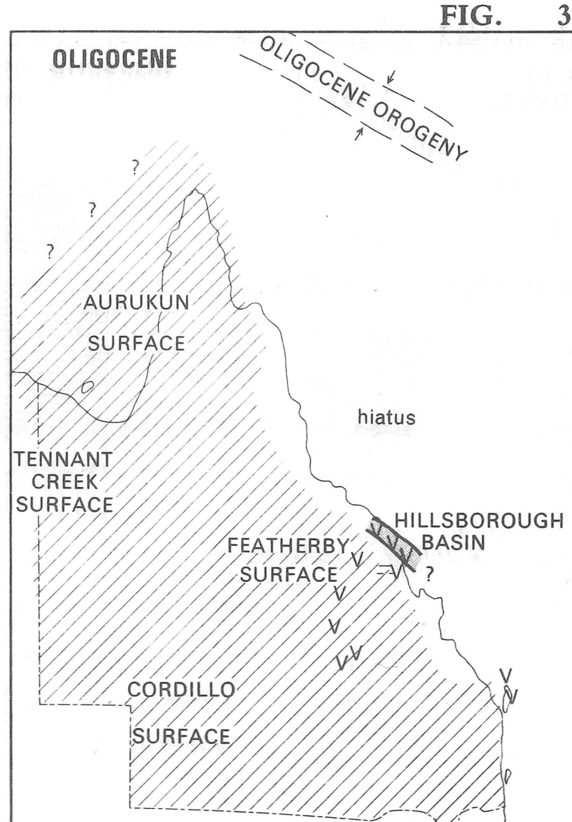


FIG. 4

FIG. 5

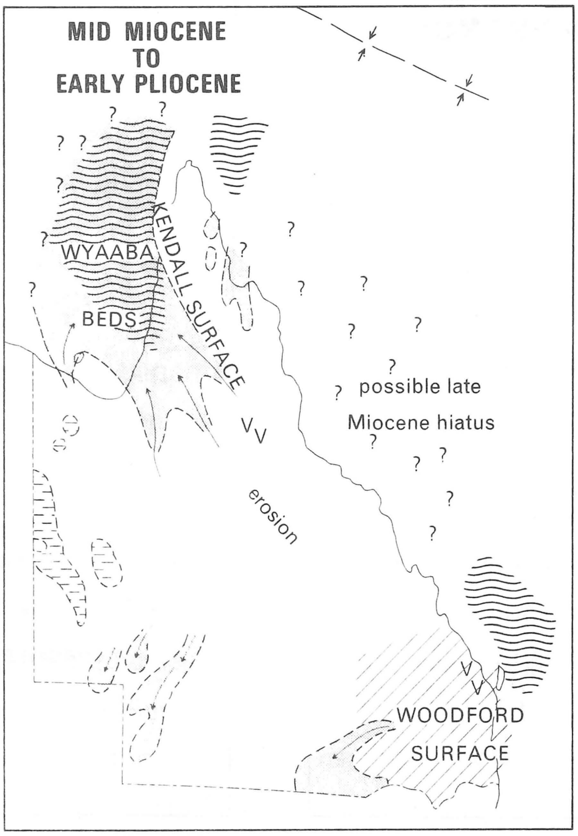


FIG. 6

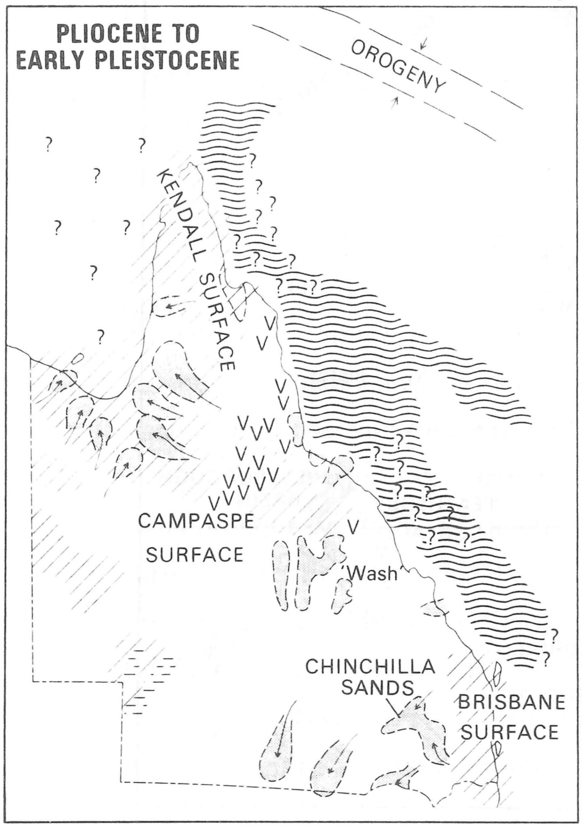
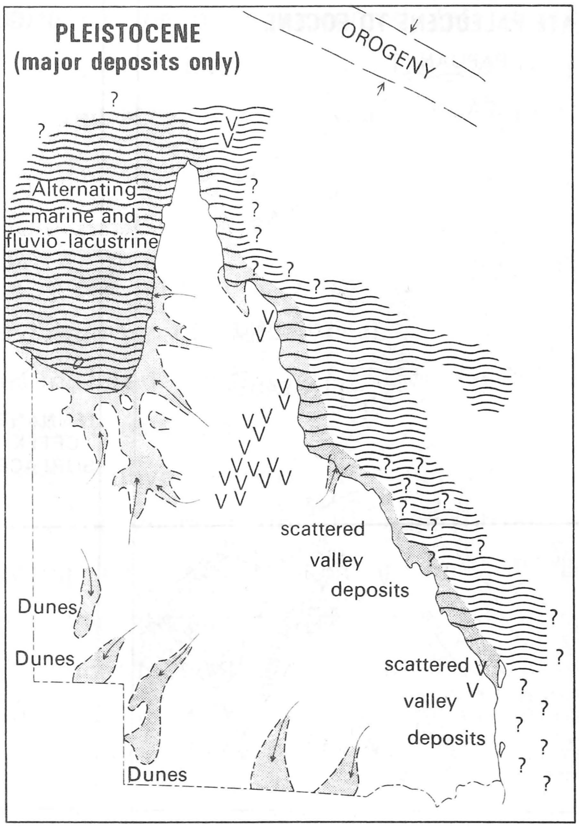


FIG. 7



This mid-Miocene weathering event has not been identified elsewhere in Queensland, though this might merely reflect the lack of accurate age control on some of the lateritised surfaces. The origin of the weathering would seem to be dominantly climatic, rather than a combination of both stability and climatic factors as is the case with the older weathered surfaces.

The stable phase at the end of the second cycle of activity is not as well defined as that which marks the end of the first cycle. In the Inland Region, and possibly parts of the eastern regions, stability appears to have been achieved in the late Miocene. However, in the Karumba Basin, the terminal Kendall Surface apparently developed only in the Pliocene (Grimes, 1979) though this is based on a single fossil date of uncertain reliability. In the Brisbane Region, the low-lying, lateritised Brisbane Surface (Beckmann & Stevens, 1978) might represent a terminal surface of this cycle, but its age is poorly controlled, and could be as young as the early Pleistocene.

In the Carpentaria Region, the Pliocene was a period of ferruginous weathering of the Kendall Surface (Grimes, 1979). The Inland Region was generally stable during the Pliocene; there was minor upwarp about the margins and localised deposition of fluviatile and lacustrine sediments. However, no weathering events have been reported.

A period of deep weathering during the late Pliocene or earliest Pleistocene produced the ferricrete of the Campaspe Surface in the Charters Towers area (Grimes, 1979), and the laterite of the Brisbane Surface might be as young as this. Some low-lying ferruginised and silicified deposits of similar age also occur in the Carpentaria, Burdekin, and Fitzroy Regions.

The third Cainozoic cycle (Fig. 7)

This commenced near the start of the Quaternary and is continuing at present. No deep weathered surfaces have developed, though 'lateritic' weathering could be occurring at present in some tropical areas.

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GEOCHRONOLOGY IN DEEPLY WEATHERED TERRAINS

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The Pb-Pb isotopic technique has the potential to date highly weathered rocks in areas of negligible outcrop where conventional U-Pb, Rb-Sr and Sm-Nd techniques are not suitable.

The Pb-Pb isotopic technique makes use of the fact that U-Pb systems remain closed after crystallization or major metamorphism and Pb generated by radioactive decay is subsequently incorporated

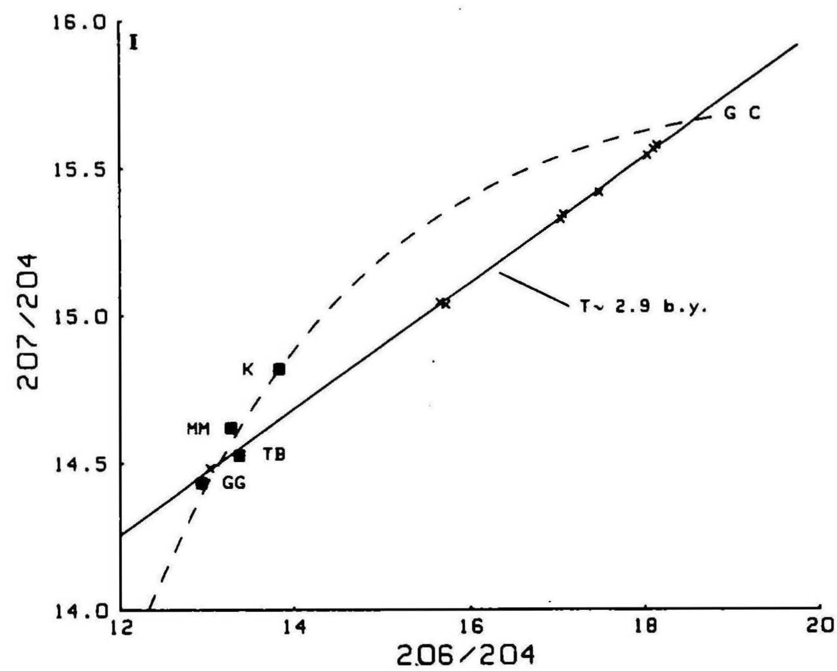

Figure 1 $^{207}Pb/^{204}Pb-^{206}Pb/^{204}Pb$ diagram for one bedrock and seven pisolite samples from the Yilgarn Block. The MSWD is 0.2 and the apparent age calculated from the slope of the line is 2935±10 Ma (2σ). The intercept of the line with the Cumming and Richards growth curve (GC) is 2920 Ma. K, MM, GG and TB refer to isotopic compositions of Kambalda feldspar, Mugga Mugga, Golden Grove and Teutonic Bore deposits; the error bars in the top left hand corner are the 2σ levels for the isotopic ratios.

into surface material such as ironstones, pisolites and soils. Thus the method dates the time interval between crystallization/ metamorphism and weathering.

The isotopic data for a suite of surface samples usually lie on well-correlated lines on the $^{207}Pb/^{206}Pb-^{204}Pb/^{206}Pb$ (or $^{207}Pb/^{204}Pb-^{206}Pb/^{204}Pb$) diagrams, for example Figure 1, and the calculated ages are consistent with the regional framework. The data for fresh material from diamond drill holes often lie on the same lines as the surface material. It may be necessary to make a correction for the interval from the time of formation of the regolith to the present day.

To date most of our case histories are from the Yilgarn Block, West Australia, but the method is also applicable in areas such as Broken Hill. Data from these case histories will be presented.

PALAEOMAGNETIC DATING OF CHEMICAL WEATHERING

M. Idnurm* and P.W. Schmidt**

The ages of chemically weathered profiles may be used to define the lower limits of antiquity of land surfaces, help establish a framework for stratigraphic correlation of continental sediments, link chemical weathering processes to environmental factors, etc. The development of quantitative dating techniques has not matched these needs. This is largely attributable to the technical difficulties of working with authigenic minerals that are almost invariably very fine-grained and constitute open systems. Of the possible dating methods - e.g., fission particle track replication[1], thermoluminescence[2], and oxygen and hydrogen isotope fractionations[3] - the best developed method at present is by palaeomagnetism of authigenic iron sesquioxides[4-10].

In the palaeomagnetic method the remanence directions of weathered profiles are measured and compared with dated poles on an existing apparent polar wander (APW) path. The principle is illustrated schematically in Fig. 1. Clearly continents

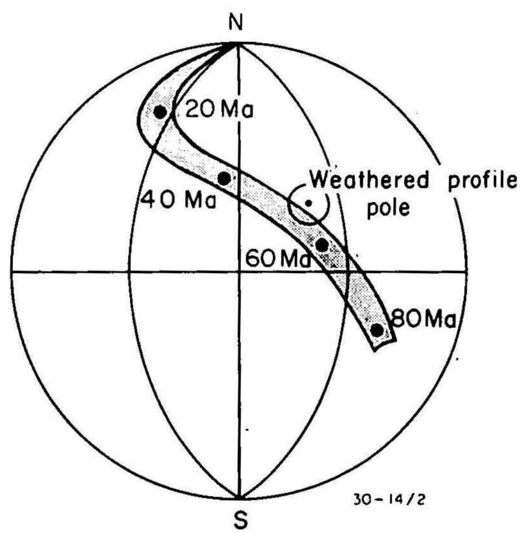

Fig. 1 Principle of palaeomagnetic dating.

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that have had the highest drift rates, and hence the longest APW segments over the relevant time period, give the best prospects for dating. In this respect Australia and the Indian sub-continent are the most suitable regions for dating Cenozoic weathering.

Except for differences in sampling strategy the field and laboratory techniques for dating weathered profiles are in general similar to those used in other palaeomagnetic studies (e.g., refs. 11 and 12). A modified approach to sampling is required because of the long period of remanence acquisition that is likely in weathering. On the one hand, the prolonged magnetisation process assists dating by averaging out short-term secular variations in the geomagnetic field, so that the palaeomagnetic pole may be estimated, at least in principle, from a single weathered unit. This contrasts for example studies on volcanics where the determination of a palaeomagnetic pole of equal quality requires measurements on a large number of flows. On the other hand, the polarity of the geomagnetic field is likely to reverse during a long period of magnetisation, introducing both normal and reversed remanence components into the same sample. Any departure of the oppositely directed components from strict antiparallelism is amplified and may cause large errors, especially if the components are of comparable magnitude (Fig. 2). For reliable results it is therefore necessary to measure a relatively large number of samples so that the discrepancies from opposing components would be statistically averaged out.

Stable remanence in weathered profiles is generally carried by hematite. Goethite, while very common in ferruginous parts of the profiles, has a low Néel point and is therefore remagnetised at moderate temperatures, such as those encountered at surfaces of outcrops exposed to the sun on a hot day. The

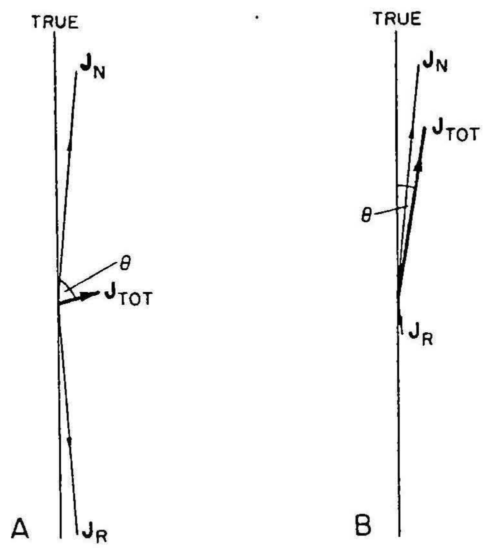

Fig. 2 The effect of normal, $\mathbf{J}_N$, and reversed, $\mathbf{J}_R$, components on the net remanence, $\mathbf{J}_{TOT}$, of the sample. The angle Θ is the deviation of $\mathbf{J}_{TOT}$ from the true field direction. A: $\mathbf{J}_N \sim \mathbf{J}_R$; B: $\mathbf{J}_N >> \mathbf{J}_R$.

only other important authigenic magnetic mineral in weathering is maghemite. Though reported less commonly in chemical weathering than goethite and hematite, maghemite has a high saturation magnetisation and can therefore contribute significantly to remanence even in very small amounts.

The magnetisation process in weathering, chemical remanent magnetisation (CRM), has been explained qualitatively by Haigh[13] on Néel's theory[14] of an assemblage of fine, noninteracting magnetic particles. According to the theory in the initial stages of crystallisation the grains are superparamagnetic, and therefore magnetically unstable. Stable remanence is acquired as the grains grow through a certain narrow threshold range of grain sizes, which centres at approximately 0.03 μm for both hematite and maghemite. With continued crystallisation the grain size reaches a second threshold where the magnetic structure within the grain changes from single to pseudo-single and then multiple domains. Thereafter the magnetic stability decreases again. In hematite this second threshold is 15 μm, so that its stable grain size spectrum spans parts of the pigment and specularite size ranges. In maghemite the single- to multi-domain threshold is approximately 0.06 μm, giving a fairly narrow range of stable grain sizes.

In interpreting palaeomagnetic dates of weathered materials it is important to distinguish between relict profiles and those that are forming at present, i.e. between weathered and weathering profiles. In the former the processes of precipitation, leaching and reconstitution of iron sesquioxides are assumed to have slowed down sufficiently to contribute at worst a magnetic overprint. The central problem in the interpretation is the stage of the weathering cycle at which the remanence is acquired. On the one hand, magnetisation may be continuous throughout the weathering cycle so that palaeomagnetic dates would give the mean age of weathering. On the other, magnetisation may commence only after a certain stage of weathering has been reached. Palaeomagnetism then dates the mean age of maturity. From studies of present-day pedogenic processes a continuous magnetisation throughout weathering seems unlikely. Firstly, several agents in soil solutions appear to inhibit crystal growth of iron sesquioxides and oxyhydroxides[15]. This is confirmed by Mössbauer spectrometry, which shows the minerals to be predominantly superparamagnetic[16-19]. Secondly, the soil fabric itself is modified from time to time by bioturbation, groundwater refluxing, gravitational instabilities, etc. These processes tend to update any remanent magnetisation. The minimum requirements for stable magnetisation in weathered profiles, i.e. adequate crystal growth and a degree of induration, are therefore unlikely to be met in soil processes, and appear to be best satisfield at either the terminal stages of weathering or during dehydration reactions following intense weathering.

Palaeomagnetic dating of polygenetic profiles is more complex. In principle dates of the different weathering phases may be obtained by multicomponent analysis[20-22] of remanence directions. This is however only possible if parts of earlier profiles have survived subsequent weathering cycles, and if the weathering phases are characterised by different magnetic stability spectra. A special case of polygenesis is weathering that is taking place today in regions containing remnants of former profiles.

Finally, concerning the precision of palaeomagnetic dating, it seems unlikely that the dates could be determined to better than a few million years even in the most favourable circumstances. This uncertainty, though large, is nevertheless not a serious drawback in dating chemical weathering, since the weathering processes themselves probably proceed over similar time spans. Future advances in palaeomagnetic dating would need to come from refinements of the existing APW paths as well as from improved understanding of the stage of weathering at which remanence is acquired. A new Cenozoic APW has now been determined for Australia[23], and systematic studies of continent-wide weathering, currently in progress, may provide further insights on the timing of magnetisation.

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SILCRETE IN SOUTH CENTRAL VICTORIA : COMPOSITION, AGE AND RELATIONSHIP TO LAVA FLOWS

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Only in the last few years have several extensive silcrete areas been recognized near Melbourne (Fig. 1). At Morrison, west of Melbourne, Bolger (1981) has described a large area of silcrete, and other areas north of Melbourne have been recorded during land systems mapping (Jeffery 1981). The present authors' interest came about from the mapping of an unusual river cave in the valley of Taylor Creek, near Keilor, which was drawn to the attention of one of us in 1975 (Fig. 2).

Mapping of the cave led to the discovery of other silcrete outcrops along valley sides in the Keilor area, north of Melbourne. It was also found that the geological Quarter Sheets of the 1860's show "siliceous rock", "quartz rock" and "crystalline grit and conglomerate" at Keilor and to the north. Archaeologists have also been aware of "quartzite" pebbles and blocks in the stream beds and river terraces, and artefacts of this material are found locally. Recent maps of the Geological Survey of Victoria also refer to silcrete as sometimes occurring in the Tertiary deposits of the area.

A brief account of the silcrete in the Keilor area has been given elewhere (Joyce and Webb 1983) and a description of the cave has been prepared (Webb and Joyce in press). During 1983 further work by several Honours students in the Department of Geology has located further sites, and a detailed study of several areas is under way (Tidey, in prep.).

Interest has centred on the material in which the silcrete has developed, the composition of the silcrete, including lateral variations across the region, and variation with depth in profile, and its age. The latter aspect is also concerned with the relationship of the silcrete to the lava flows of the Newer Volcanics of the region.

The silcrete at Keilor has formed in fluviatile clays, sands, grits and gravels of probable Pliocene age. At Morrison the silcrete is in quartz gravel and sand of possible Pliocene age. Other occurrences at Toolern Vale and Bacchus Marsh are apparently developed, at least in part, in regolith formed on Ordovician shale and greywacke.

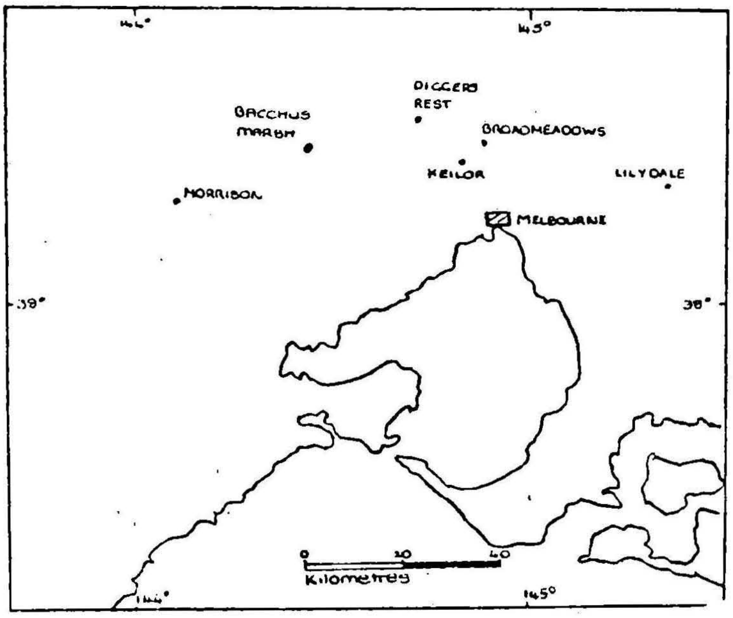


Figure 1 Some silcrete localities in South Central Victoria

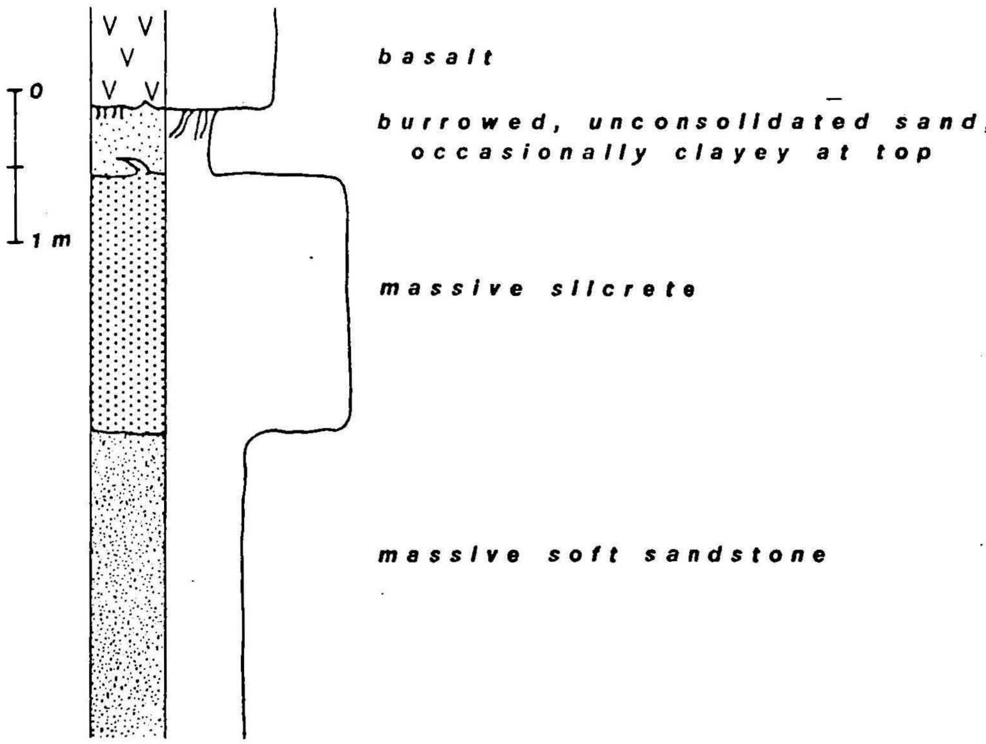


Figure 3 Stratigraphic section in the east bank of Taylor Creek, immediately to the south of the cave entrance (from Webb and Joyce, in press).

The best exposed profile yet located is that at the Taylor Creek cave site (Fig. 3) where a 2 m cliff alongside the creek exposes basalt of the Newer Volcanics overlying silcrete, with a thin unit of yellowish unconsolidated sand between. The silcrete forms the roof of the river cave, and sandstone is exposed below. As well as forming a broad pavement and the cave roof, silcrete occurs as small vertical or inclined bodies, up to 2 m wide, extending down into the underlying sandstone. Thin tongues of silcrete penetrate upwards into the unconsolidated sand (Fig. 3), and discrete silcrete masses of irregular shape are also found in the sand. The silcrete and the underlying sandstone show almost identical texture, but the silcrete is cemented by crystalline quartz, while the sandstone is cemented by opaline silica. It appears that varying degrees of silica cementation have occurred in a single sedimentary unit.

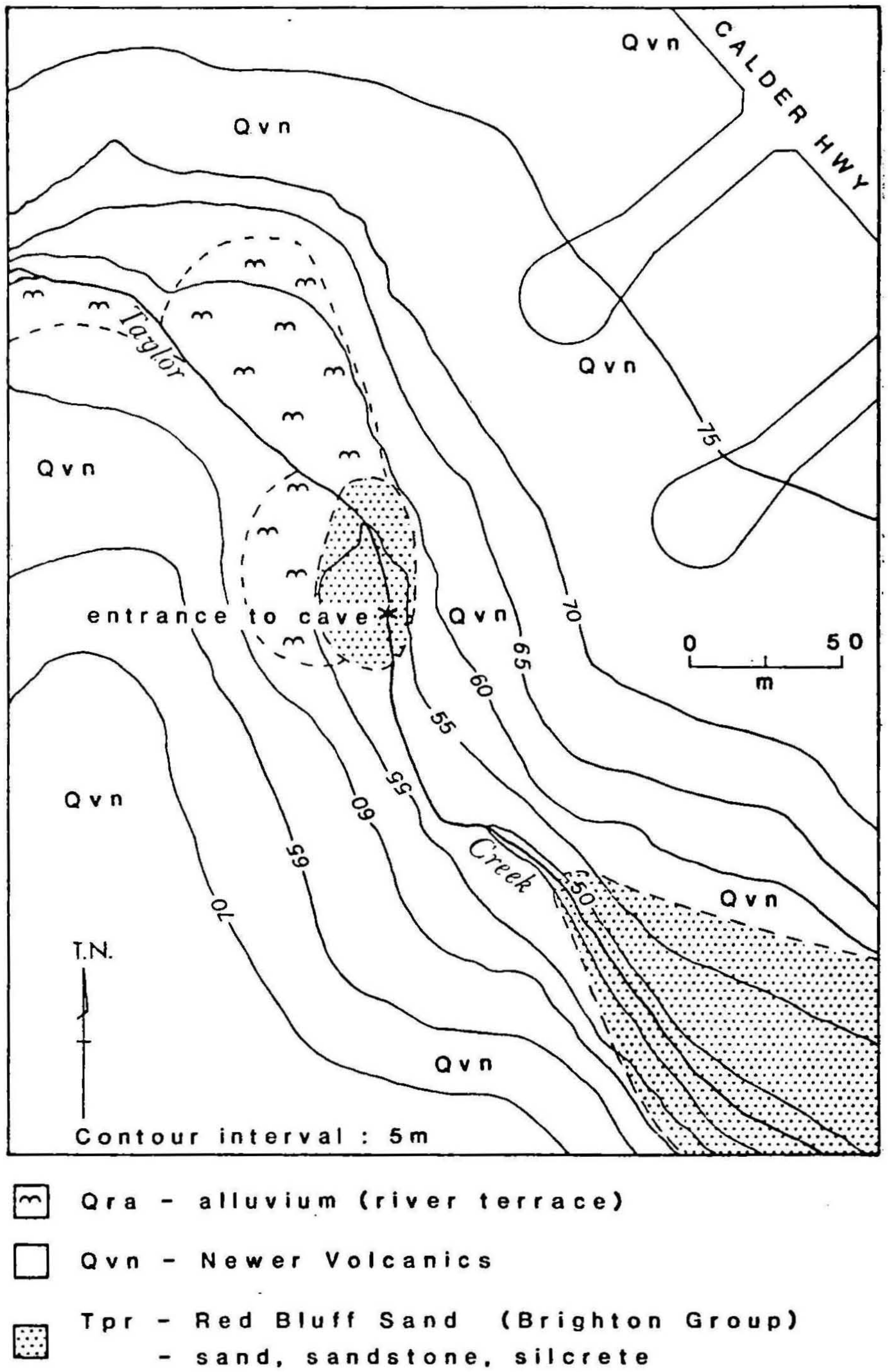
A maximum age for the silcrete may be deduced from the age of the material in which it has formed. The regolith at Bacchus Marsh and Toolern Vale cannot be dated in any detail, and the sediment at Morrison can only be estimated as Pliocene. However at Keilor the sediment has been identified as Red Bluff Sand, the upper formation of the Brighton Group, and this unit is generally agreed to be Middle - Late Pliocene in age. The identification is however not certain, and the sediment could be as old as the youngest underlying unit, which is an Older Volcanic deposit of Early Miocene age.

Overlying basalt provides another key to the age. The basalt at Morrison is undated, but at Keilor a possible age may be indicated by several radiometric dates obtained further south of 2.5 to 2.7 Ma (Late Pliocene); however other dates nearby of about 4.5 Ma might instead correlate with the flows at Taylor Creek.

In addition the relationship of the silcrete and the overlying basalt is not clear. At Keilor the silcrete occurs in a sedimentary unit underlying the basalt and now exposed along valley walls. Only parts of the unit are cemented, and at Taylor Creek appear to be the midslopes of a buried landscape of some relief, possibly the sides of a valley infilled by the later lava flows. A cross-section (Fig. 4, A - A') indicates the slope on the silcrete surface, and the corresponding slope of the basalt-sediment contact.

Between the silcrete and the lava uncemented sand and clay may be found (Fig. 3) and this material has been dragged up by the movement of the flow, indicating a similar condition at the time of the flow. Elsewhere the basalt is in direct contact with the silcrete.

Figure 2 Geology of the Taylor Creek area, near Keilor, NNW of Melbourne, showing cave site (from Webb and Joyce, in press).



Joyce and Webb (1983) tentatively concluded that "the silcrete ... was formed in Tertiary terrestrial sediments before the eruption of the basalt. The silcrete formation represents a period of silica mobility in the landscape in the Pliocene, and has helped preserve the landforms and landscape of that time, although now largely buried under the later lavas".

The occurrences of silcrete so far located and studied in the region have invariably been associated with the Newer Volcanic lavas. Silcrete may occur as surface outcrop on the plains e.g. at Sunbury, but a former covering of basalt, now eroded, is not difficult to imagine. The extensive plateaus of silcrete around Morrison are harder to explain. Bolger (1981) has argued that in this area "Although spatially related to basalts of the Newer Volcanics, the genetic affinities of the silcretes and basalts are not clearly established". He has suggested that silcrete formation may have resulted from severe alteration of the drainage system imposed by a drainage reversal before the lava flows occurred (Bolger 1981, p.155). He has also recorded clasts of silcrete beneath the valley flows of basalt which suggest that silcrete had formed, and been eroded and redeposited, before the basalt flow occurred. The extensive plateaus of silcrete which surround the infilled valley may never have had a basalt cover.

While silcrete occurs elsewhere in Victoria (Fig. 5), it has so far in South Central Victoria been found in general association with Newer Volcanic basalt flows, if not actually sub-basaltic. The possibility of the silcrete forming after the lava flow, and therefore being younger must still be considered. At Keilor this might mean an age of less than 2.5 Ma.

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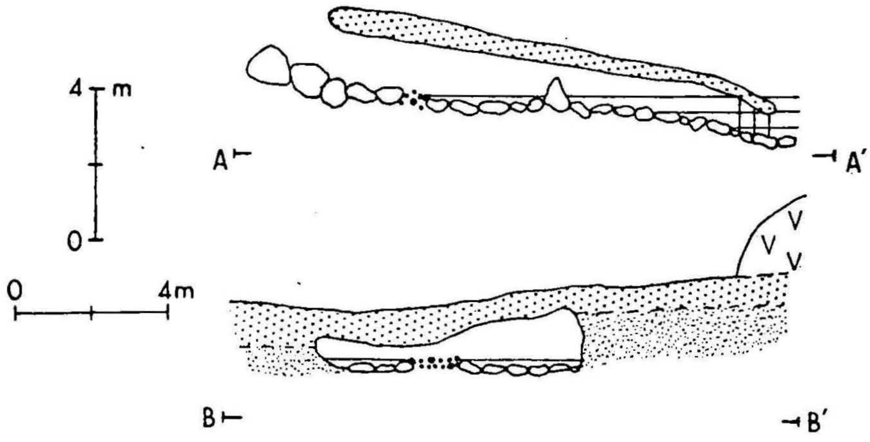

Figure 4 Cross-sections at cave site : A - A' along stream course, and B - B' across stream course, looking upstream (from Webb and Joyce, in press)

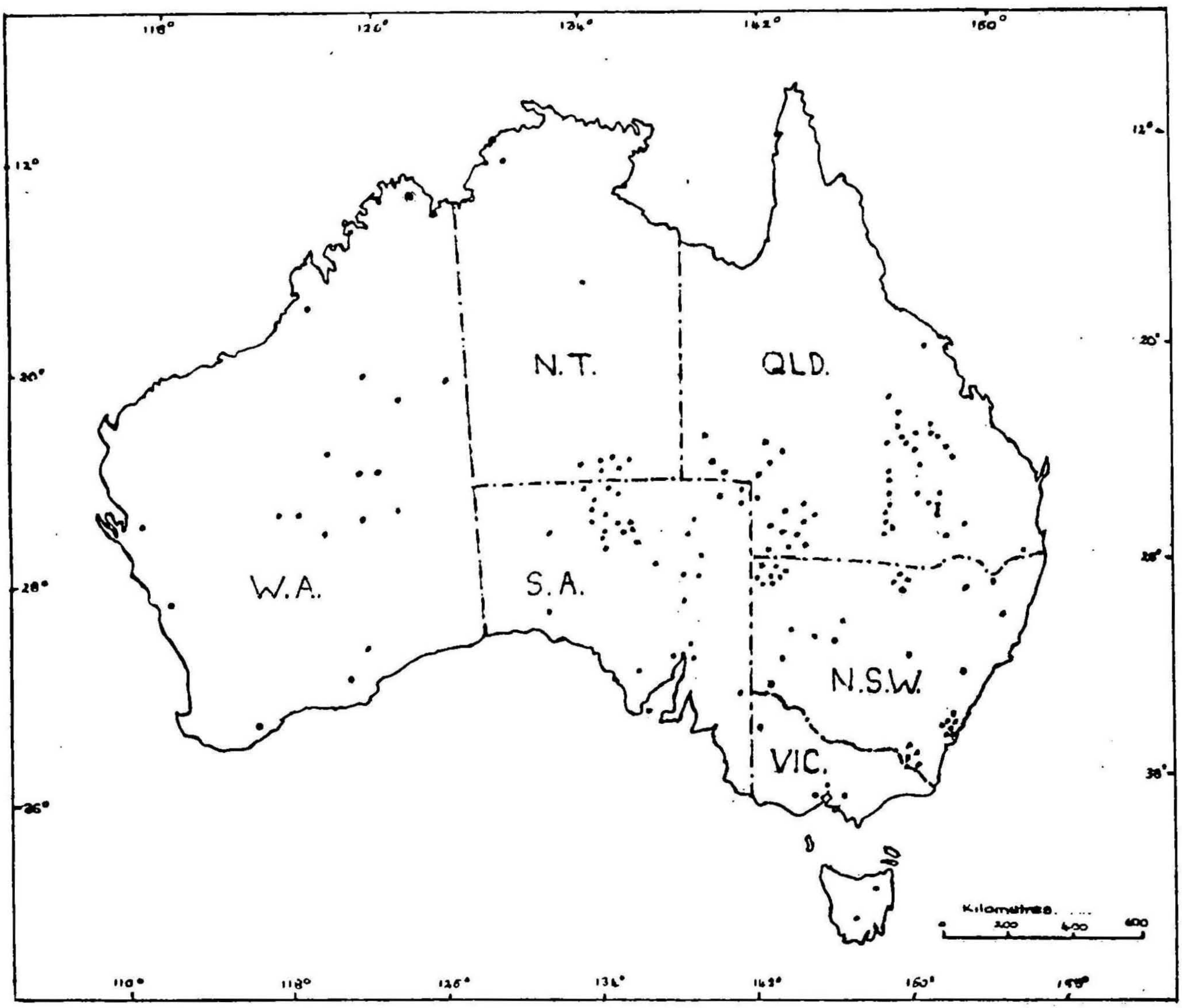

Figure 5 The distribution of silcrete in Australia (compiled from various sources by A. Tidey)

THE WANTABADGERY LANDSCAPE: EVIDENCE FOR LOCAL VERSUS REGIONAL LANDSCAPING FACTORS

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ABSTRACT

Twelve 'landscape units' are recognised in the Wantabadgery landscape. Four of these units are colluvial and seven are alluvial depositional terraces. Six of these terraces have formed in approximately the last 10,000 years. Variation in the sequences of terraces and their distribution within and between catchments is not considered to be satisfactorily explained by regional factors; generally accepted as the main factors in terrace formation. Instead, the present Wantabadgery landscape is seen as developing primarily through 'complex - responses' and re-adjustments to the internal attainment and crossing of thresholds. Acceptance of this view has implications for the validity of regional correlations of soil-stratigraphic units and for the use of landscape and landscape instability for palaeoclimate reconstruction.

INTRODUCTION

The landscapes, surficial deposits and soils of southeastern Australia are relatively well studied. Frequently the information derived from these studies has been used as a basis for the reconstruction of regional palaeoclimates and/or regional correlation of landforms or soil-stratigraphic units e.g., Bowler (1967), Butler (1967), Van Dijk *et al* (1968), Hickin (1970), Walker (1970), Beattie (1972), Coventry and Walker (1977) and Williams (1978).

The fundamental assumption of this conventional treatment of landscape data is that the initiation of landforms and different soil-stratigraphic units is the result of large scale regional, usually climatic, change. Evidence from a study of the landscape, surficial deposits and soils of a small (c.6 x 10 km), previously unstudied area of southeastern Australia (refer Fig.1), the Wantabadgery area (McConnell 1979), suggests that this assumption is not always valid. In this case local internal, rather than climatic, variations are considered to be the main factor in initiating the landforms and soil-stratigraphic units.

THE WANTABADGERY LANDSCAPE AND SURFICIAL DEPOSITS

The *Wantabadgery Granite* bedrock (Vallance 1953) has no apparent landscape-controlling structural features and the region is tectonically stable. The Wantabadgery landscape is a typical granite multiconcave or basinal landscape (Thomas, 1974) with a local relief of c.180m. Four catchments were studied in the area, each comprising of a number of basins and a major valley, and with drainage into the Murrumbidgee River (Fig.1). To describe the landscape, twelve 'landscape units' are defined using land form and position, surficial materials and soil. The characteristics of these landscape units are summarised in Figure 2.

In the main catchment the basins are predominantly colluvial but in some cases contain discontinuous gullies and associated deposits. In the main valley the slopes are colluvial and up to seven alluvial depositional terraces form the valley fill. The oldest terrace occurs as isolated remnants and the second oldest terrace, the most conspicuous terrace, forms the wide valley 'flood plain'. The youngest terraces are inset into this major terrace. The terraces are paired. Tracing the terraces downstream revealed that within valley segments (defined by nickpoints or nodes) the number of terraces differs. Moreover there appears to be no patterning to this presence/absence of terraces within the catchment.

With the exception of isolated areas of parna accession (the land-scape unit) the surficial materials of the area are derived from the texturally and mineralogically relatively uniform granite bedrock. The granite derived colluvium is composed of diffusely intertonguing clayey gravels and gritty and sandy clays which are laterally highly variable. The gully deposits are composed of interbedded, graded and cross-bedded sands and gravels and homogeneous silty gravels. The alluvial deposits consist of spatially variable units of graded and cross-bedded sands and gravels, sandy silt laminae with sand and gravel lenses, gravelly clays and gravelly loams. Most of these units occur within each terrace

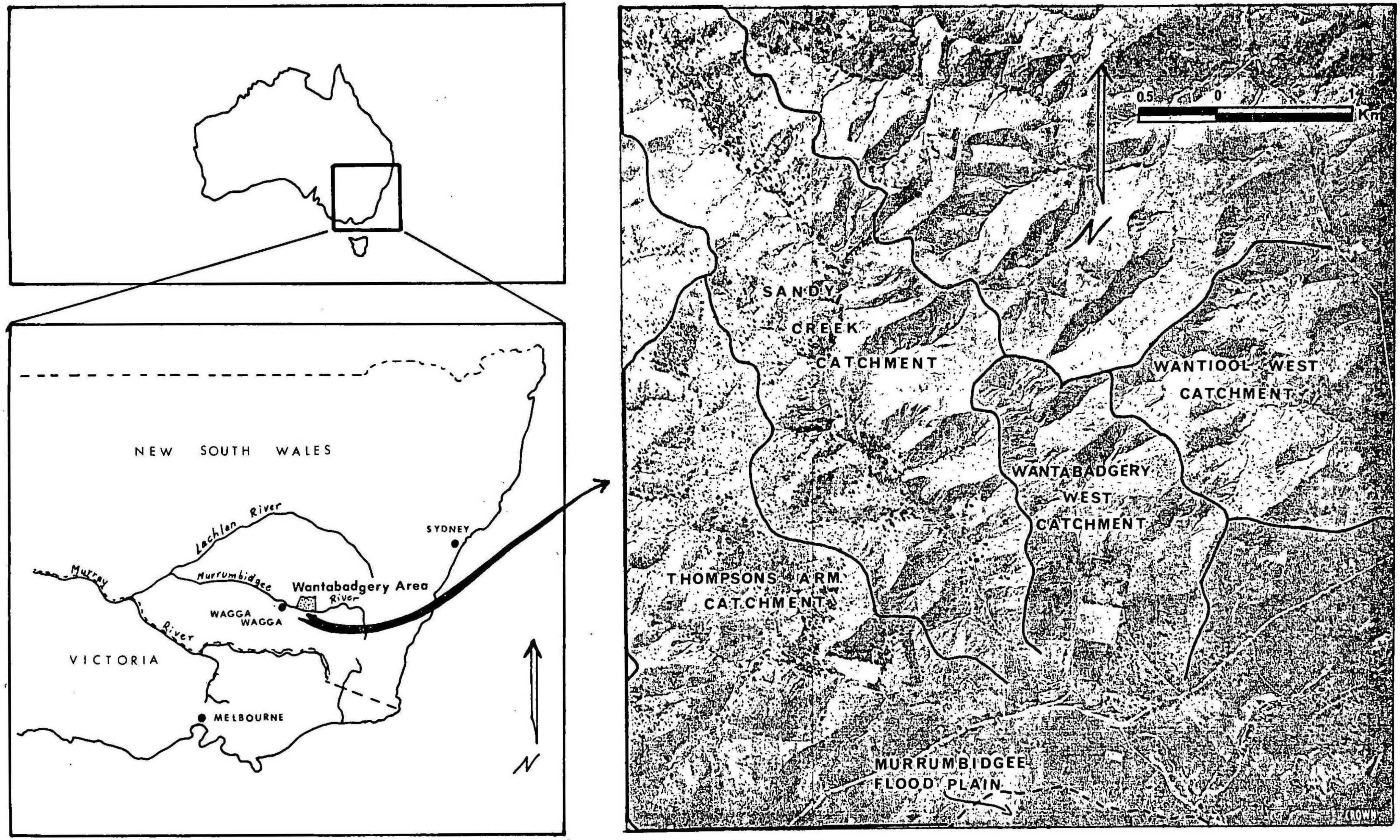
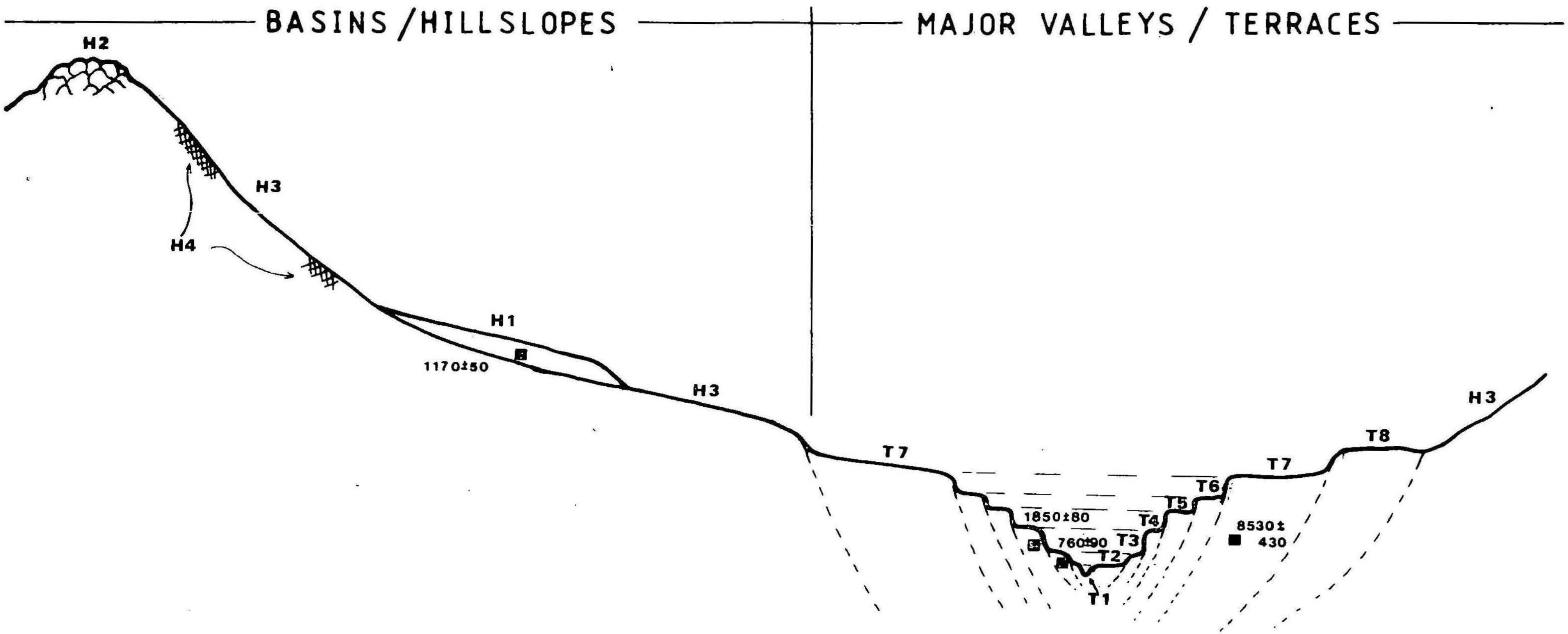


FIGURE 1 : The location of the Wantabadgery area and the catchment distribution of the area.



COLLUVIAL UNITS

H1 - Discontinuous gullying deposits, minimal prairie soils.

H2 - Areas of significant erosion, rock outcrop.

H3 - Areas of erosion and deposition by hillslope processes, lithosols, red and yellow podzolics and uniform profile soils.

H4 - Areas of parna accession, red earths

FLUVIAL UNITS

T1 - Present stream bed, deposits range from silts and clays to boulders.

T2 - T7 - Terraces, diffusely interbedded gravels, sands, laminated sandy silts, gravelly loams and clays and cross-bedded gravels and sands; uniform profile soils to minimal podzolics.

T8 - Interbedded colluvial and alluvial deposits, medial podzolic.

FIGURE 2 : Summary characteristics and relative topographic position of the Wantabadgery landscape units. Sites from which radiocarbon dates were obtained are marked ■ with the date in years BP. (Note: the cross section is not to scale, V/H 7.5).

although the sequences of units differ. All surficial materials are characterised by a high degree of spatial variation of texturally diverse deposits with no apparent systematic arrangement.

The soils on the hillslopes form a toposequence which varies downslope from lithosols, to red and yellow duplex soils to uniform profile soils. Red earths are developed on areas of parna. The terrace soils form a developmental sequence from uniform profile alluvial soils through to medial podzolic soils.

Other catchments are similar, containing a similar arrangement of landscape units with comparable characteristics. However the other catchments contain fewer terraces. One catchment contains six terraces, while the other two contain four terraces. As in the main catchment the number of terraces within each valley segment varies in an apparently non-systematic way.

A broad chronological framework for the initiation of the different landforms has been established by radiocarbon dating. The dates (refer Figure 2) indicate that all but the oldest terrace has been deposited within the last 10,000 years and that discontinuous gullying and deposition in the smaller basins has been occurring for about the last 1,500 years. No dates could be obtained for the colluvial deposits.

DISCUSSION AND CONCLUSIONS

Most of the landscape features in the Wantabadgery area can be attributed to normal slope and fluvial processes operating in drainage basins (Gregory & Walling 1973, Carson & Kirkby 1972, Leopold *et al* 1964). However the existence of the terraces is less straightforward.

The large number of Holocene terraces can be fitted to changes in the southeastern Australian palaeoclimatic record and therefore their initiation and formation might be explained as the result of a commonly accepted mechanism, in this case regional climatic change. However terraces formed as the result of regional changes in climate would be expected to produce a regionally observable response. This is not the case at Wantabadgery where terraces vary in number both within and between adjacent catchments within a region.

On the basis of this lack of systematic terrace distribution it is proposed that at Wantabadgery, the terraces have been formed as the result of local internal, rather than regional climatic, factors in a manner similar to that proposed by Schumm (1973, 1977). Schumm's model proposes that landscaping occurs primarily through *complex-responses* and *internal readjustments* to the crossing of *thresholds* within the landscape system or subsystems. For this model external stimuli are not necessarily required to initiate change.

Similar concepts of terracing have also been formulated in other recent studies of terraced landscapes, (Born & Ritter 1970, Kottlowski *et al* 1965, Hey 1977, and Schumm 1977). Furthermore this concept of landscaping is regarded as satisfactorily explaining the formation of the other landscape features at Wantabadgery. Features such as the terrace soil chronosequence and the similarity of sediment types throughout the terrace deposits and within the colluvial deposits are also considered as providing evidence that large scale regional climatic change has not occurred or has been minimal.

It is highly likely that this type of process operates more commonly in the landscape than is generally accepted. Acceptance of this view may require reassessment of conclusions, involving regional correlations of soil-stratigraphic units and/or palaeoclimatic reconstructions which are drawn from landscape studies. Regional correlation and palaeoclimatic reconstruction will only be valid if it can be demonstrated that the landscape elements used in interpretation result from regional changes.

Note: Research discussed in this paper was undertaken as part of an MSc. degree in the Geology Department, Australian National University (McConnell 1979).

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The potential of very small scale satellite imagery for regional regolith studies

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The advent of the Landsat series of satellites has produced a large and increasing user community throughout the world. This has been stimulated by advances in ground-based technology, and in the growing global network of receiving stations. To a large extent Landsat activities have dominated and overshadowed developments with other satellites. The purpose of this paper is to draw attention to "small-scale" (coarse resolution) satellite data - in particular those produced by the Coastal Zone Colour Scanner - and their potential for regional regolith studies.

The Coastal Zone Colour Scanner (CZCS) is a 6 channel multispectral scanning radiometer carried on a Nimbus-7 earth orbiting satellite. The satellite was launched to a 954 km orbital altitude on October 24, 1978 and it is still operational. This satellite has a northbound equatorial crossing time within 10 minutes of local noon and an orbital path which repeats every 6 days (83 orbits). The CZCS has a nadir (sub-satellite) pixel size of 825 metres and a swath width of 1636 km. Data are encoded with 8 bit precision, giving 256 gray levels, and three gain settings may be selected to ensure that the range is appropriate. Gain settings are chosen to accommodate the radiance over oceans, and as the radiance over land is much greater, several bands (in particular bands 3 and 4) may saturate during onshore imaging.

In the early 1970's experiments with airborne instruments demonstrated the feasibility of accurate remote sensing of ocean radiance. During that period it was also shown that the spectral composition of ocean radiance could be reliably related to levels of planktonic pigments, in particular chlorophyll 'a' and the pheopigments that are its breakdown products. The CZCS was developed to allow quantitative estimation of near-surface oceanic planktonic pigment concentrations.

Australian region real time CZCS data from Nimbus-7 are transmitted to the Orroral Valley satellite tracking station near Canberra during those overpasses within acquisition range. Data are recorded on a wide band video (analogue) high density tape and later played back, decommutated, and saved on 800 bpi digital tapes. The data discussed here were subsequently reformatted by personnel at the Australian National University's Research School of Physical Sciences prior to being used by BMR.

With the exception of a thermal band (channel 6, 10.5-12.5 micrometres) sensitive to surface temperature, the CZCS senses reflected sunlight wavelengths. Overpass time close to local noon was chosen to maximise this quantity at the risk of including specular reflection from the sun i.e. sun glint. Channels 1 to 4 have very high sensitivity and narrow (20 nanometre) bandwidths, (Table 1). Channel 5 (0.7 - 0.8 micrometres) has a wide bandwidth equivalent to the Landsat MSS band 6. This was included to allow discrimination between land, sea and clouds, and to locate imagery; it plays no part in pigment estimation. Though the CZCS was designed for ocean sensing some bands, in particular 1, 2, 5 and 6, can be used for geoscience investigations.

A CZCS image with a swath width of 1636 km covers an area of approximately 2.6 million square km and would require about 75 Landsat scenes for duplication. Though Landsat has an advantage of far better spatial resolution, regional multi-scene investigations present problems owing to the differences in acquisition times between adjacent orbits. To duplicate a single CZCS scene with optimum Landsat imagery would require data from 9 consecutive days of cloud-free imagery. Though the large area

NIMBUS CZCS	LANDSAT 1,2,3 MSS	LANDSAT 4 TM
1) .433 - .453		1) .45 - .52
2) .510 - .530		
3) .540 - .560	4) .5 - .6	2) .52 - .60
4) .660 - .680	5) .6 - .7	3) .63 - .69
5) .7 - .8	6) .7 - .8	4) .76 - .90
	7) .8 - 1.1	
		5) 1.55 - 1.75
		7) 2.08 - 2.35
6)10.5 - 12.5		6)10.4 -12.5

Table 1. Spectral bands (in micrometres) of Landsat 1, 2, 3, 4(TM), and Nimbus CZCS.

coverage of the CZCS images contains illumination differences owing to variations in sun angle and azimuth throughout the scene, at this stage of investigations these differences are considered relatively minor compared to the problems encountered during spectral matching between adjacent Landsat images.

During investigation of CZCS scenes the authors were impressed by data from Orbit 19498 (acquired 4/9/1982), and in particular the strong spectral differences displayed by terrain materials on the Barkly Tableland. The region was selected for additional detailed study. Digital tapes were acquired and displayed on BMR's Comtal Vision One/20 image analysis system. A 512 x 512 pixel segment of CZCS data (equivalent in area to 5 Landsat scenes) has a screen scale of 1:1.65 million which is convenient for comparison with small scale thematic maps. In this case maps of the Barkly Tableland at 1:1 million (CSIRO, 1954), 1:1.2 million (CSIRO, 1967), and 1:2.5 million (BMR, 1976) were used. Discussion on soils, vegetation, topography and geology which follow are based on information from these thematic maps and some judgements - e.g. whether certain spectral responses are due to soil types or vegetation differences related to a soil change - have not been established.

If CZCS bands 1, 2 and 5 are used with colours blue, green, and red respectively to make a false-colour image it is almost the same in appearance as a conventional Landsat false-colour made from MSS bands 4, 5, and 7. This is because of the relative similarity in the spectral bands (Table 1). Though CZCS band 2 is spectrally closer to MSS band 4 than is band 1 we prefer to use the former because it is less saturated over land. Almost any combination of CZCS bands can be used to delineate the boundary between the extensive area of cracking clays of the Barkly from the dominantly sandy surrounds (the best combination for delineating this boundary was the 1st principal component). Band 1 on its own with a contrast stretch and pseudocolour (i.e. effectively applying colour density slicing) is useful for differentiating some of the soil types within the cracking clays. Other combinations involving use of the thermal band (band 6) also appear to relate more to soils distribution than other factors. Again principal components analysis, especially analysis using only the four bands 1, 2, 5, and 6 provided some of the best comparisons with published soils distributions. The soils maps used in the exercise (CSIRO, 1954; 1967), carry comments that the classes shown are combinations of soils and associations of landscapes. Certainly in this exercise CZCS digital image manipulations had a much closer correlation with these data than with geological maps.

The major spectral difference between the CZCS and the Landsat MSS is in the thermal data of band 6. Preliminary investigations show that this band is also useful for comparison with some soil distributions. False-colour composites using bands 1, 5, and 6 displayed as blue, green, and red give better correlations than using the thermal band on its own. Band 6 is useful for detecting areas of relatively recent fireburn. It should be mentioned that the sandy areas of the Barkly show extensive fireburn, much more than the clay areas, and the presence of fireburn considerably influences ability to make useful correlations. Comments above on map correlation do not hold so well in the burnt sandy areas. The thermal band shows some interesting geological phenomena, particularly lineaments, but it will require considerably more evaluation to understand the dominant contributing factors in the thermal imagery.

At this stage no attempt has been made to compare CZCS data with Landsat of the same date to allow more precise evaluation of similarities or differences. Our preliminary investigations indicate that the CZCS data can be very useful for small scale thematic investigations, in particular those dealing with surficial materials. Thus it has considerable potential in regolith studies. It may be a useful tool for upgrading some small scale maps, however we believe that it has a more significant role as the first data set to be studied in any regional investigation. It could be used to rapidly pinpoint apparent inconsistencies or differences between the image data and published maps. The next logical step would then be to zero in on those areas using the larger scale Landsat data for more detailed evaluation.

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Problems of Regolith Distribution in Mainland Australia

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The distribution of weathering profiles and surficial sediments in Australia depends on the geomorphic history of the continent, including relevant aspects of geological and tectonic history. Our concept of regolith distribution depends also on our model of landscape development. We know enough at present to see that earlier models of the geomorphic evolution of Australia are incorrect, but we cannot erect a new model - only point out some salient facts and highlight the problems.

Early explanations of Australian geomorphology were based on the peneplain concept, modified in later years to pediplains. Quite early there were attempts at general synthesis, with Andrews providing the Great Australian Peneplain, and Woolnough adding a major weathering and duricrusting event, said to be of Miocene age. There are, indeed, several major planation surfaces and major weathering events, but the story appears complex and landscape history goes back to the Palaeozoic.

The Palaeoplain

This term refers to an ancient plain, the widespread surface that can be seen or generalised in wide areas. The old plateau of Western Australia might be an example, or the plateaus along the Great Divide in eastern Australia. Some of it is found in areas that have a history as dry land (and presumably long continued erosion) throughout the Phanerozoic. This plain pre-dates the break-up of Gondwanaland. When Gondwanaland did break up, new continental margins were formed and new erosion surfaces which related to new base levels. On this hypothesis one might expect a continent-wide palaeoplain separated by an escarpment from strips of younger erosion surfaces.

The Great Escarpments

In eastern Australia a Great Escarpment can be traced almost continuously from north of Cairns to the Victorian border. It separates a high palaeoplain from a coastal strip, and fits the simple model described above. A few outlying plateaus have been isolated from the main palaeoplain.

In eastern Victoria the simple escarpment soon gives out, and the Great Escarpment cannot be traced across most of southern Australia.

In Western Australia there is a structural complication with the Darling Fault, but the equivalent of the eastern Great Escarpment is probably the Meckering Line, and its extensions. This is not so much an escarpment as a line separating an area of active seaward drainage, and the palaeoplain with ancient inactive river courses. Whereas the eastern Great Escarpment has created a few outlying plateaus, west of the Meckering Line there are major plateaus (e.g. Hamersley, Pilbara) with more complicated geomorphic histories. The Meckering Line is much further inland than the eastern Great Escarpment, possibly reflecting the greater age of the West Australian continental margin. It was created in the Jurassic and is much older than the 80 m.y. old eastern continental margin.

The Meckering Line reaches the northern coast. The Canning Basin has no escarpment, and the palaeoplain is apparently warped down to sea level.

East of the Canning Basin is another series of dissected plateaus, roughly equivalent to the plateaus west of the Meckering Line. This group including the Kimberley, Victoria and Arnhem Plateaus, can be separated by a line, roughly analogous to the Meckering Line, from the relatively undissected palaeoplain to the south.

East of the Arnhem Plateau and south of the Gulf of Carpentaria there is a distinct though not "great" escarpment separating the Barkly Tableland from the coastal plains. To the east this turns into a mere watershed, and cannot be traced to continue with the Great Escarpment around north Queensland.

The Palaeodrainage

Elements of the Australian drainage network have widely different ages. The drainage lines on those parts of the palaeoplain that have been land since the lower Palaeozoic may also have drainage patterns that go back to Palaeozoic times. However the Permian glaciation would have provided a fresh start in many areas. Some drainage lines can be traced back to the Permian (e.g. Loddon in Victoria). Even where modern rivers follow Permian precursors there has been a lot of cut-and-fill in between.

Most significantly, much of Australia was covered by shallow seas in the Cretaceous. The fact that a rise in sea level could affect so much of the continent shows it was already well planated. The Cretaceous seas withdrew leaving plains with marine sedimentary cover, on which new drainage was developed. Existing rivers on the older land would be extended over the new plains. The same thing would happen later when the sea retreated from Tertiary basins of deposition. This process of extended rivers means that the palaeodrainage is of different age in different places. As an example, the palaeodrainage on the Yilgarn Block may date back to early Palaeozoic, but that of the Officer Basin is post-Cretaceous.

In central Australia it is harder to date the drainage lines, but the superimposed drainage, as at Alice Springs, is generally thought to date back to the Cretaceous. This Cretaceous drainage on bedrock would have been extended onto Cretaceous surfaces when the Cretaceous sea withdrew. Later differential erosion has dismembered the early drainage pattern.

In the Great Artesian Basin drainage development was entirely consequent on uplift after extensive Mesozoic deposition. Drainage is essentially to the south and west, emphasising the dominance of north to south drainage on continental Australia. In some places the Great Divide seems to correspond to the edge of Mesozoic rocks, but the significance of this is not yet clear.

The Murray Basin is almost separated from the basins to the north by the bedrock ridge from Cobar to Broken Hill. Many of the rivers that flow into the Murray have histories that can be traced back to the Eocene or earlier, such as Permian (Loddon) or Cretaceous (Bendigo high gravels).

The Flinders block in South Australia has been very tectonically active, and has had complex but controversial effects on palaeodrainage. North of this block is the Eyre-Frome depression, which has been a sump for drainage from the north for a long time. Tectonic movements have affected this area too, and the present lakes may not represent long standing sumps - there may have been migration of the lakes.

Warps and watersheds

Watersheds may be in their present position after a long time of drainage pattern evolution, and may be newly created by tectonic movements. Some of the watersheds on the West Australian palaeoplain are very old, probably as old as any watersheds in the world. Others arise from younger axes of uplift.

In Western Australia the Ravensthorpe Axis is an axis of uplift that warps the palaeodrainage, so that some appear to flow uphill and over the crest. A similar warp may also occur in western Victoria around Ballarat. In eastern Victoria an axis of uplift may be inferred from the distribution of High Plains, eventually leading to the alpine plateaus of New South Wales.

Many river captures in eastern Australia have been attributed to warping in the vicinity of the Great Divide, and although some of these are controversial, there seems to be a general consensus that the palaeoplain of eastern Australia has been warped since the palaeodrainage was established.

In northern Australia there seems to be a warp along the Barkly Tablelands and across the Winton Downs. If original watersheds were even further north than at present, the origin of the northern continental margin of Australia must be more complicated than we know.

Deep weathering

Very deep weathering profiles, often with ferricrete, and generally known as "laterites" have undoubtedly been formed at several times in Australias history.

On the ancient palaeoplains of Western Australia weathering profiles of 100 m are common, and are certainly pre-Eocene. Palaeomagnetic investigations have shown major weathering events in the Miocene, and in Cretaceous/Palaeocene times. Ferricrete and silcrete formation have continued until the last few million years in some places, although the onset of aridity would have slowed weathering in dry Australia.

Stripping of the weathered profiles to varying degrees, producing etchplains, is an important process in any explanation of regolith in deeply weathered terrain. In some places simply the degree of removal is what matters, as in south west Western Australia. Elsewhere weathering profiles are complex, and landscape evolution may involve stripping to a silcrete layer, or stripping to bedrock, giving several different apparent landsurfaces related to a single older weathering profile.

Elsewhere a succession of genuine erosion surfaces may have weathering profiles that relate to the age and origin of each surface. Such flights of erosion surfaces match cyclic theories of geomorphic evolution, but widespread correlation has proved difficult in Australia.

Nevertheless correlations must be made if progress is to be made in the study of weathering profiles.

The basalts

In eastern Australia volcanic eruptions have punctuated the last 100 million years of geomorphic evolution. The basalts have their own distinctive regoliths, but are of further interest because of their potential for dating underlying and related weathering profiles and sedimentary deposits.

The onset of aridity

Throughout the Mesozoic and much of the Cainozoic, Australia appears to have enjoyed a warm and humid climate over the entire continent, despite lying at high latitudes for much of the time. Aridity set in in the late Miocene or Pliocene, after Australia had reached almost its present position. The aeolian deposits of the arid phase are a mere veneer on the surface of much older regolith, despite the great area they cover. It is also important to realise that the chlorides and sulphates so common in many areas today are a relatively recent addition to the landscape, and were not involved in the creation of the deep weathering profiles in which they may now be found.

The Map

Fig. 1 is a map showing some of the features discussed in this paper, and showing the most significant features determining the nature of the regolith in different parts of mainland Australia. It is partly physiographic, partly geological, reflecting the multiple factors that determine the nature of the regolith in this continent. The regolith programme at the BMR aims to produce more detailed regolith maps at 1:2,500,000: the present map is a crude first approximation.

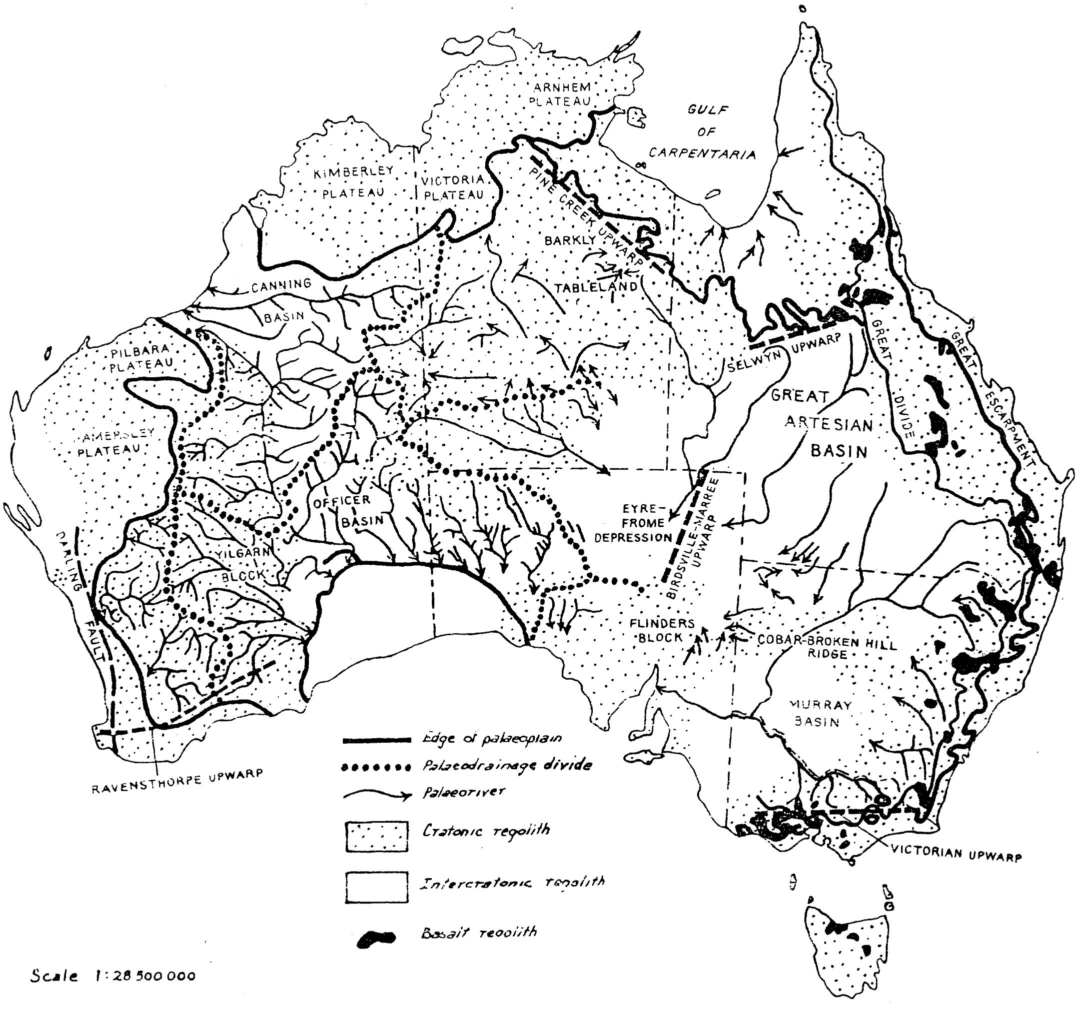

Fig.I DOMINANT FEATURES DETERMINING THE REGOLITH IN MAINLAND AUSTRALIA

PALAEOMAGNETISM OF OLD WEATHERED PROFILES IN NEW ENGLAND

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In the Armidale-Uralla region of New England an old deep weathering profile is exposed in several localities. The most complete section is revealed at Bald Knob, where a young, fresh basalt overlies a deep weathered profile that has in places become bauxite. There are many interbasaltic weathering profiles in the region, but the degree and depth of weathering of this profile seem to be of a different order of magnitude from most local interbasaltic weathered horizons. The weathered material is an older basalt, at least 30m thick, and is weathered right to its base on Palaeozoic rocks. The younger basalt has given a K-Ar age of 21.2 ± 1.0 m.y. (McDougall and Wilkinson, 1967), but the older basalt is far too weathered for potassium-argon dating. Similar deep weathering profiles, so far correlated on no more than their similar appearance, are found on other hills including Mt Butler South, Richleigh Hill, Uralla Trig, and Sugarloaf south of Uralla. There appear to be other suitable localities south of Uralla, where a succession of lava flows, weathering events, and inversion of relief awaits interpretation. M. Connolly has mapped widespread, thoroughly weathered older basalts between Uralla and Armidale (see his contribution, this volume). Clearly an age on these older basalts would be very useful in working out the geomorphic evolution of the area. Since isotopic dating is not possible, an investigation was made into the feasibility of palaeomagnetic dating.

Of twelve weathered profiles, samples from one, Sugarloaf, have yielded consistent palaeomagnetic results. The results from the remainder indicate a protracted period of

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magnetisation, probably spanning several reversals of the geomagnetic field. Although the results from the one well-behaved profile reveal a hard overprint magnetisation, the most stable magnetisation suggests an early to mid-Jurassic magnetic field direction. This may place an upper limit on the age of weathering. Work is continuing and it is hoped that further experimental work will give a more definitive result, and field work includes a search for more weathering profiles that are potentially suitable for palaeomagnetic work. The prospect of Jurassic basalts and weathering profiles suggests that ideas on geomorphology and regolith production in the region may need considerable revision.

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ACID AND ALKALINE WEATHERING IN GRANITOIDS FROM EASTERN AUSTRALIA

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Chemical weathering of granitoid rocks in different environments results in distinctive weathering patterns. Drainage and small differences in the original compositions of the rocks appear to be particularly important in determining how the weathering proceeds. Such parameters have repercussions for mineral exploration, physical properties of materials used in constructions and hydrological investigations. In this paper weathering in the Ardlethan Granite and "Mine Granite" in the Ardlethan Tin Field in southern NSW is compared with that in the Crows Nest Granite and Eskdale Granodiorite in the Toowoomba area of southern Queensland.

ARDLETHAN GRANITE

Fresh coarse- to medium-grained Ardlethan Granite consists of pink-grey assemblages of quartz, albite, microcline, muscovite, biotite (and chlorite) with some hornblende. Intense weathering results in the development of kaolinite and goethite with residual quartz and muscovite. Although it often affects only the upper few centimetres of outcropping granite, weathering may extend to greater than 30 m especially when there is some hydrothermal alteration (Scott and Rampe, 1983).

"MINE GRANITE"

This whitish coarse-grained rock is really a granodiorite which is spacially closely related to the Ardlethan Granite. It is comprised of quartz, orthoclase, albitic plagioclase, biotite, muscovite and chlorite. Weathering occurs down to 60 m and results in the development of kaolinite and iron oxides with progressive destruction of biotite, plagioclase and orthoclase.

CROWS NEST GRANITE

Fresh granite consists of pink coarse-grained assemblages of quartz, albite, orthoclase, chlorite, muscovite and biotite. In the samples studied, weathering produced assemblages similar to those at Ardlethan except that orthoclase was never completely removed and kaolinite is not as well developed. Weathering is usually shallow (~2 m).

ESKDALE GRANODIORITE

Adjacent to the Crows Nest Granite the Eskdale Granodiorite crops out. It is medium-grained consisting of quartz, andesine (An_{46}), biotite, chlorite, microcline, hornblende, muscovite and accessory pyrite. Biotite, plagioclase and hornblende are very much more abundant than in the rocks described above. Weathering produces only a shallow soil profile (< 0.5 m) on top of 15 m of disaggregated pebble-sized fragments of apparently unweathered material. However X-ray diffractometry reveals that this friable mass is composed of quartz, plagioclase, hornblende, microcline, goethite with significant amounts of montmorillonite and a 12Å mineral (sepiolite and/or hydrobiotite), and lesser amounts of chlorite, biotite, kaolinite and ? muscovite.

DISCUSSION

Comparison of the bulk compositions of fresh and weathered granitoids reveals a systematic loss of Ca, Mg, Na and K during weathering of the Ardlethan granitoids (Tables 1 and 2). In the Toowoomba area, K is enriched in the weathered Crows Nest Granite, reflecting its retention as orthoclase and muscovite. Within the Eskdale Granodiorite Ca increases and only K is depleted during weathering. This general removal of alkaline earths reflects the preferential weathering of hornblende, biotite and plagioclase in the granitoids (cf. Weathering Potential Index). However, details of the weathering mechanisms of these minerals are instructive.

Table 1: Compositions of granitoids (wt %) and their plagioclase compositions (An %) - Ardlethan and Toowoomba areas

	Ardlethan Granite	"Mine Granite"	Crows Nest Granite	Eskdale Granodiorite
Reference	Scott and Rampe (1983)	Scott (1981)	This paper	This paper
No. samples	4	4	1	1
SiO_2	75.6	70.8	76.3	65.2
Al_2O_3	12.9	15.2	11.7	16.2
Fe_2O_3(total)	1.52	3.46	1.84	4.66
MgO	<0.10	1.26	0.45	1.93
CaO	0.21	0.65	0.41	4.30
Na_2O	2.99	2.18	3.24	3.64
K_2O	4.56	5.31	4.35	1.84
TiO_2	0.09	0.43	0.20	0.48
P_2O_5	0.18	0.11	<0.10	0.16
MnO	0.05	0.05	0.05	0.09
S(total)	<0.01	ND	0.01	0.25
An content (%)	1[a]	<10[b]	2[c]	46[d]

[a]Average of six values (range 0-2). [b]Determined to be albite (Ramsden and Hesp, 1974). [c]Single determination (this paper). [d]Average of eight values, range 33-54 (Jones, 1955). ND, not determined

Table 2: Compositions of weathered granitoids (wt %) - Ardlethan and Toowoomba areas

	Ardlethan Granite	"Mine Granite"	Crows Nest Granite	Eskdale Granodiorite
Reference	Rigby (1975)	Rigby (1975)	This paper	This paper
No. samples	1	17	1	1
SiO_2	72.3	73.1	73.2	65.6
Al_2O_3	14.5	15.0	13.3	16.8
Fe_2O_3(total)	3.00	4.41	2.19	4.20
MgO	<0.10	0.16	0.25	1.92
CaO	0.10	0.10	0.29	4.92
Na_2O	0.09	0.07	1.42	3.84
K_2O	2.30	3.33	6.18	1.56
TiO_2	0.15	0.37	0.23	0.39
P_2O_5	0.02	0.06	<0.10	0.11
MnO	0.01	0.02	<0.05	0.09
S(total)	ND	ND	<0.01	<0.01

ND, not determined

Surfaces in contact with water form a thin film in which H^+ replaces the large alkaline ions and the mineral structure is disrupted by incorporation of an ion with a high charge/radius ratio. However, when the structure breaks up the Al-Si ions in tetrahedral coordination remain intact and persist in the resultant sheet structure.

In a closed system, incorporation of the H^+ into the mineral causes the remaining water to become alkaline. Amphiboles and Ca-rich plagioclases in contact with water produce a pH > 9 (abrasion pH) sufficiently high to start dissolving Al as aluminates. Therefore the breakup of the linked Si-Al tetrahedra gives rise to the Al-depleted clay minerals, sepiolite-palygorskite (Loughlan, 1960). In an open system the alkalis introduced into the water are removed from the system by outflow and a pH around neutrality is maintained. If the rate of removal exceeds the rate of release from decomposing minerals, an acid pH can develop. Except below pH 4, Al does not dissolve, so Al freed during the breakup of Si-Al tetrahedra moves into octahedral coordination and forms kaolinite.

During the weathering of granitoids the system is normally open, and in both granitoids at Ardlethan, progressive weathering of hornblende, biotite, plagioclase and K-feldspar ultimately results in kaolinite-rich assemblages. In the Crows Nest Granite (quoted in Table 2) the process has not gone far and some muscovite and plagioclase remain with the orthoclase. The Eskdale Granodiorite, despite its K loss, displays no obvious chemical weathering. However, examination by scanning electron microscope reveals exfoliation and curling at the edges of the biotite sheets.

Chemically the biotite loses K and incorporates Ca and Mg (? freed from plagioclase and hornblende) in its interlayer sites whilst retaining the essential features of its original structure (Table 3). Changes to sepiolite or montmorillonite require major structural changes involving loss of Al from Si-Al-tetrahedra and

Table 3: Electron microprobe determinations (wt %) and structural formulae for biotite and montmorillonite mineral

	Fresh	Altered biotite			Montmorillonite mineral	
No. analyses	3	4	2	2	1	1
SiO_2	39.7	36.6	36.7	36.8	52.4	49.3
Al_2O_3	14.4	13.5	13.4	13.3	20.4	19.9
FeO(total)	18.6	19.0	18.1	17.3	9.12	5.30
MgO	11.0	10.9	11.3	11.2	<0.10	1.60
CaO	0.96	1.26	1.78	2.25	7.63	4.51
Na_2O	ND	ND	0.43[a]	ND	3.41	6.21
K_2O	8.44	5.14	3.52	2.67	0.17	1.33
TiO_2	3.56	3.60	3.38	3.49	0.04	0.83
MnO	0.48	0.37	0.44	0.33	<0.10	0.13
No. ions on basis 22 oxygen atoms						
Z Si	5.86	5.74	5.81	5.87	7.48	7.06
Al_{tet}	2.14	2.26	2.19	2.13	0.52	0.94
Y Al_{oct}	0.37	0.26	0.31	0.37	2.91	2.42
Ti	0.39	0.43	0.40	0.42	0	0.09
Fe^{2+}	2.30	2.52	2.39	2.31	1.09	0.63
Mn	0.06	0.05	0.06	0.05	0	0.02
Mg	2.42	2.57	2.66	2.66	0	0.34
X Ca	0.15	0.21	0.30	0.38	1.17	0.69
Na	ND	ND	0.13[a]	ND	0.94	1.72
K	1.59	1.04	0.71	0.54	0.03	0.24
Y	5.54	5.83	5.82	5.81	4.00	3.50
X	1.74	1.25	1.14	0.92	2.14	2.65

[a]One value only. ND, not determined

its going into octahedral coordination. Such breakup results in mineralogically complex pseudomorphs in the exfoliated layers of biotite (Gilkes and Suddhiprakarn, 1979) and may be reflected by the montmorillonitic composition recorded in Table 3. Its significant Na and Ca contents suggest substantial contributions from weathered plagioclase or hornblende. Such contents cannot be incorporated in the interlayer-sites of montmorillonite and might be better considered in octahedral sites, making the phase a trioctahedral smectite.

Weathering of the Eskdale Granodiorite appears to have occurred under alkaline conditions leading to the formation of montmorillonite (and ? sepiolite) in preference to kaolinite. As kaolinite is not as well developed in the Crows Nest Granite as in the granitoids from Ardlethan it appears that alkaline weathering conditions may occur in this area of SE Queensland. Whether inflowing groundwater derived from the abundant Tertiary basalts in the area help produce the alkaline conditions or whether the drainage is poor (i.e. a closed or restricted system) cannot be determined without hydrological information. However, the high abrasion pH of these rocks relative to the Ardlethan granitoids (Table 4) suggests that most of the alkalinity is due to the granitoids themselves, with the increased An content and more abundant hornblende biotite and plagioclase of the Eskdale Granodiorite making its weathering environment particularly alkaline.

Table 4: Abrasion pH[a] for granitic rocks

	"Fresh"	Weathered
Ardlethan Granite	8.5	5.6
"Mine Granite"	9.3	7.1
Crows Nest Granite	9.6	7.7
Eskdale Granodiorite	10.2	9.5

[a]Instantaneous pH, determined using 3 g of powdered rock in 25 ml of distilled water

CONCLUSIONS

Usually the weathering of granites leads to the development of kaolinite-rich assemblages. However, in the Toowoomba area where the granites are poorly drained and/or are subjected to alkaline groundwater flow, products indicative of alkaline weathering conditions result. The presence of abundant An-rich plagioclase, hornblende and biotite especially favour such development in the Eskdale Granodiorite. There the weathering of biotite proceeds by leaching of K from the structure and exfoliation at the edges of the sheets. Such physical movements, coupled with some alteration of the hornblende and plagioclase, may be enough to cause the rock to disaggregate.

Indications of alkaline conditions are readily shown up by the lack of kaolinite development but this would require an X-ray diffraction determination. However, a field test using the abrasion pH of weathered and fresh rock would indicate areas where alkaline conditions may be developed and counsel against assuming that the normal acid weathering of granite has occurred.

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SHUTTLE IMAGING RADAR OVER WESTERN AUSTRALIA

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Radar imagery of several tectonic regions within different physiographic settings of Western Australia was acquired by the SIR-A in November 1981. These include the Phanerozoic Carnarvon and Officer Basins and the Precambrian Hamersley and Bangemall Basins.

The study's prime objective of evaluating the potential of spaceborne radar as a mapping and exploration tool is demonstrated by the identification and delineation of:

1. lineaments, faults, fractures and contacts;
2. topographic structural features including domes, basins and fold structures;
3. sand dune fields and dune patterns;
4. drainage patterns and stream order:
5. rock lithologies and where possible, stratigraphic sequence;
6. vegetation patterns; and
7. landform boundaries within the diverse range of geomorphologic units.

The feasibility of extending the spectral coverage into the microwave region of the electromagnetic spectrum is demonstrated by the capability of the Shuttle Imaging Radar to differentiate these landform features. Landsat-2 MSS and Landsat-3 RBV was available for part of the image swath, and was compared with the SIR-A.

The outcropping Proterozoic rock types within the Hamersley Basin provide many examples of the ability, using radar imagery, to map structural and stratigraphic features. The distinct fault controlled boundary between the banded iron formations of the Hamersley Basin and the younger sediments of the adjoining Ashburton Trough is very prominent. The differing intensities of signal return as a consequence of the steeply sloping terrain and strike ridges enhance the landform. A series of north-west trending faults that control the changing topography within the banded iron formation are shown as being intermittent on the geological maps. On the SIR-A imagery, they are clearly visible and continuous. The strong expression of linearity and structural control within the BIF is a function of the angle of illumination by the radar beam on the land surface.

Intereference folding is recognized from the "checker board" echelon pattern and zig-zag in alignment of synclinal and anticlinal structural features.

The characteristic folding and the east-west axial trend of the main folds is demonstrated by the strongly folded form of the bedding units within the eastern limbs of the prominent "domes and basins". Variations in the radar backscatter due to changes in topography and in vegetation type and vigour, which are associated with different rock units, enabled clear recognition of bedding units and unconformities.

Whilst structural features are easily identified on the radar imagery, different rocks may not be discriminated unless they have associated with them characteristic drainage patterns and/or surface roughness. A classic stratigraphic sequence of conformable rock formations within the Lower Proterozoic Fortescue Group in the Hamersley Basin can be identified on the SIR-A imagery, partially due to changes in topography, and from surface roughness variations.

The discrimination of drainage networks are a significant feature of SIR-A imagery. The extensive dissection by small tributary streams of the catchments and the structural control of the drainage basins are clearly defined on the imagery, as are the structurally controlled palaeodrainage systems (Tertiary) within the Gibson and Great Victoria Deserts.

Recognition of the dune fields is based on the radar pattern of the extensive monotonous tracks of easterly and south-easterly trending longitudinal sand dunes. Changes in the dune structure, pattern and direction in different areas can be assigned to changing wind patterns, and to local disturbance of prevailing winds by the buttes and mesas of a relict duricrust peneplain.

Other observed features include the massive intrusion of dolerite sills within the Bangemall Basin which have a particularly strong radar return, the dense lineament and joint patterns within the Hamersley Basin, and the characteristic mulga grove/intergrove growth patterns within the hardpan country of the Ashburton River catchment.

The SIR-A imagery is shown to be a powerful tool for geologic mapping and as a source of inventory information. Used in conjunction with other data collected from air photos and resource satellites, radar will undoubtedly provide another significant step to terrain investigation sequences.

Preliminary results (Honey and Tapley 1982) were presented at the ERIM Remote Sensing in Geology Conference, December 1982, Dallas, USA. The potential and applicability of the SIR-A imagery has been extremely useful in the forming of a collaborative CSIRO/BMR proposal to NASA to evaluate digitally recorded SIR-B imagery for geologic and geomorphic mapping, hydrology and oceanography in Australia in August 1984.

DISPERSION IN WEATHERED BEDROCK

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Geochemical exploration has traditionally utilized surficial material (soils, stream sediments, gossans, weathered outcrop, vapours and waters) in the search for outcropping or near-surface mineralization. The success of such techniques has been highly variable depending on the nature of mineralization, climate and geomorphology. However, many of the deposits which have been, or are presently being, exploited in Australia were discovered by the correct identification of gossan outcrop.

As more of these outcropping and near-surface deposits are found, the need is to locate blind or buried mineralization. In much of Australia this is difficult and costly because of extreme weathering and depth of transported overburden. The purpose of this paper is to discuss the nature and extent of geochemical dispersion within weathered bedrock, and its application in exploration for concealed mineralization.

DEVELOPMENT OF GEOCHEMICAL HALOES

Geochemical haloes within weathered bedrock may be derived from:

(1) the weathered remainder of the primary halo;
(2) the hydromorphic halo formed by dispersion from the mineralization as it weathered, or later from the gossan; and
(3) the hydromorphic halo formed by dispersion from weathering of the primary halo, or later from the weathered primary halo.

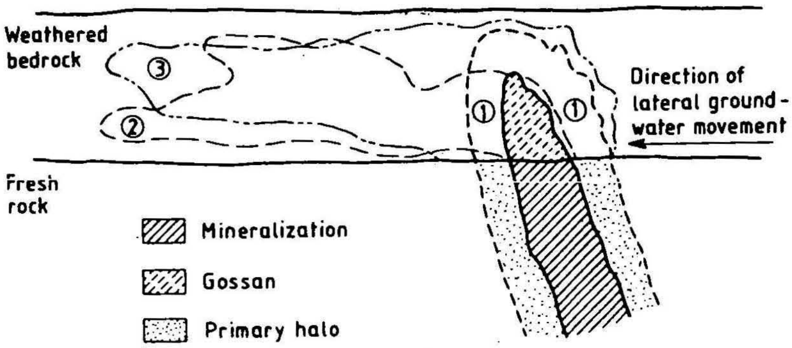

Figure 1 Generalized model for geochemical haloes in weathered bedrock (for description see text; from Smith, 1982).

These have recently been discussed by Smith (1982) and are illustrated in Figure 1. In addition, these haloes may be eroded, concealed beneath transported overburden or, in the case of an ancient erosional surface, hidden beneath younger rocks. Detection of any of these haloes may lead to the discovery of the associated mineralization.

The nature and extent of these geochemical haloes are determined by the pH, Eh, salinity and flow direction of groundwater, the nature of the mineralization, and the mineralogy, porosity and permeability of the wall rocks. However, some generalizations can be made about the mobility of target, pathfinder and lithophile elements (Table 1).

Table 1: Mobility of elements (adapted from Butt and Smith, 1980)

Commonly mobile:	S K Na Ca Mg Mn V Cu Zn Ni Co As Cd In Mo Hg Ag (Au less commonly)
Commonly immobilized:	
Secondary minerals	Fe Mn P Cu Pb Zn Ba S As
Native metals	Ag Au Cu
Minor components in secondary minerals	Cu Zn Ni Co As Sb Ag Hg Bi Mo Se V U
Resistant minerals	Si Al Fe Ti Cr V Sb Sn W Ce Y Au Pd Pt Ir
Elements in armored relics of sulfides	

The following case histories serve to illustrate the role of various factors in determining the nature and extent of dispersion haloes within weathered bedrock.

DUGALD RIVER - NW QUEENSLAND

The Dugald River Zn-Pb lode is a thin (< 10 m) lenticular body of pyrite, pyrrhotite and sphalerite with subordinate galena. The lode is conformable within black steeply west-dipping graphitic shale. It is defined at the surface by a gossan 2.5 km long occurring as a slight depression between siliceous wall rocks near the crests of a line of low ridges rising up to 20 m above the surrounding flat plain (Figure 2).

Three traverses were made across the lode and its wall rocks to determine the nature of dispersion (Taylor and Scott, 1983). Whereas Fe_2O_3, Pb, Cu, Ag, As and Ba are confined to the lode horizon, Mn, Zn and Cd are concentrated within the slate-hornfels footwall rocks (Figure 2). However, no Zn or Cd is found in fresh footwall rocks. Dispersion is probably related to an older weathering surface when the topography was more subdued. Groundwater flow east from the Knapdale Quartzite is considered to have leached Zn from the lode which was then precipitated in the slate-hornfels as hemimorphite. An increase in pH from moderately acid to neutral ensured complete precipitation minimizing dispersion into the Footwall Limestone, a more typical environment for Zn precipitation. Cadmium was similarly leached from the lode and precipitated, whereas less mobile elements were retained within the gossan.

Subsequent erosion has substantially lowered the lode and its wall rocks. Recent hydromorphic dispersion from the slightly elevated gossan has resulted in a more even distribution of target and pathfinder elements. Generally the dispersion trains of even the most mobile elements are restricted by the carbonate-rich wall rocks.

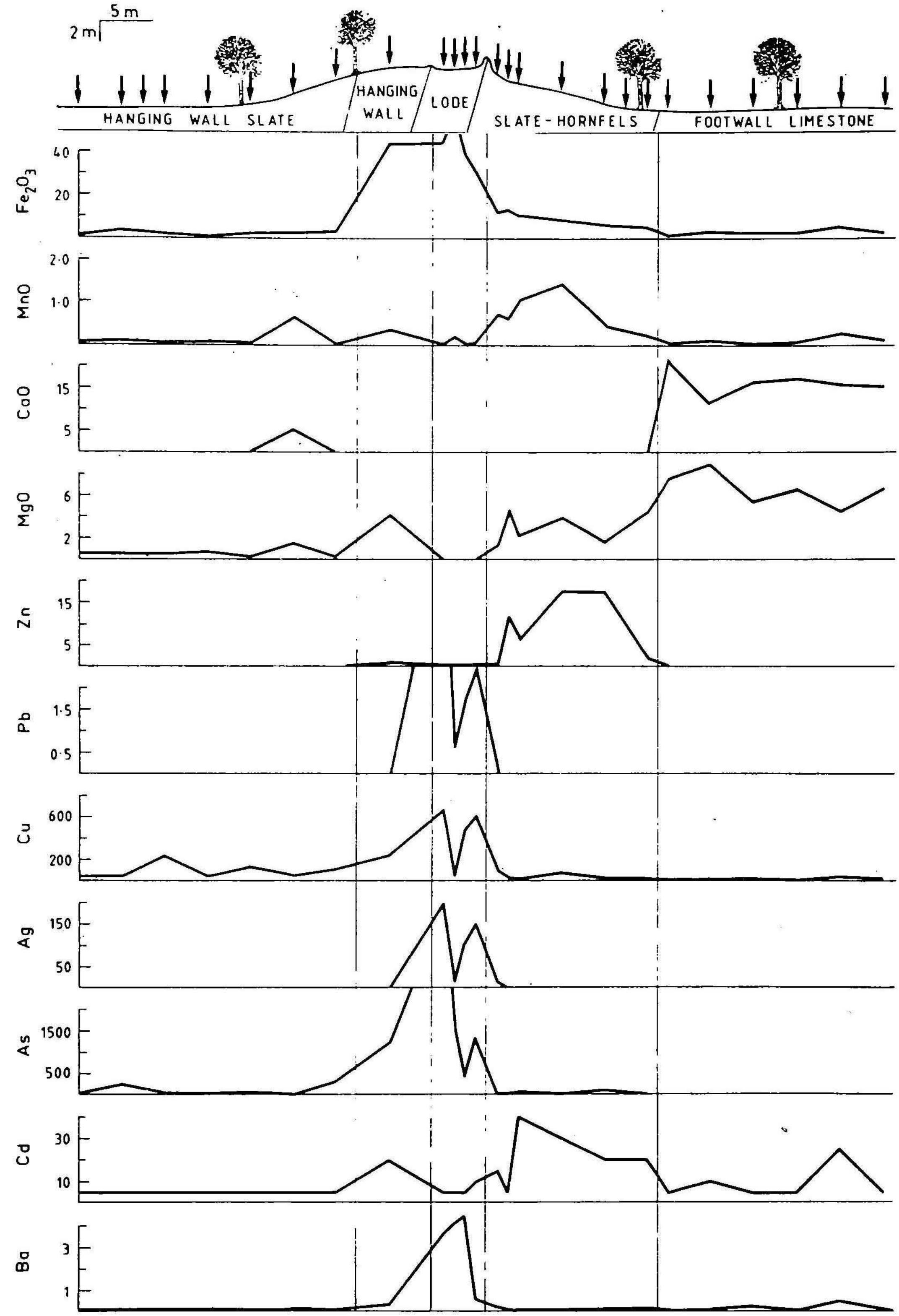

Figure 2 Outcrop profile showing the distribution of selected elements in weathered wall rocks of the Dugald River Lode from Traverse 1 of Taylor and Scott (1983).

MOUNT TORRENS - SOUTH AUSTRALIA

Pyrite-andalusite-muscovite-quartz schist, muscovite schist and feldspathic sandstone of the Nairne Pyrite Member occur at the base of the Brukunga Formation in the Kanmantoo Trough. Base metal mineralization is associated with the pyrite-andalusite-muscovite-quartz schist.

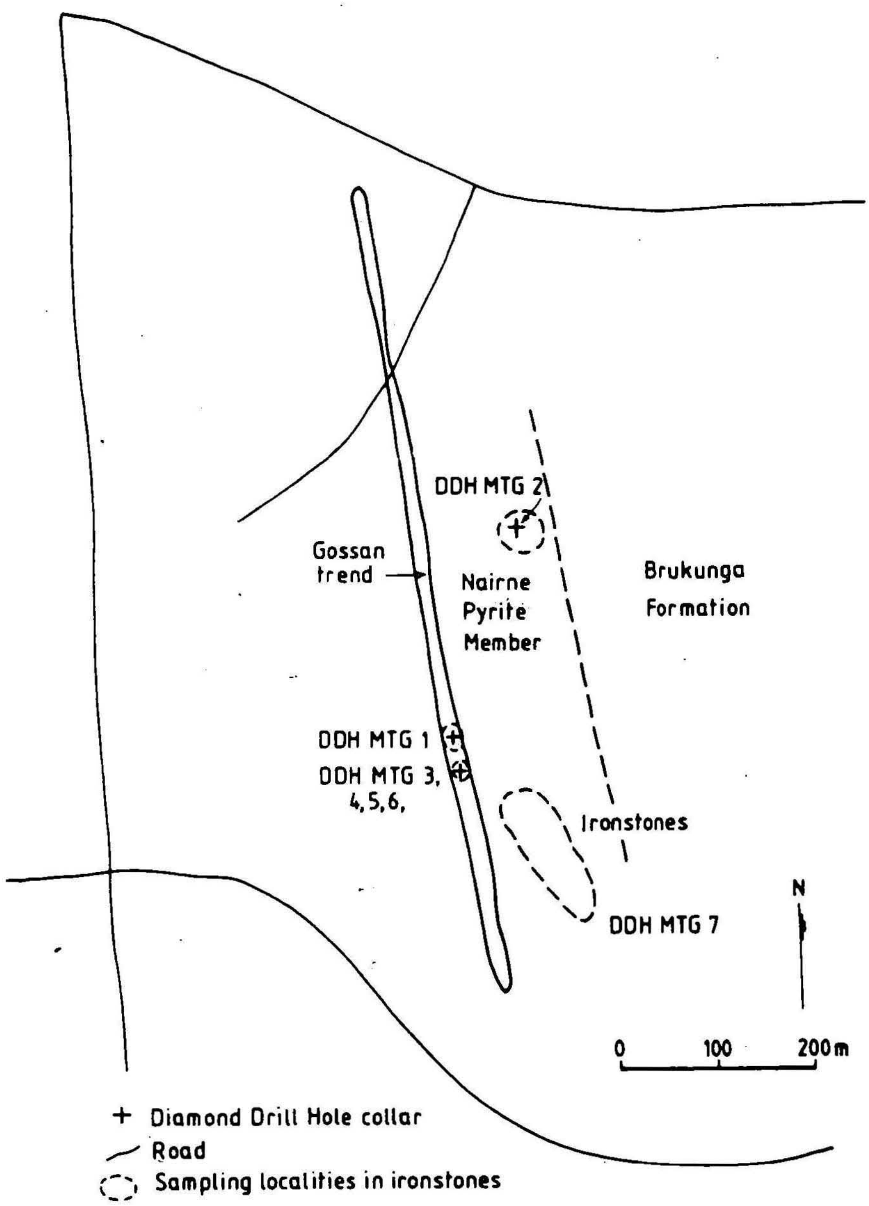

Figure 3 Location of gossans, ironstone and diamond drill collars at the Mount Torrens prospect, South Australia.

At the Mount Torrens prospect, diamond drilling located base metal mineralization (9.5% Pb, 2.1% Zn, 42 ppm Ag) at depth in the vicinity of the "gossan trend" (Figure 3). Despite anomalous values in the gossans (8000 Pb, 2340 Cu, 40 Ag, 3240 As) extensive down-dip drilling (DDH MTG 1, 3, 4, 5, 6, Figure 3) failed to intersect the base metal mineralization, and even passed out of gossan at a depth of 10 m.

Reassessment of the prospect (G.F. Taylor and B. Murrell, in prep.) has shown that all gossans and ironstones (Figure 3) are derived from pyrite mineralization either directly or by solution transport and deposition. Trace element anomalies in the "gossan trend" are derived from oxidation and hydromorphic dispersion of the essentially "blind" base metal mineralization. The target and pathfinder elements have been preferentially concentrated in the iron oxides and alunites of the gossan, and not in the weathered wall rocks. All other gossans and ironstones upslope of the base metal mineralization have low geochemical signatures.

ELURA - WESTERN NEW SOUTH WALES

The Elura Pb-Zn-Ag deposit occurs in the CSA Siltstone, a distal turbidite sequence, approximately 40 km north of Cobar. Deep weathering has produced a bleached quartz-muscovite-kaolinite rock to a depth of approximately 80 m. Weathered bedrock is covered by a thin layer of soil so that outcrop in the area is poor. The base of complete oxidation coincides with the water table. Groundwater is highly saline with up to 2.5% total dissolved solids.

Dispersion in weathered bedrock has been recognized to the south-west of the deposit and is marked by anomalous Pb, As, Bi, Sb and Hg contents below 5 m (Figure 4) with highest values being associated with the secondary Pb mineral, hidalgoite, approximately 50-100 m from the orebody (Taylor, 1982). The Cu and Zn anomalies are diffuse whilst Ag, Co, Mo, Ni and Sn values are below the limits of detection. This dispersion train is due

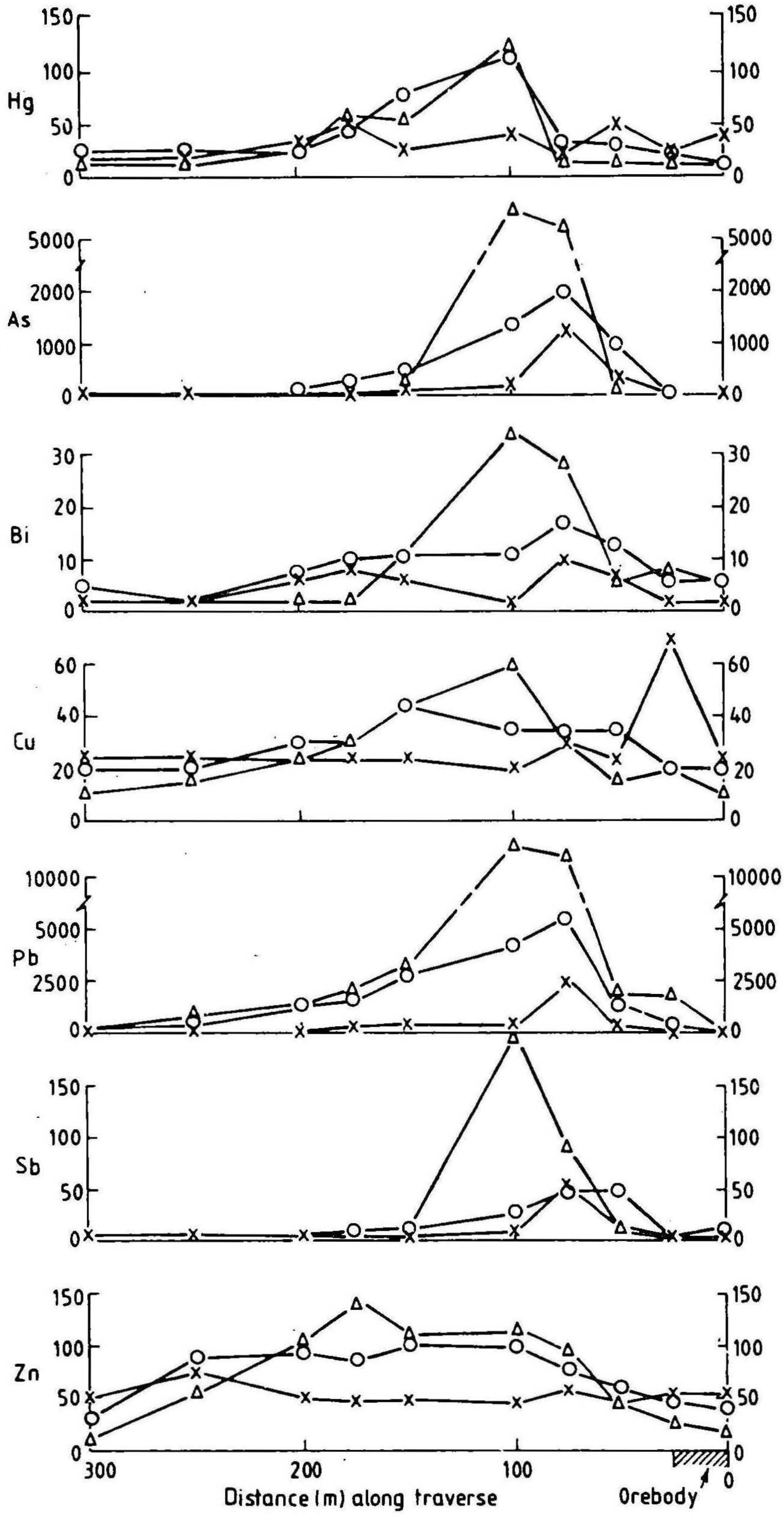

Figure 4 Distribution of some key elements in weathered bedrock adjacent to the Elura Pb-Zn-Ag deposit, western NSW (sample depths: **x** 0-1 m, o 2-3 m, Δ 5-6 m).

to recent and present leaching by saline groundwaters of the gossan which carries high levels of Pb, As, Sb, Ba, Hg, Sn and Se.

More mobile elements were leached during gossan formation so that an extensive Zn anomaly occurs at the water table along what is presumed to be a paleodrainage channel. The least mobile element, Sn, is retained within the gossan.

Except for a zone immediately surrounding the orebody, the bleached, weathered siltstones have extremely low geochemical signatures. However, throughout the completely weathered zone, Fe-rich bands, which vary from 5 to 120 cm in thickness, are common. These bands were formed by leaching of Fe from the siltstones and precipitation from solutions passing along bedding planes, fractures, shears and cracks. Low intensity anomalies of As, Bi, Co, Cu, Mn, Ni and Zn in these Fe-rich bands are believed to be derived from the primary halo surrounding the deposit (Taylor, 1982). Again the Fe oxides are better traps for target and pathfinder elements than the phyllosilicates of the weathered siltstones.

Lithophile element anomalies about the deposit are not retained within the weathered bed rock because of the mobility of Na, K, Ca and Mg during weathering.

DAPVILLE - WESTERN NEW SOUTH WALES

A narrow west-dipping lode of Cu mineralization grading 5% Cu occurs in the Great Cobar Slate approximately 2 km south of Cobar. Mineralization is essentially "blind" with Fe-stained quartz veins being the only surface expression. Complete oxidation is to a depth of 80 m with the present water table being at 43 m. Weathered Great Cobar Slate consists of quartz, muscovite, kaolinite and goethite with minor and variable hematite and feldspar. Calcite and dolomite occur near the surface as calcrete.

Elements associated with the pyrite-pyrrhotite-magnetitechalcopyrite mineralization are Bi, Sn, Co, Mn, As, Sb, Ni, Pb, Zn, Sb and Ag. Of these elements Bi, Co, Ni and Ag are below limits of detection in the weathered host rocks. Dispersion of the other elements, except Zn, is limited, with the anomalies being associated at depth with hematite and goethite immediately about the lode. Lead and Zn occur in a shear zone to the west of the Cu lode, but generally Zn has been widely dispersed with the greatest concentration being at or below the present water table. Copper also follows this trend and is therefore not a good near-surface indicator of "blind" Cu mineralization.

IMPLICATIONS FOR EXPLORATION

These four case histories serve to show that:

(1) geochemical anomalies in weathered bedrock may be derived from weathering of the primary halo, oxidation of the mineralization, or leaching of gossans;

(2) anomalies derived from primary haloes are much more subtle than hydromorphic dispersion from mineralization or gossans;

(3) primary lithogeochemical haloes are difficult to detect in weathered bedrock because of the high mobility of Na, K, Mg, Ca and S during weathering;

(4) dispersion may be limited by moderate pH due to the low iron-sulfide content of the mineralization, and reactive gangue and wall rocks such as carbonates;

(5) phyllosilicates are poor traps for trace elements compared with iron oxides, carbonates and some secondary minerals such as alunites-jarosites;

(6) although dispersion of highly mobile elements such as Zn is extensive, detectable anomalies may be found at or below the water table;

(7) anomalies of even the least mobile target and pathfinder elements may be removed from mineralization by continued hydromorphic dispersion;

(8) "blind" mineralization is often not indicated by target element anomalies at or near the surface; and

(9) many geochemical anomalies occur at some depth within weathered bedrock because of leaching by surface waters.

In using weathered bedrock, the exploration geochemist should sample the scavenging minerals such as iron oxides, carbonates and some secondary minerals to obtain the highest contrast anomalies. Widely-spaced deep drilling to the water table may detect anomalies of the more mobile elements, particularly Zn and Cu, whereas close-spaced but shallow drilling is needed to detect anomalies of the less mobile elements. If the mineralization lies completely below the weathered zone, subtle trace element anomalies derived from the primary halo may be detected in the weathered zone. As has been shown by Smith and Perdrix (1983), multi-element geochemistry often gives more meaningful results than analysis for the target elements alone.

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GEOCHEMISTRY OF GOSSAN FORMATION

by M.R. Thornber & E.H. Nickel, Division of Mineralogy, CSIRO.

Introduction

Two main processes control the formation of gossans: 1) the electrochemical redox reactions whereby the sulphide minerals are oxidized, coupled with the reduction of oxygen supplied by the atmosphere; and 2) the hydrolysis process whereby the elements that are released by the redox interaction interact with the water and other minerals. These two processes influence each other profoundly, and although they are usually conceptualized as separate processes, they actually control each other, e.g. the electrochemical weathering of the sulphides provides the elements in solution and controls the pH that is a vital part of the hydrolysis processes. Our studies, which combine experiments in the electrochemical simulation of weathering with mineralogical observations of material from naturally-occurring gossan profiles, have contributed to an understanding of the geochemical factors involved.

BEHAVIOUR OF ELEMENTS DURING GOSSAN FORMATION

Certain broad generalizations can be made about the behaviour of the elements in a weathering environment, with respect to their solution behaviour and the type of ion that is formed. The charge on the ion relative to its size (ionic potential) and its bonding characteristics will affect the complex interactions with the electrolyte solutions (solubilities) and with the surfaces of existing minerals. The behaviour of each individual element is discussed separately.

H^+, OH^- or pH. The activity of the hydrogen ion in water is the single most important parameter associated with the chemical weathering of sulphide ores. The compositions of the gossan minerals, the adsorption properties of mineral surfaces, the solubilities of cations and anions, the leaching of carbonate and silicate minerals, and the binding of humic materials are all pH dependent. At high pH, most minerals are more stable than at low pH, and cations are immobilized as hydroxides. At low pH, minerals tend to dissolve, cations remain in solution, and anions tend to be immobilized by adsorption.

Iron. The iron activity during the gossan-forming process is a major factor because its complex hydrolysis behaviour associated with the 2+ and 3+ oxidation states can dominate gossan-forming reactions. If any iron sulphides are present, iron is always the major element present in any remnant material that forms during anodic oxidation.

Under natural conditions, a relatively low oxidation gradient may exist in the region of the oxidizing sulphide body, and the iron from the oxidizing sulphides may remain in the more soluble Fe^{2+} state for some time. This iron will tend to diffuse away from its original site toward a region of higher O_2 activity, commonly leaving a porous spongey boxwork from which most of the iron has been leached. Where the oxidation potential is sufficiently high, such as at water/air interfaces, the Fe^{2+} oxidizes to Fe^{3+} and is hydrolyzed:

$$4Fe^{2+} + 10H_2O + O_2 \rightarrow 4Fe(OH)_3 + 8H^+.$$

The initial precipitate is commonly amorphous, or nearly so, but it is unstable and tends to be converted to hematite. Slower oxidation produces goethite and lepidocrocite. In nature, goethite is the major iron oxide in mature gossans, and lepidocrocite is rarely found; either it has not been formed at all, or it has been transformed into goethite during maturation.

The pH decreases as a result of the hydrolysis of Fe^{3+}, and this increased acidity promotes the dissolution of other minerals and the adsorption of anionic species.

Aluminium. The solution chemistry of Al^{3+}, like that of Fe^{3+}, is dominated by its being a small, highly charged ion, and thus it is readily hydrolyzed. Its solubility is significant only at extreme pH levels - below pH 5 where Al^{3+} is the major species in solution, and above pH 9 where the anion $Al(OH)_4^-$ is soluble. In the laboratory experiments, aluminium was leached from silicates associated with the oxidizing sulphides, and it precipitated with the Fe oxide scales that formed on the sulphides, or it precipitated where there was a pH gradient. The minerals from which it was leached showed a silica-rich remnant surface, and it was apparent that the Al was being solubilized at the same time as the alkalis and alkali earths. The Al is commonly precipitated in the form of clay minerals or allophane, and, where the sulphate activity is high, as minerals of the alunite group.

Silicon. Most silicates are unstable under acid conditions, and therefore they break down during gossan formation buffering the environment to higher pH values as they do. If the iron oxides precipitate slowly, and the supply of silica is maintained, it co-precipitates with, or is adsorbed onto the iron oxides, resulting in a silicified gossan. Silica is adsorbed by goethite over the pH range 4-12, with a slight maximum at about pH 9, so that the silicification of precipitating iron is relatively pH independent compared with the co-precipitation of other cationic or anionic species.

Copper. The behaviour of copper during gossan-forming processes is dominated by the fact that the Cu^{+}/Cu^{2+} couple is near the Eh of this environment, by the quasi-noble nature of copper metal, and by the interplay between copper and iron in solution and its effect on the redox processes. The salient features can be summarized as follows:

1) Copper will catalyze the oxidation of Fe^{2+} to Fe^{3+} at more acid pH values.

2) The thermodynamic relations between Cu^{+}/Cu^{2+} and Fe^{2+}/Fe^{3+} couples are such that, at pH above 6, Fe^{3+} and Cu^{+} are stable in solution together at the expense of Fe^{2+} and Cu^{2+}, so that there is a rapid precipitation of practically all Fe and Cu under these conditions. Copper minerals typical of these conditions are cuprite (Cu_2O) and native copper.

3) Below pH 6, Cu^{2+} and Fe^{2+} can exist together. Cu^{+}, if present, should keep the Fe^{2+} in that state; however, it is

likely to disproportionate to give Cu^{2+} and Cu metal. The Cu^{2+} can then catalyze the Fe^{2+} oxidation.

4) Catalysis of the $Fe^{2+} \rightarrow Fe^{3+}$ reaction by Cu, causes Cu to be bound up with the hydrolysed Fe^{3+} where the oxygen activity is greatest. Analyses of goethite in gossans have demonstrated copper contents of up to 6% Cu.

5) Copper forms extremely stable carbonate minerals near neutral pH values, malachite ($Cu_2CO_3(OH)_2$) is a typical example.

6) Clays, oxide mineral surfaces and organic materials tend to inhibit the mobility of Cu relative to other cations, because Cu^{2+} is strongly adsorbed onto these materials.

Lead. In an oxidizing environment, galena reacts more rapidly than most other sulphide minerals. Lead solubility, although it is low, is significant by geochemical standards, due to the formation of soluble complexes with sulphate, carbonate, chloride, and hydroxyl ions. Lead in solution readily attacks other carbonate minerals to form hydrocerussite ($Pb_3(CO_3)_2(OH)_2$), which is subsequently transformed to more stable minerals on dehydration.

Lead in solution is also adsorbed very strongly onto iron oxy-hydroxide surfaces, and analyses of goethite in gossans have given values up to 4% Pb. Secondary Pb minerals are common in gossans because of their low solubilities.

Nickel and Cobalt. These two elements are linked because their behaviour in gossan-forming reactions are similar. In reactions typical of deep anodic reactions, pentlandite the principal primary nickel mineral is replaced by violarite, which ultimately goes into solution, releasing Ni^{2+}, Fe^{2+} and SO_4^{2-}. At higher pH values (≥ 8) hydrated carbonates of the pyroaurite type are precipitated, at a pH between 6 and 8, hydrated sulphates of similar structure are formed and at a pH below 6, Ni and Co mainly remain in solution, with some co-precipitation with Fe oxides at higher pH values.

Ni and Co replace Ca and Mg from carbonates, forming gaspeite ($NiCO_3$), and co-precipitate with silica in the form of serpentine-type minerals.

Cobalt has a particular affinity to manganese oxide minerals, and this is the only major factor that distinguishes the behaviour of cobalt from that of nickel in a gossan-forming environment.

Zinc. The oxidation of sphalerite released Zn^{2+} which is mobile below pH 6. In laboratory experiments at higher pH and in the presence of Fe, it precipitates in the form of pyroaurite-type compounds, similar to those formed by Ni and Co; however, these compounds have not yet been found as minerals under natural conditions, and must therefore be unstable. The most common secondary zinc minerals are smithsonite ($ZnCO_3$), hydrozincite ($Zn_5(CO_3)_2(OH)_6$) and hemimorphite ($Zn_4Si_2O_7(OH)_2.H_2O$).

Magnesium, Calcium, Sodium and Potassium. These elements, of low ionic potential are readily leached from the wallrocks under the acid conditions prevailing during gossan development.

Manganese. This element behaves as a distant relative of iron, although it is generally much more soluble. The Mn^{2+} form dominates in the early stages of gossan formation, when it is quite mobile. In this form it can precipitate as a carbonate, commonly as rims around existing carbonate grains. Mn^{3+} and Mn^{4+} oxides and hydroxides precipitate at higher Eh, and this process is favoured by higher pH values (>7). Such oxides are common in gossans, usually as films on fracture surfaces, and are generally referred to by non-specific names like wad or psilomelane. They commonly contain major amounts of ore-forming elements such as Co, Pb and Cu, sometimes forming compounds, e.g. coronadite ($PbMn_8O_{16}$).

Vanadium, Chromium, Niobium, Molybdenum, Tantalum and Tungsten. These transition elements all have varying oxidation states and, at the Eh of the gossan-forming environment, the +3 to +6 states dominate so that they have relatively high ionic potentials; thus they largely form anionic species in solution that tend to be bound up with the Fe hydroxides.

Cadmium. Cadmium is geochemically similar to zinc. It is present in sulphides only in trace amounts and the limited data available indicate a greater mobility than Zn at pH values round 8.

Barium. Barium is present in some sulphide deposits as primary barite, which is relatively insoluble under normal weathering conditions. However, barium also occurs as a minor component of feldspars, and is released into solution as the feldspars decompose. When it encounters sulphate from sulphide decomposition, it precipitates as secondary barite, and can therefore indicate the presence of sulphides.

Gold. Gold, if present in the sulphides, is likely to form thiosulphate complexes during weathering, and these will move to locations of further oxidation within the gossan minerals, e.g. Fe hydroxides, where gold is deposited as the thiosulphate oxidizes to sulphate. Mineralogical evidence shows that particles of this secondary gold are generally coarser than in the primary mineralization, and that its silver content is substantially reduced.

Silver. Silver occurs as a minor, but often important component in sulphide ores. When the sulphides carrying the silver are oxidized, native silver is commonly precipitated, but during maturation of the gossan profile, it is oxidized and taken into solution again. Where chloride is available silver can have some mobility as the silver chloride complex or the silver may be in solution as a silver thiosulphate-halide complex, from which silver is precipitated as a halide when the thiosulphate is oxidized. Silver halides are relatively common in gossans derived from silver-bearing sulphides; Iodargyrite (AgI) is particularly stable.

Bismuth, Antimony and Arsenic. These elements have hydrolysis properties transitional between those that form cations and those that form anions, and therefore large cations, ions of zero charge and anions all form. These elements are likely to co-precipitate readily with ferric iron over most of the pH range, and analyses of goethite from an arsenide-rich deposit have given values as high as 2.7% As.

Sulphur and Selenium. These elements occur as sulphates and selenites in the gossan-forming environment. In our experiments, sulphate was bound up with all the iron precipitates that formed at all pH levels. At the higher pH levels, "green rust" compounds formed; these compounds are unstable, and further oxidation and leaching readily takes the SO_4^{2-} into solution again. At lower pH, increasing sulphate is incorporated into the iron precipitates; however, this could be expected to be readily leached out with neutral water with a low sulphate concentration. This is supported by observations of natural gossans, in which sulphur concentrations are normally very low. Exceptions occur, however, when jarosite-type minerals have been formed.

The available data relating to selenite adsorption suggests that selenium is bound more strongly to the iron hydroxides than is sulphur.

Tin. Tin in sulphide deposits is commonly present as the oxide cassiterite, which is highly resistant to weathering, and consequently remains unaltered during gossan formation. In some cases, however, tin occurs in the form of stannite (Cu_2FeSnS_4) which is subject to oxidation in a similar fashion to the other sulphide minerals. Initially, the tin will be present in the divalent form, which is soluble below pH 5 as the cation Sn^{2+}, and above pH 9 as the anion $Sn(OH)_3^-$. At intermediate pH values the divalent tin is present as $Sn(OH)_2^0$. In one or more of these forms the tin can be co-precipitated with, or adsorbed onto iron hydroxides, but eventually it will be oxidized to Sn^{4+}, which forms virtually insoluble hydroxides and oxides.

CONCLUSION

Mineralogical observations made on gossan materials have been presented in conjunction with chemical studies on elemental behaviour during gossan formation. The brief discussions of the important elements have demonstrated that such a combined approach is useful, and should be applied to other weathering problems.

THE TERTIARY AURIFEROUS ALLUVIAL DEPOSITS OF NORTH CENTRAL VICTORIA

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The history of gold prospecting in North Central Victoria over the last 130 years reveals that auriferous alluvial settings ranged from 300 feet below the present land surface up to residual cappings of interfluves 400 feet above it.

Mapping and lithological considerations can group these alluvial settings into four environments with chronological implications stretching through most of the Tertiary and probably the uppermost Mesozoic.

Some of these chronological stages imply rejuvenation/uplift of a Mesozoic, deeply weathered, surface, although some lines of deposition do not show these stages as separate events, the same channels being continuously used throughout the Tertiary.

Starting with the youngest : Stage 4; we find the present day creeks which flow across faulted blocks without reference to the major fault lines. In this category would fall Bendigo Creek and Bullock Creek in the Bendigo area, and Forest Creek in the Castlemaine - Chewton area. These creeks are consequent to differential erosion of Ordovician greywackes, granites and aureole rocks together with a general grading to the major tributaries of the Murray : the Loddon, Campaspe and Goulburn Rivers.

Although these present day creeks were the original "RUSH" sources of the early 1850's most of the gold that they yielded was recycled from higher level sources - the alluvial channels of Stage 2.

Older and deeper than the present surface drainage channels but on the same lines are the Stage 3 auriferous deposits. These include both Alluvial Deep Leads and Basaltic Deep Leads. Northwards from the present Divide for a distance of 50-60 miles the drainage channels of Stage 3 have been filled or nearly filled by Plio/Pleistocene Basalts which capped and preserved the auriferous bed load as Basaltic Deep Leads. Near Kyneton the bed load is over 300 feet below the top of the basalt flow. Northwards and down valley the basalt dies out, firstly into isolated patches and later completely but the auriferous bed-load is still capped by a considerable depth of clays, silts and sands, these being 120 feet thick at Huntly, 6 miles north of Bendigo. These are the Alluvial Deep Leads. They are the same river channels as were the Basaltic Deep Leads and in the Maldon area the two types alternate down valley.

Much older than the drainage channels of the Stage 3 (Deep Leads) system and of Miocene age are the channels which are now residual cappings of the interfluvial areas - Stage 2. In the Bendigo area they cap the Ordovician Hills and are up to 400 feet above the present land surface (Stage 4) which itself is 120 feet above the Deep Lead channel beds (Stage 3).

In every case mapping reveals that these high level auriferous alluvial materials rest directly on protruding Ordovician bedrock.

In the Heathcote-Bendigo region these cappings strongly suggest a large East to West drainage channel of high energy and a wide valley floor (See diagram 1). Block tilting could explain the east-west drainage, which at Bendigo turns northwards when the system meets the Whitelaw Fault. Atthe Heathcote end they contain pebbles of jasper derived from the Heathcote Cambrian ridge but the identifiable Cambrian material diminishes as we follow the system westwards toward Bendigo. Throughout the length of this system no lutitic detritus is found, all are arenaceous and dominated by rounded quartz boulders and pebbles. This is in sharp contrast to the Deep Lead detritus which yields much slate in the bed load.

At White Hills (Bendigo) these higher level conglomerates show a classic river cross section, complete with braiding (diagram 2) where the Ordovician directly beneath the old river valley is deeply weathered to a friable clay, quite unlike the weathering of the Ordovician bedrock elsewhere in the Bendigo

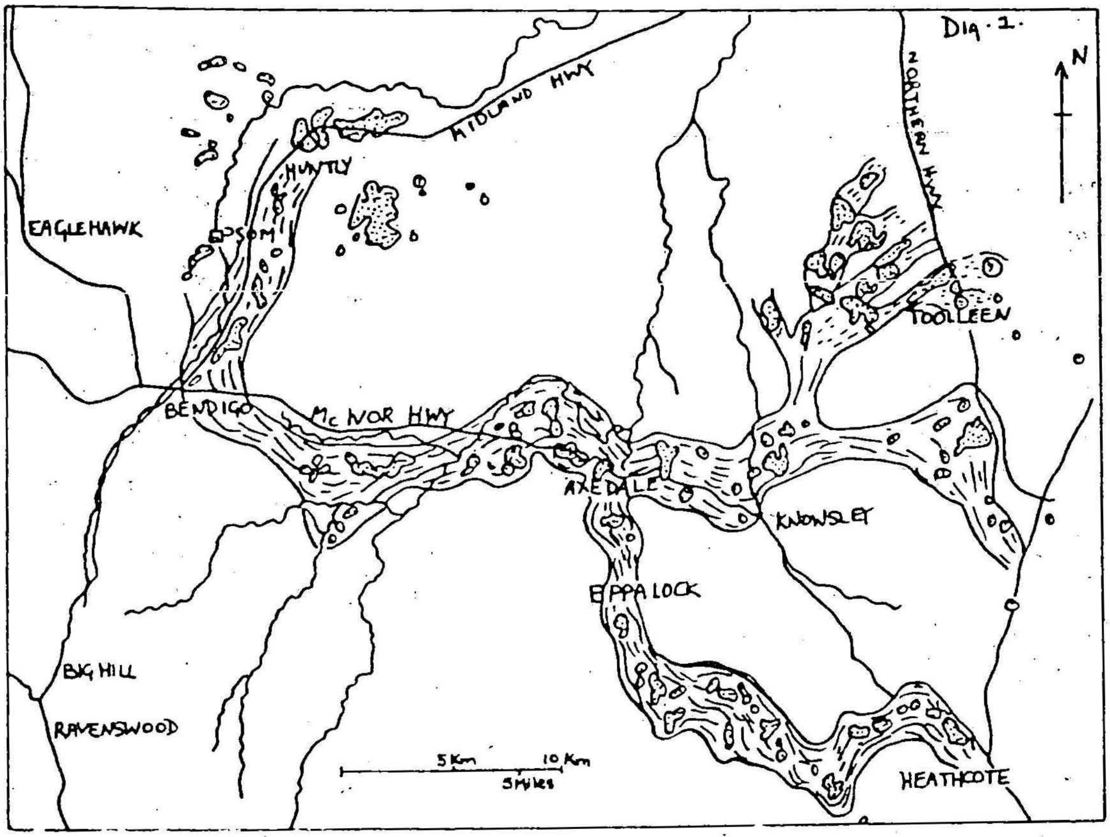


Diagram 1.

Distribution of auriferous lead gravels in the Heathcote-Bendigo area.

The dashed line pattern is one interpretation of the courses of the large ancient rivers that deposited these sands and gravels.

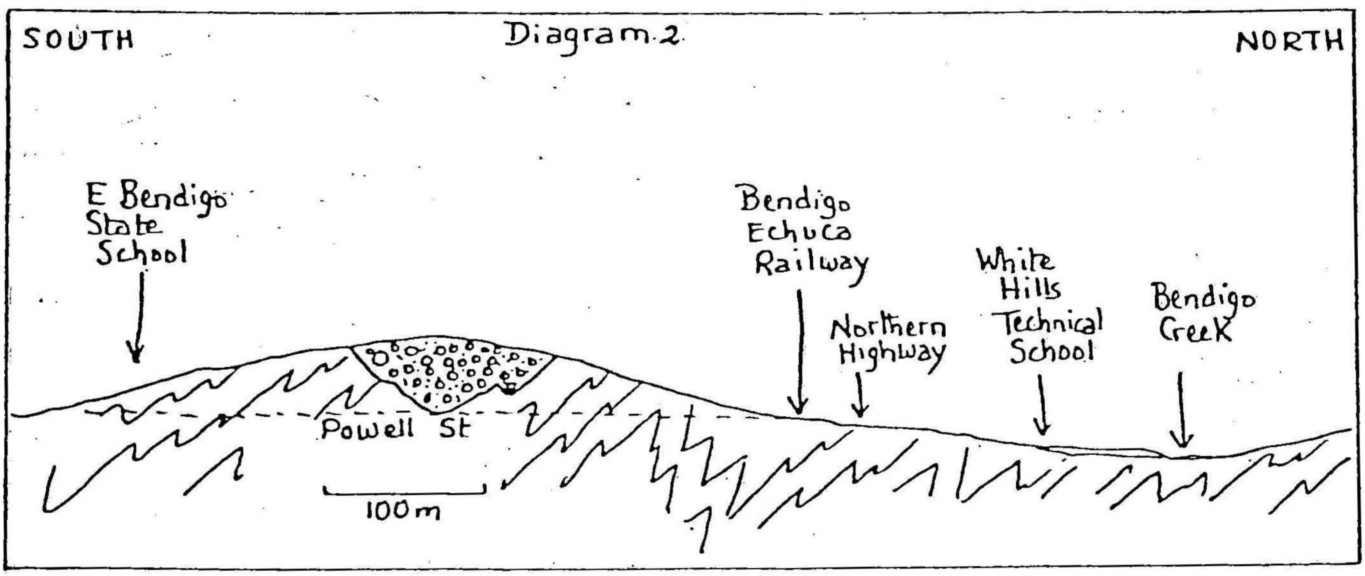


Diagram 2. Cross section of part of the White Hills gravels to show that old valleys become watersheds to the present drainage.

district. The White Hills gravels are 40 feet thick at the deepest part of the old channel.

Similar gravels at high levels are found at Vaughan Springs, seven miles south of Castlemaine and other areas of North Central Victoria, recognisably similar to the White Hills gravels and quite distinctive.

It is believed that these gravels of Stage 2 were the original suppliers of the gold which was later recycled into the channels of Stages 3 and 4. The large gold nuggets found in the Bendigo and the "Golden Triangle" areas probably "grew" in these gravels.

The following scheme is proposed for their origin:-

1. Peneplanation and very deep weathering throughout the Mesozoic of the Victorian surface, releasing a vast amount of reef gold and quartz from the Ordovician bedrock. (diagram 3)

2. Uplift and Doming of the Central Victorian Highlands concomittant with the down-warping of the Murray Valley. This accounts for the Miocene marine transgression into the lower Loddon Valley (diagram 4).
   The uplift caused rejuvenation in the pre-Miocene tectonically controlled drainage (Stage 1) and also formed new channels on the intervening block-faulted areas. Both systems acted as "Sluice boxes" for the deeply weathered Ordovician rocks and the released gold was concentrated in physiographic traps along the channels. The Miocene marine sediments interfinger with these fluviatile gravels at depth, near Kerang in the lower Loddon Valley.

It is believed that the concentration of the gold is a "once only" event during the Miocene doming/downwarp and though later, smaller, uplifts may have occurred there is insufficient time to produce another deep weathering zone for much gold to be released from the bedrock. The auriferous alluvia of the rivers belonging to Stage 3 (Deep Leads) and Stage 4 (present surface creeks) are recycled by colluvial and alluvial process from the Stage 2 systems.

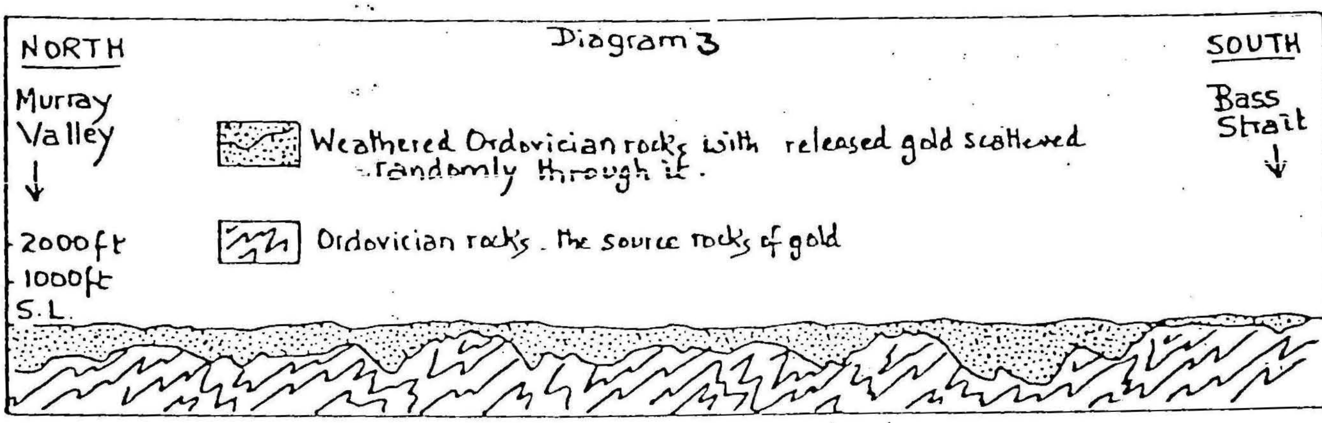


Diagram 3. North-South cross section of Central Victoria after the 200 million years weathering and before the uplift of the Middle Tertiary.

Total distance N-S is 400 km or 240 miles.

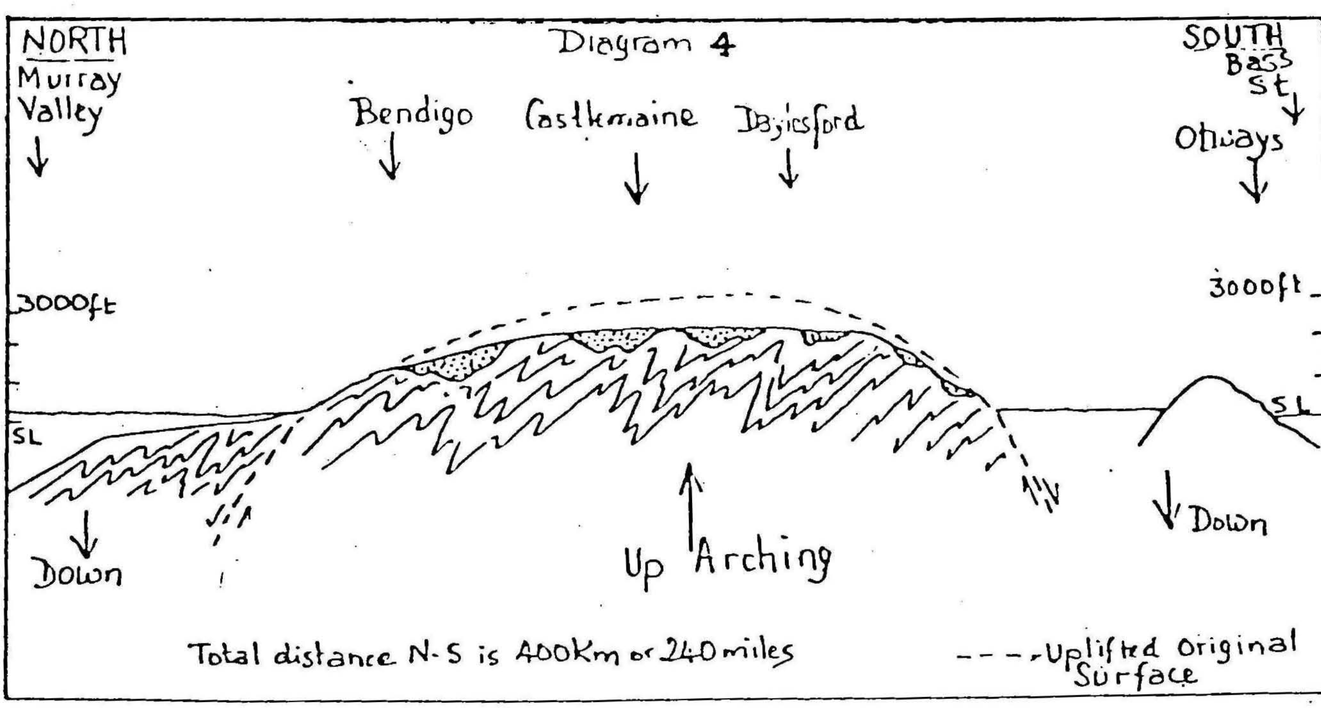
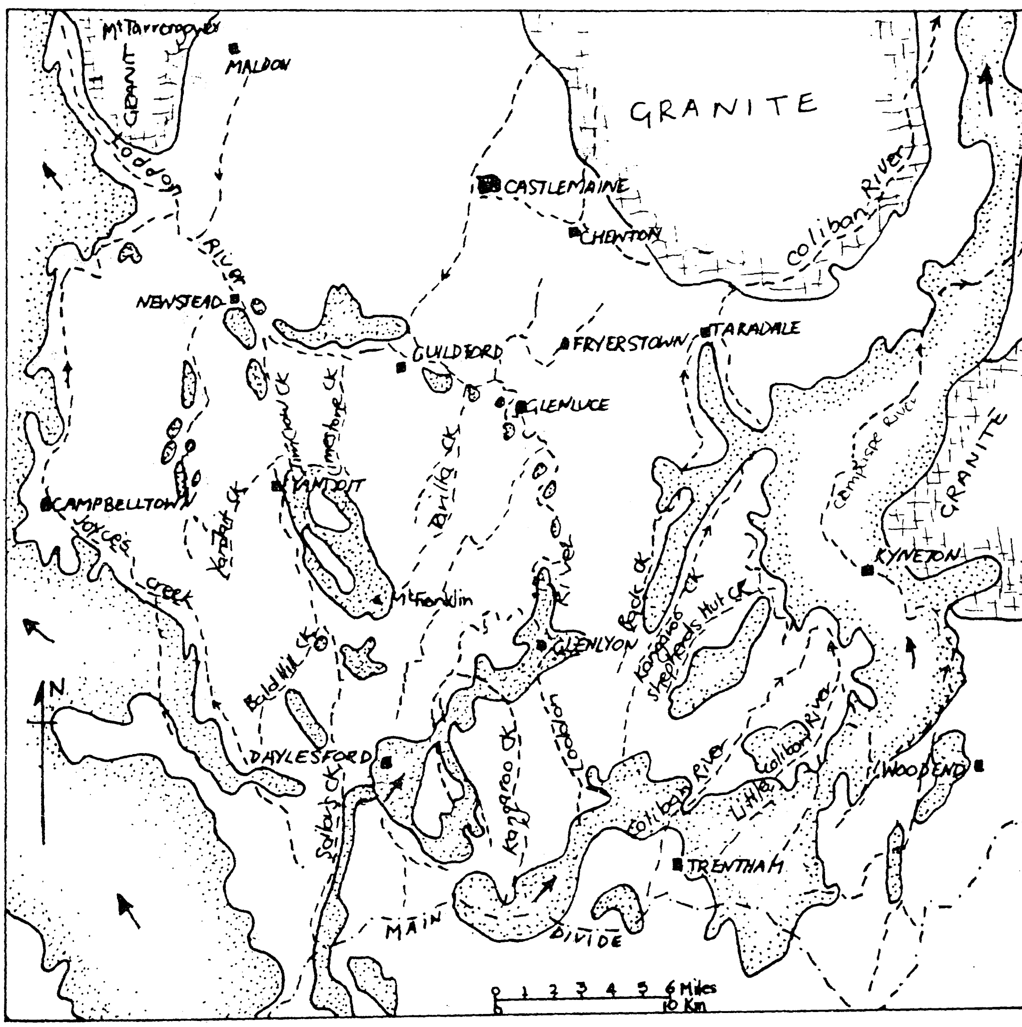


Diagram 4. North-South cross section of Central Victoria today. The dashed line indicates the original position of the uplifted surface shown in diagram 3 before erosion by the rejuvenated river systems.

The oldest auriferous alluvia in North Central Victoria (Stage 1) probably dates back to the upper Mesozoic. The lower valleys of the Loddon, Campaspe and the Goulburn belong here. There seems to be tectonic rifts between major faults which also produced northerly projecting promontories from Boort, Bendigo and Heathcote, the major valleys occupying embayments between them throughout the Tertiary. Throws of over 10,000 feet are shown by the Mt. Ida, Heathcote, Whitelaw and Muckleford faults and recurrent movement can be demonstrated on some. It is more than likely that they have had a profound influence on the drainage systems of North Central Victoria since Palaeozoic times. The lower Loddon Valley certainly predates the Miocene transgression.

These major tectonic valleys of Stage 1 were also in existence during the alluvial depositions of the other stages so that within these drainage channels the other stages cannot be distinguished.

The stages of auriferous deposition as set out above present a simplification of a complex interrelationship of drainage channels of differing ages and size and the unravelling of the strands is the subject of continuing work.



Distribution of:-
Basaltic Deep Leads in Central Victoria.
Present surface drainage