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Cooperative Research Centre for Landscape Evolution & Mineral Exploration

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OPEN FILE REPORT SERIES

REGOLITH-LANDSCAPE CHARACTERISTICS, EVOLUTION AND REGIONAL SYNTHESIS OF THE MT ISA REGION

PROGRESS REPORT

R.R. Anand, C. Phang, J. Wilford, J.E. Wildman, Li Shu, I.D.M. Robertson and T.J. Munday

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(CSIRO Exploration and Mining Report 158R/CRC LEME Report 1R, 1996. Second impression 2002)

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CRC LEME is an unincorporated joint venture between CSIRO-Exploration & Mining, and Land & Water, The Australian National University, Curtin University of Technology, University of Adelaide, University of Canberra, Geoscience Australia, Bureau of Rural Sciences, Primary Industries and Resources SA, NSW Department of Mineral Resources-Geological Survey and Minerals Council of Australia.
Headquarters: CRC LEME c/o CSIRO Exploration and Mining, PO Box 1130, Bentley WA 6102, Australia

CSIRO/CRC LEME/AMIRA PROJECT P417
GEOCHEMICAL EXPLORATION IN REGOLITH-DOMINATED TERRAIN, NORTH QUEENSLAND 1994-1997

In 1994, CSIRO commenced a multi-client research project in regolith geology and geochemistry in North Queensland, supported by 11 mining companies, through the Australian Mineral Industries Research Association Limited (AMIRA). This research project, "Geochemical Exploration in Regolith-Dominated Terrain, North Queensland" had the aim of substantially improving geochemical methods of exploring for base metals and gold deposits under cover or obscured by deep weathering in selected areas within (a) the Mt Isa region and (b) the Charters Towers - North Drummond Basin region.

In July 1995, this project was incorporated into the research programs of CRC LEME, which provided an expanded staffing, not only from CSIRO but also from the Australian Geological Survey Organisation, University of Queensland and the Queensland Department of Minerals and Energy. The project, operated from nodes in Perth, Brisbane, Canberra and Sydney, was led by Dr R.R. Anand. It was commenced on 1st April 1994 and concluded in December 1997. The project involved regional mapping (three areas), district scale mapping (seven areas), local scale mapping (six areas), geochemical dispersion studies (fifteen sites) and geochronological studies (eleven sites). It carried the experience gained from the Yilgarn (see CRC LEME Open File Reports 1-75 and 86-112) across the continent and expanded upon it.

Although the confidentiality period of Project P417 expired in mid 2000, the reports have not been released previously. CRC LEME acknowledges the Australian Mineral Industries Research Association and CSIRO Division of Exploration and Mining for authority to publish these reports. It is intended that publication of the reports will be a substantial additional factor in transferring technology to aid the Australian mineral industry.

This report (CRC LEME Open File Report 125) is a second impression (second printing) of CSIRO, Division of Exploration and Mining Restricted Report 158R, first issued in 1996, which formed part of the CSIRO/AMIRA Project P417.

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PREFACE

Project P417 began in April 1994. The Co-operative Research Centre for Landscape Evolution and Mineral Exploration (CRC LEME) was established in July 1995 and in December 1995, sponsors agreed that P417 became part of CRC LEME. This has allowed increased involvement of staff, including Mal Jones from Qld Mines Dept. This project is also being conducted collaboratively with the Cooperative Research Centre for Australian Mineral Exploration Technologies (CRC AMET).

The principal objective of the CSIRO/AMIRA 417 Project is to improve substantially geochemical methods of exploration for base metals and Au in areas obscured by weathering or under cover. The research includes geochemical dispersion studies, regolith mapping, regolith characterisation, dating of regolith and investigation of regolith-landscape evolution. This report presents progress on several of these aspects based on regional- and district-scale orientation studies.

The report is organised by chapters dealing with discrete issues and districts which are further subdivided. The regional setting of the Mt Isa region is covered in Chapter 3. The subsequent four chapters describe the district- and local-scale regolith-landforms and geochemical dispersion studies, drawing attention to their exploration significance. The landscape evolution is synthesised in Chapter 7, underlining its importance to exploration strategy.

The sponsors requested a critical assessment of the RED regolith mapping scheme, used successfully in the Yilgarn Craton. The last chapter covers regolith mapping and how this differs from the Yilgarn Craton. There are similarities and differences in the weathering history and sedimentary events between the two regions which have necessitated the proposal of a more complex scheme. This is now open for comment and other interpretative schemes are being considered.

Substantial district-scale investigations including regolith mapping (Eloise-Maronan, Selwyn, Tringadee, Mammoth Mines, Little Eva-Dugald River) will continue and be reported upon separately. In view of the scope of this report, inevitably it is large, but has been carefully structured for access at several levels of interest and has also been indexed for ease of reference.

R.R. Anand
Project Leader

I.D.M. Robertson
Deputy Project Leader

TABLE OF CONTENTS

1. SUMMARY

Weathering, erosion and depositional history
The Mt Isa region is characterised by complex history of weathering and landscape development. Following marine incursion, Mesozoic sediments were deposited on a landsurface of significant relief. Thus, Cretaceous sandstone, shale, claystone, siltstone, limestone, and conglomerate at that time overlay most of the Mt Isa Inlier and since has been partly eroded. Subsequent regional uplift and drainage incision has led to the development of the broad features of the present landscape, in which extensive plains surround a central hill zone. Some of the plains have been further modified by the deposition of Tertiary sediments.

Long periods of stability have favoured the development of a deep, weathered mantle which has been differentially eroded during more active phases of erosion. Ferruginous or siliceous duricrusts can occur in the upper parts of weathered profiles. Where relatively fresh rock is exposed in erosional terrains, these are partly mantled by calcareous soils.

Regional regolith distribution and geomorphic provinces
As an aid to geochemical dispersion studies, a regolith-landform framework was established for the Mt Isa region. Mapping of an area of 84,000 km^2 (17°30'S - 22°00'S; 137°30'E - 141°00'E) at a scale of 1:500,000, has shown the broad distribution of ferruginous materials, silcretes, soils, saprolite, Proterozoic bedrock, Mesozoic sediments, colluvial-alluvial and lacustrine sediments. In the mapped area, Mesozoic sediments are more widespread in the southeast and to the north than in the centre of the Mt Isa Inlier. Lateritic duricrusts are more common in the Western Succession than in the Eastern Succession. Large areas of alluvial deposits occur west and east of the Mt Isa Inlier. Narrow corridors of coarse alluvium trend northeast across the Inlier and small areas of coarse colluvium cover the footslopes of steep hills.

In the present study, three broad geomorphic subdivisions are recognised, namely hill belts, a complex of mesas and plains, and plains. These show varying degrees of weathering, erosion and deposition and are developed on Proterozoic bedrock and Mesozoic sediments. The three major provinces were further subdivided on the basis of their dominant geology and topography.

The *hill belts* occupy the central portion of the region and consist predominantly of north-trending ridges and hills. Here, the detailed sculpturing of the landsurface is intimately related to differential weathering and erosion of various lithologies. Mesozoic sediments are sporadically distributed generally capping small mesas. Not all the rocks in the hill belts are fresh and many have signs of former and present weathering that involves formation of kaolinite, smectite and pedogenic carbonates. Zones of superficial, secondary silification are marked. The colluvium is generally less than one metre thick but reaches thickness of 12 m in places. Soils developed in colluvium are calcareous to non-calcareous.

The terrain characterised by a *complex of mesas and plains* indicates the variable distribution of former lateritic weathering. These areas are interpreted as a dissected plateau on which the original old surface forms a significant component of the landscape. This terrain occupies part of the Western and Eastern Successions. Deeply weathered profiles, with ferruginous or siliceous cappings, occur on stable parts of the landscape (mesas crests) but, even here, the total depth of weathering is variable. In contrast, relatively shallow weathering profiles occur on pediments and erosional plains. The depositional plains are mantled with shallow alluvium (1-5 m) which are underlain by deeply weathered profiles with or without a ferruginous or siliceous capping.

The *plains* feature variable thicknesses of weathered and partly eroded Cainozoic, Tertiary and Mesozoic sediments, underlain by Proterozoic bedrock.

Weathering profiles
The nature and depth of weathering profiles on Proterozoic and Mesozoic rocks are variable and are largely controlled by bedrock composition and palaeo-topography. However, the depth of weathering of the Proterozoic rocks is also controlled by the presence (or absence) of overlying Mesozoic sediments at the time of weathering. Proterozoic rocks are weathered to greater depths where Mesozoic sediments have been removed or were never deposited. Lateritic duricrust and indurated ferruginous saprolite were developed on ferruginous lithologies, with silcrete and silicified saprolite in equivalent situations on siliceous bedrock.

The 'complete' weathering profile, from top to base, has a lag of lateritic nodules and pisoliths, pockets of duricrust, indurated ferruginous saprolite, a clay zone, saprolite (silicified in part), saprock and bedrock. Lateritic duricrust and silcrete have also developed on some Mesozoic sediments. Mottled zones are common on Tertiary sediments.

The characteristics of weathering profiles reflect both past and present weathering conditions. The ferruginous and siliceous duricrust-capped weathering profiles, containing Al_2O_3, Fe_2O_3 and, probably, SiO_2 corresponds to wet climates, whereas calcrete and smectite are products of arid conditions. Calcrete and smectite are typically developed on partially weathered rocks of hill belts and on erosional plains, and are products of weathering under the present climate. Duricrust-capped, deeply weathered, kaolinised profiles on mesas are inherited from past climates.

Soils

Soils have formed on sediments (Mesozoic and Cainozoic), Proterozoic bedrock and on saprolites formed from these bedrocks. Lateritic, gravelly soils have developed on lateritic profiles of the plateau erosion surface on Proterozoic and Mesozoic sediments. Red, brown and yellow earths occur on slopes and plains in erosional terrain developed below the lateritic plateau remnants. They are formed on the underlying saprolite and saprock. Yellow earths are generally associated with more siliceous Proterozoic bedrocks but, on the more ferruginous rocks, red earths occur. In places, however, these residual soils are overlain by recent fluvial deposits.

Lithosols or skeletal soils are associated with resistant rocks and areas of high relief and steeper slopes. Soils of the hill belts contain abundant pedogenic carbonates from recent weathering of underlying rocks.

In depositional plains, the soils vary from black through red to grey sandy clay, sands or clays and generally contain polymictic gravels. The nature of the soil depends on the provenance and thickness of the parent materials and on the history of post-depositional erosion. Brown and red soils are developed where the drainage is good. Hydromorphic conditions in depressions and gentle slopes favour formation of black soils. Some soils are cemented by Fe oxides and others by silica.

Ferruginous materials

These are six main categories of ferruginous materials in the Mt Isa region. These include lateritic gravels (mottles, nodules and pisoliths), lateritic duricrusts, ferricretes, indurated ferruginous saprolite, ferruginous bands and ferruginous veins; the origin of these materials vary. Mottles and nodules are residual; pisoliths have experienced local transport. The Fe-rich composition in lateritic duricrusts is the result of either or both of two processes: (1) relative concentration of Fe and Al by removal of Si and bases and landscape lowering; (2) concentration of these elements by absolute accumulation from outside sources. Duricrusts, (*e.g.*, slabby duricrust) formed by laterally accumulated Fe were originally formed in locally derived substrates in valleys and the topography has since been inverted. Ferricretes are formed by the Fe enrichment of sediments and are not genetically related to the underlying lithologies. Where the bedrock is rich in Fe, pseudomorphic replacement of kaolinite by Fe oxides has lead to strongly indurated hematite-goethite-rich ferruginous saprolite. Ferruginous bands occur in the lower and middle part of the profile and appear related to fluctuations in the water table and texture of sediments. Ferruginous veins follow bedding planes and fault systems.

Ferruginous materials in the Mt Isa region have formed in a variety of substrates derived from Proterozoic bedrock, Mesozoic, Tertiary and recent sediments. However, the degree of development of the ferruginous horizon depends upon the nature of the parent material. The ferruginous horizon on Tertiary sediments is limited to mottles; duricrust is not developed.

Silcrete

Silicification has affected a range of regolith materials. Well-developed silcrete on plateau remnants are interpreted as a landscape near-equivalent of the lateritic duricrust. Silcrete is not only developed on bedrock but is also developed in alluvium, sand and gravel sediments of valleys, many of which have since undergone topographic inversion.

Erosional surfaces
No reliable indication of age can be obtained from the morphology, chemistry and mineralogy of duricrusts as similar ranges of weathering and ferruginous and siliceous duricrusts occur at different levels. Variation in altitude of duricrusts may result from differential erosion of a single, broadly undulating, deeply weathered landsurface and to variations in local geology and groundwater conditions. The variable Fe oxide mineralogy of lateritic duricrusts suggest that they have formed in differing hydrological environments. Duricrusts dominated by hematite may be older than those dominated by goethite. The variety of ferruginous and siliceous materials suggest that formation of landsurfaces in the Mt Isa region has been complex. It would be unwise to ascribe a single age to the regolith or imply a single extensive surface of planation, since different parts of the surface may have formed at different times.

Pilot studies
Five pilot studies of areas characterised by base metal geochemical anomalies (Python, Lady Loretta, Drifter, Blinder, Tringadee) are summarised within their district-scale regolith-landform settings. Common regolith-landform situations and their implications to exploration, particularly in relation to geochemical sampling media and data interpretation, are discussed.

The Python Cu Prospect (Buckley River-Grey Ghost district) has a Cu, Sb, As and Pb anomaly restricted to slabby duricrust and lateritic nodules and pisoliths. There are three sources of Fe and trace elements at the Python Prospect, namely pyritic units in the Proterozoic bedrock, a fault that cuts through the duricrust-capped hill and absolute accumulation from outside sources. The fault is rich in Pb, Au and Sb and is probably related to underlying mineralisation. Dispersion from the fault has caused a broad anomaly in the slabby duricrusts and lateritic nodules and pisoliths.

At Lady Loretta Deposit, patchily developed nodular duricrust is widely enriched in As, Sb, Mo, W, Pb and Zn and is related to underlying Pb-Zn-Ag mineralisation. The duricrusts are located on mesa which is strongly dissected. This confirms that analysis of even widely-spaced duricrust may reveal base metal mineralisation below a deeply weathered lateritic surface.

A cherty breccia (Cambrian unconformity) and soils at the Drifter Prospect are anomalous in Cu, Zn and Pb without any known underlying significant mineralisation. Copper and Zn anomalies in the cherty breccia appear to be related to leakage from the Proterozoic Drifter Fault into the overlying Cambrian. These elements exhibit similar dispersion characteristics and have strong affinities for Fe and Mn oxides, implying hydromorphic dispersion. Iron in the cherty breccia is derived from several sources, including the fault and the underlying Proterozoic bedrock. The high concentrations of Pb and Sb in soils imply a nearby source, since Pb and Sb are relatively immobile. However, the source may be minor.

At the Blinder Prospect there are significant Zn and Pb anomalies in the Mt Hendry Formation but no mineralisation has been found by drilling. The Fe oxides that host the anomaly in conglomerate (Mt Hendry Formation) are not derived from the underlying Paradise Creek Formation or from the overlying Cambrian. Bedding in the Mt Hendry Formation suggest a fluvial environment that has transported the anomalous Fe-rich material into place before burial by the Cambrian.

At the Tringadee Prospect there is a widespread Zn anomaly in the Mesozoic cover. The Zn anomaly is associated with accumulated Fe and Mn oxides, probably related to fluctuating water tables and fractures in the Mesozoic cover. The latter appear to have conducted Fe-rich fluids from external sources. The source of these anomalies could be nearby deposits such as Cannington and Pegmont.

Regolith-landform mapping
Application of an interpretive or derivative mapping scheme established for parts of the Yilgarn Craton (colloquially referred to as the "RED mapping scheme") is assessed for the Mt Isa region. An interpretative scheme for the Mt Isa region is proposed. This is now open for comment and other interpretative schemes are being considered.

2. INTRODUCTION

2.1 Background and Exploration Problems

Regolith is used in this report as a general term for the entire cover, cemented or unconsolidated, that overlies unweathered bedrock (Proterozoic, Cambrian, Mesozoic), and was formed by weathering, erosion and sedimentary or chemical deposition. Thus, regolith materials include residual weathered materials (saprolite, mottled zone, some soils) and transported materials (colluvium, alluvium, some slabby duricrusts evaporitic sediments, aeolian deposits).

The regolith is a major impediment to mineral exploration in some areas of northern Queensland, as well as other parts of Australia. The exploration problems are:

(1) Correctly interpreting element concentrations in the weathered Mesozoic and Cambrian sediments overlying mineralised Proterozoic bedrock.

(2) Discriminating gossans and related ironstones from partially dismantled lateritic residuum.

(3) The complex geochemical signatures arising from multiple profiles.

(4) Recognising *in situ* and transported ferruginous materials.

(5) Distinguishing sedimentary cover from weathered bedrock.

Most geological studies have focussed on the bedrock of the Mt Isa region. There has been little consideration given to the regolith except for Twidale (1966), Connah and Hubble (1960), Senior *et al.* (1978), Grimes (1979, 1980) and Taylor and Scott (1983). The success of exploration relies heavily upon the development of an understanding of the regolith and associated landscape features in the region.

A study of the regolith-landscape of the Mt Isa region commenced in April 1994 by CSIRO, AGSO and the University of Queensland as a part of CSIRO-AMIRA Project 417 (Geochemical exploration in regolith-dominated terrain of North Queensland). This study has begun to establish a regional regolith-landform framework and to characterise some of the regolith materials. This report describes the main regolith and landform characteristics of the Mt Isa region to assist with a better understanding of geochemical dispersion and to provide an initial framework for dating the regolith. The accompanying 1:500,000 regolith map is based on reconnaissance regolith-landform mapping, published geological maps (1:100,000, 1:250,000), photo-interpretation and field work in selected areas (Appendix 1). The area mapped is located between latitudes 17°30'S and 22°00S, and longitudes 137°30'E and 141°00'E. The 1:500,000 regolith-landform map is intended to provide a guide to the general distribution of regolith materials. Substantial district-scale investigations are continuing in the Western Succession (Buckley River-Grey Ghost-Drifter) and in the Eastern Succession (Little Eva, Tringadee, Selwyn, Eloise-Maronan) (Figure 1). The work includes regolith mapping (1:25,000-1:50,000), regolith characterisation and regolith stratigraphy, regolith dating, orientation sampling of different sample media and correlations of these characteristics within the framework of a regional regolith-landform evolution model.

2.2 Objectives

The overall objective of the Mt Isa regional study is to provide a regional regolith-landform framework for the geochemical dispersion studies. Specific objectives were:

(1) To map broad regolith-landform features and relationships.

(2) To characterise and establish the origin of ferruginous materials, silcrete, lag, soil and sediments.

(3) To determine the relevant characteristics of old landsurfaces.

(4) To examine the age relationships of weathering stages.

(5) To develop models of regolith-landscape evolution.

(6) To assess the application of the existing interpretative RED scheme (Anand *et al.*, 1993) of regolith mapping.

(7) To assess the impact of regolith history on geochemical exploration.

(8) To summarise pilot studies into a regional perspective

This report presents progress on several of these issues.

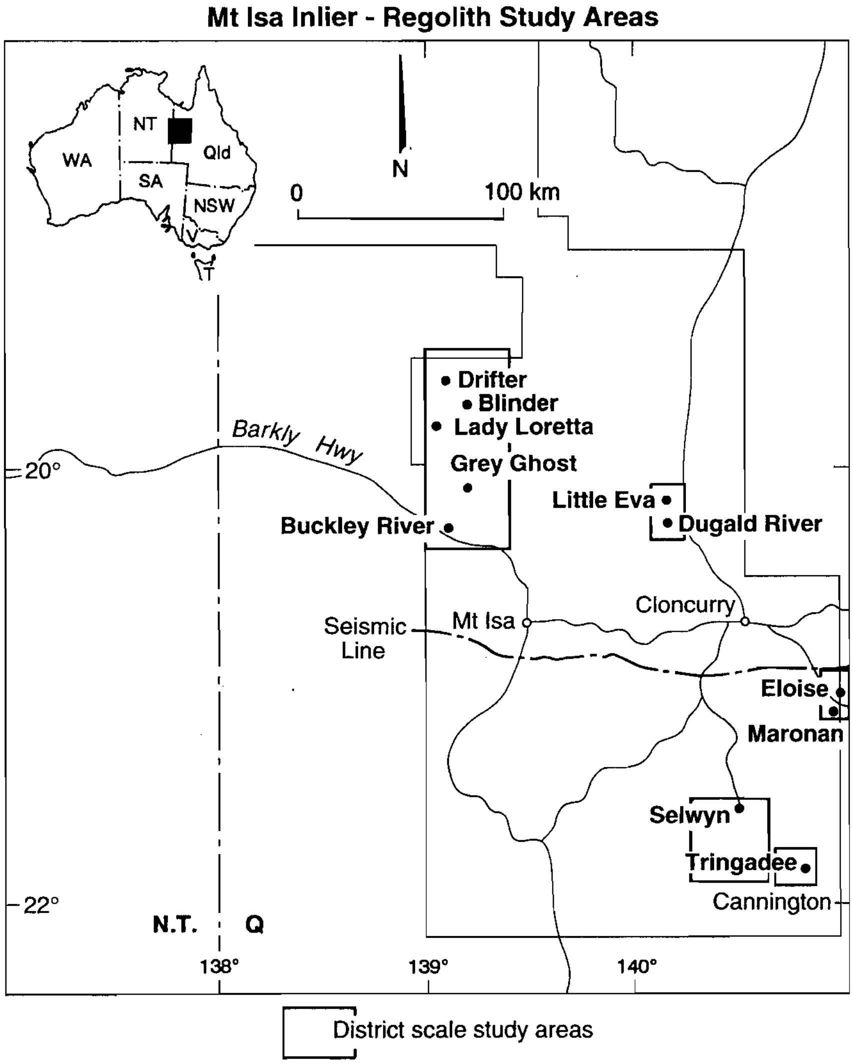


Figure 1. Map showing the location of orientation studies, P417.

3. REGIONAL SETTING OF THE MT ISA REGION

3.1 Climate and Vegetation

The region has a semi-arid, tropical, monsoonal climate with a hot, wet season from October to March and a mild to warm, dry season from April to September. The vegetation reflects the semi-arid climate, consisting mainly of eucalyptus, acacia shrub woodland with spinifex and ephermal grasses below. Outcrops of Proterozoic rocks typically have a sparse cover of shrubs, low trees and spinifex.

3.2 Regional Geology

Figures 2 and 3 detail the tectonic setting and generalised regional geology of the Mt Isa Inlier. These are described in detail by Blake, 1987. The Mt Isa Inlier is an area of exposed early and middle Proterozoic rocks, covering more than 50,000 km^2, in northwest Queensland (Blake, 1987). It is bounded by younger basins, namely the Proterozoic South Nicholson Basin to the west and south, the Mesozoic Eromanga Basin to the south and southeast, and the Mesozoic Carpentaria Basin to the northeast (Figure 3). Gravity and aeromagnetic data indicate that the rocks of the Mt Isa Inlier extend for considerable distances below these basin sediments. Three broad tectonic divisions are distinguished within the Mt Isa Inlier: the Western Fold Belt, Kalkadoon-Leichhardt Belt and the Eastern fold Belt, which consist of early and middle Proterozoic sedimentary and volcanic rocks, many thousands of metres thick. These are assigned to four major sequences, and numerous igneous intrusions (Blake, 1987).

3.3 Weathering Patterns

Weathering profiles have developed on Proterozoic bedrocks, Mesozoic and Tertiary sediments and extend to variable depths below the present landsurface. The nature and depth of weathering profiles on Proterozoic bedrock and on Mesozoic sediments are variable and are largely controlled by the nature of bedrock and palaeo-topography. However, depth of weathering on Proterozoic rocks is also controlled by the presence (or absence) of overlying sediments at the time of weathering. At many locations, Proterozoic bedrocks are weathered to greater depths where overlying Mesozoic sediments have been removed or were never deposited. Lateritic profiles are best preserved in areas where the former lateritic surface is flat or only gently undulating. Thus, generally deeply weathered profiles are common on plateau remnants, but relatively shallow profiles occur on erosional plains and hill belts. Exploration drilling beneath the plateau remnants typically records depths of weathering of up to 150 metres (*e.g.*, 20°14'46"S - 139°8'11"E). Although deep weathering may be favoured by long, undisturbed periods of evolution beneath ancient plateau surfaces, weathering depths are affected by other factors as well. Water circulation and advance of the weathering front would probably both be retarded by the stagnant conditions at depth beneath extensive plateaux, but would be accelerated where there is dissection and fissuring of rocks, as along faulted margins of the continents (Thomas, 1989). Topography determines the intensity of erosion at the time of weathering, which is an important factor in determining whether a profile can develop at a given place and time. Thus, many factors interact to determine the environment at a specific site and limit our ability to predict weathering depths from surface appearances. The actual depths of weathering must come from detailed observations.

The general pattern of the profile is similar at many locations, but the development of the individual units of the profiles is not uniform. Although saprolite is common in many weathering profiles on Proterozoic bedrocks, the upper, ferruginous (lateritic duricrust, ferruginous saprolite, mottled zone) or silcrete horizons may be absent due to incomplete formation or later erosion. Ferruginous saprolite is the most common ferruginous horizon on Fe-rich lithologies. In places, silcrete has developed on siliceous bedrock instead of the ferruginous horizon. Some Fe-rich rocks such as basalts and shales are prone to rapid, deep weathering, but their high Fe content leads to duricrust formation at an early stage, protecting the underlying saprolite from erosion. This is an important factor in preserving saprolite profiles, and a reason why only shallow regoliths are present over many Fe-poor rocks and did not form thick or extensive duricrust caps. As would be expected, no weathering profile was observed on quartzite. Although it is assumed that no profile was developed, the possibility of stripping can not be ruled out.

Weathering profiles on Mesozoic sediments are variable and are largely controlled by the nature of the sediments; as would be expected, more deeply weathered profiles are developed on claystones and siltstones than on sandstones.

In the Mt Isa region, the characteristics of weathering profiles reflect both past and present weathering conditions. The formation of duricrust-capped (ferruginous and siliceous) weathering profiles containing Al_2O_3, Fe_2O_3 and SiO_2 corresponds to wet climates, but development of calcretes and smectites indicate more arid conditions. Calcrete is typically developed on partially altered rock. Duricrust capped deeply weathered, kaolinised profiles are relict; they are inherited from past climates, and the weathering products are not in equilibrium with the prevailing climate. However, most profiles of 30-150 m depth have formative histories of many millions of years, during which time changes in climate and elevation will have taken place.

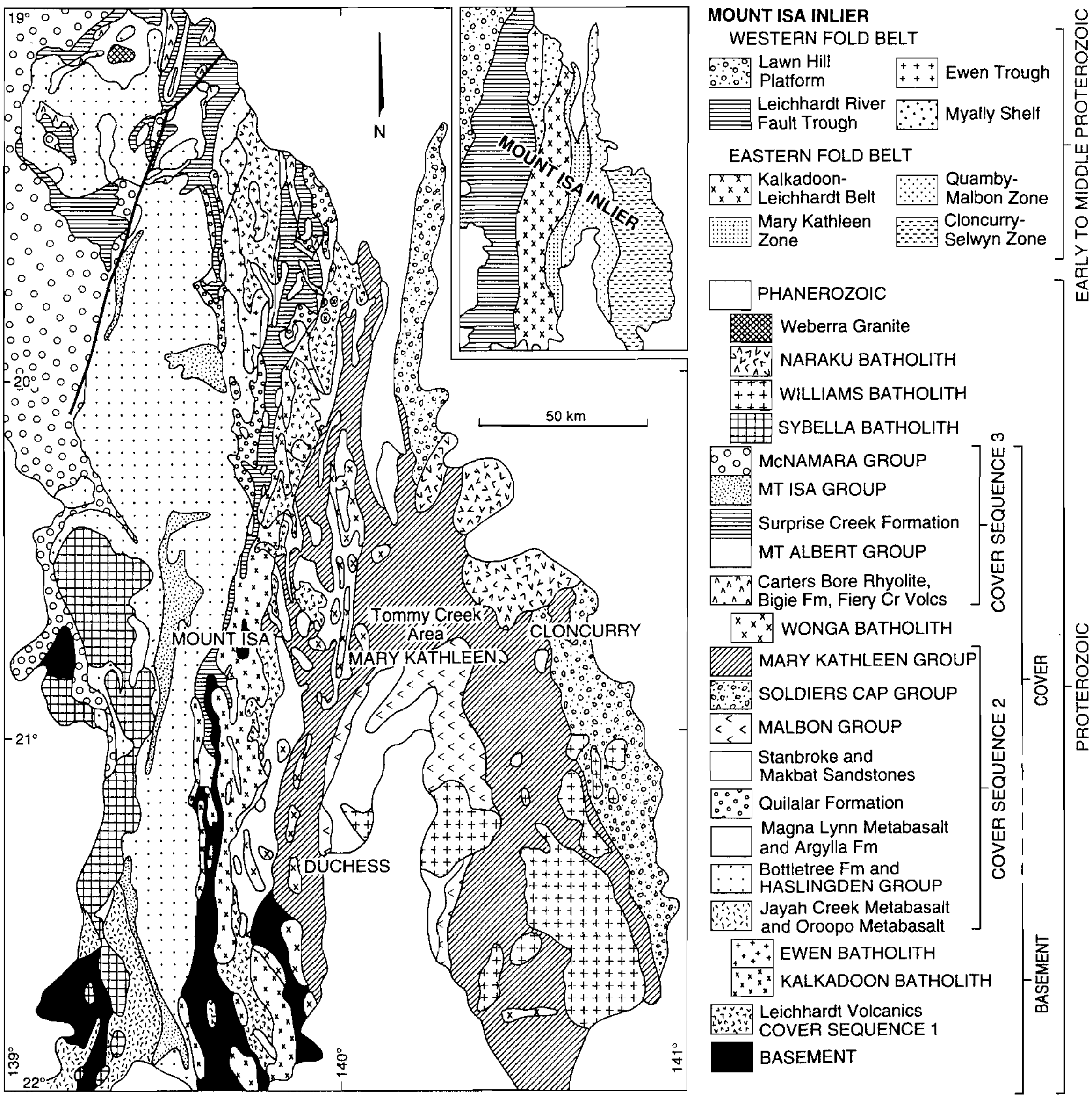


Figure 2. Simplified geology of the Mt Isa region (after Blake, 1987).
Inset - generalised structural province map (see Fig. 3).

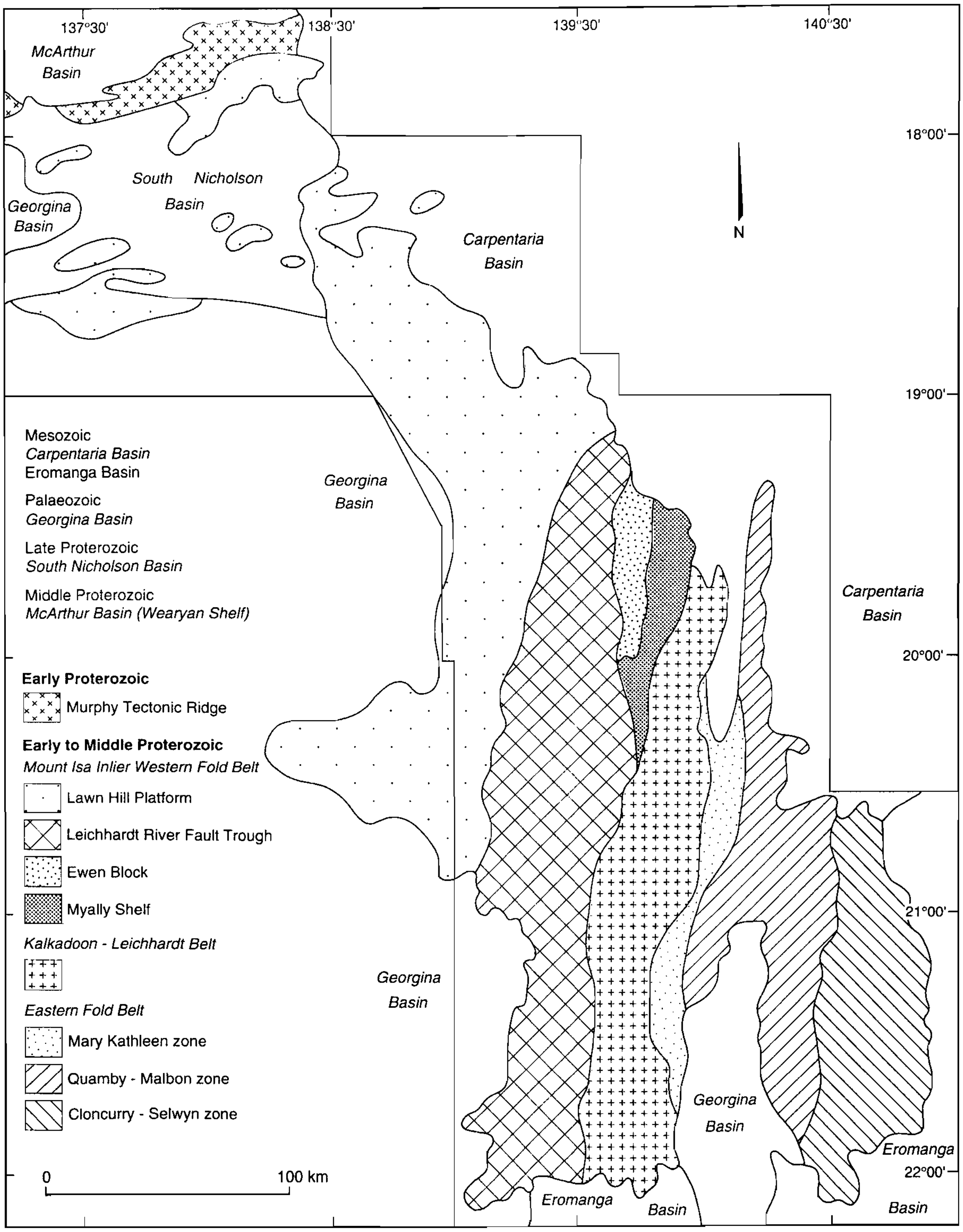


Figure 3. Tectonic zones (after Blake, 1987).

3.4 A 'Typical' Weathering Profile on Proterozoic and Mesozoic Bedrock

3.4.1 Ferruginous profile

Two major zones have been identified in weathered profiles on plateau remnants in the Mt Isa region (Figure 4A,B). These are:- (1) zone of hydration, at the base and (2) ferruginous zone. The zone of hydration consists of saprock, saprolite and clay zone. Saprock and clay zone are not always present. The ferruginous zone consists of a ferruginous saprolite or mega-mottled zone, collapsed ferruginous saprolite and lateritic nodules and pisoliths. In many profiles, soil and lateritic duricrust are either very thin or not present above ferruginous saprolite. It is assumed that these have been stripped off or were never formed. In some situations, lateritic duricrust is developed in transported materials. The lateritic profile over Mesozoic bedrock typically contains lateritic nodules overlying patchy, massive, mottled duricrust which passes downwards into a mottled zone characterised by blocky megamottles (Figure 4B). The mottled zone is underlain by saprolite, which also can be mottled. The strong development of mottling in regolith on Mesozoic bedrock may be due to iron originating largely by concentration from external sources, whereas on Proterozoic rocks iron accumulation has largely resulted from weathering losses from the profile.

Within saprock and saprolite, parent rock fabrics and structures are roughly preserved, indicating that weathering largely has been isovolumetric. The saprock is compact, slightly weathered rock with less than 20% of the weatherable minerals weathered. Saprolite is characterised by dissolution of most weatherable primary minerals; the least mobile elements (Al, Fe), liberated by weathering, reorganise almost *in situ* with little or no mobilisation. Saprolite may be mottled and/or silicified and is largely kaolinitic but, at the base of the saprolite and saprock, smectite and mixed layer clay minerals can form where drainage is poor and/or over particular lithologies (*e.g.*, schist and basalts); smectite is generally related to restricted leaching environments and is a product of recent arid environments.

A clay zone generally occurs above the saprolite but may be absent. Where present, it consists of strongly leached, massive, kaolinitic clays, commonly with a mesoscopically homogenous clay fabric. It has been referred to as a 'pallid zone'(Smart *et al.*, 1980). Loss of lithic fabric is caused by solution and authigenesis of saprolitic, kaolinitic clays and mechanical processes such as clay shrinking and swelling.

Ferruginous saprolite forms an indurated, yellowish brown to dark reddish brown zone, with hematite, goethite and kaolinite as dominant secondary minerals and quartz as the main primary or residual mineral (Figure 11A) Ferruginous saprolite is developed by progressive ferruginisation of the kaolinitic saprolite. Here, relict rock fabrics and structures are preserved by ferruginisation. This contrasts with any underlying clay zone where fabrics have been destroyed by pedogenesis. Higher in the profile, soft, clay-rich masses in the ferruginous saprolite have been dissolved, producing numerous irregular voids which may be occupied by secondary kaolinite, goethite, hematite and fine grained quartz to form indurated masses. The voids weaken the saprolite structure, leading to its eventual collapse (collapsed ferruginous saprolite). Goethite-rich cutans develop in the collapsed ferruginous saprolite.

Lateritic nodules and pisoliths can form a thin near surface horizon and/or occur as lag formed from the fragmentation of the underlying collapsed ferruginous saprolite. Fragments of collapsed ferruginous saprolite break into small hematitic nodules. The hematite is subsequently transformed to goethite and is reprecipitated as cutans on the hematite-cored nodules. As the sphericity of nodules increases by repeated dissolution and reprecipitation, some develop into pisoliths. In general, however, pisoliths are uncommon in the Mt Isa region.

Two types of nodules are recognised, lithic and non-lithic (Figure 4). Lithic nodules contain recognisable pseudomorphs after primary minerals or relics of amphibolite, schist and shale. The non-lithic nodules show no relic rock fabrics but several generations of Fe-oxides, impregnated or disseminated through the clay or sand matrix. Where there has been extreme ferruginisation, lithic and non-lithic nodules become similar and the distinction between the two is difficult.

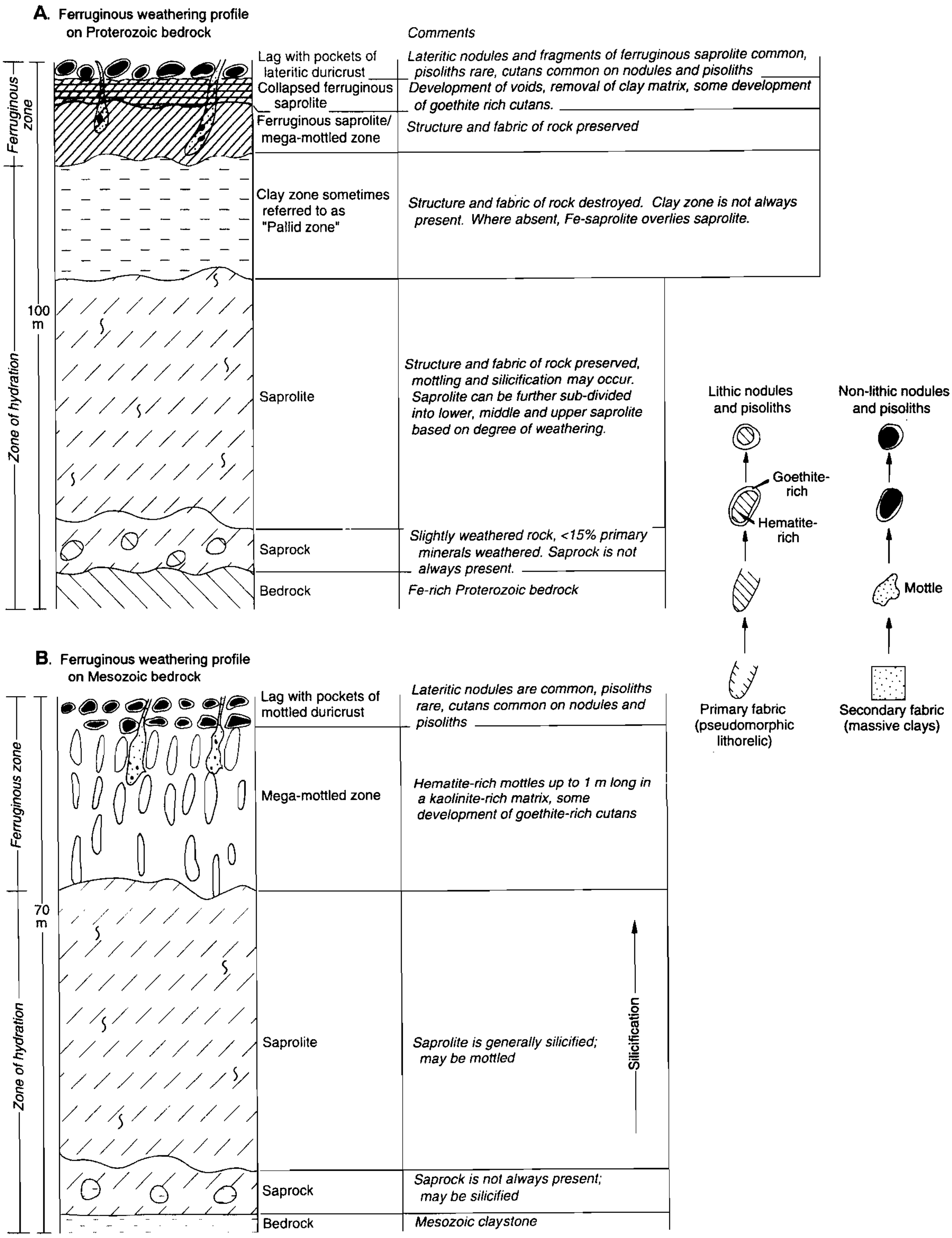


Figure 4. Typical ferruginous weathering profiles developed from weathering of Proterozoic bedrock (A) and Mesozoic bedrock (B).

The ferruginous weathered profiles cannot be regarded as static, but must be thought of as slowly descending columns, losing mobile elements and fine particles, accumulating less mobile elements and even some locally derived transported materials in the upper horizon. The enhanced mobility of Al^{3+}, Fe^{2+} and SiO_2 in the presence of organic acids leads to lowering of the landsurface. This process is central to formation of a horizon of lateritic nodules, pisoliths and duricrust, and leads to the accumulation of Au and base metals in some profiles. Some specific mechanisms of ground surface lowering by combining chemical and physical processes can be identified in the Mt Isa region, which may have taken place in a tropical environment. These include:

(1) Accumulation of Fe and heavy minerals (zircon) in weathering profiles.
(2) Accumulation of gravel layers at the base of slopes.
(3) Dissolution of clays in ferruginous saprolite and the mottled zone and formation of collapsed ferruginous saprolite and collapsed mottles.

3.4.2 Silcrete profile

An idealised silcrete profile consists, from top to base, of silcrete, silicified saprolite, saprolite and bedrock. Silcrete is an indurated, greyish, 0.5-2.0 m thick, massive to nodular horizon rich in quartz and microcrystalline quartz. In places, large massive sheets have columnar jointing. On a large scale, no relict rock fabrics or structures are preserved in the silcrete horizon. Hematitic mottling is common, and a lag of mottles and silcrete fragments occurs on the surface from degradation of the silcrete.

Silcrete overlies bleached, quartz-and kaolinite-rich silicified saprolite (5-15 m thick), with rock structures and fabrics at least partially preserved. Mottling can also occur in this horizon. Silicification in silcrete and silicified saprolite probably occurred concurrently with weathering. Silica is locally derived from the profile. At depth, silicified saprolite merges into kaolinitic saprolite, which is similar to that of the ferruginous profile.

3.5 Regional Geomorphology and Regolith

3.5.1 General features

Jennings and Mabbut (1977) refer to the surface of the Mt Isa Inlier as an immaturely dissected, undulating plateau that forms part of the Western Plateau Division. The maximum elevation is about 550 m above mean sea level (amsl) near Mount Guide in the southwest, and the lowest is about 60 m in the northeast. Local relief is generally less than 100 m. A low divide separates drainages flowing north to the Gulf of Carpentaria from south flowing streams of the Georgina-Diamantina inland drainage system. Both regionally and in detail, the relief of the Mt Isa region directly reflects underlying structures and lithologies (Birot, 1958; Twidale, 1966). The eastern margin of the Mt Isa Block is a strong tectonic lineament trending NNW-SSE. Warping is clearly evident, but there are also faults parallel to this lineament at the margin of upland and plain (Carter and Opik, 1959).

A regolith-landform framework was established for the Mt Isa region by mapping an area of 84,000 km^2 (17°30'S - 22°00'S; 137°30E' - 141°00'E) at a scale of 1:500,000 to aid geochemical dispersion studies. The regolith-landform map shows a broad distribution of ferruginous materials, silcretes, soils, saprolite, bedrock, Mesozoic sediments, colluvial-alluvial sediments, lacustrine sediments and black soils (Appendix†1).

Superimposition of the northeast flowing drainage on the predominantly north-striking structural grain of the Proterozoic rocks possibly reflects an early drainage pattern inherited from a post-Palaeozoic cover (Appendix 1). This inherited drainage implies that the Mesozoic cover extended over a very large part, if not all, of the Mt Isa Inlier. Resistant lithologies may have protruded as islands surrounded by a Mesozoic sea. The inherited drainage pattern probably developed after emergence of the Mesozoic sediments in the Late Cretaceous, as the palaeo-coastline retreated to the north-east. Only larger streams have been superimposed on the Proterozoic rocks; minor streams are structurally controlled by this basement. In places, streams flowing to the west and northeast might have been captured and diverted to the north as more youthful, northerly drainages eroded the landscape. Much of the soft, Mesozoic sediments had been eroded by the end of the Cretaceous, uncovering the basement to form the Mt Isa inlier. Mesozoic rocks are now restricted to the edges of the exposed basement, and occur as patchy outliers, mesas or valley infills.

3.5.2 Geomorphic provinces

The topography of the region is dominated by a central spine of hills flanked by a series of rolling, undulating and flat plains, together with isolated mesas. For convenience, three broad geomorphic subdivisions are recognised (Figure 5), the nature and regolith characteristics of which are shown in block diagrams (Figures 6-7). These are:

1. Hill Belts.

2. Complex of mesas and plains: these are developed both on Proterozoic basement rocks and on Mesozoic sediments. On the basis of their dominant geology, these can be further subdivided into:
   (a) Mesas and plains largely on Proterozoic bedrocks.
   (b) Mesas and plains largely on Mesozoic sediments.

3. Plains: On the basis of topography, these can be further subdivided into:
   (a) Gently sloping plains.
   (b) Undulating to rolling plains.
   (c) Flat plains.

3.5.2.1 Hill Belts

The hill belts occupy the central portion of the region (Appendix 1, Figure 5). They comprise deeply incised country consisting of predominantly north-trending ridges and hills which exceed 520 m in places, but which average between 320 m and 480 m amsl (Figure 10A). There are some small plateau remnants that have a marked concordance of crests.

The hill belts consist of Proterozoic metamorphic and igneous rocks of the Cloncurry complex (granite, quartzite, gneiss, schist, amphibolite, limestone and shale). The geological complexity is reflected in the landforms; there was no complete prior 'planation' and, instead of a single summit level for the duricrust capped plain, there is a complexity of upland forms, including ridges with a variable degree of bevelling and variously dissected plateaux. The detailed sculpture of the landsurface is intimately related to differential weathering and erosion of the various rock types. Quartzite, for instance, forms upstanding masses; granite and limestone each have developed a characteristic suite of landforms; siltstone and claystone tend to offer little resistance and are eroded relatively easily to form lowlands and valleys.

Mesozoic sediments are sporadically distributed, but are most common in the Cloncurry district. They rest unconformably on the Proterozoic rocks and give rise to small, isolated mesas that protrude above a generally flat skyline (Figure 10B). North of Mt Isa, the most common Mesozoic land forms are long, flat ridges and plateau remnants topped by low mesas. Twidale (1966) refers to this area as a "narrowly dissected plateau". The plateau surfaces are best preserved on resistant quartzitic rocks and bevel various Proterozoic strata. In places it is silicified and ferruginous gravels occur in depressions. This was observed in number of localities north west of Mt Isa. Twidale (1966) observed that, where the plateau has been dissected, the hill slopes have steep upper bluffs and straight debris slopes. Not all slope units are present everywhere and there is considerable variation in the relative development of units.

South and southeast of Mt Isa, there are areas dominated by outcrops of less resistant rocks such as granite, shale, amphibolite and gneiss. Here, there are no remnants of the plateau and the only sign of its previous existence is concordance of hill and ridge crests. Valleys are more extensive, pediments are common, and steeply sloping, coalescent rocky plains occur in many localities, for example along the Cloncurry-Duchess road. Twidale (1966) refers to these as "areas of more advanced dissection". However, not all the rocks are fresh and many have signs of former and present weathering that involves formation of kaolinite, smectite and pedogenic carbonates. Zones of superficial, secondary silicification are marked; kaolinisation and calcification of basalt, schist, amphibolite and siltstone have taken place and the weathered rock is generally Fe stained. Weathered rocks are also mantled by a thin veneer of skeletal, calcareous to non-calcareous soils that support sparse woodland and spinifex. It would appear that a large part of the upper, lateritic weathering profile has been stripped from the weathered surface. Evidence for their former presence being the occurrence of lateritic materials in colluvium. These features were observed along the 260 km AGSO/AGCRC Seismic line (Drummond, 1996) which passes through the hill belts of Proterozoic assemblages while overlapping on the east and west onto the more recent sediments of the Eromanga and Georgina basins (Appendix 1).

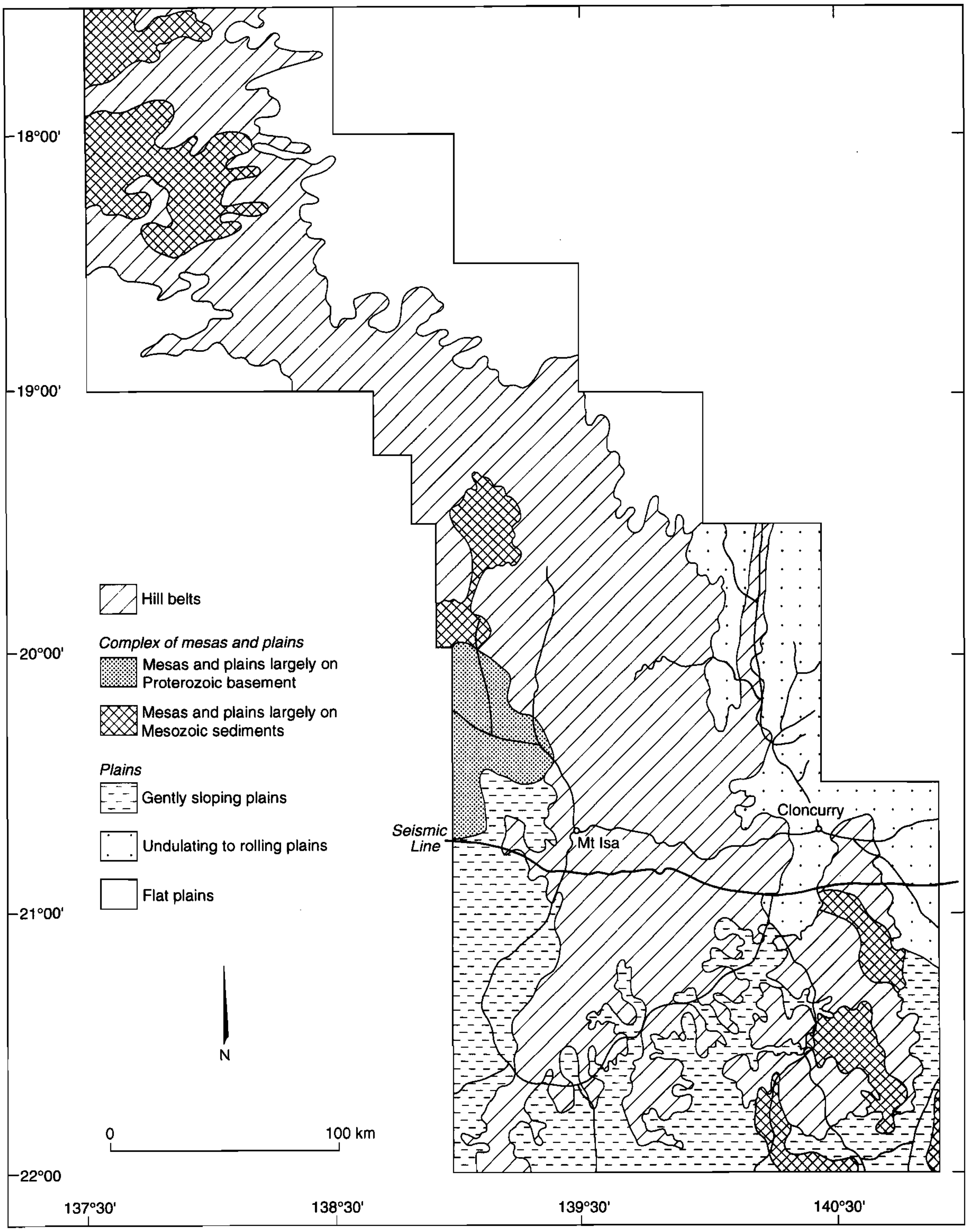


Figure 5. Generalised geomorphic provinces of the Mt Isa region.

Weathering profiles along the Seismic Line

Australian Geological Survey Organisation recorded a 260 km seismic reflection profile, oriented approximately east-west and centred some 25 km to the S of Mt Isa (Figure 5). The Seismic Line consisted of 1200 drillholes spaced at 240 m intervals along the entire length of the transect. The profiles selected for detailed examination are located in lower and midslopes of hills (195-429m amsl) and are developed over mafic schist, schist, schistose mudstone, basalt, metasediments, granite and siltstone. The profiles shown in Figure 8 are representative of the regolith developed on these lithologies along the seismic line.

In general, the regolith thickens away from the hills, but there is no strict correlation between surface elevation and thickness of regolith. The degree of truncation increases with relief and it is also dependent on bedrock lithology, so that even where the relief is low, saprolite is adjacent to almost unweathered rocks of contrasting lithology. The weathered profiles consist of saprock and saprolite with some mottled saprolite horizons; the profiles range in thickness from 5-40 m and are overlain by variable thicknesses of residual soil and locally derived colluvium (Figure 8 A-G). The upper part of the saprolite is generally silicified. Lateritic duricrust and mottled zone are absent.

The colluvium is generally less than one metre thick but may be up to 12 m in places. It is derived from erosion of older lateritic profiles and contains transported lateritic nodules and pisoliths, quartz, gravel, sand and rock fragments in a clayey matrix that has been transported by creep down slope.

Schist, siltstone, metasediments and granite are composed of variable amounts of feldspar, quartz and mica; mafic schist and basalt also contain amphiboles. Over mafic schist and basalt, amphiboles have been altered to smectite and mixed layer clays and feldspar has weathered to kaolinite. Weathering of mafic schist and basalt has not been intense, as shown by abundance of primary minerals in saprolite. However, the upper saprolite is extremely calcareous and largely consists largely of calcite and dolomite, with moderate amounts of quartz, smectite and mixed layer minerals. Calcite and dolomite decrease in abundance in the surface soil, whereas quartz and amphiboles increase. It is possible that the upper soil horizons have been leached of Ca, which has been redeposited in a lower horizon. Carbonates are finely dispersed in the soil matrix and also are present as coatings and nodules.

Siltstone-derived saprolite consists of quartz, kaolinite and mica with variable amounts of goethite. Generally, the upper saprolite is variably mottled and dominated by goethite. Pedogenic carbonates are absent. Distribution of carbonate is controlled by abundances of Ca and Mg in the parent rock. Carbonates are more abundant on mafic schist than over schistose mudstone and are absent in regolith derived from Ca-poor rocks, such as schist and siltstone. Dolomite is only present over mafic schist and granite. It was not detected in other profiles. The dominance of calcite, dolomite and smectite in saprolite and soils suggest that they have formed in an environment of slow drainage and mild leaching, which are characteristic of the semi-arid climate in which they now occur.

The major and trace element compositions of profiles developed on mafic schist, schist, schistose mudstone, basalt, calcareous metasediment, granite and siltstone are shown in Figure 9. The mineralogical data are consistent with the chemical composition, which suggests that there has been no major gains or losses of elements except Ca and Mg. The Ca contents increase from the rock or saprolite to the upper saprolite and this correlates with losses of Si, Al, Na, Mg and K. The zone of accumulation of Ca indicate a reactive zone; the lower part of the saprolite is not chemically inert. Most of the mass loss from this zone is due to leaching of Si, Al, Na and K.

Mafic schist, basalt and schistose mudstone have greater Fe, Mg, Mn, Zn and Ni contents compared to schist, calcareous metasediment, granite and siltstone. The higher concentrations of Mg and Fe are attributed to amphiboles.

Figure 6. Block diagrams showing nature of landscape-regolith of geomorphic provinces.

LEGENDS

Hill Belts

1. Flat topped Proterozoic hills.
2. Granite hills.
3. Amphibolite hills.
4. Quartzite hills.
5. Schist and gneiss *hill belt* with crests at similar levels.
6. Lithosols, red clay and colluvium, saprock and saprolite.
7. Colluvium and alluvium.

Mesas and plains largely on Proterozoic bedrocks

1. Mesas and associated backslopes; lag of lateritic nodules, pisoliths and fragments of ferruginous saprolite overlying lateritic duricrust and/or ferruginous saprolite on Fe-rich lithologies (dolomitic siltstone, shale, basalts) and silcrete on siliceous lithologies. In places, silcrete and lateritic duricrust are developed on remnant of Mesozoic sediments.
2. Rises and associated backslopes; lateritic nodules and pisoliths, mottled zone or ferruginous saprolite overlying saprolite.
3. Erosional plains; gravelly soils overlying mottled zone or upper saprolite.
4. Pediments; mixed lag of lateritic nodules, fragments of ferruginous saprolite and lithic fragments derived from erosion of mesas, minor gravelly colluvium (< 1m thick), residual soils overlying saprolite or saprock.
5. Depositional plains; ferruginous sheet wash gravels, alluvium (1-5 m thick) overlying ferruginous or silicified saprolite.
6. Alluvial clays, minor gilgai, saprock, bedrock.
7. Lithosols overlying saprock or bedrock.

Mesas and plains largely on Mesozoic sediments

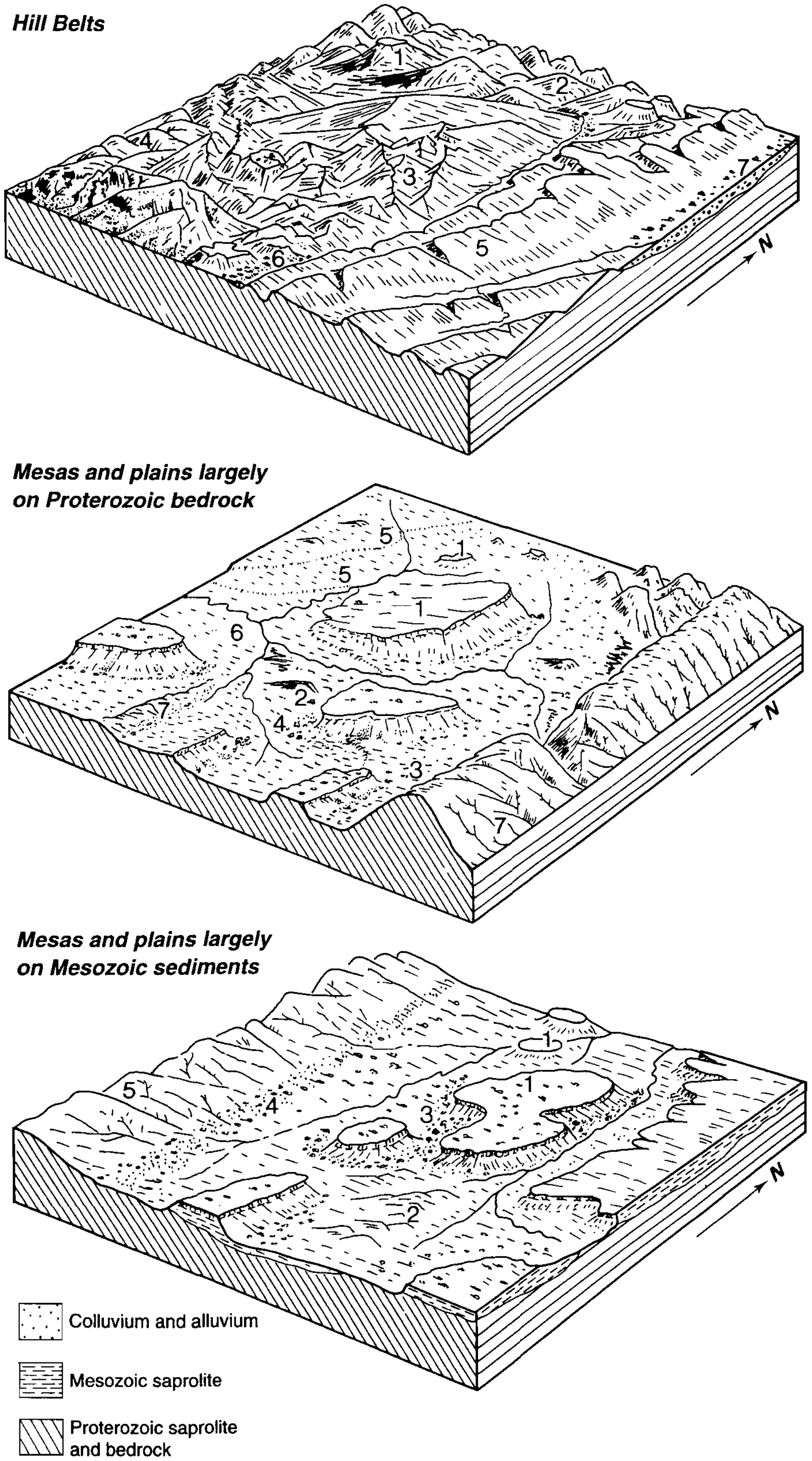
1. Mesas; lag of lateritic nodules and pisoliths overlying lateritic duricrust and/or mottled zone, silcrete on Mesozoic claystone.

2. Rises and low hills; remnant of Mesozoic *silicified* saprolite.

3. Erosional plains; lag of mottles and silicified saprolite, colluvium and alluvium overlying Mesozoic and /or Proterozoic saprolite, in places colluvium and alluvium ferruginised.

4. Lithosols and colluvium overlying Proterozoic bedrock.

5. Proterozoic bedrock hills.


Hill Belts
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Mesas and plains largely on Proterozoic bedrock
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Mesas and plains largely on Mesozoic sediments
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Colluvium and alluvium
Mesozoic saprolite
Proterozoic saprolite and bedrock

Figure 7. Block diagrams showing nature of landscape and regolith of geomorphic provinces.

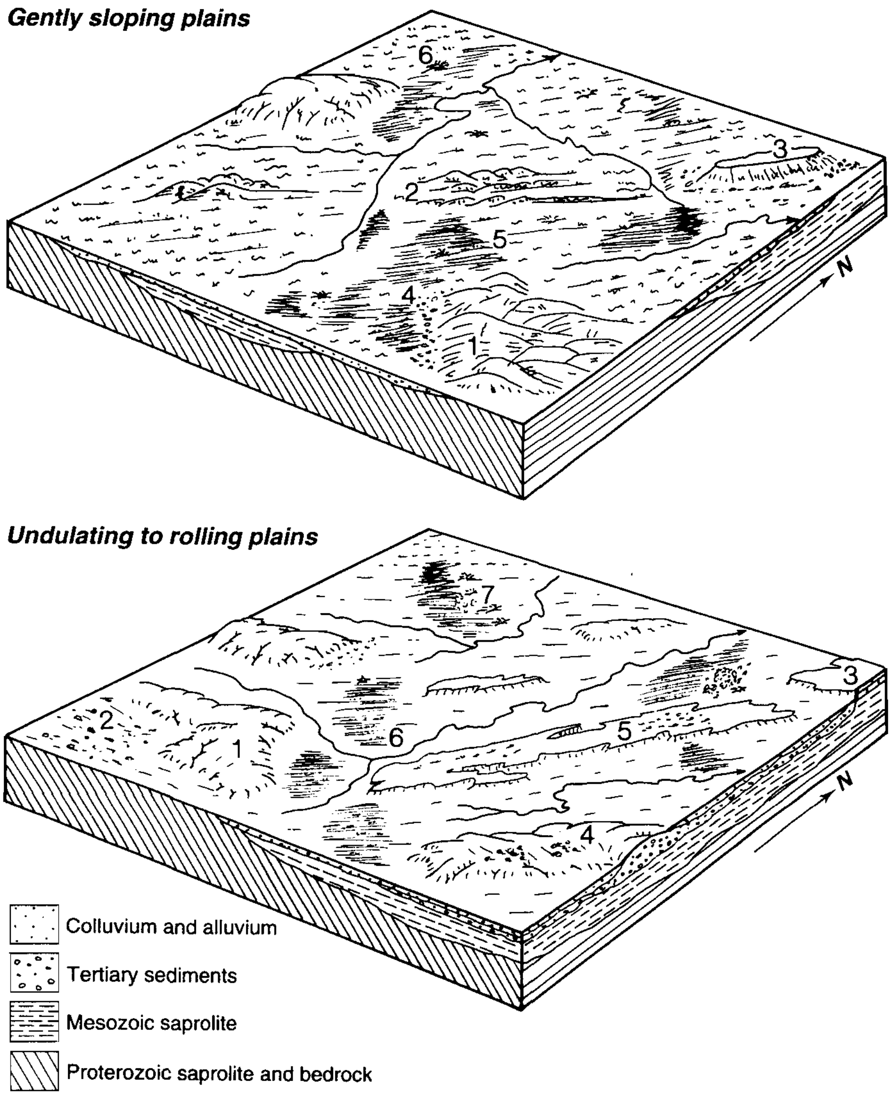
LEGENDS

Gently sloping plains

1. Proterozoic weathered to fresh bedrock hills, in places with remnants of thin cover of duricrust capped Mesozoic sediments.
2. Rise; remnants of Mesozoic silicified saprolite/saprock.
3. Mesa; Mega-mottled zone developed on Mesozoic sediments.
4. Lithosols and colluvium overlying saprock or bedrock.
5. Black soil on alluvium.
6. Gilgai.

Undulating to rolling plains

1. Proterozoic weathered to fresh bedrock hills.
2. Lithosols and colluvium overlying Proterozoic bedrock.
3. Mesozoic limestone capped hill.
4. Tertiary fluvial ridge with rounded gravel lags, brown soil and mottled sediments.
5. River terrace with brown to red soil, mottled Tertiary sediments and patches of lag of rounded gravels.
6. Black soil on recent and Tertiary sediments.
7. Gilgai.


Gently sloping plains
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Undulating to rolling plains
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Colluvium and alluvium
Tertiary sediments
Mesozoic saprolite
Proterozoic saprolite and bedrock

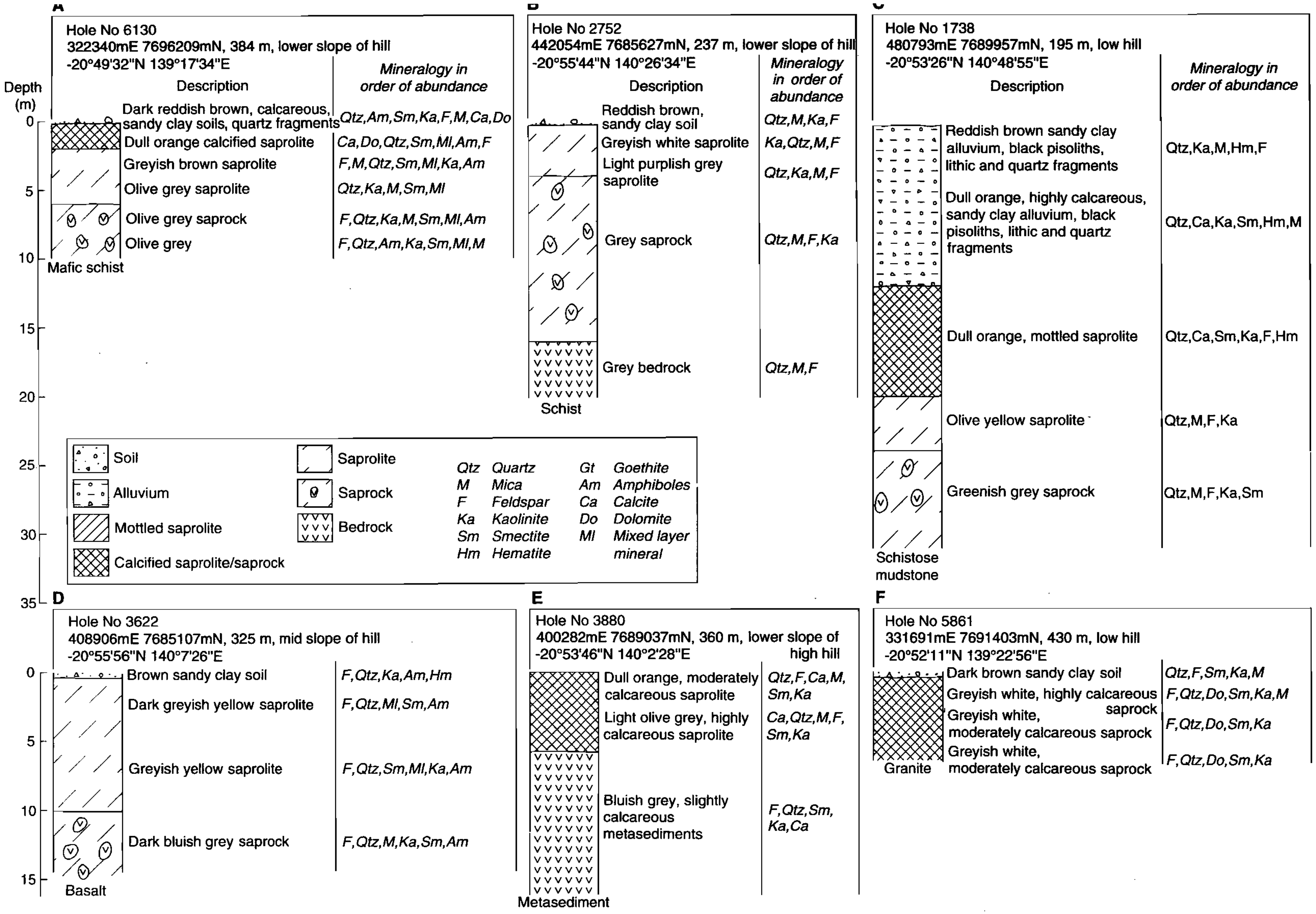

Figure 8. **Nature and characteristics of selected weathering profiles along the Seismic Line. Seismic line passes through the hill belts and plains.**

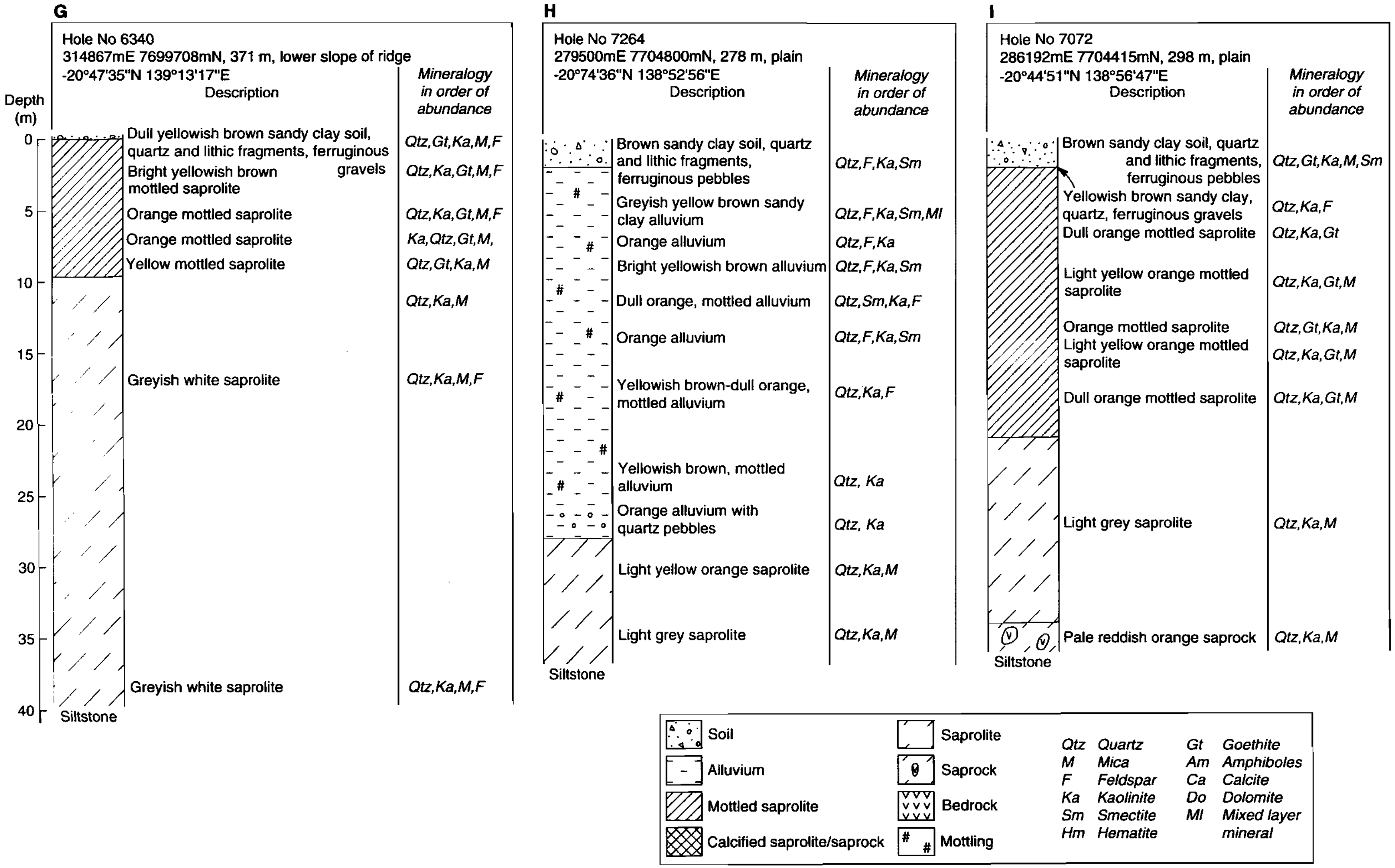

Figure 8. Continued

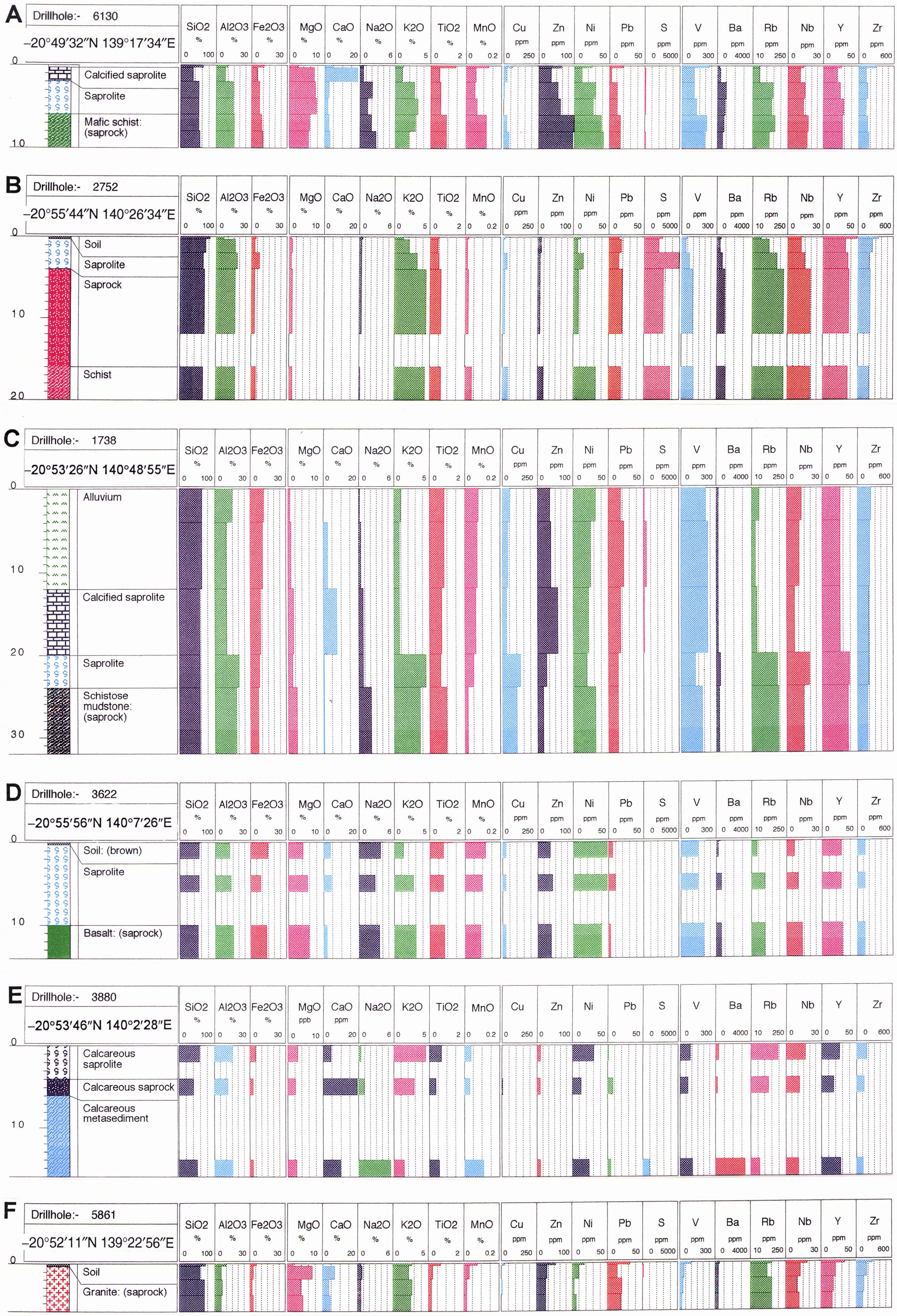

Figure 9. Geochemistry of selected weathering profiles along the seismic line.

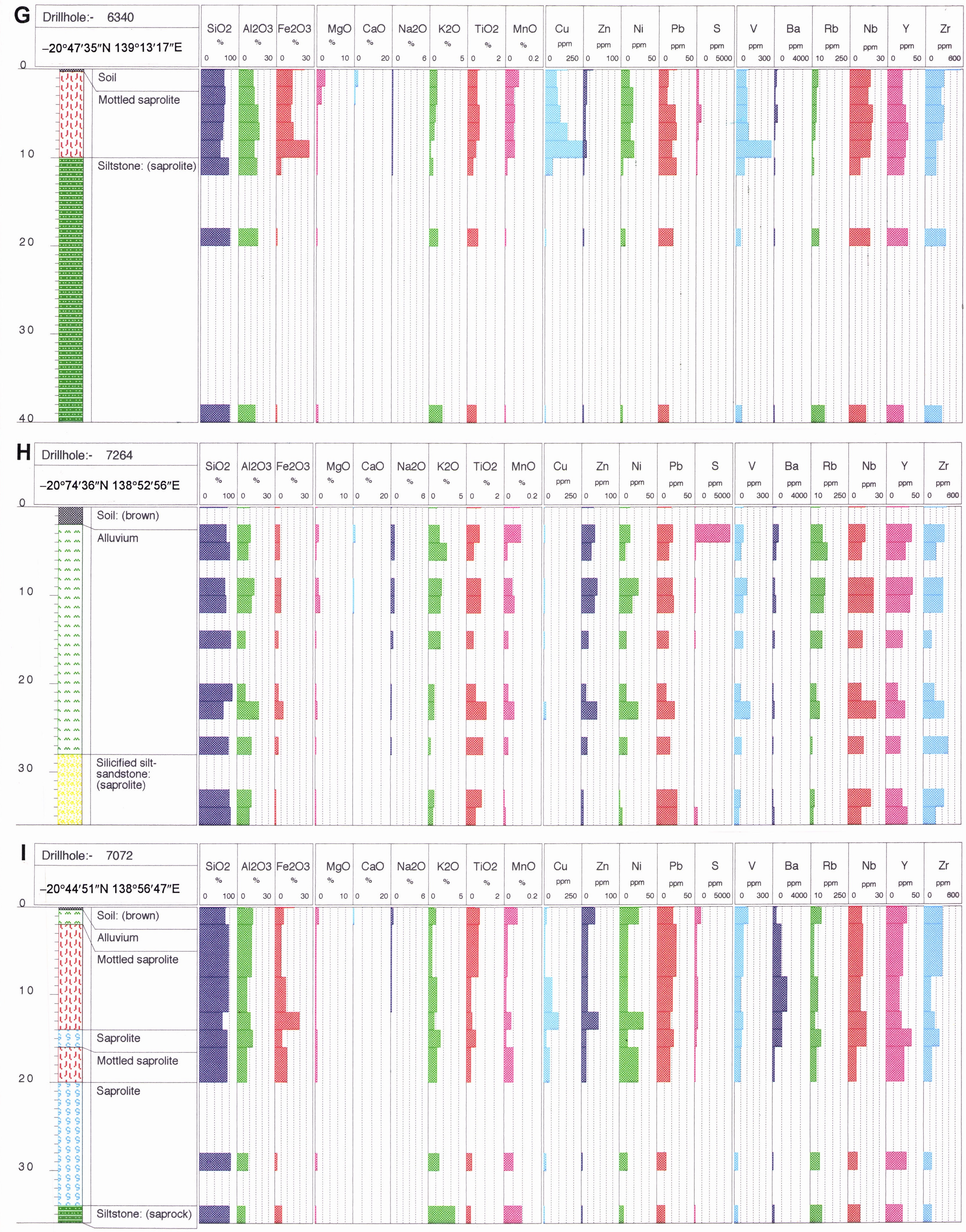

Figure 9. Continued...

Figure 10. Geomorphic provinces, landscapes and regolith materials.

(A, B) Hill Belts

(A) Hill Belts, here pictured around Selwyn showing the characteristic irregular terrain. Little of the erosional plateau surface remains. Location: 441810mE - 7590409mN.

(B) The dissected parts of the hill belts, some 30 km south of Cloncurry, showing the irregular relief and small plateau remnants as mesa form hills. Towards the foreground, a silcrete capped mesa on Mesozoic sediments emerges above the hills on Proterozoic bedrocks. Location: 459000mE - 7684000mN.

(C-F) Mesas and plains developed on Proterozoic bedrocks. Well-developed lateritic weathering profiles on mesas and, shallow profiles on pediments and erosional plains.

(C) Mesa crest with pockets of goethite-rich slabby duricrust (1) and lateritic nodules (2) underlain by indurated ferruginous saprolite. A lag of lateritic nodules is derived from the breakdown of ferruginous saprolite. The pediments (3) below, have a lag of ferruginous gravels and a shallow soil on saprolite; and quartz vein (4). Location: 324605mE - 7755409mN, Buckley River-Grey Ghost district.

(D) Eroded flanks of a mesa showing details of a weathering profile developed on dolomitic siltstone (in Figure C). The breakaway gives way to a steep debris slope below. Slabby duricrust (1), ferruginous saprolite (2) and saprolite (3) are present on the face. Coarse lag of duricrust and ferruginous saprolite are on gently inclined pediments (4). Location: 307251mE - 7756167mN.

(E) A major breakaway capped by massive silcrete (1) and silicified saprolite (2) developed on siltstone. Location: 306110mE - 7794280mN, Mammoth Mines district.

(F) Rise and associated backslope mantled with hematite-rich lateritic nodules overlying mottled zone. Location: 308170mE - 7747656mN, Buckley River-Grey Ghost district.


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3.5.2.2 *Complex of mesas and plains*

(a) Mesas and plains largely on Proterozoic basement. The areas show signs of the variable extent of former lateritic weathering and can be considered as a dissected plateau of which the original surface forms a significant component of the landscape of mesas and plains (Figure 6 and 10C-F). Where denudation is advanced, pediments and erosional plains occur between plateau remnants. Ridges, flanked by steep slopes, rise above the crest of these relics and expose fresh to slightly weathered rock. This unit occupies part of the Western Succession (Figure 5).

Mesas

The mesas are flat to gently sloping, commonly reaching 20-30 m above their surroundings, up to 2 km wide and separated by pediments and erosional plains. Mesas range in elevation from 350 to 410 m amsl. They are characterised by deep lateritic profiles with ferruginous cappings; some such relics on siliceous Proterozoic bedrocks have silcrete caps and appear to have developed instead of a ferruginous horizon (Figure 10E). Such cappings are common and are generally underlain by well-developed, thick saprolite. The margins of duricrust-capped hills generally have sharp scarps capped by lateritic duricrust or silcrete. A very good example of this is the Buckley River plateau remnants, which have a slabby duricrust capping the breakaway, breached by erosion (Figure 10D).

Ferruginous and siliceous duricrusts have formed mainly in residual regolith but, locally, they have incorporated superficial deposits that are typically gritty, with scattered quartz pebbles. In places, these duricrusts have developed on remnants of basal units of Mesozoic sediments, now generally less than two metres thick, overlying weathered Proterozoic bedrock (*e.g.*, Lady Loretta area and Grey Ghost). Although duricrust capped-mesas have been recognised to be of possible Mesozoic age (Twidale 1966), these remnant landsurfaces have a variety of lateritic materials of different characteristics. Lateritic duricrust occurs only as pockets, commonly as massive, slabby, nodular and conglomeratic duricrusts (Figure 11C-F and 19B,C). There is no evidence to suggest that a thick sheet of lateritic duricrust ever developed. Instead, ferruginous saprolite and mottled zones are the most common uppermost ferruginous horizons, developed on ferruginous lithologies such as Fe-rich shales and basalt (Figure 11A,B and 19A). Lateritic nodules commonly occur as lag or as a thin gravelly unit on these surfaces (Figure 10F and 19D). These are derived from ferruginous units in the weathering profile such as continuous sheets of ferruginous saprolite or mottles in a clay zone or locally derived colluvium.

The massive and slabby duricrusts on the mesas are characterised by a variable Fe oxide mineralogy. Massive duricrusts vary from 0.2-2.0 m in thickness and occur as massive sheets or as pods, generally underlain by ferruginous saprolite. They may be either goethite-rich or hematite-rich (Figure 13). The latter may be older, because the presence of hematite generally reflects ageing of the Fe oxides. Alternatively, it may reflect warmer conditions during formation. Massive duricrusts are characterised by high concentrations of Fe_2O_3 (55.3% median) and low concentrations of Al_2O_3 (6.7% median) and SiO_2 (25.8% median) (Table 1). Alkali and alkaline earths are strongly depleted. However, there is a large range in the concentrations of several trace elements that may indicate the lithology and the degree of ferruginisation of saprolite (V, Ni, Ni, Zr, Cu, Zn). The median abundances of Cu, Zn and Pb are 76, 27 and 13 ppm, respectively.

Slabby duricrust is 1-2 m thick and is composed of massive, horizontally arranged plates that generally grade into ferruginous saprolite at depth (Figure 11D). Microscopic examination show these duricrusts are quartz-rich and are impregnated by Fe oxides. They occur at plateau margins, where laterally moving groundwater nears the surface, leading to precipitation and oxidation of dissolved Fe. The duricrust is reddish brown to black, non-magnetic, rich in Fe_2O_3 (61.7%) and is dominated by goethite with variable amounts of quartz (Figure 13). Hematite is generally absent. Higher concentrations of Cu and P_2O_5 are associated with slabby duricrusts than massive duricrusts, but the median abundances of Zn (15 ppm) and Pb (35 ppm) are low compared to massive duricrusts.

Table 1. Chemical composition - massive duricrust on Proterozoic bedrocks.

		Mean	Count	Minimum	Maximum	Median
SiO2	%	29.4	36	5.7	81.2	25.8
Al2O3	%	7.5	36	2.3	16.3	6.7
Fe2O3	%	53.4	36	14.5	75.8	55.4
MgO	%	0.22	36	0.04	0.58	0.18
CaO	%	0.08	36	0.01	1	0.04
Na2O	%	0.03	36	0.01	0.23	0.01
K2O	%	0.64	36	0.06	2.63	0.52
TiO2	%	0.54	36	0.09	5.18	0.31
P2O5	%	0.36	36	0.04	1.22	0.24
MnO	%	0.05	36	0.01	0.26	0.02
loi	%	7.8	36	1.3	12.0	8.3
Ba	ppm	238	36	10	1670	116
Ce	ppm	62	36	13	132	57
Cl	ppm	153	36	10	2020	10
Cr	ppm	84	36	1	232	66
Co	ppm	18	36	1	220	3
Cu	ppm	237	36	1	1198	76
Ga	ppm	10	36	1	31	10
La	ppm	18	36	1	69	10
Ni	ppm	22	36	1	199	12
Nb	ppm	2	36	1	41	1
Pb	ppm	19	36	1	111	13
Rb	ppm	30	36	1	169	24
S	ppm	527	36	90	2070	440
Sr	ppm	25	35	5	193	15
V	ppm	475	36	31	6123	182
Y	ppm	20	36	4	61	18
Zn	ppm	91	36	1	708	27
Zr	ppm	149	36	29	776	127

Conglomeratic duricrusts are developed on the basal gravels of Mesozoic sediments which are generally underlain by saprolite of Proterozoic bedrock (Figure 11F).

The characteristic Fe-rich composition of lateritic duricrusts is the result of either or both of two processes: (1) relative concentration of Fe and Al by removal of Si and bases and landscape lowering; or (2) concentration of these elements by absolute accumulation from outside sources. Those duricrusts formed by laterally accumulated Fe were originally formed in valleys, and the topography has since been inverted. Thus, their evolution has been complex.

Plains

The plains include both erosional and depositional plains. Erosional plains show a variable degree of erosion of weathered profiles, greatest on pediments. Pediments occur at the foot of the breakaway and are characterised by residual soil and minor colluvium overlying saprolite or bedrock (Figure 6 and 10C,D). The lag is typically a mixture of ferruginous and lithic fragments derived from erosion of the plateau remnants. Those erosional plains that are topographically higher than the pediments show minimum or no truncation and are mantled with ferruginous, gravelly soils over mottled zones and upper saprolite. The erosional plains merge laterally with depositional plains which are characterised by low relief but have few small outcrops of silcrete and ferruginous saprolite (Figure 6). They are extensive northeast of Buckley River and are part of an old surface.

Figure 11. Ferruginous materials on plateau remnants.

(A) Indurated ferruginous saprolite (2) on an erosional escarpment. Removal of kaolinitic matrix has led to its collapse (collapsed ferruginous saprolite) (1). Ferruginous saprolite is most common ferruginous material developed on Fe-rich Proterozoic bedrocks and is generally underlain by saprolite. Location: 325510mE - 7749247mN, Buckley River-Grey Ghost district.

(B) Mottled zone consists of hematite-rich mottles (1) in a kaolinite-rich matrix (2) exposed in a road cutting through a rise. Red, gravelly unit (collapsed mottles) overlying mottled zone is result of removal of kaolinitic matrix from the mottled zone. Location: 320935E - 7745907N, Buckley River-Grey Ghost district.

(C) Massive duricrust developed from weathering of Proterozoic bedrock on a mesa. Location: 307750mE - 7774589mN, Buckley River-Grey Ghost district.

(D) Goethite-rich duricrust with a general slabby appearance, underlain by ferruginous saprolite, on plateau margins. Location: 303465mE - 7759071mN, Buckley River-Grey Ghost district.

(E) Massive duricrust on Mesozoic sandstone. Location: 298051mE - 7827000mN, Mammoth Mines district.

(F) Conglomeratic duricrust developed on basal gravels of Mesozoic sediments. Here, conglomeratic duricrust is underlain by ferruginous saprolite (not shown) which is developed from weathering of underlying shale. Location: 296959mE - 7813425mN, Mammoth Mines district.

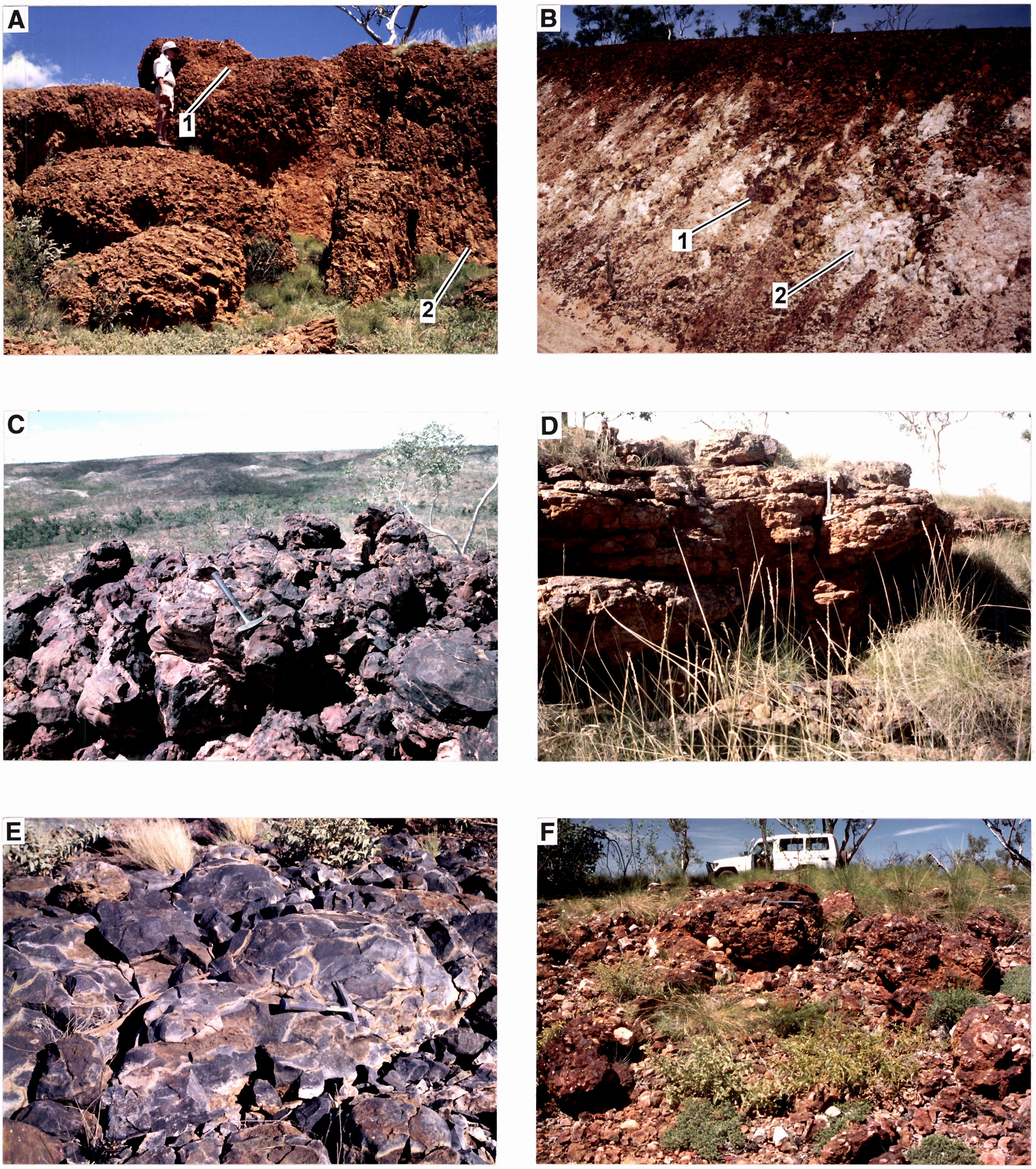
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Figure 12. Landscapes, regolith materials and profiles.

(A) Eroded flanks of a plateau remnant having a cap of mottled silcrete that is underlain by silicified saprolite on Mesozoic claystone (1); and ferruginous, siliceous fragments covering pediments and erosional plains are underlain by a shallow soil developed on saprolite (2). Location: 476170mE - 7588120mN, Tringadee district.

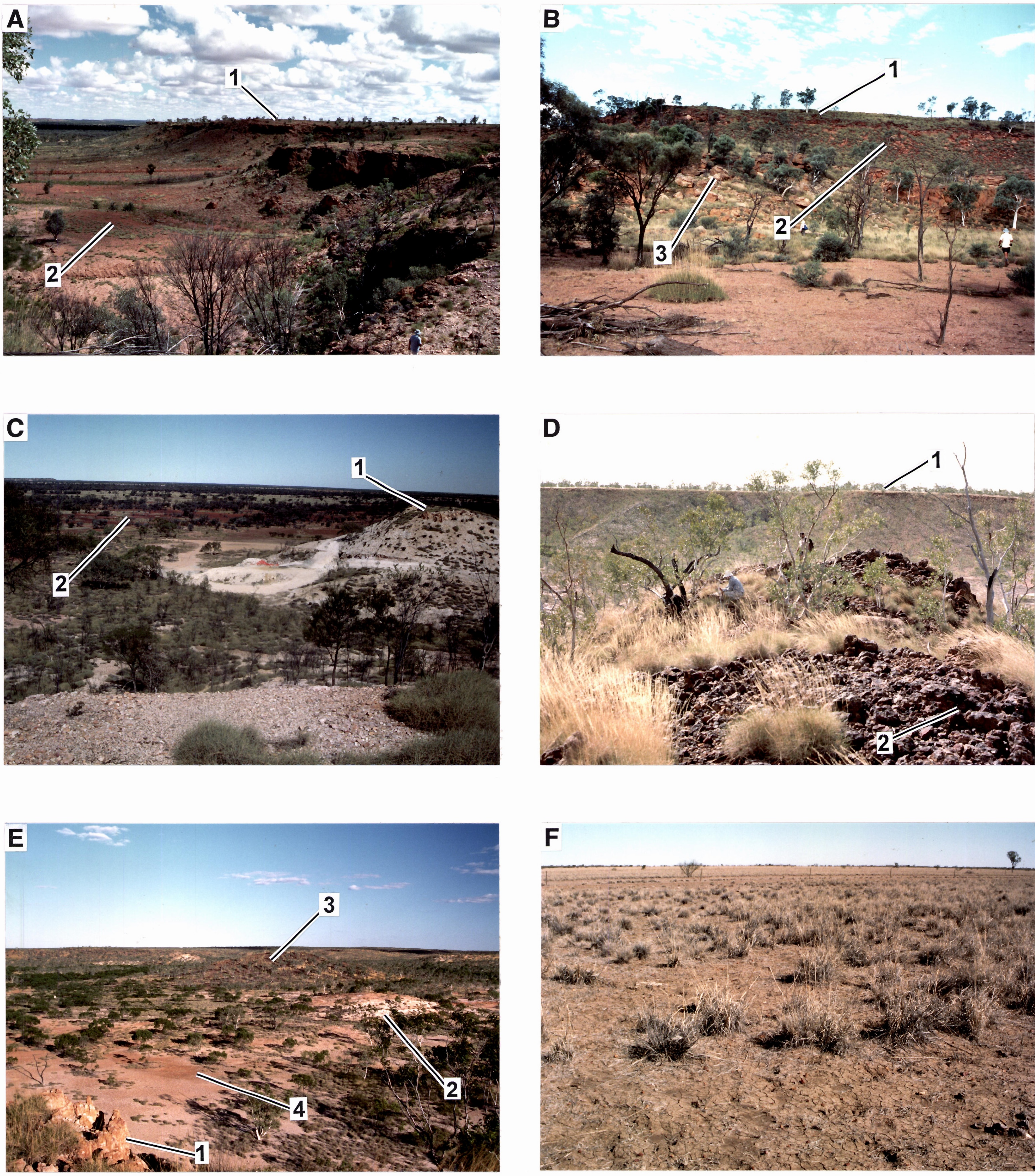
(B) Deep weathering profile developed on Mesozoic sediments overlying granite. The profile consists of lateritic nodules overlying siliceous massive duricrust (1), mottled zone and mottled saprolite (2). The weathered underlying granite retains its original structures (3), with the primary minerals weather to kaolinite and goethite. Location: 448250mE - 7627911mN, Selwyn district.

(C) The landscape shows variable degree of erosion of Mesozoic sediments. Mesas are capped by silcrete and silicified saprolite (1); and erosional plains mantled with siliceous, ferruginous gravels overlying thick Mesozoic saprolite. Ferruginous bands and veins are common in Mesozoic sediments and contribute to ferruginous lag on plains. Location: 475236mE - 7584566mN, Tringadee district.

(D) Well developed massive columnar silcrete developed on remnant of Mesozoic sediments on plateau remnant (1); and massive duricrust overlying Proterozoic saprock on mesa (2). Massive duricrust is formed by lateral accumulation of iron. Location: 309581mE - 7777178mN, Buckley River-Grey Ghost district.

(E) A landscape showing the variable degrees of erosion of Mesozoic sediments and development of ferruginous saprolite on Proterozoic bedrock. Massive-columnar silcrete on Mesozoic sediments (1); silicified saprolite on Mesozoic sediments (2); ferruginous saprolite underlain by Proterozoic saprolite (3); and ferruginous-siliceous lag covered erosional plains (4). These relationships also suggest substantial pre-Mesozoic relief. Location: 308291mE - 7777163mN, Buckley River-Grey Ghost district.

(F) Rolling plains covered with brown and black soils. Location: 497564mE - 7683063mN, Eloise-Maronan district.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Lateritic duricrust is not evident on these plains but lateritic nodules, mottles and ferruginous or silicified saprolite are common beneath a variable thicknesses (1-5 m) of alluvium. It is not certain whether the nodules are developed within locally derived alluvium or by weathering of Proterozoic bedrock. Red earths, developed in alluvium, commonly contain ferruginous and lithic fragments and some are silicified. Lag of ferruginous gravels and silicified fragments is common, possibly derived from erosion of nearby duricrust-capped low hills (Figure 19E).

(b) Mesas and plains largely on Mesozoic sediments. Uplands, comprising mesaform hills and intervening plains with some rocky ridges, are common in the south east and north west part of the region (Figure 5). Mesas and plains are common over Mesozoic sediments, whereas rocky ridges are typical of Proterozoic bedrock (Figure 6). Weathering profiles are common on mesas and their nature is largely controlled by bedrock composition; more deeply weathered profiles are developed on claystones and siltstones than on sandstones, for example at Tringadee and Selwyn where ferruginous duricrust and silcrete cappings have preserved plateaux on the Mesozoic sediments (Figure 12A-C).

In areas of flat-lying Mesozoic sediments, there is a local relief of 100 m or more. The thickness of the sediments is variable with a maximum of at least 50 m. The underlying Proterozoic rocks are weathered, for example south of Selwyn (Figure 12B). The irregular thickness of the Mesozoic sediments and the undulating basal unconformity with the Proterozoic rocks are best explained by sedimentation infilling valleys. This is not unexpected; the Proterozoic rocks have weathered differentially due to their heterogeneity (*e.g.*, shale and quartzite). In consequence, the post-depositional lateritised surface formed across the intervening, sediment-filled valleys, as is shown by its occurrence at Drifter, Selwyn and Tringadee.

The lateritised top of the Mesozoic sediments occur at several levels. Lateritised tops generally occur lower than on adjoining areas of Proterozoic rocks but, in some places, they rise to the same elevation as that of closely adjacent areas of lateritised Proterozoic rocks.

The differences in elevation of the lateritised surface suggests that the original erosion surface had significant relief, the lower areas on the Mesozoic sediments being the result of differential erosion of these softer rocks. The absence of significant weathering on the highest hills also indicates that the lateritised surface must have been somewhat higher and has since been removed by erosion. This also indicates that the landscape during weathering had a varying relief.

Lateritic duricrusts developed on Mesozoic sediments are massive to mottled (Figure 11E). The massive duricrusts are reddish brown to black and are dominated by hematite and goethite; some are mainly goethite (Figure 13). It appears that Fe accumulation has resulted from lateral movement of groundwaters from surrounding higher areas of more ferruginous Proterozoic bedrocks.

Comparison of the major element compositions of the duricrusts shows that those on Mesozoic sediments are relatively enriched in Si due to high contents of quartz, whereas duricrusts on Proterozoic bedrock are richer in Fe (Figure 14). The median abundance of Cu is much lower in Mesozoic (9 ppm) than in Proterozoic-derived duricrusts (76 ppm) (Table 2), but there are no significant differences in the abundances of Zn and Pb.

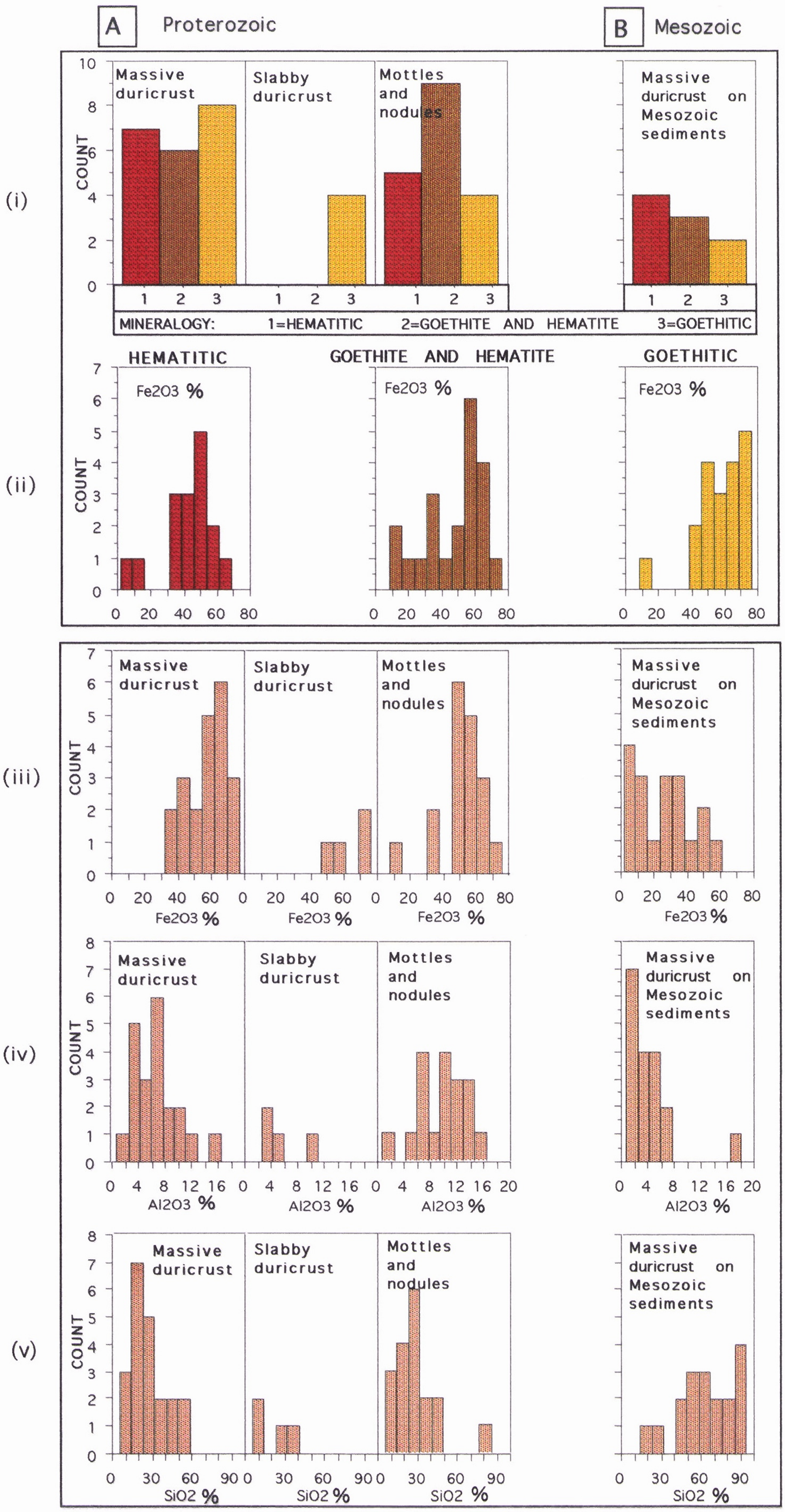

Figure 13. Comparison of Fe-oxide mineralogy and some major elements for several ferruginous sample types from weathering of Proterozoic bedrocks and Mesosoic sediments:
(i) Iron oxide mineralogy of ferruginous samples.
(ii) Fe_2O_3 concentrations of different mineralogical types.
(iii-v) Fe_2O_3, Al_2O_3 and SiO_2 distributions of ferruginous samples.

Table 2. Chemical composition - Lateritic duricrust on Mesozoic sediments.

		Mean	Count	Minimum	Maximum	Median
SiO2	%	64.5	18	22.1	94.1	66.5
Al2O3	%	4.3	18	0.8	18.1	3.5
Fe2O3	%	26.2	18	1.5	59.9	26.6
MgO	%	0.12	18	0.02	0.52	0.09
CaO	%	0.07	18	0.02	0.46	0.04
Na2O	%	0.02	18	0.01	0.10	0.02
K2O	%	0.24	18	0.03	0.73	0.21
TiO2	%	0.57	18	0.05	1.61	0.50
P2O5	%	0.24	18	0.04	1.01	0.15
MnO	%	0.03	18	0.01	0.16	0.01
loi	%	3.8	15	0.9	9.7	3.1
Ba	ppm	390	18	31	2768	248
Ce	ppm	41	18	1	138	39
Cl	ppm	59	18	10	330	10
Cr	ppm	41	18	2	143	24
Co	ppm	10	18	1	52	4
Cu	ppm	375	18	1	4805	9
Ga	ppm	8	18	1	26	5
La	ppm	17	18	1	72	14
Ni	ppm	20	18	3	153	10
Nb	ppm	7	18	1	29	5
Pb	ppm	19	18	1	48	17
Rb	ppm	8	18	1	20	7
S	ppm	379	18	130	860	360
Sr	ppm	30	13	7	79	20
V	ppm	287	18	19	1284	140
Y	ppm	15	18	5	35	13
Zn	ppm	77	18	7	838	27
Zr	ppm	208	18	29	552	162

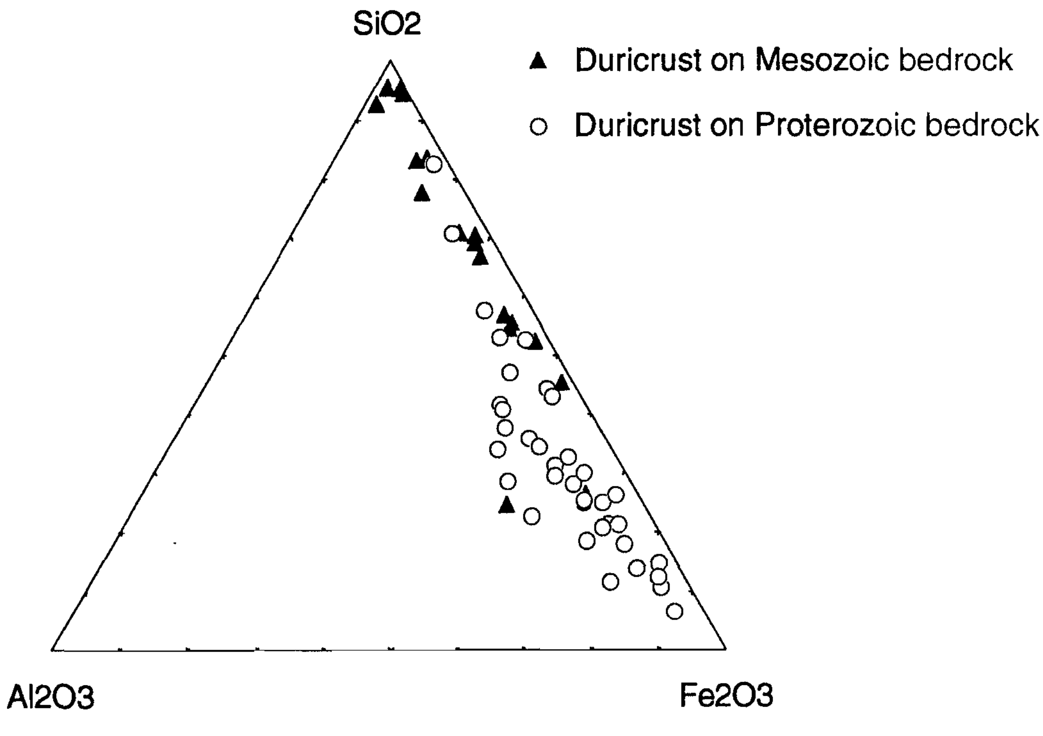

Figure 14. Tertiary diagram showing compositions of duricrusts on Proterozoic and Mesozoic rocks in terms of SiO_2, Al_2O_3 and Fe_2O_3.

3.5.2.3 Plains

(a) Gently sloping plains. These irregular plains are very extensive in the south, southwest and southeast of the mapped area (Figure 5). The stratigraphy of plains has been discussed by Twidale (1966), who refers to them as "inland plains" which drain southwards to Lake Eyre. They lie between 200-300 m amsl, and low hills and ridges are common (Figure 7). Considerable tracts are also occupied by plateaux at two levels. The higher plateaux are capped by Mesozoic sediments, with large megamottles; the lower ones can have almost level summits which bevel Proterozoic bedrocks. This lower summit surface emerges in places from beneath Mesozoic cover and, thus, may be identified as an early Mesozoic landsurface, stripped of sedimentary cover. This is apparent near Tringadee, where thin remnants of Mesozoic sediment occur in several places on weathered granitic rocks.

The plains are occupied by variable thicknesses of colluvium, alluvium and Mesozoic cover. In the Tringadee area, Mesozoic cover on gently sloping plains reaches thicknesses of 50 m or more (Figure 12C). Extensive black soil plains are common in alluvium.

The stratigraphy of the gently sloping plains was observed in drill cuttings on the western end of the Mt Isa Seismic Line (Figure 15). Brown to black soils form a variable (2 to 6 m) horizon above the alluvium. The soil clays contain round quartz pebbles and, less commonly, pebbles of the Cambrian (Beetle Creek Formation?) containing trilobite fossils. Alternating alluvial gravels and sandy clays extend to depths of 15-25 m. The alluvial gravels are predominantly quartz, with lesser chert and Cambrian cobbles and some fine ferruginous granules. Thin bands of laminar grey chert clasts occur within these alluvial deposits. The fine grained alluvium generally has goethitic mottles.

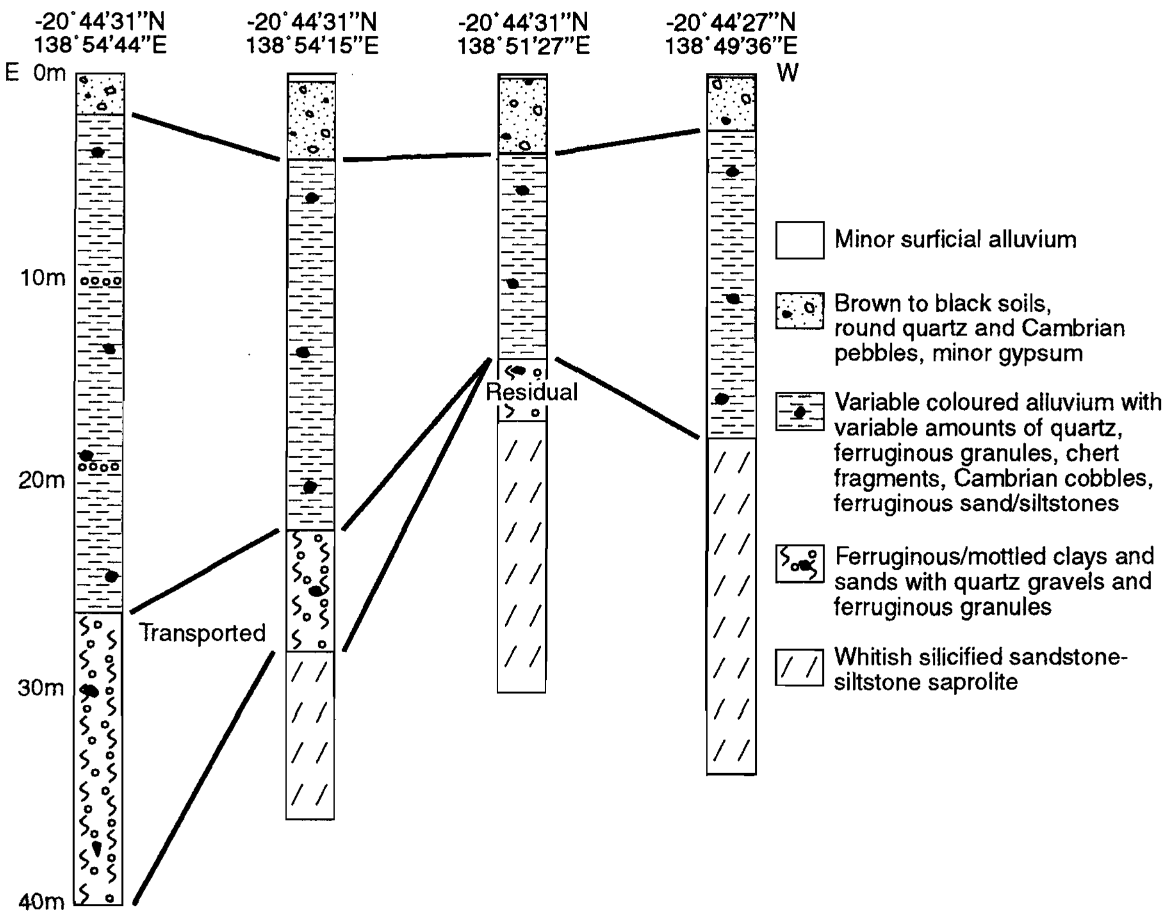

Figure 15. Regolith stratigraphy of gently sloping plains. The stratigraphy of gently sloping plains was established in drill cuttings on the western end of the seismic line.

The alluvial units, in part, contain and are underlain by 2-6 m of variably silicified and ferruginous siltstones and sandstones. These contain fine (2 mm) quartz grains, lesser ferruginous granules and common chert fragments. The lowermost units of bleached, variably silicified siltstones and sandstones extend to depths of 40 m and contain fine quartz gravels and common grey chert bands.

Two profiles with differing thicknesses (2 and 30 m) of alluvium were selected for detailed mineralogical and geochemical examination (Figure 8H,I). One profile consists of a horizon of 2 m of brown, sandy, clay soil overlying 26 m of yellowish brown to orange, mottled alluvium which in turn overlies light grey saprolite. Lenses of quartz pebbles occur at the base of the alluvial unit. The other consists of a shallow soil overlying 18 m of variably coloured mottled saprolite. A zone of grey saprolite occurs at 20 m depth.

There are differences in mineralogy and chemistry between the alluvium and underlying saprolite. The alluvium consists of quartz, kaolinite, feldspar and smectite whereas the saprolite is largely kaolinite, quartz and mica with no feldspars or smectite. This is consistent with the major element composition (Figure 9H,I). Sodium and Mg concentrations are greater in the alluvium than in the saprolite due to the presence of feldspar and smectite respectively. Potassium occurs in both units; as feldspar in the alluvium and mica in saprolite. The concentration of Mn, Cu, Zn and Ni are greater and that of Pb lower in the alluvium than in the saprolite. Copper, Zn and Ni in alluvium are contained in Fe oxides.

(b) Undulating to rolling plains. These plains, which have discontinuous, low hills become more numerous closer to the hill belts (Figure 7 and 12F). These plains extend to the south east, east and north of Cloncurry (Figure 5). Twidale (1966) referred to them as "Carpentaria plains", which drain to the Gulf of Carpentaria. The undulating plains are covered by brown and yellow earths, black clays, skeletal sands and clay loams, developed in Tertiary sediments. Pebbles and cobble-sized gravel, which commonly occur in these soils, are moderately to well rounded and consist dominantly of quartz, rock fragments, cobbles of silcrete and ferruginous pebbles. The ferruginous and silcrete pebbles are presumably derived from the silcrete and ferruginous duricrust-capped plateau remnants. Gravels and cobbles also occur as lag. The sediments are underlain by variable thicknesses of Mesozoic sediments, exposed as remnants of a former extensive cover on Proterozoic bedrocks in southwest Cloncurry.

According to Grimes (1972), some of these plains are remnants of the so-called late Tertiary Kendall surface, which is deeply weathered and ferruginised. He suggested that the sediments formed broad alluvial fans which spread out from the hill belts, across the Cloncurry plains. Their occurrence could indicate either upwarping of the Mt Isa highlands or, possibly, a change of climate to strongly seasonal conditions, which restricted vegetation cover but provided regular floods capable of carrying cobbles across the low gradient of the landsurface. In places, these sediments are being dissected by the current erosional cycle.

The detailed regolith stratigraphy of rolling plains has been established around Eloise. In the drill holes and costeans examined, the Tertiary sediments are less than 5 m thick, and overlie 40-70 m thick, weathered, Mesozoic sandstone and mudstone. A layer of coarse conglomerate about 0.2-3.0 m thick, consisting of fluvial quartz and amphibolite fragments, underlies weathered Mesozoic sandstone and mudstone. The thickness of the coarse conglomerate varies considerably within a short distance. The Mesozoic sediments contain large ammonite fossils, indicting a major marine transgression. A thin layer of limestone, 0.2-2.0 m thick, overlies mudstone and contains abundant reptilian fossils. The thin limestone and the many large limestone concretions suggest that the Mesozoic sea at this time was shallow and regression was rapid.

Development of brown and black soils (1-2 m thick) in the Tertiary sediments is largely dependent on drainage conditions. Brown soils are developed in well-drained environments and black soils in poorly drained places. The Tertiary sediments consist dominantly of kaolinitic clay, rounded and angular pebbles of rock fragments, ferruginous pisoliths and rounded quartz, most probably derived from breakdown of an earlier lateritic profile. The ferruginous pisoliths are detrital. Weathering has caused breakdown of lithic grains and formation of secondary minerals such as smectite and hematite. However, it can not be determined whether the sediments have been weathered to their base or were deposited as kaolinite. Tertiary sediments are strongly mottled but are not capped with duricrust.

(c) Flat plains. These plains rise from about 90 m in the north to about 120 m in south and their flatness is enhanced by predominant grassland vegetation. The relief is due to localised dissection along incised stream channels. Gilgai microrelief covers a large parts of the area. The plain is covered by clay-rich soils which are developed in silts with a variable quartz grit content. The silts and their derived soils are 2-3 m thick (Twidale, 1966).

An extensive black soil plain far to the southwest of Lawn Hill consists of flat to gently undulating, treeless tracts patterned with large-diameter gilgai (Grimes, 1974). The black soil overlies Cambrian dolomite. The surface drainage pattern consists of widely spaced streams that are separated by expanses of black soils without drainage channels; there are few tributaries (Grimes, 1974). Stewart (1954) explains the absence of a close drainage pattern as being due to extremely low relief, intermediate to low rainfall and the permeability of the soils, which become dissected and cracked during the dry season.

REGOLITH-LANDFORM RELATIONSHIPS AND ORIENTATION DISTRICTS

The present regolith and relief includes significant elements of earlier landscapes developed under geological and climatic conditions different from the present. Thus, understanding the present geomorphology requires reconstruction of past events. Several areas (Buckley River, Grey Ghost, Lady Loretta, Drifter, Tringadee, Eloise, Maronan, Selwyn and Little Eva) were selected for regolith and/or geochemical studies. These areas were chosen because they represent examples of geological-geomorphological-regolith associations and typical exploration problems that are common in the Mt Isa region. In each case, the regolith relationships are being studied both in reconnaissance and in detail. This section discusses the main features of some of these areas; the details of some of these will be reported separately. This information has led to development of regolith-landform models which help explain geochemical anomalies. In each chapter, the regolith-landform relationships are described on a regional scale, followed by detailed observations at a number of type sections.

4. BUCKLEY RIVER-GREY GHOST DISTRICT

4.1 Regional Regolith-Landform Relationships

The Buckley River-Grey Ghost regolith-landform map (39x35 km) was compiled using colour aerial photographs at a scale of 1:25,000 and Landsat Thematic Mapper imagery, substantiated by ground traverses. Detailed observations were made at a number of type locations, identified during reconnaissance. The regolith map generated for this area was issued in February, 1995 (Wilford and Anand, 1995) and a reduced version and the regolith-landform relationships are summarised in Figures 16 and 17.

The area forms a part of the geomorphic province, *mesas and plains largely on Proterozoic basements*, described in section 3.5.2.2. It generally has low to moderate relief with a series of remnant plateaux separated by extensive erosional and depositional plains (Figure 16). The topography of the area ranges from 310-520 m amsl. An old lateritised material is not only preserved as plateaux, but also occurs beneath depositional plains, particularly north of Buckley River area (Figure 16 and 17). The degree of dissection is minimal in the western portion, but becomes more extensive in the north-east (Grey Ghost), where it comprises actively eroding and deeply incised country with rugged relief and duricrust-capped mesa terrain. Silicified and weathered Proterozoic rocks outcrop in most of the area. Remnants of Mesozoic sediments are also scattered around Grey Ghost (Figure 12D,E).

Weathering profiles, up to 150 m thick, have developed on Proterozoic bedrock. Generally, deeply weathered profiles, with ferruginous or silcrete cappings, are common on stable plateau remnants. Relatively shallow profiles occur on erosional plains and hill belts. Incomplete removal of detritus, eroded from the weathered profiles in local and district scale uplands, has left a widespread, generally shallow, sedimentary cover beneath colluvial-alluvial plains and drainages. Such sediments bury both complete and partly truncated profiles (*e.g.*, 305337mE - 7760185mN).

Duricrust-capped mesas occur at a number of topographic levels (Figure 17). Lateritic duricrusts occur as pockets and there is no evidence to suggest that a thick sheet of lateritic duricrust ever developed. In most of the Buckley River-Grey Ghost area, it is represented by indurated ferruginous saprolite, massive, slabby, and conglomeratic duricrusts. In some localities it has developed into nodular and vermiform duricrusts. Some are residual, others are transported. Conglomeratic duricrusts occur on basal gravels of Mesozoic sediments. Thus, duricrust formation has been complex. Indurated, ferruginous saprolite is the most common of the ferruginous materials on plateau remnants and is developed on ferruginous lithologies. A lag of lateritic nodules occurs on plateau remnants that are derived from the fragmentation of underlying ferruginous saprolite. However, lateritic nodules and pisoliths are also common on backslopes and appear to have formed in soils. These are discussed in detail in Section 4.2.

BUCKLEY RIVER - GREY GHOST
REGOLITH LANDFORMS

NORTH-WEST MT ISA

1995

- **Lateritic duricrust and ferruginous saprolite with fragments of duricrust and minor nodules and pisoliths; mesas, rises and plateaux. Duricrust developed in-situ and on transported sediments.**
- **Lag of lateritic nodules, pisoliths; ferruginous lithic fragments; pockets of lateritic duricrust over ferruginous and mottled saprolite; rises and backslopes.**
- **Massive and columnar silcrete, silicified saprolite and alluvial gravels Silcrete typically stained and mottled with iron; plateaux and mesas.**
- **Silcrete / minor lateritic duricrust, ferruginised saprolite; plateaux and mesas.**
- **Silcrete, silicified saprolite, erosional plains and rises.**
- **Lag of ferruginous gravels and lithic fragments in a sandy matrix over saprolite minor alluvial sediments consisting of sand and gravel; pediments.**
- **Ferruginous sheet wash gravels, uniform textured sandy soils and minor alluvium and colluvium over lateritic gravels and mottled saprolite; depositional plain, minor flood plain.**
- **Ferruginous lithosols over mottled zone (in places silicified); erosional plain and rises.**
- **Lithosols over saprolite (saprock); low hills and hills.**
- **Gravel, sand and clay channel and over bank sediments on flood plains and alluvial terraces; in places the sediments have been indurated by iron, silica and clay to form alluvial hardpan.**
- **Coarse colluvial gravels and saprolitic fragments in a ferruginous sandy matrix over saprolite; colluvial footslopes and fans.**
- **Alluvial clays and silts (gilgai soils - swelling clays); pedogenic calcrete found as scattered float.**
- **Silicified alluvial gravels and sand over saprolite; erosional plains and rises.**

LEGEND

- Regolith landform boundary
- Erosional break
- Drainage
- Roads and cultural features
- River capture

Transects/prospects described in the text

Regional regolith-landform cross section shown in Figure 17.

0 5 10 km

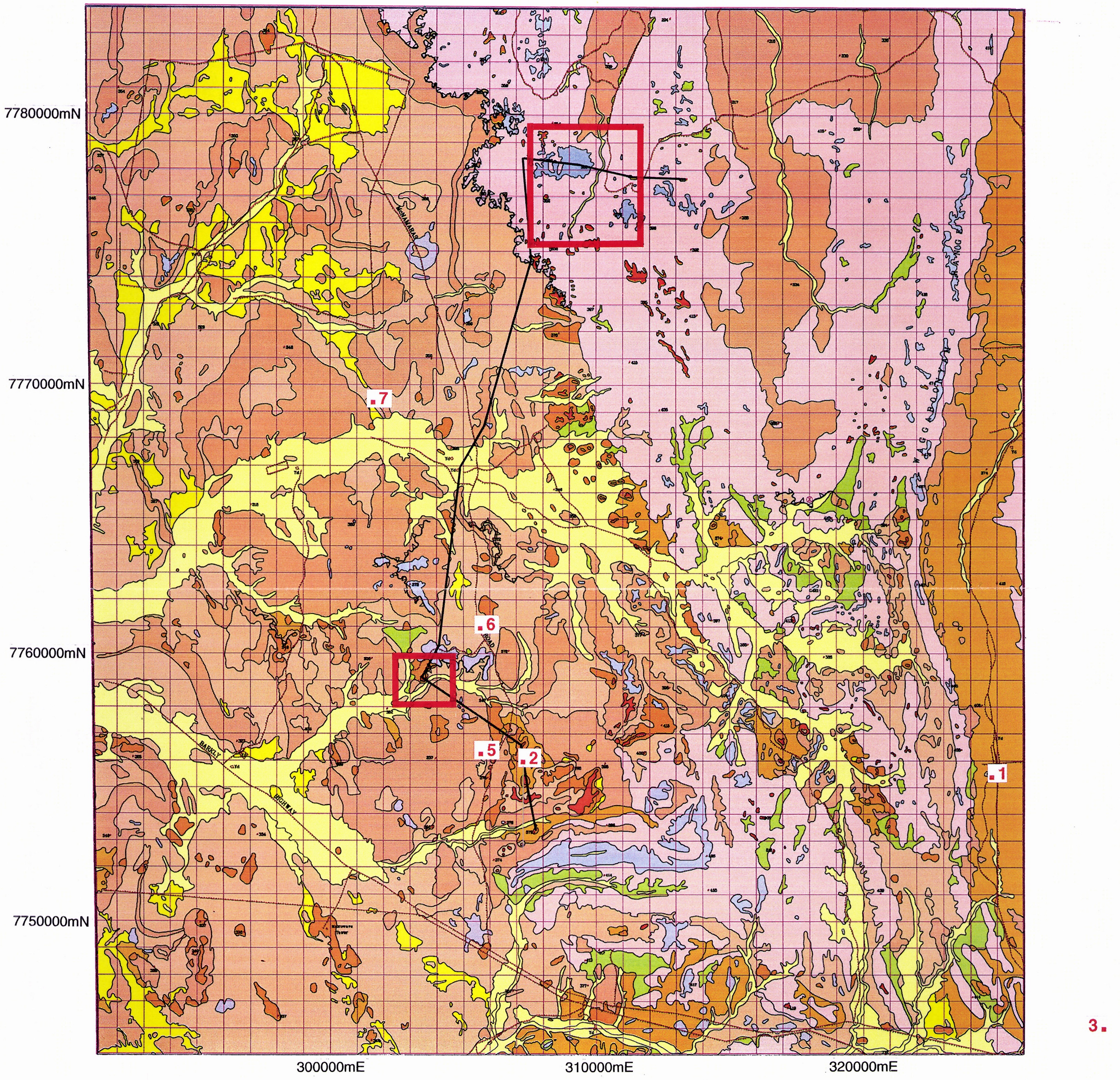

Figure 16. A reduced version of Buckley River map. Map showing the surface distribution of regolith-landform units for the Buckley River-Grey Ghost district.

The lithological control on the distributions of silcrete and lateritic duricrust is marked. They may occur within a few hundreds metres of each other, with silcrete developed instead of a ferruginous duricrust where the underlying Proterozoic bedrock is siliceous (siltstone and claystone). Stromatolite beds are particularly prone to silicification, often forming prominent chert hills and ridges. To the north, around Grey Ghost area, silcrete is also developed on remnants of Mesozoic sediments and is generally underlain by silicified saprolite. All the silcretes and their underlying horizons have some mottling. Silcrete has developed on residual regolith and on alluvium, sand and gravel in palaeo valleys that have since been inverted.

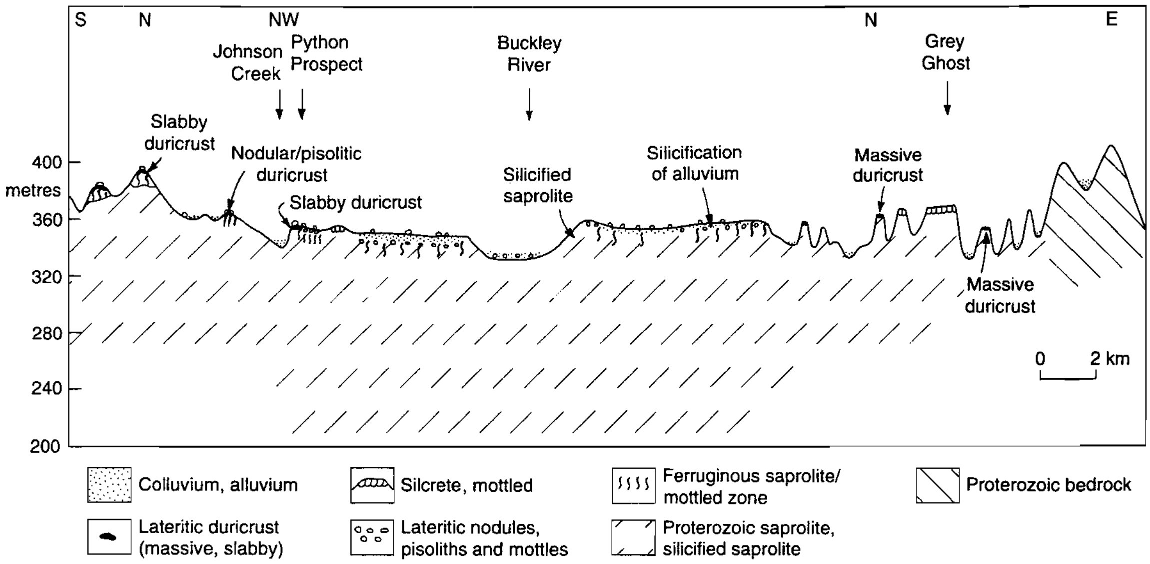

Figure 17. A schematic cross section showing the relationship between the landforms and regolith for the regional traverse shown on Figure 16, Buckley River-Grey Ghost district.

Erosional areas are dominated by truncated profiles that may or may not be covered by a thin residual soil, lag or sediment (Figure 18A,B). Lithosols, or skeletal soils, are associated with resistant rocks and areas of high relief (hills, ridges and steep slopes). Minor colluvium occurs on the footslopes. The soil profile consists of a skeletal, sandy or stony soil, generally less than 0.5 m thick, directly overlying saprock. The soils lack any profile development and contain abundant unweathered primary minerals. In areas of high relief, the rate of soil development appears to be slower than that of erosion.

Red earths are common on pediments and result from *in situ* weathering of underlying saprolite (Figure 18B). They occur on more stable parts of the landscape and are thicker (0.5-1.0 m) than the lithosols. However, these soils can be overlain by a transported, very shallow (0.1-0.2 m), light-brown to reddish-brown loamy horizon that may contain ferruginous gravels and lithic fragments.

Depositional units form some of the most extensive landforms in the Buckley River-Grey Ghost area and occupy the western part of the map. Three principal depositional units were identified. These include alluvial plains, channel and overbank sediments. Alluvial plains are characterised by low relief, but have a few small outcrops of silcrete and ferruginous saprolite, and are interpreted as being part of an old surface

(Figure 17). Exploration drilling in the plains typically records depths of weathering of up to 150 metres (*e.g.*, 305337mE - 7760185mN). Lateritic duricrust is not evident. Instead, lateritic nodules and mottles, and ferruginous or silicified saprolite are common beneath variable thicknesses of alluvium. It is not certain whether the nodules are developed within locally derived alluvium or by weathering of underlying Proterozoic bedrock. The thicknesses of alluvium are uncertain because of lack of exposure but are probably 1-5 m. The soils are red, sandy kaolinitic clays; some are cemented by silica. The ferruginous gravels of many of these soils are erosion products of nearby duricrust-capped hills. In contrast, the lag on the erosional areas is generally lithic, indicating saprolite as substrate.

Silicification of red earths indicates mobilisation and deposition of Si in the upper regolith. This silicification may have resulted from periodic flooding of the sediments followed by desiccation under semi-arid to arid conditions. This process of silicification, though weak, is similar to the formation of red brown hardpans on the Yilgarn Craton (Bettenay and Churchward, 1974).

Channel and overbank sediments are generally difficult to distinguish on aerial photographs. The alluvium generally fines upwards with coarser channel deposits overlain by finer over bank deposits. Channel and overbank sediments form broad, shallow flood plains in the western side of the mapped area. The flood plains are mainly orientated in an easterly direction and seem to reflect continuation of an older palaeo-drainage, superimposed on the predominantly northerly structural fabric of the underlying Proterozoic rocks. A typical regolith section consists of coarse gravel and sandy channel beds or lenses, which are overlain by the finer silts and clays of the flood plain. Channel deposits occur in both active and abandoned stream channels. Some of the main streams, such as the Wilfred Creek and the Buckley River, have well rounded gravels and cobbles in their channels.

More active, northerly streams are generally smaller and form narrow sediment corridors along their channels, compared with those of the easterly drainages. These smaller channels are generally less than 1 m thick and bedrock is exposed in most channel floors. In many places, channel deposits are cemented by silica, clay or iron to form alluvial hardpan, locally known as "creek rock". This hardpan commonly extends into the weathered bedrock adjacent to the channels .

4.2 Detailed Observations

Locations of the described sites are shown in Figure 16 as transects/prospects sites 1 to 7.

4.2.1 Transect 1: Development of ferruginous weathering profile on shale and soils on saprolite - plateau remnant and pediments

The mesa shown in Figures 20 and 21 provide an excellent example of a well developed weathering profile over Proterozoic bedrock in the region. The regolith profile developed from weathering of shale is situated on a mesa (324605mE - 7755409mN) at about 400 m amsl. Thin quartz veining cuts through the entire profile, showing it to be *in situ*. The mesa is some 20 m above the surrounding pediments and erosional plain, and consists of pockets of massive, lateritic duricrust over a highly ferruginous mega-mottled zone (Figure 20). The duricrust and mega-mottled zone form an indurated capping 4-6 m thick. A thin veneer of nodular and pisolitic lag has formed from fragmentation of underlying mega-mottled zone. Lateritic nodules and pisoliths are 10-15 mm in size and have goethite-rich, 1-2 mm thick, cutans (Figure 19D).

The development of the elongated, tubular mega-mottles was probably partly controlled by sub-vertical cleavage of the bedrock. They are formed by progressive ferruginisation of kaolinitic saprolite and increase upwards in the profile. Where the clay has been removed by solution, vugs and tubular holes have developed in the mottles . In places, these have been filled with ferruginous gravels. The mottled zone grades into highly weathered, diffusely mottled, friable and kaolinised shale saprolite. Goethite pseudomorphs after pyrite are common both in the saprolite and in the mega-mottles.

Figure 18. Examples of common soils.

(A) Soil profile on erosional plains. A thin layer of colluvium (1) overlies a yellow brown soil (2) formed on kaolinite-rich saprolite (3) derived from bleached siltstone. Location: 303945mE - 7758330mN, Buckley River-Grey Ghost district.

(B) Soil profile on a pediment. A thin layer of colluvium (1) overlies a residual red clay soil (2) formed on saprolite (3) derived from shale. Location: 324605mE - 7755409mN, Buckley River-Grey Ghost.

(C) On alluvium a upper veneer of fine creamy brown soil (1) overlies a pale brown soil (2) and cemented gravels and sand (3). Location: 301611mE - 7769098mN, Buckley River-Grey Ghost district (photographed by Mal Jones).

(D) Soil profile on deposits derived from erosion of Mesozoic sediments. Brown sandy soil (1) overlies transported gravels (2) and mottled clays (3). Mottled clays are underlain by Proterozoic saprolite. Location: 298500mE - 7829400mN, Mammoth Mines district.

(E) Soil profile on Tertiary sediments in well drained environments on rolling plains. Reddish brown sandy clay soil (1) over mottled Tertiary clays (2) and pebbles (3). Location: 498631mE - 7680703mN, Eloise-Maronan district.

(F) Soil profile on Tertiary sediments in poorly drained portion of the rolling plains. Black soils (1) underlain by sorted pebbles and fine sands (2). Mesozoic saprolite on mudstone underlies the Tertiary sediments (3). Location: 497564mE - 7683063mN, Eloise-Maronan district.

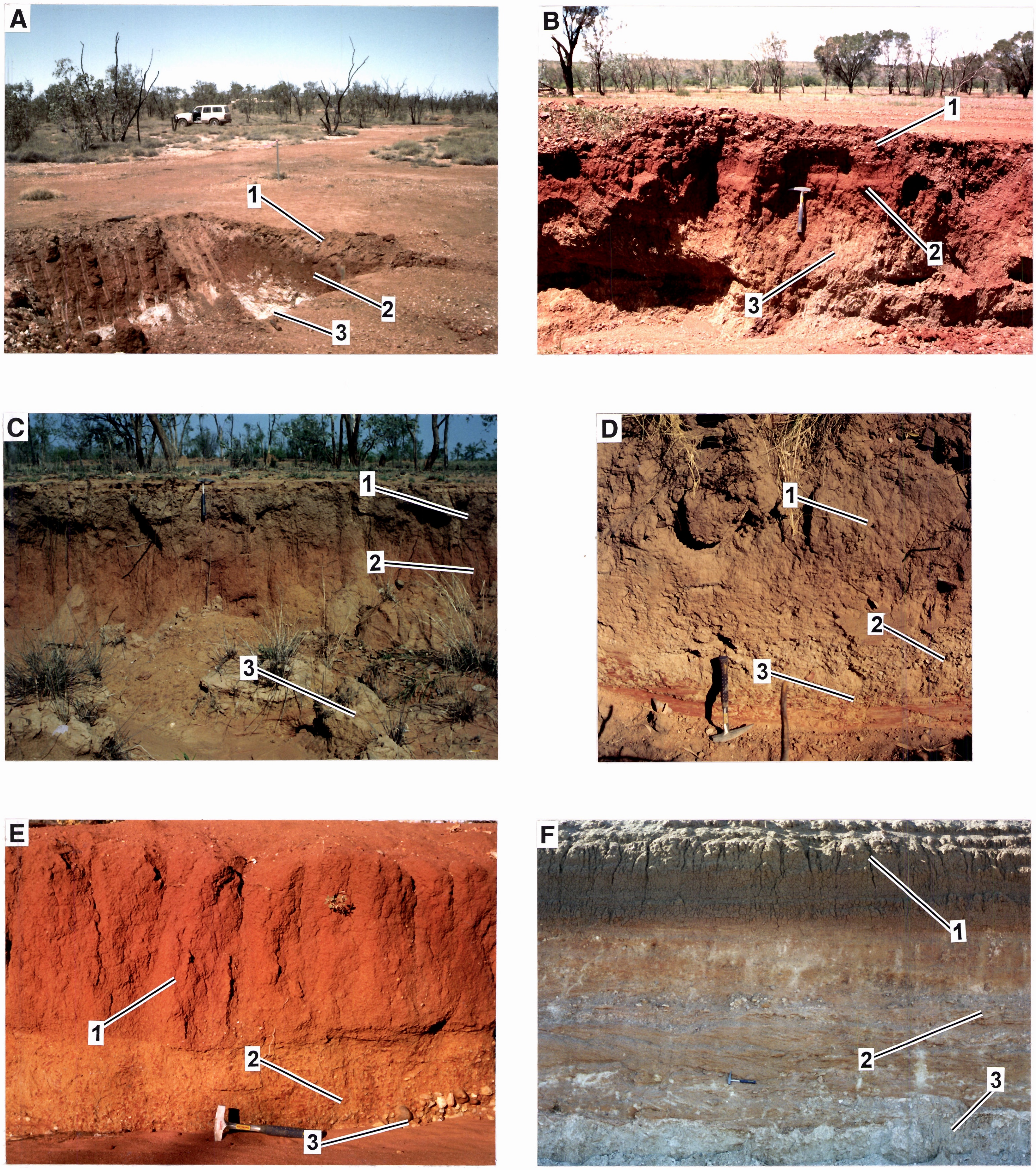
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Figure 19. Handspecimens of ferruginous materials and silcrete, Buckley River-Grey Ghost district.

(A) Ferruginous saprolite

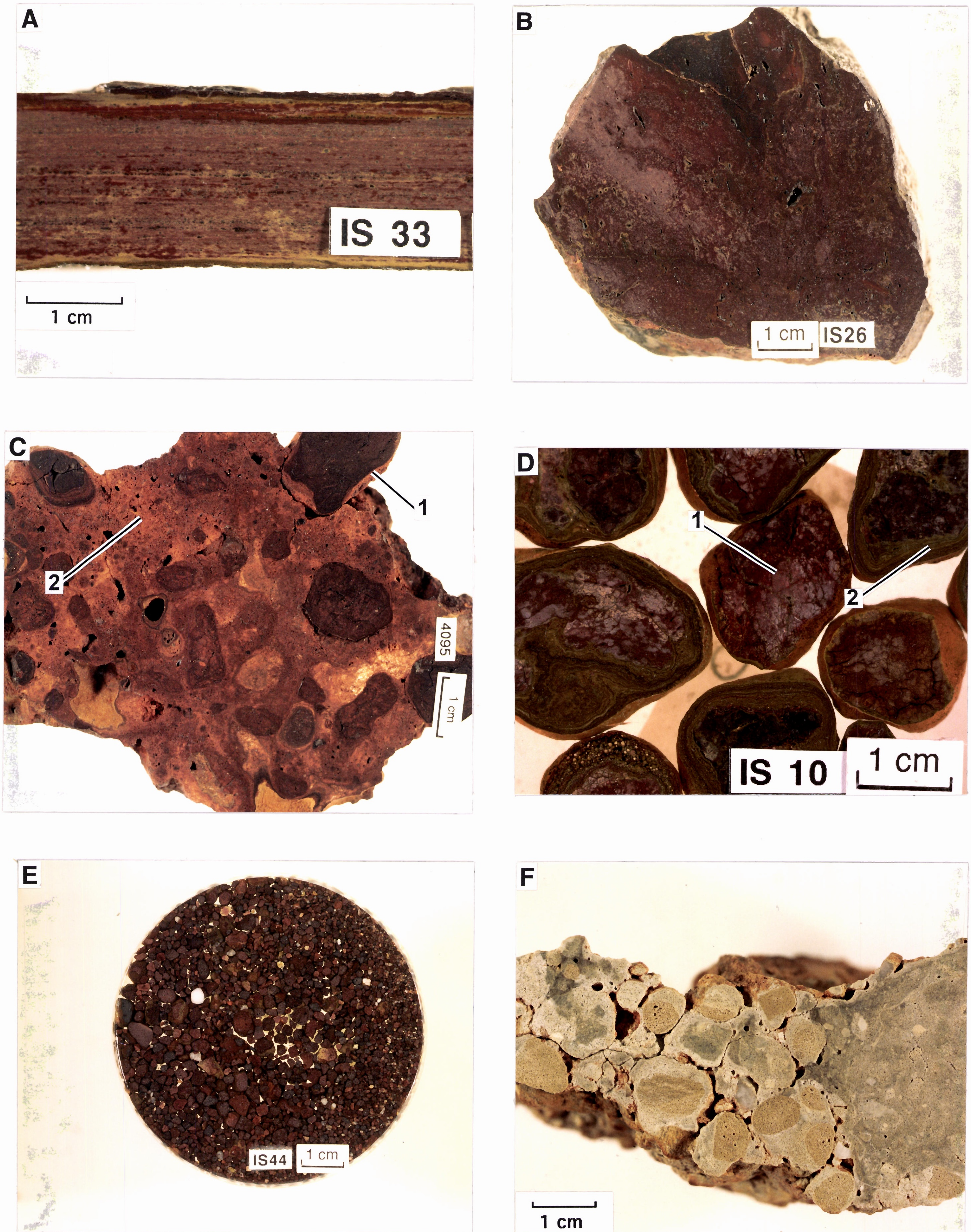
(B) Massive duricrust

(C) Nodular duricrust showing nodules (1) and matrix (2).

(D) Lateritic pisoliths with hematite-rich core (1) and goethite and kaolinite-rich cutans (2); these pisoliths form a thin lag on massive duricrust.

(E) Ferruginous granules form a common lag on depositional plains. These are hematite-rich and are locally derived from erosion of nearby duricrust capped hills.

(F) Nodular-massive silcrete.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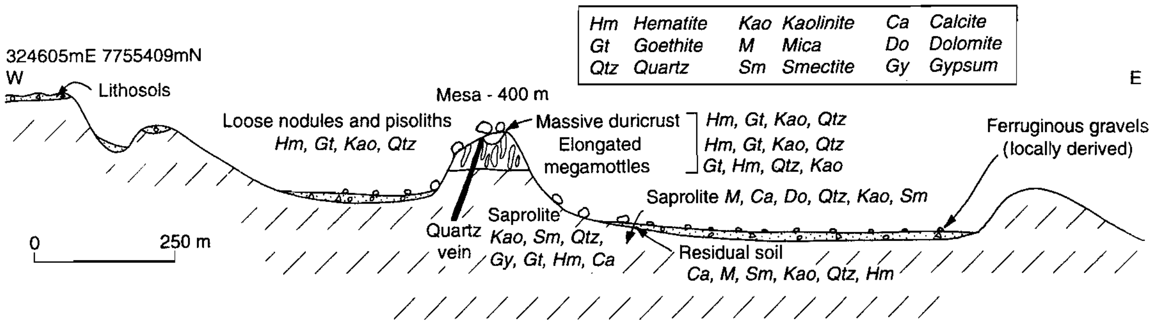


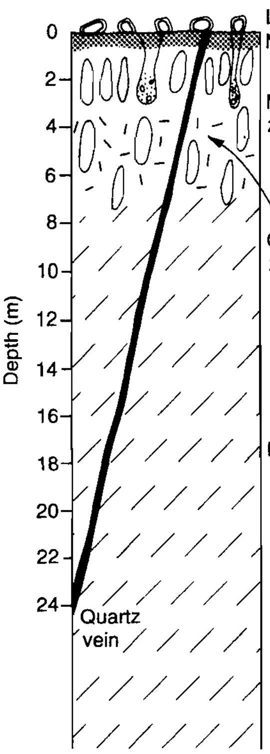
Figure 20. Schematic representation of the regolith and landform for the transect 1 shown on Figure 16, Buckley River-Grey Ghost district.

Lateritic pisoliths and mega-mottles are dominated by hematite and goethite but contain small amounts of kaolinite, quartz, mica and anatase (Figure 21). Clay of the mottled zone is dominated by kaolinite. The upper saprolite consists largely of kaolinite, smectite, quartz, goethite, hematite, gypsum and calcite. Hematite increases towards the top of the profile. The mineralogy of the regolith units is consistent with the chemical composition (Figure 21). Iron increases upwards; Si, Ca, Mg, K and Na decrease and Al remains constant. Zinc, Mn, Cu, Co, Ni, Ba, Sr and S are lost during weathering, whereas V, Pb and Cr are residually enriched. Goethite and hematite are the major minerals in the mottles and pisoliths and have strong affinities for Cu, As, V, Pb and Cr (Figure 22). Manganese appears to correlate with Cu. Clay of the mottled zone contains very low concentrations of these elements.

The surrounding landforms consist of pediments and erosional plains covered with lag gravels and residual soils. Although these materials cover an extensive area, they are generally thin (<1 m). Red, sandy clay is common on pediments and result from *in situ* weathering of underlying saprolite which is dominated by mica, calcite, dolomite, quartz, kaolinite and smectite (Figure 20 and 18B). Here, these soils are overlain by a locally derived, gravelly colluvium. The soils consist largely of mica, calcite, smectite, kaolinite, quartz, hematite and dolomite which is consistent with the chemical composition (Table 3). The red colour is due to hematite. Copper and Pb in these soils are enriched relative to the underlying saprolite; Zn is depleted.

From this, it is evident that, even when most of the pre-existing profile is preserved, some characteristics reflect the influence of the present climate. Thus, at the top of the profile on plateau remnants, the megamottled zone is leached and transformed into a kaolinite- and hematite-rich assemblage containing some relict nodules and pisoliths. At the base of the saprolite and overlying residual soils, primary minerals have weathered to smectite, calcite and dolomite rather than to kaolinite. Formation of smectite, calcite and dolomite are favoured by slow leaching environments, such as those currently prevailing. Therefore, the former lateritic profile cannot be in complete equilibrium with the present climatic conditions.

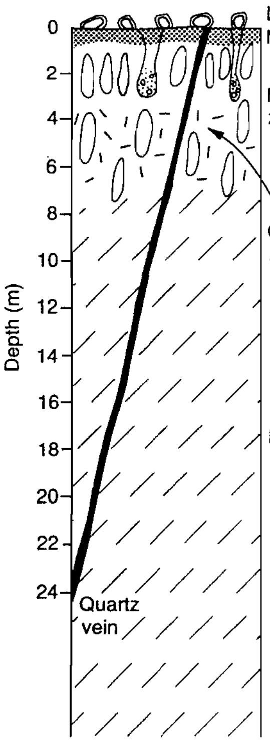
324605E 7755409N - Weathering profile on shale



Regolith units	Mineralogy	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	CaO %	MgO %	MnO %
Loose pisoliths	*Hm, Gt, Kao, Qtz, Ana*	17.12	14.42	55.45	0.10	0.07	0.02
Massive duricrust	*Hm, Gt, Kao, Qtz, Ana*	18.10	10.23	59.93	0.02	0.04	0.02
Mega-mottled zone (Matrix decreases)	*Hm, Gt, Kao, Qtz, Ana*	19.12	10.21	59.47	0.00	0.04	0.03
	Gt, Hm, Qtz, Kao	41.12	12.25	36.68	0.07	0.06	0.03
Clay of mottled zone	*Kao, Qtz*	63.86	20.52	2.16	0.07	0.08	0.04
Mottled saprolite	*Kao, Sm, Qtz, Ca, Gt*	43.40	14.05	10.16	2.43	1.79	0.29

Hm	*Hematite*
Gt	*Goethite*
Kao	*Kaolinite*
Sm	*Smectite*
Ca	*Calcite*
Ana	*Anatase*
Qtz	*Quartz*

324605E 7755409N - Weathering profile on shale



Regolith units	Mineralogy	Cu ppm	Zn ppm	Ni ppm	Pb ppm	Cr ppm	V ppm
Loose pisoliths	*Hm, Gt, Kao, Qtz, Ana*	325	53	5	44	140	1155
Massive duricrust	*Hm, Gt, Kao, Qtz, Ana*	378	45	9	30	80	780
Mega-mottled zone (Matrix decreases)	*Hm, Gt, Kao, Qtz, Ana*	384	43	11	29	78	770
	Gt, Hm, Qtz, Kao	176	55	18	3	21	493
Clay of mottled zone	*Kao, Qtz*	14	16	20	13	15	70
Mottled saprolite	*Kao, Sm, Qtz, Ca, Gt*	509	210	64	20	13	301

Hm	*Hematite*
Gt	*Goethite*
Kao	*Kaolinite*
Sm	*Smectite*
Ca	*Calcite*
Ana	*Anatase*
Qtz	*Quartz*

Figure 21. Vertical distribution of major minerals and some major and trace elements in the weathering profile over shale, Buckley River-Grey Ghost district. This profile is situated on a mesa (shown in Figure 20) which is about 400 m amsl.

Table 3. Chemical composition of soil profile situated on a pediment, Buckley River-Grey Ghost district.

Sample No	IS-15	IS-16	IS-17	Sample No	IS-15	IS-16	IS-17
Depth(m)	0 - 0.3	0.3 - 0.6	0.6 +	Depth(m)	0 - 0.3	0.3 - 0.6	0.6 +
Regolith Type	Gravelly colluvium	Red sandy clay	Saprolite	Regolith Type	Gravelly colluvium	Red sandy clay	Saprolite
SiO2 %	56.2	45.8	47.6	Pb ppm	24	13	7
Al2O3 %	14.0	12.8	13.0	Zn ppm	57	56	69
Fe2O3 %	15.7	9.8	6.7	Ni ppm	41	47	41
MgO %	1.22	2.69	4.10	Co ppm	19	22	26
CaO %	0.79	9.74	9.00	Ga ppm	23	20	20
Na2O %	0.24	0.14	0.21	Ba ppm	415	604	630
K2O %	1.62	2.74	3.91	Zr ppm	361	211	150
TiO2 %	1.71	1.01	0.68	Nb ppm	5	4	<4
P2O5 %	0.068	0.052	0.111	Ce ppm	86	69	74
MnO %	0.124	0.080	0.098	La ppm	40	35	42
LOI %	6.6	13.3	13.0	Rb ppm	93	132	182
Cr ppm	68	55	51	Sr ppm	85	142	154
V ppm	268	180	128	Y ppm	40	30	27
Cu ppm	89	29	<10	S ppm	230	400	290

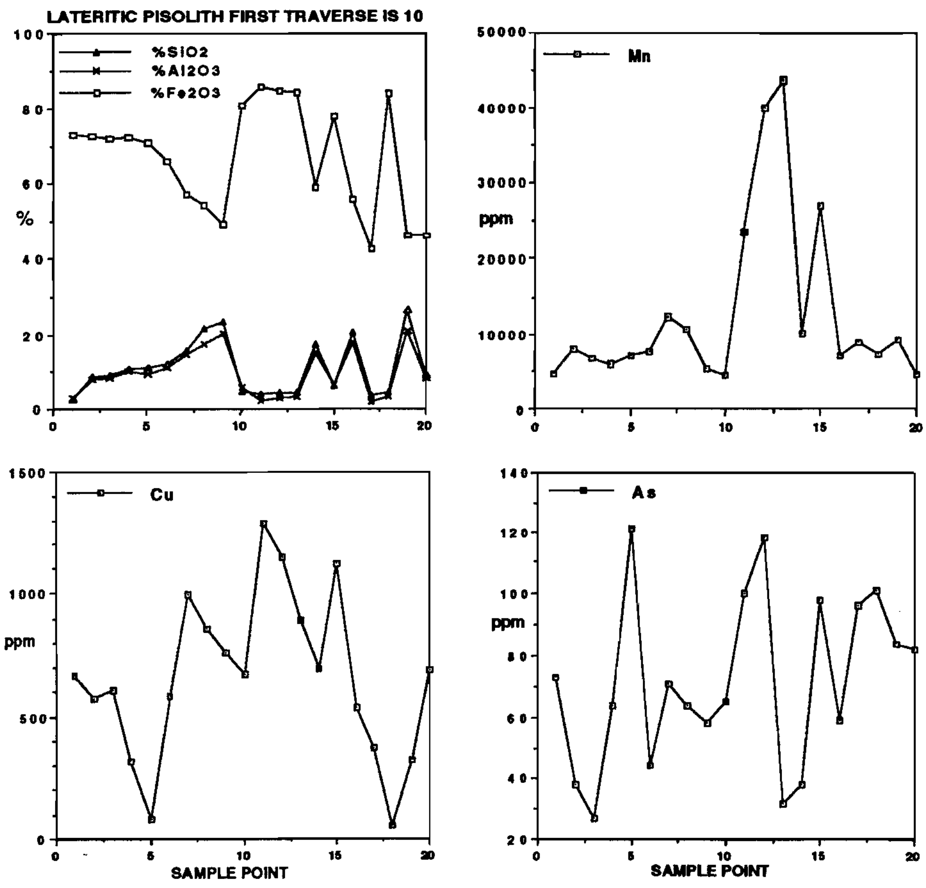


Figure 22. Stepped traverse and element distribution in laterite pisolith, sample IS 10, Buckley River-Grey Ghost district.

LA1	Lag of lateritic nodules, pisoliths and fragments of ferruginous saprolite, pockets of slabby duricrust, plateau and mesas	*MI7*	Lag of mixed siliceous and ferruginous saprolite over saprolite, low hills
LA2	Lag of lateritic nodules and fragments of ferruginous saprolite over saprolite, pediments and colluvial plains	*LI4*	Lag of quartz over saprolite
MI6	Lag of mixed ferruginous and siliceous saprolite, over saprolite, pediments	*SP5*	Silicified saprolitic lag on silicified saprolite, low hills
		AS1	Thin alluvial soils over saprolite, valley floors
		SP4	Exposed saprolite, rises

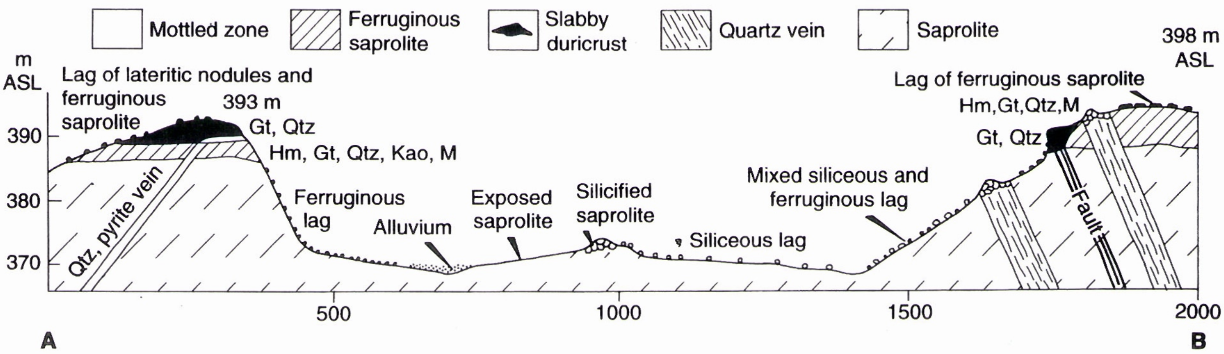


Figure 23. Map showing the surface distribution of regolith units and vegetation as an overlay to the colour aerial photograph (Commonwealth of Australia, 6757 Kennedy Gap photo 8/48, 1.10.1972) for the transect 2 and its surroundings. Here several plateaux are separated by erosional pediments and plains. The stratigraphy of the transect AB is shown. Terminology and nomenclature of regolith-landform units are adopted from Anand *et al.* (1993)

4.2.2 Transect 2: Development of ferruginous saprolite and slabby duricrust on dolomitic siltstone - plateau remnants

The lateritic profile on plateau remnants over Proterozoic rocks appears to be composite. Such a profile, developed from the weathering of dolomitic siltstone, is shown in Figures 23 and 24. Here several plateaux and rises are separated by erosional pediments and plains (Figures 23 and 8C). Saprolite, shallow soils and siliceous lags occur in valley floors. Alluvial sediments occur as narrow corridors along streams, with saprolite typically exposed on channel floors. The tops of these rises and plateaux, which stand approximately 25 m above the pediments, are generally capped with ferruginous saprolite with pockets of slabby duricrust (Figure 23). Slabby duricrust forms a prominent breakaway (Figure 10D).

The cross section in Figure 23 (transect AB) represents the stratigraphy between two mesas 2 km apart (Stop 4, Mt Isa Field Guide, 1995). The western hill has a ferruginous capping of goethitic 'slabby' duricrust with a copper anomaly of 128 ppm. A weathering profile through one of these plateau remnants (307251mE - 7756167mN) consists of both residual and transported regolith. The residual regolith consists of saprolite, ferruginous saprolite, mottled clay zone and mottled duricrust. The transported regolith is the uppermost unit of slabby duricrust (Figure 24). Although there is little field evidence to suggest that this duricrust is transported, except for a few rounded quartz pebbles, the chemical and mineralogical composition indicate that it is unrelated to the underlying bedrock. Preserved quartz veins indicate that the remaining profile was formed *in situ*.

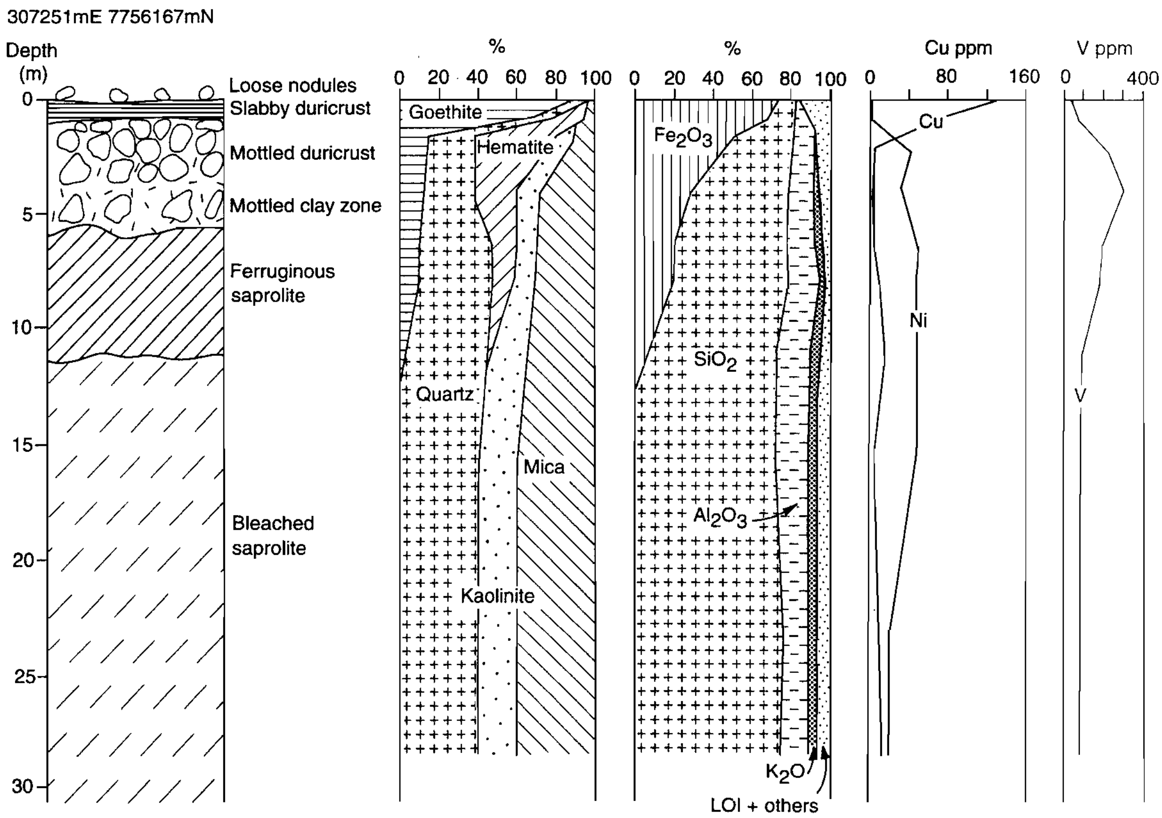


Figure 24. Vertical distribution of major minerals and some major and trace elements in the weathering profile over dolomitic siltstone, Buckley River-Grey Ghost district. This profile is situated on a plateau remnant (Unit LAl on Figure 23) and appears to be complete.

Figure 25. Photomicrographs of weathering profile developed on dclomitic siltstone, Buckley River-Grey Ghost district.

(A) Photomicrograph in crossed polarizers of goethite rich band (1) in the saprolite with partially weathered mica (biotite) flakes (2) and quartz grains (3).

(B) Photomicrograph in normally reflected light showing the goethite rich ferruginous band (1) preserving partially weathered relict mica (biotite) flakes (2) and quartz grains (3).

Clay in Mottled zone

(C) Photomicrograph in crossed polarizers of impregnation of yellowish brown goethite (1) in clay matrix and coating in vughs (2), with quartz grain (3).

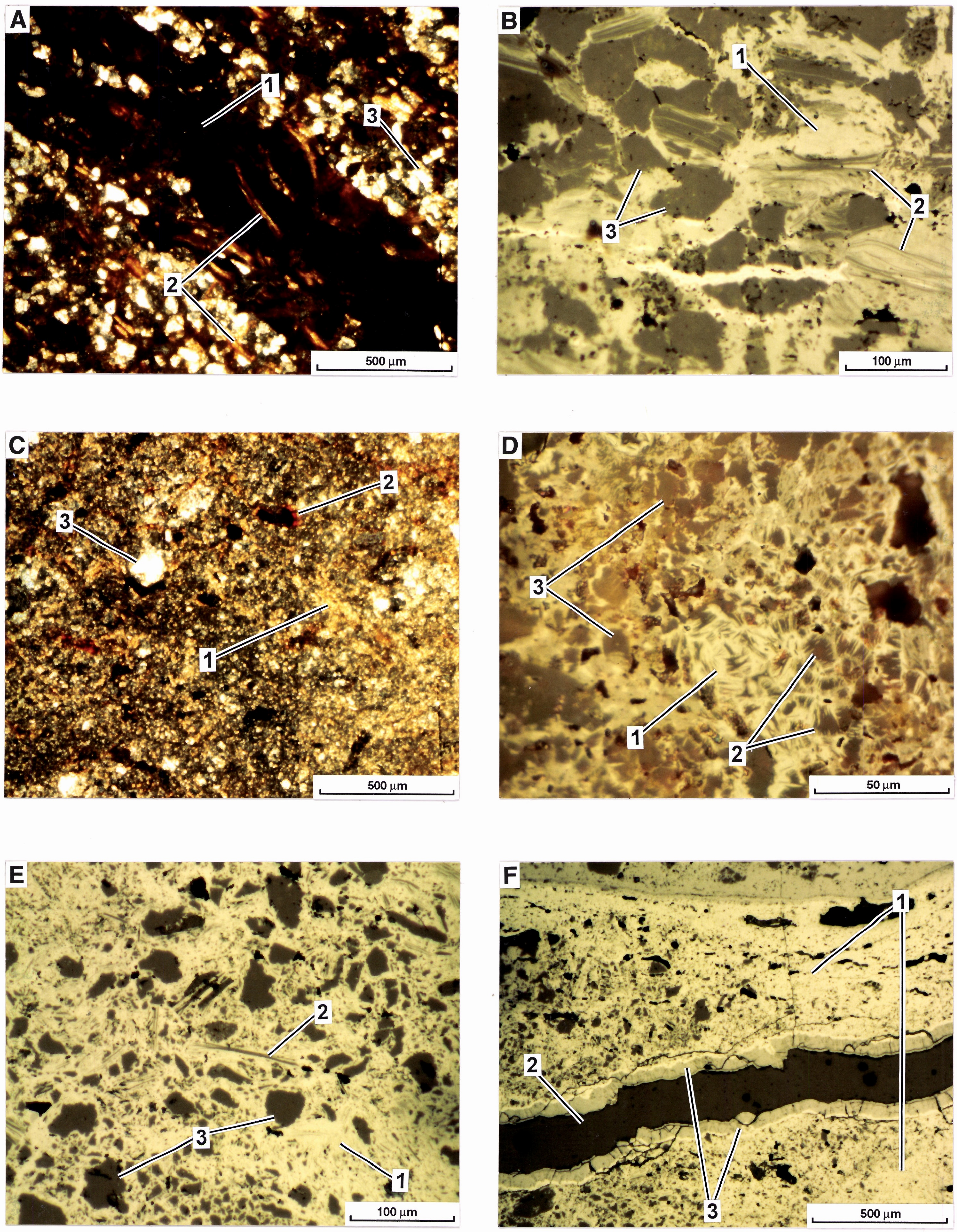
Mottles

(D) Photomicrograph in normally reflected light showing goethite (1) preserving booklets of kaolinite (2) along with quartz grains (3).

Massive duricrust

(E) Photomicrograph in normally reflected light showing a close up of goethite matrix (1) which preserves some relict mica flakes (2) similar to that found in the ferruginous saprolite in Figure B, along with quartz grains (3).

(F) Photomicrograph in normally reflected light showing goethite (1) with increasing brightness adjacent to dessication crack (2). The dessication crack occurs along a former channel infilled by clay which is being replaced by goethite (3).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Saprolite and ferruginous saprolite contain the preserved fabric and structure of the dolomitic siltstone, and weathering appears to have been isovolumetric (Figure 25A,B). The mineralogy is dominated by mica, quartz and kaolinite, with goethite and hematite present in the ferruginous saprolite (Figure 24). Goethite pseudomorphs after mica and carbonates are present throughout the saprolite and ferruginous saprolite. The upper part of the saprolite is silicified.

Ferruginous saprolite grades upwards into the mottled zone, where most of the fabric of the parent rock has been destroyed (Figure 25C,D). Mottled zone is characterised by hard, irregular, reddish brown mottles, up to 50 mm in length, set in a yellow, kaolinite-quartz-mica matrix. Here, the major difference between mottles and matrix is the iron content of the mottles which are dominated by hematite with small amounts of goethite. Mica remnants in the goethite commonly occur both in the mottles and in the matrix (Figure 25D). Secondary silicification is also common.

Towards the top of the profile, the mottled zone grades into mottled duricrust (Figure 25E,F). This is characterised by abundant, reddish brown mottles in a very small amount of goethite-kaolinite matrix. Both hematite and goethite increase in abundance in the mottled duricrust; kaolinite and mica decrease and maghemite is absent (Figure 24).

Slabby duricrust, which overlies mottled duricrust, is highly indurated, black and enriched in goethite. Hematite and kaolinite are either absent or present in very small amounts (Figure 24). This contrasts with mottled duricrust in which hematite, goethite, kaolinite and quartz are the major minerals. Quartz and mica are present in small amounts. Slabby duricrust is more Fe-rich (71% Fe_2O_3) than the underlying mottled duricrust (51% Fe_2O_3).

The iron oxide mineralogy of the mottled and slabby duricrusts suggests that they have developed in different hydrological regimes. Free drainage and high temperatures in the mottled duricrust yielded hematite; low temperatures, moist conditions, and abundant organic matter produced goethite in the slabby duricrust (Schwertmann, 1985). The Fe is interpreted as being an absolute accumulation, derived by weathering of the local, upland, transported laterally and precipitated in a low landscape positions. Subsequently, induration by ferruginisation allowed differential erosion and relief inversion to its present topographic position. This hypothesis is supported by its geochemistry. The V, Ni and Cu compositions of slabby duricrust is very different from the underlying mottled duricrust and saprolite (Figure 24). Vanadium has increased from 90 ppm in saprolite to 145 ppm in mottled saprolite and then decreased sharply to 45 ppm in slabby duricrust. The behaviour of Ni is similar to that of V. However, the behaviour of Cu and P is the reverse. Copper concentrations has decreased from 13 ppm in saprolite to 3 ppm in mottled duricrust and then markedly increased to 128 ppm in slabby duricrust. The concentrations of P are very high in slabby duricrust (1.10% P_2O_5) relative to the mottled duricrust (0.24%) and saprolite (0.09%). This implies that most Cu, V, Ni and P in slabby duricrust are not derived from the underlying bedrock. A pyritic quartz vein, cutting through the crest of the hill, was sampled and was found to contain 487 ppm Cu which possibly provided a source for the anomaly but there is still no explanation for the excess P and V in the surface ferruginous materials.

The slabby duricrust on the mesa at the southeast at the end of the transect (Figure 23) appears to have accumulated Fe from the junction of a fault and a large quartz vein on the shoulder of the hill and not from an anomalous source. The analyses show low concentrations of Cu (68 ppm) and Pb (1 ppm).

4.2.3 Transect 3: Development of lateritic nodules, nodular and massive duricrusts on a ferruginous siltstone - rise

Mottled zones commonly occur on mesas, rises and erosional plains and are generally underlain by saprolite (Figure 11B and 26). These zones have hard, irregular, hematite-rich, non-magnetic, reddish brown mottles, up to 100 mm in length, set in a yellow, kaolinite-quartz-mica matrix. A collapsed mottled zone (0.3-1.0 m) generally overlies a mottled clay zone.

The mottled zone and its associated lateritic nodules and pisoliths from the Buckley River region, well exposed in a road cutting, is typical. The profile consists of pockets of duricrust, nodules and collapsed mottles, 0.5 m thick, which grade into mottled zone and saprolite at depth (Figures 11B and 26). As the matrix of the mottled zone dissolved, the mottles collapsed upon one another and so became increasingly abundant towards the top of the profile. Mottles were later broken into nodules. The material below this ferruginous layer consists of saprolite with reddish-orange mottling.

Lateritic nodules and pisoliths are dominated by goethite and hematite with small amounts of kaolinite and quartz. They have goethite-kaolinite rich cutans, 1-2 mm thick; high abundance of pisoliths on the lower slopes suggests that some transport has taken place. They were probably formed by erosion of a mottled zone, moved downslope and modified by pedogenesis.

Pockets of nodular and massive duricrusts also occur in the upper part of the profile. Massive duricrusts occur on the lower slope of a rise and is dense, reddish brown to black (Figure 26) and is dominated by goethite and quartz. In contrast, pockets of nodular duricrust occur on the upper slope and is dominated by hematite, goethite, quartz, kaolinite and mica, *i.e.*, its mineralogy is similar to the underlying mottled zone. Nodular duricrust is formed by cementation of nodules. The position in the landscape of massive and nodular duricrusts and their variable iron oxide mineralogy suggest that they have formed under different weathering or hydrological environments. Massive duricrust contains more Fe compared to nodular duricrust, suggesting a some lateral accumulation of Fe although the source of Fe is probably local.

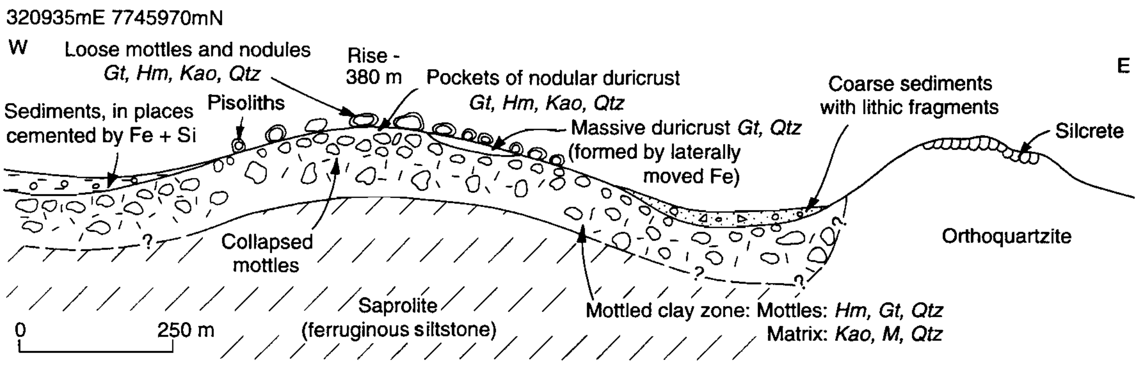


Figure 26. Schematic representation of regolith and landforms for the transect 3, Buckley River-Grey Ghost district. This section shows the development of a mottled zone and its associated lateritic nodules over ferruginous siltstone.

4.2.4 Transect 4: Development of silcrete by in situ weathering of siltstone-rise

The area generally consists of alluvial sand and sheet wash gravels over flood and erosional plains. Rises and low hills are blanketed by skeletal, gravelly soils over silicified and ferruginous saprolite.

There is a minor erosional break separating silcrete and silicified saprolite from sheet wash gravels, sand and alluvium to the south. The silcrete, 1.0-1.5 m thick, underlain by silicified saprolite, is micro-crystalline with diffuse Fe staining throughout (Figure 27). In places, well rounded to angular quartz fragments are present. The silcrete has a brecciated fabric and is dominated by quartz and anatase (Figure 28). The fabric and structure of the parent rock have been destroyed.

Near-surface silcrete is rich in Si (90.5% SiO_2), and poor in clay related elements (Al, Mg) which is consistent with its mineralogy (Table 4). It is also rich in Ti (7% TiO_2) which occurs as anatase. Abundances of Cu, Pb, Zn and Ni are very low but not so Zr (820 ppm) (Table 4). Zirconium occurs as zircon. Silcrete has formed from silicification of an originally very siliceous saprolite (*e.g.*, on siltstone), the silica being derived from the weathering profile within which it is found. The brecciated structure may have developed from loss of soluble minerals (clays) during silicification.

Black, ferruginous granules (2-5 mm) form a patchy, thin lag over silcrete and appear to be an upper part of the silcrete profile. These granules consist of hematite and quartz with small amounts of anatase and are characterised by high concentrations of Fe (66.7% Fe_2O_3) and lesser concentrations of Si (18.8% SiO_2) and Al (5.5% Al_2O_3) (Table 4). Abundances of Cu, Pb, Zn and Ni are similar to those of the silcrete, despite the high concentrations of Fe (Table 4).

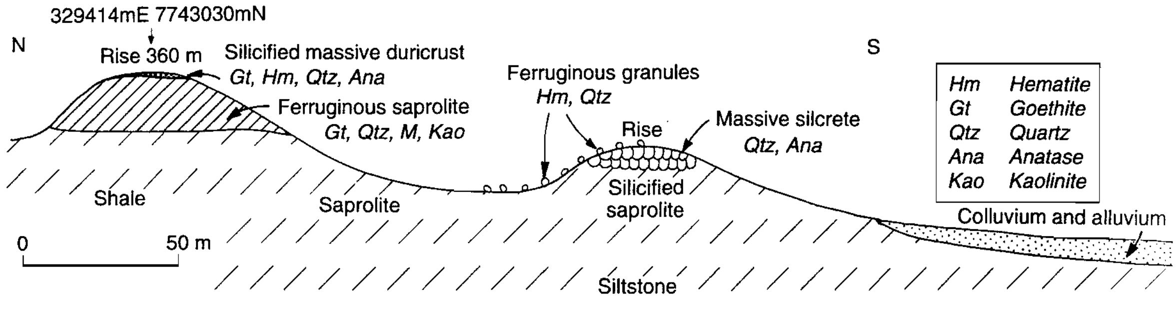


Figure 27. Diagrammatic cross section showing the relationship between silcrete and silicified massive duricrust (transect 4), Buckley River-Grey Ghost district. Silcrete is formed from weathering of underlying siltstone.

Neighbouring rises, 150 m to the north, have a well-developed capping of ferruginous, silicified duricrust (Figure 27) over shale. This profile is in sharp contrast to the nearby silcrete and consists of massive duricrust, cemented by Fe and Si, which passes into ferruginous saprolite at depth. Massive duricrust consists largely of hematite and quartz, with small amounts of goethite and kaolinite. It is characterised by high concentrations of Si (52.6% SiO_2) and Fe (31.6% Fe_2O_3) and lesser concentrations of Al (6.6% Al_2O_3) (Table 4). The concentrations of Ti (5.1% TiO_2) and Zr (776 ppm) are similar to those present in the silcrete. However, the abundances of Cu (201 ppm), Pb (49 ppm), Zn (21 ppm) and Ni (23 ppm) in the duricrust are much greater than the silcrete and black ferruginous granules.

The ferruginous saprolite below the duricrust consists of goethite, mica, kaolinite and quartz (Figure 28). Mica relicts are common in ferruginous saprolite. The major element composition of ferruginous saprolite is similar to massive duricrust, except for greater abundances of Al (12% Al_2O_3) and K (3.5% K_2O) and much lower abundances of Ti (0.56% TiO_2) (Table 4). Copper (11 ppm) and Zr (143 ppm) are much lower in ferruginous saprolite than the massive duricrust (despite similar concentrations of Fe). This may suggest that high concentrations of Cu in massive duricrust are derived from elsewhere and thus may not be related to the underlying bedrock. Copper is associated with Fe oxides which may suggest that ferruginisation of silcrete is probably younger and occurred after silicification.

4.2.5 Transect 5: Development of silcrete by relief inversion

The area consists of rises (9-30 m relief) and erosional plains (<9 m relief) with generally thin, ferruginous, gravelly soils over ferruginous saprolite. Sheetwash gravels and alluvial sediments occupy the low and flat parts of the landscape which are mainly thin and discontinuous in this area (Figure 28). Ferruginous duricrust and a lag of fragments of ferruginous saprolite occur over the surface. These form the top of a well-developed weathering profile, and grade into a mottled and bleached saprolite at depth. These profiles are lithologically controlled and develop best on Fe-rich sediments (*e.g.*, Gunpowder Creek Formation).

Massive silcrete and silcrete pods, 1-2 m, thick, form a capping and rest unconformably on moderately weathered shale (Figure 42B). Quartz pebbles, gravels and sand, within the silcrete, suggest that the original matrix was either river channel or sheetwash deposits which have been silicified. Cementation was probably caused by silica-rich groundwaters, when the sediments were low in the landscape. Induration by silicification allowed differential erosion and relief inversion to its present topographic position.

Silcrete largely consists of Si (97.6% SiO_2) with very small amounts of Fe (0.94% Fe_2O_3) and Ti (1.22% TiO_2). Abundances of Cu, Zn, Ni and Pb are very low. Zirconium in zircon is present in significant amounts (532 ppm).

Table 4. Chemical composition of individual samples of silcrete and ferruginous materials - transect 4, Buckley River-Grey Ghost district.

Sample No Depth(m) Regolith Type	IS-50 0 Silcrete	IS-2/2 0 Black Fe-granules	IS-3 0 Massive duricrust	IS-5 10 Ferruginous saprolite
SiO2 %	90.5	18.9	52.6	48.7
Al2O3 %	0.5	5.6	6.6	12.1
Fe2O3 %	1.3	66.8	31.6	30.4
MgO %	0.04	0.11	0.07	0.56
CaO %	0.07	0.27	0.06	0.05
Na2O %	0.00	0.03	<0.01	0.09
K2O %	0.03	0.12	0.06	3.53
TiO2 %	6.99	2.96	5.18	0.56
P2O5 %	0.065	0.087	0.073	0.049
MnO %	0.008	0.038	0.018	0.015
LOI %	0.5	2.8	4.3	4.1
Cr ppm	50	346	89	82
V ppm	170	1873	933	204
Cu ppm	4	3	201	11
Pb ppm	24	33	49	32
Zn ppm	0	17	21	17
Ni ppm	14	<10	23	14
Co ppm	2	<1	<1	<1
Ga ppm	3	49	18	22
Ba ppm	531	5673	319	572
Zr ppm	820	519	776	143
Nb ppm	50	13	41	<4
Ce ppm	50	20	26	29
La ppm	36	<10	16	31
Rb ppm	<5	9	<5	197
Sr ppm	53	209	18	30
Y ppm	32	10	27	20
S ppm	400	2770	430	480

4.2.6 Transect 6: Stratigraphy of depositional plain

The area consists of alluvial plains (<9 m relief), and local rises (9-30 m relief), with ferruginous lag gravels, sandy clay soils and minor alluvium on lateritic nodules and mottled saprolite. This regolith-landform is one of the most extensive units in the area and appears to be part of an old surface. Here, near complete and truncated profiles are buried beneath alluvium. Observations were made at location 305500mE - 7761000mN. Soils are red, gravelly, sandy to sandy clay, kaolinitic and are developed in locally derived alluvium 1-2 m thick. The alluvium is underlain by horizons of lateritic nodules and pisoliths and a mottled zone. The lateritic nodules are reddish brown, irregular, 3-15 mm in size and are dominated by hematite, kaolinite and quartz. These have goethite- and kaolinite-rich, 1-2 mm thick cutans and look very similar to those found on mesas. These were formed *in situ*, but it is not certain whether they have developed in alluvium or by weathering of underlying bedrock. Most of the ferruginous lag gravels, although transported, are thought to be locally derived (Figure 19E).

4.2.7 Transect 7: Stratigraphy of alluvial channel

The exposure at location 301611mE - 7769098mN provides the regolith stratigraphy of the alluvial channel (Figure 18C). An upper pale creamy brown soil, approximately 0.1 m thick, is in fairly sharp contact with the underlying pale brown soil, about 0.45 m thick. The boundary to an Fe-stained horizon below is gradational. This unit is about 0.55 m thick, becomes paler downwards, without much evidence of mottling, and is gravelly towards the base, with silcrete and ferruginous pisoliths. It overlies a cemented gravel and sand containing gravelly layer of quartz, silcrete fragments and pisoliths. The cemented sand and gravel has ferruginous mottling at the top. The cemented unit is fairly common at the base of the recent alluvial sequences in the area.

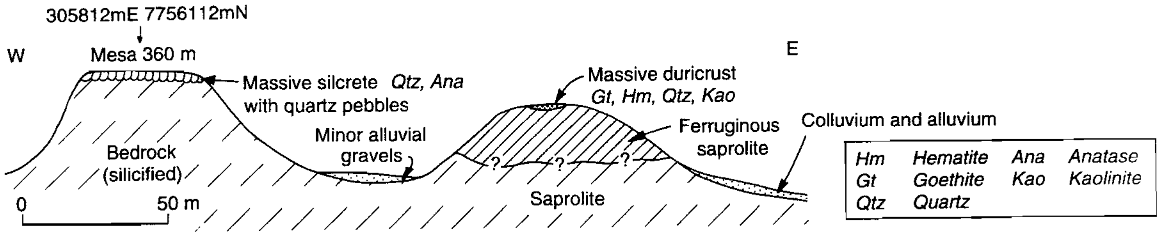


Figure 28. The development of mesa silcrete by relief inversion (transect 5), Buckley River-Grey Ghost district.

4.3 Python Prospect

4.3.1 Introduction

The Python Prospect is part of an exploration lease owned by Mt Isa Mines Exploration (MIMEX) 75 km north-northwest of Mt Isa. The study area, on the 1:100,000 Kennedy Gap geological sheet, is underlain by the Proterozoic Esperanza and Paradise Creek formations, and is centred on 303465mE - 775929mN, close to the Anthill Cu mine.

The Python Prospect is a Cu prospect with at least one drill intersection in significant oxidised Cu mineralisation. A surface geochemical anomaly of 1179 ppm Cu and 84 ppb Au occurs on a duricrust capped hill and the anomaly continues downslope in lateritic nodules and pisoliths. The origins of these materials, *i.e.* whether they were developed in sediments or on earlier residual materials is not certain. The detailed geology and weathering of a four square kilometre area around the hill were mapped to understand the evolution of these materials. Samples of surface materials were collected on a 500 x 250 m grid using a MIMEX surface geology map (Jones, 1994) as a basis.

4.3.2 Local geology

Extensively folded units of the Paradise Creek and Esperanza Formations of the McNamara Group are the main Proterozoic bedrocks exposed in the area. The Paradise Creek formation is overlain by the Esperanza Formation, and the contact between the two is at the base of a sandstone unit overlain by a distinctive, thick, stromatolitic chert. Outcrop of Paradise Creek Formation is white bleached siltstones and grey cherty lenses whereas the Esperanza Formation has extensive stromatolitic cherts and a few siltstones. Drilling in the area has shown that the dense cherts at the surface do not extend below the oxidation boundary (Buckland, 1994).

4.3.3 Regolith-landform relationships

4.3.3.1 General

A major drainage divides the ridges of the uplands in the north from colluvial plains in the south (Figure 29). In the northeast, the relief is substantial and there are active, steep drainages between siliceous ridges. Stromatolitic siltstones of the Esperanza Formation form siliceous ridges which shed cherty cobbles that dominate the lag over most of the mapped area. The relief is subdued in the northwest and brown, cracking, clay soils mark the vegetated courses of streams. The southern part consists of small, siliceous hills, surrounded by extensive areas of red, colluvial soils covered by siliceous lag. Colluvium is shallow, with most of the drainages exposing leached saprolite in their beds, which are less than two metres below the adjacent plain.

4.3.3.2 Detailed observations

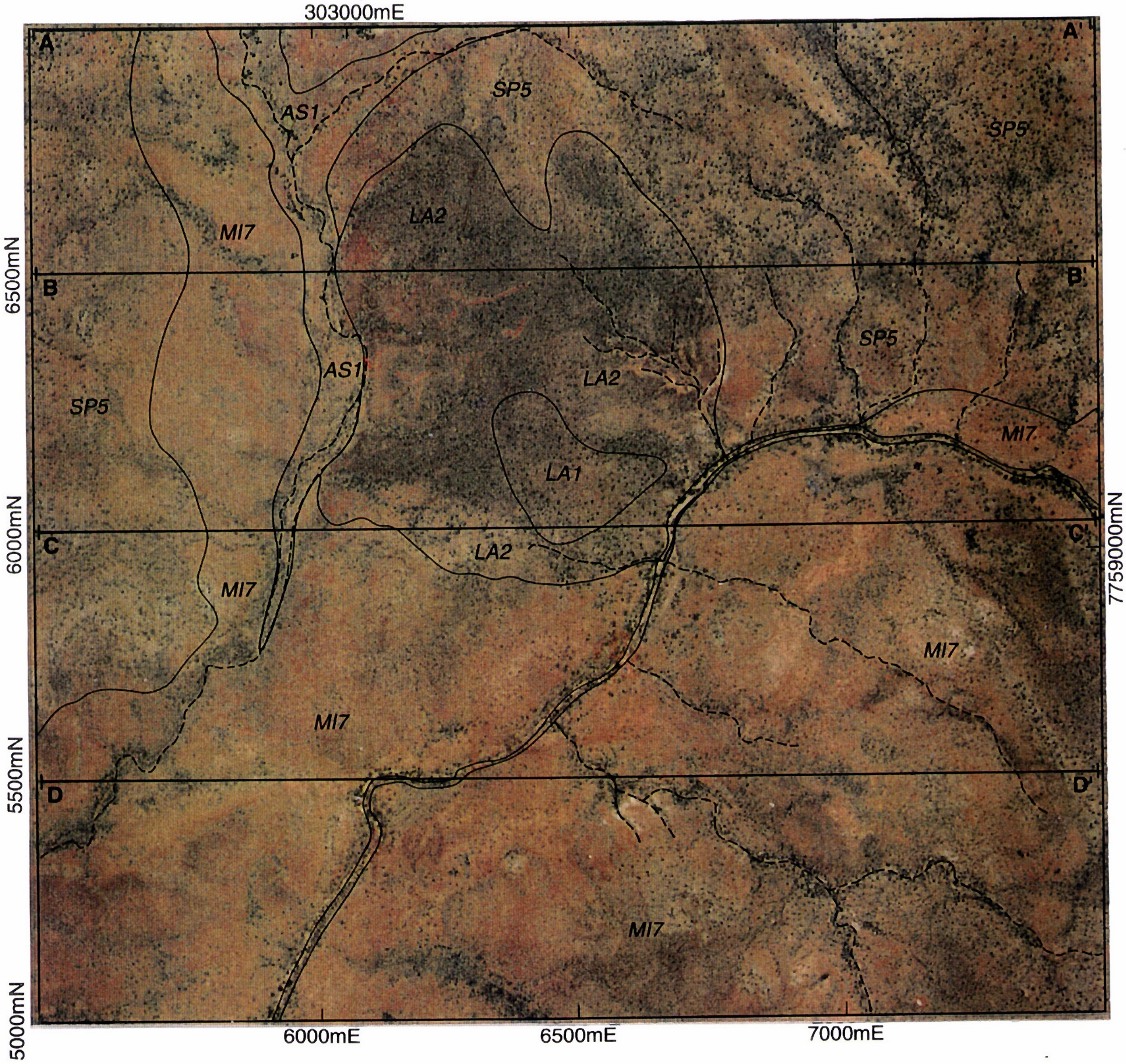
Four cross sections (Figure 30) shown on Figure 29 describe the main features of the landscape from the siliceous ridges in the northeast to the colluvial plains in the south.

The cherty lag on section A-A' is derived from hills to the west. The lag, which is on red soils, becomes more ferruginous eastwards, where it is truncated by a meandering creek bed with brown soils and three metre acacia scrub. The low hill to the east, between the small creek beds, is covered in dark, ferruginous, nodular lag. The creek bed at this point follows a fault at the boundary of the Paradise Creek and Esperanza Formations. The ground rises eastwards to a siliceous ridge and the lag becomes increasingly coarse and siliceous. The three eastern ridges are interspersed with flat areas with red soils and extensive cherty lag. The north-eastern corner of the area is the edge of an extensive plain underlain by carbonate rocks with carbonaceous and pyritic shales of the Proterozoic Lady Loretta Formation.

The western part of cross section B-B' is similar over the Paradise Creek Formation, with cherty lag on red soils which pass laterally to brown soils bordering two small streams. The fault between the Proterozoic formations has been etched by a stream with ferruginous lag on both sides. A ferruginous unit of the Esperanza Formation forms the slope east from 6500 mE and there is extensive ferruginous lag on both sides of the traverse. This ferruginous unit has produced a blocky lag on the ridges and patches of duricrust on south facing slopes. Siliceous ridges to the east shed a lag of cherty cobbles which dilute the ferruginous materials which are cut off in a steep sided creek at 7200 mE.

Cross section C-C' features a low, siliceous hill in the west, which confines the creek to a narrow channel. The hill in the middle of this section has an extensive cap of slabby duricrust, with a minor breakaway on its southwest side. The duricrust is 1-2 m thick and is composed of horizontally arranged massive plates that grade into ferruginous saprolite at depth (Figure 11D). These duricrusts are quartz-rich and impregnated by Fe oxides. They are reddish-brown to black, non-magnetic, rich in Fe and are dominated by goethite with variable amounts of quartz; they have marked solution features and dense, ferruginous accretions. The hill is covered by nodular goethitic lag and blocky material derived from duricrust. Ferruginous lag to the west and north of the hill contains lateritic nodules and pisoliths. The nodules are 5-15 mm in diameter, contain quartz and ferruginous fragments from a variety of sources. Some are composed entirely of goethitic material from the top of the hill, but most are hematitic and have textures that show they were formed in soils and locally derived colluvium. This rounded, nodular material contains more than 1000 ppm Cu and 50 ppm Pb. The eastern side of the hill slopes steeply to the creek and is covered with a scree of mixed cherty and ferruginous, lithic fragments. To the east of the creek are red, colluvial soils between rises of grey, cherty boulders and a few lenses of blocky goethitic accretions.

Section D-D' is dominated by alluvial/colluvial red soils with a covering of siliceous lag between low hills of cherty breccia. The main creek and other minor channels cut through the soil to leached saprolite. Alluvium coarsens towards the major creek where silicified cobbly conglomerate is exposed above leached saprolite.



LA1	Lag of lateritic nodules, pisoliths and fragments of ferruginous saprolite, pockets of slabby duricrust, plateau and mesas
LA2	Lag of lateritic nodules and fragments of ferruginous saprolite over saprolite, pediments and colluvial plains
MI7	Lag of mixed siliceous and ferruginous saprolite over saprolite, low hills
SP5	Silicified saprolitic lag on silicified saprolite, low hills
AS1	Thin alluvial soils over saprolite, valley floors

N

0 500 m

Approximate scale due to distortion from aerial photographs

Figure 29. **An overlay on the colour aerial photograph (Commonwealth of Australia, 6757 Kennedy Gap photo 7/990, 12.10.1972) of the Buckley River area, showing the regolith-landform units relative to the local grid at the Python Prospect.**

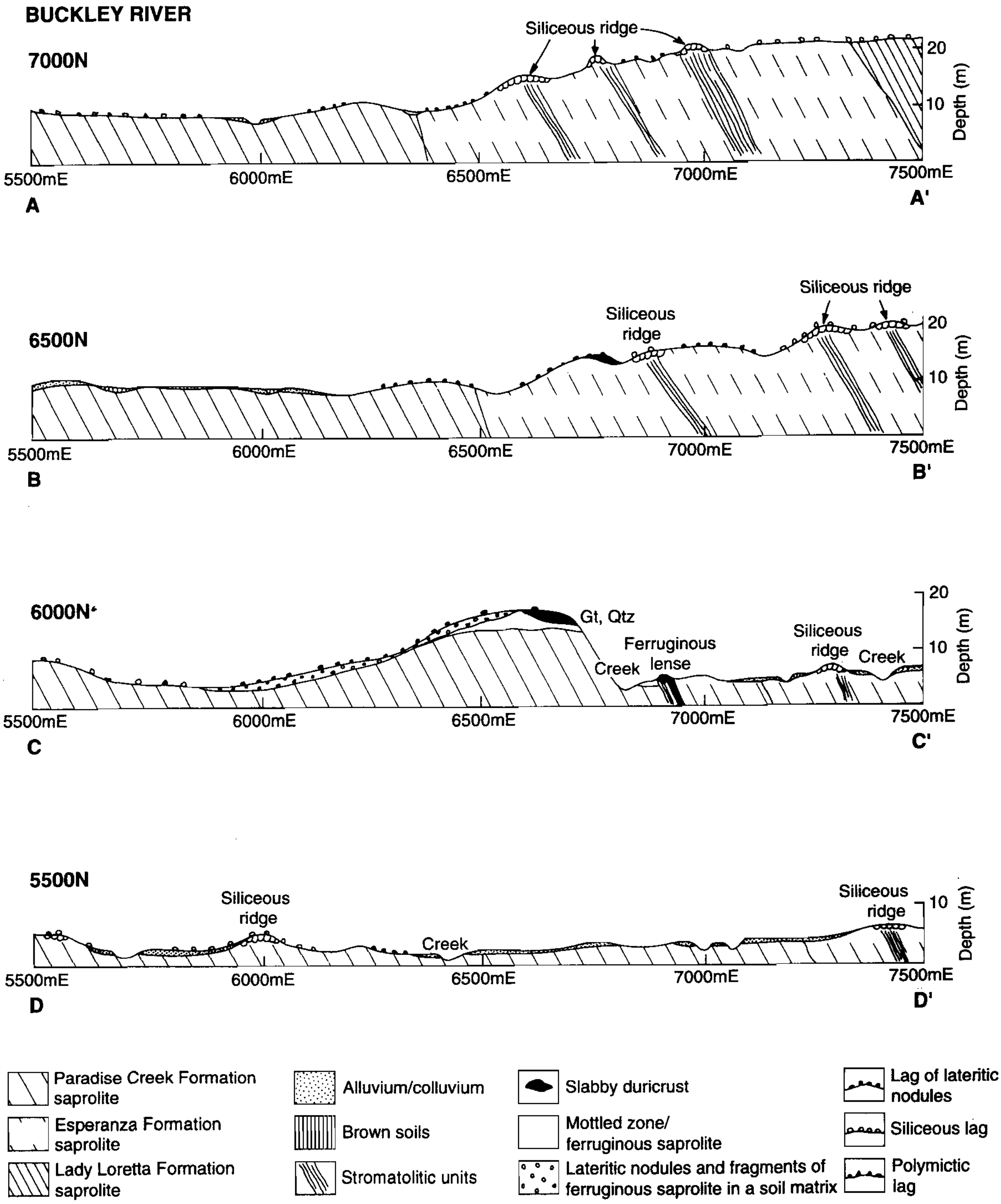


Figure 30. East-west cross sections of the regolith-landform at Python Prospect located on the overlay in Figure 29.

4.3.4 Geochemistry

4.3.4.1 General

The investigation of the geochemical anomaly at Python Prospect has focussed on ferruginous materials and the weathered profile in drill hole BR36. Samples of saprolite and siliceous lag were also analysed to provide contrast to adjacent ferruginous material and as background samples. Thirty-one samples of ferruginous surface materials were analysed from the cross sections described above. Fifty two samples were also taken from drill core (BR36) for geochemical analysis and characterisation of the profile which is located within the main anomaly. Analyses were by XRF and INAA, followed by investigation by scanning electron microscope, electron microprobe and optical microscope.

4.3.4.2 Ferruginous materials

The Fe_2O_3, As, Pb, Cu, Sb and Au data for the ferruginous samples collected over the mapped area are shown in Figure 31 and Table 5. The Cu, Au and Pb anomaly at the Python Prospect is restricted to slabby duricrust and lateritic nodules and pisoliths in the centre of the mapped area (Figure 31). Concentrations defining the anomaly were chosen from normal probability plots (Figure 32) which show breaks in the populations at the thresholds. The Pb concentrations show the most distinct break (50 ppm). Gold is at detection (5 ppb). Antimony > 20 ppm defines the anomaly, but As is little help. There are no meaningful correlations between these elements.

Slabby duricrust occurs on a rise which extends to the northeast of the mapped area. The geology of the rise (Figures 33 and 34) shows that there is a shear zone or fault under the duricrust. Geological information from company drill logs shows interbedding on a 10-20 m scale of the different units of the Paradise Creek Formation.

Table 5. Buckley River-Python Prospect.

Ident	Regolith type	East	North	SiO2	Al2O3	Fe2O3	P2O5	Ba	V	Zr	Cu	Zn	Pb	Sb	As	Au	S
		m	m	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppb	ppm
IS-46	Slabby duricrust	6550	5950	39.4	4.2	47.6	0.63	114	31	73	460	11	111	10.7	82	150	310
IS-47	Slabby duricrust	6550	5950	26.4	9.5	53.5	0.32	178	176	183	1179	12	68	22.1	86	84	650
BR-365	Slabby duricrust	6650	5940	44.1	5.7	43.0	0.18	134	53	144	388	10	84	5.9	89	2	340
BR-366	Slabby duricrust	6550	5950	35.2	4.6	50.5	0.81	149	18	87	489	9	72	14.3	111	23	300
BR-368	Slabby duricrust	6540	6010	60.2	3.2	32.9	0.07	415	20	254	450	8	17	2.7	138	2	450
IS-48	Gritty duricrust	6555	5970	29.3	12.1	52.7	0.13	122	91	172	549	14	137	4.7	92	2	330
IS-7	Silicified nodular duricrust	6545	5975	81.2	2.3	14.5	0.04	412	32	278	163	2	38	2.7	32	2	300
IS-8	Lateritic nodules	6550	5975	28.1	7.0	53.8	0.22	214	71	168	1084	7	92	7.2	70	2	390
IS-49	Lateritic nodules	6550	5990	13.7	8.3	65.6	0.29	357	50	123	1596	13	80	14.7	64	12	220
BR-311	Lateritic nodules	7000	7000	25.6	4.8	59.5	0.09	10	123	149	364	14	2	6.7	113	2	200
BR-318	Lateritic nodules	6500	7000	35.7	8.8	47.0	0.19	80	184	118	524	26	21	7.2	278	2	110
BR-319	Lateritic nodules	6250	6750	30.9	10.6	50.6	0.18	42	253	178	389	15	24	13.2	110	2	130
BR-320	Lateritic nodules	6000	7000	36.2	7.3	50.4	0.13	194	235	181	193	14	18	4.8	85	2	50
BR-328	Lateritic nodules	7250	6250	54.2	5.7	36.2	0.13	76	195	199	186	12	8	7.5	106	2	90
BR-329	Lateritic nodules	7250	6525	36.7	6.5	50.6	0.18	46	118	155	315	14	2	2.5	74	2	150
BR-330	Lateritic nodules	7000	6500	64.0	8.4	21.9	0.11	110	71	71	79	6	19	3.0	45	2	120
BR-331	Lateritic nodules	6750	6250	26.1	8.5	56.4	0.11	25	166	151	940	15	16	6.7	147	2	180
BR-332	Lateritic nodules	6500	6500	19.3	8.7	63.4	0.22	67	137	129	285	17	19	4.3	112	2	100
BR-334	Lateritic nodules	6250	6250	30.9	9.0	52.3	0.16	10	190	130	1560	24	16	13.0	38	2	90
BR-338	Lateritic nodules	6500	6000	21.8	8.9	60.0	0.23	98	155	139	1291	13	62	20.1	173	13	140
BR-345	Lateritic nodules	5750	5250	39.9	5.5	48.1	0.29	143	277	132	609	27	6	9.7	98	2	40
BR-350	Lateritic nodules	6250	5100	61.0	5.4	29.7	0.24	159	179	95	390	15	29	4.2	65	2	100
BR-335	Mixed Si/Fe lag	5500	6000	33.8	8.9	47.0	0.7	114	161	114	218	34	14	8.7	452	2	90
BR-351	Polymictic alluvium/colluvium	6500	5000	33.8	7.8	51.7	0.21	10	301	225	405	13	13	5.3	118	2	70
BR-325	Siliceous lag	5750	6250	91.6	1.1	6.0	0.03	118	105	304	14	2	26	2.5	10	2	70
BR-362	Fault ironstone	6890	5750	55.9	0.8	38.7	0.46	242	50	46	3745	15	80	27.3	178	187	230
BR-363	Fault ironstone	6720	5890	54.1	0.7	37.8	0.72	309	16	28	2254	19	196	4.4	162	130	990
BR-364	Fault ironstone	6710	5915	50.8	4.4	38.5	0.35	77	92	94	1211	6	74	61.7	136	48	510
BR-367	Stromatolitic saprolite	6540	5940	96.5	1.6	1.6	0.02	529	8	19	58	2	17	1.2	2.7	8	150
BR-369	Saprolite	6675	6100	79.8	7.5	6.2	0.03	544	24	80	160	6	6	1.5	49	2	250

NB Values used for plots and statistics are one third of detection limits.

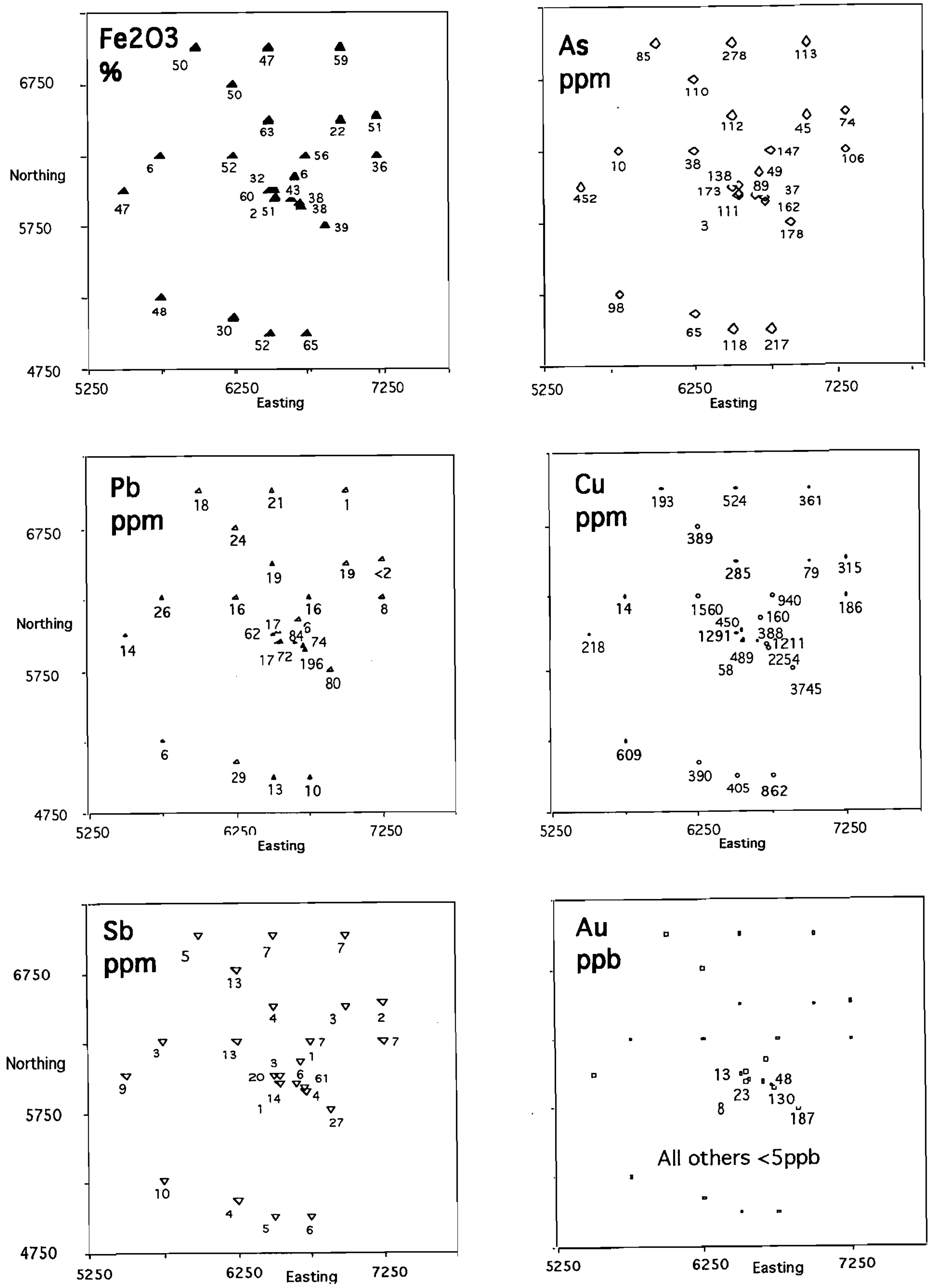
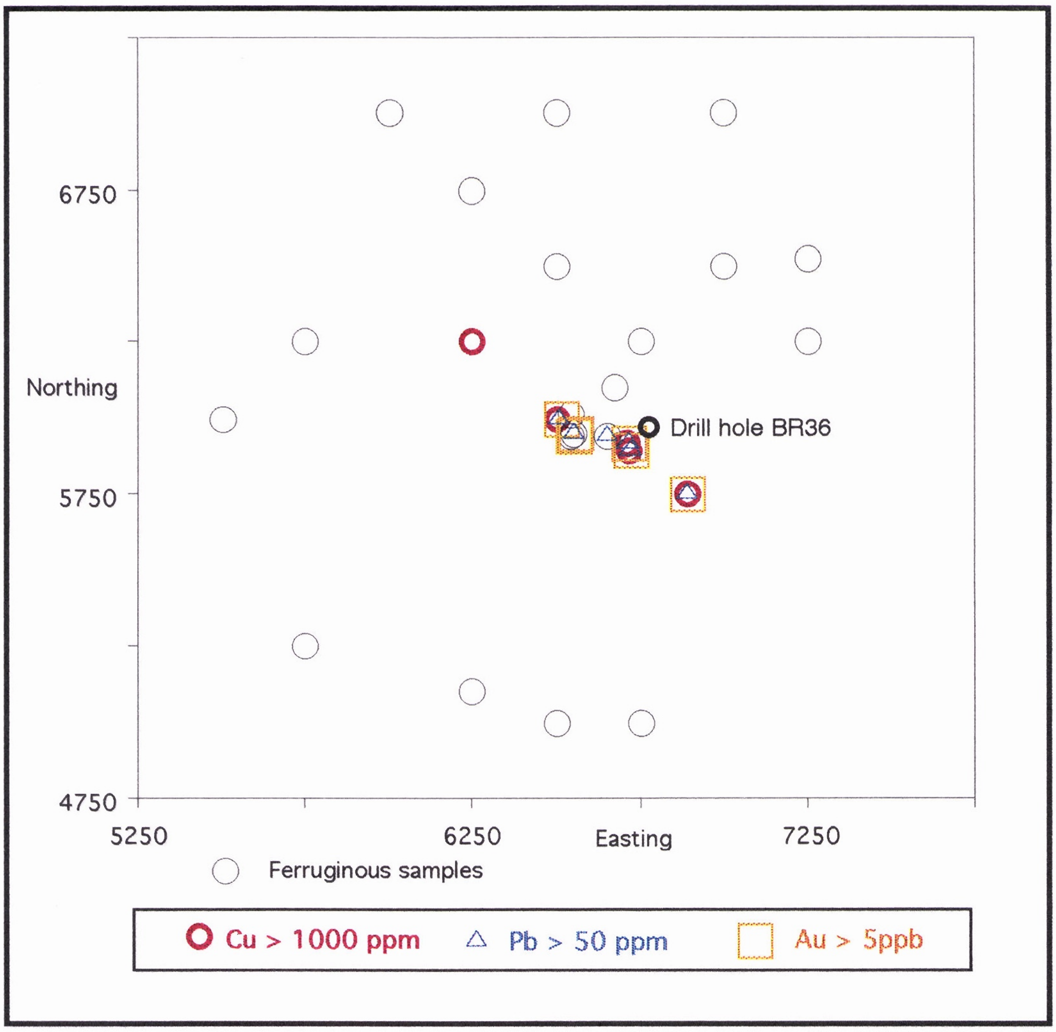


Figure 31. Maps showing the concentrations of Fe_2O_3, As, Pb, Cu, Sb and Au in the ferruginous samples, Python Prospect.

A



Normal Probability plots

B

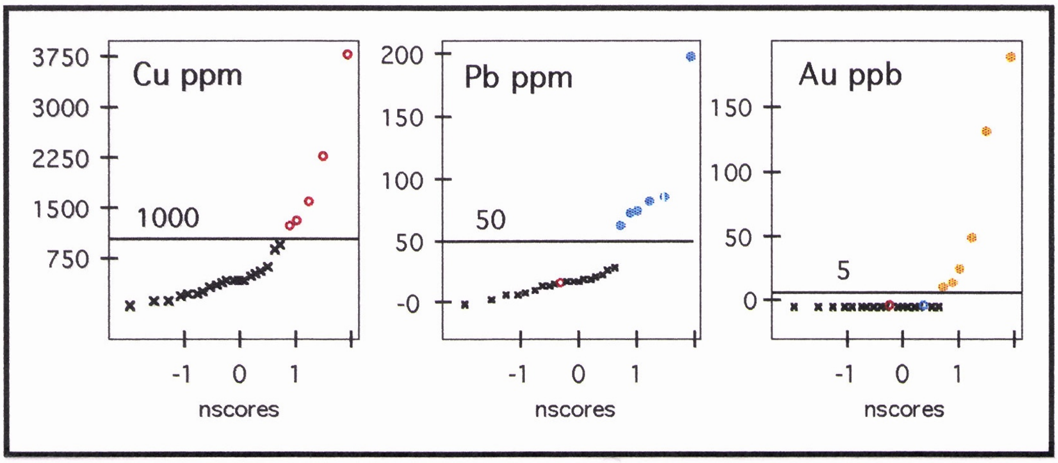


Figure 32. (A) A map of the location of selected ferruginous samples at Python Prospect. Anomalous samples were chosen from the normal probability plots (B) and coloured on the map.

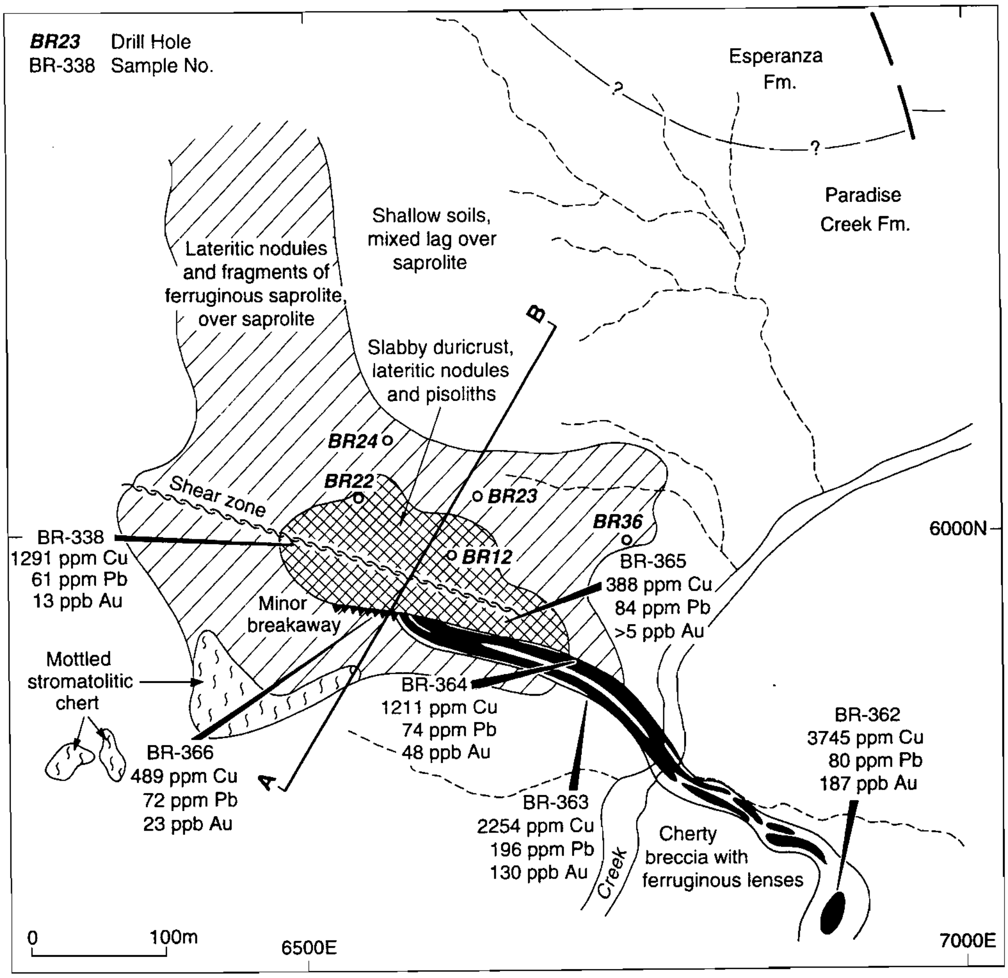


Figure 33. A map of the duricrust capped rise at Python Prospect with locations of sampling points and drill holes.

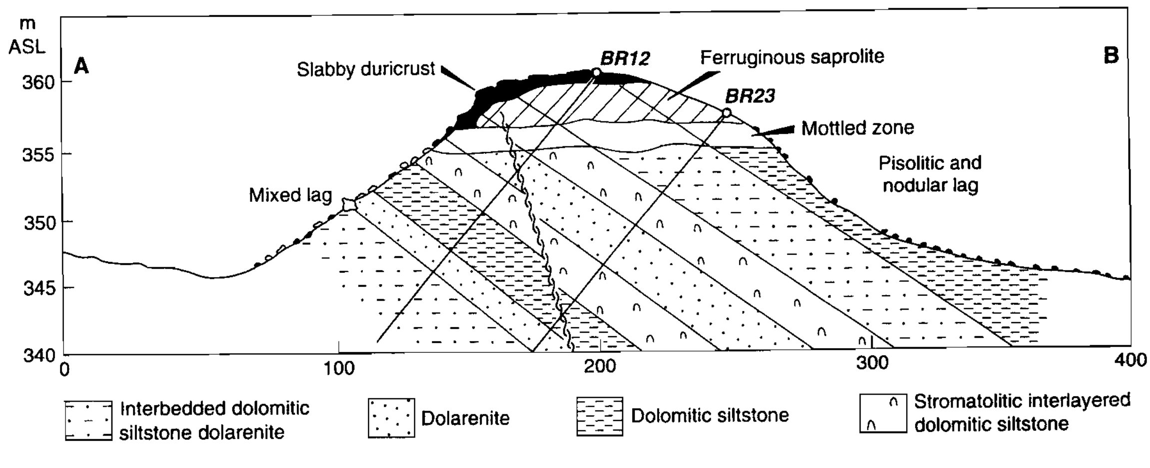


Figure 34. Cross section of rise shown as A-B in Figure 33, Python Prospect.

The fault is 2 to 5 m wide and has cherty margins and ferruginous veining (Figure 33), which is visible at surface for approximately 200 m from the eastern end of the low breakaway on the south-east of the rise to a low siliceous hill east of the creek. Several samples from the ferruginous part of the fault contain anomalous Cu, Au and Pb (Table 5). Quartz grains have inclusions of fresh sulphides. Sample BR-362, taken east of the creek, contains 187 ppb Au, 3745 ppm Cu and 80 ppm Pb (Figure 33). Sample BR-363, which has many sulphide inclusions in goethite-coated quartz grains, contains 990 ppm S. Dispersion from the fault has caused a broad anomaly in Cu, Pb and As in the slabby duricrust and lateritic nodules and pisoliths.

4.3.4.3 Drill hole BR36

General

Drill hole BR36 is located on the shoulder of the duricrust-capped hill at the Python Prospect at 5990mN, 6750mE on the local exploration grid. The intersected regolith profile was chosen for characterisation because of anomalous Cu, Pb and Au concentrations in the surface lateritic nodules (*e.g.*, 1109 ppm Cu) and in the saprolite (3% Cu) although fresh bedrock contains only 250 ppm Cu. The mineralogical and geochemical data are summarised in Figure 35.

Nodular gravels (0-0.2 m)

The ferruginous nodular gravels at the top of the BR36 consist mainly of hematite, goethite and quartz, with minor amounts of kaolinite and mica. The cores of nodules contain subrounded grains of quartz (250 μm) in a matrix of finer quartz cemented by goethite (Figure 36A). They are the most ferruginous materials in the profile (59.4% Fe_2O_3) and contain anomalous levels of Cu (1109 ppm), Pb (75 ppm), As (196 ppm), Sb (31 ppm) and Mo (3.6 ppm).

Gravelly soils (0.2-1.5 m)

These soils contain much more quartz and kaolinite than the nodular gravels but they still contain 40.75% Fe_2O_3, as hematite and goethite. They are richer in Cu (1198 ppm) and As (224 ppm) than the surface materials but poorer in Pb (45 ppm), Sb (21.3 ppm) and Mo (2.9 ppm).

Mottled zone (1.5-6.3 m)

The mottled zone samples at 2.7, 5.2 and 5.3 m contain less than 10% Fe_2O_3 and consist dominantly of quartz (>60% SiO_2). Samples from the mottled zone have homogeneous fine quartz, with uniform distribution, indicating it is undisturbed (Figure 36B). In addition to quartz, mica and kaolinite, dolomite is also present at depth 5.2 m. The trace elements (Cu, Pb, As, Sb) drop proportionately with Fe from the surface to the mottled zone.

Upper saprolite (6.3-40 m)

The upper saprolite is a bleached zone dominated by silt sized quartz, mica and kaolinite. Iron concentrations vary but all are below 3.5% Fe_2O_3. Copper concentrations follow the Fe and are generally low, but Pb is higher (55 ppm) at 23.7 m where Fe is only 0.5% Fe_2O_3.

Middle saprolite (40-75 m)

The middle saprolite has essentially the same matrix as the upper saprolite (i.e. quartz, mica and kaolinite). However, it also has goethitic veining (Figure 36C) around which the Cu (3%) and the other trace elements reach their highest concentrations in the profile (Au 16.5 ppb, Pb 366 ppm, As 238 ppm, Sb 77 ppm, and Mo 5.2 ppm).

Lower saprolite (75-95.1 m)

The lower saprolite is a silty clay with goethitic veining and minor malachite, but the chalcophile element contents are lower than in the middle saprolite (Figure 36D). The saprolite is produced by the leaching of dolomite from the bedrock.

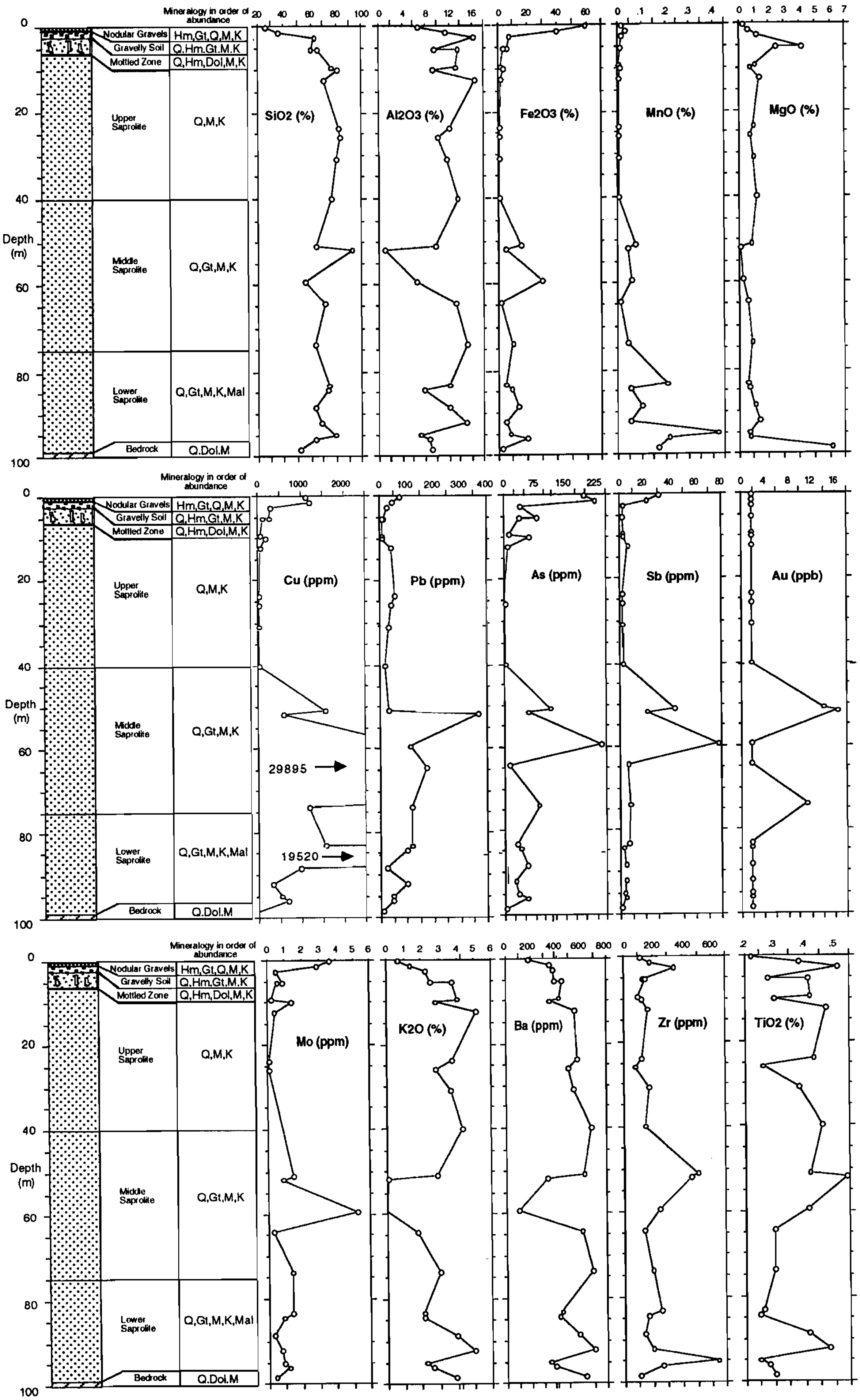


Figure 35. Geochemistry and mineralogy of regolith units, drill hole BR36, Python Prospect

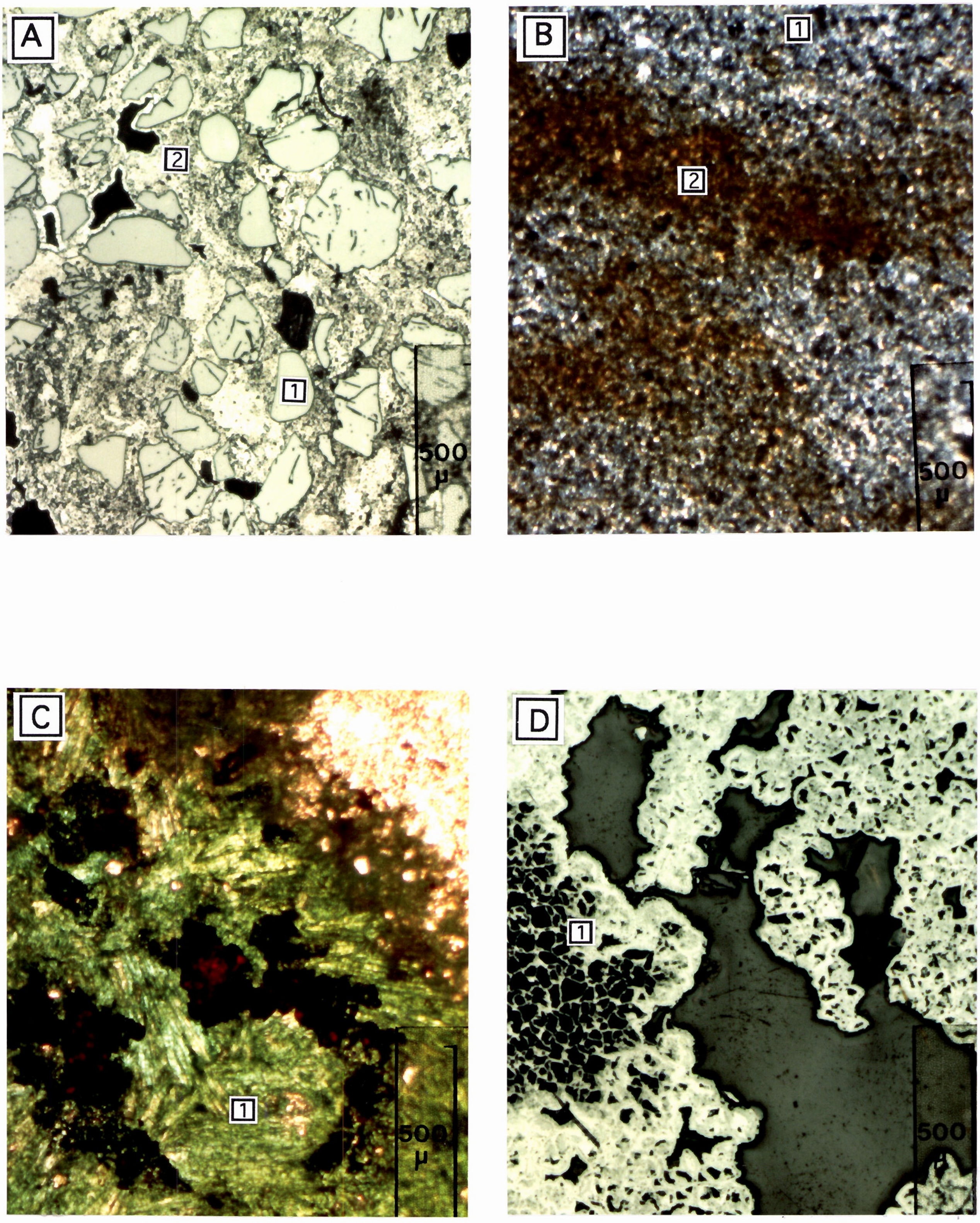
Figure 36. Photomicrographs of slabby duricrust and saprolite from drill hole BR36, Python Prospect.

(A) Photomicrograph of slabby duricrust with subrounded quartz (1) in matrix of finer quartz and goethite (2) (reflected light).

(B) Fine quartz in ferruginous saprolite (1) (transmitted light, crossed polarizers) with bands of goethite/hematite (2).

(C) Malachite (1) in silty saprolite from 64.4 m (transmitted light, crossed polarizers).

(D) Replacement of carbonates by goethite (1) at the saprolite-bedrock interface at 95 m (reflected light).


A
2
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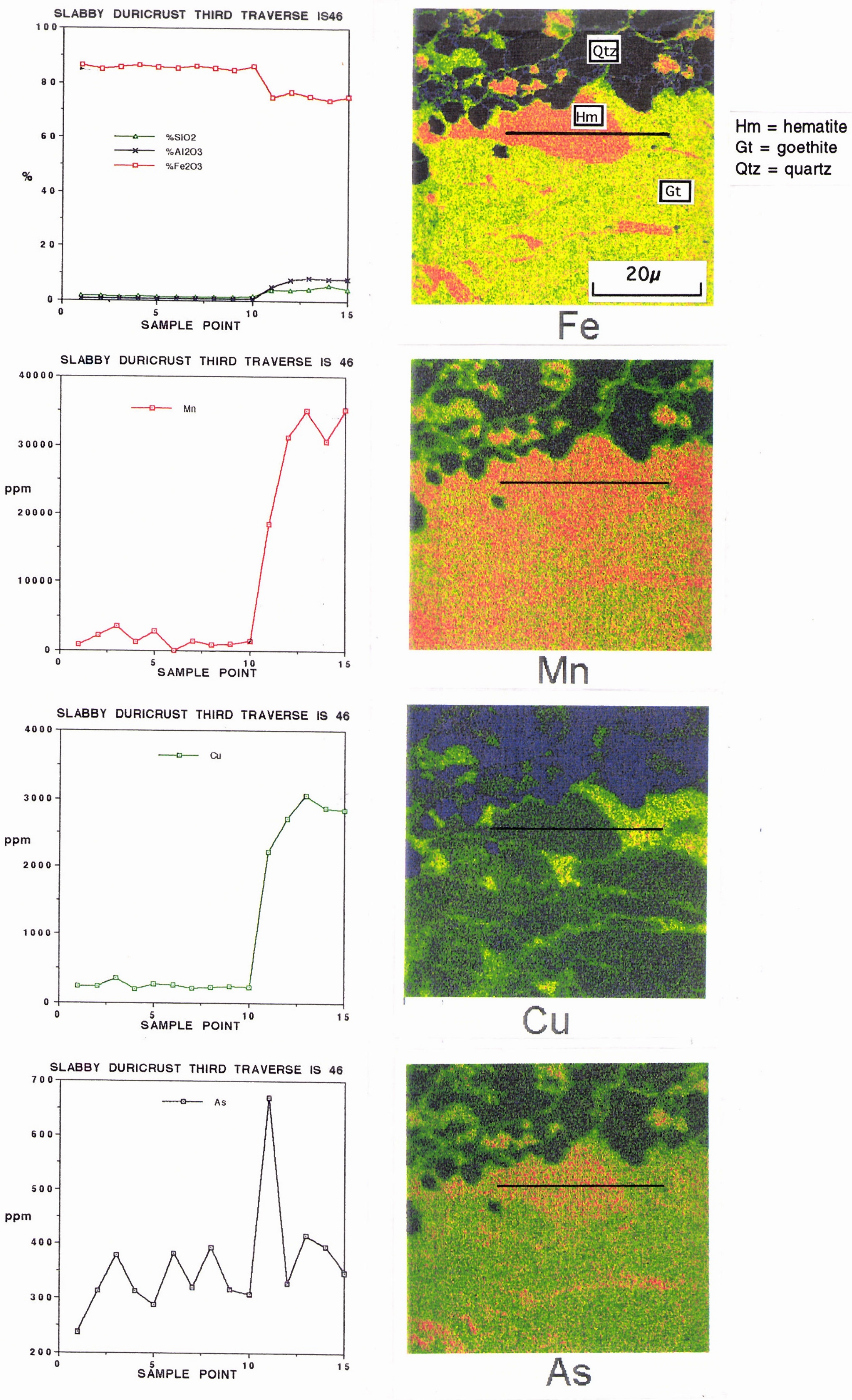


Figure 37. Stepped traverse and element maps of slabby duricrust, sample IS46, Python Prospect. Left hand plots are two micron steps across the traverse marked on the Fe element map. Coloured map show element distributions: red high, blue low.

Bedrock

Bedrock largely consists of quartz, dolomite and mica. It contains 3.5% Fe_2O_3 and less than 40 ppm Cu. The concentrations of As (8 ppm), Pb (21 ppm) and Sb (1 ppm) are very low. Gold and Ag (not shown in Figure 35) are below detection.

4.3.4.4 Electron microprobe analyses

Element mapping of the slabby duricrust material (Figure 37) has illustrated distribution of Cu and As within the Fe and Mn minerals. The sample image has an upper layer of quartz and a lower layer of hematite and goethite. The traverse crosses from a hematite grain to goethitic infilling, which is defined clearly by the Cu distribution. The Cu element map shows the highest Cu concentrations occur with Mn in cracks around goethite grains. This is confirmed in step plots of the 0.3 mm traverses, which show a greater correlation of Cu with Mn than with Fe. Arsenic is concentrated in the more Fe-rich grains. The Cu-rich manganiferous material fills cracks as the latest phase of accumulation.

4.3.5 Conclusions

4.3.5.1 Landscape evolution

The landscape model is summarised in Figure 38. The landscape at the Python Prospect is predominantly erosional, with stripped saprolite uplands and less than two metres of colluvium covering silicified saprolite in the valleys. The bedrock has been weathered to a depth of 90 m, with loss of carbonates and oxidation of sulphides. The stromatolitic units of the Esperanza Formation form strong siliceous ridges that control drainage and slow erosion in the northeast of the mapped area. The cherty lag from these stromatolitic units is very resistant to weathering and it is therefore widespread as angular fragments from 20-100 mm across. The pyritic units of the Esperanza Formation are softer and therefore are low points between the ridges and are dominated by siliceous lag. Where the ridges are truncated by faulting, the pyritic units become part of a valley slope with extensive ferruginous lag. Laterally derived-Fe from fault and groundwater subsequently has cemented saprolite and colluvium into patchy duricrust (Figure 38). Slabby duricrust forms on the slopes by induration of locally-derived colluvium and upper saprolite. Subsequent erosion around this indurated material may leave it as a small mesa shedding a ferruginous colluvium of nodules, into the adjacent drainages.

The formation of lateritic nodules and pisoliths has been complex. They were developed in soils and locally-derived colluvium and from collapsing of underlying ferruginous saprolite, and are probably older than the slabby duricrust.

On the colluvial plains, laterally-derived silica has modified erosional process. Silicification at the contact between colluvium and saprolite determines the depth of the smaller streams. Where this silicified layer has been eroded, as these streams approach the major drainage, there is an abrupt change from a shallow 'V' shape drainage in colluvium to a 'U' gully in saprolite.

4.3.5.2 Geochemistry

- There are three sources of Fe and trace elements (Cu, Pb, As, Sb, Au, Ag) at the Python Prospect, namely pyritic units of the Proterozoic bedrock, a fault that cuts through the duricrust-capped hill and absolute accumulation from outside sources. The fault is richer in Pb, Au and Sb which are probably related to underlying mineralisation. Dispersion from the fault has caused a broad anomaly in the slabby duricrusts and lateritic nodules and pisoliths.
- Copper is mobile in the weathered environment. It has precipitated as malachite in the saprolite and with Fe and Mn oxides in ferruginous materials.

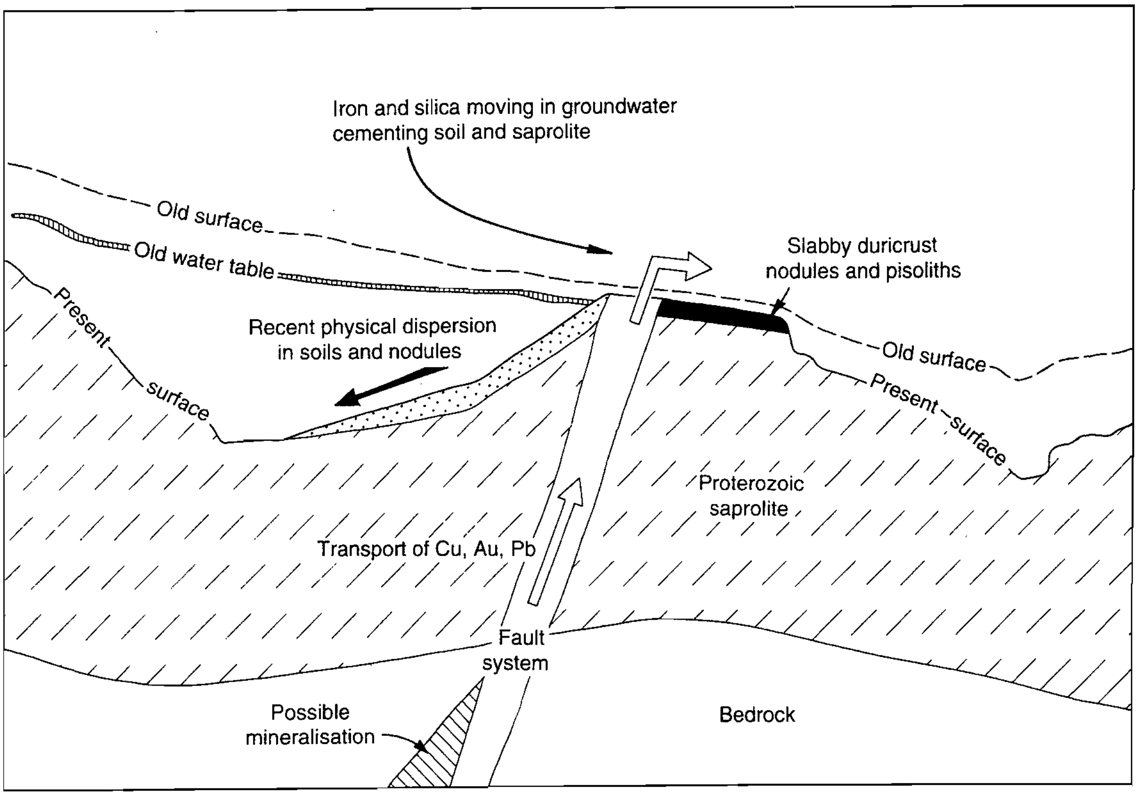


Figure 38. A model of regolith-landscape and geochemical dispersion processes which may have influenced the anomaly in ferruginous materials at Python Prospect, Buckley River-Grey Ghost district.

4.4 Grey Ghost Prospect

4.4.1 General

The Grey Ghost Prospect comprises a strongly dissected terrain, with rugged relief and mesa topography. The main structurally-controlled drainage runs in a NS direction. The area is dominated by low hills of silicified saprolite, lateritic duricrust and plateaux of silcrete (Figure 39) that rise to 60 m above the plain. Silcrete, 1-2 m thick, is generally developed on remnants of Mesozoic sediments that overlies Proterozoic silicified saprolite. Isolated pockets of thicker sequences of silicified Mesozoic sediments in various stages of truncation occur south of the Grey Ghost Prospect (Figure 12E).

Although slight, ferruginisation of the silcrete is widespread, and ranges from a brown colouration (mottling) to Fe-cementation of siliceous nodules. A zone in which kaolinisation and silicification have both occurred commonly occurs beneath the silcrete forming a silicified saprolite. Silicified saprolite is commonly mottled.

Pockets of massive, slabby and conglomeratic lateritic duricrusts appear sporadically on low hills and mesas and tend to be more abundant towards the south. Conglomeratic duricrusts are developed on the basal gravels of Mesozoic sediments.

The ridges of the low hills are sustained by resistant N-trending quartzitic layers of the Proterozoic. Some of the lower hills east of the main northerly drainage have ferruginous lithosols associated with the ferruginous siltstone lithology. Some hills are stained ochre due to interbedding of pyritic shale in the Proterozoic.

The valley floors are generally broad, possibly because the lower saprolite is less silicified and more readily eroded. Minor amounts of alluvium occur in valley floors. Representative sections through the regolith at Grey Ghost are given in Figures 40 and 41.

Massive to banded ironstone pods, rich in goethite and hematite and in some curious ferruginised pseudomorphs occur within the saprolitic dolomitic shales, lie parallel to bedding and are associated with some Pb and Zn anomalies. These have been sampled for geochemical and petrographic study and will be reported upon later. Dolomite and Zn-rich siderite occur in their equivalent fresh rocks.

LT2	Lag of lateritic nodules, lateritic duricrust and indurated ferruginous saprolite, Mesas
SI2	Silcrete plateaux
SP5	Lithosols over silicified saprolite and saprolite, low hills
SP4	Ferruginous lithosols over saprolite, low hills
——	Transect

N

0 1 km

Approximate scale due to distortion from aerial photograph

Figure 39. Map showing the surface distribution of regolith-landform units and vegetation as an overlay to the colour air photograph (Commonwealth of Australia, 6757 Kennedy Gap photo 3/750, 4.10.1972), Grey Ghost Prospect. Transect ABC and DEFG are described in the text.

4.4.2 Detailed observations

4.4.2.1 Point A on transect ABC - silcrete profile on Mesozoic sediments

Silicified, presumed Mesozoic, sediments occur as mesas. A type section from the Grey Ghost Prospect consists of vertical, elongated blocks of columnar silcrete (Figure 42B,C), form the most prominent parts of silcrete exposures in the area. Silcrete cappings are underlain by silicified saprolite which, in turn, overlies kaolinitic saprolite. Here, silicification extends to a significant depth (~10 m) into the Proterozoic saprolite. The sediments occur immediately above (at about 2.5 metres) and are marked at their base by a thin gravel bed.

Silcrete has a nodular, matrix-supported fabric; the proportions of quartz and matrix are approximately equal. Bedrock structures are not apparent. The silcrete consists of quartz and anatase and is strongly mottled by hematite and goethite. The columnar structure displays numerous pedogenic features, including nodules and silans (silica skins formed by illuviation). The silicified saprolite largely consists of quartz, kaolinite and muscovite.

Silcrete profiles were analysed for major and trace elements. The major differences in chemical composition between the Proterozoic silicified saprolite and its overlying silcrete are:

(a) Silcrete is far more siliceous (94-95% SiO_2) and much less aluminous (<1% Al_2O_3) than silicified saprolite (74-81% and 9-15% respectively).

(b) Silcrete is depleted in K (0.04% K_2O) and Ca (0.02% CaO) relative to the silicified saprolite (0.9-1.8% and 0.35-0.47% respectively).

(c) Silcrete is significantly enriched in Ti (1.7-2.3% TiO_2) and Zr (424-600 ppm) relative to silicified saprolite (0.4-1.4% TiO_2 and 111-292 ppm respectively).

Point B on Transect ABC

A yellow-brown columnar silcrete uncomformably overlies a silicified mottled zone on a mesa (Figure 42D). The silcrete columnar structures are about 3 m high with cauliflower-like tops and fluted or ropy features on the sides, akin to candle wax drippings. From a distance, the yellow-brown silcrete top can be easily mistaken for a ferruginous duricrust. Some grey-white, columnar silcretes display few fluted features. On top of the silcrete columns is a patchy mantle of silcrete rubble and mottles.

The mottled zone is about 3 m thick and consists of yellow-brown, blotchy hematitic mottles set in a silicified, kaolinite and quartz-rich matrix. The upper saprolite is more silicified than the lower saprolite and the distinct bedding planes of the Proterozoic are preserved. The silicified saprolite consists of quartz, muscovite and feldspar. Preservation of the bedding planes by silicification gives an impression of a saprock. The lower saprolite, which is less silicified, shows more disintegration of bedding planes.

Silcrete evolution

Remnants of Mesozoic sediments indicate that, during the Cretaceous, a marine incursion deposited sediments over a large part of the Grey Ghost Prospect and its surroundings. A substantial pre-Mesozoic relief is indicated by a Proterozoic basement occurring at different elevations beneath a Mesozoic cover. After Mesozoic sedimentation, formation of a relatively flat silcrete sheet is postulated. This extensive silcrete sheet then underwent major erosion, incision and physical weathering, leaving pockets of silcrete capping the higher hills and plateaux and low hills (20-30m) of pale, silicified saprolite of the Proterozoic. A cross section of the area for transect ABC, as shown in Figure 41 typifies the landforms of this area, showing the effects of three stages of erosion :

(a) Incision into the silcrete sheet, giving a dendritic drainage pattern, but leaving remnants of the plateau surface.

(b) Further disintegration of the incised, silcrete-capped plateau to give a number of interconnected plateaux.

(c) Further incision, this time penetrating the Proterozoic bedrock, to give a drainage pattern with a marked northerly structure, leaving low hills (20-30m) mantled by bleached saprolite.

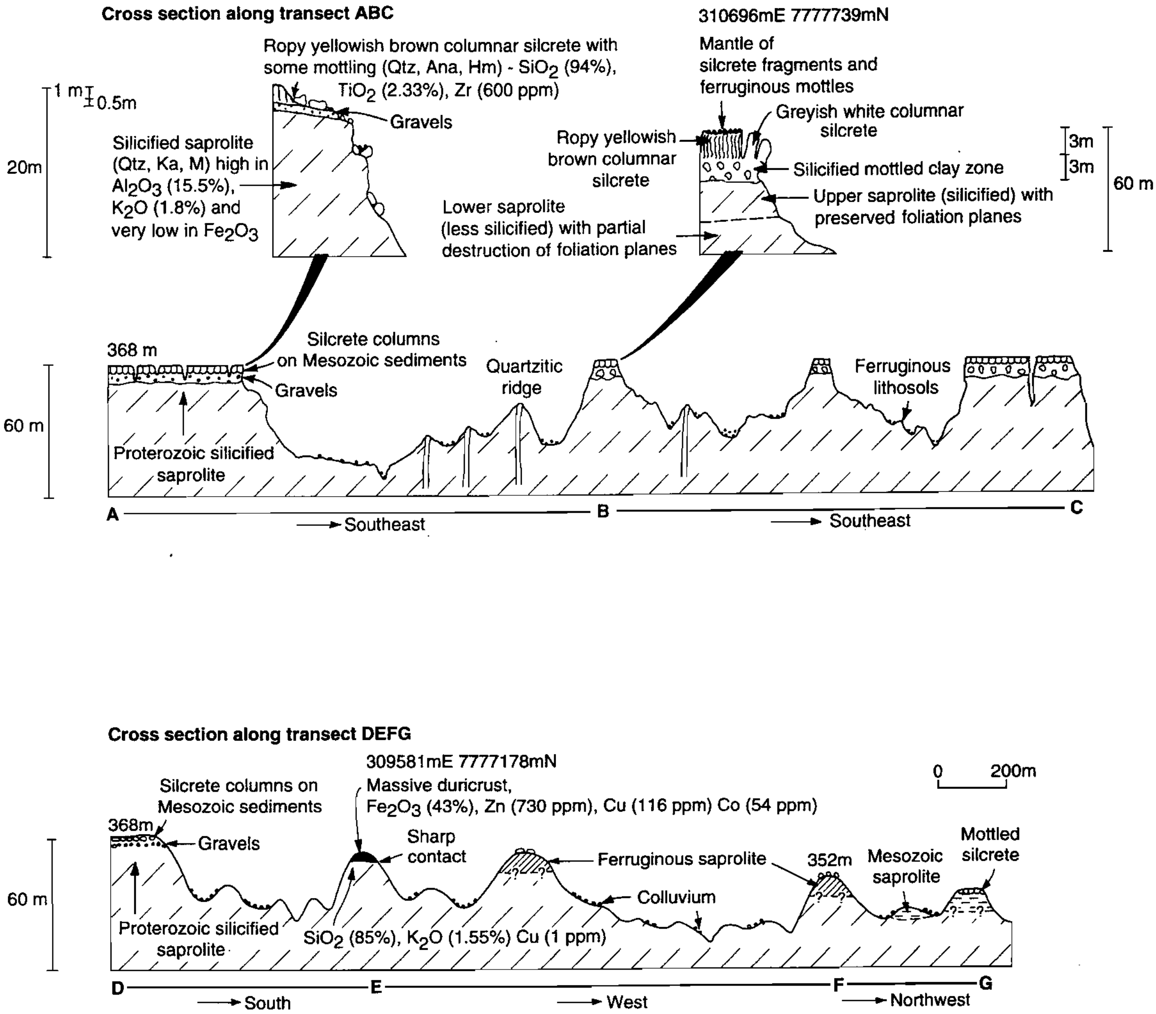


Figure 40. Cross sections along transect ABC and DEFG shown on Figure 39, Grey Ghost Prospect.

The kaolinisation of the mottled clay zone and saprolite suggests that there was a strong leaching during weathering of the Proterozoic bedrocks. Formation of the silcrete sheet could have come after kaolinisation, by precipitation of Si in surface horizons from Si-rich groundwater. Columnar silcrete may have formed by dessication cracking of the silcrete sheet. Surface silicification has preserved the foliation of the upper saprolite; the mottled zone could reflect a formerly oscillating water table caused by dry and wet cycles during formation of the silcrete sheet.

The fluted features of the silcrete could be a combination of solution weathering and silcrete formation. Iron impregnation is greater on fluted columnar silcrete, which is more porous than denser, grey-white, columnar silcrete. It occurs preferentially on the surface and in the interstices between the silcrete columns, possibly indicating that Fe was added after the silcrete formed.

4.4.2.2 Point E on Transect DEFG - Lateritic duricrusts

This is a mesa at a lower elevation than the silcrete-capped plateau; mesa is capped with 1.5 m of thick, black, massive duricrust. Minor quartz pebbles and sandy grit occur within the duricrust. The duricrust overlies silicified saprolite and is dominated by goethite and quartz (Figure 12D). There is a sharp contact between the massive duricrust and the underlying silicified saprolite which consists largely of quartz and mica. The massive duricrust is characterised by high concentrations of Fe (42.6% Fe_2O_3) and Si (49.2% SiO_2) and low concentrations of Al (2% Al_2O_3). Silicified saprolite consists largely of Si (85.4% SiO_2), Al (7% Al_2O_3) and K (1.55% K_2O) with very small concentrations of Fe (2.5% Fe_2O_3), Mg (0.4% MgO) and Ca (0.11% CaO). The abundances of Cu (116 ppm) and Co (54 ppm) in massive duricrust are much greater than the underlying silicified saprolite (1 ppm Cu), suggesting the two units are not genetically related.

Field relationships, and the different composition between massive duricrust and the silicified saprolite suggest possible differences in provenance, although this is not supported by heavy mineral analysis. It is suggested that the massive duricrust was probably formed in a low position rather than a channel, in an undulating landscape, with Fe and Cu derived laterally in groundwater. The topography has since been inverted.

4.4.2.3 Transect XYZ

At location Y, a mesa is capped with 1.5 m of thick, black, slabby, conglomeratic duricrust which overlies ferruginous saprolite and saprolite derived from shale (Figure 42). The surface is mantled with polymictic lag. The slabby duricrust contains quartz pebbles and is dominated by quartz, hematite and goethite. The underlying ferruginous saprolite largely consists of goethite, quartz and kaolinite; hematite and quartz pebbles are absent. The saprolite consists of fine-grained quartz, kaolinite and mica, which is consistent with the chemical composition.

The major and minor element concentrations of the slabby duricrust and ferruginous saprolite are very similar. Slabby duricrust consists largely of Fe (37.4% Fe_2O_3), Si (50% SiO_2) and Al (6.7% Al_2O_3). The saprolite contains more Si (73.6% SiO_2) and moderate concentrations of Al (14.6% Al_2O_3) but is very poor in Fe (0.5% Fe_2O_3). The abundances and dispersion characteristics of Zn and Cu are different from that of Pb. The concentrations of Zn (125 ppm) and Cu (35 ppm) in slabby duricrust are much greater than the underlying saprolite (15 ppm Zn, <1 ppm Cu). By contrast, Pb concentrations are below detection in slabby duricrust, compared to saprolite (63 ppm).

Slabby duricrust is formed from ferruginisation of the basal gravels of the Mesozoic sediments. Dispersion of Cu and Zn into slabby duricrust has resulted from weathering of underlying and nearby bedrocks. There is no dispersion of Pb because of its relatively immobile nature.

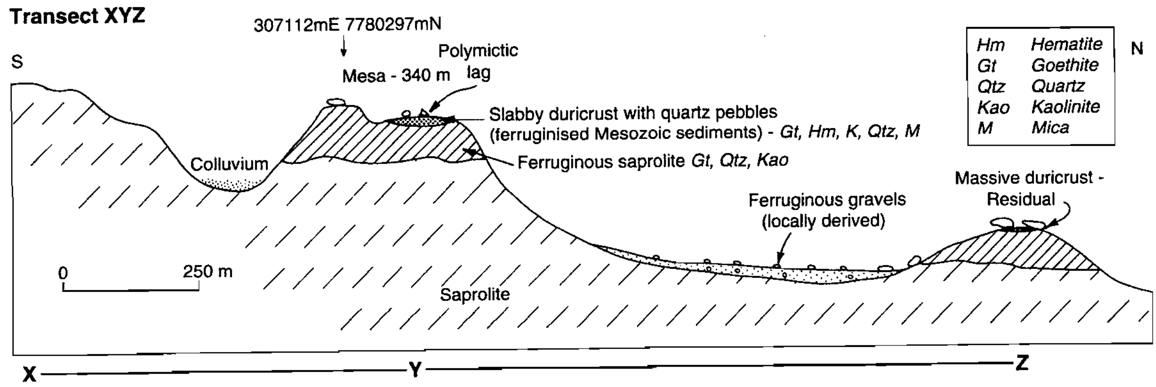


Figure 41. Cross section along transect XYZ, Grey Ghost Prospect.

5. MAMMOTH MINES DISTRICT

5.1 Regional Setting

Most of the country in the Mammoth Mines district is in the 'Gulf Fall', a term used by Stewart (1954) to describe areas drained by streams which flow into the Gulf of Carpentaria. There are three drainage systems: (a) the Gunpowder Creek system which flows into the Leichhardt River; (b) the Thornton River system (in the northwest); and (c) the Buckley River system (in the southwest). The Gunpowder Creek and Thornton River drainage systems are in the Gulf Fall, but the Buckley River system drains into the Georgina River and, eventually into Lake Eyre. All drainage systems flow intermittently, mainly in the wet season.

The district is largely dominated by hills, ridges and erosional plains which comprise actively eroding and deeply incised country, except for the far west, and include all of the Proterozoic and some Cambrian and Mesozoic sedimentary rocks. Proterozoic rocks crop out over most of the Mammoth Mines district and are covered by Cambrian and Mesozoic sedimentary rocks to the west. A sequence of basal breccia and conglomerate (Mount Hendry Formation) overlain by and laterally equivalent to dolomite and cherty dolomite (Thorntia Limestone), siltstone, chert, shale and phosphorite (Bottle Creek Formation) covered most of the region in the Middle Cambrian (Hutton and Wilson, 1985). Uplift and erosion has removed most of these rocks, except for a few remnants in the eastern Mammoth Mines Area and two troughs in the western part of the district in which thick Cambrian sediments are preserved. The Mesozoic sediments of the district have also been largely removed. Duricrust capped mesas occur in three large areas in the district, two in the northern Mammoth mines area (around Lady Loretta and Drifter) and the third in southeastern Undilla. They are lateritised remnants of Proterozoic and Mesozoic rocks and form mesas that have been dissected by modern streams.

Deposits of iron-cemented gravels occur where streams cut into the Mesozoic cover in the northwestern Mammoth Mines area (Hutton and Wilson, 1985). These comprise moderately- to well-rounded clasts in an intensely ferruginous matrix. The gravels form terraces 1-5 m above current stream levels and are being eroded by the present erosion cycle. Iron oxides in the cement were probably deposited from solution from previously lateritised material.

Erosional areas are characterised by residual soils and locally derived colluvium. Depositional areas have a cover of sand, silt and gravel that occupy active stream channels and occur as flood plain, levee and overbank deposits.

5.2 Lady Loretta Deposit

5.2.1 Geology and geomorphology

The Lady Loretta Deposit is a synclinal, stratiform, Mt Isa style Ag-Pb-Zn orebody hosted in shales, siltstones and dolomitic siltstones. It occurs beneath remnants of a deeply-weathered, lateritised land surface which occurs about 60 m above the surrounding plains. The subcrop of the ore and adjacent pyritic shales consists of barite-bearing hematitic and limonitic gossans, which are ferruginised and silicified and grade into a mottled, ferruginous zone at 5 m depth (Alcock and Lee, 1974; Carr, 1984; Hancock and Purvis, 1990). This is underlain by bleached material which passes into oxidised metasediments at 50 m; oxidation penetrating to 100 m and, near faults and shears, locally to >300 m. Secondary Pb minerals (anglesite and cerussite) occur within a few metres of the surface. Complete leaching of Zn extends to 100 m depth, but Zn forms an extensive halo lower in the landscape (Alcock and Lee, 1974; Cox and Curtis, 1977). There is little Cu.

Figure 42. Ferruginous materials and silcretes.

(A) Development of goethite-rich cutans (1) on hematite-rich mottles (2). Location: 331452mE - 7740925mN, Buckley River-Grey Ghost district.

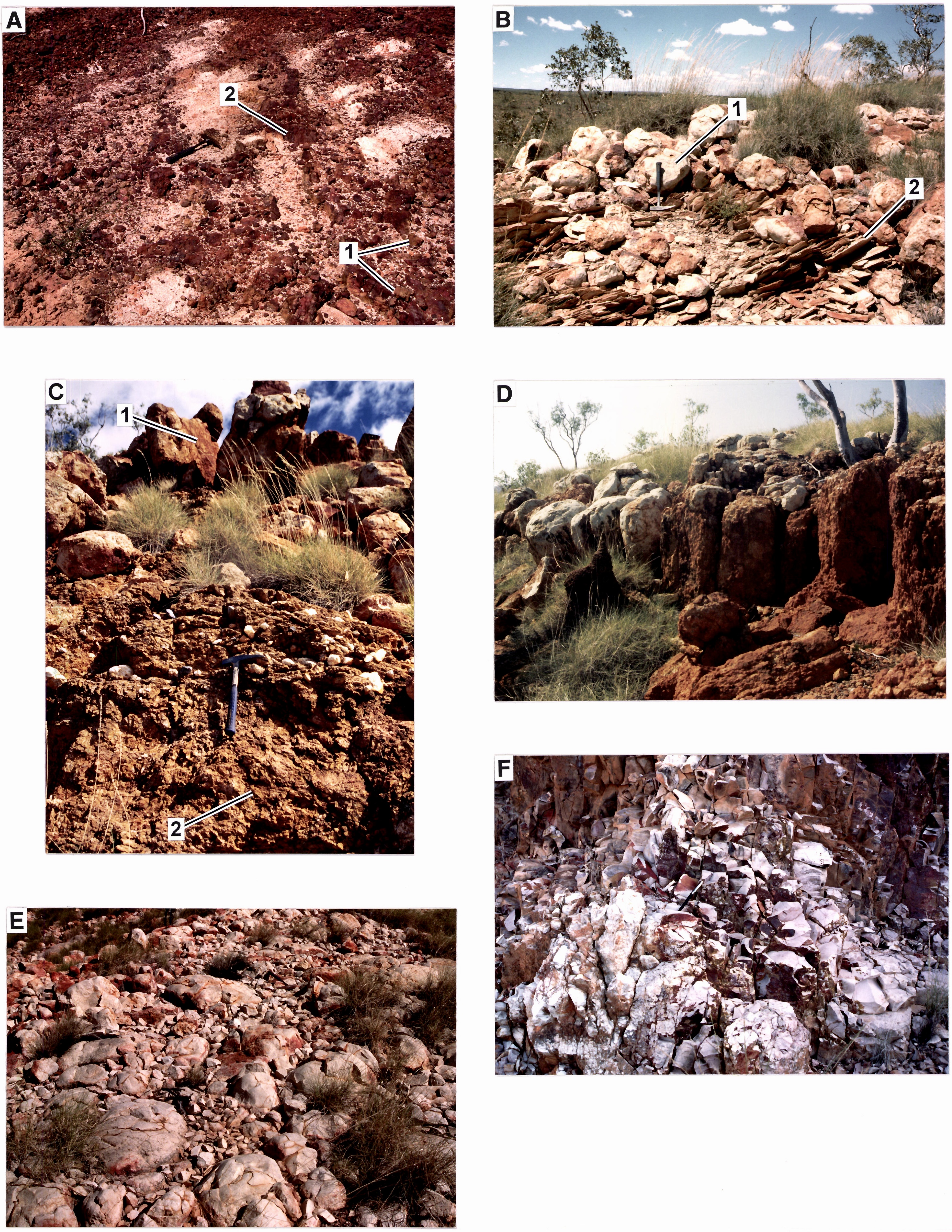
(B) Massive silcrete developed in sands and gravels (1) overlying Proterozoic bedrock (2). Location: 305812mE - 7756112mN, Buckley River-Grey Ghost district.

(C) Massive-columnar silcrete developed on Mesozoic sediments (1) overlying Proterozoic silicified saprolite (2). A gravel layer occurs below the columnar silcrete. Location: 309884mE - 7778598mN, Buckley River-Grey Ghost district.

(D) Well-developed mottled columnar silcrete overlies a silicified mottled zone on a mesa. Location: 310696mE - 7777739mN, Buckley River-Grey Ghost district.

(E) Massive silcrete developed from weathering of Proterozoic siltstone. Silcrete overlies silicified saprolite. Location: 306213mE - 7794340mN, Mammoth Mines district.

(F) Fragmental silcrete developed on Mesozoic claystone. Location: 475236mE - 7584566mN, Tringadee district.


A
2
1
B
1
2
C
1
2
D
F
E

The mine site, at which trial mining has been carried out, lies in a valley eroded into and surrounded by mesas, which represent an old land surface (Figure 43A). This old surface, largely capped by silicified saprolite (Figure 43B) and by lesser quantities of ferruginous saprolite (Figure 43C), has been slightly stripped. Despite this, abundant silcrete and some pockets of nodular duricrust remain. In places, a thin veneer of remnants of ferruginised Mesozoic sediments (conglomeratic duricrust), 1-3 m thick, overlies the saprolites of Proterozoic rocks, similar to that near the Grey Ghost Prospect (Figure 9F). Erosion in the valleys has revealed saprolites of carbonaceous shale and siltstone, covered by a very thin, skeletal soil. This is overlain, in turn, by a generally thin (<0.3 m) veneer of colluvial scree on the valley sides (Figure 43D and E), which thickens to 2 m near the valley floors. Trial mining and resultant ore stockpiling (Figure 43A) have probably contaminated the saprolite, soil and colluvium in the valley floor, downslope from the mineralisation, so that further geochemical surveys will have no significance.

Eleven duricrust samples were collected over a 1.0 x 1.5 km area as a pilot study to investigate any significant geochemical halo in the very patchily-developed relict regime. It was necessary to search extensively for very small, remnant pockets of nodular duricrust (Figure 43F), which were either developed on favourable lithologies and/or represent remnants of a once more extensive surface. These were analysed by XRF and INAA. Sample locations were obtained by GPS. It is unlikely that further search in the area would reveal many additional nodular duricrust sites.

5.2.2 Geochemistry

The geochemistry of the nodular duricrust samples are given in Appendix 2. The major element chemistry (Figure 44) indicates that these nodular duricrusts, which are depleted in Ca, Mg and Na, are typical of those developed on Proterozoic rocks, although they are less ferruginous and more siliceous than some.

Anomalous trace elements are given below. Background was *estimated* from a geometric mean of samples LLP-2, 4 and 4, which were >400 m distant from the mineralisation.

Element	Background	Max
As	170	937
Ba	81	646
Mo	7.0	23.2
Pb	37	1526
S	295	1360
Sb	3.5	359
W	2	6.05
Zn	26	108

Figure 43. Lady Loretta area.

(A) The Lady Loretta Mine site showing an old, partly eroded land surface (LS) above the mine, with steep, scree-covered hill slopes mantled by a thin layer of colluvium (SC). Saprolites of the underlying argillaceous rocks (SP) have been exposed near the transportable hut by building activities (compare Figure 43D). Mining activities have contaminated the valley.

(B) Silicified saprolite, with only a vestige of the saprolite structure, and silcrete capping the old land surface. Location: 297245mE - 7813042mN.

(C) Ferruginous saprolite of folded meta-siltstone exposed overlooking the mine site at Location: 297147mE - 7812851mN.

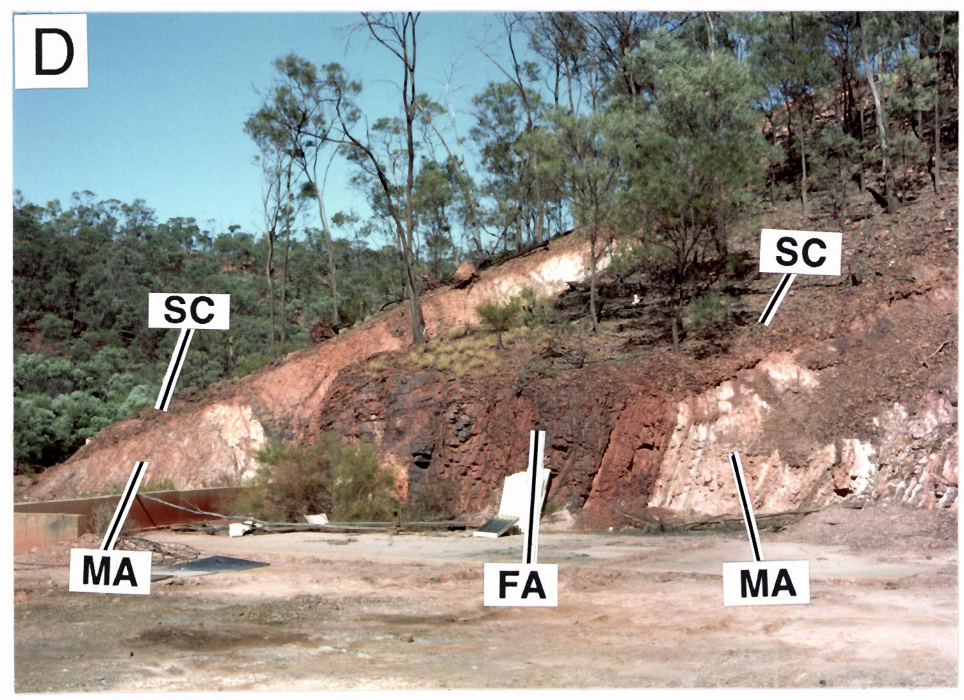
(D) Bleached saprolites of meta-siltstone and meta-argillite (MA) , near the mine site, enclosing a ferruginous unit (FA) overlain by a thin scree of ferruginous and silicified saprolite(SC) (compare Figures 43A and 43E).

(E) Bleached saprolites of meta-argillite (MA) and thin meta-siltstone (ST) units overlain by a blocky scree (SC) of silicified and ferruginous saprolite near the mine site (compare Figure 43D).

(F) Cavities in ferruginous saprolite (FS) filled with brown soil and duricrust nodules (ND) overlain by a lag of nodular duricrust (LG). Location: 297023mE - 7812884mN.


B


C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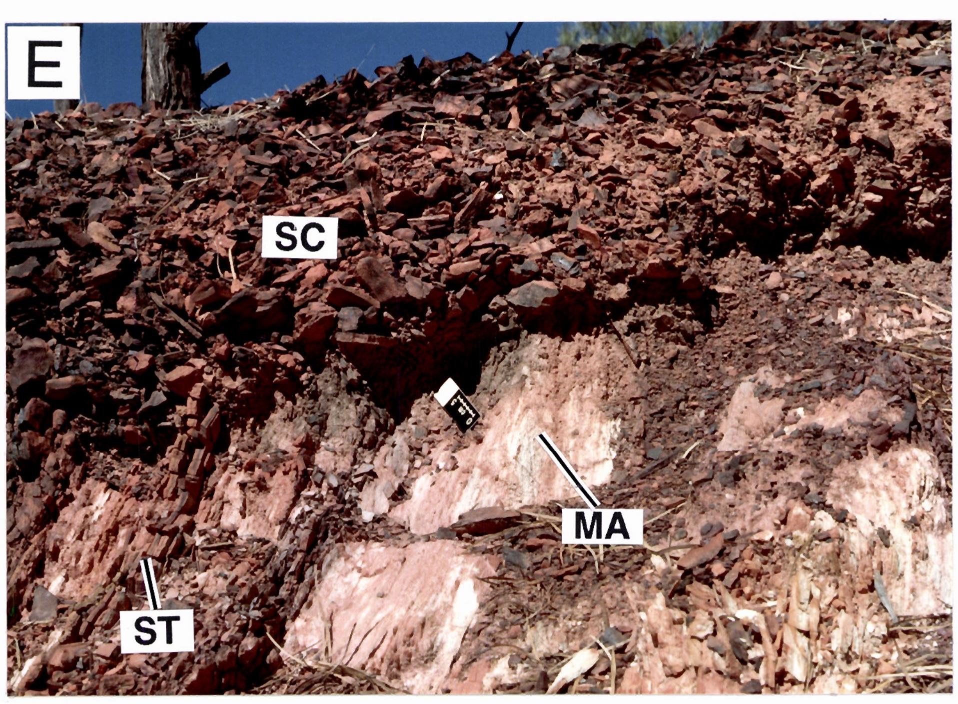
SC
SC
MA
FA
MA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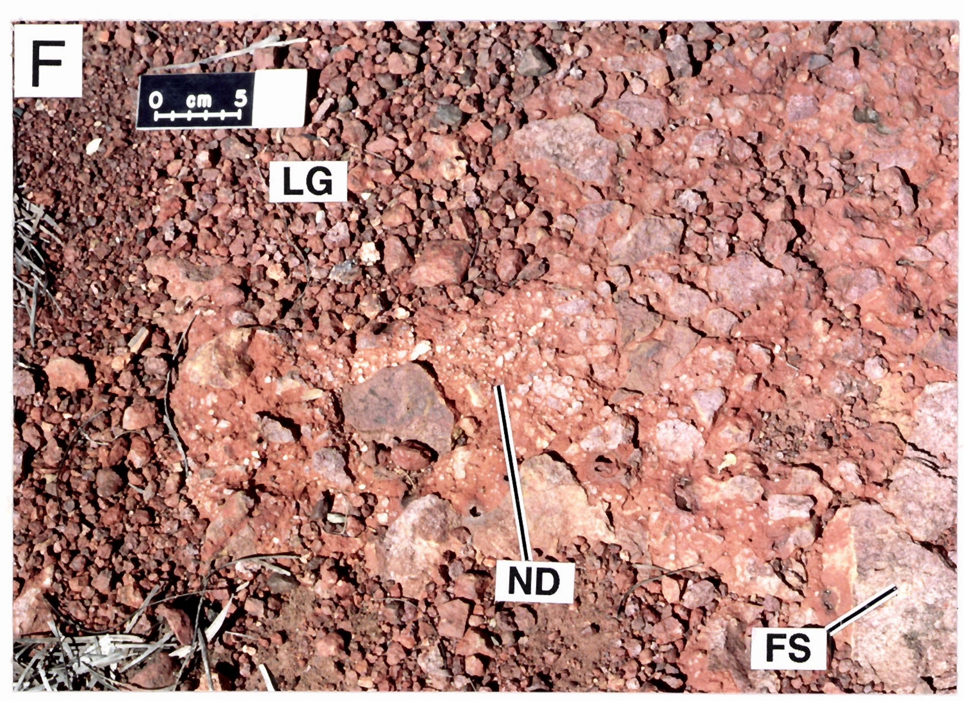
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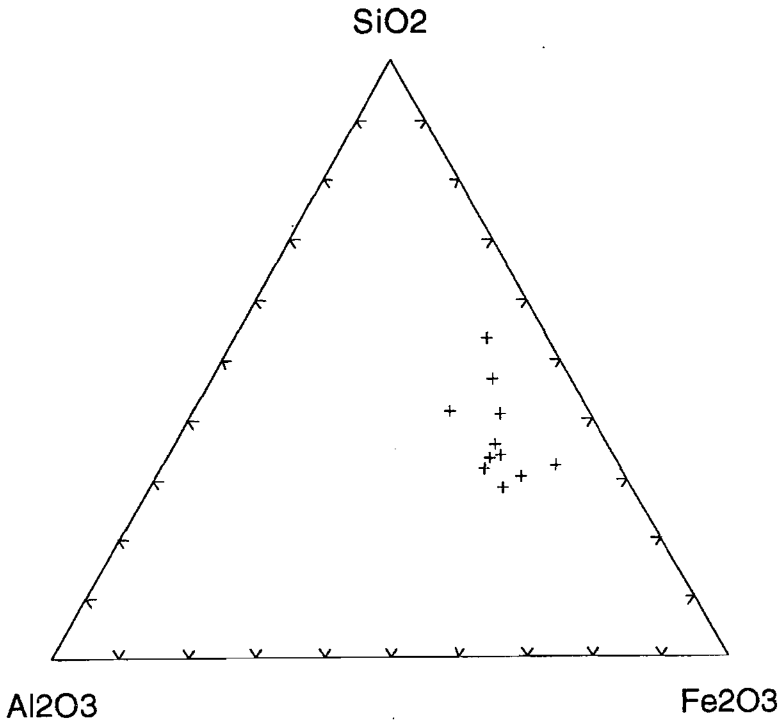


Figure 44. Ternary Si-Al-Fe plot of nodular, ferruginous duricrust samples from Lady Loretta Mine area. Compare Figure 14.

The geochemical data are plotted in Figure 45 with topography, drainage and an outline of the subcropping ore horizon (after Alcock and Lee, 1994). In the southeast of the area, the majority of the nodular duricrust sites overlie the subcrop of the ore horizon and its contiguous pyrite unit, indicating that these small remnants of nodular duricrust probably formed preferentially on ferruginous lithologies. These samples are very anomalous in As, Sb, Pb, Ba and S, and less so in V and Zn. Molybdenum and W also may be weakly anomalous, but it is difficult to assess such a small data set.

It is concluded that nodular duricrust would be a useful geochemical medium to detect Pb-Zn-Ag mineralisation in areas in which the laterite surface is well developed and that As, Sb, Ba, Mo and W should be used as pathfinders additional to Pb and Zn. Although Cd was not investigated here, it can be less labile than Zn (Robertson, 1990) and should be included, within the analytical suite.

5.3 Transect 2: Plateau Remnants-Lady Loretta Area

Silcretes are common on siliceous lithologies and cap mesas and plateaux. They vary between 0.5 and 2.0 m in thickness and overlie silicified saprolite (Figure 42E). About 15 m below the surface, the silicified saprolite is bleached and dominated by quartz, kaolinite and mica (Figure 46). From 15 to 1.5 m, there is very little change in the morphology, mineralogy and chemical composition of the silicified saprolite, except for K which decreases slight upwards. In the uppermost part of the section (0-1.5 m), the saprolite is progressively silicified to form a nodular to massive silcrete. This is partly mottled, has conchoidally fractured, lustrous zones of intense silicification (Figure 19F). The near-surface silcrete contains no clay and is dominated by microcrystalline quartz with traces of anatase. Significant concentrations of Zr (367 ppm) are also present.

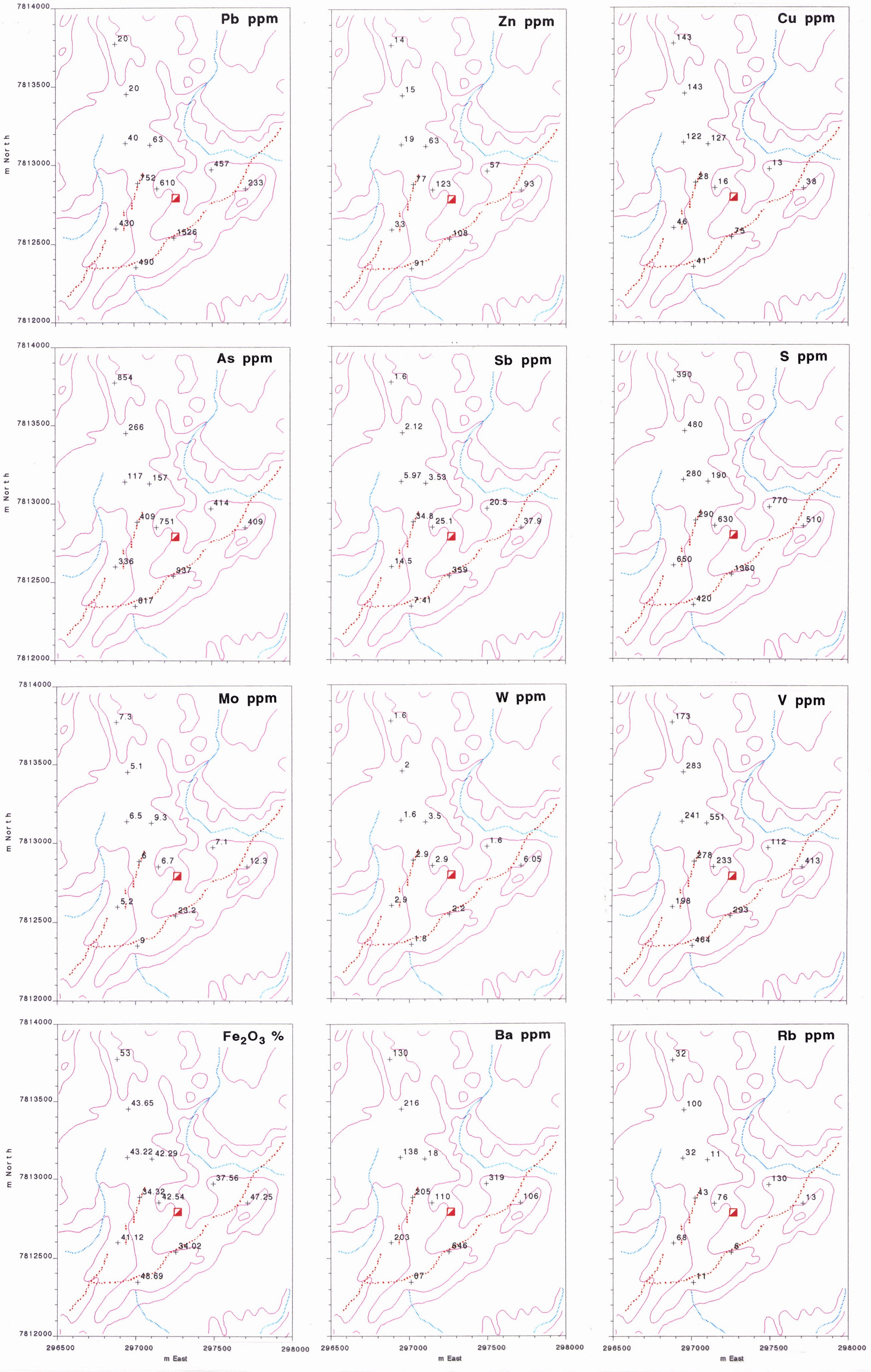


Figure 45. Geochemical maps for nodular, ferruginous duricrust sampling at Lady Loretta. with topography (magenta), drainage (cyan), subcrop of the ore horizon (red), and the shaft.

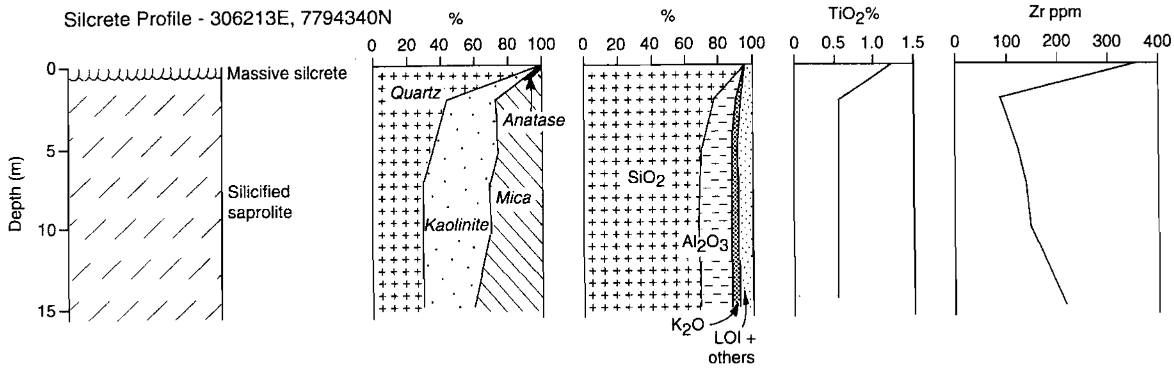


Figure 46. Mineralogy and geochemistry of the silcrete profile, Lady Loretta area.

5.4 Drifter Prospect

5.4.1 Geological setting

Drifter is about 30 km northwest of Lady Loretta. It has a sub-vertical shear zone, with chalcopyrite mineralisation at depth, which is revealed by malachite staining extending for 600 m west of the shear zone in the ferruginous Mesozoic sandstone (Figure 47). A stream sediment anomaly covers 10 square kilometres. A cherty breccia at the base of the Cambrian is also highly anomalous in Cu and Zn without any known underlying mineralisation.

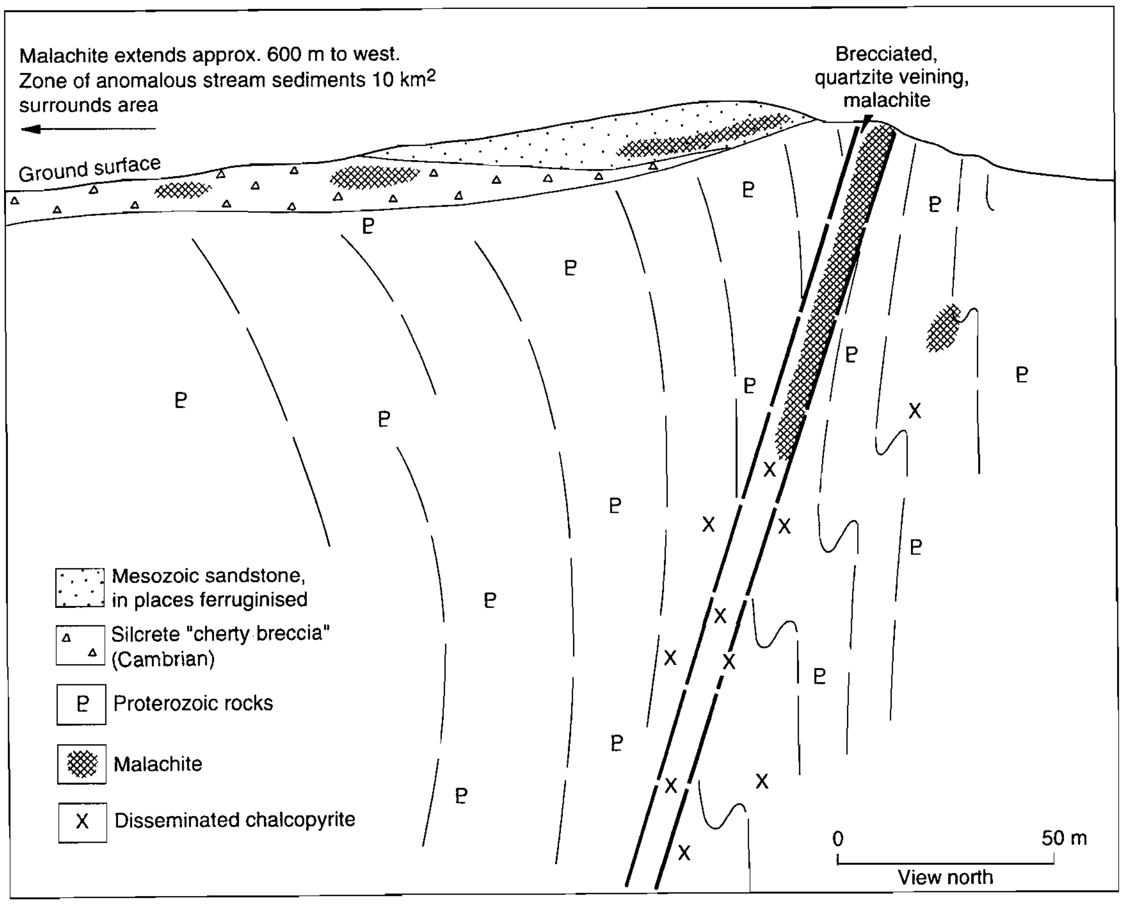


Figure 47. Dispersion of Cu from sulphides into overlying Mesozoic sandstone and cherty breccia, Drifter Prospect (Aberfoyle Resources).

5.4.2 Regolith

The regolith includes ferruginous cherty breccia (representing the unconformity at the base of the Cambrian), ferruginous or silicified saprolite, duricrust-capped Mesozoic sediments, colluvium and alluvium (Figure 48). These materials occupy different parts of the landscape. Lateritised Mesozoic sediments of varying thicknesses occur on mesas and are underlain by silicified saprolite. The upper zone of the Mesozoic sediments is generally ferruginous and varies from 1-5 m in thickness. Where the Mesozoic sediments have been removed, a thin veneer of cherty breccia (Cambrian) overlies silicified Proterozoic saprolite to form the low hills and pediments. The materials derived from the erosion of the Mesozoic sediments occur on valley floors (Figure 48B).

Regolith stratigraphy of the valley floors was established from six trenches excavated by Aberfoyle Resources Limited, north of the Drifter Prospect, to penetrate transported sand. However, the four northern trenches revealed Mesozoic sandstone and clays, beneath the sands, which could not be penetrated by the excavator. Iron and Mn rich bodies and mottling are important in the regolith in valley floors. They occur as pods and slabs up to 3 m across and are dominated by hollandite and goethite (Figure 48B). Enrichment of Fe and Mn on the broad valley floors is a modern process. Here, very sandy top soil overlies a mottled sandy clay subsoil that hardens on exposure. The topsoils are up to 3 m thick and comprise sands and gravels. Transported lateritic gravels and quartz pebbles, which are presumably derived from the erosion of Mesozoic profile upslope, occur above the mottled zone. Bleached saprolite lies beneath the mottled zone, which is dominated by quartz, kaolinite and mica.

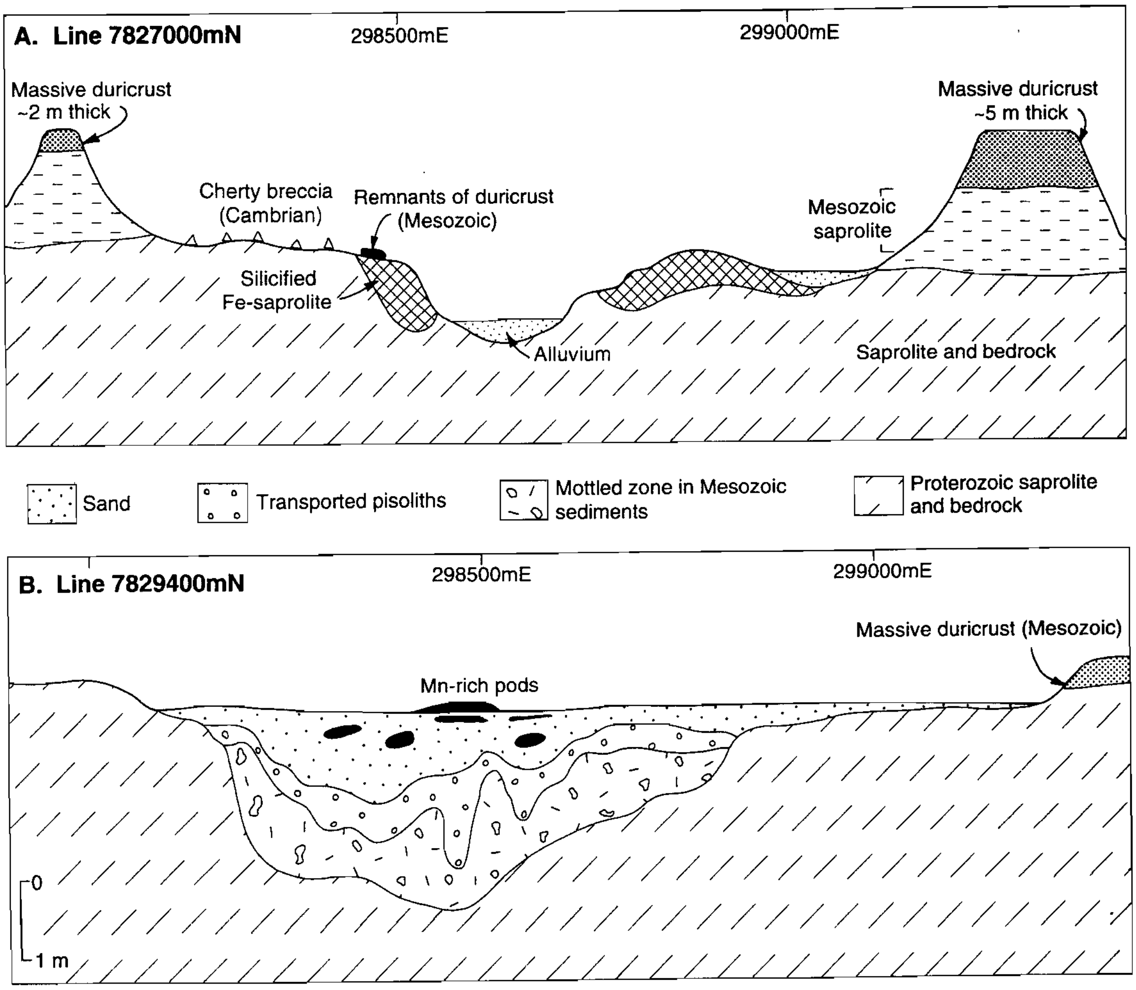


Figure 48. (A) Relationship between landform and regolith along line 7827000mN, Drifter Prospect. The Cu anomaly is concentrated in cherty breccia. (B) Cross section showing the stratigraphy of valley floor for line 7829400mN, Drifter Prospect. There is a widespread Cu anomaly in soils.

A traverse and profiles from two trenches at the site were sampled to determine:

1. The petrological, mineralogical and geochemical characteristics of the regolith to determine their origins.
2. The geochemistry of the ferruginous, silcrete breccia and soils.
3. A plausible explanation for the anomaly.

5.4.3 Traverse 7827000mN - Lateritic Mesozoic duricrust, Cambrian cherty breccia, and silicified Proterozoic saprolite

Twenty two surficial samples, mainly lateritic duricrust on Mesozoic sandstone, cherty breccia (Cambrian) and ferruginous or silicified saprolite on the Proterozoic, were sampled on traverse 7827000mN (Figure 48A). The distribution of selected elements is shown in Figure 49.

The lateritic duricrust developed on Mesozoic sediments is massive, reddish brown to black and is dominated by quartz, goethite and hematite, with traces of kaolinite and mica. Its mineralogy is consistent with its chemical composition (Figure 49). Lateritic duricrusts are characterised by greater concentrations of Si and Fe and lesser concentrations of Al. However, duricrusts show variable ferruginisation. In one location (298037mE - 7827021mN, not shown), lateritic duricrust has more Fe (50% Fe_2O_3) than Si (42% SiO_2). Calcium, Mg, Na, K and Ti are present as trace quantities. The concentrations of Cu and Zn are low, whereas those of Ti and Zr are high, relative to the cherty breccia. However, there is a trend in the distribution of Fe, Cu, Pb and Zn in the landscape. The lateritic duricrust contains increased Cu, Pb and Zn concentrations downslope (crest-upperslope-footslope) with increasing Fe (4.8-26.3% Fe_2O_3). The ranges of Cu, Pb and Zn are 10-71, 14-30 and 9-60 ppm respectively.

The cherty breccia forms white to reddish brown, irregular, 20-100 mm fragments and consists largely of quartz and hematite, with traces of goethite. Staining by Mn oxides is common on the surfaces of the breccia. Although hematite is generally uniformly distributed throughout the matrix, it concentrates with Mn oxides along cracks and veins.

The major element composition of the cherty breccia is similar to that of the lateritic duricrust on Mesozoic sediments, except for lower abundances of Ti and greater abundances of Ca, Mg and P. The cherty breccia also shows variable ferruginisation, similar to that observed in lateritic duricrust. However, the abundances of Cu, Pb, Zn, Mo, Mn and Sb are much higher than in the lateritic duricrust. Copper ranges from 530 to 4279 ppm. Associated with these high Cu concentrations are increased Fe (37.1% Fe_2O_3), Mn (0.16% MnO), P (1.3% P_2O_5), Zn (1179 ppm) and Pb (203 ppm). Zirconium contents are much lower in the cherty breccia than in the lateritic duricrust.

Copper, Zn and Mo anomalies in the cherty breccia appear to be related to leakage from the Proterozoic Drifter Fault into the overlying Cambrian. These elements exhibit similar dispersion characteristics and have strong affinities for Fe and Mn-oxides, indicating hydromorphic dispersion. The Fe in the cherty breccia may have been derived from several sources, including the fault and the underlying Proterozoic bedrock.

5.4.4 Soils

The soils in the valley floors are developed in sediments derived from erosion of lateritised Mesozoic sediments. Systematic soil sampling and geochemical analysis was undertaken by Aberfoyle Resources Limited and the data were made available to the Project. The grid sampling was along 400 m line spacing running east-west, with surface sampling at 50 m spacing. Geochemical analyses were carried out on the <180 μm size fraction. The distributions of Fe, Mn, Pb, Zn and Cu in soils are shown in Figure 50. The maximum concentrations of Cu, Fe, Mn, Pb and Zn are 4654, 74400, 7892, 805 and 449 ppm respectively. The Cu anomaly is associated with Fe, Mn, Pb and Zn.

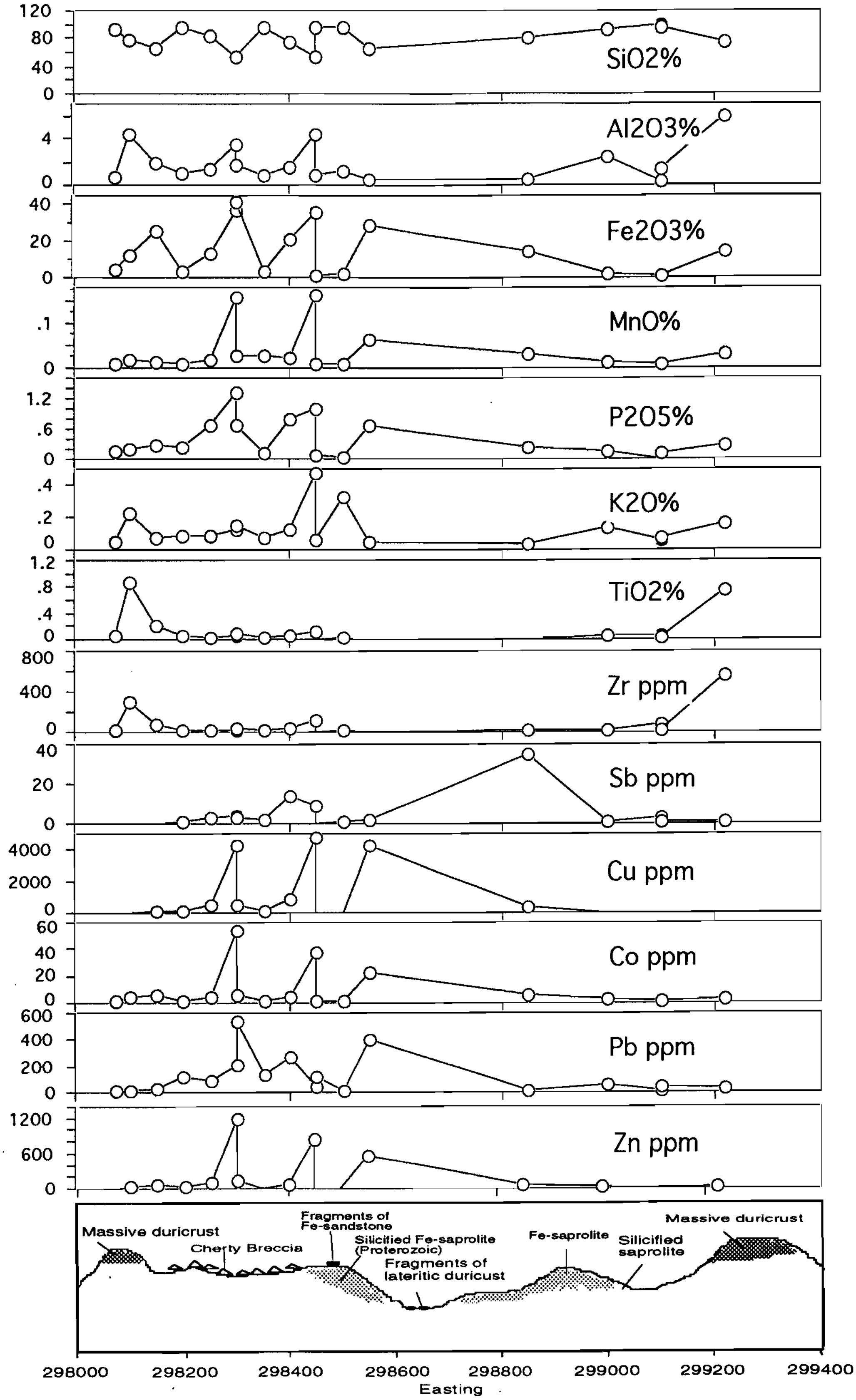


Figure 49. Traverse along line 7827000mN showing the distribution of some major and trace elements, Drifter Prospect.

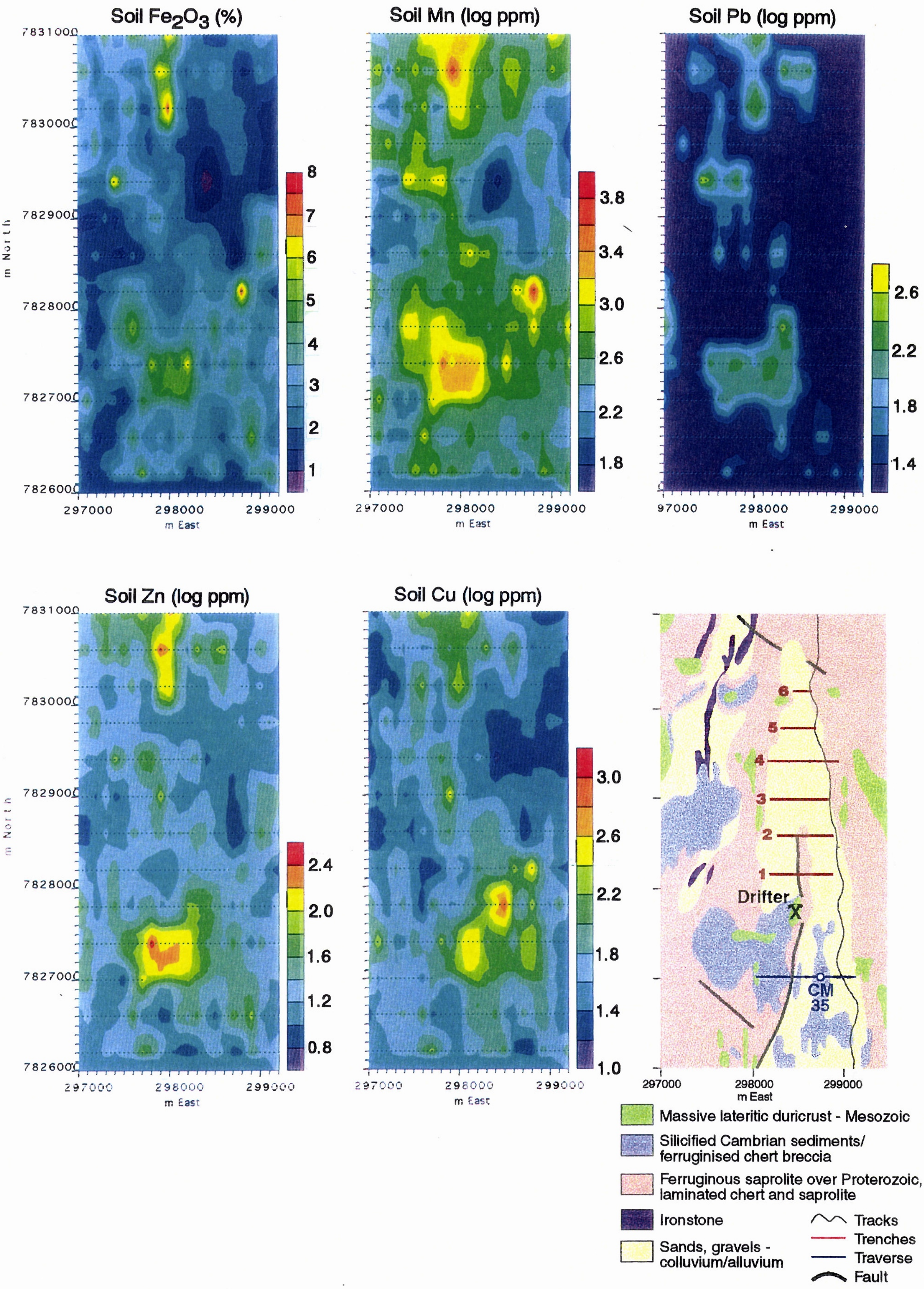
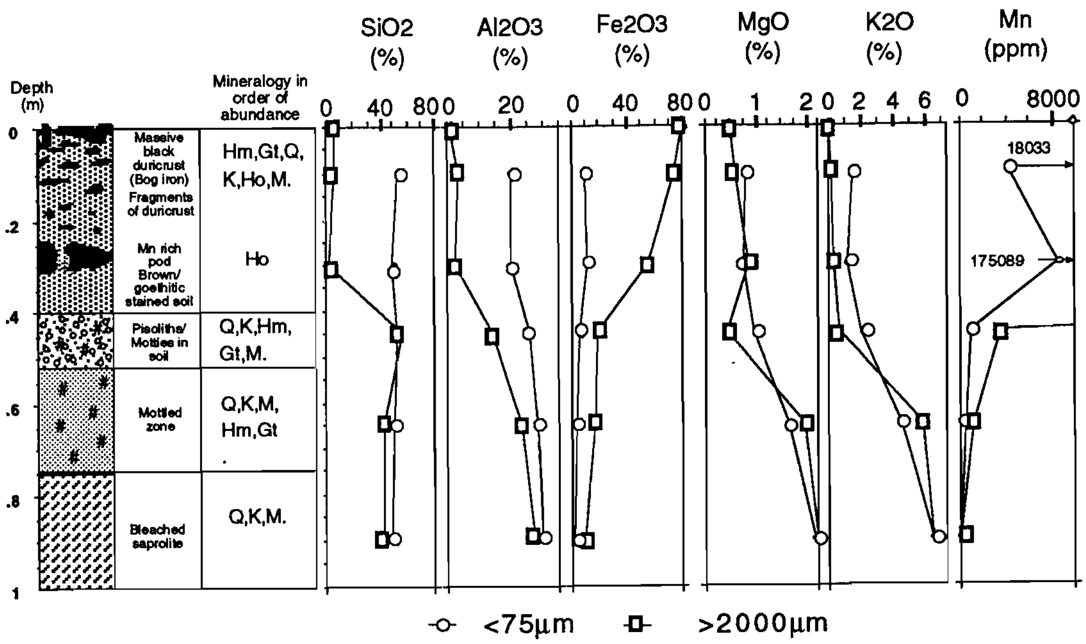
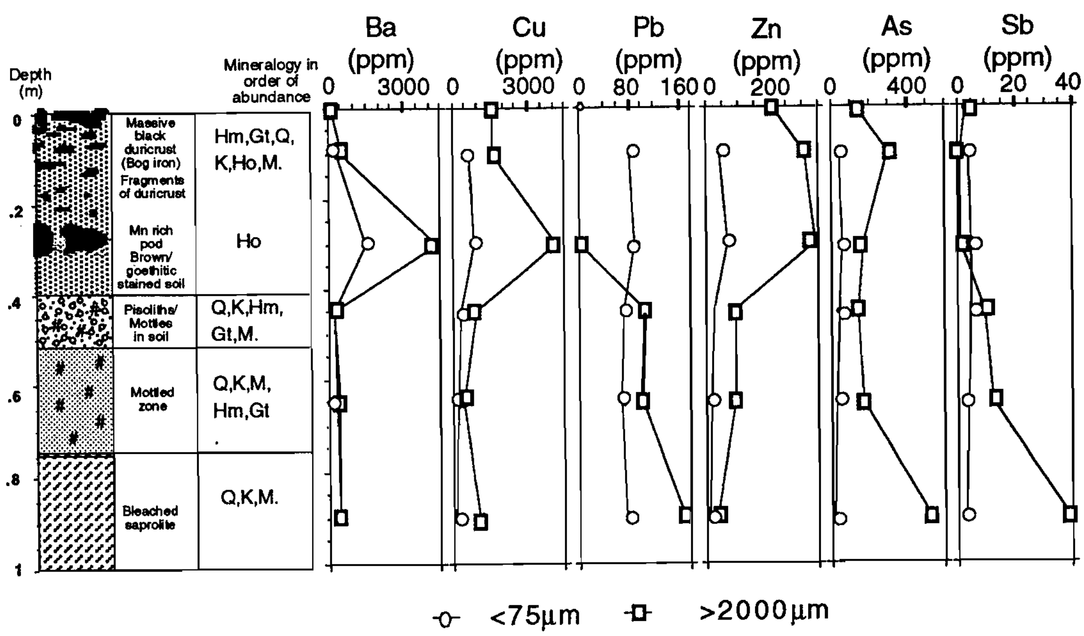


Figure 50. Colour contour plots of soil geochemical data for Fe_2O_3, Mn, Pb, Zn, and Cu, Drifter Prospect. Regolith distribution for the area is also shown (Aberfoyle Resources). Traverse and profiles from Trench 1 are discussed in the text.

DRIFTER
TRENCH1/PROFILE1



Q quartz, K kaolinite, Hm hematite, Gt goethite, M mica, H hollandite



Q quartz, K kaolinite, Hm hematite, Gt goethite, M mica, H hollandite

Figure 51. Vertical profiles showing the regolith stratigraphy, mineralogy and geochemistry for the size fractions of the regolith units for trench 1, Drifter Prospect.

Three soil profiles were sampled for detailed investigations. Two profiles from Trench 1 and one profile from Trench 4 were selected for geochemical, petrographic and mineralogical analyses. Particular attention was given to Trench 1 because of the high Cu concentrations in the nearby soils (Figure 50). Sampling extended to about 1 m in mottled Mesozoic sediments. The samples were wet-sieved into six size fractions (>2000 µm, 2000-710 µm, 710-500 µm, 500-250 µm, 250-75 µm and <75 µm). Fractions between 710 µm and 75 µm were mainly quartz and were discarded. The 2000-710 µm size fraction was similar in mineralogy to the >2000 µm fraction. The >2000 µm size fraction is dominant in abundance and was chosen for geochemical analysis; it consists largely of hematite, goethite and quartz. The <75 µm size fraction was also analysed as it contained substantial kaolinite, which increased in abundance down the profile. A total of 28 samples were analysed by INAA, XRF fusion and XRD.

Figure 51 is a schematic regolith profile showing the distribution of Cu and related elements in the soils. The two other profiles, not presented here, exhibit similar features. Three soil profiles, sampled in trenches, have high Cu contents associated with Fe oxides (goethite, hematite) and Mn oxide (hollandite) in the >2000 µm size fraction. The concentrations of Cu and Zn in the underlying Proterozoic saprolite are 1400 ppm and 40 ppm, respectively. At Trench 1-Profile 1, where there is a formation of Mn-rich pods, Cu (4133 ppm) and Zn (339 ppm) are enriched in a hollandite-bearing pod (22.6% MnO) (Figure 51). Although Fe concentrations reached 80% Fe_2O_3 in the surface fraction, the maximum concentration of Cu and Zn coincide with high concentrations of Mn. The concentrations of Cu and Zn are much less in the <75 µm fraction, which is dominated by quartz and kaolinite. A Cu-Mn scatterplot of soil samples, collected over trench 1, also shows a Cu-Mn association.

The dispersion characteristics of Pb are different from those of Cu and Zn. The >2000 µm fraction of overlying soils has very low or below detection levels of Pb, despite its high concentrations (175 ppm) in saprolite. This is in contrast to the <75 µm fraction, which contains about 80 ppm Pb. Antimony show a similar distribution. Arsenic is strongly associated with Fe oxides. The saprolite contains 520 ppm As and, where there is Fe enrichment, As is also relatively enriched. It reaches a maximum concentration of 300 ppm in the soil.

Copper, Zn, As, Sb and Pb exhibit different dispersion characteristics. Copper, Zn and As are mobile in the weathering environment; they have strong affinities with neoformed Mn and Fe-oxides in the soil and exhibit large, strong, hydromorphic dispersion halos. In contrast, the fine, kaolinitic fractions are richer in Pb and Sb, which probably indicates an early, possibly mechanical dispersion into the soil. The high concentrations of Pb and Sb imply a nearby source, since Pb and Sb are relatively immobile. However, the source may be minor.

5.5 Blinder Prospect

Aberfoyle Resources Limited Blinder prospect is 7 km southeast of Drifter. There are significant Zn and Pb anomalies in ferruginous Mt Hendry Formation cherty breccia but no mineralisation has been found by drilling. A creek has locally incised through the Cambrian rocks into the Proterozoic Paradise Creek Formation. There is a two metre thick conglomerate on the contact that forms a distinct marker on many of the slopes in the area (Figure 52). This unit the Mt Hendry Formation, contains anomalous Zn and Pb. It is generally poorly sorted, but is sandy in the top 50 cm and becomes coarser towards the bottom; it has a hematite-rich, gritty matrix. Fragments of the conglomerate are subrounded and appear to be derived from erosion of local Proterozoic pink, laminated, dolomitic siltstone. The Cambrian materials above the Mt Hendry Formation are cherty, with patchy accumulations of Fe, similar to the cherty breccia at Drifter.

The conglomerate contained 508 ppm Cu, 23 ppm Pb, 1398 ppm Zn; an overlaying ferruginous cherty breccia contained 21 ppm Cu, 188 ppm Pb and 2449 ppm Zn. Paradise Creek samples from below the conglomerate contained 1 ppm Cu, 12 ppm Pb and 107 ppm Zn.

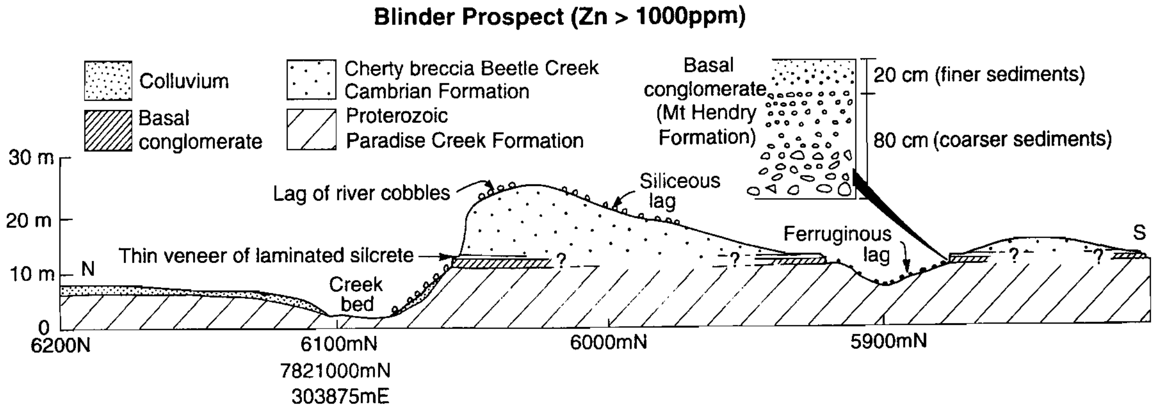


Figure 52. Cross section of the landscape at the Blinder Prospect. The Zn anomaly is concentrated in the ferruginous Mt Hendry Formation, which lies between the Proterozoic Surprise Creek Formation and the Cambrian Beetle Creek Formation.

The Fe oxides that host the anomaly, in this conglomerate are not derived from the underlying Paradise Creek Formation or from the overlying Cambrian. Both are Fe-poor, but rich in carbonates, which hinders dispersion of Fe and trace elements. Bedding in the Mt Hendry formation suggest a fluvial environment that has transported the anomalous Fe-rich material into place before burial by the Cambrian.

6. TRINGADEE DISTRICT

6.1 Regional Geomorphology and Regolith

The Tringadee area is within the Eastern Succession, 120 km south of Cloncurry, west of Cannington and south of the Williams Batholith. A study area of approximately 20 x 25 km was mapped and spans the south-eastern corner of the Selwyn 1:100,000 map sheet. It encompasses the Brumby Cu-Au and the Tringadee Zn prospects (Figure 53). This section discusses the nature and origin of some regolith materials over the study area. Detailed study of regolith-landforms of the Tringadee area will be reported later (Munday *et al.*, 1996, in preparation).

The Tringadee area is of generally low relief with extensive depositional plains covered by well-developed black clay soils over alluvial materials. These are common to the south and south east and are generally 1-2 m thick. The plains interspersed with isolated low hills and mesas that rise generally <30 m above a mean altitude of 300 m amsl. Low hills and mesas of Mesozoic sediment dominate the central portion of the area. Similar landforms developed on the Proterozoic basement characterise the north and westerly portions of the mapped area.

There are a variety of ferruginous materials, including lateritic duricrust, ferruginous saprolite, mottled zone, lateritic nodules, ferruginised fractures and ferruginised sediments found within the study area. Several types of duricrust have been identified, apparently developed from residual and lateral accumulation of Fe during weathering. These materials occur sporadically through the Tringadee district and are confined to remnant mesas and high hills. Ferruginous and mottled saprolite commonly underlie these duricrusts. Megamottles are developed in the Mesozoic sediments .

Much of the upper part of the Mesozoic has been silicified to fragmental claystones (Figure 42F). In places, these are cut by fractures that have formed the loci for Fe accumulation. Pediments, flanking the Mesozoic mesas, which are covered by a veneer of polymictic, ferruginised, lithic fragments, quartz gravel and silicified claystones are commonly found in the central part of the mapped area.

In areas consisting of erosional rises and low hills, regolith materials are predominantly skeletal soils over saprolite, saprock and unweathered bedrock. On the margins of outcropping Proterozoic rocks, ferruginous sheetwash gravels and sands have developed over mottled saprolite and bedrock.

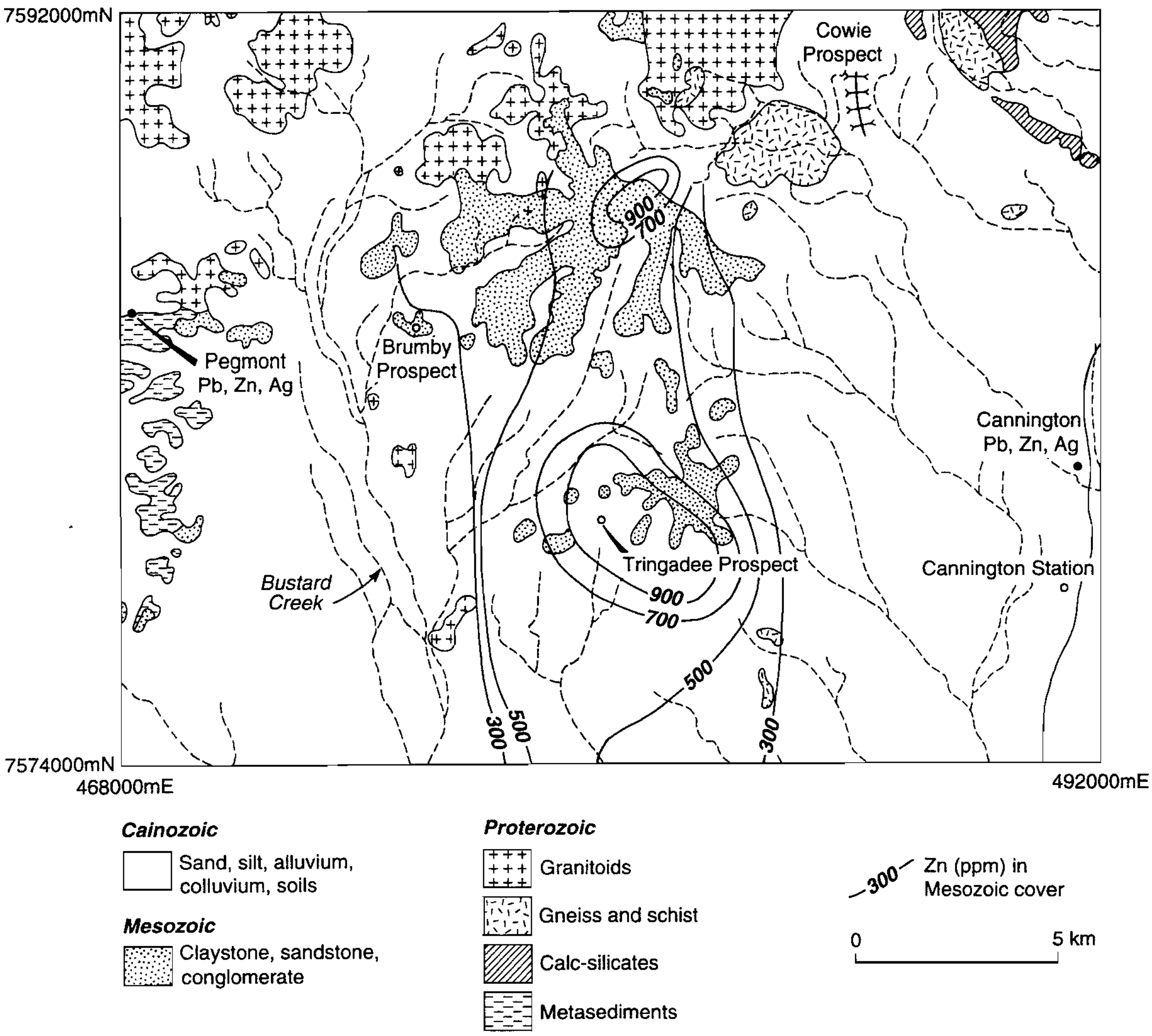


Figure 53. Simplified geological map of Tringadee area.

6.2 Detailed Observations

6.2.1 Tringadee Prospect - Transect ABC on Mesozoic dominated terrain

The landscape dominated by Mesozoic sediments is depicted in the aerial photograph of Figure 54. It generally shows a yellowish red to yellow hues with abundant dark brown patches reflecting ferruginous lag derived from the breakdown of the former Mesozoic massive duricrust. Transect ABC runs across various degrees of truncation of the regolith developed on Mesozoic claystones. The low-lying areas have alluvium, colluvium and black soil plains. The higher mesas, with a local relief of 100 m have gullies radiating from the top, appearing like white streamers on the aerial photograph. More advanced erosion has reduced some of the mesas to pale, yellowish, silicified saprolite or isolated low, conical hills.

Regolith developed from weathering of Mesozoic sediments

mLT2	Lateritic duricrust
mLA2	Lag of lateritic nodules, fragments of ferruginous saprolite and silicified saprolite
mSP2	Ferruginous saprolite-silicified/collapsed breccia
mSP5	Silicified saprolite
mSP6	Silicified saprolite with Fe vein/Mn

Regolith developed from weathering of Proterozoic rocks

pSP1	Saprolite, mottled saprolite and outcrops of fresh granite

Regolith of mixed origin - (derived from weathering of Mesozoic sediments/Proterozoic rocks)

MIAS1	Red soils, alluvium
MIAS5	Black soils
MICS4	Red brown sandy soils, colluvium

p *Proterozoic rocks*
m *Mesozoic sediments*
MI *Mixed lithologies*

—— Transect

N

0 1 km

Approximate scale due to distortion from aerial photographs

Figure 54. Map showing the surface distribution of regolith-landform units and vegetation as an overlay to the colour air photographs (Commonwealth of Australia, 7054 Selwyn photo, 10/97, 26.9.1972) Tringadee Prospect. Transect ABC is discussed in the text.

A schematic cross-section of transect ABC is shown in Figure 55. Three important features are described for this transect, which includes the Tringadee Prospect at location A, the Mesozoic weathering profile at B and the black soil at C (description will be based on observations of black soils in the overall Tringadee area).

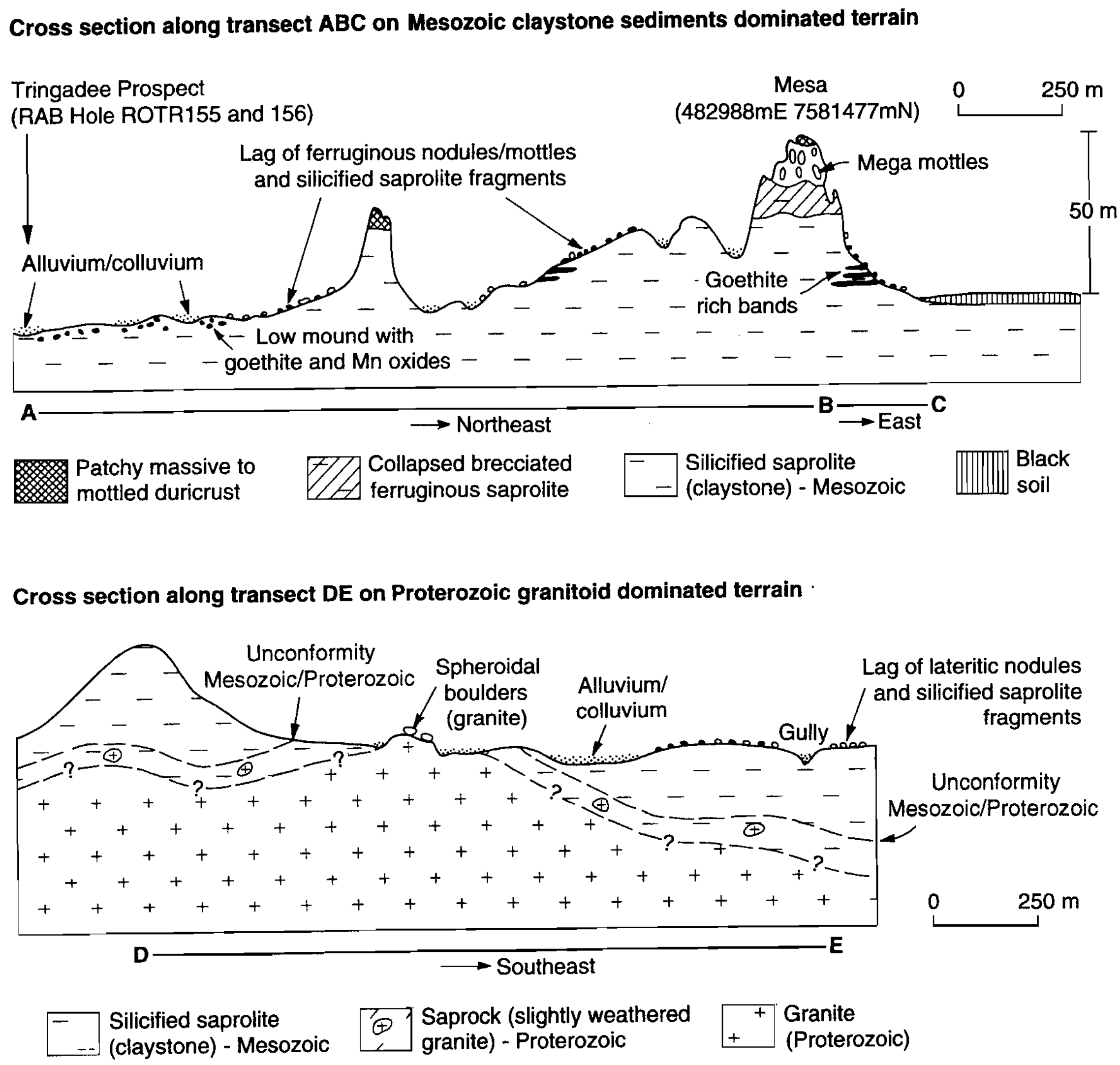


Figure 55. Cross sections of transects ABC and DE shown on Figures 54 and 58.

6.2.1.1 The Tringadee Prospect - Position A

The Tringadee prospect has a widespread Zn anomaly of >1000 ppm in the Mesozoic cover as shown by the Zn contours in Figure 53. The source of the Zn is unknown. Representative sections showing the nature of the regolith and the location of the Zn anomaly are shown in Figure 56. As part of a more detailed study directed to explaining the Zn anomaly, two RAB drill sites (ROTR 155 at 479500mE - 7580000mN and ROTR 156 at 479500mE - 7580000mN) with a Zn anomaly of >1000 ppm were investigated. This RAB drilling lies in the alluvial-colluvial plains near exposures of low mounds of Fe and Mn oxides-rich Mesozoic sediments (prominent ochre colour on the aerial photo). A schematic regolith profile of ROTR 156, showing the dispersion of Zn and related elements is given in Figure 57. Profile ROTR 155 (not presented here) shows similar element distributions.

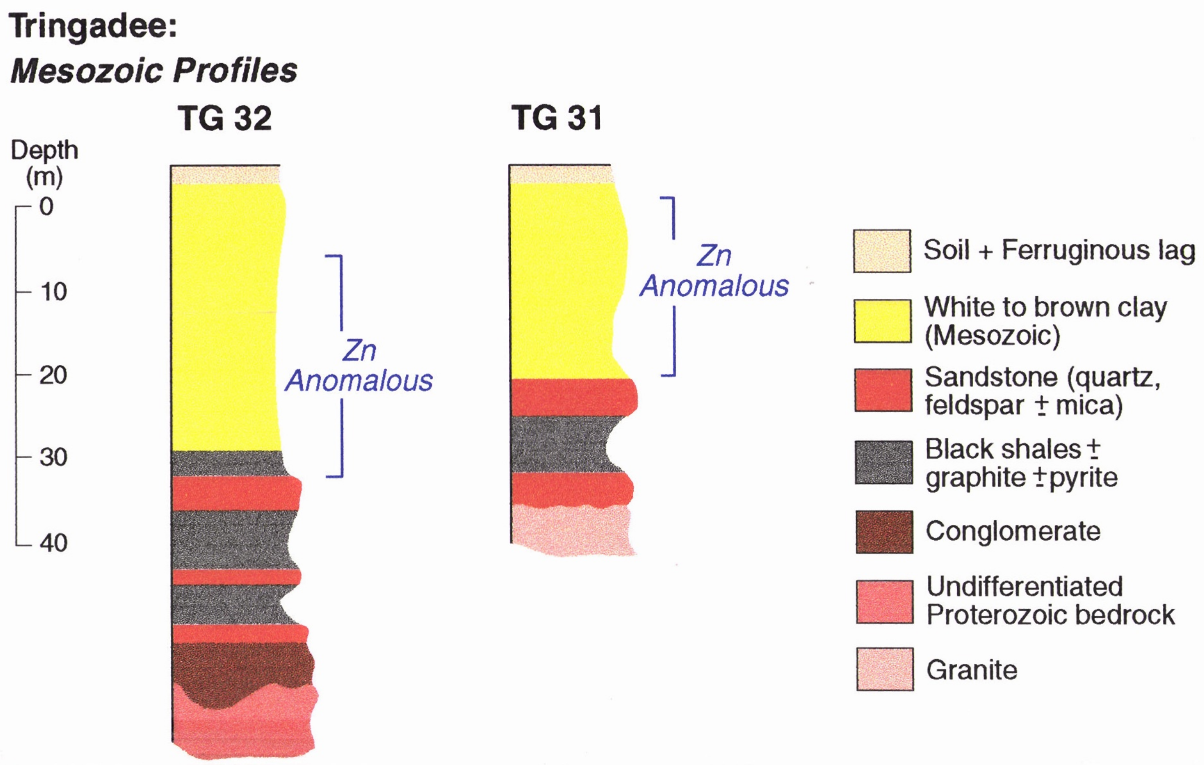
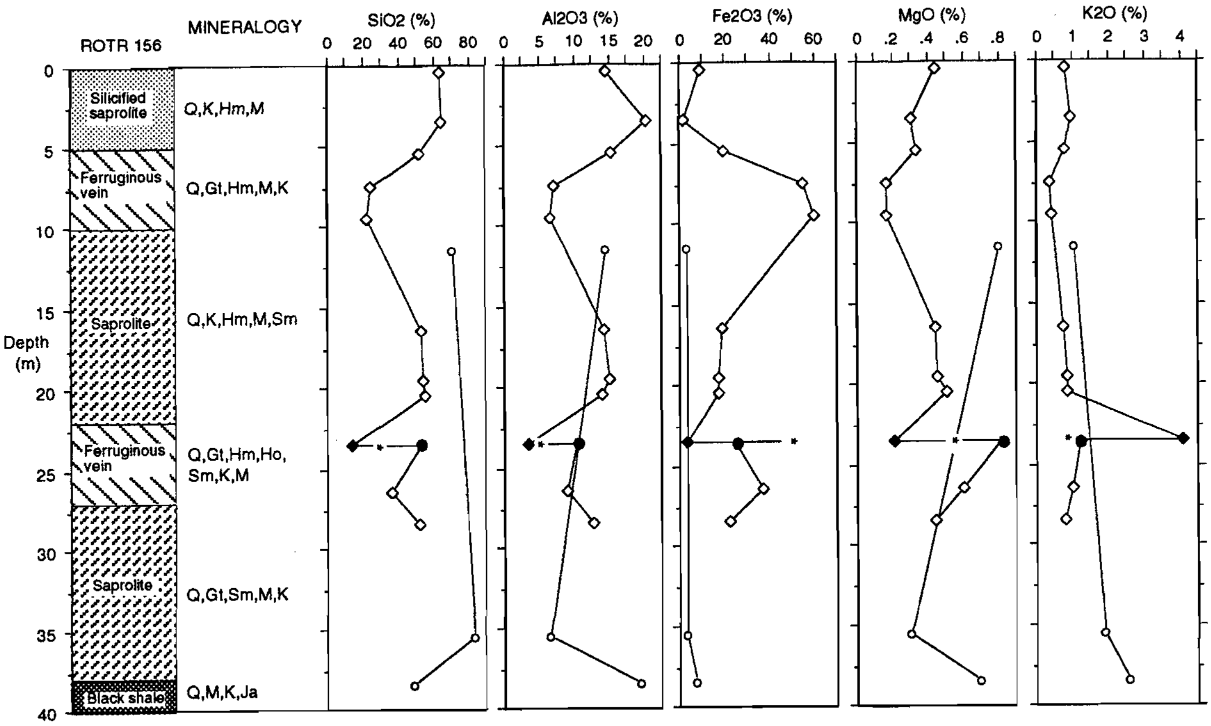


Figure 56. Representative section through the Mesozoic cover at the Tringadee Prospect show locality of anomalous Zn (Aberfoyle Resources Limited).

The size fraction that gives the best geochemical signature of the target and pathfinder elements was investigated by a geochemical orientation study. Based on the median values for the concentration of the target element (Zn) and pathfinder elements (Cu, Pb, As, Sb) the >2000 µm and 710-2000 µm fractions give comparable values. They contain variable amounts of Fe (2-60% Fe_2O_3), Al (6-20% Al_2O_3) and Si (22-70% SiO_2).

From this information, together with the practicability of obtaining enough material, the >710 µm fraction was selected for further analysis. When this was insufficient, the <710 µm fraction, which is dominated by quartz and kaolinite was used instead. Sample depths within a profile were based mainly on colour change. For ferruginous zones in the saprolite, the >710 µm fraction was further analysed and separated into Mn-rich and Fe-rich materials.

Zinc is relatively enriched in subsurface ferruginous zones at depths of 5-10 and 20-25 m, where the concentration of Fe_2O_3 reaches 60%. The 20-25 m interval contains goethite with digital overgrowths of hollandite. The Zn abundance is 1300-2000 ppm in the ferruginous materials compared to <200 ppm in the clay-rich materials. Associated with high concentrations of Zn are high concentrations of Cu which reach up to 170 ppm. Lead concentrations are low in both fine and coarse fractions but reach up to 200 ppm in two Mn-rich samples. The As contents vary from 1 to 51 ppm, with the high concentrations associated with Fe-rich samples. Goethite and hollandite serve as hosts for elements that are mobilised during weathering and soil formation.



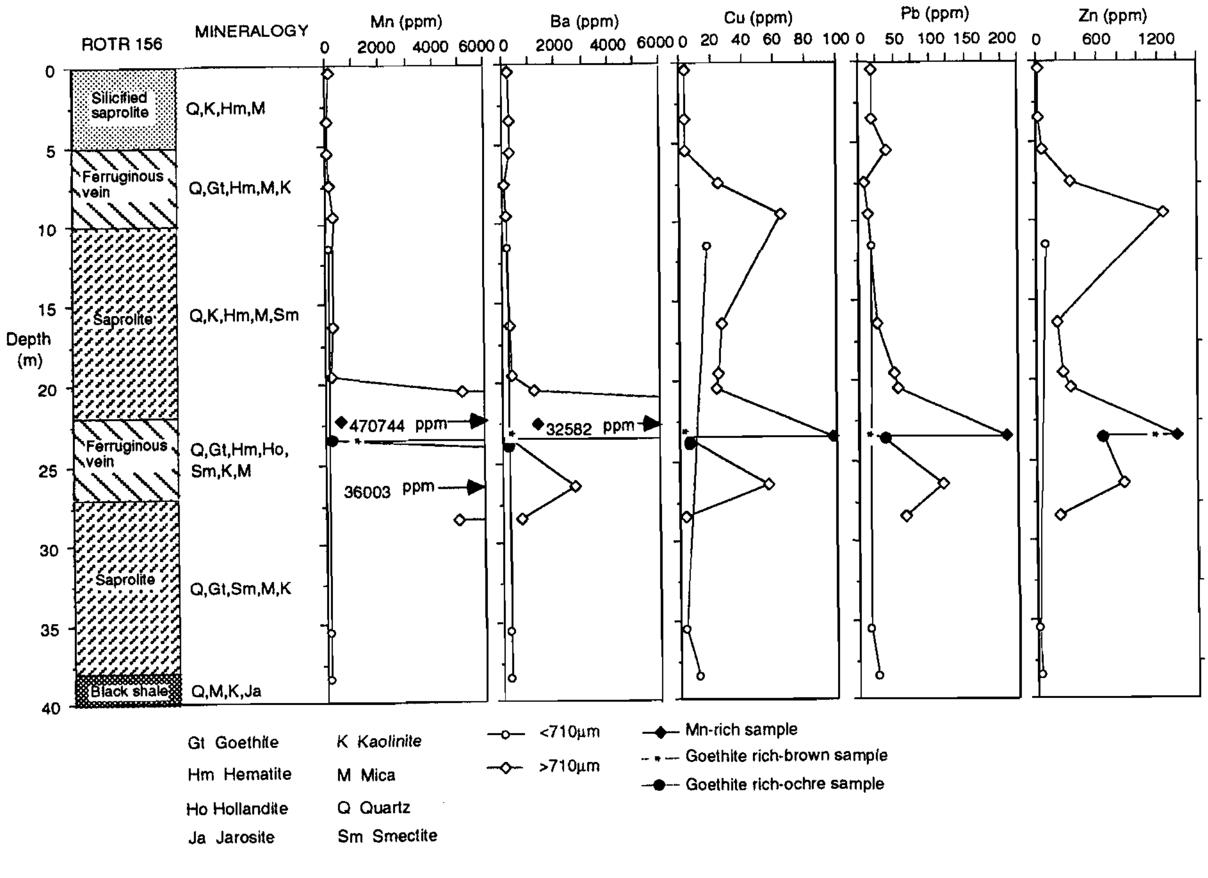


Figure 57. Schematic of the regolith profile for RAB drill hole ROTR156 showing the distribution of certain major and trace elements, Tringadee Prospect.

From these data and observations from Aberfoyle's (Aberfoyle Resources Limited) RAB geochemical data, it appears the Zn anomaly in the Mesozoic cover is associated with accumulated Fe and Mn oxides, probably related to fluctuating water tables and fractures in the Mesozoic cover. The latter appear to have conducted Fe-rich fluids from the external sources. Zinc appears to be more closely correlated to Fe than Mn, but where Fe is associated with high Mn, Zn is increased to >1000 ppm. A Proterozoic source is probable and Zn concentrated in ferruginous veins, assisted by Mn oxide scavenging is a likely explanation where Mn is concentrated. However, low contents of Pb, which is relatively less mobile indicates the source to be distal. The Tringadee area was a palaeo-low before the deposition of Mesozoic sediments and thus, it is not surprising that Fe, Mn and Zn have accumulated laterally in the Mesozoic cover. The source of anomalies could be nearby deposits such as Cannington and Pegmont.

6.2.1.2 Mesozoic claystone Mesa (482988mE - 7581477mN) - Position B

This is a typical weathering profile on a Mesozoic claystone. The upper part of the mesa is silicified and the lateritic profile contains patches of lateritic nodules overlying massive, mottled duricrust which grades downwards into a zone characterised by blocky megamottles. The mega mottled zone is underlain by ferruginous saprolite and saprolite.

The chemical composition of the principal regolith units is shown in Table 6. The massive, mottled duricrust contains 33.1% Fe_2O_3, 40.3% SiO_2 and 13.5% Al_2O_3. The Fe oxide is mainly goethite, with some hematite, and is concentrated as coatings in voids and as infillings of cracks in the claystone, forming a network pattern. Silica is present mainly as quartz, with some opal-CT. Lateritic nodules were formed by physical breakdown of massive, mottled duricrust or mega mottles. The mottled, massive duricrust and the nodules are rich in V (2500-9000 ppm) and are enriched in Si, Al, Pb, Ba and Cr compared to other regolith units in the mesa.

Table 6. Geochemical characteristics of the regolith developed over Mesozoic claystone, Tringadee district.

Sample No Depth(m) Regolith Type	TG 73 0 Lateritic duricrust	TG 72/74 0 Loose Nodules	TG 75 10 Silicified Mottled zone	TG 76 10 Fe vein in Mottled zone	TG 78 40 Fe vein in saprolite	TG 79, 128-130 60 Saprolite (<75µm fraction)
SiO2 %	40.3	23.2-29.4	75.9	15.3	42.3	56.7-63.0
Al2O3 %	13.5	14.5-16.7	8.4	4.9	11.5	19.2-21.7
Fe2O3 %	33.1	42.2-52.4	7.4	68.1	34.7	1.4-9.1
MgO %	0.10	0.06-0.10	0.34	0.12	0.22	0.70-0.78
CaO %	0.09	0.06-0.09	0.19	0.02	0.08	0.21-0.36
Na2O %	0.04	0.00-0.05	0.07	0.03	0.05	0.10-0.17
K2O %	0.06	0.02-0.10	0.69	0.25	0.70	1.19-1.36
TiO2 %	1.2	1.0-1.3	0.6	0.3	0.6	0.8-1.0
P2O5 %	0.02	0.05-0.06	0.04	0.30	0.41	0.07-0.15
MnO %	0.012	0.007-0.013	0.007	0.034	0.011	0.006-0.010
LOI %	10.1	7.7-9.9	7.4	9.0	9.0	7.2-9.2
Cr ppm	438	367-413	65	204	70	39-54
V ppm	8914	2313-2552	427	451	568	103-169
Cu ppm	25	16-18	<10	22	60	<10-11
Pb ppm	235	55-60	28	<5	12	22-28
Zn ppm	60	39-60	18	158	56	23-32
Ni ppm	22	<10	<10	89	<10	<10-101
Co ppm	<10	<10-22	<10	45	9	<10
Ga ppm	26	27-33	17	9	21	19-24
Ba ppm	466	776-821	197	100	120	237-386
Zr ppm	289	257-313	146	106	106	118-175
Nb ppm	11	5-14	6	4	9	<4-6
Ce ppm	22	6-23	32	17	47	54-83
La ppm	11	<10	22	<10	7	32-49
Rb ppm	<5	<5-5	31	10	35	58-68
Sr ppm	32	31-51	102	36	115	266-530
Y ppm	24	15-22	13	5	21	16-17
S ppm	580	550	160	870	380	160-220

The underlying mottled zone consists of abundant blocky mega-mottles. The contact between the ferruginous duricrust and the mega mottles is gradational. The matrix of the mega mottled zone is a highly siliceous porcellanite, with quartz and opal-CT minerals and contains up to 75.9% SiO_2, 8.4% Al_2O_3 and 7.4% Fe_2O_3. The ferruginous veins, within the mega mottled zone are laminated, rich in Fe (68.1% Fe_2O_3) and consist mainly of goethite, with some mica and kaolinite.

Below the mega mottled zone, there is collapsed ferruginous saprolite and the boundary between them is uneven. The collapsed saprolite consists of a siliceous breccia in a yellowish brown clay matrix. This grades downwards into white, brown or purple saprolitic clays, which are generally near the foot of the mesa. These clays are smectitic and contain some kaolinite, goethite and mica. Associated with the saprolitic clays are nearly flat, ferruginous bands which form a steplike microrelief. They consist mainly of goethite, quartz, some mica and kaolinite. These bands can contain up to 34.7% Fe_2O_3.

The composition of the silicified mottled zone matrix is broadly similar to that of the saprolitic clays except for more Si, Fe, Cr and V and lesser Al, K, Na and Mg than the clays. The saprolitic clays are relatively rich in Mg, Ca, K, Rb and Sr compared to the other regolith materials.

6.2.1.3 Black soils

The black soil plains are characterised by gilgai microrelief caused by drying and swelling of smectitic clays; black colour is due to organic matter. The black soils are commonly 1-2 m thick and are developed over colluvium-alluvium overlying Mesozoic saprolite. They are generally dark brown to black, depending on their physiographic position, with darker coloured soils occupying lower lying areas where smectite can be formed, with high Ca, Mg and silica in the groundwater. The black soils have about 70% <75 μm fraction, and the remainder being largely quartz grains and pebbles. They consist mainly of quartz with smectite, some kaolinite and feldspar. The chemical composition of the <75 μm fraction is given in Table 7. Compared to other regolith materials found in the Mesozoic and Proterozoic mesas, it is rich in Mn, Mg, Ca and Zr.

Table 7. Descriptive statistics of black soils, <75μm fraction (n=8), Tringadee district.

Element	Mean	Min	Max	Range	Median	Element	Mean	Min	Max	Range	Median
SiO2 %	62.1	57.2	67.1	9.9	62.1	Ba ppm	456	372	532	160	473
Al2O3 %	14.6	12.5	16.1	3.6	15.0	Zr ppm	403	230	555	325	414
Fe2O3 %	6.4	5.1	8.8	3.8	6.1	Nb ppm	8	<4	17	14	7
MgO %	1.11	0.78	1.45	0.67	1.19	Au ppb	<5	<5	<5	<5	<5
CaO %	0.66	0.42	1.00	0.58	0.58	Ce ppm	105	79	158	79	93
Na2O %	0.44	0.24	0.66	0.42	0.42	Cs ppm	4	3	5	2	4
K2O %	0.96	0.70	1.21	0.51	0.97	Eu ppm	2.3	1.7	4.6	2.9	2.1
TiO2 %	0.9	0.8	1.0	0.2	0.9	Hf ppm	11.0	6.3	16.0	9.7	11.1
MnO %	0.12	0.08	0.17	0.081	0.111	Ir ppb	7	7	7	0	7
P2O5 %	0.06	0.04	0.09	0.04	0.05	La ppm	48.6	33.9	80.8	46.9	43.5
LOI %	8.2	6.7	9.1	2.4	8.3	Lu ppm	0.8	0.6	1.3	0.7	0.7
Cr ppm	63	52	73	21	63	Rb ppm	66	48	79	31	68
V ppm	142	93	226	133	139	Sm ppm	10.4	7.7	15.4	7.7	10.0
Cu ppm	20	12	31	19	20	Sc ppm	14.6	12.7	16.3	3.6	14.7
Pb ppm	21	14	27	13	21	Se ppm	<5	<5	<5	<5	<5
Zn ppm	67	41	92	51	71	Ta ppm	1.65	1	2	1	2
Ni ppm	67	25	143	118	54	Th ppm	16.9	11.2	30.5	19.3	14.9
Co ppm	21	12	38	26	20	Yb ppm	5.4	3.9	9.1	5.2	5.1
As ppm	7	4	14	9	6	Br ppm	5	2	9	7	5
Sb ppm.	0.4	0.3	0.5	0.2	0.4	Sr ppm	143	116	212	96	132
Mo ppm	<5	<5	<5	<5	<5	U ppm	<2	<2	3	3	<2
Ag ppm	<5	<5	<5	<5	<5	Y ppm	49	33	90	57	43
Ga ppm	18	15	21	6	17	Cl ppm	<20	<20	<20	<20	<20
W ppm	<2	<2	<2	<2	<2	S ppm	159	120	190	70	165

6.2.2 Transect DE on Proterozoic granitoid dominated terrain

The Proterozoic granitoid dominated terrain is redder on the aerial photographs (Figure 58). The landforms are rolling and dissected, with prominent red colluvial-alluvial sands which characterise the outwash plains. Transect DE cuts across a remnant Mesozoic hill overlying granite, granite outcrops and the base of the Mesozoic claystone. The transect DE is represented in Figure 55.

In places where granite has only a thin veneer of Mesozoic sediments, as in position D, weathering is deep and is depicted by white patches of kaolinite from the weathering of feldspars and reddish hematitic mottles from weathered biotite. On thinner Mesozoic cover, drill spoil indicates that there is an indurated ferruginous, quartzitic layer or yellowish sand at the unconformity between Mesozoic sediments and granite, generally at 20-25 m. Where the unconformity is partially exposed, near the centre of the transect DE, this layer forms a slabby, ferruginous sediment consisting of medium to coarse sand with quartz pebbles indurated by Fe oxides.

There are a few spheroidal boulders of nearly fresh granite. However, the formation of lateritic profile on granite from observations elsewhere seems to indicate that it could be a remnant lateritic profile of the Mesozoic developed from the granite. An exposed vein related to late-stage hydrothermal activity associated with granite emplacement now consists of hematite with some goethite, kaolinite and mica but the presence of microscopic trellis structures indicated derivation from magnetite. The trellis microfabric is also common in ferruginous nodules over granite, indicating a likelihood that the weathering of these ferruginous veins could have contributed to a lag of lateritic nodules. The hematite is rich in Mn and Co compared to other regolith materials.

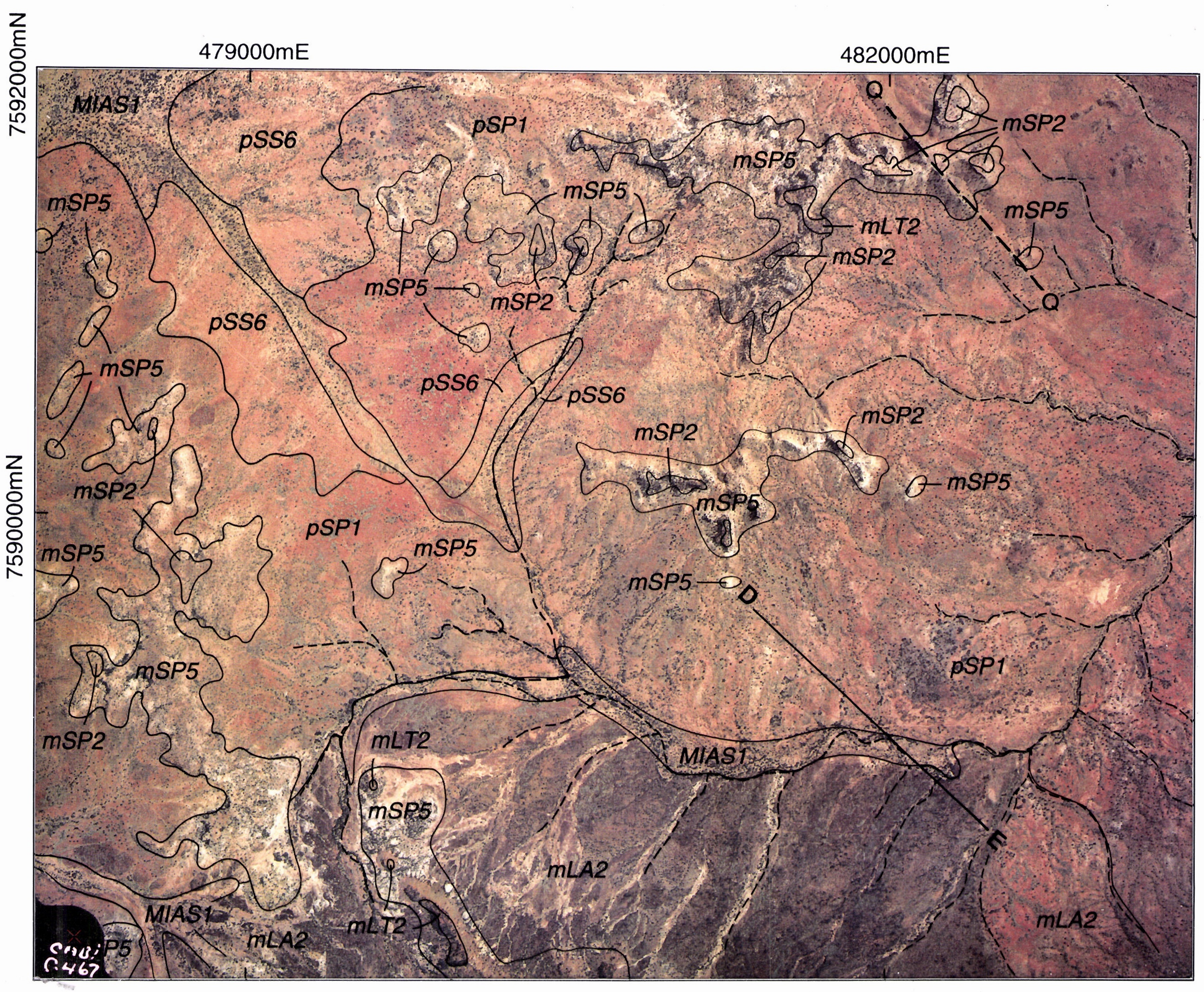
6.3 Regolith Evolution

The Mesozoic sediments are flat lying and have not been metamorphosed, reflecting that the region has been part of a relatively stable tectonic block (Blake, Jaques and Donchak, 1983). The sedimentary unit that is most extensive is the Gilbert River Formation, which consists of poorly sorted, cross-bedded, sandstone and conglomerate, in the lower part of the formation and claystone in the upper part. Late in the Cretaceous or early Tertiary, the region was gently uplifted, initiating the most recent geologic cycle of weathering, erosion and deposition.

It is postulated that during the period of gentle uplifting, lateritic weathering and silicification overprinted each other. Lateritic weathering would result in formation of mottles and lateritic duricrust. The Fe may have been derived laterally, or from the ferruginous veins emplaced in the granite during late-stage hydrothermal activity. Silicification have impregnated more permeable parts of the lateritic profile. At times of intense leaching, movement of clay out of less silicified parts of the weathering prôfile would result in a brecciated zone, which is now collapsed ferruginous saprolite. Formation of the collapsed saprolite, and differential erosion of the Mesozoic sediment surface (due to differences in intensity of silicification or ferruginisation, or local variations of sediments and intensity of rainfall) may be responsible for variety of heights of the Mesozoic mesas. The present Mesozoic mesas on granite in the north can be about 100 m higher from the present Mesozoic mesa towards the south. This variation in topography is reflected by the present main drainage (Bustard creek) which flows south. It is uncertain if deep weathering of the granitoid occurred prior to Mesozoic sedimentation.

The gentle uplifting also resulted in several palaeo still-stands in the water-table, resulting in redox zones shown by goethite-and Mn oxides-rich bands at the base of the present mesas. Some of these bands appear as steplike microrelief. Goethite and Mn oxides in these bands have scavenged Zn and other trace elements and explain why the Tringadee Prospect has a Zn anomaly in the Mesozoic cover. The area around ROTR 155 and 156 is low relative to the surroundings. Low mounds of goethite and Mn oxides here could be exhumed redox zones and, because they are low in the landscape, there has been recent movement and redeposition of Mn oxides.

The gentle uplifting also resulted in fractures in the Mesozoic profile causing conduits for fluids rich in Fe. These are common at the Brumby Prospect where ferruginous fractures crisscross each other.



Regolith developed from weathering of Mesozoic sediments

mLT2	Lateritic duricrust
mLA2	Lag of lateritic nodules, fragments of ferruginous saprolite and silicified saprolite
mSP2	Ferruginous saprolite-silicified/collapsed breccia
mSP5	Silicified saprolite

Regolith developed from weathering of Proterozoic rocks

pSS6	Red sand, undulating plain
pSP1	Saprolite, mottled saprolite and outcrops of fresh granite

Regolith of mixed origin - (derived from weathering of Mesozoic sediments/Proterozoic rocks)

MIAS1	Alluvium
Q-- Q	*Quartz dyke*

p *Proterozoic rocks*
m *Mesozoic sediments*
MI *Mixed lithologies*

—— Transect

N

0 1 km

Approximate scale due to distortion from aerial photographs

Figure 58. Map showing the distribution of regolith-landform units and vegetation as an overlay to the colour air photograph (Commonwealth of Australia, 7054 Selwyn photo, 8/41, 3.10.1972) Tringadee area. Transect DE is discussed in the text.

7. ELOISE-MARONAN DISTRICT

The Eloise Cu-Au mine is located about 60 km southeast of Cloncurry. The area selected for study is about 21 x 34 km. Detailed investigations of the regolith geology and geochemical dispersion in the regolith will be reported separately. Important features of the regolith and landscape which consist of undulating plains, fluvial ridges and patches of outcropping Proterozoic bedrock, are described here. The Proterozoic bedrock in most of the area is covered by up to 50 m of partly weathered Mesozoic sediments, which are in turn overlain by 2-8 m of Tertiary and recent sediments. The sediments do not contain any information that would constrain the time of deposition but, from their position in the landscape, they are probably Tertiary. The unconformity between the Proterozoic and the Mesozoic sediments is marked by about half a metre of conglomerate, consisting of rounded gravels in coarse sands derived from erosion of the basement. The Proterozoic is only very slightly weathered immediately below the Mesozoic. This indicated that the landscape was in an erosional regime before Mesozoic deposition.

In most parts of the area, it appears that the upper portion of the Mesozoic may have been removed to accommodate the Tertiary sediments. However, the Mesozoic sediments remain almost intact in the north-eastern part of the mapped area and contain fossil ammonites in the siltstone and limestone, suggesting a Cretaceous age. Where exposed beneath the Tertiary and recent sediments in open pits, the Mesozoic sediments have been weathered.

Costeans and drill hole data from the Tertiary sediments show various facies from large gravels to coarse sands and fine clay, derived from erosion of weathered Mesozoic and/or Proterozoic rocks. The Tertiary sediments define former channels of a major river, probably the ancestral Fullarton River. The sediments form fluvial ridges or high river terraces, give rise to rolling plains. Cross bedding and former channel changes can be identified.

Some Tertiary sediments are mottled, brown to red clays (Figure 18E). Where the material is fine, due to facies changes or backwater deposition, black soil may be formed in them depending if the area is poorly drained (Figure 18F). In places, fine material beneath coarse gravelly sands is mottled.

Lag, with a veneer of residual soil over weathered Proterozoic bedrock, occurs in the western part of the area at a similar level to the interfluve Tertiary sediments in the landscape. This suggests that intensive erosion took place while sediments were deposited to form the ridges and, ever since, the southwestern portion of the mapped area has been in an erosional phase.

The Quaternary to recent alluvium on the modern floodplains has also been weathered, forming black soil plains. Development of black soil is closely associated with poor drainage and fine parent material. At one place, a patch of black soil is formed, but next to it is brown soil. Both are developed over the same alluvium unit but under different drainage conditions. The ready supply of water on flood plains facilitates development of black soils.

8. SYNTHESIS

8.1 Regolith and Landscape Development

8.1.1 Pre-Mesozoic relief and Mesozoic sedimentation

The regolith-landscape model of the Mt Isa region is summarised in Figure 59. Twidale (1966) proposed that the Mt Isa region had been reduced to a peneplain by the early Mesozoic and this surface has been called the sub-Carpentaria surface by Grimes (1979). However, it is suggested, here, that there was quite substantial pre-Mesozoic relief (Figure 59). Although early Mesozoic weathering and erosion bevelled the landscape, irregular thicknesses of Mesozoic sediments, and an undulating pre-Mesozoic unconformity on Proterozoic rocks are best explained by sedimentation filling valley-and-ridge palaeo-topography. This is not unexpected, as the Proterozoic rocks have weathered differentially due to their heterogeneity.

Remnants of the Mesozoic sediments indicate, that during the Cretaceous, a marine incursion deposited sandstone, greywacke, shale, claystone, siltstone, limestone and conglomerate over a large part of the Mt Isa Inlier. At the close of this era only highly resistant Proterozoic lithologies protruded through the Mesozoic (Grimes, 1972). However, prior to marine progradation, the landscape was an erosional regime, as indicated by a thin layer of conglomerates over the Proterozoic bedrock and by the relatively slight weathering of the Proterozoic below the Mesozoic unconformity, where it has been unaffected by more recent weathering.

8.1.2 *Weathering, erosion and deposition*

Following deposition of the Mesozoic sediments, the region was uplifted and exposed to long periods of erosion, weathering and deposition. After Mesozoic sedimentation the landsurface was reduced to a gently undulating plain with some hilly terrain in the centre. Much of the region was deeply weathered, except for areas occupied by steeper hills, where the rugged relief caused continuous erosion and prevented the retention of regolith materials. The plains, whether gently sloping, rolling or flat, are the end result of a long and complex erosional and depositional history. Some of this is the result of large volumes of sediments that were deposited at the margins of plains in the mid to late Tertiary. Tertiary sediments were further weathered but the limited observations do not allow the extent of this weathering to be determined (*i.e.* were they weathered to their base, or were they kaolinitic when deposited?). Later mottling of the Tertiary sediments is common.

Remnants of the deep lateritic mantle that developed on the Mesozoic surface still survive on mesas and dissected plateaux in the region today. Some areas (*e.g.*, Buckley River) were eroded less than others. Within a single area, some parts have been eroded and other parts have remained relatively unchanged. Materials removed by erosion have been deposited on lower slopes, with consequent burial of deeply weathered profiles. Consequently, the landscape of the Mt Isa region is characterised by three major geomorphic provinces, namely hill belts, a complex of mesas and plains, and plains, which show varying degrees of weathering, erosion and deposition. These three major provinces can be further subdivided on the basis of their dominant geology and topography.

The hill belts occupy the central portion of the region and predominantly comprise north-trending ridges and hills. Here, the detailed sculpturing of the landsurface is intimately related to differential weathering and erosion of various rock types. Mesozoic sediments are sporadically distributed, generally as small mesas. Not all the rocks in the hill belts are fresh and many have signs of former and present weathering that involves formation of kaolinite, smectite and pedogenic carbonates. Zones of superficial, secondary silicification are marked. The colluvium is generally less than one metre thick but reaches thickness of 12 m in places. Soils developed in colluvium are calcareous to non-calcareous.

The terrain characterised by the complex of mesas and plains shows sign of the variable extent of former lateritic weathering. These areas are part of a dissected plateau on which the original surface forms a significant component of the landscape. Deeply weathered profiles with ferruginous or siliceous cappings occur on stable parts of the landscape (mesas crests) but, even here, the total depth of weathering is variable. In contrast, relatively shallow weathering profiles occur on pediments and erosional plains. The depositional plains are mantled with shallow alluvium (1-5 m) that is underlain by deeply weathered profiles with or without a ferruginous or siliceous horizon.

The plains feature variable thicknesses of weathered and partly eroded Cainozoic, Tertiary and Mesozoic sediments, underlain by Proterozoic bedrocks.

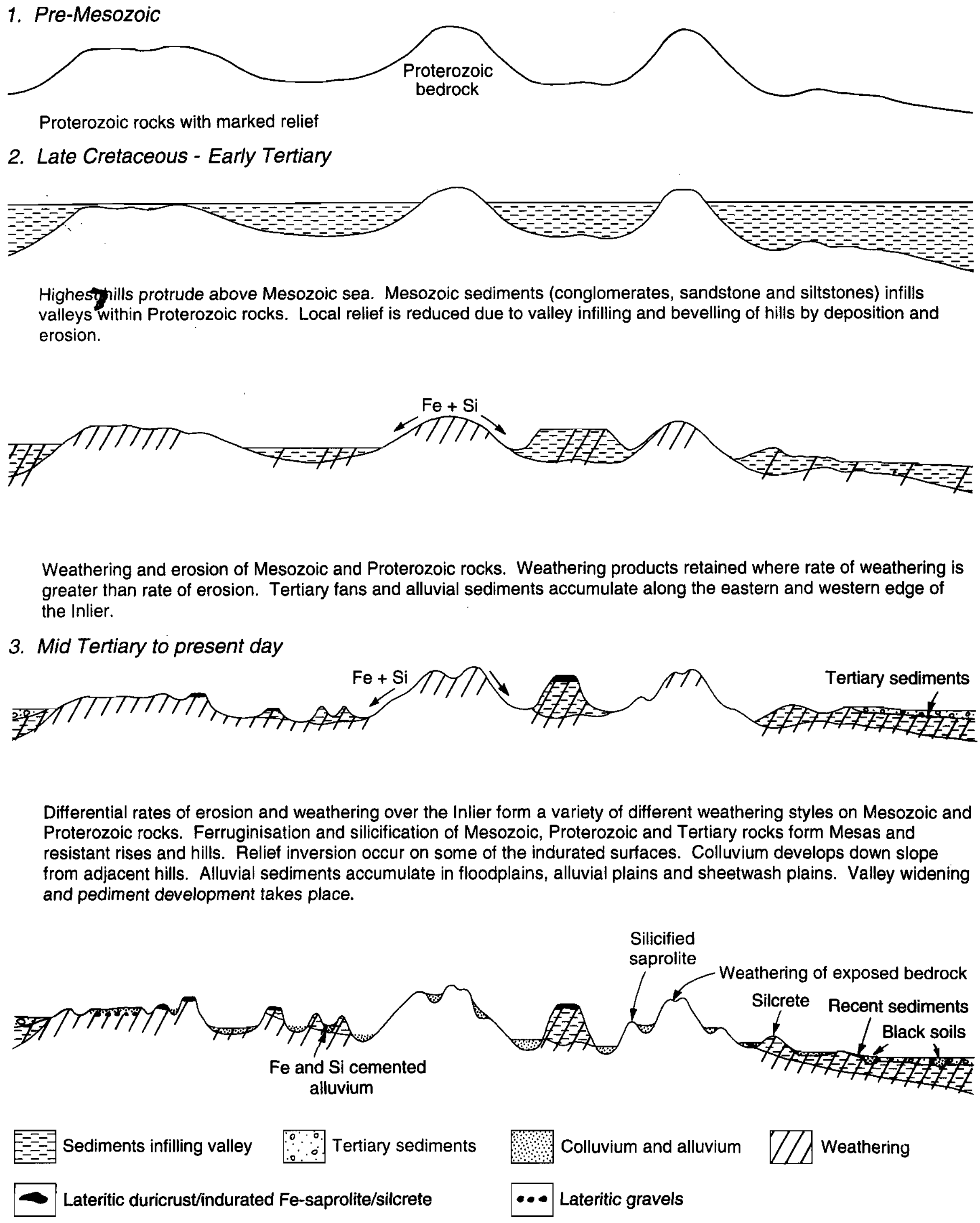


Figure 59. Regolith-landscape model for the Mt Isa region.

8.1.3 Weathering profiles

The nature and depth of weathering profiles on Proterozoic and Mesozoic rocks are variable and are largely controlled by bedrock composition. However, depth of weathering of the Proterozoic rocks is also controlled by the presence (or absence) of overlying Mesozoic sediments at the time of weathering. Proterozoic rocks are weathered to greater depths where Mesozoic sediments have been removed or were never deposited. Lateritic duricrust and indurated ferruginous saprolite were developed on Fe-rich rocks, with silcrete and silicified saprolite as equivalent horizons on siliceous bedrock. The 'complete' weathering profile has a lag of lateritic nodules and pisoliths, pockets of duricrust, indurated ferruginous saprolite, clay zone, saprolite (possibly silicified), saprock and bedrock. Lateritic duricrust and silcrete have also developed on some Mesozoic sediments.

The characteristics of weathering profiles reflect both past and present weathering conditions. The formation of ferruginous and siliceous duricrust-capped weathering profiles containing Al_2O_3, Fe_2O_3 and, probably, SiO_2 corresponds to wet climates, whereas the formation of calcrete and smectite correspond to arid conditions. Calcrete and smectite are typically developed on partially weathered rocks of hill belts and on erosional plains, and are products of weathering under the present climate. Duricrust-capped deeply weathered, kaolinised profiles are inherited from past climates.

Dating of Mn oxides from several locations (Gunpowder Creek, Selwyn, Mt Isa Mines and the Overhang Manganese Mine) indicates that weathering started at least at 65+ 1.3 Ma ago and has probably persisted throughout the Tertiary and Quaternary (P. Vasconcelos, Univ. of Qld, written communication, 1995). Samples from these areas yielded ages of Mn oxide precipitation at 65 Ma, 41-43 Ma, 36-39 Ma and 15-20, Ma, and jarosite precipitation at 2 Ma. The oldest age obtained for the Overhang Mine, 65 Ma, is a minimum age for the onset of weathering in the region so it is not possible to state when the weathering surface began to develop. Nevertheless, a complex and deeply weathered surface such as this is not the product of single weathering stage, but evolves through a series of superimposed weathering events.

8.1.4 Development of erosional surfaces

Grimes (1979) has proposed three major periods of active erosion and deposition for North Queensland, separated by two periods of stability and deep weathering. At the end of the first cycle (Oligocene), a stable, deeply weathered and duricrust capped planation surface, the Aurukun Surface, formed. This surface is now preserved as duricrust capped mesas. The second cycle, the Kendall surface, also ended with a stable landsurface which was deeply weathered and ferruginised. The third cycle, which commenced towards the end of the Tertiary, is continuing. This cyclic model for development of the deep weathering profiles differs from that of Mabbutt (1980), who considered that there was no evidence for periodicity in the development of kaolinised profiles, but accepted that ferruginisation and silicification of the upper parts of the profiles could be periodic.

There are differences in the nature and development of different regolith units (such as duricrust and depth of weathering) in a broader sense, within the framework of landsurfaces proposed by Grimes, but a more detailed understanding is necessary for geochemical exploration. A variety of regolith materials, with different characteristics and complex origins, occur on the Aurukun and Kendall surfaces. A single age, therefore, can not be ascribed to regolith developed on such extensive planation surfaces (*e.g.*, Aurukun) since different parts of the surface may have formed at different times. This is expected, since the landsurfaces remain dynamic after major planations have been 'completed' and the actual surface is in a constant state of change. These aspects are discussed further below.

8.1.5 Origin of ferruginous materials

8.1.5.1 Nature and occurrence

There are six main types of ferruginous materials in the landscapes of the Mt Isa region. These include lateritic gravels, lateritic duricrusts, ferricretes, indurated ferruginous saprolite, ferruginous bands and ferruginous veins. The first four form in the upper part of the weathered profile whereas ferruginous bands and ferruginous veins occur dominantly in the saprolite. Lateritic duricrust can be further sub-divided according to its secondary structures, i.e. massive, slabby, conglomeratic, nodular and vermiform; these materials occur in various landscape positions and have formed in both *in situ* and transported materials.

Ferruginous materials have formed in a variety of substrates derived from Proterozoic basement and Mesozoic, Tertiary and recent sediments. However, the degree of ferruginisation varies with the nature of the parent material. For example, the ferruginous horizon on Tertiary sediments is limited to mottles; duricrust is not developed. Duricrusts, lateritic nodules, pisoliths and indurated ferruginous saprolite are developed both over Proterozoic basement and Mesozoic sediments.

8.1.5.2 Lateritic gravels

Lateritic gravels consist dominantly of nodules and hardened mottles with rare pisoliths. They occur either as lag or buried beneath shallow colluvium-alluvium, as loose or cemented gravels. Lag gravels are found on mesas, rises and associated gentle slopes. Although not common, downslope mass movement of these gravels has formed surficial packed duricrust on lower slopes in some localities. Lateritic gravels are derived from ferruginous masses in the weathering profile, such as continuous sheets of ferruginous saprolite or mottles in a clay zone or locally derived colluvium. They are released by collapse of the ferruginous saprolite and mottled zone by removal of the kaolinitic matrix. These processes of formation of lateritic gravels are similar to those observed in the Yilgarn Craton.

Mottles are developed by local-scale migration and accumulation of Fe, which is largely derived from the adjacent matrix. Iron oxides are precipitated as spots, blotches, and streaks, leading to hematitic mottling of the clay zone. As the surface is lowered, the mottles harden into nodules or pisoliths, as a result of rapid wet-dry cycles in the upper, vadose zone of the profile. Loss of kaolinite from the matrix has led to accumulation of the hematite segregations as packed nodules and pisoliths (with cutans) at the surface. In moist situations, the hematite of the nodules may be dissolved and precipitate as goethite cutans on hematite-cored nodules.

Where the bedrock is rich in Fe, pseudomorphic precipitation of Fe oxides form strongly indurated hematite-goethite-rich ferruginous saprolite, containing much kaolinite. Ferruginous saprolite cappings are common over Fe-rich shales, dolomitic siltstones and basalts. Higher in the profile, soft, clay-rich masses in the ferruginous saprolite have dissolved, leaving numerous voids. The voids weaken the saprolite structure, leading to its collapse (collapsed ferruginous saprolite). Fragments of collapsed ferruginous saprolite subsequently break into small nodules at the surface, forming a lag.

Mottles are common in recent sediments, but they differ from those in Proterozoic or Mesozoic sediments. The cores of the mottles show soil fabric, they are low in Fe, do not show any development of goethite-rich cutans and have not evolved into nodules.

8.1.5.3 Lateritic duricrusts

Lateritic duricrusts do not form extensive sheets but occur as pockets on mesas, rises and footslopes. They have developed both on Proterozoic bedrock and Mesozoic sediments and their origin is much more complex than that of mottles and nodules.

Massive duricrusts on Proterozoic rock are dense, black and dominated by either goethite or hematite (or, more rarely, almost equal proportions of both) with variable amounts of quartz and mica. Massive duricrusts are typically formed by weathering of shales, basalts and some siltstones. Slabby duricrusts are massive horizontal plates of quartz-rich material impregnated by goethite. Hematite is generally absent. However, not all the Fe oxides in massive and slabby duricrusts have been accumulated from residual weathering; lateral input from Fe-rich sources, such as pyritic units, is likely as some duricrusts have very different concentrations of Cu and Zn from the underlying regolith. They are particularly goethite-rich and contain more Fe than hematite-rich duricrusts, suggesting a significant component of Fe is laterally derived. It is suggested that these duricrusts formed low in the landscape and the topography has since been inverted. They lack concentrations of zircon and other heavy minerals, implying that they have not developed in alluvium but in locally derived substrates.

Nodular duricrusts on Proterozoic rocks occur on rises and are linked to the underlying mottled zone. The nodules have a similar composition to the surrounding matrix and lack complex multiple cutans. This simplicity implies a shorter weathering history and little or no transportation.

Lateritic duricrusts on Mesozoic sediments occur on mesas. Massive and slabby duricrusts are developed on claystone and sandstone and closely resemble to those developed on Proterozoic rocks. However, they are relatively enriched in Si due to their high quartz content. Duricrusts have largely resulted from absolute accumulation of Fe because they invariably contain much more Fe than would readily have been derived from their Fe-poor parent rocks.

Conglomeratic duricrusts are developed on remnants of basal gravels of Mesozoic sediments and are generally thinner than massive duricrusts. The duricrust looks similar to massive and slabby duricrusts but contains abundant cobbles.

8.1.5.4 Ferricretes

Weathering profiles are not static and Fe and other elements have been continuously moving into and out of the profile. The process of Fe and Mn enrichment of sediments has resulted in goethite-and Mn-rich pods or Fe-rich duricrust. These materials commonly occur on footslopes and valley floors, scavenge trace elements, are not genetically related to the underlying lithologies and are referred to as *ferricretes.*

One of the characteristic feature of massive, slabby and conglomeratic duricrusts and ferricrete is the absence of goethite-kaolinite cutans. This contrasts with lateritic nodules and nodular duricrust, which commonly have cutans. Presence or absence of cutans in these materials suggest different environments of formation. The cutans on nodules and associated nodular duricrusts are formed in moist, soil environments where hematite has dissolved and precipitated as goethite with kaolinite to form cutans. Lack of cutans in massive, slabby and conglomeratic duricrusts imply their formation in soil free environments.

8.1.5.5 Indurated, ferruginous saprolite and mega-mottles

Where the bedrock is rich in Fe, pseudomorphic replacement of the kaolinite by Fe oxides has lead to strongly indurated hematite-goethite-rich ferruginous saprolite. Such cappings are common over Fe-rich shales and basalts and occupy mesas, rises and erosional plains. Iron is largely derived from weathering of the underlying bedrock.

8.1.5.6 Ferruginous bands

Ferruginous bands are redox products the deposition of which are controlled by oxidation of Fe^{2+} under favourable pH conditions within the profile. These redox products, dominantly Fe-oxides, occurs in the lower and middle part of the profile and appear related to fluctuations in the water table and texture of sediments. They are strongly developed in sandy sediments.

8.1.5.7 Ferruginous veins

Ferruginous veins follow bedding planes and fault systems and these are particularly common in the Mesozoic cover.

8.1.6 Correlation of duricrust with erosional surfaces

Many authors have related lateritic duricrusts to landsurfaces. These models have however, not been tested. No reliable indication of age can be obtained from the morphology, chemistry and mineralogy of lateritic duricrusts. Similar suites of ferruginous duricrusts occur at different levels. The variable Fe-oxide mineralogy of duricrusts also suggest they have experienced different hydrological environments. Older materials are generally richer in hematite due to ageing of the Fe oxides or to warmer conditions of formation, hence duricrusts dominated by hematite may be older than those dominated by goethite.

Lateritic duricrusts or indurated ferruginous saprolite developed in different sites in response to different geological and environmental conditions. In some parts of the landscape, these duricrusts and ferruginous saprolites have been retained, whereas in others they have been eroded. Some of the duricrusts were formed in local valleys but, following induration and erosion, now occupy positions of positive relief (relief inversion).

The variety of ferruginous materials of different characteristics suggest that formation of landsurfaces in the Mt Isa region has been complex. It would be unwise to ascribe a single age to the regolith or imply a single extensive surface of planation (*e.g.*, Aurukun) since different parts of the surface may have formed at different times. Extensive surfaces of planation can have no single age but develop through long time periods of perhaps 10^7 years (Ahnert, 1970). During such periods, the landsurface will undergo fluctuations of environment. Lateritisation and duricrust formation of such surfaces are complex processes, which require various conditions that will determine the period(s) of formation.

Nahon and Lappartient (1977) calculated that a nodular, ferruginous horizon 0.5-1.0 m thick required 0.3-0.75 Ma to form in the semi-arid zone of Senegal. It was calculated that 6 Ma was necessary to form a complex profile (containing 8-10% Fe_2O_3), to allow for the destruction of most of the kaolinite and for the massive iron crust to break down into nodules. However, the period will depend on the nature of the parent rock, climatic changes, tectonic evolution and other factors. It is thought likely that most of the duricrust- capped profiles in the Mt Isa region began to form in the Late Cretaceous and have evolved since then.

8.1.7 Origin of silcrete

Silcrete is widespread in the Mt Isa region and is closely associated with palaeosurfaces. Arguments about silcrete formation are similar to those concerning lateritic duricrust and turn on the provenance of the silica and the conditions under which it has been mobilised. Extreme positions have been taken on both issues. Long distance transport of silica from the humid environments of the eastern Highlands of Australia into the interior basins was advocated by Stephens (1971), but Wopfner (1978) and Butt (1985) have proposed that the silica is drawn mainly from the kaolinised profiles and toposequence within which it is found. Some authors assumed that silcrete indicates arid or semi-arid conditions. Although some silcrete may form in this way, there is increasing evidence that it can also form in humid climates (Wopfner, 1978; Taylor and Ruxton, 1987).

In the Mt Isa region, silcrete commonly occurs as massive, nodular and large massive columnar jointed sheets. Silcrete may contain as much as 92-97% SiO_2 as quartz, with TiO_2 (as anatase) and traces of Zr (zircon) making up the remainder. They are almost entirely depleted of Al, K, Mg, Ca, Fe and P. No universal model of silcrete development is applicable to the Mt Isa region, although some possible modes of formation are suggested;

(1) Silicification of an upper horizon of a weathering profile due to upward transfer of silica. Quartz-micro-quartz silcretes, associated with silicified, previously kaolinised profiles, occur on plateau remnants and were probably formed in acid groundwater environments in areas of subdued relief with poor drainage. Loss of primary fabric from the silcrete suggests that they have formed close to the surface. Silica was drawn mainly from the kaolinised profile within which it is found. For saprolite to provide enough silica to form a 1-2 m thick silcrete requires dissolution of SiO_2, without mobilising the Al^{3+}. The conditions for loss of Al from the profiles were considered by Summerfield (1983), who utilised isovolumetric calculations to estimate a 95% loss of Al, with Si depletion from kaolinite of 40-50%, and accumulations of 30-40% in the overlying silcrete. Titanium enrichment in the silcrete approached 120%. Titanium becomes increasingly soluble at pH <3.75, but aluminium solubility rises steeply below pH 4, and overtakes the solubility of silica in these situations. Such conditions may imply impeded drainage, with silcrete formation taking place preferentially within water-table fluctuations.

(2) Silicification of a lower horizon of a truncated profile. The stromatolite beds within the sedimentary sequence are particularly prone to silicification, often forming prominent chert hills and ridges.

(3) Silicification of sands and gravels without profile development where amorphous silica cements sediments that may be brecciated, conglomeratic or fine grained. Silicified alluvial sands and gravels now occupy topographically high areas, because of relief inversion. Indurated silicification has led to differential erosion and relief inversion. Cementing was probably associated with fluxes of silica-rich ground waters when the sediments were low in the landscape. Here, there is no genetic relationship between silcrete and the underlying bedrocks.

(4) Silicification of some soils, lateritic duricrust and mottled zones.

There appear to have been several periods of silicification which have affected materials of various types and ages.

8.1.8 Relationship between silcrete and lateritic duricrust

Various ideas have been proposed over the years about the relationships between silcrete and lateritic duricrust, but no agreement has been reached (Ollier, 1993). Some workers envisage the two materials formed at the same time in different environments, others suggest they formed at different times, perhaps related to changing environments.

Dury (1968) and Stephens (1971) produced maps showing silcrete dominant in a central zone of Australia and lateritic duricrust in the moist periphery, implying a climatic or hydrological control. In the Mt Isa region, silcrete and lateritic duricrust occur within few hundreds of metres of each other. No simple model can describe these silcrete-lateritic duricrust relationship. Conclusions drawn from profiles which have silcrete and lateritic duricrust, and from their geomorphic setting in the Mt Isa region are as follows.

(1) Similarities between deep profiles with silcrete and those with lateritic duricrust are striking in terms of thickness, in profile zonation, and in structural details of the duricrust. All the silcrete cappings on plateau surfaces, and their underlying horizons, show some mottling. The massive and nodular silcretes are similar to lateritic duricrusts, and lateritic mottles and nodules occur on silcrete surfaces.

(2) The lithology influences whether silcrete or lateritic duricrust are formed. Silcrete is preferentially developed on Mesozoic claystone and Proterozoic siltstone, whereas lateritic duricrust is found on Fe-rich shale, dolomitic siltstone and basalt.

(3) Silicification and ferruginisation can occur in any part of a lateritic profile. However, distinction should be made between the upper silcrete and the lower silicified saprolite and between the upper lateritic duricrust and the lower ferruginous saprolite. They differ in preservation of rock fabric, and in their accordance with the landsurface.

(4) Silicification and ferruginisation of sands and gravels has also taken place, but here there is no genetic relationship between silcrete and the underlying regolith.

It is clear that the silicification has affected a range of regolith materials. However, well developed silcrete on plateau remnants should be interpreted as a landscape near-equivalent of the lateritic duricrust of the laterite profile. Occurrence of ferruginous mottles and nodules among the lag possibly indicates stripping of a thin soil and/or ferruginous horizon from the silcrete.

8.1.9 Soils

The genesis of the soils in this region appears relatively uncomplicated compared to the geomorphic history of the region. Soils have formed on sediments (Mesozoic and Cainozoic), Proterozoic basement and on saprolites formed from them. Lateritic, gravelly soils have developed on older, pre-existing lateritic profiles of the plateau erosion surface on Proterozoic and Mesozoic rocks. The red, brown and yellow earths are formed on the eroded slopes and plains in erosional terrain below the lateritic plateau remnants. They are developed on the underlying saprolite and saprock so exposed by erosion of the dissected slopes. Yellow earths are generally associated with more siliceous Proterozoic bedrocks but, on the more ferruginous rocks, red earths result. In places, however, these residual soils are overlain by recent fluvial deposits.

Lithosols or skeletal soils are associated with resistant rocks and areas of high relief and steeper slopes. In areas of relief, soil development can not keep pace with erosion. Soils of the hill belts are characterised by abundance of pedogenic carbonates resulting from weathering of underlying rocks.

In depositional plains, the soils vary from black through red to grey sandy clay, sands or clays and generally contain polymictic gravels. Some are bedded and contain gravelly lenses. The nature of the soil depends on the provenance and thickness of the parent materials and on the history of post-depositional erosion. Much of the sediment is thought to have been derived from erosion of the older deeply weathered mantle. Brown and red soils are developed where the drainage is good. Hydromorphic conditions in depressions and gentle slopes favour formation of black soils. This is discussed in detail below.

Some soils are cemented by Fe and others by silica. On the valley floors, these soils are characterised by enrichment of Fe_2O_3 introduced into the subsoil by percolating groundwaters that have obtained their dissolved Fe^{2+} from surrounding higher areas. The water table has fluctuated considerably, approaching the surface in the wet months to yield a hydromorphic soil. This soil could well represent an early stage in the formation of the sandy ferricrete typical of Mesozoic valleys.

Origin of black soils
Black soils in the region are developed on a variety of parent materials including Mesozoic, Tertiary and recent sediments. They occur in depressions and are largely absent on steeper slopes and hilly areas. Black soils have formed from shrinking and swelling clayey parent materials or from materials that weather to shrinking and swelling clays (dominantly smectite). The brown to black colour is due to variable amounts of organic matter. Deep, vertical cracks penetrate them when they are dry.

An explanation of the genesis of these black soils needs first to account for the high content of clay (>35%) and the predominance of a 2:1 expanding clay (Dixon and Nash, 1968). In the Mt Isa region, it is easy to explain the presence of clay where soils have developed largely in alluvium derived from the erosion of shale and other clay-rich units. An example of genesis of black soils around the Eloise Cu Deposit is shown in Figure 60. In the Mesozoic, marine sediments were deposited on a Proterozoic basement. Sandstone, mudstone and siltstone were formed from material derived from Proterozoic hills to the southwest. After the end of sedimentation and uplift, erosional processes began. Most of the Mesozoic sediments were removed, leaving remnants as mesas. Although covered with a layer of Tertiary sediments on the plains, the Mesozoic sediments continued to be eroded as drainages shifted their course. The hill belt retreated, with further erosion over a long period, so that eventually an alluvial plain was formed via channel aggradation and course change (Figure 60). Black soil was developed on depressions where drainage was poor and the weathering environment of the profile is such that smectite is not weathered to kaolinite. It cannot be determined whether the sediments were weathered to smectite or were deposited as smectite.

Once the requisite content of smectite has been reached, a sequence of events operates in the profiles as follows (Figure 61). During the dry season, the soil cracks by shrinkage/dehydration of smectite and the cracks may extend to a depth of a metre or more. While the cracks are open, surface soil can fall into them dislodged by animal activity, wind, or, at the onset of the rainy season, by water. On wetting the smectite re-hydrates and expands, closing the cracks. Because of extra material now present in the lower parts of the soil profile, more space is required. The expanding material presses and slides aggregates against each other, developing a lenticular block structure with slickenside features on the soil ped faces. This expansion buckles the soil surface, forming gilgai microrelief.

8.2 Implications to Exploration

The Mt Isa region is characterised by complex landscape development and weathering history. The landscapes of the Mt Isa region have widespread, deeply weathered profiles on Proterozoic, Mesozoic and Tertiary sediments, overlain by variable thicknesses of recent, transported cover.

Relatively simple geochemical methods, which are successful in areas without thick cover, may be of limited use where multiple periods of intense weathering and deposition have occurred. For a geochemical method to be effective, an understanding of the materials used and, thus, of weathering profiles and regolith-landform relationships are vital. Some common regolith-landform situations in the Mt Isa region are described below.

8.2.1 Weathering profiles on Proterozoic basement, with or without thin cover

8.2.1.1 Profile with ferruginous or siliceous capping

Where the pre-existing lateritic weathering profile is mostly preserved, residual ferruginous materials (indurated ferruginous saprolite, mottles, lateritic nodules, nodular duricrust) or silcrete outcrop or are buried beneath locally derived shallow sediments. Without drilling, it is extremely difficult to determine whether the profile beneath sediments is with or without a ferruginous capping. Drilling for regolith stratigraphy and experienced interpretation of regolith-landform relationships are necessary.

Where residual ferruginous cappings are present, Cu, Zn, Pb, Sb and As exhibit enlarged dispersion haloes. However, the concentrations are low relative to the underlying bedrock, partly because they have been leached from the profile. Other elements, such as Cr and V, are commonly immobilised in resistant minerals and accumulate residually in the ferruginous horizon, together with Fe. Thus, mottles, lateritic nodules, pisoliths, indurated ferruginous saprolite and lateritic duricrust can be sampled from surface outcrop or where buried beneath shallow alluvium and may be good geochemical media. However, these different ferruginous materials have formed in several ways and in different materials, which must be taken into account when interpreting their geochemical patterns.

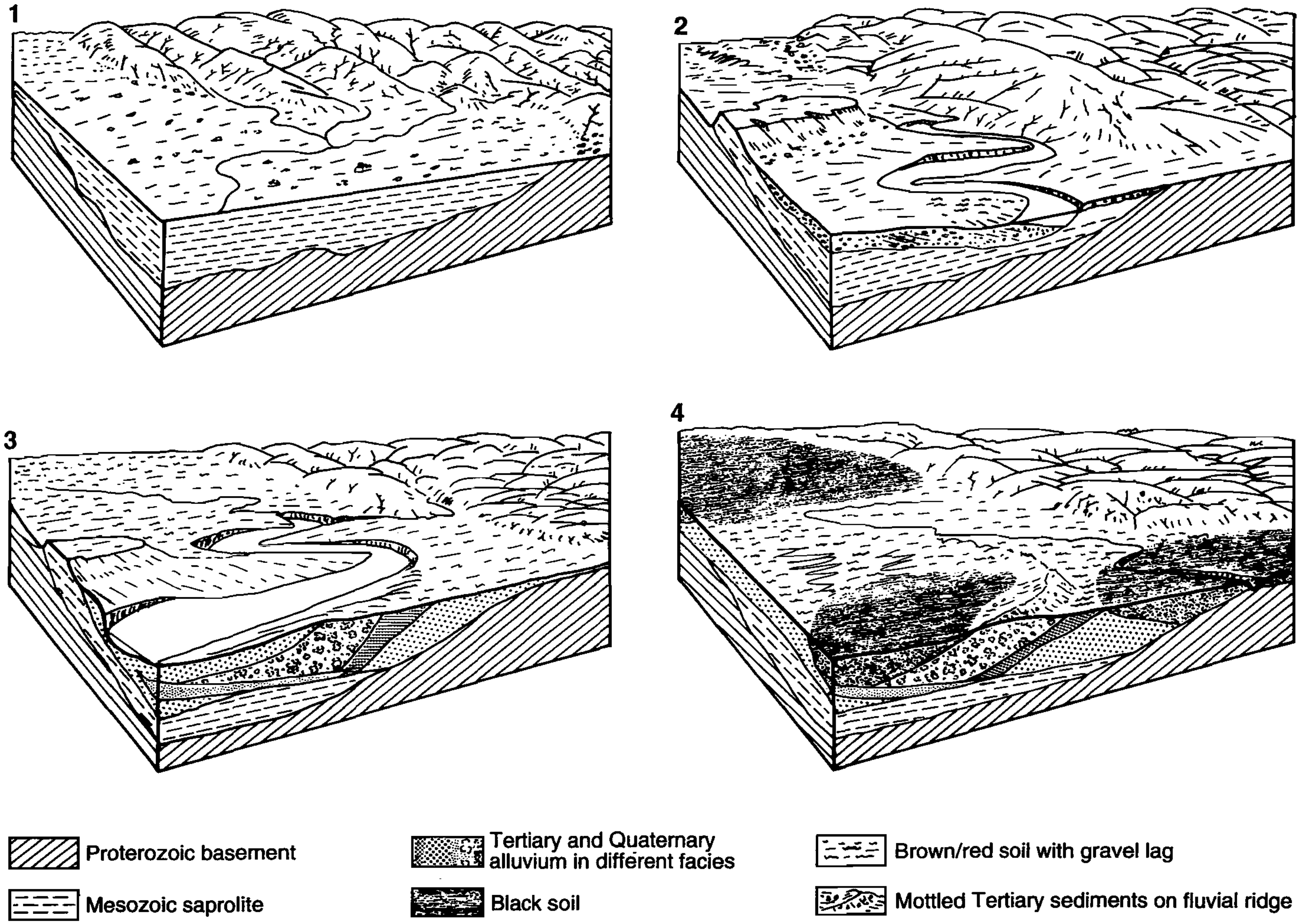
Figure 60. Origin of black soils and landscape in the Eloise area

1. In the Mesozoic, marine sediments were deposited on a Proterozoic basement. Sandstone, mudstone and siltstone were formed from material derived from Proterozoic hills to the southwest.

2. After the end of sedimentation and following marine regression and uplift, erosional processes began. Most of the Mesozoic sediments were removed leaving remnants as mesas. Although covered with a layer of Tertiary sediments out on the plains, the Mesozoic sediments continued to be eroded as drainages shifted their course.

3. The hill belt retreated with further erosion over a long period and eventually an alluvial plain was formed via channel aggradation and course change, as shown.

4. Black soil was developed on depressions where drainage was poor and the weathering environment of the profile is such that smectite is not weathered to kaolinite. Notice Tertiary fluvial ridge at the foreground, and the former hills to the southwest have become a part of the rolling plain.


1
2
3
4
Proterozoic basement
Mesozoic saprolite
Tertiary and Quaternary alluvium in different facies
Black soil
Brown/red soil with gravel lag
Mottled Tertiary sediments on fluvial ridge

Among ferruginous materials, mottles, lateritic nodules and ferruginous saprolite are generally more representative of underlying lithologies and mineralisation than pisoliths and lateritic duricrusts. Lateritic pisoliths are rare and have usually developed in soils or locally derived alluvium. Duricrusts have formed both in residual and transported materials. Nodular and massive duricrusts are largely residual, but slabby duricrust is formed by lateral accumulation of Fe, precipitated from groundwater on valley sides and, therefore it is not genetically related to underlying lithologies. Slabby duricrust can be distinguished on the basis of its landscape position on plateau edges, micromorphology, geochemistry (P-rich) and goethite-rich mineralogy.

However, the composition of both residual and transported duricrusts may reveal enrichment of elements (Cu, As, Sb) associated with Au-Cu mineralisation (*e.g.*, Python Prospect) and Pb-Ag mineralisation (Lady Loretta; Cox and Curtis, 1977; this work). The enrichment may result from local or distal underlying mineralisation. Thus, data interpretation depend upon a well-controlled, regolith-landform framework.

In silcrete, all elements are diluted except for Si, Ti and Zr, so it is unlikely to be a useful sampling media. However, mottling is common in the silcrete horizon and there may be a thin layer of lag. Lag and mottles may be useful as sampling media as they have a great affinity for trace elements.

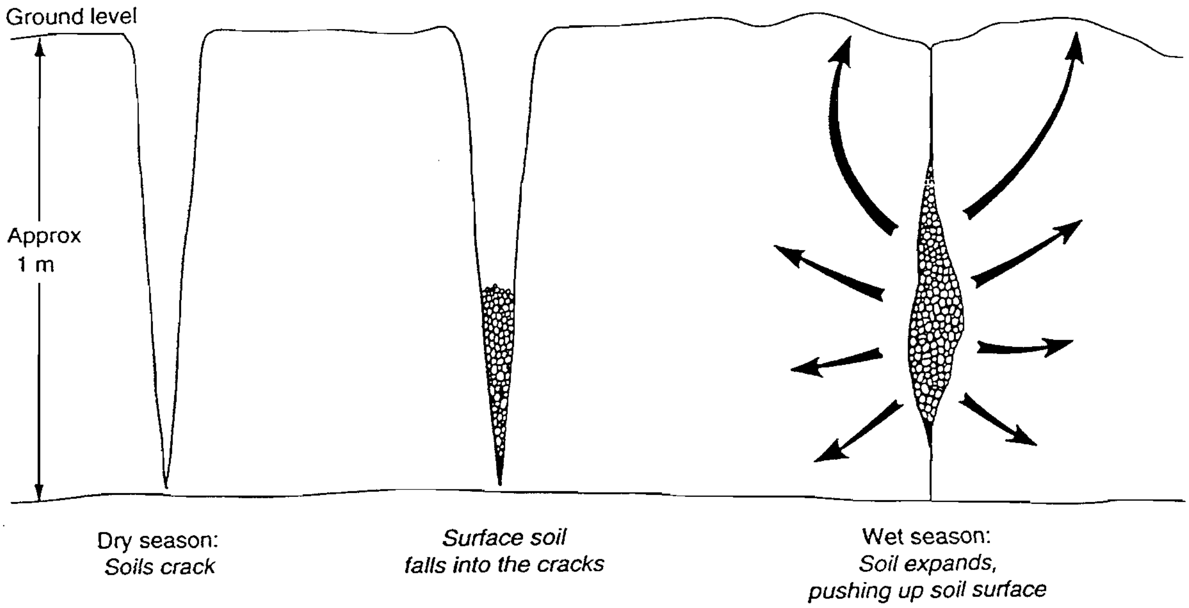


Figure 61. Sketch illustrating wetting-drying cycles of black soils (modified from Buol *et al.*, 1980).

8.2.1.2 Profile without ferruginous or siliceous capping

Such profiles may be the result of either truncation of the deeply weathered profiles or continuous erosion of weathering products which may have prevented the formation of a profile with ferruginous or siliceous capping. Soils are common on these profiles and are the product of weathering of an underlying substrate under more recent climates. However, residual soils are generally overlain by a thin layer of locally derived colluvium, which can be distinguished by having abundant ferruginous gravels, lithic fragments and/or quartz, compared to residual soils.

In the Mt Isa region, three situations are possible:

1. In the *erosional plains*, the profile is characterised by saprolite. Kaolinite is the dominant mineral and primary minerals are generally absent.
2. On *pediments and hill belts*, the profile is characterised by lower saprolite, saprock and bedrock, where primary minerals (amphiboles, feldspars, mica) are present. Weathering of these minerals results in formation of smectite, calcite and dolomite under the present climate.
   These two regolith situations, which may merge over very short distances, have different geochemical characteristics because of the different capacities of smectite and kaolinite for retaining trace elements. Thus, before a geochemical survey, it is necessary to distinguish soils developed from the lower saprolite or bedrock from those that developed from kaolinitic saprolite. Geochemical characteristics may vary over very short distances and require different sampling procedures and interpretations of element mobilities.
3. In the *valley floors and alluvial channels*, a veneer of alluvium overlies saprolite or bedrock. The alluvium contains polymictic gravels and is generally mottled and/or silicified. In places, Fe and Mn impregnate soils to form pods of ferricrete. Where mottles occur in the alluvium, they may be useful as geochemical sampling media. However, caution should be used in the interpretation of the resultant data because Fe and Mn in mottles and ferricretes can be derived from a variety of sources, including gravels in the colluvium, and from adjacent uplands. These mottles and ferricretes should be treated separately from those developed from the weathering of underlying bedrock. Furthermore, widespread anomalies in these materials may not necessarily reflect significant mineralisation; at Drifter, for example, mottles, Fe and Mn-rich pods, developed in alluvium, are very anomalous in Zn, Cu and As, but are related to only minor mineralisation. The coarsest fractions (>2000 μm) of soils which have the highest Cu, Zn and As concentrations, contain large proportions of mottles, as reflected by abundant Fe contents in the soil. The fine, kaolinite-rich fractions (<75 μm) are richer in Pb and Sb which probably indicates early dispersion of these elements into the colluvium.

8.2.2 Complex weathering profiles with transported cover

Transported cover overlies a large portion of the Eastern and Western Successions. Some basal Cambrian and Mesozoic sediments are highly anomalous in indicator elements. The anomalies are largely hosted by newly formed or introduced Fe and Mn oxides which may (a) bear no relation to underlying basement mineralisation and (b) may not necessarily reflect significant underlying mineralisation. At Drifter, the cherty breccia is highly anomalous in Cu, Zn and Pb. The source of these elements may be from hydromorphic dispersion from the Drifter Fault and adjacent areas. The Zn and Cu accumulation was retained by Fe and Mn oxides, which are typically enriched in the cherty breccia. Similarly, the Zn anomaly in the Mesozoic cover at Tringadee is closely associated with Fe and Mn oxides. Iron and Mn oxides occur as bands, probably related to a previously fluctuating water-table, and to ferruginised fractures in the Mesozoic cover, which may have conducted Fe-rich fluids from external sources. Although the Mesozoic sediments now occupy areas of high ground, actual deposition probably occurred low in the landscape. Thus, lateral accumulation of Fe, Mn and trace elements into Mesozoic cover from nearby external sources could readily take place.

Copper, Zn and Pb are dispersed differently in the weathering profile. Copper and Zn are mobile in weathering environments, but have strong affinities for Mn and Fe oxides and are, therefore, readily fixed in ferruginous bands, veins and pods, after hydromorphic processes have enlarged the dispersion halo. High Pb concentrations, however, may suggest that the base metal source is nearby since Pb is less mobile. Inclusion of Fe and Mn in the analytical suite is essential to data interpretation.

The possibility of using lateritic duricrusts developed on Mesozoic sediments as sample media requires an appropriate orientation study. However, it is possible that there may be hydromorphic dispersion from the underlying mineralisation into ferruginous materials, if these materials were weathered at the same time. The widespread ferruginous lag in the erosional areas on Mesozoic sediments (*e.g.*, Tringadee area) could be sampled for reconnaissance in the expectation that this mechanism has operated.

Similarly the use of soils developed in transported overburden (*e.g.*, black soils) and interface sampling can not yet be recommended. Geochemical dispersion studies are being carried out at the Eloise and Maronan deposits to test the suitability of these materials as sample media

9. REGOLITH MAPPING

9.1 Introduction

Geochemical dispersion of elements from mineralisation into the regolith, including Mesozoic and Tertiary sediments, can only be understood and modelled with knowledge of the landscape and regolith stratigraphy. The first step is to map the regolith-landform relationships and to develop a regolith model for the area. In the Yilgarn Craton, regolith-landform relationships were mapped over a series of type districts. Thereafter, an interpretation was established based on these type districts and for brevity has been referred to as the RED scheme (Anand *et al.*, 1993). Such an approach and the derived RED scheme needed to be tested and possibly modified before it could be applied to the Mt Isa region as there are significant differences in the weathering and sedimentary history between the two regions. These differences influence regolith mapping and the definition of a regolith model.

9.2 The RED Regolith Mapping Scheme as used in the Yilgarn Craton

Several well-defined regolith types occur throughout the Yilgarn Craton and relate, directly or indirectly, to a deeply weathered mantle and to its modification. The regolith materials are either horizons of a deep profile developed by *in situ* weathering of bedrock, or consist of transported debris, derived from eroded local weathering profiles. A first step is always to *objectively* map the regolith units present in the area being studied (Craig *et al.*, 1993). As lateritic residuum (lateritic gravels, duricrust) can be an important geochemical medium, it is important to establish the presence or absence of lateritic residuum (which can be an *interpretative* step) and to delineate areas where there is substantial sedimentary cover. Therefore, two important boundaries needed to be established; that which marks the base of the lateritic residuum and that which encloses areas of sedimentary cover (Figure 62). From these, the regolith-landform relationships can be mapped as relict, erosional and depositional (RED) regimes. The focus is on evidence of preservation versus truncation of the lateritic residuum (Anand *et al.*, 1993). These *interpretative regimes* form the basis of regolith-landform models where the development of an extensive, deeply-weathered mantle is proposed as the first stage and this is subsequently modified by erosion and deposition.

The *relict regime* is a mappable area characterised by widespread preservation of a lateritic residuum and, conceptually consists of relicts of an ancient weathered surface. An *erosional regime* is characterised by erosion and removal of the lateritic residuum to a level where the mottled zone, clay zone, saprolite, or fresh bedrock are either exposed, concealed beneath soil, or beneath a thin mantle of locally-derived sediments. The *depositional regime* is characterised by widespread sediments which may be many metres thick. The boundary between regimes can be gradational or sharp, and the substrate to the sediments in depositional regimes can range from incomplete to a complete weathering profile. Specific media are preferred for geochemical sampling in each of these regimes. In relict regimes, the lateritic residuum should be sampled in preference to soils, because geochemical anomalies in lateritic residuum are relatively large and consistent relative to the ore-deposit source. In erosional regimes, ferruginous saprolite or soil should be sampled. In depositional regimes, broad Au anomalies and anomalous concentrations of ore-related elements in buried lateritic residuum can be effective indicators of primary and supergene mineralisation.

9.3 Can the RED Scheme be Applied to the Mt Isa Region?

There are similarities and differences in weathering and sedimentary events between the Mt Isa and the Yilgarn Craton that influence regolith mapping, particularly in defining the regimes. The use of the RED scheme needs to incorporate the following precautions:

(1) For many areas in the Yilgarn Craton, the interpretation has been made that the landscape was originally extensively mantled by a lateritic profile and that the present landsurface is the result of long-continued differential stripping, movement and sorting of detritus. This has resulted in a regolith consisting of a complex array of variously weathered and unweathered materials. Mapping

at Mt Gibson, Bottle Creek, Boddington and Lawlers showed that lateritic duricrust/lateritic gravel was extensive and, from its lithodependence, essentially residual. The RED scheme was an interpretative scheme based on these type districts. In the Mt Isa region, there have been several weathering and sedimentary events and the sediments themselves have been deeply weathered and lateritised. For example, remnant landsurfaces are not only capped with ferruginous duricrusts over Proterozoic bedrock, but also over Mesozoic and Tertiary sediments. The ferruginous horizon on the Tertiary sediments in the Mt Isa region are weakly developed compared to that on the Mesozoic sediments. Lateritic duricrust and mottled zones are well developed on Tertiary sediments in the North Drummond Basin. Because of their minor occurrence in the Yilgarn Craton, provision for them has yet not been made in the RED scheme. In Queensland, they need to be mapped as a relict regime because of preservation of a ferruginous horizon. However, a relict regime on Mesozoic and Tertiary sediments must be mapped separately from a relict regime on Proterozoic bedrocks because the geochemical characteristics of these materials could be very different (Figure 62). Furthermore, caution should be used in mapping duricrusts developed apparently on Proterozoic bedrocks, but may have in fact developed in a thin veneer of transported materials and may have subsequently suffered relief inversion.

(2) Deep weathering profiles, which consist of lateritic gravel, lateritic duricrust, mottled zone, ferruginous saprolite and saprolite, occur on remnant landsurfaces of the Yilgarn Craton. However, such profiles are rare in the Mt Isa region. Rather, ferruginous saprolite and mottled zone, with sporadic pockets of duricrust, are common to many weathering profiles on plateau remnants. There is no evidence to suggest that a thick, fully developed lateritic profile ever developed in most areas. Thus, it is proposed that ferruginous saprolite and mottled zone should be mapped as a relict regime (despite the absence of a true lateritic residuum) rather than an erosional regime (Figure 62). Experiences on the Yilgarn Craton have shown that geochemical responses in ferruginous saprolite and mottles can provide useful information similar to that provided by lateritic residuum, although anomalies are liable to be more restricted in size.

(3) Silcrete has developed instead of the ferruginous horizon in places, particularly where the underlying Proterozoic bedrock is siliceous. Similarly, silcretes have developed in siliceous Mesozoic sediments. These commonly occur on remnant landsurfaces in the Mt Isa Region and it is proposed that they are mapped as a relict regime. However, silicified saprolite should be mapped as an erosional regime because the predominant landscape process has been dismantling followed by minor armouring.

9.4 Interpretative Scheme

An interpretative scheme proposed in this study for the Mt Isa region is outlined below:

Relict regime: This can be divided according to lithology such as

R/P= Relict regime developed over Proterozoic basement

R/M= Relict regime developed over Mesozoic sediments

R/T= Relict regime developed over Tertiary sediments

Similarly erosional regimes can be divided according to lithology

E/P= Erosional regime developed over Proterozoic basement

E/M= Erosional regime developed over Mesozoic sediments

E/T= Erosional regime developed over Tertiary sediments

D= Depositional regime. Colluvium and alluvium derived from the erosion of weathering profiles developed over different rock types. However, if the regolith stratigraphy is known it can be noted by a backslash and the symbol for the underlying lithology at the point of known regolith stratigraphy. For example, D/P, D/M, D/T

Other interpretative schemes are being considered and will be discussed separately.

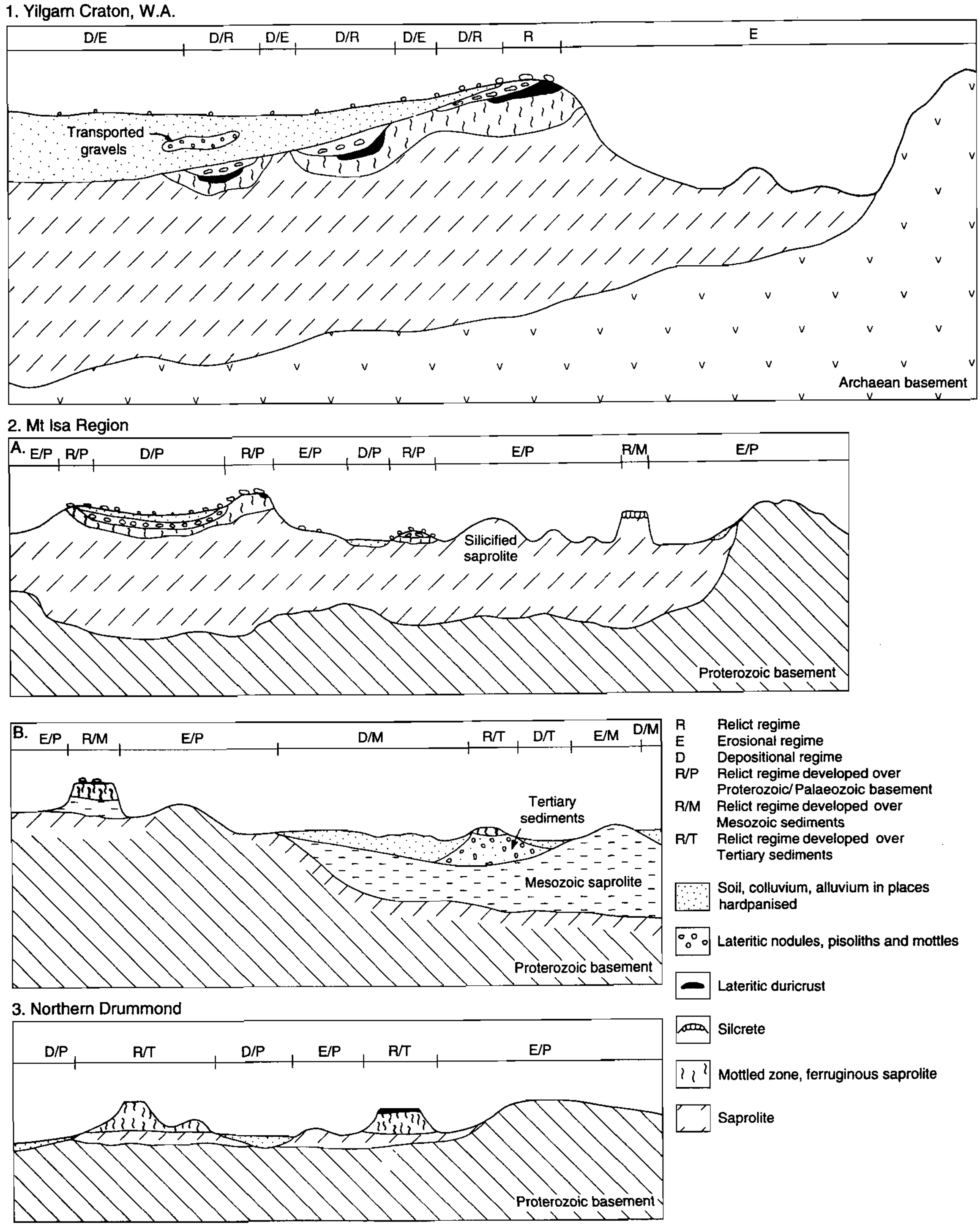


Figure 62. Regolith mapping scheme proposed for the Mt Isa region. Application of the RED scheme to the Yilgarn Craton and Northern Queensland (Drummond Basin) are also included for comparison.

10. GLOSSARY

In this section terms used to describe mapping units and regolith units of the weathering profile are defined. They are largely derived from Terminology and classification of laterites and associated ferruginous materials (Anand *et al.*, August, 1989), Classification and Atlas of regolith-landform mapping units (Anand *et al.*, 1993) and RTMAP regolith database field handbook (Pain *et al*, 1991).

Alluvial Sediments
Materials deposited on the landsurface from transport by flowing water confined to a channel or valley floor.

Alluvial Swamp
Almost level, closed or almost closed depression with a seasonal or permanent water table at or above the surface, commonly aggraded by over bank stream flow. They typically have a gilgai micro-relief caused by shrinking and swelling clays (*i.e.* smectite and mix layered illitic clays).

Alluvial Terrace
Former flood plain on which erosion and aggradation by channelled and over-bank stream flow is slightly active or inactive because of deepening or enlargement of the stream channel has lowered the level of flooding. A pattern that includes a significant active flood plain, or former flood plains at more than one level, becomes terraced land.

Alluvium
A general term for clay, silt, sand, and gravel deposited as a sorted or semi-sorted sediment during comparatively recent geological time on the bed or flood plain of a river or stream.

Breakaways
Erosional scarps usually capped indurated and subindurated parts of the weathered mantle. Breakaways can mark the limits of the erosional destruction of a deeply weathered landsurface.

Channel Deposits
Alluvium which is deposited in an alluvial channel. It is commonly coarser than surrounding deposits, and is found in both active and relict channels. It includes deposits in cut-off meanders, and point bar deposits.

Colluvial Deposits
Colluvial deposits, generally less than 5 m thick, occur as footslope deposits adjacent to steeper ridges and hills. The deposits are typically poorly sorted and consist largely of sheet flow deposits and fanglomerates overlain by stony soils. Near valley floors, these deposits typically inter finger with alluvial sediments.

Colluvial Footslope
Very gently to moderately inclined complex landform pattern of extremely low relief with a generally fan-shaped plan form. Divergent stream channels are commonly present, but the dominant process is colluvial deposition of materials. The pattern is usually steeper than an alluvial fan.

Colluvium
A general term for recent sedimentary deposits on slopes or at the base of slopes transported chiefly by rainwash, sheetwash, or slow continuous downslope creep.

Drainage Floors
Flat alluvial tracts having little, if any, stream incision. Major floors are to 0.5 km wide. Small floors are <0.2 km wide.

Erosional plain
Level to undulating or, rarely, rolling landform pattern of extremely low relief (<9 m) eroded by continuously active to slightly active or inactive geomorphic processes.

Ferricrete
Ferricrete is sometimes used in the same sense as lateritic duricrust/lateritic nodules/indurated ferruginous saprolite, but here it refers to iron-cemented weathering detritus which has only a poor or even negligible profile development

Ferruginous Granules
Fragments of Fe-rich (hematite, goethite, and maghemite) material, somewhat rounded, between 2 and 4 mm in diameter, generally having no cutans, and comprised of a mixture of magnetic and non-magnetic Fe oxides. Commonly occur in soils or as surface lag.

Ferruginous Saprolite
Ferruginous saprolite is commonly developed over Fe-rich bedrocks. It is firm to hard, massive to mottled, and is dominated by goethite and kaolinite. Fragments of ferruginous saprolite are yellowish-brown to reddish-brown, non-magnetic, and may have an incipient nodular structure. Ferruginous saprolite may form a continuous blanket and is generally overlain by collapsed ferruginous saprolite where soft, soluble, less ferruginised material has been removed by leaching, causing the whole structure to collapse.

Flood Plain
Level landform pattern with extremely low relief. The shallow to deep alluvial stream channels are sparse to widely spaced, forming a unidirectional integrated network. Alluvial plain characterised by frequently active erosion and aggradation by channelled or over-bank stream flow. Unless otherwise specified, "frequently active" is to mean that flow has an Average Recurrence Interval of 50 years or less.

Hills
Landform pattern of high relief (90-300 m) with gently sloping to precipitous slopes. Fixed, shallow erosional stream channels, closely to very widely spaced, form a dendritic or convergent integrated tributary network. There is continuously active erosion by wash and creep and, in some cases, rarely active erosion by landslides.

Lag
Lag covers much of the surface in the Mt Isa region and consists of a variety of clast types, including lithic fragments, ferruginous granules, pebbles and cobbles, lateritic pisoliths, nodules, and quartz clasts. Lag concentrates at the surface by deflation of the soil by wind and water, by root plucking and by eluviation. The various clast types are commonly mixed but their distribution may be related to source material, such as regolith substrate, and to the regolith-landform framework.

Lateritic Duricrust
Lateritic duricrust is indurated lateritic residuum, consisting of various secondary structures such as nodules, pisoliths, and ooliths, set in a matrix of kaolinite and Fe-oxides. Both magnetic and non-magnetic varieties of nodules and pisoliths occur in lateritic duricrust. The magnetism is generally due to maghemite.

Lateritic Gravels
Lateritic gravels consist of loose lateritic nodules, pisoliths and hardened mottles. Lateritic pisoliths and nodules typically have 1-2 mm thick, yellowish-brown to greenish cutans around hematite-rich, black to red nuclei. Both lithic and non-lithic nodules are common in this unit.

Lateritic Nodule
A ferruginous lateritic particle with an irregular shape, usually with rounded edges, 2 to 64 mm in diameter, and which may have a cutan around a nucleus or core. As sphericity increases, the term pisolith becomes appropriate. The core can be of a variety of materials, such as hardened, variably ferruginised sandy grit and lithorelics. Lateritic nodules commonly occur as loose aggregates, as a lag, in soil, and in lateritic duricrusts.

Lateritic Pisolith
A ferruginous lateritic particle resembling a pea in shape, 2 mm or more in diameter. Pisoliths can have a concentric internal structure, but concentric lamination is not diagnostic; however, most pisoliths have a cutan. Lateritic pisoliths and nodules commonly occur together, but the former rarely exceed 20 mm in diameter.

Lateritic Residuum
Lateritic residuum is a collective term for certain ferruginous units of the laterite profile, where there is a demonstrated or inferred residual relationship to substrate/bedrocks. It is formed by weathering, precipitation of minerals, and residual accumulation in the upper part of a lateritic weathering profile. Lateritic residuum includes units consisting of loose lateritic pisoliths and nodules (forming lateritic gravel) as well as lateritic duricrust. The colour of this regolith unit varies from yellowish-brown, through dark reddish-brown to very dark brown. The mineralogy is mainly kaolinite, hematite, goethite, with or without subordinate and variable amounts of gibbsite, quartz, maghemite, muscovite, zircon, ilmenite, and anatase. Lateritic residuum may occur at surface or subsurface when the weathering profile has been buried.

Low Hills
Landform pattern of low relief (30-90 m) and gentle to very steep slopes, typically with fixed erosional stream channels, closely to very widely spaced, which form a dendritic or convergent integrated tributary pattern. There is continuously active sheet flow, creep, and channelled stream flow.

Mottled Zone
The mottled zone differs from the overlying lateritic duricrust and/or lateritic gravels by lesser accumulation of Fe-oxides and lacks induration. The mottled zone has contrasting kaolinite-rich bleached domains and ferruginous mottles, which may be distinguished easily in outcrops and in samples on a centimetre scale.

Overbank Deposits
Alluvium which is deposited outside an alluvial channel from flowing water which has overflowed from the channel. It includes levees and back swamp deposits.

Pediment
Gently inclined to level (<1% slope) landform pattern of extremely low relief, typically with numerous rapidly migrating, very shallow incipient stream channels which form a centrifugal to diverging integrated reticulated pattern. It is eroded, and locally aggraded, by frequently active channelled stream flow or sheet flow, with subordinate wind erosion. Pediments characteristically lie down-slope from adjacent hills with markedly steeper slopes.

Plateau
Level to rolling landform pattern of plains, rises or low hills standing above a cliff or escarpment that extends around a large part of its perimeter. A bounding scarp or cliff may be included or excluded; abounding escarpment would be an adjacent landform pattern.

Rises
Landform pattern of very low relief (9-30 m) and very gentle to steep slopes. The fixed erosional stream channels are closely to very widely spaced and form a dendritic to convergent, integrated or interrupted tributary pattern. The pattern is eroded by continuously active to slightly active creep and sheet flow.

Saprock
Saprock is a compact, slightly-weathered rock of low porosity, with less than 20% of the weatherable minerals altered. The boundary between bedrock and saprock is generally very irregular. Corestones of fresh rock may occur in the saprock and saprolite.

Saprolite
Saprolite is weathered rock that retains much of the fabric and structure of the parent bedrock. Saprolite can be firm (rather than hard), soft, or friable. Isovolumetric weathering is commonly envisaged. Saprolite may become more massive upwards as the proportion of clay increases and cementation by secondary silica, carbonates and, especially, Fe-oxides is common. Saprolite is typically lighter in colour than the overlying mottled zone and lateritic residuum. Its mineralogy is variable, depending upon the nature of the parent bedrock.

Soil
Upper part of the regolith, commonly defined as that which supports plant life. In particular, refers to those surface horizons reacting to the present environment; *palaeosols* are soils that formed under past environmental conditions. *Black soils* are commonly, but not always, dark in colour, due mainly to dispersed organic matter, a property reflected in local names such black earths, black cracking clays and Regur (India).

Stratigraphic ironstones
In situ weathering products of Fe-rich lithologies.

Valley Floors
This is applied to valley bottoms when the site in question is not on other features that might be present within the valley, such as alluvial or colluvial plains.

11. ACKNOWLEDGMENTS

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12. REFERENCES

Ahnert, F., 1970. Functional relationships between denudation relief and uplift on large, mid-latitude drainage basins. *American Journal of Science*, **268**: 243-263.

Alcock, P.J and Lee, M.F., 1974. Aspects of the geology and exploration of the Lady Loretta Lead-zinc-silver Deposit, north west Queensland. Aus.IMM., north west Queensland Branch Regional Meeting August, 1974. 207-215.

Anand, R.R., Smith R.E., Innes, J., Churchward, H.M., Perdrix, J.L. and Grunsky, E.C., 1989. *Laterite types and associated ferruginous materials, Yilgarn Block, WA. Terminology, Classification and Atlas*. CSIRO Division of Exploration Geoscience Restricted Report 60R, 90pp.

Anand, R.R., Churchward, H.M., Smith, R.E., Smith, K., Gozzard, J.R., Craig, M.A. and Munday, T.J., 1993. *Classification and Atlas of Regolith-Landform Mapping Units*. CSIRO Restricted Report 440R, 87pp.

Anand, R.R., Wilford, J., Munday, T.J., Phang, C., Wildman, J.E. and Scott, K.M., 1995. *Geochemical exploration in regolith-dominated terrain of north Queensland, Mt Isa field trip, 26-28 July, 1995*. CSIRO Division of Exploration and Mining Restricted Report 156R, 41pp.

Bettenay, E. and Churchward, H.M., 1974. Morphology and stratigraphic relationships of the Wiluna hardpan in arid Western Australia, *Journal of Geological Society of Australia*, **21**: 73-80.

Birot, P., 1958. *Morphologie Structurale*. Presse University of France, Paris.

Blake, D.H., 1987. Geology of the Mount Isa Inlier and environs, Queensland and Northern Territory. *BMR Bulletin 225*, 83pp.

Blake, D.H., Jaques, A.L. and Donchak, P.J.T., 1983. Selwyn region, Queensland, 1:100,000 Geological map commentary, BMR, Australia, 29pp.

Buckland, R., 1994. Exploration permit for minerals No.'s 7337 'Buckley River' and 7867 'Johnson Creek'. Technical Report No.2231. MIM Exploration Pty Ltd.

Buol, S.W., Hole, F.D. and McCracken, R.J., 1980. Soil Genesis and Classification. The Iowa State University Press, America, 404pp.

Butt, C.R.M., 1985. Granite weathering and silcrete formation on the Yilgarn Block, Western Australia. *Australian Journal of Earth Sciences*, **32**: 415-432.

Carr, G.R., 1984. Primary geochemical and mineralogical dispersion in the vicinity of the Lady Loretta Zn-Pb-Ag deposit, north west Queensland. *Journal of Geochemical Exploration*, **22**: 217-238.

Carter, E.K. and Opik, A.A., 1959. Geological map of north western Queensland, BMR, Australia, Q.G. 34.

Connah, T.H. and Hubble, G.D., 1960. Laterites. In: D. Hill and A.K. Denmead (Editors), The Geology of Queensland. *Journal of Geological Society of Australia*, **1**, 373-386.

Cox, R. and Curtis, R., 1977. The discovery of the Lady Loretta Zinc-Lead-Silver deposit, northwest Queensland, Australia - a geochemical exploration case history. In: C.R.M. Butt and I.G.P. Wilding (Editors), Geochemical Exploration, 1976. *Journal of Geochemical Exploration*, **8**, 189-202.

Craig, M.A., Anand, R.R., Churchward, H.M., Gozzard, J.R., Smith, R.E. and Smith, K., 1993. *Regolith-landform mapping in the Yilgarn Craton, Western Australia: Towards a Standardized Approach.* Discussion Paper, CSIRO Division of Exploration Geoscience Restricted Report 338R, 42pp.

Dixon, J.B. and Nash, V.E., 1968. Chemical mineralogical and engineering properties of Alabama and Mississippi black belt soils. South Coop Series No. 130. Auburn University, Auburn, Alabama.

Drummond, B., 1996. AGCRC Mt Isa Geodynamic Transect. (Unpublished.)

Dury, G.M., 1968. An introduction to the geomorphology of Australia. In: G.H. Dury and M.I. Logan (Editors): *Studies in Australian Geography*, 1-36, Heinemann Education, Melbourne.

Grimes, K.G., 1972. The Mesozoic and Cainozoic geology of the Cloncurry 1:250000 sheet area, Queensland. BMR, Australia, Record 1972, 57, (unpublished).

Grimes, K.G., 1974. Mesozoic and Cainozoic geology of the Lawn Hill, Westmoreland, Mornington, and Cape Van Dieman 1:250,000 sheet area, Queensland. BMR, 1974/106 (unpublished).

Grimes, K.G., 1979. The stratigraphic sequence of old land surfaces in north Queensland. *BMR Journal*, 4, 33-46.

Grimes, K.G., 1980. The Tertiary geology of north Queensland, In: R.A. Henderson and P.J. Stephenson (Editors), *The Geology and Geophysics of northeastern Australia*, Geological Society of Australia, Queensland Division, Brisbane, pp.329-347.

Hancock, M.C. and Purvis, A.H. 1990. Lady Loretta silver-lead-zinc deposit, In: R.E. Hughes (Editor), *Geology of the Mineral Deposits of Australia and Papua New Guinea.* The Australasian Institute of Mining and Metallurgy. pp.943-948.

Hutton, L.J. and Wilson, I.H., 1985. Mammoth Mines Region, Queensland - 1:100 000 Geological map commentary, BMR, Australia.

Jones, P.A., 1994. Python Grid geology and drill hole locations. 1:5 000 scale, Drawing No. ISA/276, Figure No.25. Technical Report No.2231. MIM Exploration Pty Ltd.

Mabbutt, J.A., 1980. Weathering history and landform development. In: C.R.M. Butt and R.E. Smith (Editors), Conceptual Models in Exploration Geochemistry - Australia. *Journal of Geochemical Exploration*, **12**: 96-116.

Munday, T.J., Phang, C. and Wildman, J.E., 1996. Regolith-landscape evolution, Tringadee District. (Report in preparation.)

Nahon, D. and Lappartient, J.R., 1977. Time factor and geochemistry in iron crust genesis. *Catena*, **4**: 249-254.

Ollier, C.D., 1993. Aspects of silcrete formation in Australia. *Geomorphology*, **35**: 151-163.

Pain, C., Chan, R., Craig, M., Hazell, M., Kamprad, J. and Wilford, J., 1991. RT Map BMR Regolith Database Field Handbook. BMR Geology and Geophysics, 125pp.

Robertson, I.D.M. 1990. Mineralogy and geochemistry of soils overlying the Beasley Creek Gold Mine - Laverton, WA. CSIRO Division of Exploration Geoscience Restricted Report 105R, pp.53.

Schwertmann, U., 1985. The effect of pedogenic environments on iron oxide minerals. In: B.A. Stewart (Editor) *Advances in Soil Science*, Vol.1, Springer-Verlag, New York, pp.172-196.

Senior, B.R., Mond, A. and Harrison, P.L., 1978. Geology of the Eromanga Basin. BMR, Geology and Geophysics, Bulletin 167, 102pp.

Smart, J., Grimes, K.G., Doutch, H.F. and Pinchin, J., 1980. The Mesozoic Carpentaria Basin and the Cainozoic Karumba Basin, north Queensland. BMR, Geological and Geophysics, Bulletin 202, 72pp.

Stephens, G.C., 1971. Laterite and silcrete in Australia: A study of the genetic relationships of laterite and silcrete and their comparison materials, and their collective significance in the formation of the weathered mantle, soil, relief and drainage of the Australia continent. *Geoderma*, **5**: 5-52.

Stewart, G.A., 1954. Geomorphology of the Barkly region. In: *Survey of the Barkly region, Northern Territory and Queensland*, 1947-48. CSIRO, Australia, Land Research Series, **3**: 113-149.

Summerfield, M.A., 1983. Silcrete. In: A.S. Goudie and K. Pye (Editors), *Chemical Sediments and Geomorphology*, pp.59-61, Academic Press, London.

Taylor, G.F. and Scott, K.M., 1983. Evaluation of gossans in relation to lead-zinc mineralisation in the Mt Isa Inlier, Queensland. Australia. BMR, Geological and Geophysics, Bulletin 7, 158-159pp.

Taylor, G. and Ruxton, B.P., 1987. A duricrust catena in south-east Australia. *Geomorphology*, **31**: 305-410.

Thomas, D.S.G., 1989. Reconstructing ancient arid environments. In: D.S.G. Thomas (Editor) *Arid Zone Geomorphology*, pp.311-334, Belhaven, London.

Twidale, C.R., 1966. Geomorphology of the Leichhardt-Gilbert Area of north-west Queensland. Land Research Series No.16, CSIRO, Melbourne, 1966, 56pp.

Wilford, J. and Anand, R.R., 1995. Buckley River regolith-landform map. 1:50 000, Feb. 1995, CSIRO Division of Exploration and Mining.

Wopfner, H., 1978. Silcretes of northern South Australia and adjacent regions. In: T. Langford-Smith, (Editor): *Silcrete in Australia*, pp.93-141. Department of Geography, University of New England, Armidale.

13. APPENDICES

Appendix I

Mt Isa regolith-landforms 1:500,000.

Appendix II

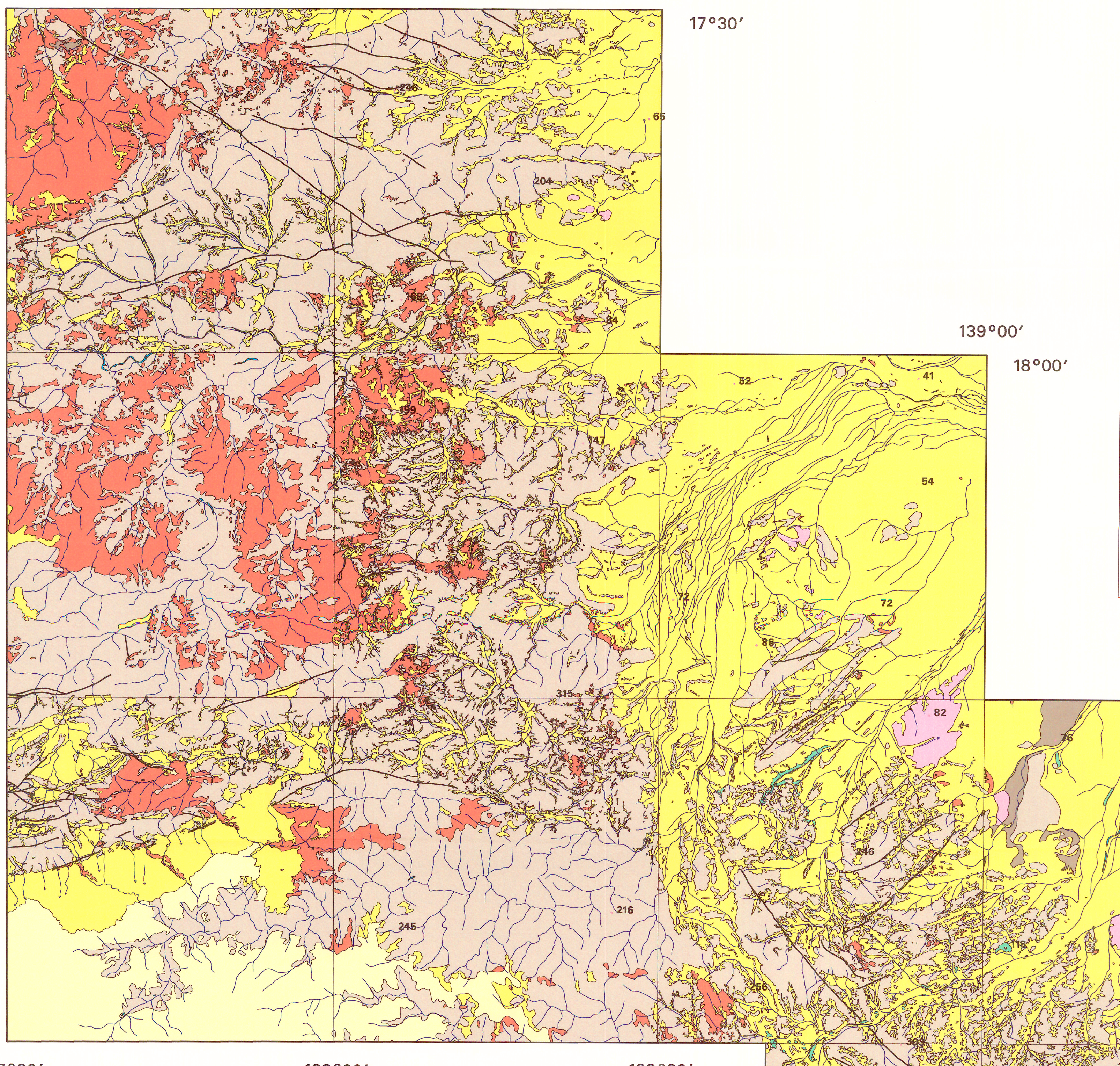
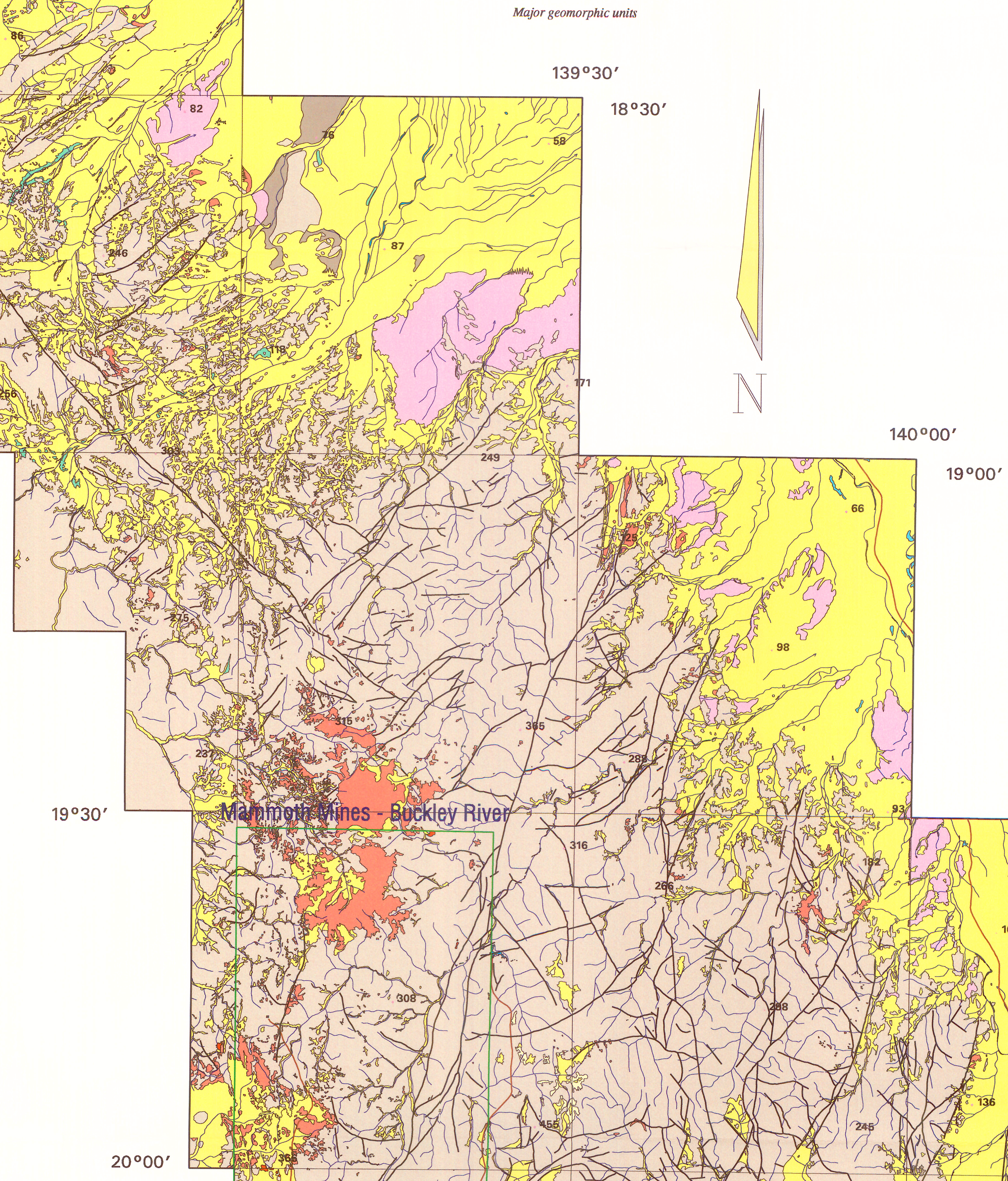
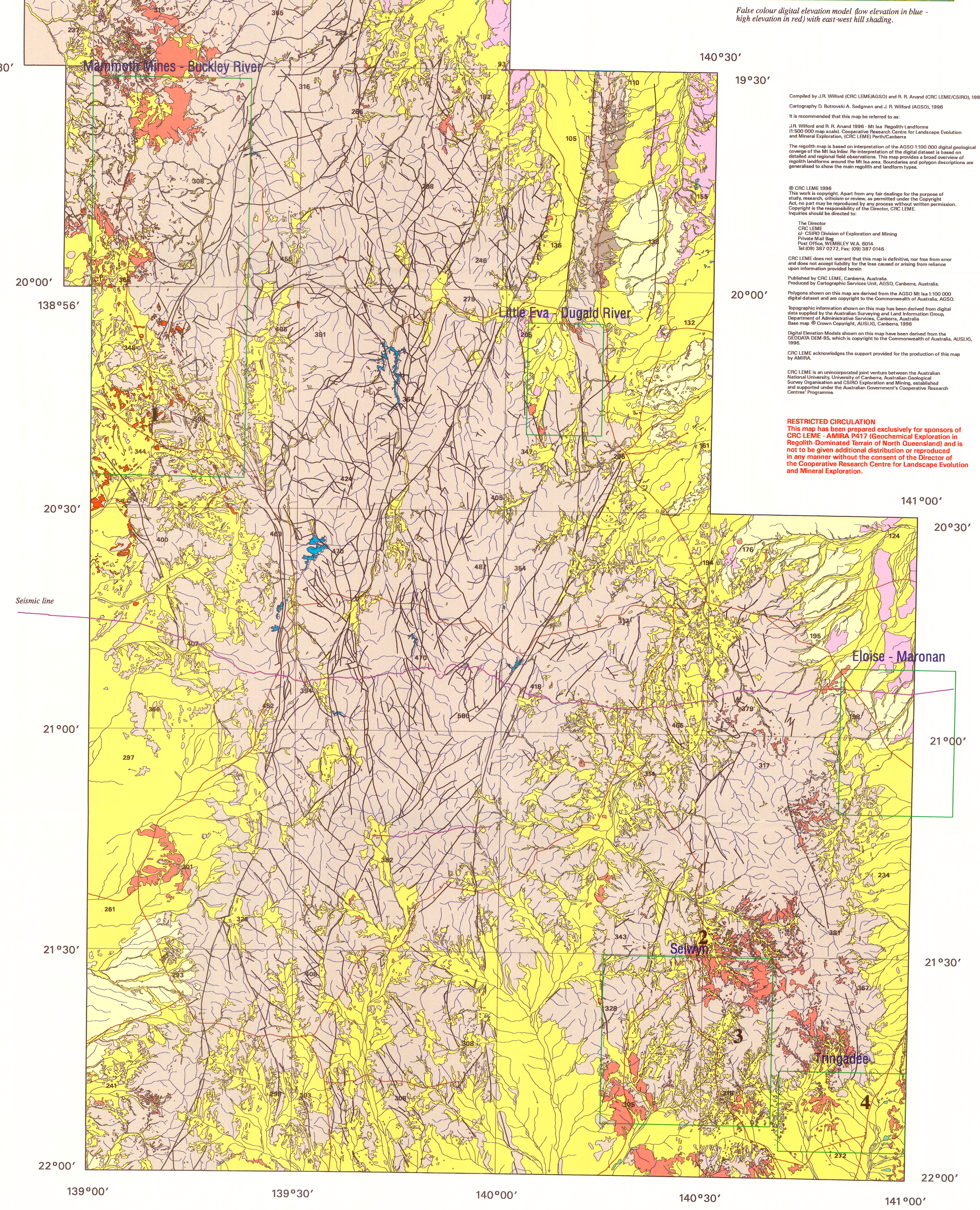
Mt Isa regolith-landforms draped over digital terrain model, 1:500,000

This appendix is not supplied in the Open File version as it is available in digital form on the CDs in the Final Report - Open File Report 120

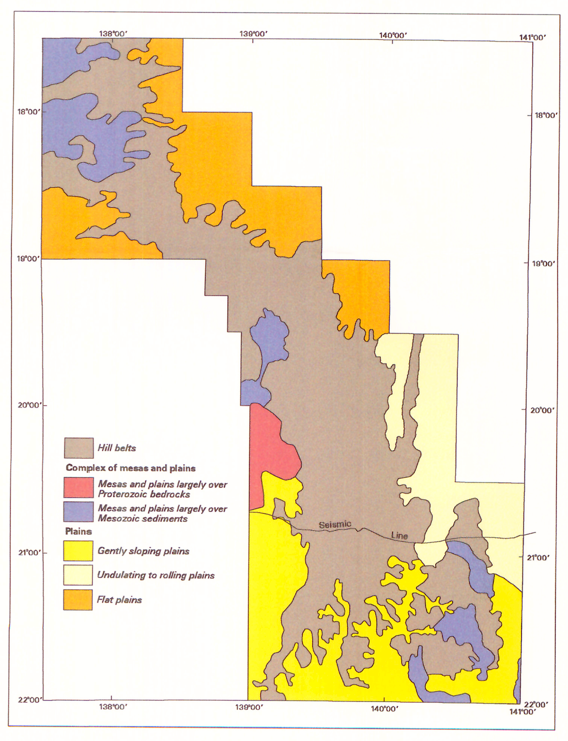
INDEX

MT ISA REGION
REGOLITH-LANDFORMS

1 : 500 000

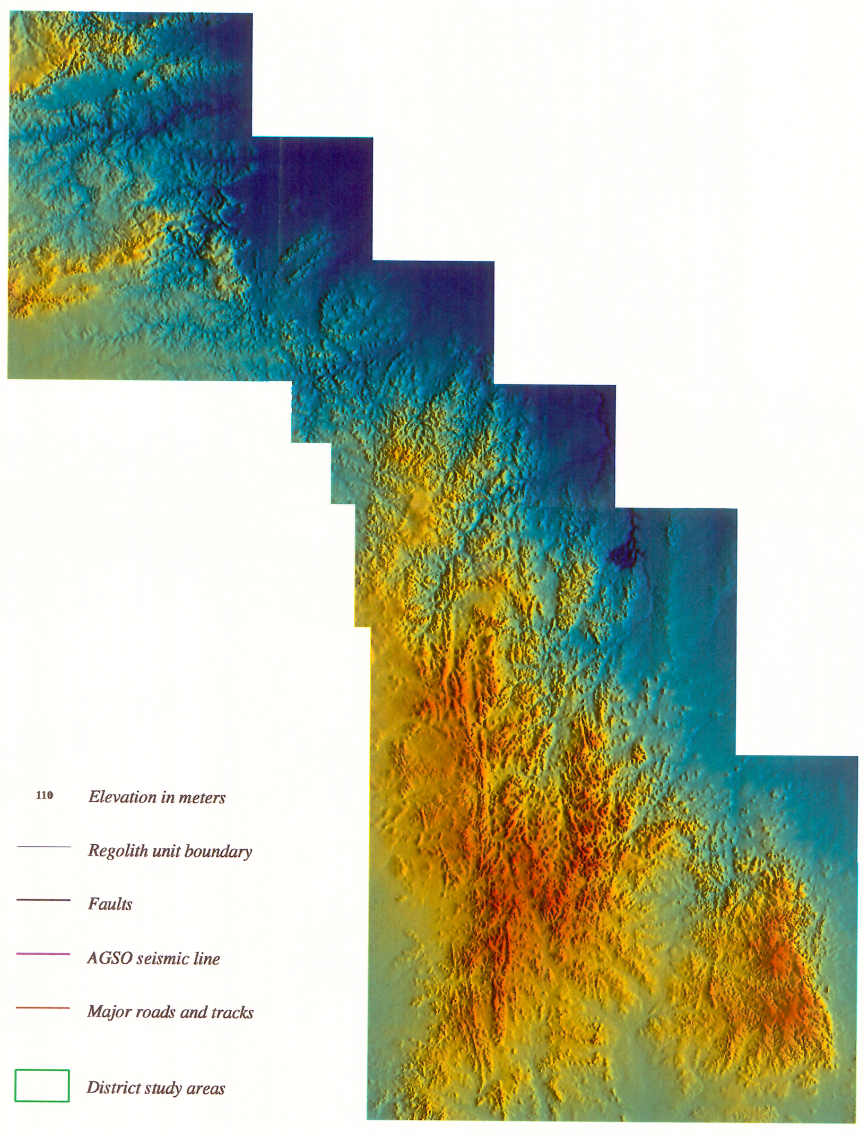
(Polygons based on AGSO 1:100 000 Digital Dataset)



Major geomorphic units

REFERENCE

- *Lag of lateritic nodules, pisoliths and mottles. Gravelly soils, lateritic duricrust, indurated ferruginous saprolite and silcrete developed on highly weathered Proterozoic bedrock. Mesas, plateau, rises and backslopes.*
- *Lag of lateritic nodules and mottles. Lateritic duricrust, mega mottles, residual sand and silcrete developed over weathered Mesozoic sediments. Mesas and low hills.*
- *Weathered Mesozoic sediments in places silicified. Erosional plains and rises.*
- *Lithosols, red and yellow earths with locally derived colluvium. Saprolite (in places silicified and ferruginised) and saprock over mainly Proterozoic bedrock. Hills, ridges, rises and erosional plains.*
- *Ferruginous gravelly soil, residual sand, silt, minor colluvial sediments over mainly Proterozoic rocks. Minor ferruginous saprolite and mottled sandstone. Rises and erosional plains.*
- *Alluvial and colluvial sediments derived from the erosion of Proterozoic and Mesozoic rocks. In places these sediments are underlain by Tertiary and Mesozoic sediments of varying thicknesses. The Tertiary sediments (gravels and clays) are typically mottled and in places cemented by iron and silica. Polymictic gravel lags, black soils (minor gilgai) and residual soils. Alluvial plains, floodplains and minor erosional plains.*
- *Black soils developed on transported sediments. In places these soils overlie Tertiary and Mesozoic sediments. Alluvial and minor erosional plains.*
- *Lacustrine sediments consisting of clays and silts.*
- *Tertiary carbonates including calcrete and limestone.*
- *Lakes.*



False colour digital elevation model (low elevation in blue - high elevation in red) with east-west hill shading.

110 *Elevation in meters*

Regolith unit boundary

Faults

AGSO seismic line

Major roads and tracks

District study areas

1

A major breakaway consisting of an erosional escarpment that is surrounded by a steep debris slope. Slabby duricrust, ferruginous saprolite and silicified saprolite occurs on the breakaway face. Surrounding pediments consist of coarse duricrust fragments and ferruginous saprolite.

2

Deep weathering profile on Mesozoic sediments overlying granite near Selwyn mine. The profile consists of lateritic nodules overlying siliceous black, massive duricrust, mottled zone and saprolite. The underlying granite still shows its original structure, with the primary minerals altered to kaolinite and goethite.

3

Ironstone outcrop, as shown in the lower left corner at Selwyn mine. Hills in the background consist of silicified saprolite and lithosols over bedrock.

4

Black soil plains near Tringadee (with gilgai micro-relief).

Compiled by J.R. Wilford (CRC LEME/AGSO) and R. R. Anand (CRC LEME/CSIRO), 1996

Cartography D. Butrovski A. Sedgmen and J. R. Wilford (AGSO), 1996

It is recommended that this map be referred to as:

J.R. Wilford and R. R. Anand 1996 - Mt Isa Regolith-Landforms (1:500 000 map scale). Cooperative Research Centre for Landscape Evolution and Mineral Exploration, (CRC LEME) Perth/Canberra

The regolith map is based on interpretation of the AGSO 1:100 000 digital geological coverge of the Mt Isa Inlier. Re-interpretation of the digital dataset is based on detailed and regional field observations. This map provides a broad overview of regolith landforms around the Mt Isa area. Boundaries and polygon descriptions are generalised to show the main regolith and landform types.

The Director
CRC LEME
c/- CSIRO Division of Exploration and Mining
Private Mail Bag
Post Office, WEMBLEY W.A. 6014
Tel:(09) 387 0272, Fax: (09) 387 0146

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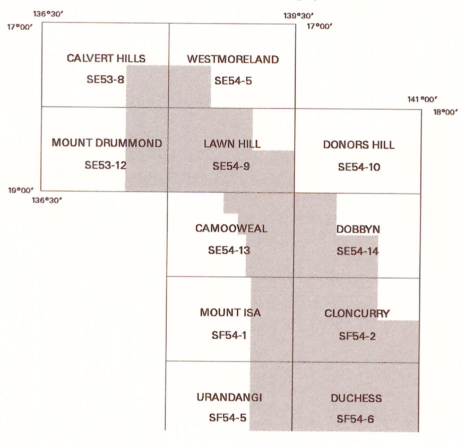
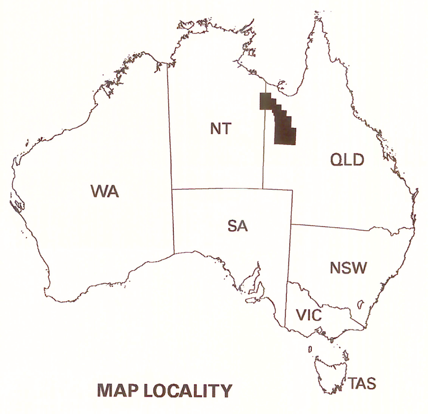
INDEX TO ADJOINING 1:250 000 SHEETS

1:500 000 special map shown in grey



AUSTRALIA



MAP LOCALITY

SCALE 1:500 000

10 0 10 20 30 40 50 Kilometres

MT ISA
REGOLITH-LANDFORMS
1:500 000
SUBJECT TO AMENDMENT

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