CRCLEME
Cooperative Research Centre for
Landscape Evolution & Mineral Exploration

AMIRA
Australian Mineral Industries Research Association Limited ACN 004 448 266

OPEN FILE
REPORT
SERIES

GEOCHEMICAL EXPLORATION IN REGOLITH-DOMINATED TERRAIN, NORTH QUEENSLAND

(CRC LEME - AMIRA P417) FINAL REPORT

R.R. Anand, S.J. Fraser, M.R. Jones, Li Shu, T.J. Munday, C. Phang, I.D.M. Robertson, K.M. Scott, P. Vasconcelos, J.E. Wildman, J. Wilford

CRC LEME OPEN FILE REPORT 120

February 2002

(CSIRO Exploration and Mining Report 447R/CRC LEME Report 63R, 1997. Second impression 2002)

Australian Mineral Industries Research Association Limited ACN 004 448 266

CRCLEME
Cooperative Research Centre for Landscape Evolution & Mineral Exploration

GEOCHEMICAL EXPLORATION IN REGOLITH-DOMINATED TERRAIN, NORTH QUEENSLAND

(CRC LEME - AMIRA P417) FINAL REPORT

R.R. Anand, S.J. Fraser, M.R. Jones, Li Shu, T.J. Munday, C. Phang, I.D.M. Robertson, K.M. Scott, P. Vasconcelos, J.E. Wildman, J. Wilford

CRC LEME OPEN FILE REPORT 120

February 2002

(CSIRO Exploration and Mining Report 447R/CRC LEME Report 63R, 1997. Second impression 2002)

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 120) is a second impression (second printing) of CSIRO, Division of Exploration and Mining Restricted Report 447R, first issued in 1997, which formed part of the CSIRO/AMIRA Project P417.

Copies of this publication can be obtained from:
The Publication Officer, c/- CRC LEME, CSIRO Exploration and Mining, P.O. Box 1130, Bentley, WA 6102, Australia.. Information on other publications in this series may be obtained from the above or from http://leme.anu.edu.au/
Cataloguing-in-Publication:

Geochemical exploration in regolith dominated terrain, North Queensland (CRC LEME - AMIRA P417 Final Report).
ISBN 0 643 06780 9
1. Geochemistry - North Queensland 2. Regolith - North Queensland 3. Landforms - North Queensland
I. Anand, R.R. II. Title
CRC LEME Open File Report 120.
ISSN 1329-4768

Addresses and affiliations of authors:

Dr R.R. Anand
Cooperative Research Centre for
Landscape Evolution and Mineral Exploration
c/- CSIRO Exploration and Mining
Private Bag, PO
Wembley
WA 6014
Australia

Mr M.R. Jones
Cooperative Research Centre for
Landscape Evolution and Mineral Exploration
c/- Queensland Department of Mines & Energy
GPO Box 194
Brisbane
Qld 4001
Australia

Dr T.J. Munday
Cooperative Research Centre for
Australian Mineral Exploration Technologies
c/- CSIRO Exploration and Mining
Private Bag, PO
Wembley
WA 6014
Australia

Dr I.D.M. Robertson
Cooperative Research Centre for
Landscape Evolution and Mineral Exploration
c/- CSIRO Exploration and Mining
Private Bag, PO
Wembley
WA 6014
Australia

Dr P. Vasconcelos
Cooperative Research Centre for
Landscape Evolution and Mineral Exploration
c/- Department of Earth Sciences
University of Queensland
Brisbane
Qld 4072
Australia

Mr J. Wilford
Cooperative Research Centre for
Landscape Evolution and Mineral Exploration
c/- Division of Regional Geology and Minerals
Australian Geological Survey Organisation
PO Box 378
Canberra City ACT 2601
Australia

Mr S.J. Fraser
Cooperative Research Centre for
Landscape Evolution and Mineral Exploration
c/- CSIRO Exploration and Mining
PO Box 883
Kenmore
Qld 4069
Australia

Dr Li. Shu
Cooperative Research Centre for
Landscape Evolution and Mineral Exploration
c/- CSIRO Exploration and Mining
Private Bag, PO
Wembley
WA 6014
Australia

Mr C. Phang
Cooperative Research Centre for
Landscape Evolution and Mineral Exploration
c/- CSIRO Exploration and Mining
Private Bag, PO
Wembley
WA 6014
Australia

Mr K.M. Scott
Cooperative Research Centre for
Landscape Evolution and Mineral Exploration
c/- CSIRO Exploration and Mining
PO Box 136
North Ryde
NSW 2113
Australia

Mr J.E. Wildman
Cooperative Research Centre for
Landscape Evolution and Mineral Exploration
c/- CSIRO Exploration and Mining
Private Bag, PO
Wembley
WA 6014
Australia

PREFACE AND EXECUTIVE SUMMARY

Extensive, variable, and generally thick regolith is a major impediment to mineral exploration in parts of northern Queensland, as well as in many other parts of Australia. The Mount Isa and Charters Towers - north Drummond Basin regions host numerous base-metal and gold deposits and have a long history of mineral exploration. The well-exposed parts of these regions have been effectively explored by traditional methods. Exploration is now concentrating on areas obscured by deep weathering or by transported cover.

The main aim of this project was to develop suitable geochemical exploration methods for regolith covered areas based on an improved knowledge of the nature and evolution of the regolith and landscape. To achieve this, this project undertook regolith-geochemical dispersions studies in a variety of geomorphological and sedimentary environments with particular emphasis on distribution, characteristics and origin of the regolith. The activities of the project ranged from regional to district-scale investigations, with more detailed studies at specific sites or prospects. Sites were selected to address specific problems and, in many cases, mapping was extended to place them in their regolith-landform context. The outcomes of district-scale and specific studies are available as investigation reports. The purpose of this report is to summarise the results and to develop models, conclusions and recommendations. Regolith maps and geochemical data are available on a compact disc (Appendix III).

MT ISA REGION

Regolith

As an aid to geochemical dispersion studies, a regolith-landform framework was established for the Mt Isa region. There has been complex erosion, deposition and weathering during the Mesozoic and Cainozoic forming complex landscapes and regoliths. Mesozoic sediments were deposited on a landsurface of broad river valleys with low hills and interfluves. By the early Cainozoic most of the Mesozoic sediments had been eroded except in the southeast and north of the region studied. Field relationships and dating of Mn oxides strongly suggest that evolution of the weathering profiles spans the Tertiary, possibly extending into the Cretaceous. Weathering of Cambrian, Mesozoic and Proterozoic bedrocks left lateritic profiles capped, in places, by ferruginous or siliceous duricrust. The depth of weathering varies and is controlled largely by landscape position, bedrock, structural features and any overlying sediments at the time of weathering. Palaeoplains and topographic lows are more deeply weathered than the erosional plains and hill belts. At many locations, Proterozoic bedrocks are weathered to greater depths where overlying Cambrian or Mesozoic sediments have been removed or were never deposited. In places, remnant river channel and sheet wash deposits have been silicified and ferruginised.

Massive, fragmental and nodular duricrusts have formed *in situ* on Fe-rich weathered rocks by accumulation of ferruginous materials from mottled saprolite and were left by down-wasting of the profile as clays and soluble elements were removed. Slabby duricrust formed on lower slopes by induration of locally derived colluvium and saprolite with lateral accumulation of Fe. Slabby duricust can be distinguished by its landscape position on plateau edges, micromorphology (platy), geochemistry (Mn and P-rich) and its goethite-rich mineralogy.

Silcretes have formed on a variety of bedrocks but are most common on siliceous materials. In places, silica has cemented alluvial sands or sheet wash sands and gravels. Silicified alluvial sands and gravels now occupy topographically higher areas, because of relief inversion since induration.

The plains feature variable thicknesses of Cainozoic and Mesozoic sediments, underlain by weathered or fresh Proterozoic bedrock. Soils have formed on fresh and weathered Mesozoic and Cainozoic sediments and Proterozoic bedrock. Lithosols are associated with resistant rocks, areas of high relief and steeper slopes. In depositional areas, the soils vary from black through brown to grey sandy clay, sands or clays and generally contain polymictic gravels. Some soils have been weathered (mottling, silicification) since their deposition. Black and brown soils have developed extensively on Cainozoic and Mesozoic sediments. Black soils were developed progressively from brown soils where the alluvium was fine, water was retained and kaolinite was transformed to smectite.

Recommendations for exploration practice

Several geochemical sample media were demonstrated to have specific application in exploration in the Mt Isa region. Appraisal of geomorphology and regolith at a district scale is an important pre-requisite for efficient exploration of a regolith-dominated terrain. Regolith-landform maps and regolith stratigraphy should guide the selection of sampling media, sample interval, sampling procedure, analytical method, element suite and data interpretation. A regolith 'fact map' is produced to describe regolith materials in a landform framework and to divide these broadly into duricrusts, saprolites and colluvium-alluvium. Each, with the exception of colluvium and alluvium, are subdivided according to their bedrock (Proterozoic and post-Proterozoic). The bedrocks have different prospectivities and require different interpretation.

Residual ferruginous materials (massive, fragmental or nodular duricrusts), where they occur, should be collected for district- to prospect-scale surveys. Data from partly transported slabby duricrust should be interpreted with care as their Fe and trace element (Cu, As) content may have been derived laterally.

Soil sampling is effective in areas of shallow overburden (1-5 m). The best materials are mottles or the soil matrix rather than clastic grains. Where Fe and/or Mn oxides have adsorbed significant quantities of indicator elements (e.g., Cu, Zn) multiple regression, followed by a residual treatment of these indicator elements would remove the effects of adsorption and draw attention to anomalies that would otherwise remain hidden.

Areas dominated by thick (>5 m) Cambrian, Mesozoic and Tertiary sediments present significant exploration problems. Coarse sediments should be collected at and just above the unconformity (interface sample) in areas of unweathered or slightly weathered Mesozoic cover to detect a near-miss when drilling a geophysical target. When sediments have been weathered, buried ferruginous bands at palaeosurfaces or at watertables may provide a continuous sampling medium. Horizontal ferruginous bands formed within sediments should be preferentially collected. These are more useful than structurally controlled sub-vertical ferruginous veins within the Mesozoic sediments.

CHARTERS TOWERS - NORTH DRUMMOND BASIN

Regolith

The landscape of the region is a product of several sedimentation and weathering episodes. The dominance of a southerly flowing river system in the early Tertiary, the formation of a large lake system in the middle Tertiary, and the reversal of the river system in the late Tertiary are the main episodes of landscape evolution in the north Drummond Basin. Deposition and erosion in the north Drummond Basin has been dictated by drainage changes. When the southerly drainage was choked during the Tertiary, rapid sedimentation formed the Suttor Formation in the south and the Southern Cross Formation in the north. In view of their extent and fluvial nature, these were deposited over a considerable time span and were not restricted to a single event.

Deep weathering of both the fluvial sediments and the basement formed the duricrust, red earths and, to a lesser extent, yellow earths. Campaspe Formation sediments were deposited on the Southern Cross Formation. In areas where intense erosion of the Southern Cross Formation occurred, Campaspe Formation sediments were deposited in lower levels in the landscape. Yellow and grey earths with ferruginous pisoliths are developed on the Campaspe Formation.

In drill spoil, the Southern Cross Formation is more clay-rich than the Campaspe Formation and contains clasts of the basement rocks. The Campaspe Formation tends to be sand-rich and more sorted than the Southern Cross Formation. The Campaspe Formation may contain detrital nodules and pisoliths throughout the sediment, whereas most of the pisoliths and nodules in the Southern Cross Formation are concentrated near its top. There are no consistent mineralogical and geochemical criteria but hiatuses in feldspar and kaolinite abundances, rounding of quartz grains and geochemical parameters such as hiatuses in Ti/Zr ratios can be used to distinguish the Campaspe Formation from basement volcanics.

Recommendations for exploration practice

The focus of most of the geochemical studies in the Charters Towers - north Drummond Basin was on investigating dispersions in sedimentary cover. Regolith-landform procedures are similar to those described for the Mt Isa region with the exception that regolith units should be divided into Palaeozoic or post-Palaeozoic. The geochemical dispersions appear to be similar to those of the Mt Isa region, with geochemical responses where the cover is shallow (1-5 m). Here, soil sampling (including specific sampling of mottles) would be effective. The probability of hydromorphic dispersion is better in sediments that have been weathered since deposition.

In areas dominated by a thick (>5 m) regolith on Campaspe, Southern Cross and Suttor Formations, dispersion is predominantly mechanical near the base. In places, elevated indicator elements and Au are hydromorphically dispersed with Fe oxides and dolomite-rich bands at least 10 m above the unconformity. Thus, basal sediments and ferruginous bands (redox products) should be sampled preferentially. Extensive sheets of ferruginous pisoliths, developed in the Campaspe Formation, also appear to be a promising sampling medium in the region.

R.R. ANAND
Project Leader

I.D.M. Robertson
Deputy Leader

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Exploration problems

Extensive, variable and often thick regolith is a major impediment to mineral exploration in large areas of northern Queensland, as well as in many other parts of Australia. Here, deep chemical weathering, erosion and sedimentation have concealed ore deposits in the underlying rocks; their geological, geochemical and geophysical expression is greatly altered, weakened or buried. The Mount Isa and Charters Towers-north Drummond regions host numerous base-metal and gold deposits and have a long history of mineral exploration. These regions have been effectively explored by traditional geological methods, *i.e.,* mapping and sampling of outcropping bedrock. Exploration is now targeting mineralisation under deeply weathered or transported cover. Regolith geochemical models, successfully used in areas lacking thick cover, are of reduced relevance where multiple cycles of deposition and weathering have occurred. Thus, it is necessary to understand the influences that landscape evolution and weathering have had on element dispersion into the regolith of north Queensland, and use this to guide geochemical exploration programs.

Up to now there have been few regolith-landform investigations of the Mt Isa and Charters Towers regions, hence little information is available to aid geochemical investigations in weathered parts of these terrains to guide interpretation of geochemical data. In the Mt Isa region, the regolith includes saprolitic profiles, areas of cover within generally outcropping terrain, and Cambrian, Mesozoic, Tertiary and Cainozoic cover sequences that have impeded exploration in some areas. Other exploration problems are:- (i) strongly anomalous element concentrations in the weathered Cambrian and Mesozoic sediments overlying mineralised Proterozoic bedrock; (ii) recognising *in situ* from transported ferruginous materials; (iii) discriminating gossans and gossanous ironstones from partially dismantled duricrust, (iv) distinguishing sedimentary cover from weathered bedrock and (v) the complex geochemical signatures arising from multiple profiles. The various types of regolith and weathering profiles are difficult to recognise because they are poorly characterised and their stratigraphy is poorly defined.

A variety of sedimentary cover sequences, including the Campaspe, Southern Cross and Suttor Formations, occurs in the Charters Towers-north Drummond Basin. Because of their widespread distribution, there is considerable interest in the use of these sediments as geochemical sampling media. However, sedimentary cover presents formidable challenges to exploration because of (i) its allochthenous origin (exploration strategy has relied on drilling through the cover into bedrock) and (ii) it has been subjected to post-depositional weathering and diagenesis. Notwithstanding this, older cover sequences might have potential for mechanical or chemical dispersion from underlying mineralisation. However, characteristics of the cover and weathered rocks are poorly known and it is difficult to distinguish residual from transported regolith. Consequently, the use of cover sequences as geochemical sampling media has not previously been assessed.

In northern Queensland, cycles of deposition, erosion and weathering, leading to the development of several landsurfaces, have been proposed by earlier workers (Twidale, 1956, 1960; Grimes, 1979). Hypotheses of erosion surfaces and cyclic development brought about the first understanding of the regional landscape. However, identifying landsurfaces should be used with caution as different workers have different perceptions of them (*e.g.,* Nott, 1994). Many authors have related duricrusts to landsurfaces. However, these models have not been tested.

To address the exploration problems, this project undertook regolith-geochemical dispersion studies in a variety of geomorphological and sedimentary environments, with particular emphasis on distribution, characteristics and origin of the regolith. Regolith-landform frameworks were developed for the Mt Isa and Charters Towers-north Drummond Basin region, criteria were sought to distinguish residual from transported regolith, and various regolith materials were evaluated as sample media. Attempts have been made to explain the causes of anomalies in areas lacking mineralisation. Recommendations for exploration procedures for some of the more common regolith environments have been developed.

1.2 Objectives

1.2.1 Principal objective
To substantially improve 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) Charters Towers-north Drummond Basin region.

1.2.2 Specific objectives

(i) To establish sound operational procedures, within the finite resources of the project, for exploration geochemistry in the two regions, based on investigation of dispersion patterns, dispersion processes and regolith-landform settings by:

- a series of case studies:
- establishing geochemical dispersion models based primarily on these case studies;
- determining a field scheme for identification and classification of sample type for use with exploration drilling and surface sampling, which takes into account regolith-landform setting and weathering history.

(ii) To develop appropriate methods of regolith mapping that take into account weathering and geomorphological histories in the regions to control exploration geochemistry and geophysics.

(iii) To facilitate the transfer of research findings into exploration practice through project reports, review meetings and field trips.

To achieve these objectives, the research had two main thrusts, regolith characterisation and geochemical dispersion studies on known mineralisation.

1.3 Work programme

1.3.1 Regolith characterisation
This involved investigating the nature and distribution of the regolith and its stratigraphy, weathering, erosional and depositional history that have led to a variety of residual and transported regolith types. It was achieved by (i) regolith-landform mapping at a local to district scale, using aerial photography, remote sensing, radiometrics and field traverses, (ii) determining regolith stratigraphy from drill cuttings, core and field exposures, (iii) construction of palaeotopography (where possible), (iv) mineralogical and micromorpholgical studies of regolith and (v) weathering geochronology. The district and local scale studies formed the essential building blocks of the project and the resultant knowledge was applied to a broader, regional perspective that has resulted in an improved understanding of weathering, erosion and depositional history of the regions.

Based on district-scale studies, procedures were devised for regolith mapping and geochemical sampling strategy map. Furthermore, the nature and characteristics of the principal regolith types occurring in the toposequence have been compiled in a reference Atlas of regolith (Phang *et al.*, 1997 (450R)).

1.3.2 Geochemical dispersion

The nature of geochemical dispersion patterns were investigated to determine possible dispersion mechanisms involved, and to recommend sample media and exploration procedures. Multi-element studies concentrated in areas selected for regolith-landform characterisation. Dispersion studies at individual sites included analysis of weathered rocks, ferruginous materials, soils and in places, transported overburden, and selected fractions of these materials.

1.3.3 Research sites

The activities of the project ranged from district-scale investigations to more detailed studies at specific sites and prospects. In general, individual sites were selected to address specific problems. In many cases, studies were extended to place these within their landscape context by regolith and landform mapping at appropriate scales. A wide range of districts and sites for study were proposed during discussions with sponsors, based on the nature and importance of residual and transported regolith and the perceived exploration significance. These were then visited by members of the project team and pilot geochemical studies were undertaken particularly in the Mt Isa region. Decisions to continue or terminate the investigations were made on the basis of field inspections or the results of pilot studies, in consultation with sponsors.

A fundamental problem was that none of the Mt Isa region's significant base metal or gold deposits with thick transported cover were offered for study. Late in the project, a specific request was made to two non-sponsoring companies (Amalg Resources NL and Mining Project Investors Pty Ltd) who offered the Eloise and Maronan deposits. The Charters Towers-north Drummond Basin provided better opportunities to investigate the nature of dispersion patterns in transported overburden. In the planning meeting, it was decided that two-thirds of the emphasis should be placed on the Mt Isa region and one-third on the Charters Towers-north Drummond Basin. However, during the research and field excursion to Charters Towers-north Drummond Basin it was strongly recommended by some sponsors that further work to be done in this region. This project benefited from the additional resources available through Cooperative Research Centre for Landscape Evolution and Mineral Exploration (CRC LEME) and made it possible for the two regions have equal emphasis.

The location of districts and sites studied during the course of the project are shown in Figures 1.1. The nature of investigations undertaken at each site is listed in Table 1.1.

1.4 Achieved benefits

The benefits from the research include:

(i) Regolith-landform frameworks and weathering histories for the two regions and a better understanding of regolith and landforms on a local to district scale. These provide a basis for planning and interpreting geochemical exploration programmes in the regions.

(ii) Regolith models for several districts which also provide an important basis for the interpretation of geochemical data.

(iii) Regolith-landform maps and geochemical sampling strategy maps.

(iv) An improved understanding of the nature and characteristics of regolith materials that may serve as criteria for distinguishing transported from residual regolith units.

(v) Type areas to illustrate district variations and dispersion processes.

(vi) An improved understanding of geochronology of the weathering history.

(vii) Geochemical case studies from a range of environments in both the regions to characterise the geochemical expression of concealed mineralisation in residual and transported regolith.

(viii) Recommendations for appropriate sampling procedures for regolith-dominated areas.

(ix) Transfer of research information to sponsors through informal discussions, field excursions and reports.

These benefits should ultimately lead to improved efficiency and confidence in geochemical exploration surveys, resulting in reductions in the cost of exploration.

1.5 Sponsorship

The following companies sponsored the research.
- Aberfoyle Limited
- BHP Exploration
- CRA Exploration Pty Limited
- Homestake Gold of Australia Limited
- MIM Exploration Pty Limited
- North Exploration
- Newcrest Mining Limited
- Normandy Group
- RGC Exploration Limited
- Ross Mining NL
- WMC Resources Limited

The following organisations collaborated with the project through the CRC LEME.
- Qld Dept Minerals and Energy
- CRC for Australian Mineral Exploration Technologies
- University of Queensland, Department of Earth sciences

The project commenced on 1st April, 1994 and formally concluded with the Final meeting on 1st May 1997.

1.6 Project staff

The project represented the first major attempt to apply the regolith-landform approach to exploration geochemistry outside the Yilgarn Craton. It was therefore given high priority from its commencement in 1994 and benefited from additional resources available through CRC LEME. The project was managed from Perth, with research staff based in four locations, Perth, Sydney, Canberra, and Brisbane, and derived from four institutions, CSIRO-DEM (Division of Exploration and Mining) , AGSO (Australian Geological Survey Organisation), QDME (Queensland Department of Mines and Energy) and University of Queensland. This spread of expertise and backgrounds was a major strength of the project.

The following staff contributed to the project.

Project Leader Dr. R.R. Anand, CSIRO
Deputy Leader Dr. I.D.M. Robertson, CSIRO

Professional staff
Mr. I.D. Campbell (from August 1994 to August 1995), CSIRO
Mr. S.J. Fraser (from September 1995), CSIRO
Mr. M. Jones (from December 1995), QDME
Dr. T.J. Munday, CSIRO

Mr. C. Phang, CSIRO
Mr. K.M. Scott, CSIRO
Dr. Li. Shu (from October 1995), CSIRO
Dr. P.V. Vasconcelos, University of Queensland
Mr. J.E. Wildman, CSIRO
Mr. J.R. Wilford, AGSO

Support Staff
Mrs. P. Phillips (from February 1995), CSIRO
Ms. G. Ashton (from January 1995), CSIRO

Mr. K. Lim (July 1995-December 1996), CSIRO
Mr. W. Maxwell (until March 1995), CSIRO

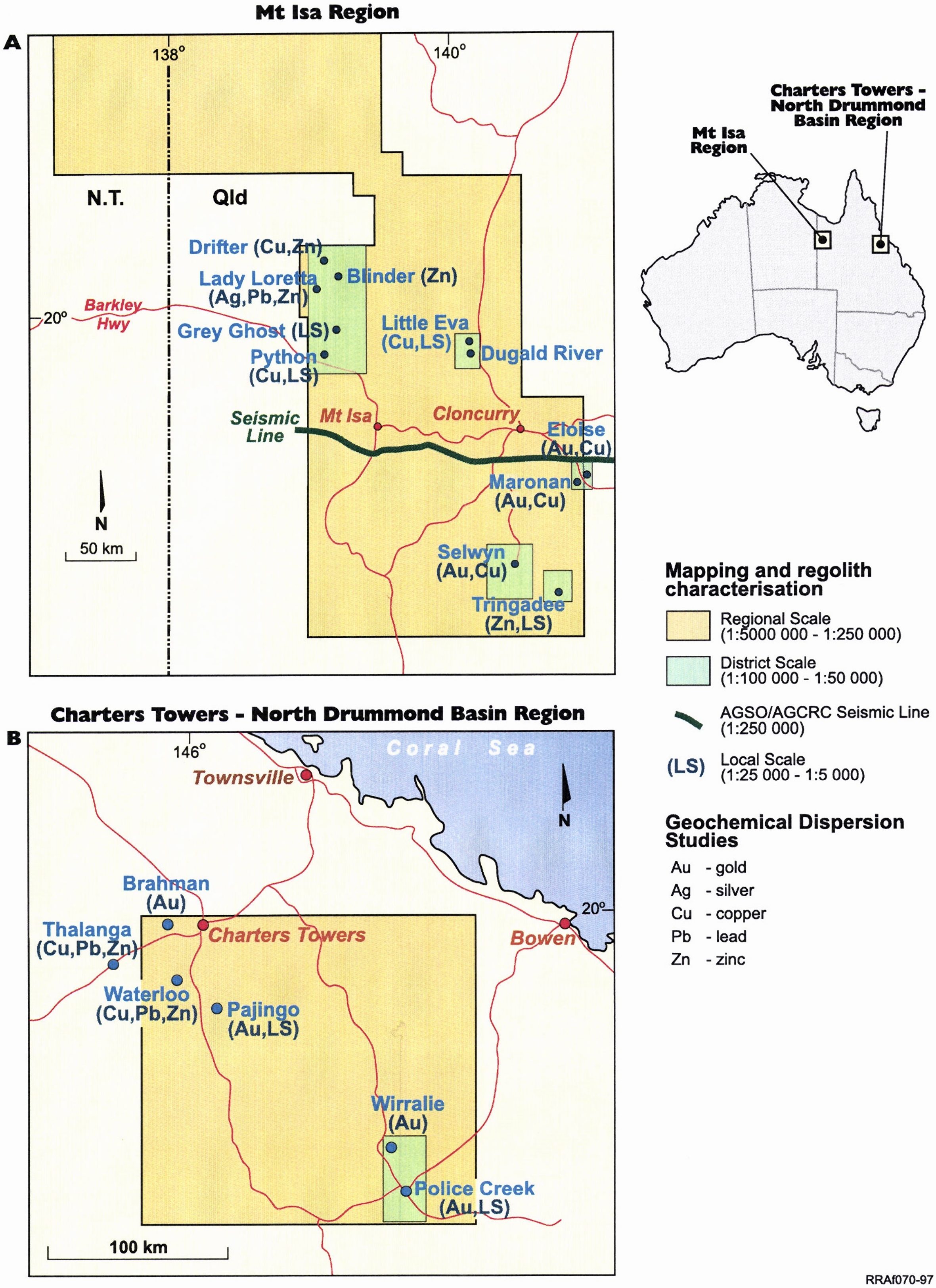

Figure 1.1. (A) Location of study areas in the Mt Isa region. (B) Location of study areas in the Charters Towers-north Drummond Basin region.

Table 1.1. The main research components of the P417 project.

Mt Isa region

- *Regional regolith-landform framework of the Mt Isa region*
- *Regolith-landform mapping, characterisation, regolith-landscape processes and models*

    - Buckley River-Lady Loretta district
    - Selwyn district
    - Eloise district
    - Maronan district
    - Tringadee district
    - Little Eva-Dugald River district

- *Australian Geological Survey Organisation (AGSO) and Australia Geodynamics Cooperative Research Centre (AGCRC) Seismic Line*

- *Quaternary landscape processes*

    - Kennedy Gap region
    - Maronan region

- *Weathering geochronology*

    - Mt Isa Mines
    - Lake Moondarra prospect
    - Kennedy Gap
    - Century deposit
    - Overhang deposit
    - Selwyn deposit
    - Pegmont prospect
    - Cowie prospect
    - Tringadee prospect
    - Tick Hill region

- *Geochemical dispersion studies*

    - Python prospect (Cu)
    - Lady Loretta deposit (Ag-Pb-Zn)
    - Blinder prospect (Zn)
    - Drifter prospect (Cu, Zn)
    - Eloise deposit (Au-Cu)
    - Maronan prospect (Cu-Au)
    - Selwyn deposit (Cu-Au)
    - Little Eva prospect (Cu)
    - Tringadee prospect (Zn)
    - Brumby prospect (Cu-Au)

Table 1.1 Con't

Charters Towers - North Drummond Basin Region

- *Regional geomorphological provinces Charters Towers - North Drummond Basin region*

- *Regolith mapping, characterisation and regolith - landscape process*

    - Pajingo
    - Police Creek - Mt Coolon

- *Weathering geochronology*
    - Scott Lode

- *Geochemical dispersion studies*
    - Pajingo deposit (Au)
    - Waterloo - Thalanga East (Cu, Pb, Zn)
    - Brahman prospect (Au)
    - Police Creek prospect (Au)
    - Wirralie deposit (Au)

2. MT ISA REGION: REGOLITH-LANDFORM DISTRIBUTION, CHARACTERISTICS AND EVOLUTION

2.1 Introduction

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 clastic or chemical sedimentation. Thus, regolith includes residual weathered materials (saprolite, lateritic residuum, some soils) and transported materials (colluvium, alluvium, evaporitic sediments, aeolian deposits, some slabby duricrusts, other soils).

Most geological studies have focused on the bedrock, with little consideration given to the regolith except for Twidale (1956), Connah and Hubble (1960), Grimes (1972, 1980), Cox and Curtis (1977), Senior *et al.* (1978), Smart *et al.* (1980), Taylor and Scott (1982), Scott (1987) and Britt (1993). The regolith is a major impediment to mineral exploration in some areas of northern Queensland, as well as other parts of Australia. The success of exploration in regolith-dominated terrain relies heavily upon development of an understanding of the regolith and associated landscapes in the region.

The regolith-landform synthesis of the Mt Isa region presented here is based on a number of district and local scale regolith studies in the region (Figure 2.1), including regolith-landform mapping, regolith characterisation and geochemical studies (Anand *et al.*, 1996 (158R); Wilford 1997a, b (372R,407R); Li Shu and Robertson, 1997 (405R); Jones, 1997a,b (374R, 382R); Robertson *et al.*, 1997 (409R); Phang *et al.*, 1997 (429R)). A generalised map 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 and regolith-landform maps for the selected districts (Buckley River-Lady Loretta, Selwyn, Eloise, Maronan, Tringadee, Little Eva-Dugald River, Seismic Line) were produced by interpretation of aerial photographs and Landsat TM imagery and were substantiated by ground traverses. Stratigraphic sections showing variations in regolith and weathering features were constructed from natural exposures and drill cuttings; samples were collected for laboratory study. Regolith samples were characterised by mineralogy, petrography and geochemistry.

The Mt Isa regional study provided a regional regolith-landform framework for the geochemical dispersion studies. Its specific objectives were:

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

(2) To characterise and establish the origin of regolith materials.

(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 impact of regolith history on geochemical exploration.

2.2 Regional setting

The Mt Isa Inlier is an area of exposed early and middle Proterozoic rocks, covering more than 50,000 km^2 (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. Gravity and aeromagnetic data indicate that the rocks of the Mt Isa Inlier extend for considerable distances below these basins. Jennings and Mabbutt (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

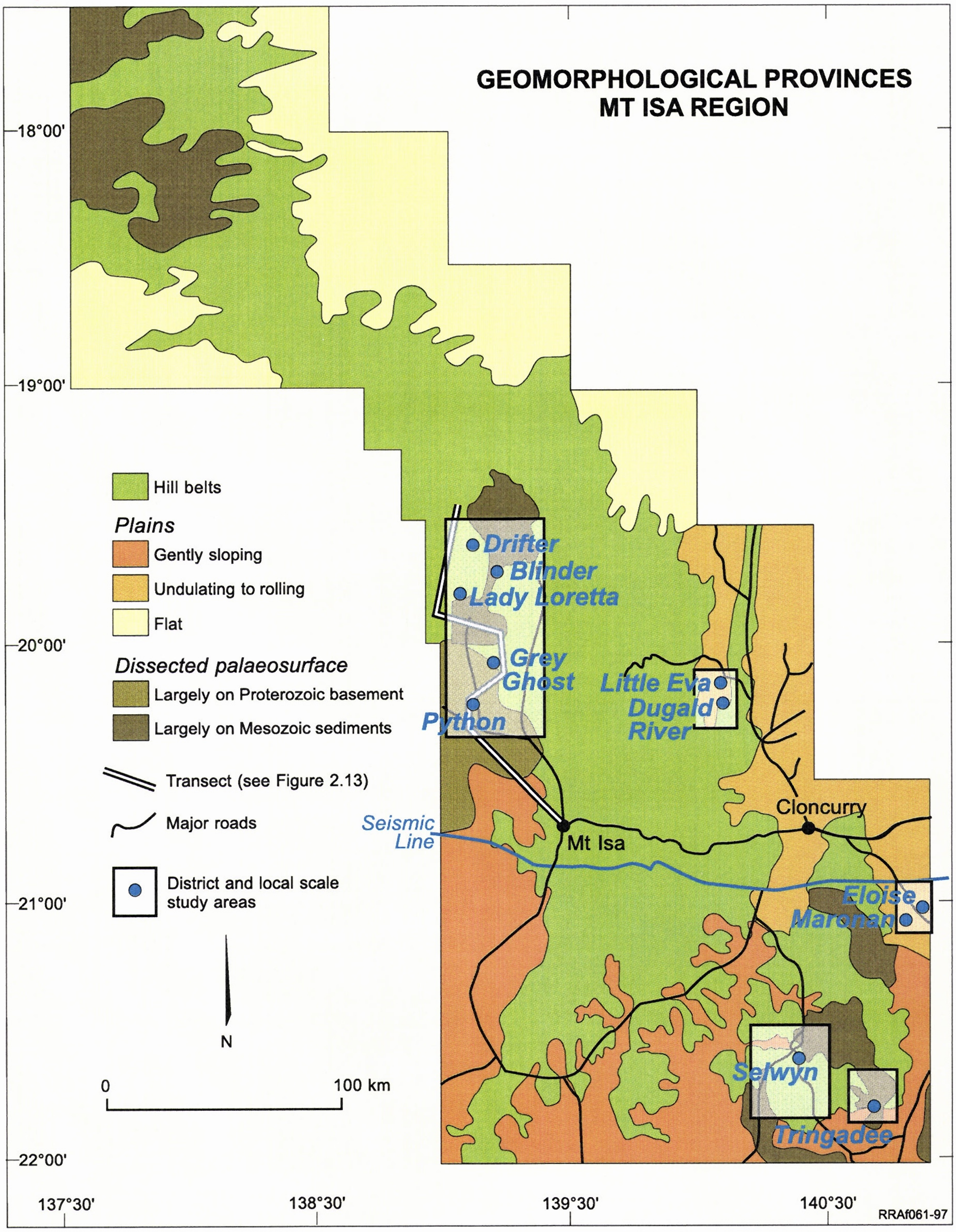

Figure 2.1 Generalised geomorphological provinces of the Mt Isa region (After Anand, *et al.*, 1996 (158R)).

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. Both regionally and in detail, the relief of the Mt Isa Inlier directly reflects underlying structures and lithologies (Birot, 1955; Twidale, 1966).

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. Most of the summer rainfall (300-500 mm) occurs between October and March but it is unpredictable and droughts are common. Mean temperature ranges are from 25-35^{0}C in December with corresponding winter temperatures some 10 to 15 degrees cooler. The vegetation reflects the semi-arid climate, consisting mainly of eucalyptus and acacia shrub with spinifex and ephermal grasses. Outcrops of Proterozoic rocks typically have a sparse cover of shrubs, low trees and spinifex.

A low divide separates drainages flowing north to the Gulf of Carpentaria from south flowing streams of the Georgina-Diamantina inland drainage system. Drainage patterns include open and close dendritic, weakly braided and trellis (Anand *et al.*, 1996 (158R)). Open dendritic and braided patterns are associated with low relief palaeoplains and high relief, actively eroding landscapes, respectively. Trellis drainage reflects the prominent north-south structural fabric of the Proterozoic bedrocks.

The northeast flowing drainage is superimposed on the predominantly north-striking structural grain of the Proterozoic rocks, possibly reflecting an early drainage pattern inherited from a post-Palaeozoic cover. This inherited pattern probably developed after emergence of the Mesozoic sediments in the late Cretaceous as the coastline retreated to the north-east. This inherited pattern implies that the Mesozoic cover extended over a very large part, if not all, of the Mt Isa Inlier. 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. They are now sporadically distributed and occur as patchy outliers, mesas or valley infills, but are most common in the Eastern Succession.

2.3 Weathering patterns

The detail of the Mt Isa landsurface is intimately related to differential weathering and erosion of the various lithologies. Quartzite forms upstanding masses; siltstone and claystone tend to offer little resistance and are eroded relatively easily to form lowlands and valleys. The flat summits (400-520 m), preserved on quartzite, lack weathering profiles. However, in places, soil materials and colluvium in depressions contain ferruginous pisoliths and nodules, suggesting that even these summits may have been blanketed by weathering profiles, now eroded (Anand *et al.*, 1996 (158R); Vasconcelos, 1997 (452R)). This is observed in number of localities northwest of Mt Isa and along the AGSO/AGCRC Seismic Line (Drummond, 1996).

The depth of weathering profiles varies and is largely controlled by landscape position, bedrock, structural features and any overlying sediments at the time of weathering. The Mesozoic cover extended over a very large part of the Mt Isa region but now Mesozoic sediments are more wide spread in the southeast and to the north than in the centre of the Mt Isa Inlier. Palaeoplains and topographic lows are more deeply weathered than the erosional plains and hill belts. At the Python prospect and Lady Loretta deposit, the depth of weathering is about 90 m on dolomitic siltstones but, near faults and fractures, penetrates to >300 m. At many locations, Proterozoic bedrocks are weathered to greater depths where overlying Cambrian or Mesozoic sediments have been removed or were never deposited. Such is the case in the Buckley River area (Kennedy Gap) in the Western Succession where exploration drilling beneath the palaeoplains, north of Buckley River, typically record weathering depths of up to 150 metres (*e.g.*,20°14'46"S- 139°8'11"E). This contrasts with the Eloise area, where bedrock is remarkably fresh beneath 50 m of Mesozoic sediments (Li Shu and Robertson, 1997 (405R)).

2.4 Weathering profiles

Weathering profiles have developed on Proterozoic bedrock, Cambrian and Mesozoic sediments and extend to variable depths below the present landsurface. Although the general pattern of the profile is similar at many locations, development of the individual units is non-uniform. Saprolite is common in many weathering profiles, the upper, ferruginous (lateritic duricrust) or silceous horizons may be absent due to incomplete formation or later erosion. In places, lateritic duricrust is developed on Fe-rich bedrock (*e.g.*, basalt, gabbro, dolomitic siltstone and shale). They are more common in the Western Succession than in the Eastern Succession. Silcrete has developed on siliceous bedrock (*e.g.*, stromatolitic shale, siltstone), indicating a lithological control. Lateritic duricrust and silcrete may occur within a few hundreds metres of each other which may suggest that they are coeval (Anand *et al.,* 1996 (158R)).

The *ferruginous profile on Proterozocic bedrocks* consists of massive or nodular duricrust, mottled saprolite, saprolite, saprock and bedrock (Figure 2.2A). Saprolite may be silicified and is largely kaolinitic but, at the base of the saprolite and saprock, smectite and mixed layer clay minerals occur over particular lithologies (*eg*., schist and basalts). Mottled saprolite, 2-5 m thick, which overlies the saprolite, is characterised by hematite-goethite-rich mottles in a kaolinite-rich matrix (Figure 2.3A) and becomes more indurated towards the top of the profile. Development of mottles is partly controlled by sub-vertical cleavage or schistosity of the bedrock. There is a gradual transition between mottled saprolite and overlying massive duricrust which ranges in thickness from 0.5 to 1.5 m. In places, higher in the profile, soft, clay-rich masses in the mottled saprolite have been dissolved leading to its collapse (collapsed mottled saprolite). Collapsed mottled saprolite is composed of large fragments of mottled saprolite in a small amount of silty matrix. Where cemented, these form fragmental duricrust (Figure 2.3B).

On the surface, hematite-goethite-rich lateritic nodules may form from fragmentation of the underlying duricrust (Figure 2.3C). Hematite increases in abundance towards the top of the profile. At the surface however, the hematite of fragments is dissolved and is reprecipitated as goethitic cutans on hematite-cores. Formation of these yellowish brown, 1 mm thick, goethite-kaolinite cutans begins in the upper part of the mottled saprolite and become dominant in collapsed mottled saprolite. As the sphericity of nodules increases by repeated dissolution and reprecipitation and downslope movement, some develop into pisoliths. In general, however, pisoliths are uncommon in the Mt Isa region.

Iron abundance increases upwards, whereas Si, Ca, Mg, K and Na decrease and Al remains unaltered. Zinc, Mn, Cu, Co, Ni, Ba, Sr and S are lost during weathering, whereas V, Pb and Cr are residually enriched (*e.g.*, Anand *et al.*, 1996 (158R)). Goethite and hematite are the major minerals in the mottles and pisoliths and have strong affinities for Cu, As, V, Pb and Cr. Copper appears to correlate with Mn. Kaolinite of the mottled saprolite contains little of these elements.

An idealised *silcrete profile on Proterozoic bedrock* consists, from top to base, of silcrete, silicified saprolite, saprolite, saprock and bedrock (Figure 2.2B). Kaolinitic saprolite is overlain by a bleached quartz-kaolinite-rich silicified saprolite (5-15 m thick) with rock structures and fabrics at least partially preserved. Silcrete overlying silicified saprolite is an indurated, greyish, 0.5-2.0 m thick, massive horizon (Figure 2.3D) rich in quartz and microcrystalline quartz with small amounts of anatase. Some large massive sheets have columnar jointing (Figure 2.3E). On a macro scale, no 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. Silica increases in abundance up the profile in the sites examined and Al decreases (Anand *et al.*, 1996 (158R)). Zirconium and Ti are enriched.

Weathering of Cambrian sediments forms a profile comprising cherty breccia or silcrete over mottled saprolite (Figure 2.2C). In places, silcrete on Cambrian sediments is overlain by massive, ferruginous duricrust on Mesozoic sediments (Figure 2.2D; 2.3F).

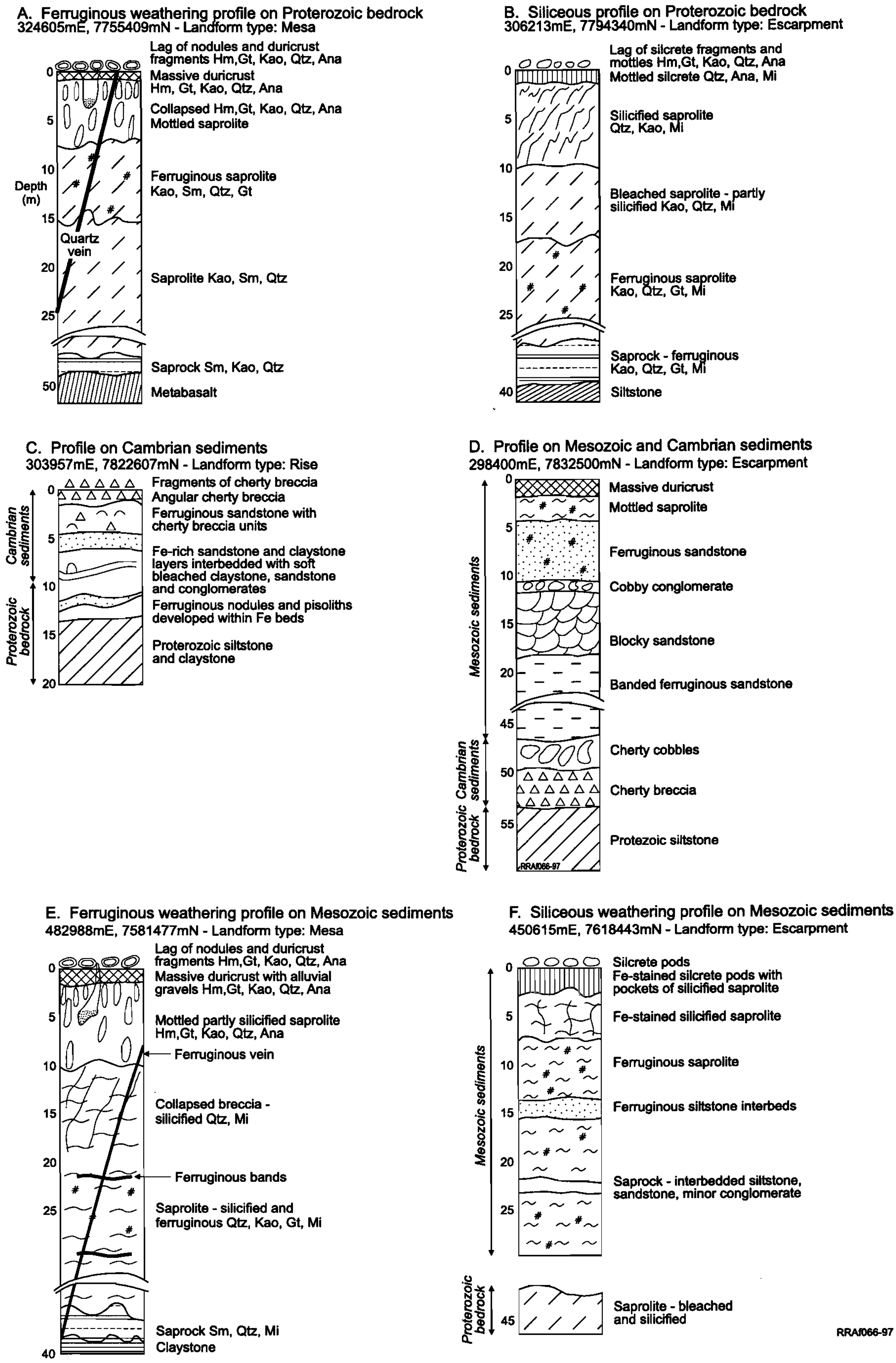

Figure 2.2. Weathering profiles developed from weathering of Proterozoic bedrock, Cambrian and Mesozoic sediments.

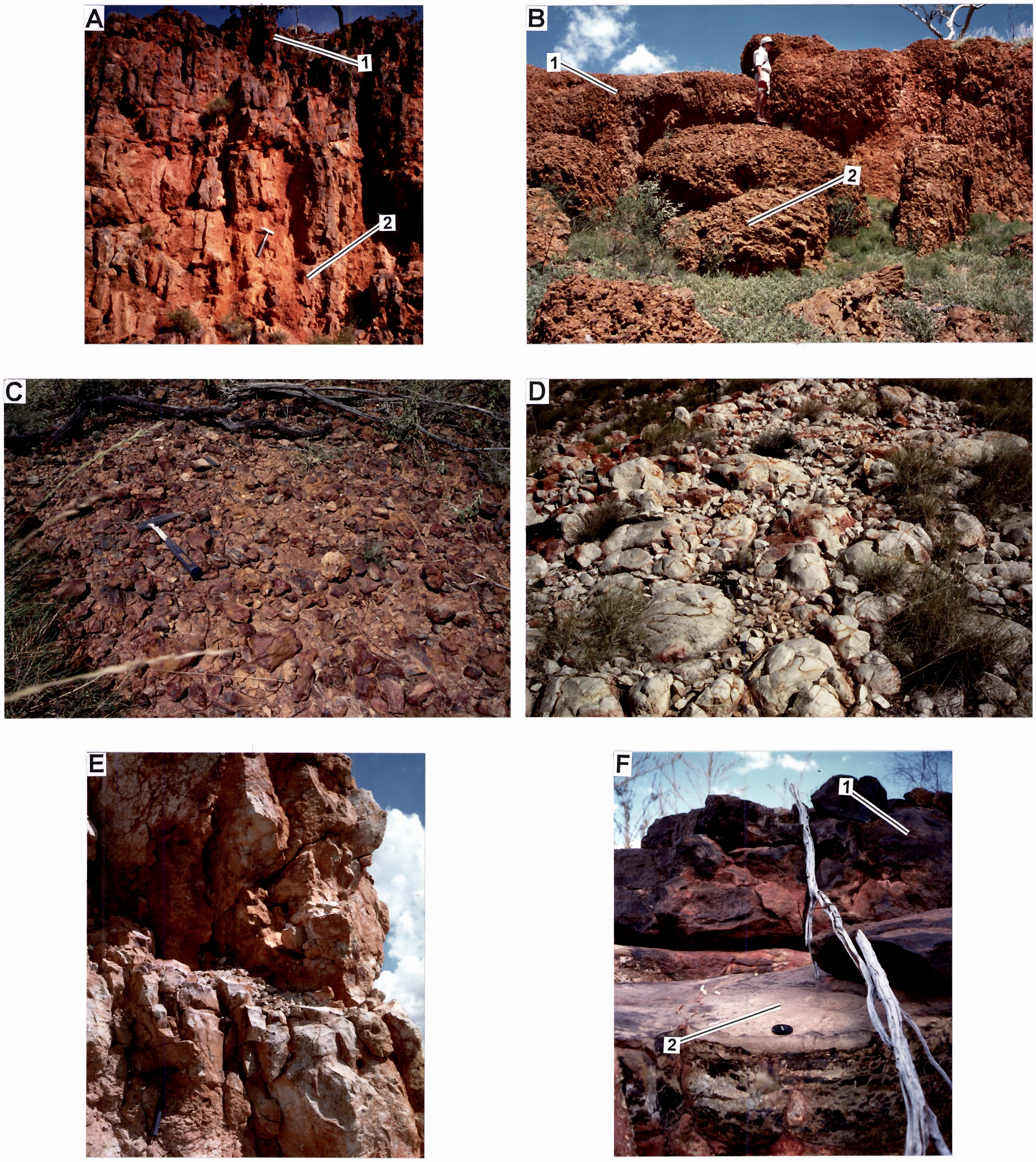

Figure 2.3. (A) Massive lateritic duricrust (1) over elongated mottled saprolite (2) on a mesa, Gidya Creek, Buckley River area. (B) Fragmental duricrust (1) over collapsed ferruginous saprolite (2) on the edge of an erosional scarp, Buckley River area. (C) Lag of fragments of mottled saprolite and nodules on a duricrust-capped surface, Buckley River area. (D) Massive silcrete developed on Proterozoic siltstone, Lady Loretta area. (E) Columnar silcrete developed on Proterozoic bedrock, Lady Loretta area. (F) Massive duricrust developed on Mesozoic sediments (1) underlain by silcrete (2) on Cambrian sediments, Drifter prospect.

The brecciated nature of the Cambrian sediments is most likely related to weathering and removal of carbonates and clays from the original sediments, resulting in the collapse of the more resistant cherts and siliceous siltstones beds. These resistant materials have now been re-cemented by Si, Fe and Mn oxides. The degree of weathering beneath the breccia is largely controlled by lithological variations; argillites are highly weathered to clays whereas more siliceous units are generally only moderately to slightly weathered (Wilford, 1997b(407R)).

Weathering profiles on Mesozoic sediments are variable and are largely controlled by the nature of the sediments; as would be expected, more thick weathered profiles are developed on claystones and siltstones than on sandstones. Ferruginous or siliceous duricrust have developed on some Mesozoic sediments (Figure 2.2E,F). The ferruginous profile over claystones contains ferruginous nodules overlying patchy, massive or slabby duricrust which passes downwards into a mottled saprolite characterised by blocky mega mottles (Figure 2.2E). The contact between the goethite-hematite-rich massive duricrust and the mottled saprolite is gradational. Below the mottled saprolite, there is silicified 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. These clays are generally smectitic and contain some kaolinite, goethite and mica. Associated with the saprolitic clays are nearly flat, ferruginous bands that form a steplike microrelief. They consist mainly of goethite, quartz, some mica and kaolinite. Ferruginous bands are redox products the deposition of which are controlled by the watertable position within the profile. The structurally controlled hematite-rich ferruginous veins follow tectonically induced partings that are at different angles to the bedding of sediments.

Tertiary sediments are commonly mottled but are not capped with duricrust.

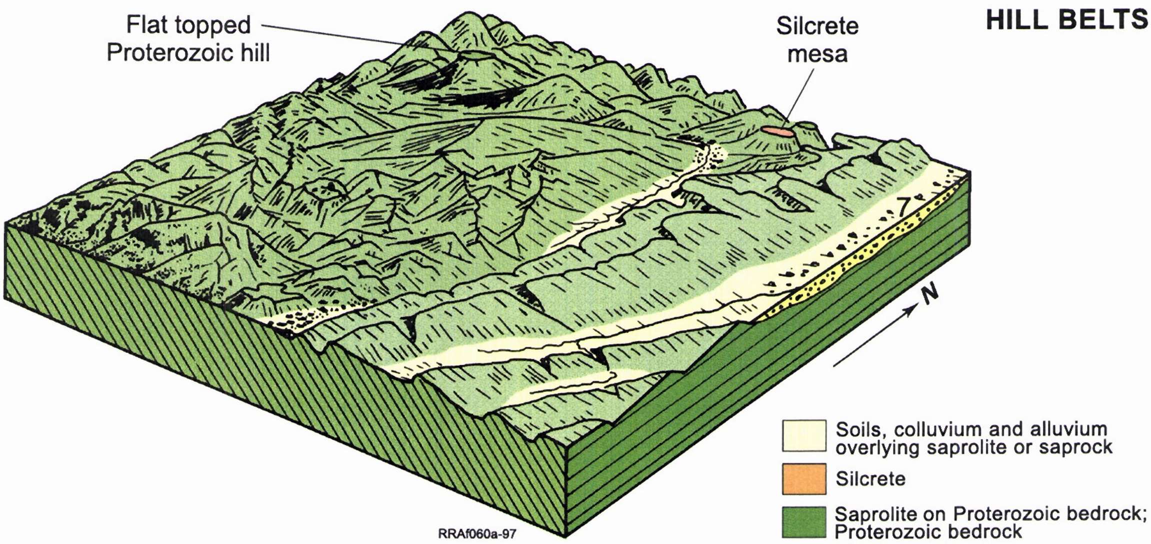

Figure 2.4. Block diagram showing nature of landscape-regolith in hill belts (After Anand *et al.*, 1996 (158R)).

2.5 Geomorphological provinces and regolith

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 geomorphological subdivisions are recognised (Figure 2.1). Geomorphic provinces are:

1. Hill Belts.

2. Dissected palaeo-landsurfaces developed both on Proterozoic rocks and on Mesozoic sediments. These can be subdivided on the basis of their dominant geology into:
   (a) dissected palaeo-landsurface largely on Proterozoic rocks;
   (b) dissected palaeo-landsurface largely on Mesozoic sediments.

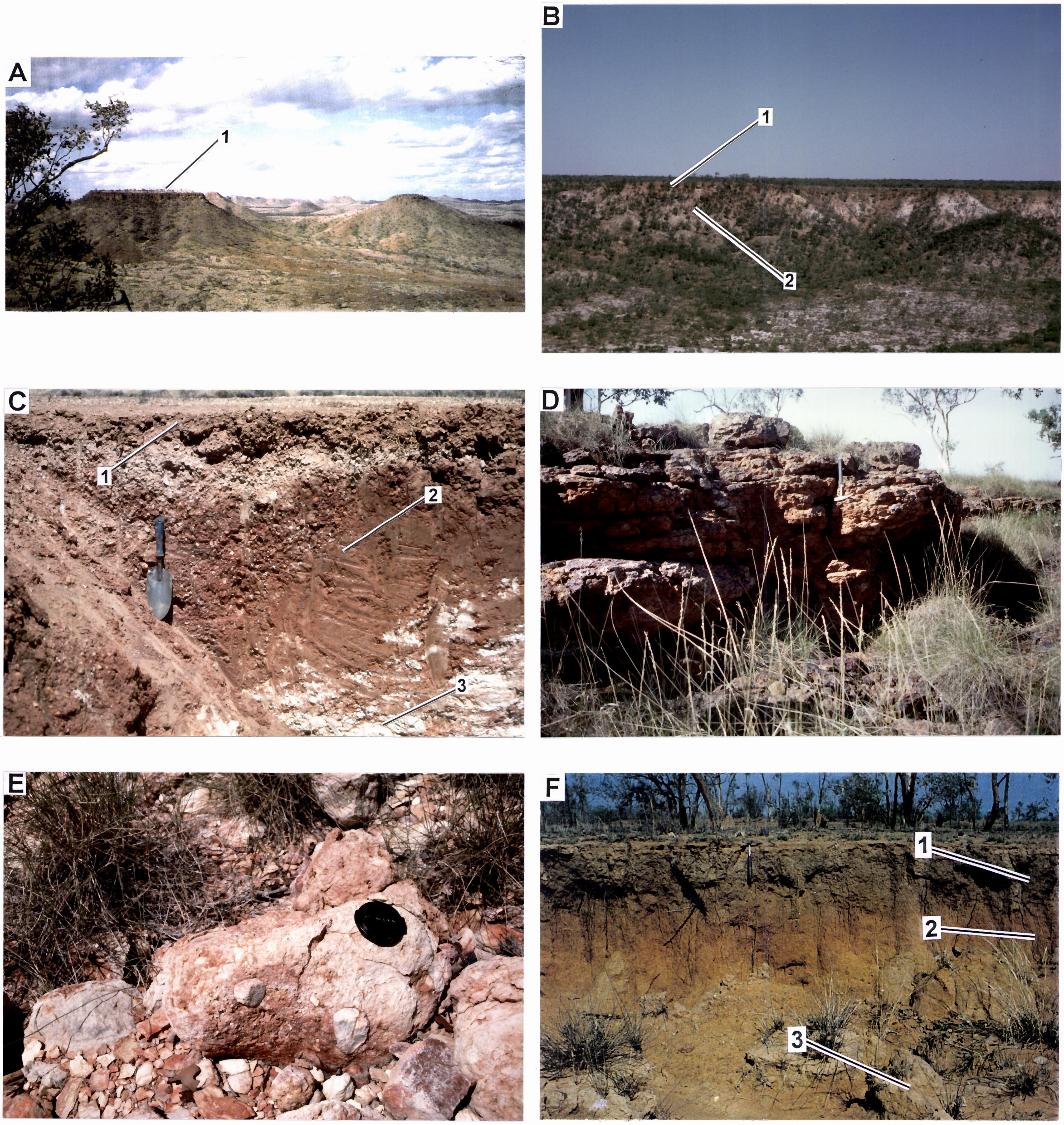

Figure 2.5. (A) The dissected parts of the hill belts, some 30 km south of Cloncurry, showing the irregular relief and small plateau remnants as mesa form hills. Towards the foreground, a silcrete-capped mesa on Mesozoic sediments (1) emerges above the hills on Proterozoic bedrocks. (B) Pre-Cretaceous concordant summits forming palaeoplains and mesas. Proterozoic bedrocks are capped by either ferruginous or siliceous duricrust (1) overlying saprolite (2), Grey Ghost area. (C) Soil profile on erosional plains showing a thin layer of colluvium (1) overlying a red soil (2) formed on a kaolinite-rich saprolite (3). (D) Slabby duricrust on plateau margin, Python prospect. (E) Silicified sands and gravels, Buckley River area. (F) On alluvium an upper veneer of fine creamy brown soil (1) overlies a pale brown soil (2) and cemented gravels and sand (3), Buckley River area.

3. Plains subdivided on the basis of topography into:
   (a) gently sloping plains;
   (b) undulating to rolling plains;
   (c) Flat plains.

2.5.1 Hill belts

The hill belts occupy the deeply incised central portion of the region (Figure 2.1) which consists predominantly of north trending ridges and hills that average between 320 m and 480 m amsl (Figure 2.4) but in places exceed 520 m. Some small plateau remnants show a marked concordance of crests. The detailed sculpture of the landsurface is intimately related to differential weathering and erosion of the various rock types. Mesozoic sediments occur sporadically, particularly over the Cloncurry district. They rest unconformably on Proterozoic rocks as small, isolated mesas (Figure 2.5A).

Not all the rocks in the hill belts are fresh; many show signs of former and present weathering. There are marked zones of superficial, secondary silicification; basalt, schist, amphibolite and siltstone kaolinised and the weathered rock are generally Fe stained (Anand *et al.*, 1996 (158R)). Weathered rocks (5-10 m thick) are also mantled by a thin veneer of residual, skeletal, calcareous to non-calcareous soil and locally derived colluvium. The colluvium is generally less than two metres thick but reaches 12 m in places. The presence of ferruginous nodules and pisoliths in the colluvium suggests that they are largely derived from a former, more weathering profile. These features were observed along the 260 km seismic line (Anand *et al.*, 1996 (158R); Dell, 1997 (451R)).

Distribution of calcrete 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 siltstone. Dolomite is present only over mafic schist. The dominance of calcite, dolomite and smectite in saprolite and soils suggest that they have formed by slow drainage and mild leaching, characteristic of a semi-arid climate.

2.5.2 Dissected palaeo-landsurface

(a) *Dissected palaeo-landsurface largely on Proterozoic bedrock.* This geomorphological province occupies the Kennedy Gap area in the Western Succession (Figure 2.1) and forms a complex of mesas and plains largely over Proterozoic bedrock (Figure 2.6). Generally, Mesozoic sediments are thin or absent which suggests that they were never deposited or have been removed. The area has low to moderate relief and shows signs of variable extents of former deep weathering (Wilford, 1997b (407R)). It appears to be a dissected palaeo- landsurface (Figures 2.5B). An erosional scarp separates old landforms and regolith over a palaeo-landsurface on the western side, from younger landforms and regolith on the east (Figures 2.7; 2.8). The eastern side of the scarp is dominated by erosional processes and consists mainly of thin skeletal soils over slightly to moderately weathered bedrock. However, exceptions to this are isolated mesas that preserve older remnant surfaces of the palaeoplain which once extended further to the east. These mesas consist of siliceous or ferruginous duricrusts and are common around the Grey Ghost prospect. Other smaller, less continuous scarps occur around the headwaters of some drainage basins, around mesas, and parallel to some streams (*i.e.,* Buckley River).

Regolith on mesas and pediments

The mesas are flat to gently sloping, commonly reaching 20-30 m above their surroundings, up to 2 km wide and are separated by pediments and erosional plains (Figure 2.8). They range in elevation from 350-420 m. In many places the erosional scarps form important contacts between different types of regolith, with generally older and typically indurated (Fe or Si) regoliths on mesas and younger materials below on pediments. An example of such regolith-landform relationships is shown in Figure 2.9. The mesa (420 m) consist of residual, hematite-rich massive lateritic duricrust over a 3-4 m of mottled saprolite. Manganese oxides from this profile yield ages ranging from 30-40 Ma (Vasconcelos, 1997 (452R), See also Section 3). The surrounding landforms consist of pediments and erosional plains covered with locally derived ferruginous gravels and much younger thin (<1 m) residual soils formed from *in situ* weathering of underlying saprolite (Figure 2.5C). Pockets of smectite-rich *in situ* 'black' soils occur as gilgai. In places, fresh bedrock outcrops.

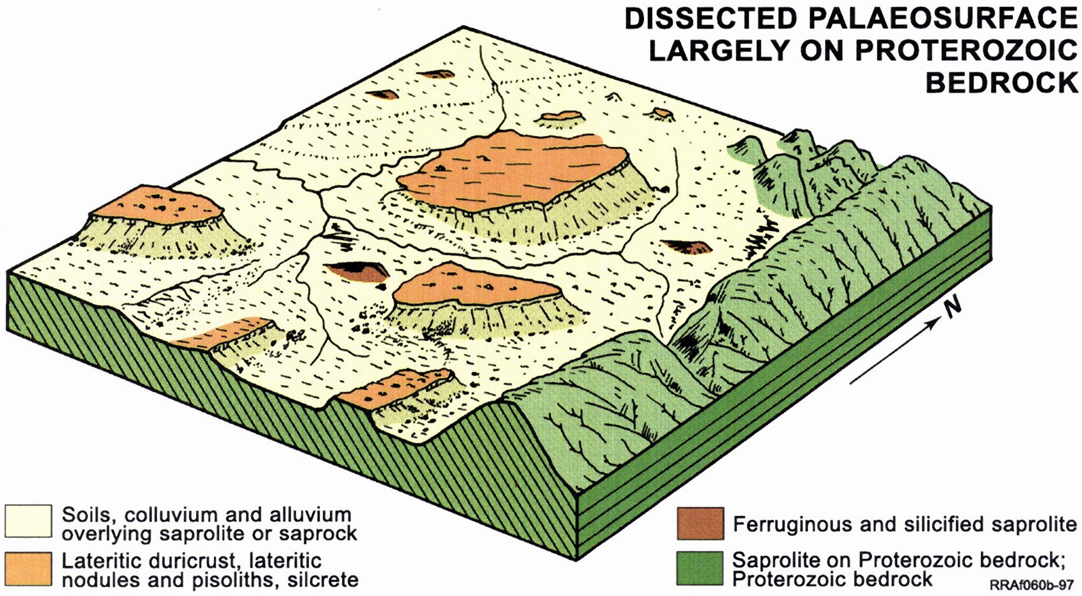

Figure 2.6. Block diagram showing nature of landscape and regolith on dissected palaeo-landsurface developed largely on Proterozoic bedrock (After Anand *et al.*, 1996 (158R)).

Lateritic or siliceous duricrusts have formed mainly in residual regolith, but, locally, they were also developed in transported sands and gravels in valleys which have been subsequently indurated and now form high points in the topography due to relief inversion. These relationships occur around the Python prospect and the Grey Ghost area (Anand *et al.*, 1996 (158R); Wilford, 1997b (407R)). The Grey Ghost area is dominated by low hills of silicified saprolite, ferruginous duricrust and plateaux of silcrete that rise to 60 m above the plain (Figure 2.10). A mesa at a lower elevation than the columnar silcrete capped plateau is capped with slabby, ferruginous duricrust, developed in sandy grit and rounded quartz gravel, cemented by goethite. At the Python prospect, slabby duricrust occurs on plateau margins and forms massive, horizontal plates of quartz-rich material, impregnated by goethite but lacking quartz pebbles (Figure 2.5D). It is suggested that the slabby duricrust was probably formed in a low position in an undulating palaeo-landsurface; the topography has been inverted since induration. In places, Si has cemented alluvial sands and gravels (Figure 2.5E) with a similar result.

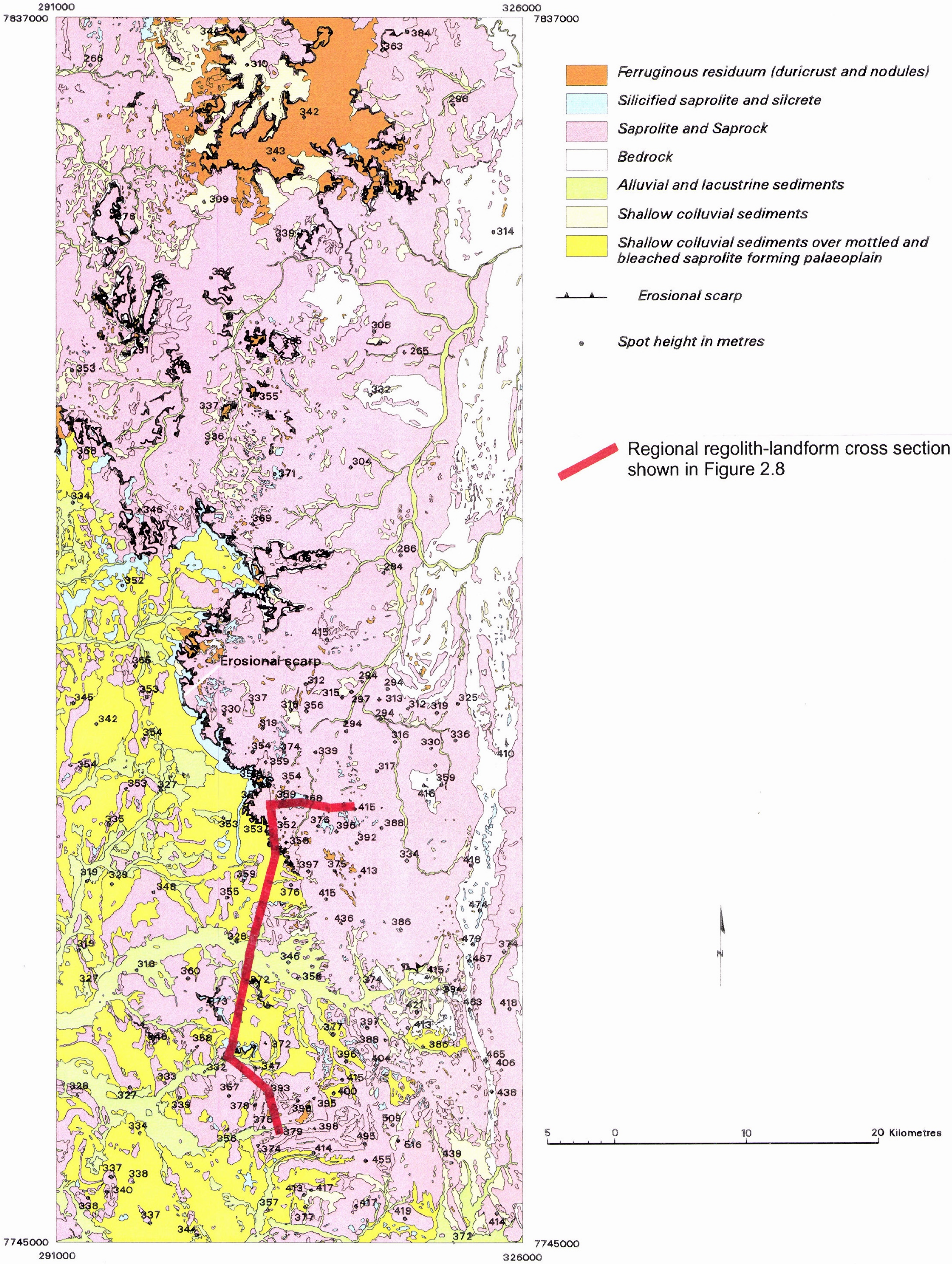

Figure 2.7. Major erosional scarp separates old landforms and regolith over a palaeo-landsurface on the western side from younger landforms and regolith on the east, Buckley River-Lady Loretta area (After Wilford, 1997b (407R)).

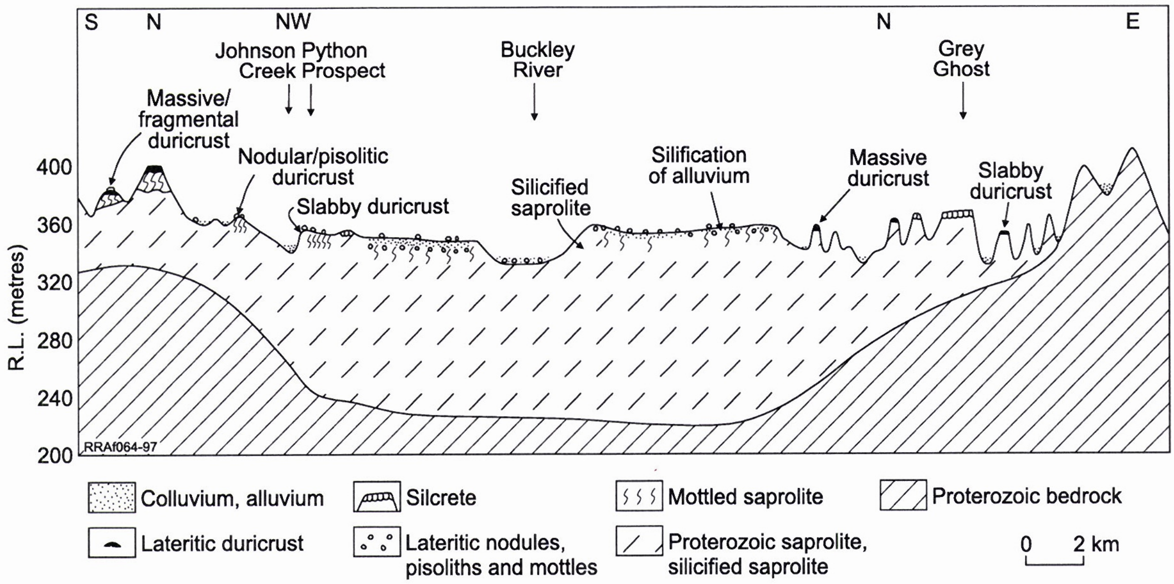

Figure 2.8. A schematic cross section showing the relationship between the landforms and regolith for the regional traverse, Buckley River-Grey Ghost area (note depth of weathering beneath palaeo-lows) (After Anand *et al.*, 1996 (158R)). See location of this traverse on Figure 2.7.

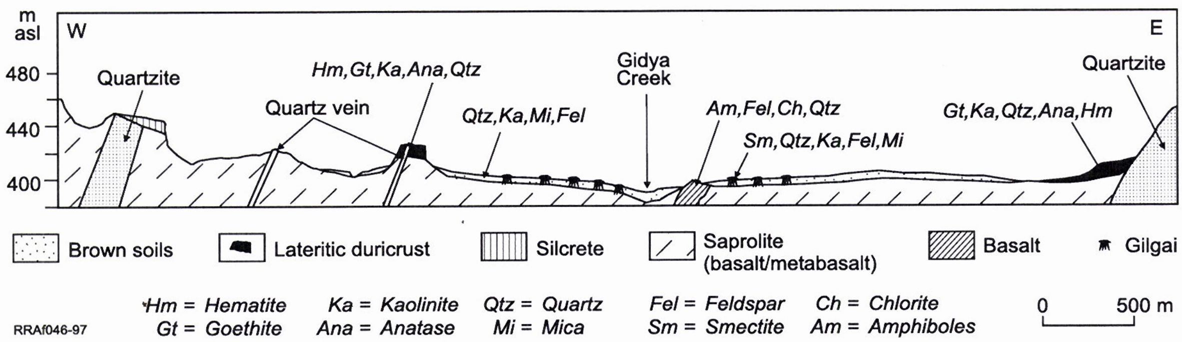

Figure 2.9. Schematic representation of variation in regolith on mesa, pediments and erosional plains.

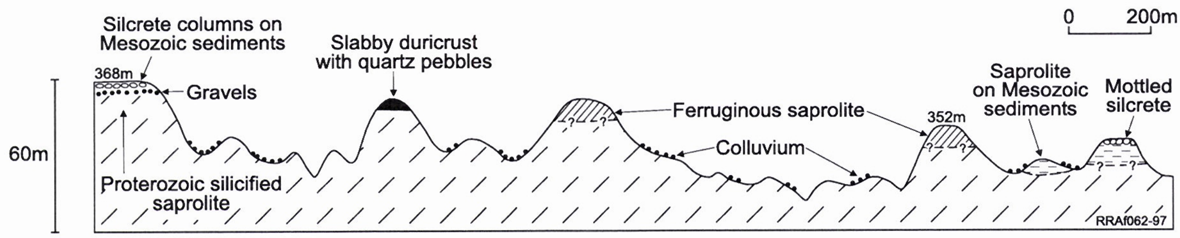

Figure 2.10. Cross section showing slabby duricrust below the silcrete-capped mesa. Here, slabby duricrust is developed in sandy grit and rounded quartz gravel, Grey Ghost prospect (After Anand *et al.*, 1996 (158R)).

Regolith on palaeoplains
Areas characterised by low relief (northeast of Buckley River) have preserved some of the most deeply weathered regolith, due to relatively low erosional rates (Figures 2.8). Drilling in this palaeoplain typically reveal weathering depths of up to 150 m. The low relief areas have received colluvium, Fe and Si continuously from upslopes during weathering. Ferruginous or silicified saprolite is common beneath variable thicknesses (1-5 m) of alluvium. Red earths, developed in alluvium, are silicified indicating mobilisation and deposition of Si in the upper regolith. This silicification may have resulted from periodic flooding and dessication of the sediments under semi-arid to arid conditions. This process of silicification, though weak, is similar to the hardpans of the Yilgarn Craton (Bettenay and Churchward, 1974). A lag of hematite-rich ferruginous gravel and silicified fragments is common, probably derived by erosion of duricrust-capped low hills nearby.

Regolith in recent alluvial channels
The alluvial deposits consist mostly of channel and over-bank sediments. The alluvial sediment generally exhibit upwards fining (coarser channel deposits overlain by finer over bank deposits). A typical regolith section consists of gravel and sand beds and lenses overlain by flood plain silts and clays (Figure 2.5F). The flood plains are mainly oriented in an easterly direction and reflect continuation of an older palaeo-drainage system superimposed on the predominantly northerly fabric of the Proterozoic rocks. Channel deposits occur in both active and abandoned stream channels. Some of the main streams, such as Wilfred Creek and Buckley River, have well-rounded gravel and cobbles in their channels (Jones, 1997a (382R)).

More active, northerly streams are generally smaller than the easterly drainages and have narrower sedimentary corridors. These 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 (Jones, 1997a (382)).

(b) *Dissected palaeo-landsurface largely on Mesozoic sediments.* Unconformably overlying the Proterozoic rocks are mesas and buttes of consolidated Mesozoic sediments in the southeast (*e.g.*, Tringadee, Selwyn) and northwest (*e.g.*, Drifter) (Figure 2.1; 11A,B). These retain evidence for prolonged deep weathering; the upper ferruginised and silicified saprolite contains a well-developed ferruginous duricrust or silcrete (Figures 2.12, 2.11C). The basal unit of these sediments is a silicified conglomerate, up to 5 metres thick, comprising pebbles and subangular rock fragments (Figure 2.11D). There are abundant plant, leaf, bark and stick casts on the upper surface of the conglomerate.

The duricrust-capped Mesozoic sediments occur at several levels. Most are lower than adjoining areas of Proterozoic rocks but, in some places, they rise to the same elevation as the adjacent areas of weathered Proterozoic rocks (Figure 2.13). The differences in elevation of the weathered surface suggests that the pre-Mesozoic landsurface had significant relief. Furthermore, irregular thicknesses of Mesozoic sediments and an undulating Proterozoic-Mesozoic unconformity can be best explained by infilling of valleys. A palaeosurface then formed across the intervening infilled Mesozoic sediments valleys, as at Drifter (Figure 2.13), Selwyn and Tringadee.

Where the Mesozoic sediments have been removed, a thin veneer of cherty breccia or silcrete is revealed which is the base of an older sedimentary sequence (Cambrian) formed on silicified Proterozoic saprolite (*e.g.*, at Drifter Figure 2.13). The erosion products of the Mesozoic sediments now occur on valley floors (Figure 2.14; Anand *et al.*, 1996 (158R)), ferruginised to goethite and Mn oxide-rich vesicular duricrust.

Figure 2.11. (A) Dissected palaeo-landsurface showing remnants of Mesozoic sediments as mesa capped with lateritic duricrust on Mesozoic sediments (1) overlies unconformably granitic saprolite (2), and shallow soils on saprolite on erosional plains (3), Tringadee area. (B) Eroded flanks of a plateau remnant having a cap of mottled silcrete (1) underlain by silicified saprolite on Mesozoic claystone, Tringadee area. (C) Fragmental silcrete on Mesozoic claystone, Tringadee area. (D) silicified polymictic gravels at the base of Mesozoic sediments, Selwyn area. (E) Exhumed deeply weathered palaeo-landsurface on Proterozoic bedrock from which softer Mesozoic sediments have presumably been removed, Selwyn area. (F) Patchwork of brown (1) and black (2) soils developed in the same unit of alluvium, Eloise area.

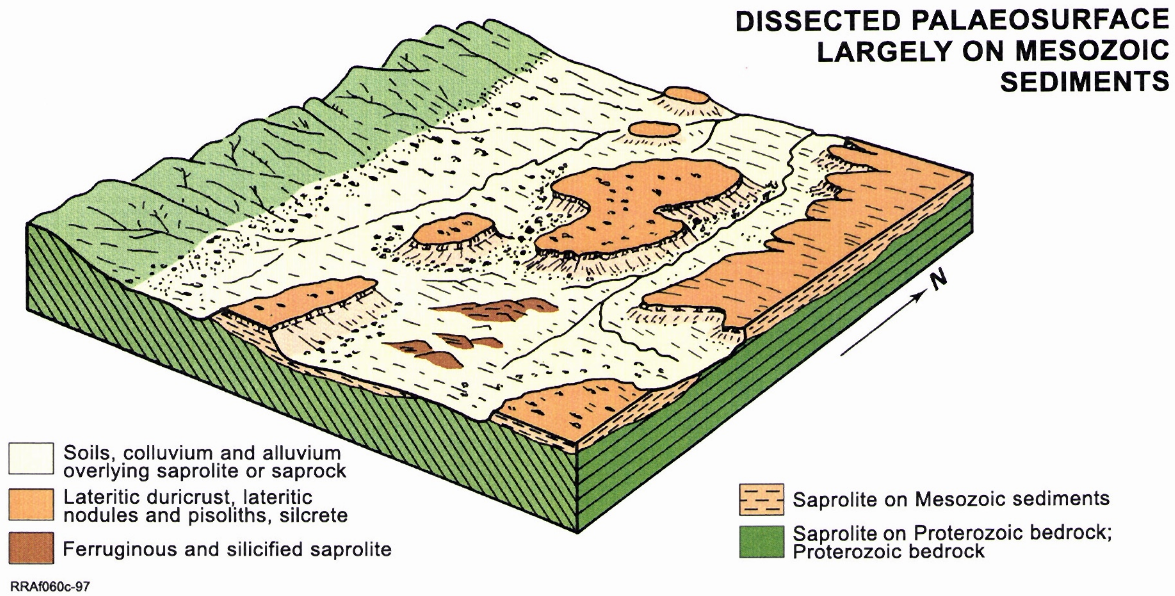

Figure 2.12. Block diagram showing nature of landscape and regolith on dissected palaeo-landsurface developed largely on Mesozoic sediments (After Anand *et al.*, 1996 (158R)).

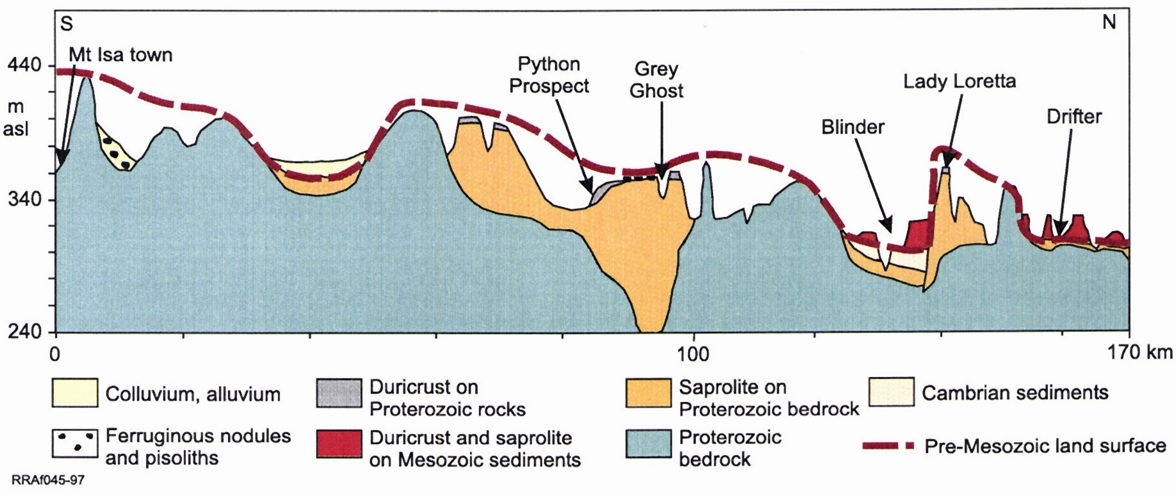

Figure 2.13 Regional traverse showing probable pre-Mesozoic landsurface with substantial relief, Western succession. Here, palaeo-landsurface formed across the intervening infilled Mesozoic sediment valleys. See location of this traverse on Figure 2.1.

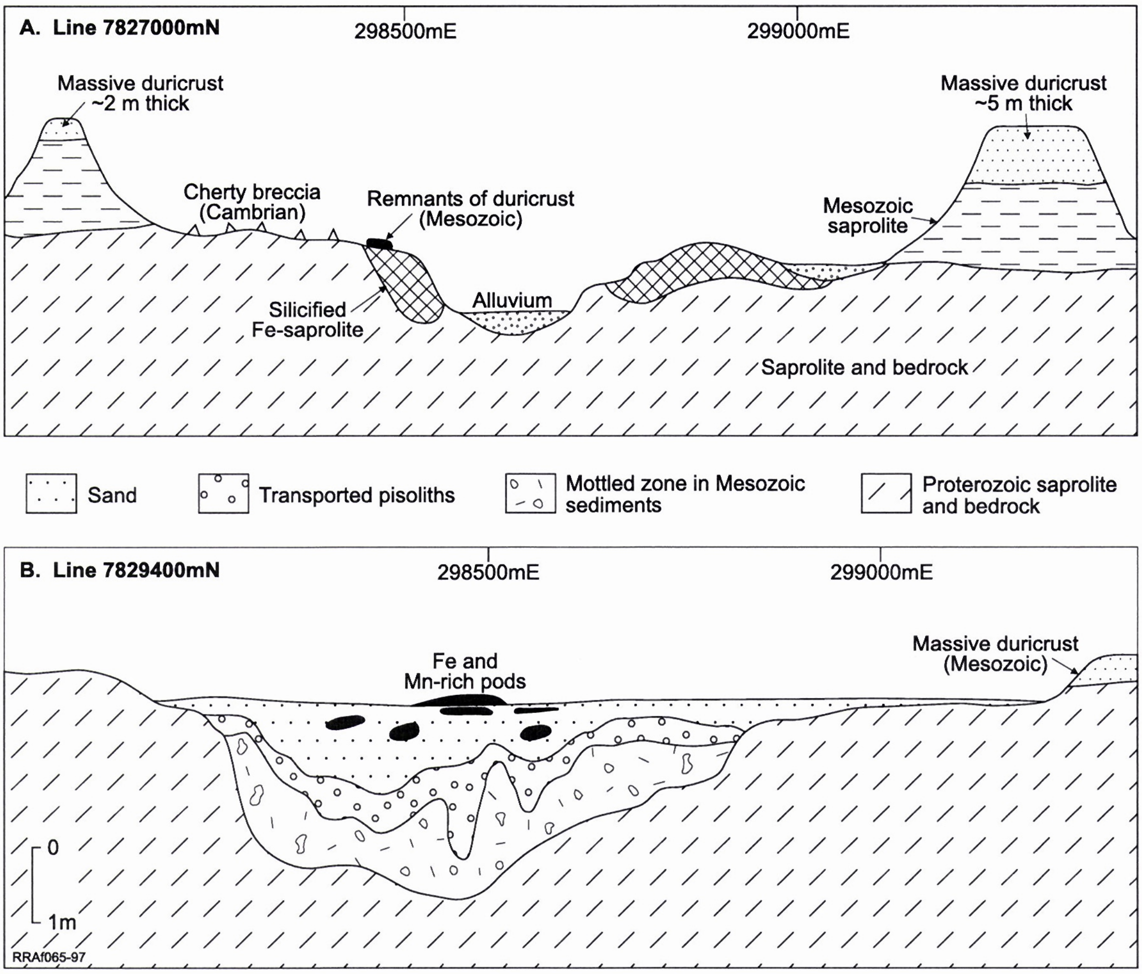

Figure 2.14. (A) Relationship between landform and regolith, Drifter prospect. (B) Cross section showing the stratigraphy of valley floor and development of mottling and Fe-Mn-rich pods in soils, Drifter prospect (After Anand *et al.*, 1996 (158R)).

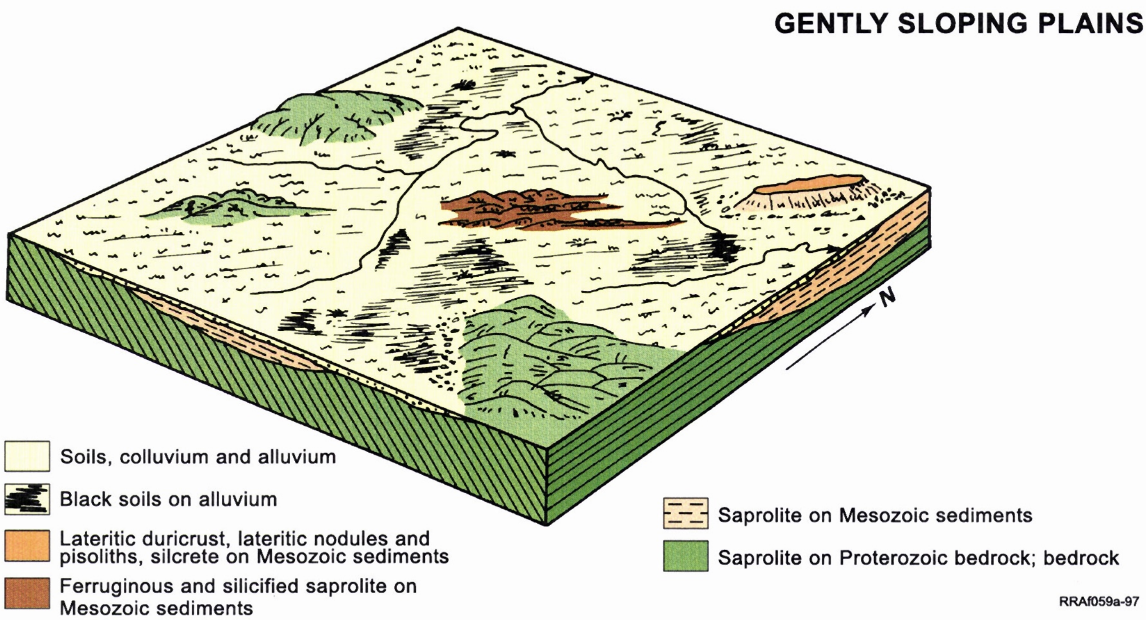

Figure 2.15 Block diagram showing nature of landscape and regolith on gently sloping plains (After Anand *et al.*, 1996 (158R)).

2.5.3 Plains

(a) *Gently sloping plains.* Irregular plains at 200-300 m elevation are very extensive in the south, southwest and southeast of the mapped area (Figure 2.1). Twidale (1966) refers to them as "inland plains which drain southwards to Lake Eyre". Low hills and ridges are common on the plains (Figure 2.15) and considerable tracts are also occupied by plateaux at two levels. The higher plateaux are capped by mottled, Mesozoic sediments; the lower ones 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 as at Selwyn and Tringadee (Figure 2.11E).

The plains are covered by variable thicknesses of colluvium, alluvium and Mesozoic sediments. Their stratigraphy was revealed from drill cuttings at the western end of the Mt Isa Seismic line (Anand *et al.*, 1996 (158R); Dell 1997 (451R)). Brown to black soils form a variable horizon (2 to 6 m) above alluvium (Figure 2.16). The soil clays commonly contain round quartz pebbles and, less commonly pebbles of the Cambrian (Bottle Creek Formation?) containing trilobites fossils. Alternating alluvial gravels and sandy alluvial clays extend to 15-25 m. The alluvial gravel is predominantly of quartz with lesser chert and Cambrian cobbles; fine ferruginous granules are less common. Thin bands of laminar, grey chert occur within these alluvial deposits. The fine grained alluvium is generally mottled and goethitic.

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 quantities of ferruginous granules and common chert fragments. The lowermost units of bleached, variably silicified siltstones and sandstones extend to depths of 40 m and contain quartz gravels and common grey chert bands.

(b) *Undulating to rolling plains.* Plains with discontinuous low hills become more numerous closer to the hill belts (Figure 2.1). They extend to the south east, east and north of Cloncurry (Figure 2.17). Twidale (1966) referred to them as the Carpentaria plains because they drain to the Gulf of Carpentaria.

The detailed regolith stratigraphy of these rolling plains was established around Eloise (Figure 2.18; Li Shu and Robertson, 1997 (405R)). In the drill holes and costeans examined, the Tertiary sediments are less than 5 m thick, and overlie 40-70 m of weathered, Mesozoic sandstone and mudstone which become fresh at depth. A layer of coarse conglomerate about 0.2-3.0 m thick, consisting of quartz and amphibolite fragments underlies weathered Mesozoic sandstone and mudstone. Various fossils found in the mudstone and limestone, such as belemnites, small bivales, ichthyosaur remains, shark teeth and ammonites, indicate an early Cretaceous age. The thin limestone and many large limestone concretions indicate a shallow water environment.

The Tertiary sediments consist dominantly of kaolinitic clay, rounded and angular pebbles of rock fragments, ferruginous pisoliths and rounded quartz probably derived in part from breakdown of an earlier lateritic profile. The Tertiary sediments are strongly mottled but are not capped with duricrust.

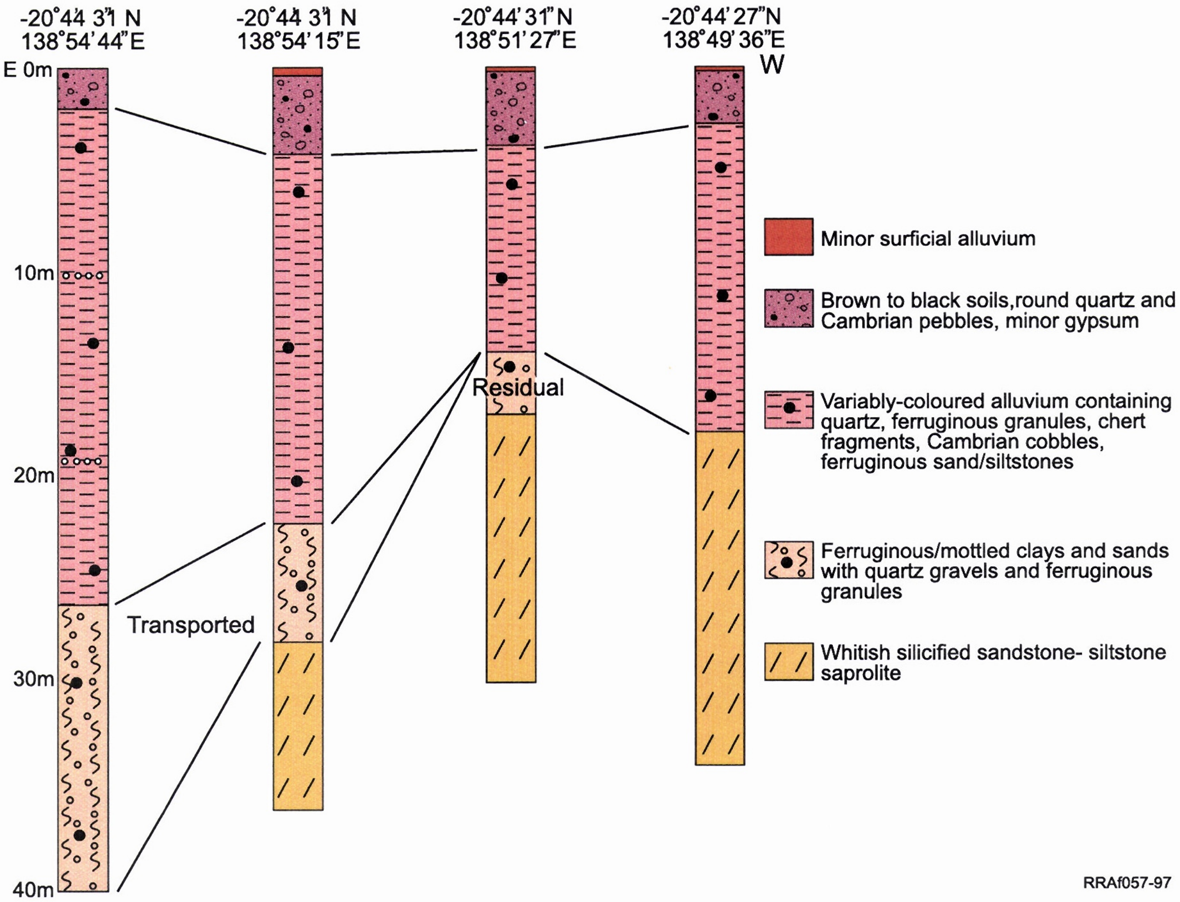

Figure 2.16. Regolith stratigraphy of gently sloping plains. The stratigraphy of gently sloping plains was established in drill cuttings on the western end of the Seismic line, SW of Mt Isa (See Figure 2.1) (After Anand *et al.*, 1996 (158R)).

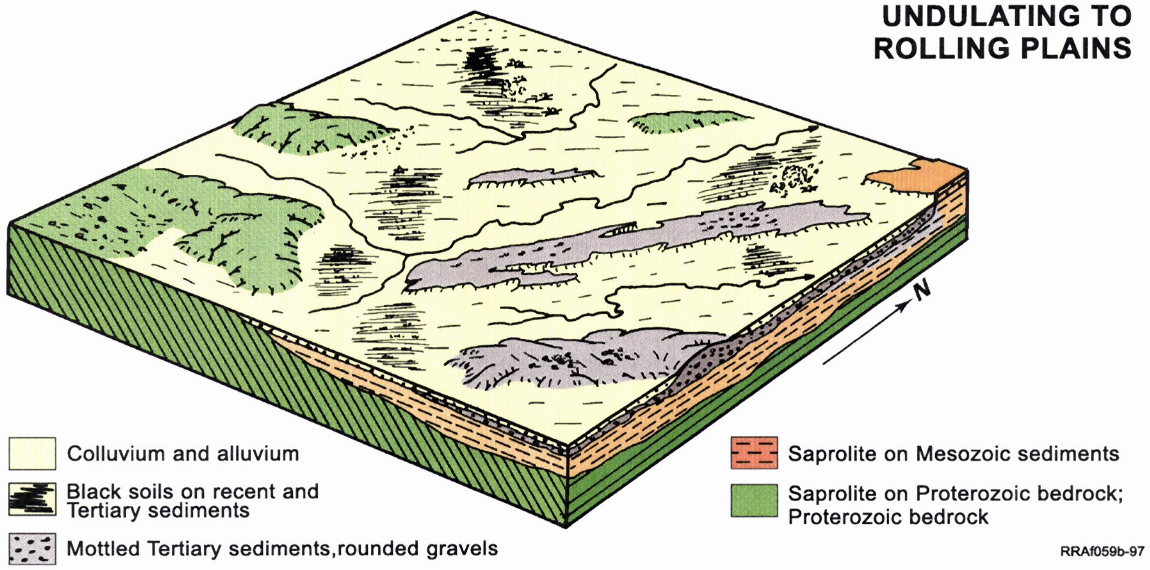

Figure 2.17 Block diagram showing nature of landscape and regolith on undulating to rolling plains (After Anand *et al.*, 1996 (158R)).

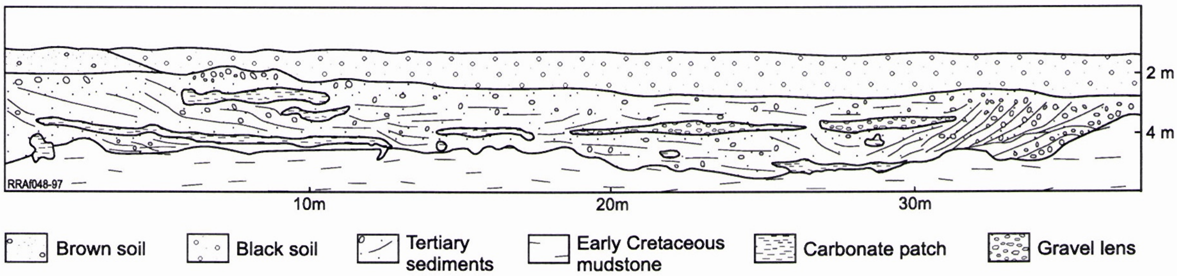

Figure 2.18. Regolith stratigraphy of the rolling plains, Eloise area (After Li Shu and Robertson, 1997 (405R)).

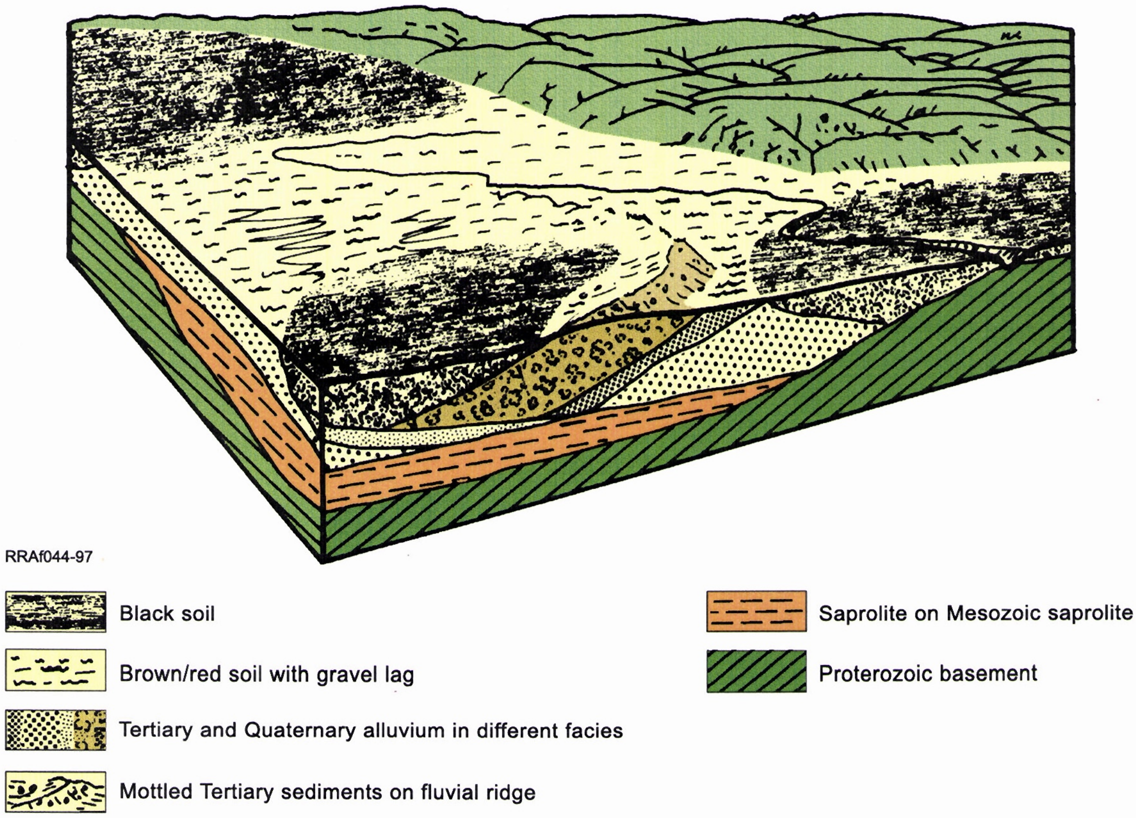

Figure 2.19. Block diagram showing the relationships between brown and black soils developed in alluvium, Eloise area (After Li Shu and Robertson, 1997 (405R)).

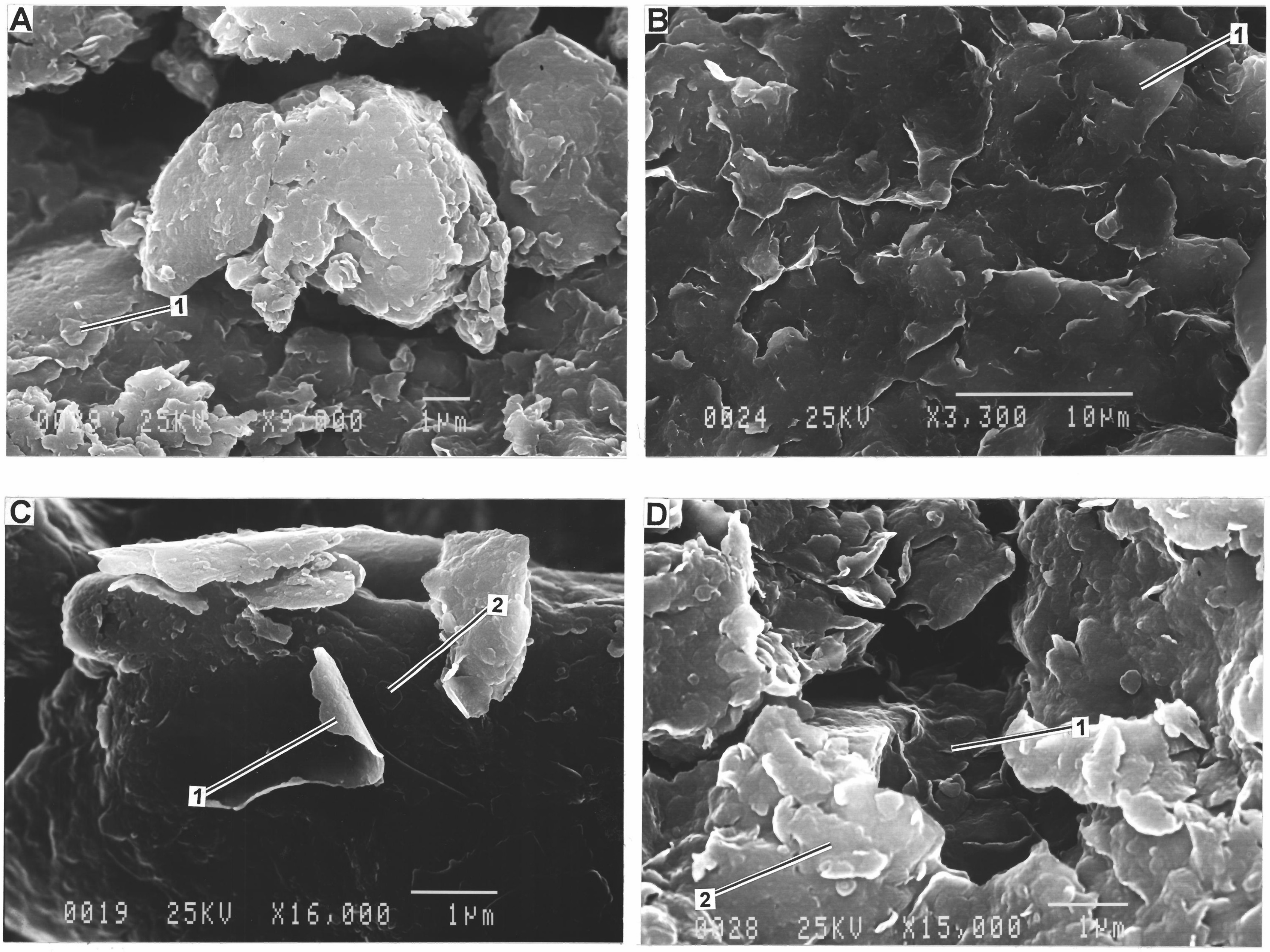

Figure 2.20. Scanning electron micrographs of brown, black and intermediate soils. (A) Platy crystals of kaolinite (1) from brown soils. (B) Thin, curled and large crystals of smectite (1) from black soils. (C, D) Intermediate soil samples showing platy, thin, curled crystals of smectite (1) as an alteration product of kaolinite (2).

Brown and black soils are common on the Tertiary sediments (Figure 2.19). The areas of brown to black soils form a honeycomb pattern on aerial photographs (Li Shu and Robertson, 1997 (405R)). The contact between brown and black soil can be seen in places, but it is mostly gradational (Figure 2.11F). Close examination shows that both are developed over the same alluvium unit. Clay mineral investigations by XRD and scanning electron microscopy confirm that, in brown soil, kaolinite is predominant; in black soil, smectite is significant and kaolinite minor. Some samples contained varying proportions of smectite and kaolinite and vary in colour brown to black. Small amounts of quartz, feldspars and mica are also present. Kaolinite-crystals are platy and small (0.2-0.6μm) whereas smectite crystals are thin, curled and large (2-10μm), (Figure 2.20A,B). In intermediate samples, containing both smectite and kaolinite, kaolinite appears to be transforming into smectite (Figure 2.20C,D). This suggests that black soils can be developed progressively from brown soils.

(c) *Flat plains*. The plains rise from about 90 m in the north to about 120 m in the south and their flatness is enhanced by predominant grassland (Figure 2.1). Local relief is due incision by streams. The plains are covered by cracking clay-rich soils developed in silts with a variable quartz grit content. Gilgai microrelief covers a large parts of the area. The silts and their derived soils are 2-3 m thick (Twidale, 1966).

2.6 Regolith evolution

Several regolith materials and landform features contain important clues to understanding the evolution of the Mt Isa region. These are discussed before a summary of landscape evolution is presented.

2.6.1 Duricrusts

Duricrusts are classified into two main types according to their major cementing agent, Fe or Si.

Lateritic duricrust

The pathways of evolution of lateritic duricrust in the Mt Isa region are summarised in Figure 2.21. The massive, fragmental and nodular duricrusts have formed *in situ* on weathered rocks by accumulation of ferruginous material from the mottled saprolite left by down-wasting of the profile as clays and soluble elements were removed. Mottles were developed by local-scale migration and accumulation of Fe, largely derived from the weathering of bedrock. In many places, mottle development is controlled by a sub-vertical foliation in the bedrock. Towards the top of the profile, mottles coalesce into an indurated homogeneous mass. In places, a partly consolidated, collapsed, mottled saprolite was developed. Where hard, it is referred to as *fragmental duricrust*. The fragmental fabric has developed from removal of the clay matrix-causing the saprolite to collapse. Further breakdown of fragmental and massive duricrusts has left nodules and pisoliths on the surface, to form a lag.

Nodular duricrusts appear to have developed by cementation of hematitic nodules and pisoliths in the soil and locally-derived colluvium (Figure 2.21). The nodules have a similar composition to the surrounding matrix and lack complex multiple cutans. This simplicity is interpreted to reflect a short weathering history and little to no transportation. Although not common, downslope mass movement (10-50 m) of these nodules has formed surficial packed pisolitic duricrust on lower slopes. Here, pisoliths are cemented by goethite introduced from upslope (Figure 2.21).

The Fe oxide mineralogy and field relationships suggest that *slabby duricrusts* formed on the lower slopes by induration of locally derived gritty colluvium and upper saprolite. Slabby duricrusts lack zircon and other heavy minerals, suggesting that they have not developed in alluvium, but in locally derived regolith. The Fe oxide mineralogy of the slabby, massive,

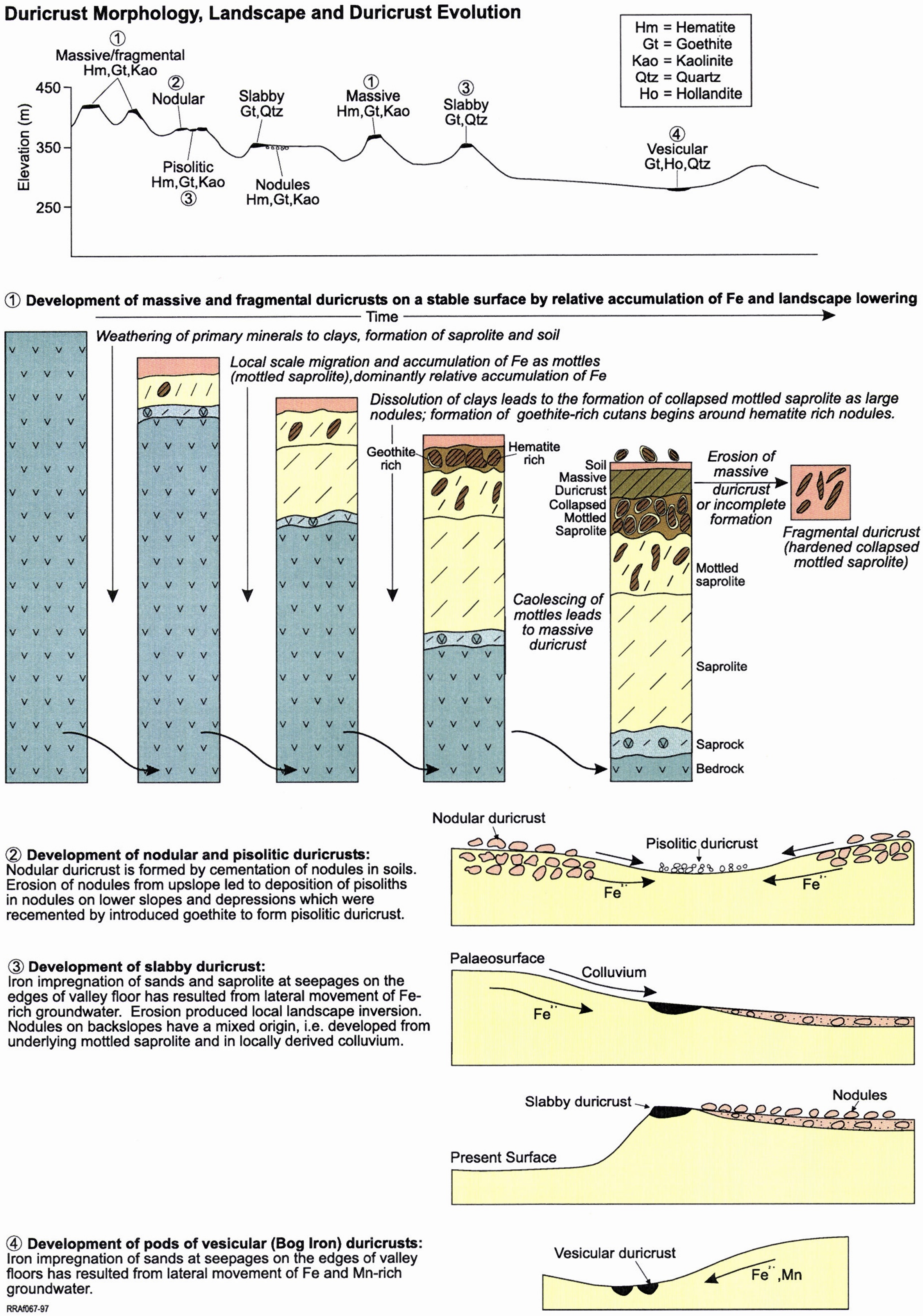

Figure 2.21. Pathways of evolution of duricrusts in the Mt Isa region.

fragmental and nodular duricrusts suggests that they have developed under different hydrological regimes. Free drainage and a high Fe precipitation temperature in the massive, fragmental and nodular duricrust yielded hematite; low precipitation temperature, moist conditions, and abundant organic matter produced goethite in the slabby duricrust. Iron in slabby duricrust is thought to be enriched by an absolute accumulation, derived from weathering of a local, upland area, lateral chemical transport and precipitation in a low landscape position. Subsequently, induration by ferruginisation allowed differential erosion and relief inversion to its current topographic position.

Goethite- and hollandite-rich *vesicular duricrust* is probably the youngest duricrust in the landscape. Iron and Mn in vesicular duricrust (equivalent to bog iron ore) is derived from the degradation of regolith upslope (Figure 2.21).

The *massive and slabby duricrusts*, which developed on Mesozoic sediments (claystone and sandstone), closely resemble those developed on Proterozoic rocks in that their Fe oxide mineralogy is similar to those on Proterozoic rocks. However, they are relatively enriched in Si, Zr and Ti. Duricrusts, in many places, have resulted from absolute accumulation of Fe because most contain more Fe than normally be obtainable from their Fe-poor parent rocks by relative accumulation.

Evidence for continued formation of ferruginous materials lies in development of mottles in recent sediments.

Silcrete

Silcretes have formed on a variety of bedrock lithologies but are most common on siliceous materials. The massive silcretes may be due to groundwater precipitation of silica. However, other structures within some silcretes, including columnar jointing patterns and candle-stick beading, could be indicative of a pedogenic origin. Jointing may reflect columnar peds in a palaeosol and candle-stick beading may relate to movement of solute particles down an old soil profile which has since been silicified. Alternatively the jointing may relate to shrinking and cracking of the silcrete during de-watering.

In places, silica has cemented alluvial sands or sheet wash sands and gravels. Silicification is probably associated with fluxes of silica-rich groundwaters while the sediments were low in the landscape. Silicified alluvial sands and gravels now occupy topographically high areas, because of relief inversion since induration. The inversion can be very subtle with only a few metres elevation difference between an older, silicified alluvium and a modern channel. In other places (*e.g.*, Grey Ghost area) the silicified sediments are some 40 m high above present drainage channels.

Silicification appears to be occurring at the present with siliceous hardpans developing within extensive, low-lying, colluvial plains. Both Fe and Si secondary cements are common within the same weathering profile. Either Si overprins ferruginous materials or the reverse, suggesting that conditions favourable for both silicification and ferruginisation have occurred recently.

Timing of the major silicification period is unknown. Silicification has affected a range of regolith materials over a very long time, possibly since the Palaeocene. Some authors assumed that silcretes indicate 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, quartz-micro-quartz columnar silcretes, associated with silicified, kaolinised profiles, occur on plateau remnants and were probably formed in acidic 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 derived mainly from the kaolinised profile and local toposequence 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 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 from Southern Africa. Titanium enrichment in the silcrete approached 120%. Titanium becomes increasingly soluble at pH <3.75, but aluminium solubility rises sharply below pH 4 and overtakes the solubility of silica in these situations. These conditions may imply impeded drainage, with silcrete formation taking place preferentially within watertable fluctuations.

2.6.2 Soils

Soils have formed on fresh and weathered Mesozoic and Cainozoic sediments and Proterozoic bedrock. Thin, gravelly soils have developed on older, pre-existing weathering profiles of the plateau erosion surface on Proterozoic and Mesozoic sediments. The red, brown and yellow earths are formed on the eroded slopes and plains in erosional terrain below the plateau remnants. They are developed on the underlying saprolite and saprock so exposed by erosion of the dissected slopes.

Lithosols or skeletal soils are associated with resistant rocks, areas of high relief and steeper slopes. Soils of the hill belts are characterised by abundance of pedogenic carbonates, resulting from weathering of underlying rocks in semi-arid climate.

In depositional plains, the soils vary from black through brown to grey sandy clay, sands or clays and generally contain polymictic gravels. Some are bedded and contain gravelly lenses, others are cemented by Fe and others by silica.

Field relationships suggest that black and brown soils are found side-by-side across the same sedimentary structure in a similar morphological setting. However, the nature of the soil developed is a function of its texture which, in turn, determines drainage conditions and the formation of clay minerals. Black soils develop in fine materials and in poor drainage; brown soils develop in coarse materials and well-drained environments.

It is suggested that, in the initial stages of soil formation, various brown, fine and coarse kaolinite-rich facies of alluvium were deposited on the plains. Where the alluvium was coarse, little water was retained and the alluvium remained brown and kaolinitic; where the alluvium was fine and water was retained, the kaolinitic soil matrix transformed into smectite. Thus, formation of black soil from brown soil is essentially a process of partial transformation of kaolinite to smectite. This transformation was supported by detailed SEM examination of clays. To convert kaolinite ($Al_4Si_4O_{10}(OH)_8$ to smectite ($(Ca,Na)_{0.7}(Al,Mg,Fe)_4(Si,Al)_8O_{20}(OH)_4nH_2O$), requires addition of Ca, Na, Mg, Fe and Si. Experimental transformation of kaolinite to smectite has been reported by Imasuen *et al.* (1989). The timing and climate under which this transformation has occurred are not known but it is more likely to have occurred after deposition of Tertiary sediments. According to Imasuen *et al.* (1989), extrapolation to typical soil temperatures of the tropics would indicate conversion times of one year at 100°C, 15 years at 45°C and 54 years at 25°C.

Grasses grow preferentially on black soil rather than brown soil because black soil is finer grained and retains water. Biological activity facilitates weathering and the black colour of the soil is probably related to an increase in biomass (carbon content). However, the amounts of organic carbon content in black soils were not measured but do not contain significant amounts (Dr Leigh Bettenay, written communication). Gilgai seem to have developed at least in part by differential expansion and contraction of smectitic black soils due to seasonal changes in moisture content, leading to churning action. Expansion of the soil pushes gravel up the profile; gravel rims to the depressions are common (Paton, 1974; Beckman *et al.*, 1981).

2.7 Summary of regolith-landscape history

The following model of landscape evolution of the Mt Isa region has been derived from observations and field, mineralogical and geochemical data produced by the P417 team and observation made by previous workers in the Mt Isa region (Twidale, 1956; Grimes, 1972, 1980; Senior *et al.,* 1978; and Smart *et al.*, 1980).

There has been a complex history of weathering, erosion and deposition during the Mesozoic and Cainozoic. Field relationships and dating of Mn oxides strongly suggest that evolution of the weathering profiles in the Mount Isa region spans the whole of the Tertiary, possibly extending into the Cretaceous. The $^{40}Ar/^{39}Ar$ results obtained for jarosite samples also indicate that weathering-related mineral precipitation continued until the Quaternary (see Section 3).

The concordance in Mn oxide ages from similar geomorphic provinces is encouraging, even where samples were from chemically different and spatially separated profiles. The ages of the Mt Isa Mines gossans (20.9 Ma) and gossans exposed at Lake Moondarra (19.5-20.7 Ma) indicate that Mn oxides exposed in the dissected part of the landscape were precipitated in the early Miocene (Vasconcelos, 1997 (452R); also see Section 3). At Kennedy Gap, Mn oxides from duricrust-capped mesas consistently yield ages ranging from 30-40 Ma. At Selwyn, Pegmont, and Tringadee weathering ages (12-13 Ma) represent the Cannington Region. Geomorphic provinces with more complete and stratified weathering profiles (Overhang, Selwyn, and Kennedy Gap) are older, the most dissected parts of the landscape yield the youngest weathering ages (Century deposit).

Late Jurassic-Early Cretaceous

Remnants of Mesozoic sediments indicate that marine incursion deposited sandstone, greywacke, shale, claystone, siltstone, limestone and conglomerate over a large part of the Mt Isa Inlier (Twidale, 1956). Fossils found in the Eloise area are early Cretaceous and are similar in age to those of the Gilbert River Formation (late Jurassic to early Cretaceous) to the west. At the close of this era, only highly resistant Proterozoic lithologies protruded through the Mesozoic. Irregular thicknesses of Mesozoic sediments and an undulating pre-Jurrasic unconformity on Proterozoic rocks are best explained by infilling of valley-and ridge-palaeo-topography. Thus, the late Jurassic-early Cretaceous landsurface was of broad river valleys with low hills and interfluves.

Prior to marine progradation, the landscape was erosional as indicated by a thin layer of conglomerates over the Proterozoic bedrock and by relatively slight weathering of the Proterozoic below the Mesozoic unconformity (where it has been unaffected by more recent weathering).

Late Cretaceous

As the sea retreated, the sea floor was exposed. Immediately after emergence, the area was relatively flat, with most of the Proterozoic hills having been bevelled by the marine transgression. Much of the relatively soft Mesozoic sediments had been eroded by the end of the Cretaceous, uncovering the basement rocks of the Mt Isa Inlier. Regional uplift of the Inlier and slight-down warping of the Carpentaria and Georgina basins were probably the driving forces behind regional erosion and aggradation (Twidale, 1956). Subsequent differential erosion left the Proterozoic basement rocks high in the landscape.

Late Cretaceous-Miocene

Weathering and differential erosion during the late Cretaceous and the Cainozoic has formed most of the present day landforms. The climate favoured weathering of Cambrian, Mesozoic and Proterozoic bedrocks, leaving lateritic profiles capped, in places, by ferruginous or siliceous duricrust. Some areas are more deeply weathered than others as in the Buckley River-Lady Loretta area, where the Mesozoic cover probably was never very thick and was removed shortly after uplift. This exposed the Proterozoic rocks to weathering throughout the Cainozoic. In places, remnant river channel and sheet wash deposits have been silicified and ferruginised.

The weathering geochronology implies that the Mount Isa region experienced very wet periods, when redistribution of elements within weathering profiles was facilitated by abundance of meteoric water. It appears that the late Cretaceous to early Palaeocene, the early to middle Oligocene and the early to middle Miocene were most conducive to redistribution of elements in the weathering profiles (Vasconcelos, 1997 (452R)). These wet periods may give some indications to the history of various ferruginous or siliceous duricrusts. For example, Mn oxides separated from a quartz vein in a weathering profile capped with residual, massive duricrust yielded ages between 32 and 37 Ma. Thus, it is possible that well developed hematitic massive, fragmental and nodular duricrusts on mesas were formed at least during the early Oligocene, if not earlier. Formation of goethitic slabby duricrust could be related to movement of Fe, possibly during the early to mid Miocene.

The timing of the major silicification is not clear. At Tick Hill, Mn oxide breccia is composed of silcrete replaced by Fe and Mn oxides indicating that Mn oxide precipitation post-dates silcrete formation. Manganese oxide ages give a minimum age of silcrete formation as16 to 19 Ma.

Pliocene-Quaternary
In the Pliocene, instability and erosion led to lowering of the watertable and hardening of duricrust, along with dissection of parts of the weathered mantle, resulting in an undulating landsurface with formation of mesas. Some areas (*e.g.*, Buckley river-Lady Loretta) were eroded less than others due to low relief and induration by Fe and Si. Elsewhere, erosion products were deposited as colluvial and alluvial sediments. Later, during the Pleistocene, the effects of seasonality and sufficient rainfall, coupled with long periods of stability, may have led to overprinting of Tertiary weathering features by Quaternary ones (Grimes, 1980), such as reworking of lag gravel to form pisolitic duricrust on lower slopes and transforming kaolinite to smectite in black soils in poorly drained areas. It may have been during this time that Fe was mobilised and transported laterally, cementing sands on valley sides or floors in seeps to form vesicular duricrust. Erosion since the Quaternary has continued shaping the topography. Some silcretes (silicified sands and gravels) and duricrusts (slabby) have produced resistant caps on the deep weathering profiles, resulting in local inversion of relief.

Silica precipitation appears to occur at the present time, forming hardpans within alluvial sediments. Smectite and calcrete are typically developed on partially weathered rocks on hill belts and erosional plains and are products of weathering under the present semi-arid climate.

2.8 Landsurfaces

Twidale (1956 and 1966) recognised three major erosion surfaces in the Leichhardt-Gilbert area of NW Queensland. These were: (i) a high plateau (pre-middle Mesozoic) of the Isa Highlands and the Cloncurry Plain, (ii) the undulating plateau of the Isa Highlands (Early to Middle Tertiary), and (iii) the Julia Plain and Wondoola Plain (Late Tertiary-Quaternary). His concept of erosion surfaces was followed by Grimes (1972, 1980a) who 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 resulted in a stable landsurface which was deeply weathered and ferruginised. The third cycle, which commenced towards the end of the Tertiary, is continuing.

Although there was a planation surface developed on a local scale, marked by lateritised Proterozoic and Mesozoic rocks, which is clearly visible on aerial photographs, the appropriateness of regional extrapolation and naming of such surfaces is open to doubt. In the Western Succession around the Buckley River-Lady Loretta area, the landscape is 'stepped' with two main surfaces (Wilford, 1997b (407R)). Whether these surfaces correlate with those proposed by Grimes is problematical, since erosional surfaces will have different ages on different parts of the surface. The higher of these stepped surfaces forms a palaeoplain in the Buckley River area and is bounded along its eastern edge by an erosional scarp. The surface consists of mesas, erosional plains and rises with typically highly weathered profiles capped with ferruginous or siliceous cappings. This surface was probably developed by the mid to late Mesozoic, and thus equivalent to the early Mesozoic Surface of Twidale (1956). Since then, relatively low erosional rates, due to the low relief, have preserved some of the most deeply weathered regolith over the Mt Isa region.

Bevelled Proterozoic bedrock hills and extensive Mesozoic plateaux around the Lady Loretta and Drifter prospects to the north may have also been part of this broad plain. However, irregular thicknesses of Mesozoic sediments and undulating contacts with the underlying Proterozoic and Cambrian rocks suggest that this surface was not flat but broadly undulating in a regional context (See Figure 2.13). In places, a lower, stepped surface, in the form of benches or plateaux are preserved below this higher surface. The regolith developed on this lower level is generally not as thick as that of the palaeoplain above.

2.9 Exhumed surfaces

In many places, the pre-Mesozoic landsurface or a derivation similar to it, has been exhumed. The term exhumation refers to a process relating to the exposure by denudation of a landsurface that has, in the past, been buried. The exposed pre-Mesozoic surface may be highly weathered, bleached and, in places, silicified. At a local scale, around the Drifter prospect, it would appear that erosion during the late Tertiary has exhumed the unconformity between the Proterozoic and Cambrian sediments (See Figure 2.13). The unconformity is delineated by either silcrete or silicified Proterozoic bedrock. In the Selwyn region, several stages of exhumation can be recognised, depending on the relative rates of erosion and the original thickness of the Mesozoic sediments (Wilford, 1997a (372R)).

Exhumation has probably developed by a combination of deep weathering and competency contrast between the siliceous layer and softer Cambrian and Mesozoic sediments which have now been largely removed. How closely the exhumed surface will reflect the original pre-Mesozoic topography will largely depend upon post-Mesozoic tectonism in the area.

3. MT ISA REGION : WEATHERING GEOCHRONOLOGY

3.1 Introduction

This section summarises the results of weathering geochronology to resolve specific regolith stratigraphy problems in the Mount Isa region. The principles and technical aspects of K-Ar and $^{40}Ar/^{39}Ar$ analyses, sample characterisation and the methods used are described by Vasconcelos, 1997 (452R). Below is a summary of weathering geochronology and focus on the implications of these results to landscape evolution, paleoclimatic history, and the dispersion of ore and trace elements in weathering profiles in the Mount Isa region. The geochronology results are also summarised in Table 3.1.

3.2 Mount Isa region

The Mount Isa region is partly blanketed by silcretes, lateritic duricrust, gossans, and other undifferentiated weathering profiles (Day *et al.*, 1983; Scott, 1987; Anand *et al.*, 1996). Abundant jarosite, alunite, K-phosphates, and Mn oxides occur in the gossans overlying Pb-Zn-Cu (Taylor and Scott, 1982; Scott, 1987) and Cu-Au deposits.

Table 3.1 Most probable ages of Mn oxides - Mt Isa region

Locality	Most Probable Age Ma	Geological Period
Mt Isa Mines	20.9	Early Miocene
Lake Moondarra prospect	19.5	Early Miocene
Mesa 1 outcrop (Kennedy Gap)	37	Early Oligocene
Gunpowder Creek Road (Kennedy Gap)	35	Early Oligocene
Century deposit	10	Late Miocene
Overhang deposit	65, 37	Late Cretaceous-Early Oligocene
Selwyn deposit	41	Late Eocene
Pegmont prospect	12	Late Miocene
Cowie prospect	12	Late Miocene
Tringadee prospect	12	Late Miocene
Tick Hill Region	16	Mid Miocene

Mount Isa and vicinity

The area immediately surrounding Mt Isa is characterised by a series of roughly N oriented flat-topped hills, surrounded by deeply dissected plains. Hill summit elevations range from 400 to 520 m. Base level in the surrounding valleys and plains ranges from 300-320 m. The highest summits in the area are generally lithologically controlled. Quartzites are generally the least weathered, least eroded material, comprising the majority of the hill tops. Volcanic rocks and calcareous or carbonaceous shales and siltstones generally underlie the more deeply dissected parts of the landscape.

The flat summits investigated during this study are devoid of complex, weathering profiles. The absence of weathering may be a function of lithology. However, careful examination of thin soil layers and soil material on rock ledges and in crevices in these summits reveals pisoliths and ferruginous lag, suggesting that even these summits may have been blanketed by a more complex and well developed weathering profile, now eroded. Despite extensive search from 1994-1997, no minerals suitable for weathering geochronology were found on the 400-520 m summits.

The valleys and small ridges on valley floors are more deeply weathered than the summits. The depth of weathering varies, depending on lithology, structure, landscape position and possibly an alteration. At the Mount Isa and Hilton Mines, the depth of weathering in the Urquart Shale is consistently greater than on adjacent unmineralised siltstones. The depth of complete oxidation lies at ~50 m below the current surface, although oxidation can be deeper along faults. Below the zone of complete oxidation, there is a transition zone, where moderate leaching of the bedrocks is identified by changes in colour and loss of certain elements. This zone of moderate leaching extends in places to 400 m below the present surface; again, this depth is often dependent on structural features.

Mount Isa Mines
Location: 342560E-7707000N
Elevation: 320-360 m
Geomorphologic Setting: Dissected terrain adjacent to 400-520 m mesas .

Manganese oxide coatings on ferruginous silicified outcrops (Mt. Isa gossan) were sampled for weathering geochronology. These Mn oxides occur as 1-5 cm thick crusts along bedding and fracture planes.

Four Mn oxide samples, dated by the K-Ar method, yielded the following results: 15.8 ± 3, 17.4 ± 4, 20.5 ± 2, and 17.1 ± 1 Ma. In addition, 15 Mn oxide grains from 6 hand specimens were analysed by the laser-heating $^{40}Ar/^{39}Ar$ dating method.

Six jarosite ($KFe_3(SO_4)_2(OH)_6$) samples were dated by the laser-heating $^{40}Ar/^{39}Ar$ method.

The Mn oxides yielded well defined $^{40}Ar/^{39}Ar$ plateau ages from 14.6 ± 0.1 to 21.5 ± 0.3 Ma, consistent with the K-Ar results, plotted on the ideogram below. Jarosite $^{40}Ar/^{39}Ar$ ages range from 0.5 to 3 Ma, with the exception of one sample which yielded 13 Ma date (Figure 3.1).

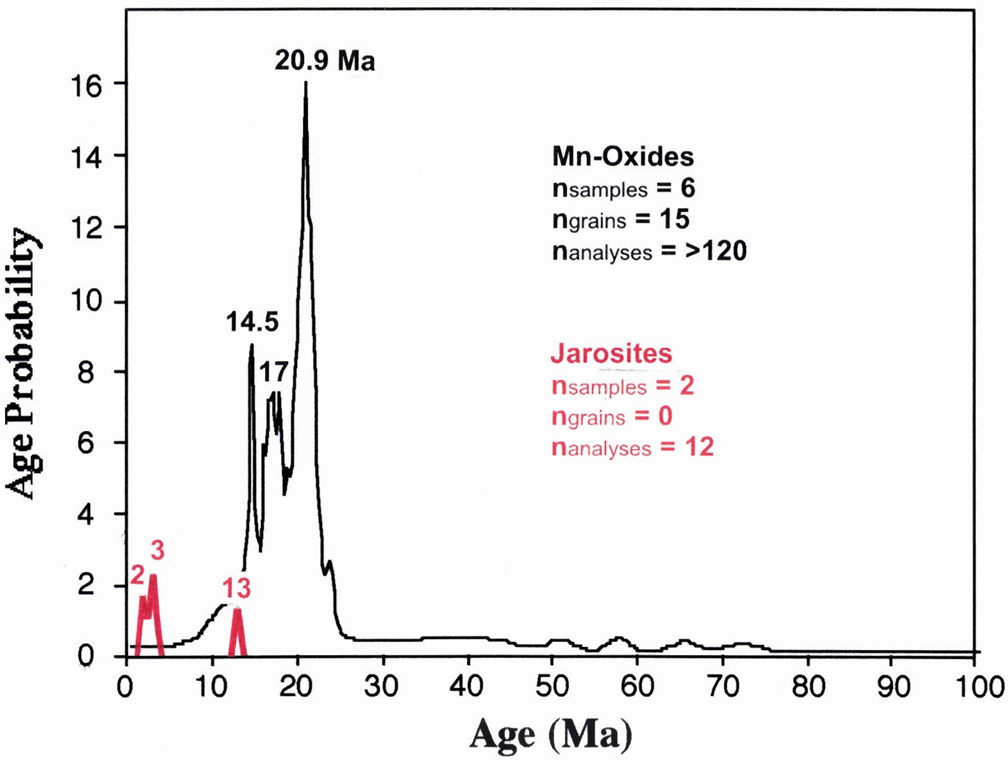

Figure 3.1 Ideogram for Mount Isa Mines samples.

Lake Moondarra Prospect
Location: 354500E-7723600N
Elevation: 320 m
Geomorphologic Setting: Dissected terrain proximal to 400-520m mesas.

In the Lake Moondarra area, oxidised fault breccias in the Spillway Fault host Mn oxides in a similar topographic/geomorphological setting to those of the Mount Isa gossan. Three Mn oxide grains, from one hand specimen, were analysed by the laser-heating $^{40}Ar/^{39}Ar$ method. The samples yielded well-defined plateau ages ranging from 19.0 ± 0.4 Ma to 20.7 ± 0.3 Ma. The samples yield two most probable age peaks, one at 19.5 Ma and the other at 20.7 Ma (Figure 3.2).

Seven grains from two distinct hand specimens yielded well defined plateaus ages ranging from 17.2 ± 0.2 to 24.0 ± 0.7 Ma. The ideogram below indicates that the most probable age for the samples is also 20.7 Ma.

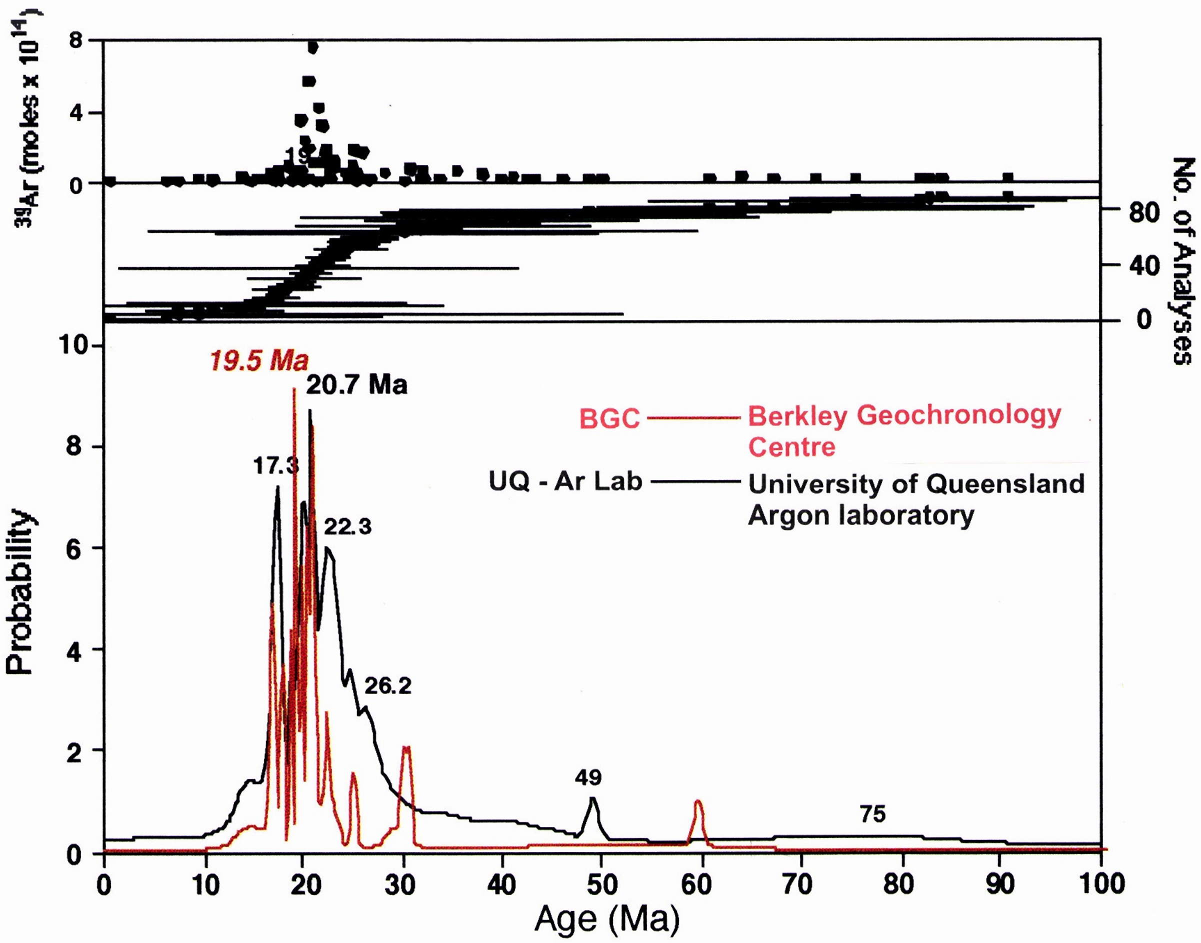

Figure 3.2 Ideogram for Lake Moondarra (n_{sample} = 2, n_{grains} = 10, n_{steps} = >120).

Western Succession
Mesa 1 Outcrop (Kennedy Gap)
Location: 324605E-7755409N
Elevation: 410 m
Geomorphologic Setting: Plateau remanent in dissected valley.

A small, isolated mesa, capped by ferruginous duricrust and a mottled zone, was studied in detail (Anand *et al.,* 1996, Transect 1, p. 44). At the southern end of the mesa, a section of the underlying saprolite is exposed in querry, small quartz veins can be traced to the mesa surface. These quartz veins were coated by small encrustations of Mn oxides which are intimately intergrown with quartz and silicates. However, some contained clean, pure, botryoidal Mn oxides also occur.

Twenty-five Mn oxide grains extracted from 8 samples of Mn oxide-bearing quartz veins were dated by the laser-heating $^{40}Ar/^{39}Ar$ method. Among the 25 grains analysed, only 15 yielded well-defined plateaux. The plateau ages obtained varied from 13.2 ± 0.9 to 38.7 ± 0.6 Ma. However, when all the steps (> 350 individual gas analyses) are plotted (Figure 3.3), the results suggest that, despite the scatter in the data, expected given the nature of the samples, two well-defined "most likely age peaks" occur at approximately 32 and 37 Ma. These results are significant when compared to the results obtained from another weathering profile in the same region (below).

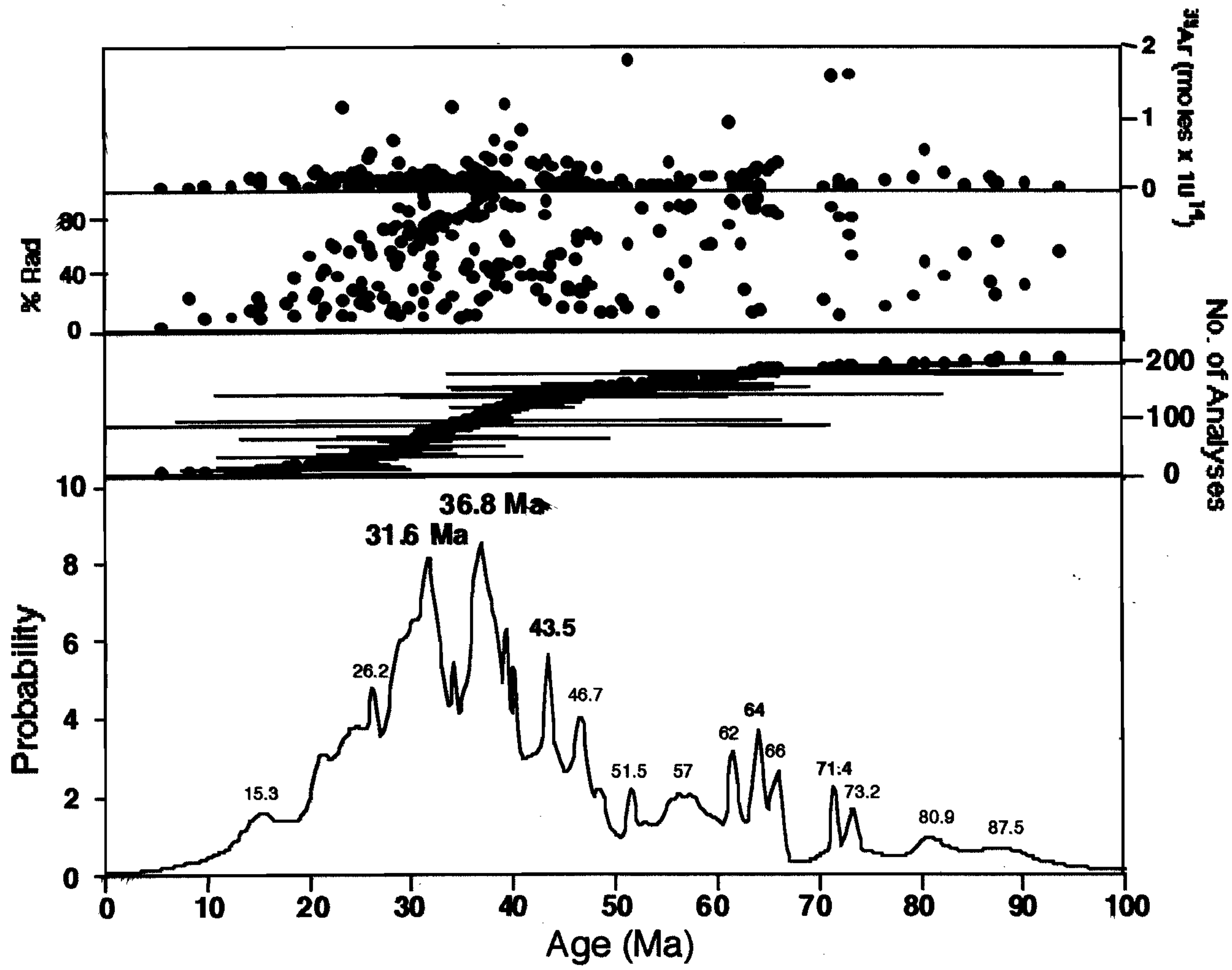

Figure 3.3 Ideogram for Mesa 1 outcrop (Kennedy Gap) (nsample = 8, ngrains = 25, nsteps = 350).

Gunpowder Creek Road Outcrop (Kennedy Gap)
Location: approximately 301550E-7783000N
Elevation: 420 m
Geomorphologic Setting: Dissected plateau on deeply weathered Proterozoic bedrock.

A large quartz vein outcrops at this location and hosts abundant well-crystallised Mn oxides. Three grains from 2 hand specimens were analysed by the laser-heating method and yielded well-defined plateaux (38.9 ± 0.8 Ma, 37.1 ± 0.2 Ma, and 35.9 ± 0.2 Ma).

Thirteen additional grains from 2 hand specimens also yielded well-defined plateau ages; however, they show a greater age spread (29.8 ± 0.3 Ma to 41.6 ± 0.6 Ma). When all the results are plotted, the best age estimate is 35 Ma, close to the 36.6 Ma age (Figure 3.4).

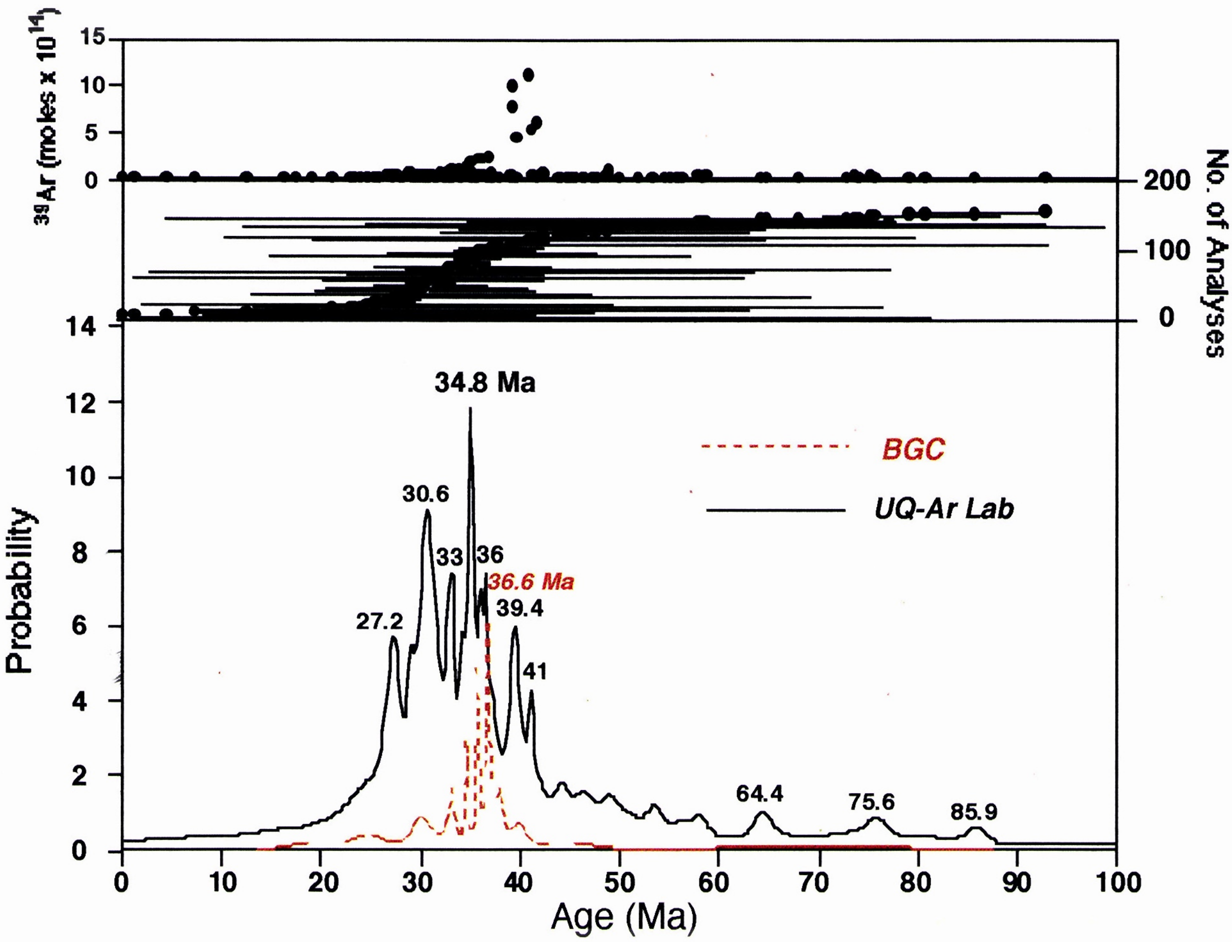

Figure 3.4 Ideogram for Gunpowder Creek (n_{sample} = 2, n_{grains} = 16, n_{steps} = >200).

Lawn Hill Region

Unlike the weathering profiles in the Mount Isa and Buckely River areas, weathering profiles in the Lawn Hill region are poorly developed. Even profiles overlying the sulphide-rich reactive mineral assemblage at Century lack extensive weathering. No supergene enrichments are present and the exposed mineralised lithology is saprock to saprolite. Despite absence of deep weathering, the area has several Fe/Mn oxide-rich outcrops formed by incipient weathering.

Century Deposit
Location: 138°36'E-18°43'S
Elevation (sampled outcrops): ~ 150-180 m
Geomorphologic Setting: Dissected hills on shallowly weathered Proterozoic bedrock and overlying Cambrian limestone.

Several Fe/Mn oxide outcrops occur in areas adjacent to the Century orebody, one within five to ten metres of the exposure of the Century host sequence. These Mn oxide occurrences are called "false gossans" because they are hosted by the basal Cambrian limestone which overlies the Proterozoic Century deposit.

Several samples were analysed by the K-Ar and $^{40}Ar/^{39}Ar$ methods to determine the timing of Mn oxide precipitation. The results (5.6 ± 1.5, 8.7 ± 0.7, 10.7 ± 2.9 and 11.5 ± 2.6 Ma) were the youngest Mn oxide weathering ages obtained for the Mount Isa Inlier. Seven grains from the same specimens yielded well-defined plateau ages from 5.6 ± 0.1 to 9.0 ± 0.3 Ma by the laser-heating $^{40}Ar/^{39}Ar$ method, consistent with the K-Ar results (Figure 3.5).

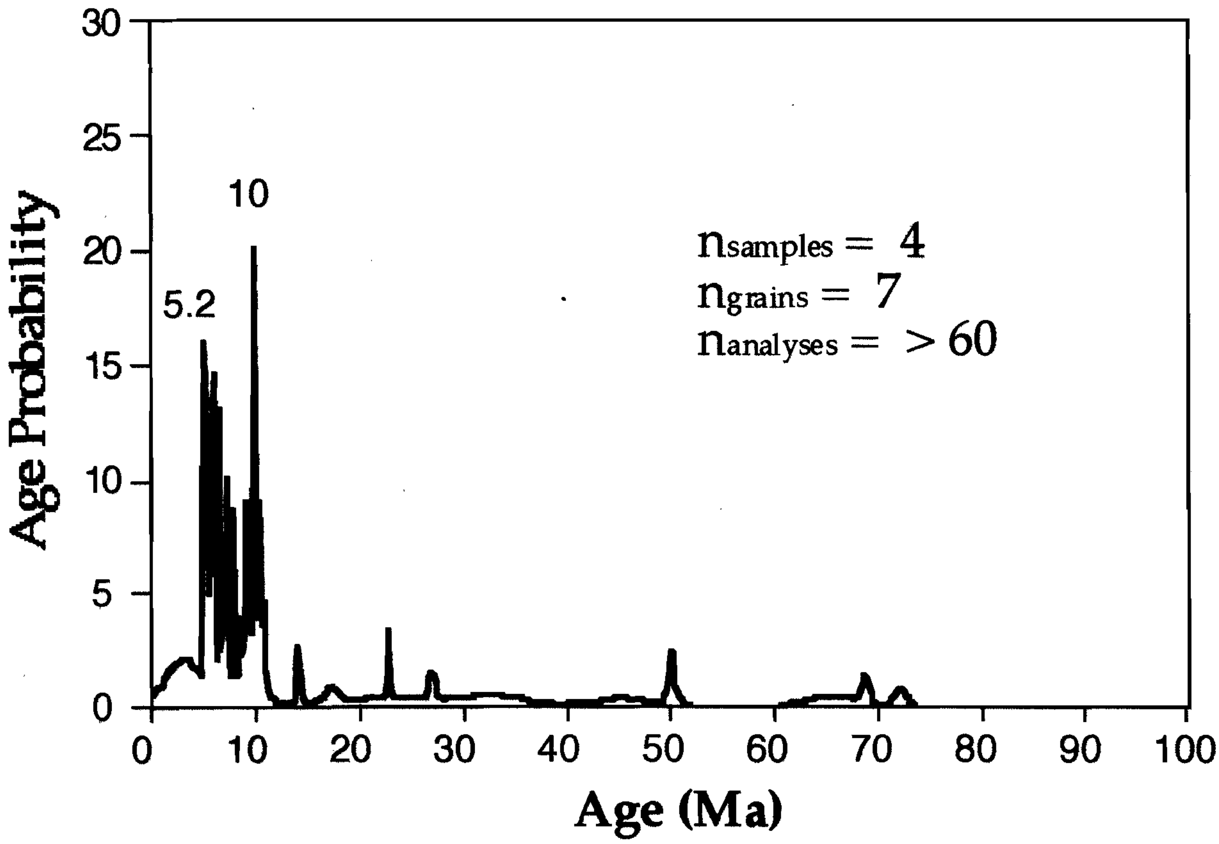

Figure 3.5 Ideogram for Century samples.

Eastern Succession

The landscape of the Eastern Succession, particularly between Cloncurry and Selwyn, is characterised by steep ridges and plateaux (400-500 m elevation) surrounded by deeply dissected valleys. These ridges and plateaux are generally associated with Proterozoic ironstones and banded-manganese metasediments. Given the nature of the parent material, some of the plateaux and ridges host deeply weathered, oxide-rich profiles, suitable for weathering geochronology.

Overhang Deposit
Location: 343650E-7679000N
Elevation (sampled outcrops): ~360-400 m
Geomorphologic Setting: Ridge on deeply weathered (60 m) and dissected Proterozoic bedrock.

A deeply weathered (>60 m) Proterozoic banded-manganese formation hosts the now abandoned Overhang mine. The host rock to the weathering profile is a rhodochrosite-bearing banded-manganese formation. Unweathered bedrock outcrops at the bottom of the valley (~300-320 m elevation) just SW of the Overhang mine. The weathered manganese formation forms a resistant oxide-rich ridge and hosts abundant hollandite, cryptomelane and pyrolusite ore.

Three hand specimens from the area were analysed by the K-Ar method and yield Cretaceous dates for the formation of the weathering profile (80 ± 6, 77 ± 1, and 82 ± 2 Ma). Three grains from the same samples were analysed by the $^{40}Ar/^{39}Ar$ laser step-heating method. The results confirm the presence of very old Mn oxides; but the dates (37 ± 2, 57.4 ± 1.4, and 64.7 ± 0.5 Ma) are significantly younger. The most likely explanation for the disparity is the presence of intergrown, unweathered muscovite crystals in some of the samples. The bulk nature of the K-Ar method does not permit the selection of sensibly pure grains, as is possible with the $^{40}Ar/^{39}Ar$ single grain method.

Selwyn Mine
Location: 447188E-7601545N
Elevation (sampled outcrops): ~340- 380 m
Geomorphologic Setting: Ridge on deeply weathered and dissected Proterozoic bedrock.

One surface sample (300-400 m elevation) of barren ironstone from the Selwyn Mine (SE159) was analysed by the $^{40}Ar/^{39}Ar$ method. No information on elevation or geomorphic setting is available, but an estimate from ARIMCO's topographic maps suggest that the sample came from approximately 340-380 m elevation.

Three Mn oxide grains from sample SE159 were analysed by the $^{40}Ar/^{39}Ar$ method. Two grains yielded well-defined plateaux at 41.1 ± 0.3 and 43.8 ± 1.2 Ma. The third grain analysed did not yield a plateau age (Figure 3.6).

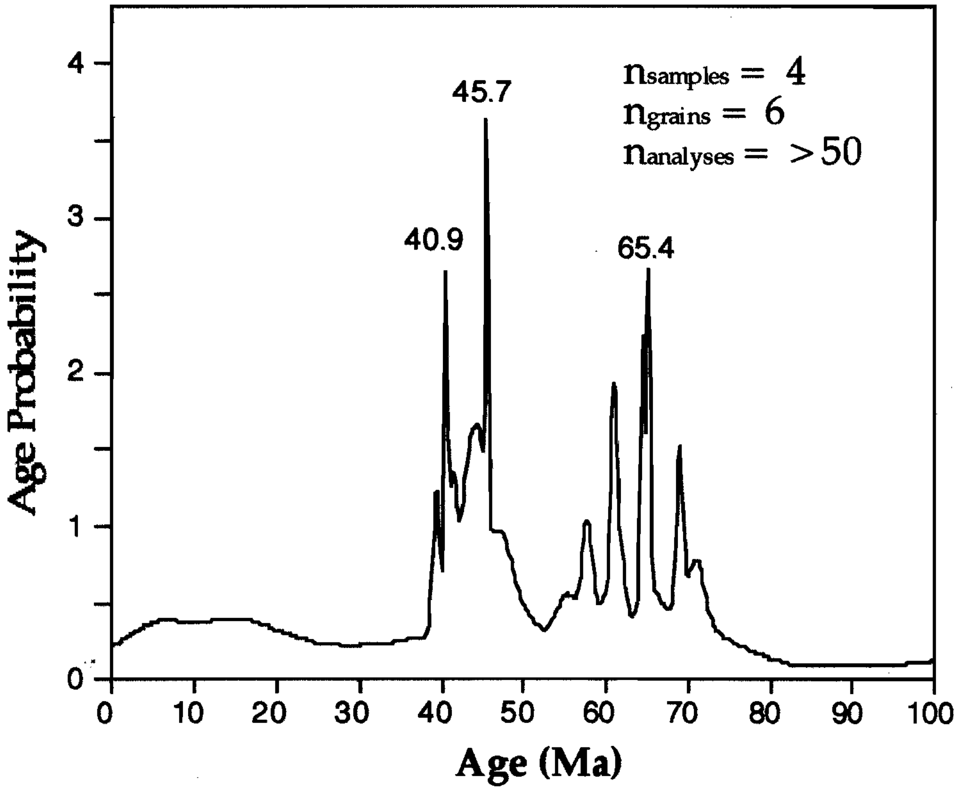

Figure 3.6 Ideogram for Selwyn and Overhang samples.

Cannington Area
South of the Selwyn Ranges, the landscape is more subdued, with small mesas and plateaux, 5-40 m above the surrounding landscape covered by deeply weathered Mesozoic sediments. The rocks in the plains have been deeply weathered.

Pegmont Prospect
Location: 467660E-7683300N
Elevation (sampled outcrops): ~300 m
Geomorphologic Setting: Not visited.

Two grains from a Mn oxide sample recovered at 2 m depth from the Pegmont prospect (Sample 11-0445) were dated by the $^{40}Ar/^{39}Ar$ method. The samples yielded well defined plateau ages from 13.0 ± 0.1 to 13.8 ± 0.1 Ma.

Cowie Prospect
Location: 486108E-7589140N
Elevation (sampled outcrops): ~250 m
Geomorphologic Setting: Not visited.

Three grains from a surface Mn oxide sample from the Cowie Prospect (Sample 11-0446) were dated by the $^{40}Ar/^{39}Ar$ method at the BGC. The samples yielded relatively well defined plateau ages ranging from 11.7 ± 0.3 to 12.7 ± 0.1 Ma.

Tringadee Prospect
Location: 486108E-7589140N
Elevation (sampled outcrops): ~250 m
Geomorphologic Setting: Deeply weathered plains surrounded by 5-20 m high Mesozoic sediment mesas (also deeply weathered).

Six grains from a surface Mn oxide sample from the Tringadee Prospect (Sample TG147) were dated by the $^{40}Ar/^{39}Ar$ method. The samples yielded relatively well defined plateau ages ranging from 12.6 ± 0.1 to 13.1 ± 0.2 Ma.

The Pegmont, Cowie, and Tringadee prospects are located in the same geomorphological province and were derived from similar weathering profiles. The remarkable concordance in the ages suggests a common weathering history. An ideogram for the Cannington area suggests that the best estimate for precipitation of Mn oxides in the weathering profiles is 12.7 Ma (Figure 3.7).

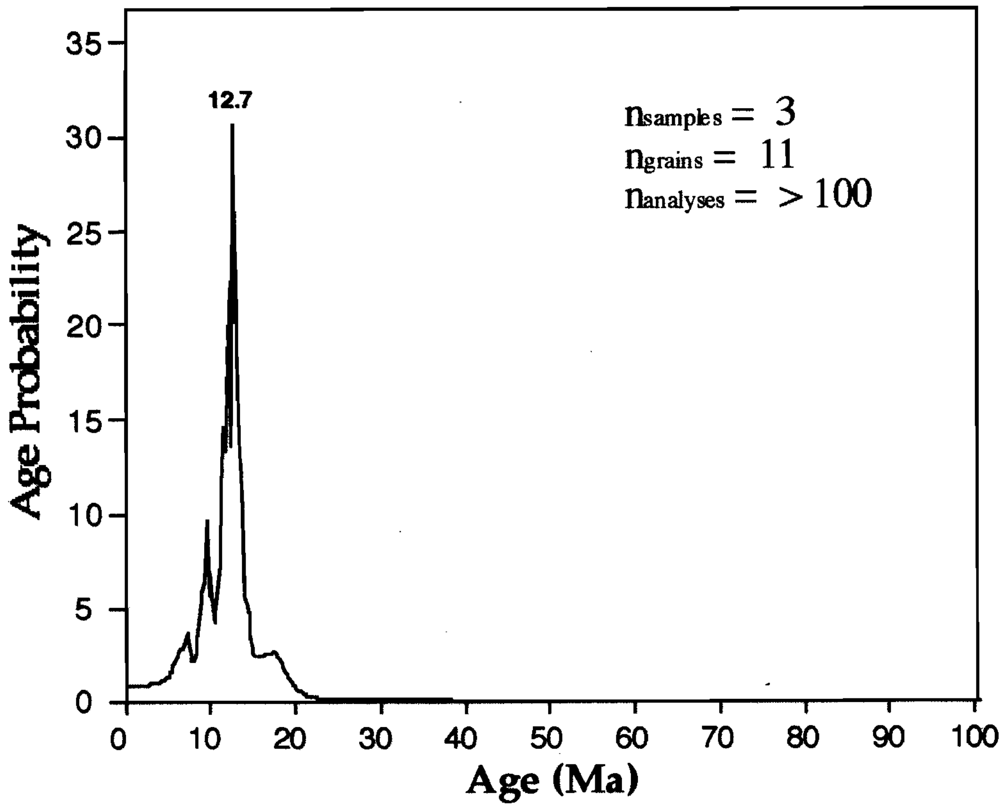

Figure 3.7 Ideogram for Cannington Area samples.

Tick Hill Region
Location: 392550E-7604920N
Elevation (sampled outcrops): ~340 m
Geomorphologic Setting: Manganesiferous "breccia" on silcrete-blanket low-lying surface.

The Tick Hill gold mine site is located adjacent to a 450-470 m elevation silcrete-capped mesa. Several other silcrete-capped mesas occur in the area. In addition, similar silcretes and some ferruginous duricrusts are also present on the low lying plains (320-340 m elevation) east of the Tick Hill deposit. The silcrete-capped mesas are separated from the silcretes and lateritic duricrust of the plain by the Pilgrim fault.

Along the Pilgrim fault, there are many occurrences of Mn oxide "breccias". Detailed petrography indicates that these Mn oxide breccias are silcrete replaced by Fe and Mn oxides and their Mn-oxide $^{40}Ar/^{39}Ar$ ages were used to determine the minimum age of silcrete formation. Seven pure cryptomelane grains from one hand specimen from the manganese "breccia" were dated by the $^{40}Ar/^{39}Ar$ and yielded relatively well-defined plateau ages from 16.3 ± 0.3 to 18.9 ± 0.5 Ma (Figure 3.8).

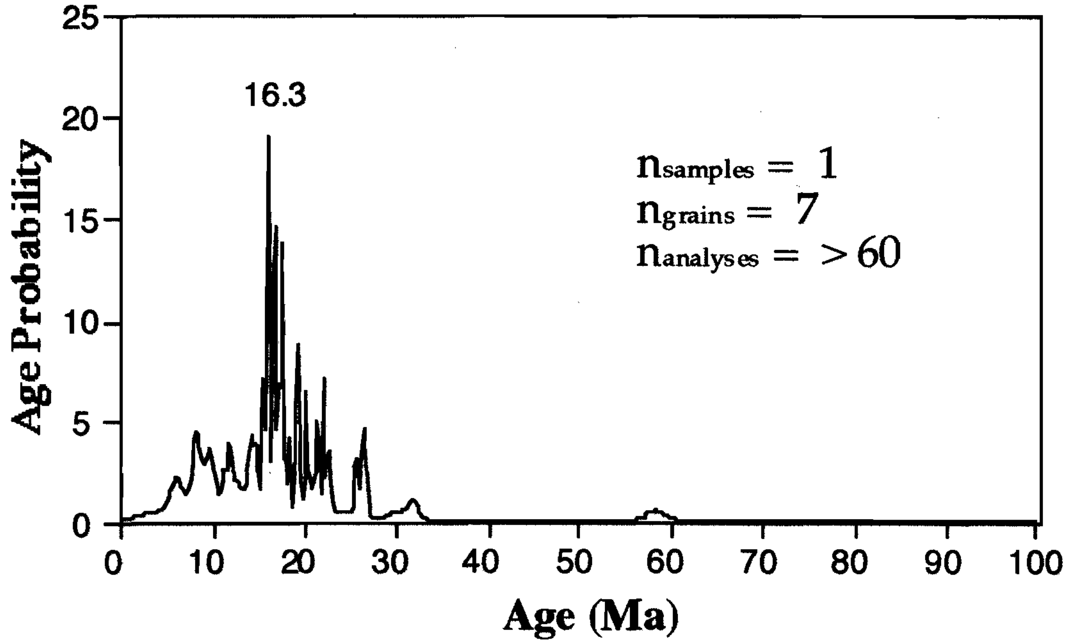

Figure 3.8 Ideogram for Tick Hill samples.

3.2.1 Interpretation of weathering geochronology of the Mount Isa region

This project is the most comprehensive weathering geochronology study ever undertaken in a single region. More than 103 $^{40}Ar/^{39}Ar$ laser step-heating and 11 K-Ar analyses provide a substantial geochronology database which permits answering some surficial geochemistry and landscape evolution questions for the region.

The Mn oxide results indicate that the evolution of weathering profiles in the Mount Isa Region spans the whole of the Tertiary, possibly extending back into the Cretaceous. The $^{40}Ar/^{39}Ar$ results obtained for the jarosite samples also indicate that weathering-related mineral precipitation continued until the Quaternary. However, these weathering reactions are driven by groundwater with little recrystallisation of Mn oxides at the surface.

A remarkable feature is the concordance in the ages from similar geomorphic provinces, even where samples were from chemically different and spatially separated profiles. The ages of the Mount Isa Mines gossans (14.5-21 Ma , with 20.9 Ma as the most probable) and gossans exposed at Lake Moondarra (17-24 Ma, with 19.5 or 20.7 Ma as the most probable) indicate that the Mn oxide minerals in the dissected part of the landscape were precipitated in the early Miocene. The results for the Kennedy Gap area are also very consistent. Manganese oxides from the Mesa 1 and the Gunpowder Creek Road site yield ages ranging from 30-40 Ma, with best estimates at 32, 35, and 37 Ma. Finally, samples from the Selwyn, Pegmont, and Tringadee prospects are concordant with the weathering ages (12-13 Ma) for the Cannington Region. Geomorphological provinces with more complete and stratified weathering profiles (Overhang, Selwyn, and Kennedy Gap) are older; the most dissected parts of the landscape yield the youngest weathering ages (Century).

The weathering geochronology implies that the Mount Isa region has seen some very wet periods, when dissolution, redistribution and reprecipitation of elements within weathering profiles was facilitated by an abundance of meteoric water. These periods were probably the late Cretaceous-early Palaeocene, the early to middle Oligocene, and the early to middle Miocene.

The geochronology is significant because it may be combined with mineral chemistry to suggest mechanisms, pathways and rates of element migration in the past that may, in turn, help explain patterns of surficial geochemical anomalies. A complete explanation of this is given by Vasconcelos (1997). Some important issues are summarised below.

- The Mn oxides overlying the Mount Isa deposit are rich in Pb, Zn, and Ba. In addition to cryptomelane (KMn_8O_{16}), coronadite ($PbMn_8O_{16}$), chalcophanite ($ZnMn_3O_7.3H_2O$), hollandite ($BaMn_8O_{16}$) and barite are present, suggesting large-scale migration of Pb, Zn and Ba in solution between 14-21 Ma.

- The Mn oxides of the Century profiles host coronadite, chalcophanite and plumbogummite ($PbAl_3(PO_4)_2OH_5.H_2O$). The high concentrations of Pb and Zn suggest that these elements were derived from a nearby source, and did not precipitate at the Cambrian-Proterozoic unconformity by long-range transport in the groundwater system. The most likely source for Mn, Zn, Pb, Ba and K in the Mn oxide outcrops is the weathering Century mineralisation.

- Since solubility and oxidation-reduction constraints would prevent large-scale migration of Pb, Zn and Mn in solution by oxidising surface waters, the precipitation of the Mn-rich "false gossans" at Century most likely occurred in a shallow subsurface environment. Lead, Zn and Mn, derived from weathering of the Century mineralisation, migrated in solution and were precipitated at the chemical barrier imposed by the basal Cambrian limestone. Erosion of 5-50 m of overburden in the past 5 Ma is implied.

- The Mn oxides (coronadite and chalcophanite) from Pegmont and Cowie are also significantly enriched in Pb and Zn, respectively indicating association with nearby Pb and Zn mineralisation.

- The Mn oxides at Tick Hill and Selwyn are different from those associated with Pb-Zn deposits in that they are enriched in Co and Zn (~0.5 wt%) with negligible Pb contents.

- Manganese oxides from the Tringadee prospect are devoid of Pb, contain only moderate Zn contents (~0.5 wt%), and are enriched in Co which is consistent with association with Cu-Au or Au mineralisation.

- Manganese oxides on the Pilgrim Fault in the Tick Hill area replace silcretes. Given the extreme cation-depleted (except for Si and Ti) nature of the silcretes it is unlikely that the cations in the Mn oxides (Mn, K, Ca, Ba, Na, Co) were precipitated from descending groundwaters. The most likely source of these oxides is mineralised groundwater ascending along the Pilgrim Fault. The geochemical anomalies associated with these manganese "breccias" may reflect leaching of elements from distal sources (100's to 1000's of m) and are unlikely to be from nearby or underlying mineralisation.

4. MT ISA REGION: REGOLITH MAPPING

4.1 Introduction

Geochemical dispersion of elements from mineralisation into the regolith, including Mesozoic and Tertiary sediments, can only be understood and modeled with knowledge of the regolith-landscape characteristics and regolith stratigraphy. The first step is to map the regolith-landform relationships and to develop a regolith model for the area. This section summarises results from regolith mapping research in the Mt Isa region. In particular, it presents the methods and data sets used in regolith mapping and the approaches adopted in preparing regolith-landform maps and geochemical sampling strategy maps. The Buckley River-Lady Loretta (407R), Selwyn (372R), Tringadee (429R), Eloise (405R) and Maronan (409R) districts proved to be excellent district scale studies for illustrating how regolith-landform relationships can be determined from interpretation of air-photographs, Landsat TM imagery and airborne gamma ray imagery. Maps produced are appended in a compact disc as Appendix III.

4.2 Regolith-landform units and mapping surrogacy

The approach to regolith-landform mapping is built upon previous work in the Yilgarn (*e.g.*, Anand *et al.*, 1993; Craig and Churchward, 1995) and Broken Hill (Gibson, 1996). The regolith-landform unit (RLU) is the basic mapping unit and consists of areas with similar landform and regolith characteristics that can be isolated at the scale of mapping. Due to the variability of regolith materials both spatially and compositionally, it is often difficult to map regolith directly or, more importantly, consistently across the map sheet. Thus, mapping units are defined mainly on the basis of landform types (*i.e.* floodplain, mesa *etc.*). Landforms can be used as a surrogate for mapping regolith because landforms and regolith are usually related both spatially and genetically. Relationships between landforms and regolith are then described within each RLU. Using landforms as surrogate provides an efficient and quick method for mapping regolith and allows extrapolation of fieldwork observations beyond the study area. Regolith-landform units, therefore, do not necessarily show uniform or pure regolith materials, but more typically associated and linked landform and regolith attributes. Purity of regolith shown on the map is largely scale dependent. Variation of regolith materials within a landform unit can be described using other mapping surrogates such as Landsat Thematic Mapper ™ and air borne gamma-ray spectrometery.

Regolith and landform types for each RLU are indicated on the maps by a series of codes. Each RLU has either a three or four-letter code. The capital letters describe the regolith type and lower case letters describe the landform type. For example, alluvial floodplain sediments deposited on a river floodplain would be expressed in the following manner;

Regolith type

Modifier

ACaf1

Landform type

The suffix 1 at the end of the RLU code is a modifier which allows the unit to be subdivided into one or more groups (*i.e.* suffix 1,2,3 *etc*). This is useful when showing subtle but nevertheless important differences within each RLU. For example, alluvial sediments might be carbonate-rich and elsewhere carbonate-poor. This difference is shown on the map using the suffix 1 and 2 (*i.e.* Acaf1 and Acaf2).

4.3 Datasets used to compile regolith maps

Regolith maps were compiled using field site observations, 1:25 000 colour aerial photographs, airborne gamma-ray imagery and Landsat Thematic Mapper imagery processed to enhance clay, Fe oxides and silica. Geological maps (1:100 000) were used for the major lithology and topographic maps supplied elevation, relief and drainage patterns. Polygons were initially drawn on the map from landforms interpretation from airphotos. These polygons were then sub-divided in places or modified based on the enhanced Landsat TM and airborne gamma-ray imagery.

Landsat TM imagery proved to be a highly effective regolith mapping tool due to the relative sparse vegetation cover and good exposure over the Mt Isa region. Landsat TM band combinations which were found to be useful in separating different regolith materials are;

7 + 1	for silica-rich materials (*e.g.*, siliceous bedrock, quartz gravel lags);
5/4	for ferric (Fe^{3+}) iron (*e.g.*, hematite, lateritic duricrust, ferruginous saprolite);
5/7	for argillic materials - clays and carbonates;
3/4	for saprolite versus vegetation;
4/2	for ferrous (Fe^{2+}) versus non-ferrous saprolite; and
3/1	for ferric (Fe^{3+}) iron (*e.g.*, goethitic saprolite and lateritic duricrusts).

These combinations can be displayed individually or in three as false-colour combinations. The most effective enhancement for discriminating a range of different regolith materials is the use of a technique called Directed Principal Component Analysis (DPCA) developed by Fraser and Green (1987) and ratio of bands. The DPCA is used to separate clays in the imagery by deriving principal components from ratios 4/3 and 5/7. Ratio of 4/3 enhances vegetation and ratio of 5/7 enhances a mixed response of vegetation and clay. The DPCA treatment of these ratios separates the vegetation from the clay response. The 'clay' data derived from the second principle component are then combined with ratio 5/4 and band 7 + band 1. Ratio 5/4 highlights ferruginous materials, and band 7 + band 1 highlights silica-rich materials. The final enhanced image is displayed as a three colour (RGB) composite with clay in red, Fe oxides in green and silica in blue. The processed imagery may be used to extend or further subdivide regolith units, particularly in areas of poor landform expression (see section on thematic maps).

Interpretation of the image is enhanced when combined with digital elevation models. Three-dimensional perspective views, which integrate Landsat TM imagery and digital elevation models, allow the TM response to be interpreted within a geomorphological framework (e.g., Figure 4.1). Combining regolith-landforms with images may provide useful information when interpreting surface geochemistry (*e.g.*, soil, rock chip and stream). For example, geochemical background concentrations can be interpreted in relation to type of regolith (ferruginous, siliceous, transported, residual), landform type (actively eroding, stable areas) and surface composition (clay, Fe oxides, silica) derived from processed Landsat images.

4.4 Map generation using Geographical Information Systems (GIS)

The digital regolith-landform maps consist of polygons, lines, point features and raster images. Polygons define each regolith-landform unit. Lines are associated with cultural, drainage and landform features, including palaeo-landform slopes, palaeo-drainage, erosional scarps and superimposed drainage. Points are associated with mineral occurrences, geochemistry and field site descriptions. Raster images include geo-rectified and processed imaged datasets

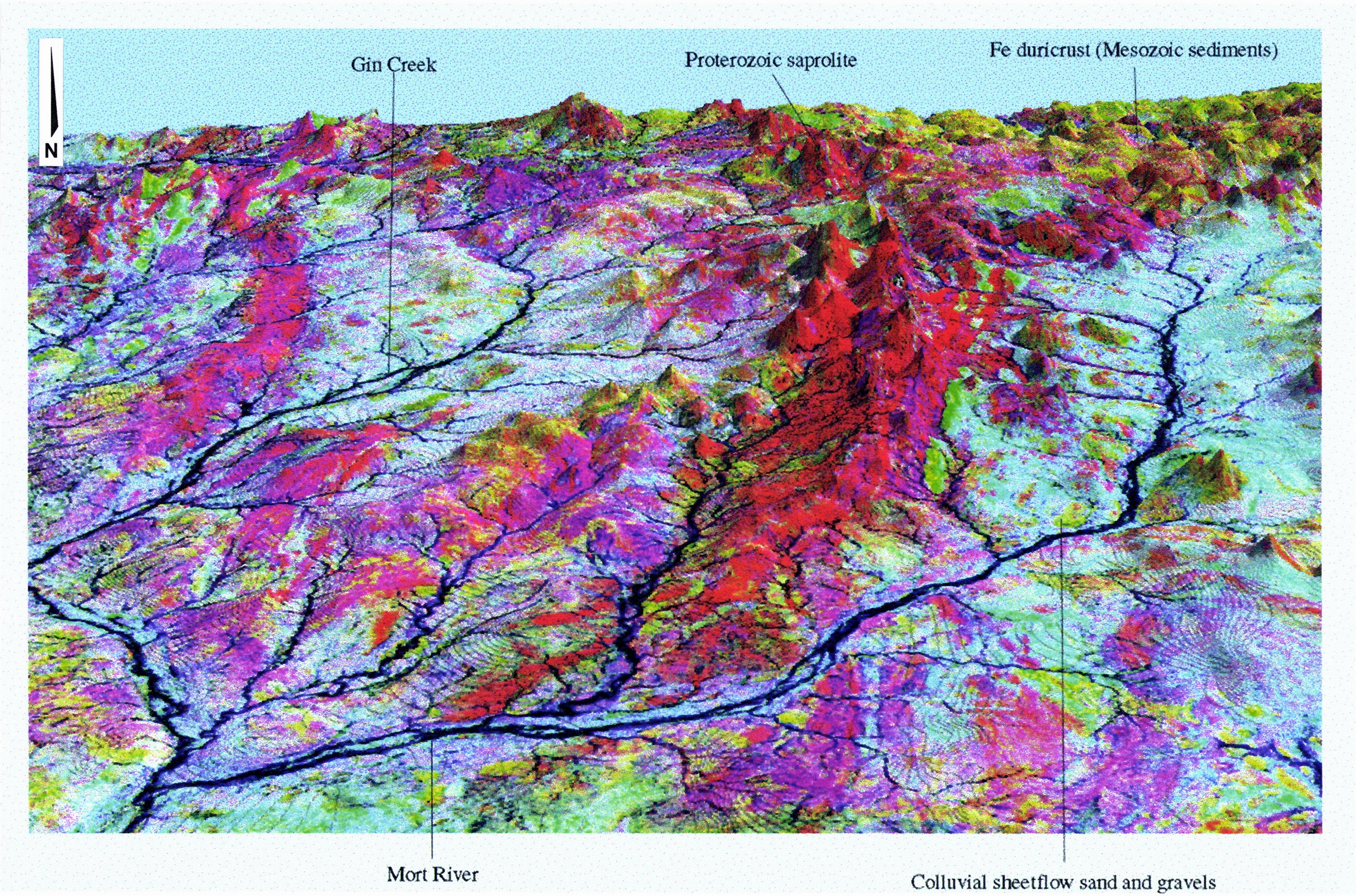

Figure 4.1 Three band TM image draped over a digital elevation model (looking northwards), Selwyn district. Surface spectral responses can now be interpreted with a geomorphological perspective (After Wilford, 1997a (372R)).

Red=clay; green=Fe oxides and blue=silica.

REGOLITH TYPES

Duricrust

Proterozoic bedrock

Ferruginous

DFls1	*Massive and in places slabby Fe duricrust or collapsed ferruginous saprolite over mottled and bleached saprolite. Lags of ferruginous lithic fragments, Fe duricrust gravels and pisoliths. Pods of Fe segregations in the mottled zone. Silicification of the saprolite is common and typically extends into the bleached zone beneath the mottled zone. Plateaux, mesas and local rises.*

Siliceous

DSls1	*Silcrete common as indurated pavements or pods. Silicified and ferruginised saprolite overlying mottled and bleached saprolite. Ferruginous saprolite partly covered by lithosols and gravel lags. Mesas, minor rises and bevelled hill tops.*
DSls2	*Silicified Proterozoic saprolite which is in places overlain by silicified Mesozoic sediments. Massive and columnar silcrete, silicified saprolite. In places silcrete contains quartz gravels and pebbles. Silcrete typically stained and mottled with iron. Plateaux, mesas and buttes.*
DSer3	*Fe stained silcrete and silicified saprolite forming massive pavements. Lags and lithosols consist of silcrete pods, silicified saprolite gravels, ferruginous saprolite and minor ferruginous granules. Silcrete overlies mottled and bleached saprolite at depth. Rises (9-30 m relief).*

Post-Proterozoic bedrock

Ferruginous

DFls3	*Massive Fe duricrust and highly ferruginous saprolite over mottled (irregular to mega sub-circular) and in places bleached bedrock. Saprolite partly silicified. In places silcreted caps rather than Fe duricrusts have developed. Pods of Fe segregations in the mottled zone in places extends into Proterozoic saprolite which is typically mottled, bleached and in places silicified. Duricrust partly covered by Fe duricrust fragments and ferruginous saprolite gravel lags. Plateaux, mesas and minor erosional plains.*

Siliceous

DSls5	*Silcrete, silicified saprolite and Fe-stained sediments over kaolinised and ferruginous Proterozoic bedrock. Silcrete pods and columnar jointing common. Silicification typically extends into the underlying saprolite. In places Fe duricrust rather than silcrete have developed. Plateaux, mesas and buttes.*
DSer6	*Patchy veneer of silicified Mesozoic sediments over silicified Proterozoic saprolite. Saprolite partly covered by gravel lags of ferruginous lithic, silcrete, quartz pebbles and silicified saprolite gravels. Veneers of sheet wash sand, minor clays and Fe pisoliths. Fe stained silcrete common, forming massive micro-crystalline pavements. Narrow tracts of alluvium. Underlying Proterozoic saprolite typically intensely mottled and bleached. Rises (9-30m relief), minor erosional plains (<9m relief).*

Saprolite

Proterozoic bedrock

Sep2	*Ferruginous and in places silicified Proterozoic sediments. Saprolite partly covered by a veneer of sheet wash gravels, residual gravelly earths, lithosols and lags. Lags of lithic fragments, quartz, Fe duricrust fragments, ferruginous saprolite and minor Fe pisoliths. Erosional plains (< 9m relief).*
Sei4	*Mottled and bleached mainly Proterozoic sediments. Saprolite is in places silicified and largely covered by a veneer of sheet wash gravels, lithosols and lags. Lags and sheet wash consist of mainly bleached lithic fragments together with quartz, Fe duricrust fragments, ferruginous saprolite and minor Fe pisoliths. Rises (9-30m relief) minor pediments.*
Ser5	*Highly ferruginous saprolite with pockets of Fe duricrust and collapsed lateritic gravels over mottled saprolite. Saprolit partly covered lithosols and gravel lags consisting of Fe duricrust fragments, ferruginous saprolite, Fe nodules and pisoliths. Rises (9-30m relief).*
Ser6	*Ferruginous, silicified and mottled saprolite largely covered by lithosols, gravel lags, residual sands and clays. In places bleached saprolite exposed. Silcrete pavements and pods common. Lags and lithosols consist of ferruginous lithic gravels, silcrete pods and gravels, silicified saprolite and Fe duricrust gravels. Rises and erosional plains*
Ser7	*Bleached and ferruginous saprolite. In places silicified saprolite. Saprolite partly covered by lithosols, shallow earths and gravel lags. Local scree and colluvial gravels flanking steeper slopes. Bedrock structure and fabric generally poorly preserved. Local pockets of deep weathering and Fe duricrust typically on argillaceous lithologies. Lags of lithic, ferruginous saprolite, bleached saprolite, Fe duricrusts fragments and minor Fe pisoliths. Minor alluvial gravels and sand. Rises (9-30m relief).*
Ser8	*Ferruginous, mottled and bleached mainly Proterozoic sediments. Saprolite is in places silicified and largely covered by a veneer of sheet wash gravels, residual gravelly earths, lithosols and lags. Lags of lithic fragments, quartz, Fe duricrust fragments, ferruginous saprolite and minor Fe pisoliths. Saprock exposed on steeper slopes. Minor Fe or silicified duricrusts. Rises (9-30m relief) and local mesas.*
Sbh9	*Ferruginised saprolite overlying mottled and bleached saprolite. In places silicified saprolite and minor silcrete. Saprolite partly covered by lithosols and gravel lags. Bevelled hill tops minor mesas.*
Sel10	*Ferruginous and mottled saprolite, in places silicified. On steeper slopes saprock partly covered by lithosols, shallow earths and gravel lags. Local scree and colluvium flanking hills. Local pockets of deep weathering and Fe duricrust typically on argillaceous lithologies. Lags of lithic, ferruginous saprolite, Fe duricrusts fragments and minor Fe pisoliths. Narrow corridors of alluvial sands and gravels. Low hills (30-90m relief) and local mesas*
See11	*Saprolite (mainly Proterozoic) partly covered by scree and lithosols. Weathering variable including; ferruginous, bleached and silicified saprolite and minor saprock. Escarpment.*

Alluvial sediments

Aaf	*Alluvial channel, overbank and terrace sediments consisting of various proportions of clay, sand, gravel and minor cobbles. In places partly cemented by clay, Fe or Si. Overbank and terrace sediments are typically finer textured consisting mainly of clay and sand. Soils consist of reddish orange, brown and grey earths and duplex soils. Minor pebble silcrete. Flood plains, alluvial terraces and channel floors.*
Aap	*Alluvial and lacustrine clays and silts. Massive cracking olive green, grey-brown smectitic clay soils over mottled saprolite. Forms treeless plains with gilgai micro-relief. Clays generally thin (< 2 m) with islands of residual clays and gravel lags. Pedogenic calcrete and 'heaved' saprolite fragments as scattered float. Alluvial plains and lacustrine plains.*
ACer1	*Silicified alluvial and colluvial sands and gravels forming silcrete. Minor quartz pebbles (generally 1-4cm). Silcrete pods and silicified sandstones fragments as float. Underlying saprolite typically bleached and silicified. Silcrete commonly diffusely stained and mottled with Fe. Rises (9-30m relief), erosional plains (<9m relief) and local mesas.*

Colluvial sediments

CHpd1	*Colluvial sheet flow deposits. Sediments typically > 1.5 metres thick include silty clay loam, clay, sand, gravels and minor Fe pisoliths. Sediments overlie mottled and typically silicified saprolite. Local cracking clay soils. Extensive lags of ferruginous and siliceous saprolite, lithic fragments, ferruginous granules, quartz and silcrete gravels with minor Fe duricrust and pisoliths. Siliceous hardpan common at about 60cm depth. Minor alluvium and residual soils. Depositional plains minor erosional plains (<9m relief).*
CHpd2	*Colluvial sheet flow, residual and minor alluvial deposits consisting of variable proportions of sand, clay and gravel (generally < 2 m thick). Ferruginous sand and gravels overlie mottled and bleached saprolite. Soils consist of lithosols and gravelly earths. Extensive lags of Fe duricrust fragments, lithic fragments, quartz and ferruginous saprolite gravels. Minor alluvial sand and gravel. Depositional and erosional plains (<9m relief).*
CFfc1	*Colluvial footslopes consisting of quartz, ferruginous saprolite, Fe duricrust and lithic fragments in a coarse poorly sorted sandy to gravelly earthy matrix. Footslopes.*

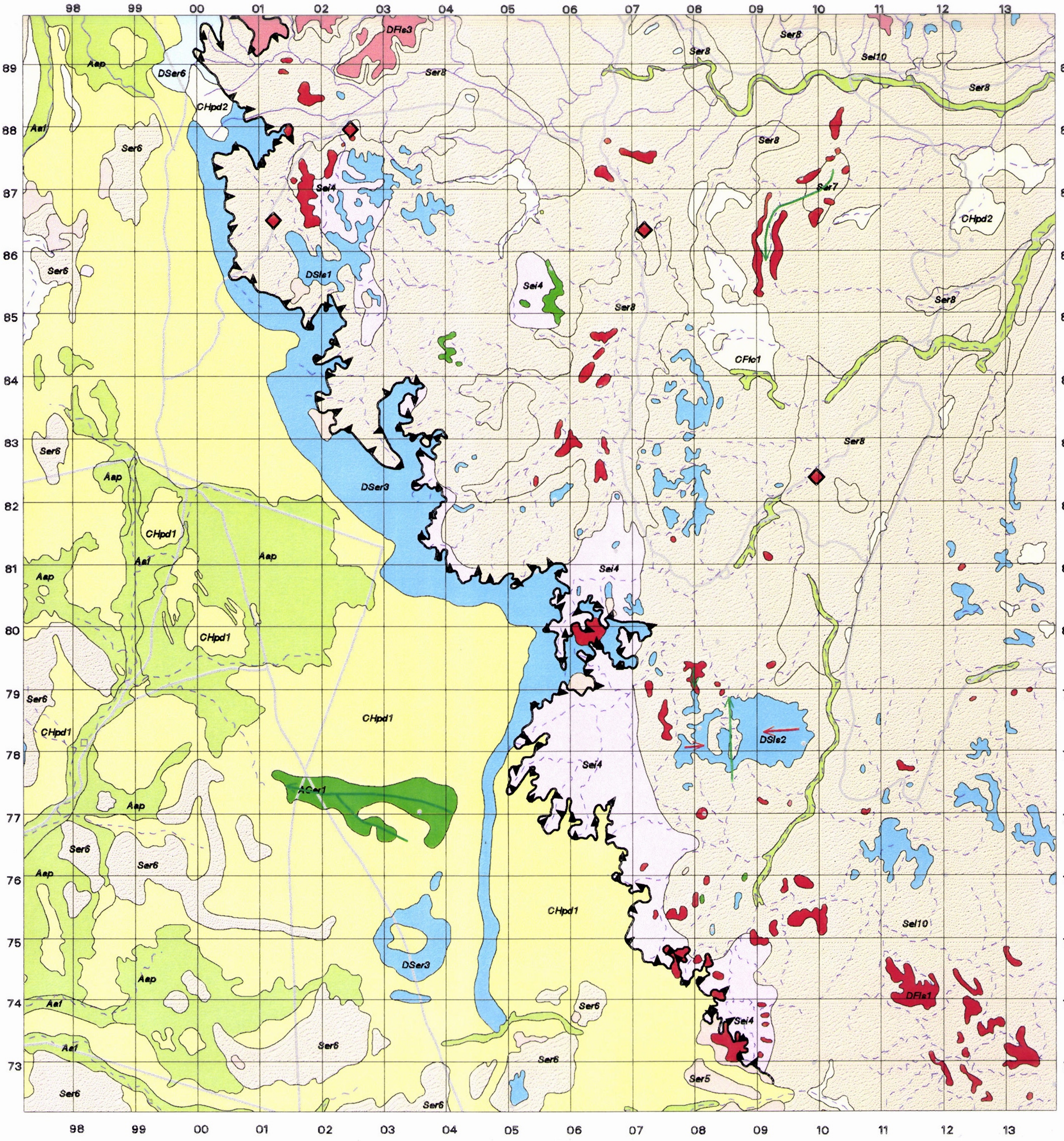

Figure 4.2. A portion of the Buckley River-Lady Loretta regolith-landform map. This map is descriptive based, legend is shown opposite. Black saw-tooth lines (black triangles point downslope) are major erosional scarps, red arrows palaeo dip slopes and green arrows palaeodrainage channels. Red diamonds are known Cu deposits (After Wilford 1997b (407R)).

(*e.g.*, Landsat TM images, DEM and scanned photographs). These raster datasets are stored in band inter-leaved (BIL) format.

When the capture of this digital information and the database (INFO) which stores attributes with the spatial features is complete, the GIS (ArcInfo) can be used to generate not only regolith maps but also a variety of different thematic or integrated hardcopy maps (see section on thematic maps). Thematic maps highlight a particular theme or attribute from the database and are generalised for specific purposes. A theme might, for example, be the depth of weathering or it might be an expression of an interpretative model such as the Relict, Erosion and Depositional (RED) scheme. A well-structured and organized database, which separates descriptive information from classified or interpreted fields, is essential to generate different map themes effectively and integrate regolith data layers with other datasets.

4.5 Thematic and integrated regolith maps over the Mt Isa region

A series of thematic maps has been generated over study areas in the Mt Isa region to show the inter-relationships between regolith attributes and other datasets and to simplify and customize regolith maps specifically for geochemical exploration. These thematic maps are described by Wilford (1997a, (372R); 1997b (407R)) and include;

1. descriptive based regolith-landform map,
2. highly weathered regolith units superimposed over Landsat TM band 5,
3. regolith-landform units superimposed over enhanced Landsat TM imagery and
4. interpretative geochemical sampling strategy map.

Examples of three of these maps from the Buckley River-Lady Loretta study area are shown in Figures 4.2 to 4.4. The regolith unit boundaries from each of the four maps are the same. The differences between the maps reflect the selection of particular polygon attributes and images from the GIS database.

The first map describes the major regolith-landform types (Figure 4.2). The units on the map are, as far as possible, factual or descriptive with little or no genetic bias. Regolith-landform units are described by their observed physical and chemical properties without implying interpretative models which might explain their origin. Regolith materials are divided into four major categories, namely:

1 - duricrust,
2 - saprolite,
3 - alluvial sediments and,
4 - colluvial sediments

Duricrusts are further divided into ferruginous and siliceous materials. They are typically associated with some of the most highly weathered parts of the landscape and are important in understanding the regolith-landscape history. In addition, lateritic duricrusts are important geochemical sampling media.

Saprolite includes weathered rock that retains much of the fabric and structure of the parent bedrock. Regolith-landforms in this category may be partly covered by lag or soil but the major feature is the occurrence of saprolite at or near the surface. Bedrock materials exhibit variable degrees of weathering from mottled, bleached and ferruginous saprolite to saprock.

Duricrust and saprolite units are divided into whether the original bedrock is Proterozoic or post-Proterozoic in age. This subdivision is critical in the Mt Isa region where the mineralisation is confined to Proterozoic bedrocks.

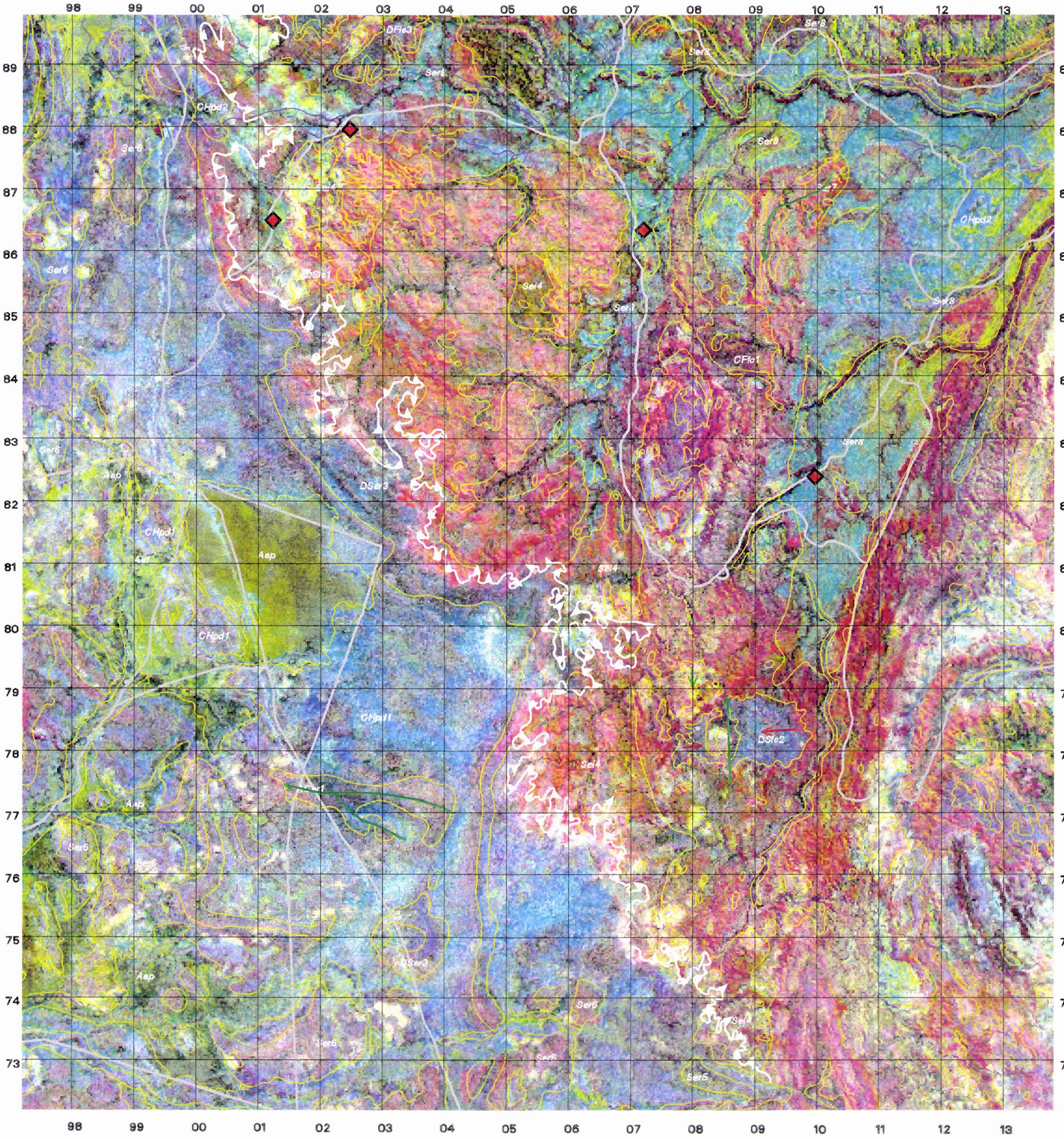

Figure 4.3. Three band Landsat TM image of second principal component of 4/3 and 5/7 in red, ratio 5/4 in green and the addition of bands 7 + 1 in blue over part of the Buckley River-Lady Loretta. Regolith-landform polygons shown in yellow, palaeo-slopes in red lines and palaeo-channels in green lines and erosional scarps in white. Blue hues corresponds to sheetwash colluvium and silcrete, reds to saprolite, yellows to ferruginous lags and Fe duricrust. For comparison with regolith units see Figure 4.2 and 4.3 (After Wilford, 1997b (407R)).

REGOLITH/GEOCHEMICAL SAMPLING GUIDE

Duricrust

Proterozoic bedrock

Ferruginous

Indurated materials cemented mainly by Fe oxides, including massive duricrust, slabby duricrust and highly ferruginous saprolite. Duricrust, nodules, pisoliths and ferruginous saprolite can be used for geochemical sampling in detecting underlying mineralisation. Massive Fe duricrusts are likely to be developed in-situ whereas slabby Fe duricrusts have developed from vertical and lateral movement of iron oxides. Broad spaced sampling recommended for Fe nodules and pisoliths.

Siliceous

Indurated materials cemented by mainly silica, including silcrete, Fe oxide stained silicified/bleached saprolite, mottled silicified saprolite and minor Fe duricrusts, silicified/bleached saprolite. Mottling developed within the silcrete and ferruginous lags can be used as a broad geochemical sampling media, otherwise drilling recommended.

Post-Proterozoic bedrock

Ferruginous

Indurated materials cemented mainly by Fe oxides, including massive, slabby and nodular duricrust and ferruginous saprolite. Sampling ferruginous materials (duricrust, nodules, pisoliths and ferruginous saprolite) may be useful as broad geochemical indicators due to possible hydromorphic dispersion or reworking of mineralised bedrock into the sediments otherwise drilling recommended.

Siliceous

Indurated materials cemented mainly by silica, including Fe oxide stained silicified saprolite, silcrete and mottled silcrete. Mottling developed within the silcrete might be used as a broad geochemical sampling media due to possible hydromorphic dispersion or reworking of mineralised bedrock into the sediments otherwise drilling recommended.

Saprolite and skeletal soils

Proterozoic bedrock

Highly ferruginous saprolite, minor pockets of Fe duricrust. Duricrust, nodules, pisoliths and ferruginous saprolite can be used for geochemical sampling in detecting underlying mineralisation. Fe duricrust and ferruginous saprolite developed in-situ. Close spaced sampling recommended for ferruginous saprolite.

Ferruginous saprolite and saprock partly covered by lithosols. Surface rock chip and soil sampling, good exposure. Close spaced sampling recommended for soils.

Saprolite covered by extensive lags and thin residual soils

Soils or ferruginous lags (fragments of ferruginous saprolite, minor nodules and pisoliths) may be used for geochemical sampling. Cover is thin (typically < 1 metre) and consists of residual soils and locally derived sheet wash sediments over ferruginous and mottled saprolite. Close spaced sampling recommended.

Alluvium

Alluvial and lacustrine sediments of varying thickness. Stratigraphic drilling required to determine underlying regolith substrate. Suitable for stream sediment sampling - may give broad catchment geochemical indicators. Heaved saprolite fragments in swelling clay soils may provide an indication of the substrate below.

Silicified alluvium and colluvium, unlikely to relate to the present day drainages. May give broad palaeo-catchment geochemical indicators.

Colluvium

Extensive colluvial, residual and minor alluvial sediments. Most materials locally derived, colluvium generally < 2 metres. Ferruginous lags may be used as regional geochemical sampling media, otherwise shallow RAB recommended.

Extensive colluvial and minor alluvial sediments. Cover over several meters deep in places, may or may not be locally derived. Sediments largely derived from Proterozoic bedrock. Ferruginous materials (fragments of ferruginous saprolite, nodules and pisoliths) may be useful in reconnaissance exploration, otherwise RAB recommended.

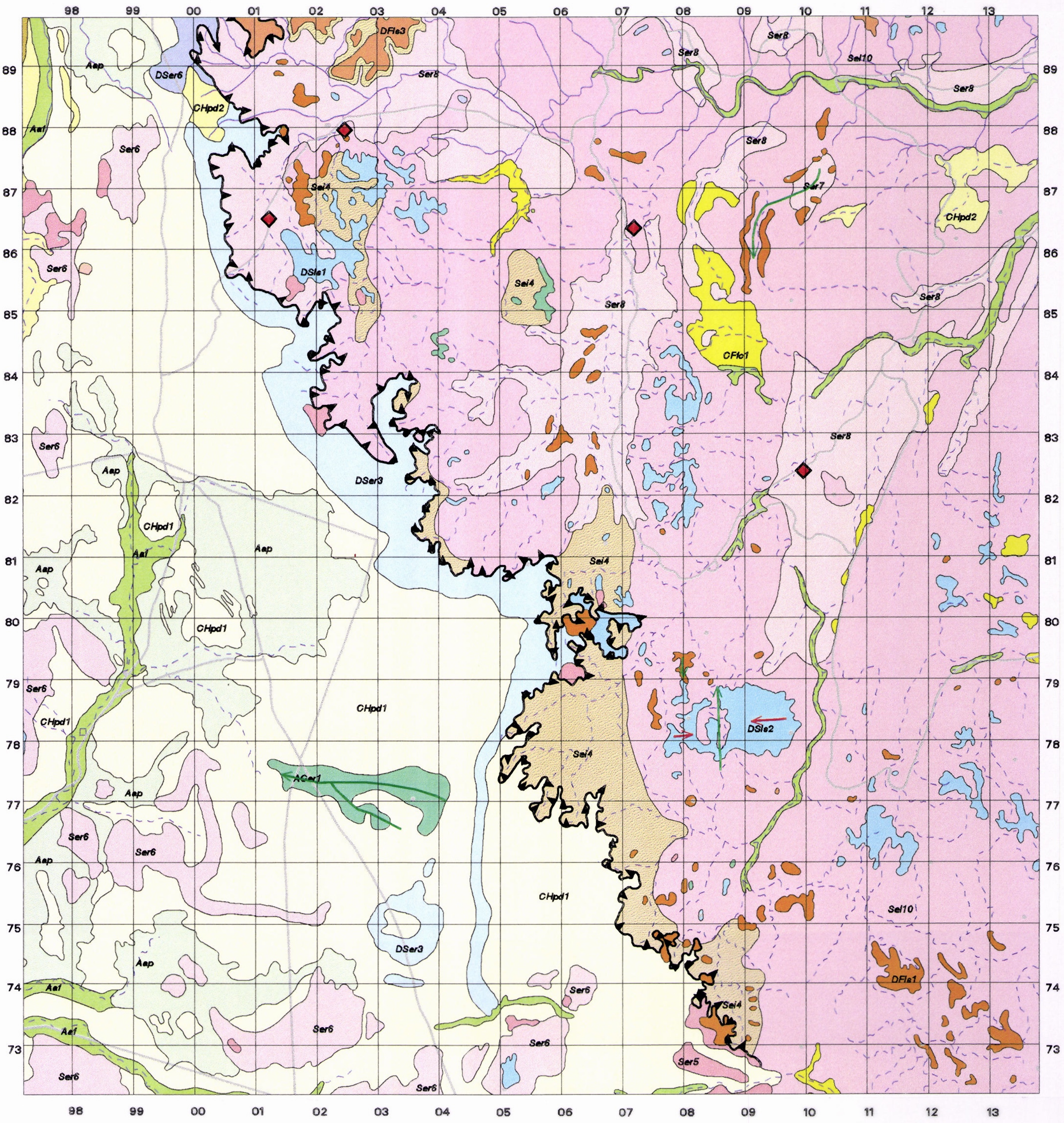

Figure 4.4. A portion of the Buckley River-Lady Loretta geochemical sampling strategy map. This map is interpretative, legend is shown opposite. Black saw-tooth lines (black triangles point downslope) are major erosional scarps, red arrows palaeo dip slopes and green arrows palaeo-drainage channels. Red diamonds are known Cu deposits (After Wilford, 1997b (407R)).

Alluvial and colluvial categories describe sediments including channel, terrace and overbank clay, sands and gravels, sheetflow and footslope deposits. Indurated sediments, which have been cemented by either Si or Fe, are separated from unconsolidated sediments.

The thematic map showing regolith-landform units superimposed on Landsat TM imagery (Figure 4.3) enables clay, Fe oxide and silica signatures, from the enhanced satellite image, to be interpreted within a regolith-landform context. Superimposing regolith polygons over the Landsat imagery also provides an estimation of the relative purity of surface materials within each regolith unit. The other two maps are to varying degrees, interpretative. For example, the geochemical sampling strategy map (Figure 4.4) is based on genetic groupings of regolith and associated geomorphological features. The ability to separate fact clearly from interpretation is a critical process in map generation. Separating factual from interpretative information allows the user to generate new interpretative maps based on different landscape and geochemical models from the original factual data. A flow chart, showing the major steps in generating regolith and interpretative thematic maps, is shown in Figure 4.5.

STEPS INVOLVED IN REGOLITH MAP PRODUCTION

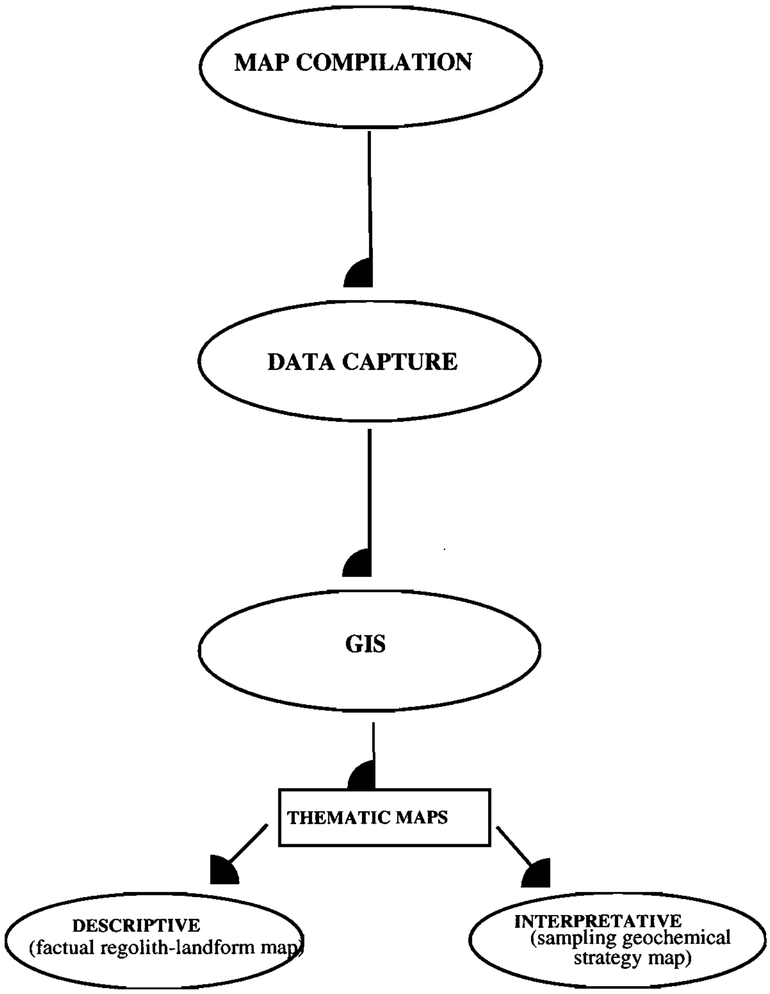

Figure 4.5. Regolith maps are compiled using airphotos 1:25 000 scale processed Landsat TM, site observations, topographic maps (elevation, relief and drainage patterns), digital elevation models, airborne gamma-ray spectrometry and regolith geochemistry (used to characterise or describe regolith materials within landform units). Data are captured as either polygons, lines, points or raster images into the Geographic Information System (GIS). Attribute data (*e.g.*, regolith geochemistry) is spatially linked to digital elements. GIS is used to display, store, integrate and model regolith information with other geo-referenced datasets. GIS allows interpretative modelled thematic layers to be integrated with other datasets. The GIS is then used to generate descriptive and interpretative hardcopy thematic maps.

4.6 Geochemical sampling strategy map

A single geochemical sampling method is unlikely to be suitable over a large area encompassing different regolith units. For geochemical surveys to be effective, an understanding of the origins of the sample media, style of weathering, geomorphological processes and regolith-landform relationships are necessary. Several major regolith-landform associations should be considered when interpreting surface and sub-surface geochemistry. These associations form the basis of the geochemical sampling strategy map (Figure 4.6). This strategy map divides the landscape into major geochemical sampling groups, as outlined below, for which different sampling procedures are appropriate.

Geochemical Sampling Groups

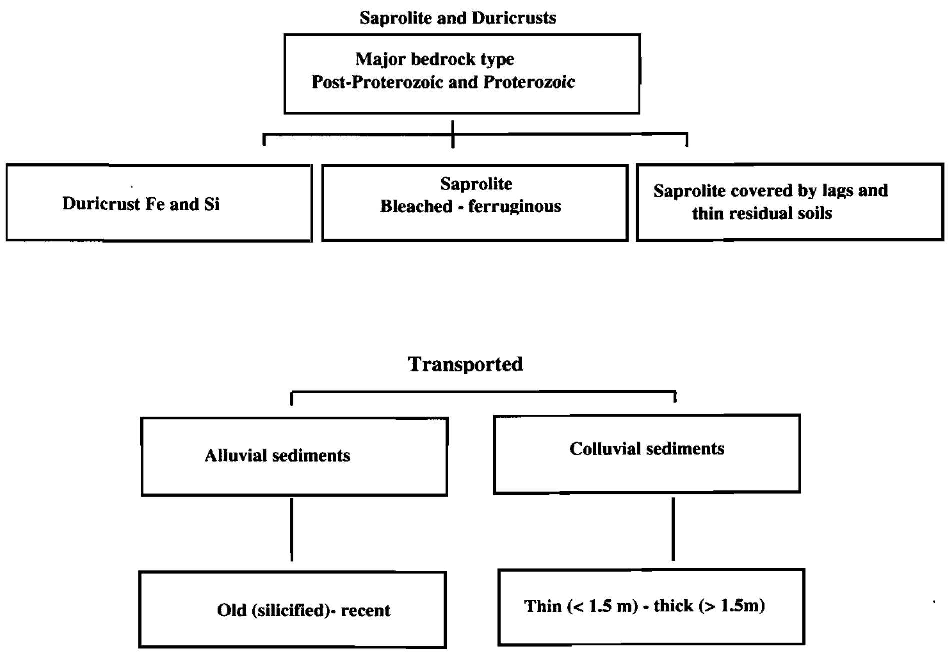

Figure 4.6. The major geochemical sampling groups depicted on the geochemical sampling strategy map.

Each of these groups, with the exception of the alluvium and colluvium, are divided into Proterozoic and post-Proterozoic bedrock types. Subdividing regolith materials by bedrock age is essential in this case since they have completely different geochemical attributes and mineral potential and require different interpretations. Each unit within these groups describe regolith properties in a geochemical context. For example, highly weathered, bleached regolith is separated from ferruginous saprock; thick (> 1.5 m) colluvial cover, which is likely to have a dilute geochemical response, is separated from thin colluvium over bedrock. The map provides a direct tool for designing sampling programmes and for interpretation of surface and sub-surface geochemical data.

5. QUATERNARY LANDSCAPE PROCESSES, MT ISA REGION

5.1 Introduction

From a mineral exploration perspective, much of the Mt Isa landscape consists of a mobile carpet of Quaternary sediments overlying potentially mineralised Proterozoic basement. These sediments provide opportunities for as well as obstacles to the search for mineral deposits.

The Quaternary geology consists mainly of alluvial sediments in transit from source areas in the Mt Isa Inlier to depositional areas on the surrounding plains. The deposits include unconsolidated surficial units 3-5 m thick, in places overlying semi-consolidated or cemented alluvium 2-3 m thick. Chemical activity, associated with cementation and mottling of these deposits, may also have involved trace elements mobility. Hence these deposits may have some potential as sampling media for geochemical exploration.

On the western side of the Mt Isa Inlier, the cemented alluvium overlies Proterozoic bedrock, providing opportunities for hydromorphic movement of pathfinder elements. However, on the eastern side, the environment is less favourable because semi-consolidated deposits are less widespread and, on the plains, Mesozoic marine sediments separate the Quaternary sequence from the Proterozoic bedrock.

Across the plains, channel-bed sands and gravels form linear sediment bodies containing placer deposits of heavy minerals that may be related to distal, upper catchment sources. Channel deposits undergo less diffusive transport across the plains than sediments on the interfluves. Accordingly, former channels have potential for containing trace elements from up-catchment sources.

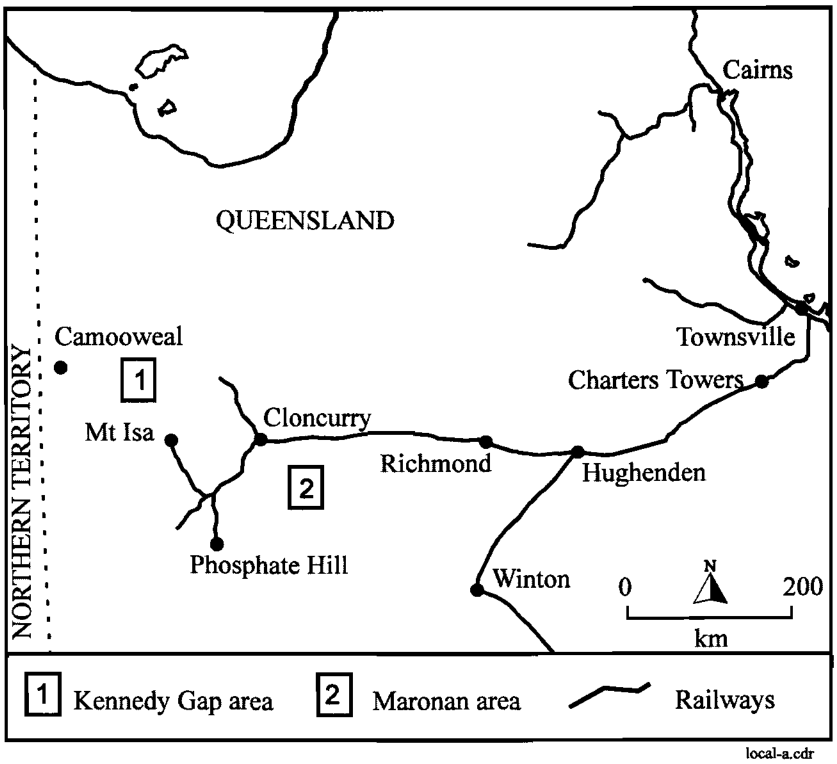

Figure 1: Location of Quaternary landscape study areas in the Mt Isa district.

Studies in the Maronan and Kennedy Gap areas (Figure 5.1) investigated Quaternary landscapes, sediment sources, transport processes and depositional sites. Models of landscape evolution were developed, and the significance of the Quaternary units for mineral exploration was assessed.

5.2 Quaternary processes - Northern Kennedy Gap area

5.2.1 Location

The study area is on the northwest part of the Kennedy Gap 1:100 000 sheet, about 50 km northwest of Mt Isa. The area includes the drainage divide separating coastal and continental draining streams (Jones, 1997a (374R)).

5.2.2 Quaternary landscape

The central and southern area comprises an inland plateau that slopes gently to the west and south, and is drained by the Buckley River and its tributaries. In general, these streams have gentle slopes, and flow across the underlying bedrock terrain of north-northwest strike ridges. In the north, the coastward draining streams have steeper slopes and are more erosional than the inland draining streams. Erosional scarps are present in their upper catchments along the margin with the inland plain. These streams are either confined by bedrock strike ridges, or are eroding the Proterozoic rocks along a wide front. The patterns of streams reflect differences in the mechanical properties of the underlying rocks and the greater erosive power of coastal versus inland draining streams.

The Quaternary deposits consist largely of transported regolith distributed as alluvium across the valley floors. The sequence comprises unconsolidated surficial alluvium, up to 3-5 m thick, overlying cemented alluvium, 2-3 m thick, on bedrock. The unconsolidated deposits show little weathering profile development, whereas the cemented deposits are variably consolidated and are mottled with Fe oxide staining at some locations. The differences in consolidation suggest two phases of accumulation separated by an erosional interlude.

The alluvial deposits of the valleys and plains are primarily sourced from the upper catchments in a zone 2-5 km from the catchment divides. In the study area, the total Quaternary sequence is mostly less than 5-10 m thick, indicating a long-term trend of high sediment throughput from the upper catchments to distant depositional areas on the plains.

5.2.3 Hydromorphic dispersion of trace elements

There is little potential for trace elements to be concentrated in the surficial cover. The alluvium is deposited and reworked in a cyclic fashion, which would disperse any hydromorphic anomalies. However, in the basal cemented alluvial deposits, longer term stability is inferred. Chemical dispersion has occurred and is preserved as ferruginous mottling. The sources of this migrating Fe include:

- lateral ground water movement;
- *in-situ* chemical breakdown of minerals and lithic clasts;
- hydromorphic dispersion from underlying bedrock either as a broad diffuse source, or as a localised source due to solutions moving along faults.

Other elements, in addition to Fe, may be redistributed and concentrated as part of the mottling process. Hence, the cemented and mottled alluvium has potential as a geochemical sampling medium. The most useful anomalies may be present in the matrix or cement rather than the clastic components. The matrix is more likely to be associated with underlying or nearby sources than the clastic grains whose chemistry may have been "locked in" at another location before being transported to the present depositional site.

5.2.4 Mechanical dispersion of trace elements

Mechanical dispersion of trace elements occurs by downstream movement of alluvial sediments. Downstream transport largely diffuses these minerals by deposition of widespread overbank deposits in flood corridors. However, stream placer concentrations are possible in channels.

5.2.5 Cycles of weathering and erosion

Cycles of regolith development and erosion influence the upper catchments. Long term weathering produced erodable regolith which is stripped and transported to the valleys, where temporary deposition takes place. The deposits are re-eroded as the supply dwindles from the source areas. New weathering profiles then develop on the stripped bedrock in the upper valleys to renew the cycle. The upper catchment valleys are most sensitive to variations in sediment supply. Further downstream, the fluctuations are partly absorbed by the larger store of sediment on the valley floors. However, long periods of reduced supply from the upper catchment can produce an erosional phase which moves downstream through the catchment. This progressively exposes older alluvial deposits and bedrock on the valley floor. These cycles prevent long term build-up of alluvium in the upper catchments and, hence, work against preservation of hydromorphic geochemical haloes in the regolith. On the plains, erosional and depositional episodes, associated with sediment supply variations can be recognised in the geological record.

5.3 Quaternary processes - Maronan Area: Cloncurry - McKinlay district

5.3.1 Location

The Maronan area extends approximately 70 km northwest of McKinlay and includes the Isa Highlands and adjacent plains (Figure 5.2). Braided channels in wide flood corridors are common on the plains (Jones, 1997b (382R)).

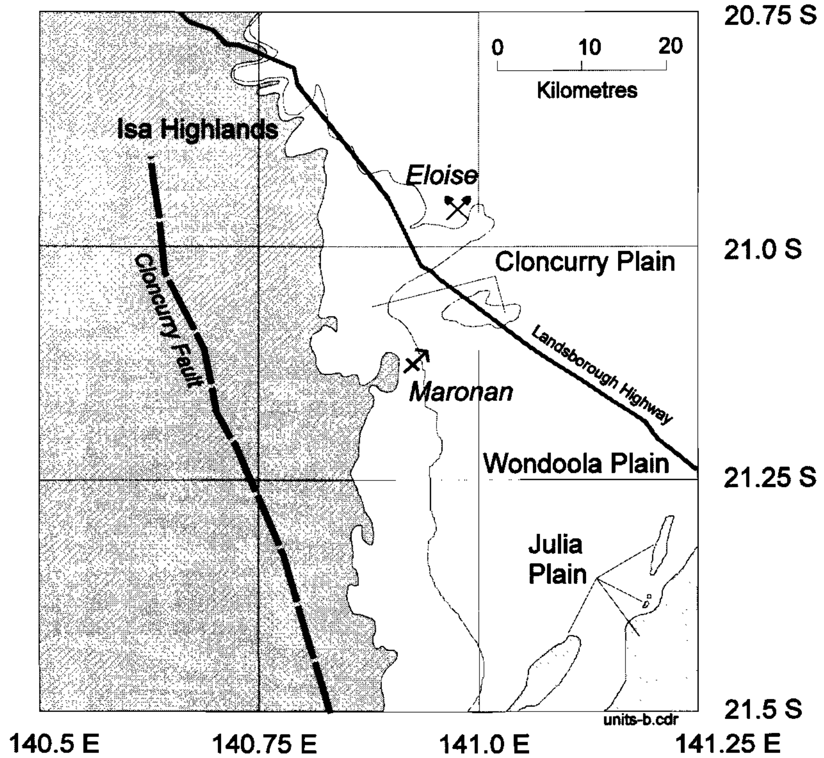

Figure 2: The Maronan district includes four geomorphological units: the Isa Highlands, Cloncurry Plain, Wondoola Plain and Julia Plain. The Eloise mine and Maronan prospect are also shown.

The Proterozoic rocks form most of the Isa Highlands and continue eastwards at depth beneath the plains. In the highlands, there is very little *in situ* regolith over Proterozoic bedrock. However, on the plains, Cretaceous sediments as much as 100 m thick cover the Proterozoic basement. The surficial Tertiary and Quaternary sequence is mostly less than 10 m thick.

5.3.2 Quaternary landscape

The Isa Highlands (Figure 5. 2) are a long-term source of sediments which are eroded and transported on to the plains by the northeast flowing streams. Fluctuations in sediment supply from the upper catchments produce episodes of accretion and erosion affecting interfluve and channel floor deposits on the plains. The interfluves accumulated during earlier cycles of catchment accretion, but incised braided channels continue to be active in distributing very coarse sands and gravels across the plains.

5.3.3 Hydromorphic dispersion of trace elements

Hydromorphic dispersion of trace elements into the regolith is likely to produce a detectable geochemical halo if the regolith is undisturbed for a long time. The regolith formed on the Proterozoic rocks is commonly Fe oxide-stained, indicating chemical mobility during development of the profile. However, in the Maronan area, the *in situ* regolith on the Proterozoic rocks is generally quite thin. Most has been eroded from the Selwyn Range and transported on the plains where it has been reworked intermittently. The oldest, and likely to be the least disturbed of the interfluves are on the Wondoola Plain and on the Julia Plain (Figure 5. 2). Iron oxide staining in some of these deposits may have continued following deposition, due to the breakdown of minerals such as biotite. Chemical activity provides further opportunities for hydromorphic dispersion in these transported deposits. However, the thick sequence of Mesozoic sediments beneath much of the alluvial plains forms a barrier to upward hydromorphic dispersion from the Proterozoic rocks. Such dispersion could produce geochemical haloes in the Mesozoic sediments more readily than in the younger surficial deposits.

In the upper catchment areas, the regolith is directly derived from Proterozoic bedrock. In these areas, the *in situ* regolith is thin and the transported regolith comprises restricted valley-floor alluvium subject to frequent overturning. Overall, the prospects for finding hydromorphic geochemical haloes in the Quaternary regolith appear to be poor.

5.3.4 Mechanical dispersion of trace elements

Stream sediment geochemistry should determine if there is any mechanical dispersion of geochemical pathfinder elements. Most of the sand and gravel supplied from the upper catchments is confined to the flood corridors crossing the plains, rather than being dispersed widely. Hence, sources in the upper catchment may be detectable by sampling the channels on the plains. Further downstream, trace elements from sources in the Proterozoic rocks would become too diffuse for detection. Windows of Proterozoic bedrock, such as at Kevin Downs northeast of the Landsborough Highway, could be investigated for trace elements and compared with Selwyn Range samples to determine regional variability between Proterozoic rocks in the range and beneath the plains.

5.4. Regional implications for exploration

Close to the Inlier, the alluvial deposits may be re-eroded and re-transported in inverted sequence further down-catchment. This zone of active sediment transport around the perimeter of the Mt Isa Inlier contains thin alluvial deposits, whose potential for containing geochemical haloes is low. Further away from the base of the Inlier, sediment thicknesses should increase and the proportion of the regolith pile that is frequently reworked should decrease. Hence, with more stability in the depositional units, the potential for hydromorphic dispersion haloes improves, provided that the transported regolith overlies potentially mineralised and weathered Proterozoic bedrock below. Where rocks of intermediate age separate the regolith from the Proterozoic rocks, the chances of geochemical haloes are decreased. However, faults and fracture zones provide opportunities for groundwater percolation to assist trace elements to penetrate the regolith.

In view of the cyclic processes of formation, transport and deposition affecting the alluvial deposits, selective sampling of recent sediments appears to be essential. Clastic components in particular may contain a complex chemical record of addition and subtraction of distally-derived trace elements during cycles of transport and deposition. The matrix is commonly less durable and is more likely to represent local sources of anomalies. Clastic grains may indicate remote sources that are difficult to identify.

6. SUMMARISED CASE HISTORIES, MT ISA REGION

During the course of this project a number of sites were selected for detailed study. The objective is to relate geochemical dispersion patterns to underlying mineralisation, within a well-controlled regolith-landform framework. Here the various regolith types were characterised, where necessary mapped and samples were collected for detailed mineralogical and geochemical examination. Many of the sites initially offered by sponsors contained unexplained anomalies (*e.g.*, Python, Drifter, Blinder, Tringadee), a few had small to significant mineralisation (Selwyn, Lady Loretta, Little Eva, Brumby). Towards the end of the project two additional mineralised sites were offered (Eloise, Maronan) by companies who were not sponsoring the project.

The case histories are summarised below; further details may be obtained from the project reports. Geochemical data are appended in a compact disc as Appendix III.

6.1 Python prospect - Western Succession

Location

The Python Cu prospect is 75 km north-northwest of Mt Isa (Figure 1.1A). The area was offered as a district-scale study by MIM Exploration, who are actively exploring the region for Isa-style Cu (Dr Leigh Bettenay, personal communication).

Geology and mineralisation

Extensively folded units of the Paradise Creek and Esparanza Formations of the McNamara Group are the main Proterozoic bedrock exposed in the area. The Paradise Creek Formation is overlain by the Esparanza Formation and the contact between the two is at the base of a sandstone unit overlain by a distinctive, thick stromatolitic chert. In outcrop, the Paradise Creek Formation is white bleached siltstones and grey cherty lenses whereas the Esparanza Formation has extensive stromatolitic cherts and less siltstone. Drilling in the area has shown that the dense cherts at the surface do not extend below the weathering front (Buckland 1994).

Regolith

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 (Anand *et al.*, 1996 (158R)). The Proterozoic bedrock has undergone extensive post-weathering faulting that has disrupted the continuity of ferruginous and siliceous units in the landscape. The bedrock has also been weathered to a depth of 90 m with loss of carbonates and oxidation of sulphides. The stromatolitic units of the Esparanza Formation form high siliceous ridges which control drainage and slow erosion in the northeast of the mapped area. The pyritic units of the Esparanza Formation are softer and form low points between the ridges and are dominated by siliceous lag.

The hill in the middle of the prospect has an extensive cap of duricrust, with a minor breakaway of slabby duricrust on its southwest side. The slabby duricrust is 1-2 m thick and is composed of horizontally arranged massive goethite-quartz-rich plates that grade into ferruginous saprolite below. The hill is covered by nodular lag and blocky material derived from the duricrust, which has marked solution features and dense, ferruginous accretions. The formation of slabby duricrust and ferruginous nodules and pisoliths has been complex (Anand *et al.*, 1996 (158R); Britt, 1993). Slabby duricrust has formed on the slopes by induration of locally derived colluvium and upper saprolite. Ferruginous nodules and pisoliths were developed in soils and locally derived colluvium and from the collapse of underlying mottled saprolite, and are probably older than the slabby duricrust.

Geochemical dispersion in the regolith

Investigation of the geochemical anomaly at the Python prospect has focused on ferruginous materials and the weathered profile from MIM Exploration drill hole BR36 (Anand *et al.*, 1996 (158R)). 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 collected on a 500 x 250 m grid using the MIMEX surface geology map (Jones, 1994). Fifty two samples were also taken from drill core (BR36) located within the main anomaly for geochemical analysis and characterisation of the profile.

The Cu, Au, Sb and Pb anomalies at the Python prospect are restricted to slabby duricrust and lateritic nodules and pisoliths. Thresholds were chosen from normal probability plots. The Pb concentrations show the most distinct break at 50 ppm. Antimony (> 20 ppm) defines the anomaly. Gold is at or below the detection limit. There are no meaningful correlations between the indicator elements. In slabby duricrust, the greatest Cu concentrations occurs in cracks around goethite grains with the greatest Mn concentration. Arsenic is concentrated in the more Fe-rich grains.

In conclusion, the enrichment of trace elements (Cu, Pb, As, Sb, Au, Ag) in partly transported duricrust and nodules and pisoliths sourced largely from the fault that cuts through the duricrust-capped hill with some contribution from a distal source (Anand *et al.*, 1996 (158R)). The fault is richer in Pb, Cu, As, Sb and Au which are probably related to underlying mineralisation. Copper is mobile in the weathered environment and is not restricted to ferruginous materials, but is precipitated as malachite in the saprolite.

6.2 Lady Loretta deposit - Western Succession

Location

Lady Loretta Ag-Pb deposit is near Paradise Valley, 115 km north-northwest of Mt Isa (Figure 1.1A). RGC Exploration made the site available.

Geology and mineralisation

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 landsurface relics of which appear on hilltop 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, saprolite which passes into oxidised metasediments at 50 m; oxidation penetrating to 100 m and, near faults and shears, locally to >300 m. Lead oxidation products (anglesite and cerussite) occur within a few m 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). There is little Cu.

Regolith

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 landsurface (Anand *et al.*, 1996 (158R)). This palaeosurface, largely capped by silicified saprolite and by lesser quantities of ferruginous saprolite, has been slightly stripped. Despite this, abundant silcrete and some pockets of nodular duricrust remain. In places, a veneer of remnants of ferruginised Mesozoic sediments (massive duricrust), 1-3 m thick, overlies the saprolites of Proterozoic rocks. Erosion in the valleys has revealed saprolites of carbonaceous shale and siltstone covered by a very thin, skeletal soil, overlain, in turn, by generally thin (<0.3 m) veneer of colluvial scree on the valley sides, which thickens to 2 m near the valley floors. Trial mining and resultant ore stockpiling are likely to have caused geochemical contamination to the saprolite, soil and colluvial materials in the valley floor, down slope from the mineralisation, so that a geochemical survey would have little significance.

Geochemical dispersion in the regolith

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 duricrust (Anand *et al.*, 1996 (158R)). It was necessary to search extensively for very small, pockets of nodular duricrust, which were developed on favourable lithologies. Background was estimated from a geometric mean of samples collected over >400 m from the mineralisation.

In the southeast of the area, the majority of the nodular duricrust sites overlie the subcrop of the ore horizon subcrop and its contiguous pyrite unit, indicating that they probably formed preferentially on ferruginous parts of the stratigraphy. 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 residual nodular duricrust would be a useful geochemical medium to detect Pb-Zn-Ag mineralisation in areas where the duricrust is well developed and that As, Sb, Ba, Mo and W should be used as pathfinders additional to Pb and Zn. Although ICP analysis for Cd was not investigated here, it has proved less labile than Zn elsewhere (Robertson, 1990) and should be included within the analytical suite.

6.3 Drifter prospect - Western Succession

Location

Drifter Cu prospect is about 30 km northwest of Lady Loretta (Figure 1.1A). Aberfoyle Resources Limited were actively exploring the area and offered it as a site where dispersion was evident in Mesozoic sediments and possibly in the Cambrian unconformity. .

Geology and mineralisation

This prospect contains a sub-vertical shear zone, with chalcopyrite mineralisation at depth, which is also revealed by malachite staining extending for 600 m west in the ferruginous Mesozoic sandstone. A stream sediment anomaly covers 10 square kilometers (Aberfoyle Resources Ltd, unpublished data). A cherty breccia at the base of the Cambrian is also highly anomalous in Cu and Zn.

Regolith

Ferruginous cherty breccia marks the unconformity at the base of the Cambrian. Duricrust-capped (1-3 m) Mesozoic sediments of varying thicknesses (3-30 m) occur on mesas and are underlain by silicified saprolite (Anand *et al.*, 1996 (158R)). These ferruginous duricrusts are massive, reddish brown to black and are dominated by quartz, goethite and hematite, with traces of kaolinite and mica. Where the Mesozoic sediments have been removed, a veneer of cherty breccia overlies silicified Proterozoic saprolite that forms low hills and pediments. The cherty breccia is white to reddish brown with 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, the hematite has concentrated with Mn oxides along cracks and veins.

The materials derived from erosion of the Mesozoic sediments cover the valley floors. Regolith stratigraphy was established from six trenches north of the Drifter prospect The four northern trenches revealed Mesozoic sandstone and clays, beneath the sands (Anand *et al.,* 1996 (158R)). Very sandy top soil overlies a mottled sandy clay subsoil. The topsoil is up to 4 m thick and comprise sands and gravels. Transported ferruginous gravels and quartz pebbles, which are presumably derived from the erosion of Mesozoic profile upslope, occur above the mottled zone. Iron-and Mn- rich bodies and mottling occur in the colluvium and alluvium as pods and slabs up to 3 m across and are dominated by hollandite and goethite. Bleached saprolite lies beneath the mottled zone; saprolite is dominated by quartz, kaolinite and mica.

Geochemical dispersion in the regolith

Twenty two surficial samples, mainly massive, ferruginous duricrust on Mesozoic sandstone, cherty breccia, and ferruginous or silicified saprolite on the Proterozoic, were sampled on traverse 7827000mN (Anand *et al.*, 1996 (158R)) The concentrations of Cu and Zn in ferruginous duricrust are low, whereas those of Ti and Zr are high, relative to the cherty breccia. The abundances of Cu, Pb, Zn and Mo are greater in the cherty breccia than in the ferruginous duricrust and are controlled by the abundances of Mn and Fe. Copper and Zn anomalies in the cherty breccia appear to be related to leakage from the Proterozoic Drifter Fault.

Soils developed in colluvium and alluvium overlie mineralised mottled saprolite Soil sampling of the <180 μm fraction by Aberfoyle Resources Limited on a 400 m x 50 m grid showed maximum concentrations of Cu, Fe, Mn, Pb and Zn (4654, 74400, 7892, 805 and 449 ppm respectively). The Cu anomaly is associated with Fe, Mn, Pb and Zn. Three soil profiles from trenches 1 and 4 were sampled for detailed investigation (Anand *et al.,* 1996 (158R). Sampling extended to about 1 m in mottled Mesozoic sediments. The three soil profiles have high Cu contents associated with high Fe (goethite, hematite) and Mn (hollandite) contents in the >2000 μm fraction. The concentrations of Cu and Zn are much less in the <75 μm fraction, which is dominated by quartz and kaolinite.

The dispersion characteristics of Pb and Sb are different from those of Cu and Zn. The >2000 μm soil fraction has very low concentration of Pb, despite its high concentrations (175 ppm) in the saprolite. This contrasts with the <75 μm fraction, which contains about 80 ppm Pb. 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.

It is concluded that soils developed in alluvium are appropriate sampling media where the sediments are less than 4 m thick and have been weathered since deposition. Hydromorphic dispersion of Cu, Zn and As in the >2000 μm soil fraction is controlled by the neoformed Mn and Fe-oxides. In contrast, relatively immobile Pb and Sb are concentrated in the fine <75μm kaolinitic fractions which probably indicates an early, possibly mechanical (bioturbation) dispersion into the soil.

6.4 Blinder prospect - Western Succession

The Blinder Cu prospect (Aberfoyle Resources Limited) is 7 km southeast of Drifter (Figure 1.1A). There are significant Zn and Pb surficial anomalies in the ferruginous Mt Hendry Formation but no mineralisation has been found by drilling. A creek has locally incised the Cambrian rocks and Proterozoic Paradise Creek Formation. There is a two metre thick conglomerate on the contact that forms a distinct marker on many of the slopes. The Mt Hendry Formation in outcrop 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 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 (Anand *et al.,* 1996 (158R)).

The Fe oxides that hosts 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.

6.5 Little Eva prospect - Eastern Succession

Location

The Little Eva Cu prospect is 12 km north of the Dugald River Pb-Zn-Ag deposit, about 90 km north-east of Mt Isa in the Quamby district (Figure 1.1A). CRA Exploration Pty Limited made the site available.

Geology and mineralisation

This prospect lies in the Corella Formation of the Eastern succession in an area of greenschist facies. pelitic metasediments, limestones, scapolitic limestones and a podiform magnetite horizon with scapolite-biotite granofels, red feldspathic rocks and feldspar porphyry. These are faulted against near amphibolite facies metasediments and intrusive granitoids to the east.

Regolith

Most of the Proterozoic rocks around Little Eva are obscured by extensive gravel plains. The regolith includes a colluvium-alluvium of rounded quartzite clasts, a sandy alluvium in the vicinity of Cabbage Tree Creek and, where basement rocks subcrop, thin, skeletal, carbonate-rich soils (Robertson *et al.*, 1995 (128R)). The thickness of the alluvium is estimated at about three to five metres; the colluvium is probably very thin, generally one to two metres. These colluvial and alluvial mantles hinder exploration; a common problem throughout the Eastern Succession, where stony colluvium masks much of the ground between low ridges and on pediments. Weathering of the basement is slight and there is no evidence for lateritic duricrust or mottled zone materials.

The Little Eva Cu prospect lies near the confluence of two braided river channels that drain the Knapdale quartzites. The prospect is sited on a gently inclined, undulating pediment, covered by a thin veneer of colluvium and carbonate-free ferruginous lithosols. In detail, there are two main regolith regimes, erosional and depositional; the depositional regime may be subdivided into an alluvial and two colluvial units (Robertson *et al.*, 1995 (128R)). Along a narrow strip flanking Cabbage Tree Creek, erosion has exposed low outcrops of fresh Corella Formation and its saprolite, partly mantled by a skeletal, grey soil, rich in lithic fragments. It is overlain by a lag of quartz, quartzite and magnetite. To the north and east, the Proterozoic rocks have been eroded into gently undulating country, with surface carbonates probably related to crystalline carbonate-rich rocks in the basement.

Soils, formed on the eroded basement, are immature and contain chips of the relatively fresh metamorphic rocks and derived mineral matter of this basement and are rich in carbonates. Small pods of magnetite outcrop in the basement and shed a lag of black magnetite fragments. These are lenses of slightly weathered 'primary' magnetite which is common in the soil of the erosional regime.

The depositional regimes consist of an alluvial unit, north of the eroded basement, and two colluvial units to the south. One, in the south-central part of the area, in slightly higher parts of the landscape, is mantled by a lag of quartz and exogenous quartzite clasts with minor magnetite pebbles, on a red-brown, lithic, carbonate-free lithosoil. The other subdivision is a red-brown, acidic lithosol mantled by a polymictic lag of subangular pebbles of quartz, numerous nodules of magnetite and cobbles of exogenous quartzite. It is interspersed with numerous, elongated, shallow, grassy depressions (gilgai), underlain by grey-brown cracking clays with no lag.

The 'gilgai' soils are characteristically rich in smectite and quartz, poor in kaolinite, feldspar and hematite and free of mica and carbonates. The alluvium is rich in amphibole, mica and kaolinite, is poor in smectite, hematite, feldspar and quartz, and free of carbonates and chlorite. Compared to the soils on the eroded basement, the soils on the colluvium ('gilgai' soils excepted) are slightly poorer in kaolinite, smectite, hematite and feldspar but richer in quartz, amphibole and magnetite.

Geochemical dispersion in the regolith

Bedrock Cu forms a north-striking anomalous band, over 1 km long. Although the highest Cu abundances occur below and on the edge of the colluvium, significant Cu concentrations occur near the Little Eva shaft and in the erosional regime. This well-established bedrock Cu anomaly formed the target for the soil geochemical survey.

The soils were sampled on an approximately triangular 200 m grid to determine whether they could be used as reliable geochemical sampling media in areas masked by colluvium and alluvium and, if so, to determine the most useful size fractions and the most effective indicator elements (Robertson *et al.*, 1995 (128R)). After a pilot study of a few selected samples, which compared maximum abundances and compositional ranges of elements in each soil size fraction, two size-contrasted fractions (<75 µm and 710-2000 µm) were selected for analysis and assessment.

Indicator elements for Little Eva mineralisation are restricted to Cu and Au (Robertson *et al.*, 1995 (128R)). Both are effective in soils on the erosional regime for both soil fractions, although the strength of the signal is improved five fold in the fine (<75 µm) fraction. As expected, the exposed area south of the Little Eva shaft is targeted very clearly. Copper, in both size fractions, also showed a muted ridge-like anomaly in the colluvium which closely follows the Cu distribution in bedrock but is an order of magnitude less than in the exposed area. Gold also shows this trend but only in the fine fraction. Although W could be useful, a more sensitive analytical method is required to assess it properly. No other elements (in particular Pb, Zn, As, Sb or REEs) appear to be directly associated with the mineralisation and there is no apparent phyllic halo.

Magnetite is, in part, associated with the mineralisation. A magnetic soil concentrate was briefly investigated. Elements concentrated in this material are V, Cr, Ti, Ni, Co, Ga and Nb; most of these occur in the spinel (magnetite) lattice. Iron, V and Co soil geochemistry may be used to detect magnetite-rich stratigraphy. A ground magnetic survey would be expected to be equally effective. However micro-analysis of magnetite grains may provide an additional pathfinder to this style of mineralisation, distinguishing prospective from barren magnetites.

Bioturbation by soil mesofauna plays an active role in mixing soils in near surface horizons. Termitaria are restricted to but are well developed on areas mantled by colluvium, where they are an important feature of the landscape. Here, although some of the fine fraction would be expected to have been remotely derived, a significant portion of fines would be expected to have been moved upwards, from the weathered basement, and mixed with the exogenous component of the soil. It is probably this bioturbated fine material, consisting of clays and Fe oxyhydroxides and some coarser particles, that carries the geochemical signal from the basement into the colluvium, although there may have been some hydromorphic dispersion of Cu and Au.

It is concluded that a thin (<2 m) colluvial mantle provides little barrier to the dispersion of Cu and Au from basement to soil, provided that the fine fraction (<75 µm) is used. However, anomalies tend to be muted by an order of magnitude. The alluvium was not penetrated successfully by soil geochemistry.

6.6 Eloise deposit - Eastern Succession

Location
Eloise Cu-Au Mine lies 60 km south-east of Cloncurry (Figure 1.1A). Amalg Resources NL (non-sponsoring company) made the site available.

Geology and mineralisation
The Eloise is on the margin of the Eromanga Basin where the Proterozoic metamorphic rocks of the Mt Isa Inlier have been partly covered with Mesozoic, Tertiary and Quaternary sediments. This has provided some considerable challenges to exploration which, to date, has been by drilling geophysical targets. The intent of this study was to determine the geomorphological and linked sedimentary history of this region and to investigate any opportunities for using geochemistry in this difficult environment.

The Eloise deposit has an indicated reserve of 3.2 Mt at 5.8% Cu, 1.5 g/t Au and 19 g/t Ag and is hosted by greenschist metamorphosed metasediments and metabasic rocks. Mineralisation is associated with major retrograde shears. The deposit and its Proterozoic host rocks are buried beneath 50-70 m of Mesozoic cover and by 5-7 m of Tertiary-Quaternary alluvium. The basement has been cut by a westerly-dipping, partly mineralised fault that has concealed the southern part of the deposit beneath a wedge of barren Proterozoic metamorphics. Leakage along this fault is the only way by which a geochemical signal could reach the Proterozoic-Cretaceous unconformity at the south end of the deposit.

Regolith

Regionally, the landscape of the Eloise area consists of extensive alluvial plains and flat-lying erosional terraces. To the southwest of the Landsborough Highway and in the southwestern corner of the study area, erosion has predominated. Materials eroded from the southwest have been carried to and deposited on low floodplains in the northeast, forming alluvial plains and other related landforms (Li Shu and Robertson, 1997 (405R)).

Beneath the depositional area, Proterozoic rocks are almost entirely covered by Mesozoic siltstone, mudstone and minor limestone. The unconformity consists of a thin layer of coarse conglomerate and suggests an extended period of erosion prior to the onset of marine sedimentation. The Proterozoic rocks beneath the unconformity are all remarkably fresh (weathered to saprock at most).

The Mesozoic sediments vary in thickness of 1-2m in the south to greater than 150 m, 10 km north of Eloise (Komyshan, 1993). Dominant mudstone, siltstone and sandstone of the Wallumbilla Formation represent a shallow marine environment and are capped in the north and northeast parts by thin beds of limestone of the Toolebuc Formation, much of which has been eroded leaving limestone remnants scattered north and northeast of the mine.

Where covered by Tertiary and recent alluvium, the Mesozoic sediments have been weathered to saprolites. There is no way of determining if the weathering took place prior to or after deposition of the Tertiary sediments.

Fluvial Tertiary sediments, 2-8 m thick, overlie the Mesozoic sediments, with a large proportion of rounded gravels in a matrix of coarse sand, derived from various types of Proterozoic bedrock. The top of this unit is generally ferruginous, brown to red and its surface is mantled with a lag of pebbles and ferruginous pisoliths. These were deposited in former channels of a major river, probably the precursor to the Fullarton River which later changed its course to the east. The Tertiary sediments form either fluvial ridges or high river terraces.

Quaternary alluvium, in the lower part of the landscape, has built up plains on Mesozoic sediments. Recycling of these post-Mesozoic sediments has formed rolling plains at Eloise. Where it is fine, poorly-drained, black soil is developed.

Geochemical dispersion in the regolith

The thick Mesozoic cover at Eloise presents an effective barrier to geochemical exploration. Apart from the orebodies, the most promising geochemical target at Eloise is the Proterozoic-Mesozoic unconformity. A very thin and probably discontinuous layer of coarse sediments (grit and conglomerate), at the unconformity, formed from erosion of the basement, are sealed by a thick mass of semi-pelitic to pelitic sediments. These would be expected to retain any mechanical or hydromorphic dispersions from the Eloise deposit. Details of the palaeo-topography of this unconformity were obtained from drilling.

Exposed parts of the decline were sampled to the unconformity and core from drillholes ENG1 and ENG2 were also sampled, all in particular detail close to the unconformity as a near-mineralisation data set. This was compared to a 'background' data from diamond drillholes 1TT, 2TT, 3TT and 4BTT about 3 km from the mine (Li Shu and Robertson, 1997 (405R)).

Close to mineralisation, indicator elements were Cu, Au As and Sb. Significant anomalies occur within the coarse Cretaceous sediments only at or very close to the unconformity in diamond drillholes ENG1 and ENG2 (Au 90 ppb, Cu 75 ppm, As 125 ppm, Sb 0.7 ppm). The decline showed no such anomalies.

In the background, three drillholes contain no significant Cu, there being a small Cu anomaly (80 ppm) at the upper surface of the basal sandstone in one drillhole, about 2.5 m above the unconformity. Gold is at background concentrations (< 5 ppb) in two diamond drillholes but shows a significant anomaly (57 ppb) at the base of the sandstone in one and a weak anomaly (26 ppb) in a thin conglomerate in sandstone 0.3 m above the unconformity. Arsenic and Sb anomalies (102 and 1.5 ppm respectively) occur in one drillhole in sandstones and conglomerates 1.3 m above the unconformity.

Most diamond drilling was precollared and restricted to the basement; precollar drillspoil was no longer available. Thus, availability of materials and the layout of drilling to test this dispersion were not ideal. Despite this, some general conclusions may be reached.

Where the Mesozoic cover is significantly thick, the Proterozoic rocks are relatively fresh (saprock) so the extent of dispersion by weathering is likely to be minimal. The only useful dispersion is mechanical and restricted to the unconformity. Mechanical dispersion halos at the unconformity at Eloise may have extended 100 m from the mineralisation or mineralised faults and were strongly influenced by palaeo-topography.

Drilling about 3 km from the mine indicated some anomalies, notably slightly above the unconformity. This site seems to have been directly down-slope of Eloise and early sediments here may have been derived from Eloise inpart. The remainder of the Mesozoic stratigraphy is argillaceous, so any weak geochemical halos are likely to have been sealed in. However, where the Mesozoic and Proterozoic are weathered as at Maronan (Robertson *et al.*, 1997(409R)), there are opportunities for hydromorphic dispersion.

When investigating geophysical targets in areas of unweathered or slightly weathered Mesozoic cover, coarse sediments should be collected at and just above the unconformity to detect a near-miss. The configuration of the palaeolandscape needs to be thoroughly understood and would require accurate logging and surveying of all available drilling.

Other opportunities
Alluvium is generally unsuitable for sampling but may carry a detrital dispersion halo. Ferruginous nodules and soil developed over Proterozoic rocks, both on the erosional terrace and on the erosional plain at a lower level, would be valid sampling media. However, where there has been active erosion, weathered profiles would not survive for long so extensive hydromorphic dispersion patterns would not be expected.

6.7 Maronan prospect - Eastern Succession

Location
The Maronan Cu-Au Prospect lies 60 km south-east of Cloncurry (Figure 1.1A). Mining Project Investors Pty Limited (MPI) Resources (non-sponsoring company) made the site available.

Geology and mineralisation
Maronan is hosted by Proterozoic metasediments and metabasic rocks of the Eastern Succession, buried beneath 20 m of Tertiary cover and soil on the margin of the Eromanga Basin. The Tertiary cover here consists of fluvial sediments.

Regolith
The Proterozoic basement around the Maronan Prospect has been weathered to grey saprolite, with no upper ferruginous crust and contrasts with the very fresh Proterozoic metamorphic rocks beneath the Mesozoic sediments at Eloise. The lowermost 12 m of the Tertiary consist of silty alluvium with sandy intercalations; the upper eight metres are largely sandy. This is a depositional regime underlain by regime eroded into but not through the saprolite of the residual profile.

Geochemical dispersion in the regolith
Only one drillhole was investigated to determine what dispersion, if any, occurred in the Tertiary cover that could be used to indicate mineralisation in the basement (Robertson *et al.*, 1997 (409R)). None was detected. There appears to be dispersion within the saprolite of Au, Cu and Pb, but the

top 6 metres of the residual profile appears to be leached of these elements. Other anomalous elements may include W, As, Sb, K, Rb and Ba (the last three possibly defining an alteration halo). The extent of any suspected dispersion could not be determined from a single drillhole. There was no indication of a useful geochemical signature in the soil over the mineralisation.

It is concluded that geochemical prospecting in similar parts of the Eromanga Basin, covered with a veneer of Tertiary sediments but lacking Mesozoic cover, could target quite small anomalies a little beneath the upper surface of the residual profile. Useful elements seem to be Au, Cu and Pb, possibly supplemented by As, Sb, K, Rb and Ba.

6.8 Tringadee prospect - Eastern Succession

Location
The Tringadee Zn prospect is about 120 km south of Cloncurry, west of Cannington and south of the Williams Batholith (Figure 1.1A). Aberfoyle Resources Limited made the site available.

Geology and mineralisation
Variably eroded Mesozoic sediments lying on the margin of the Eromanga Basin characterises the Tringadee area. These thin to the north of the study area, where granite of Proterozoic age outcrops (Phang *et al.*, 1997 (429R)). The Mesozoic sediments comprises siltstone with a basal sandstone and conglomerate. There is no known mineralisation at the Tringadee prospect, which has a widespread Zn anomaly of >1000 ppm in the Mesozoic cover (Aberfoyle Resources Limited unpublished data) which is confined to a N-S palaeovalley, but is isolated from Cannington Pb-Zn-Ag deposit by a palaeohigh. This is an interpreted feature defined from drilling. The source of the Zn is unknown.

Regolith
Regionally, the Tringadee area is of generally low relief with extensive depositional plains covered by well-developed black clay soils over alluvial materials. 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 portion of the mapped area. The higher mesas on Mesozoic sediments, with a local relief of 100 m, have gullies radiating from the top, appearing as white streamers on the aerial photograph. More advanced erosion has reduced some of these mesas to pale, yellowish, silicified saprolite or isolated low, conical hills.

At the Tringadee prospect, the landscape is dominated by 30-80 m thick weathered Mesozoic sediments and has abundant dark brown patches of ferruginous lag from the breakdown of former Mesozoic massive duricrust (Anand *et al.*, 1996 (158R); Phang *et al.*, 1997 (429R)). The underlying granite is fresh to slightly weathered. Within the Mesozoic sediments, fine sandy layer occur. The percolation of Fe-rich fluids through these porous sandy layer form ferruginous bands.

Geochemical dispersion in the regolith
As part of a more detailed study directed to explaining the Zn anomaly, two RAB drill sites (ROTR 155) and ROTR (156) with a Zn anomaly of >1000 ppm were investigated (Anand *et al.,* 1996 (158R); Phang *et al.*, 1997 (429R)). These lie in the alluvial-colluvial plains near exposures of low mounds of Mesozoic sediments rich in Fe and Mn oxides. The dating of Mn oxides on surface samples indicates a probable age of 12 Ma, which is late Miocene. Similar age is also reflected from Mn oxide samples from Cowie and Pegmont prospects (see Section 3).

The size fraction in RAB cuttings 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.

From this information, together with the practicality of obtaining enough material, the >710 μm fraction was selected for further analysis. 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 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. 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.

From these data and observations from 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 watertables and fractures in the Mesozoic cover (Anand *et al.,* 1996 (158R)). 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. 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 gentle uplifting also resulted in fractures in the Mesozoic profile causing conduits for fluids rich in Fe. The source of anomalies could be nearby deposits.

6.9 Brumby prospect - Eastern Succession

Location
Brumby is a Cu-Au prospect, situated within the Tringadee area (Figure 1.1A). Aberfoyle Resources Limited made the site available.

Local geology and mineralisation
The Cu-Au prospect is situated in low hills of Mesozoic cover (up to 70m thick) over steeply dipping Proterozoic bedrocks.

Regolith
The regolith is similar to that of the Tringadee prospect. However, both horizontal ferruginous bands and sub-vertical ferruginous veins occur within the Mesozoic sediments. The structurally controlled ferruginous veins follow tectonically induced partings.

Geochemical dispersion in the regolith
Surface samples were collected along two transects over minor mineralisation drilled by Aberfoyle Resources Limited (Anand *et al.,* 1996 (158R); Phang *et al.,* 1997 (429R)). These include ferruginous veining and induration on bedding planes and faults in the Mesozoic and consist largely of hematite, goethite, kaolinite and quartz. Goethite abundance tends to increase with depth. Bulk analyses showed Au <5 ppb and low abundance of Cu (50 ppm). Partial extractions using buffered ammonium acetate followed by hydroxylamine hydrochloride did not add to the bulk analysis information. Thus, it is concluded that there is no expression of mineralisation in the surficial ferruginous veins.

Sub-surface samples were chosen from RAB drilling clustered holes around percussion drillhole PETD6 which all showed Cu less than 50 ppm in the 15 m of Mesozoic drilled (Aberfoyle Resources Limited unpublished data). The Mesozoic is approximately 45 m deep. Zinc increases in the top ten metres, showing an accumulation that is unrelated to mineralisation. However, Au, Cu, Zn and other trace elements increase around the Fe-rich Mesozoic/Proterozoic boundary. At 25 m, there is a ferruginous band which represents old watertable at which Cu and Zn have accumulated. Below 25 m Fe, Au and Cu correlate well but, above 25 m, the correlation between Au and Cu, and Au and Fe break down. Copper is increasingly depleted towards the surface droping from a maximum of 8,000 ppm in the Proterozoic to 400 ppm at 25 m and 40 ppm at the surface.

In conclusion, Au and Cu are sourced from mineralisation and their dispersion is controlled by redox processes. Ferruginous bands formed within the sediments should be preferentially collected. These are more useful than structurally controlled ferruginous veins.

6.10 Selwyn deposit - Eastern Succession

Location

The Selwyn Au-Cu deposit, 150 km south of Cloncurry (Figure 1.1A), forms two parallel ridges 70 m above the local landsurface. Arimco (non-sponsoring company) made the site available.

Geology and mineralisation

Bands of metamorphosed Proterozoic ironstones run approximately N-S and host several deposits. Both ridges were massive magnetite but the eastern ridge appears to have been more extensively oxidised. Hematite on the ridges is massive, with blocky crystals up to 5 cm across. Although parts of the western ironstone host Cu-Au mineralisation, the eastern ironstone is barren. Geochemical exploration of the mineralised ironstones is hindered by extreme variation in Cu, Au and trace elements both along and across strike. The mineralised parts of the western ironstone form subdued topography because sulphide oxidation has caused more intense weathering. Copper from weathering sulphides is leached to the watertable, where it has precipitated as chalcocite and native copper.

Geochemical investigation

Samples of mineralised and barren ironstones were analysed for 38 elements by XRF and INAA. The mineralised samples are distinguished by Au and W and the barren samples by Ba and Mn (Wildman, 1997 (341R)). Copper is high in the mineralised samples but because there is a large overlap of concentrations with the barren samples it is not useful for discrimination. There is also a significant difference in many element concentrations between and within the deposits at Selwyn. Two mineralised veins at Deposit 257, which are only 25 m apart, have large differences in Sb, Au, Cu and Sr.

Photomicrographs and backscattered electron images were used to describe the mineralogy and textures of selected samples (Wildman, 1997 (341R)). The mineralogy of the Cu-Au ore is magnetite plus quartz with varying amounts of chalcopyrite. Scheelite is also common in the ore.

In the oxidised surface samples, chalcopyrite has been oxidised to goethite that contains up to 6300 ppm Cu. Magnetite has been oxidised to hematite which is low in copper but is dense enough to protect small, enclosed grains of chalcopyrite from weathering. The SEM investigation showed that Au, W, Sn and Cu are preserved in hematite derived from the magnetite.

In conclusion, the Proterozoic ironstones differ from recent accretionary ironstones in the size of magnetite crystals (75 mm across). On a microscopic scale, inclusions in the crystals are spherical, indicating they were trapped in a molten state (Steve Barnes, personal communication). At the surface, the Cu-rich goethite is in the most weathered part of the ironstone.

The Au and W are trapped in dense hematite after magnetite in surface samples of the mineralised western ironstone. This hematite may be a source of local stream sediment anomalies at Selwyn but elsewhere may occur at a palaeosurface if the ironstones have been buried by Mesozoic or recent sediments.

7.0 CLASSIFICATION OF FERRUGINOUS MATERIALS OF THE MT ISA REGION AND THEIR USE IN EXPLORATION

7.1 Introduction

Residual ferruginous materials are excellent sample media for Au and base metal exploration because they adsorb or incorporate pathfinder elements. Although anomalies in them are less intense than in the ore deposit itself, they are broad, allowing a greater sampling interval and a higher probability of detection during broad-spaced sampling (Smith *et al*, 1992; Anand *et al.*, 1993). However, ferruginous materials may be formed in a variety of substrates and are produced during different episodes and by different processes. Consequently, anomalies in ferruginous materials may not always be related to the underlying mineralisation. Their use needs an understanding of their distribution, characteristics and genesis.

The ferruginous materials of the Mt Isa region can be divided into several broad categories which relate to their history of formation:

(i) Lateritic duricrusts, nodules and pisoliths.

(ii) Ferruginous veins and horizontal bands. Ferruginous veins follow bedding planes and faults and are particularly common in Mesozoic cover. Ferruginous bands are redox fronts formed by oxidation of Fe^{2+} in sediments and saprolites.

(iii) Mottles in recent colluvial-alluvial cover.

(iv) Bedrock ironstones (BIF's, massive magnetite bands, gossans and oxidised pyritic sediments).

The use of these categories for geochemical exploration is described below with examples from several sites.

7.2 Lateritic duricrusts, nodules and pisoliths

Deep weathering profiles with lateritic duricrusts have developed and remain preserved on Proterozoic bedrocks in stable areas that have not been covered by Cambrian or Mesozoic sediments. Several different types of lateritic duricrusts occur. Massive, fragmental and nodular duricrusts are residual whereas slabby and vesicular duricrusts are formed by lateral transport of Fe. Mechanisms of their formation are described in Section 2 and criteria to distinguish residual from transported duricrusts are discussed in 7.6. Examples are from the Western Succession of the Mt Isa region at Python prospect and the Lady Loretta deposit (Anand *et al.*, 1996 (158R). Both occur on Proterozoic dolomitic siltstones of the MacNamara Group.

At the Python Cu-Au prospect, an extensive sheet of partly transported slabby duricrust and nodules and pisoliths has developed on Proterozoic dolomitic siltstones. Formation of nodules and pisoliths has been complex; they were developed in soils, locally derived colluvium and by collapse of underlying mottled saprolite. Slabby duricrust and nodules are anomalous in Cu, Sb, As and Pb; the Cu anomaly (>1000 ppm) is 1 km wide (Figure 7.1). The enrichment in partly transported duricrust sourced largely from the fault with some contribution from a distal source.

At the Lady Loretta deposit, patchily developed, residual, nodular duricrust is widely enriched in As, Pb, Ba, S, Zn and Sb and is related to underlying Pb-Zn-Ag mineralisation (Figure 7.2). This confirms that analysis of even widely-spaced residual duricrust samples may reveal base metal mineralisation below a deeply weathered surface.

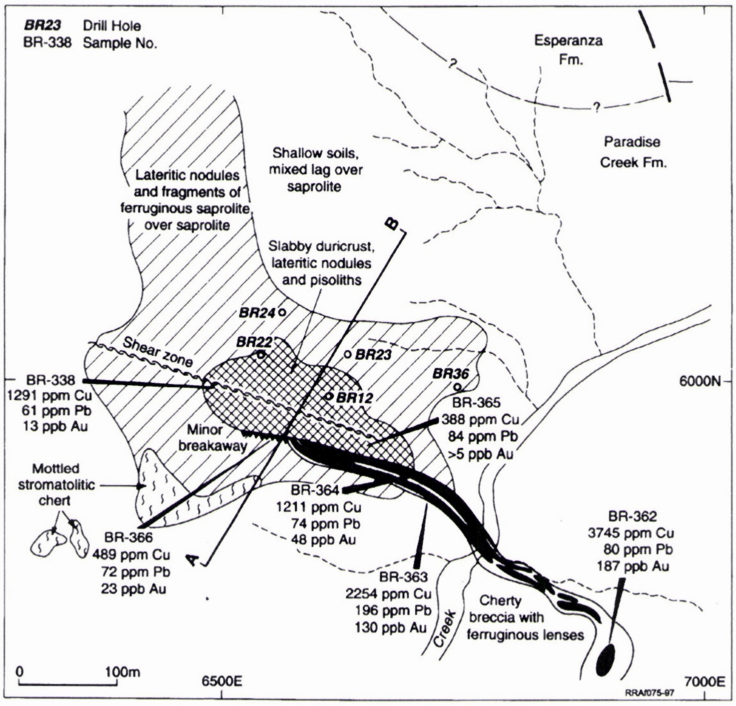

Figure 7.1 A map of the duricrust-capped rise at Python prospect with location of sampling points, drill holes and geochemical data (Coordinates are MIM Exploration grid) (After Anand *et al.*, 1996 (158R)).

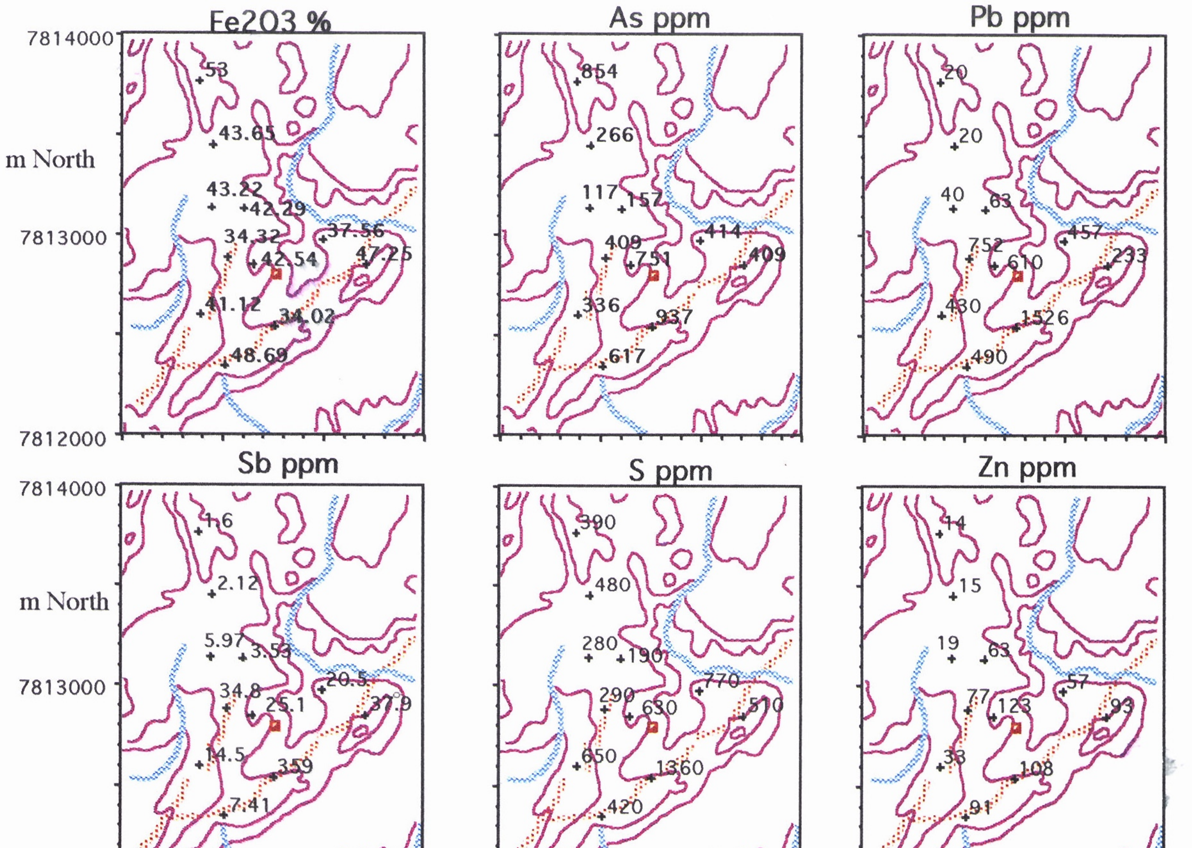

Figure 7.2. Geochemical maps for nodular, lateritic duricrust sampling at Lady Loretta, with topography (magenta), drainage (cyan), subcrop of the ore horizon (red), and the shaft (After Anand *et al.*, 1996 (158R)).

7.3 Ferruginous bands and veins

Pathfinder elements are commonly enriched in ferruginous bands that represent old watertables, aquifers and bedrock contacts. These materials are common in the Mesozoic sediments in the Eastern Succession near the Cannington mine. At the Brumby prospect, the Mesozoic sediments are up to 70 m thick (Anand *et al.*, 1996 (158R); Phang *et al.*, 1997 (429R)). Iron accumulates as sub-vertical structurally controlled veining in the Mesozoic sediments, as a horizontal surface at the interface with Proterozoic bedrock and within the sediments. The sub-vertical veining at Brumby was not anomalous in Au, Pb, Cu or Zn by bulk analyses or by partial extractions. Data from several company drill holes was available for Fe, Cu, Pb, Zn, Mn and Au which indicated a redox front (ferruginous band) at 25 m that contained up to 60% Fe_2O_3. The Mesozoic/Proterozoic boundary at 45 m has the second highest Fe concentration in the profile and Cu and Zn also accumulate at this interface (Figure 7.3). Gold and Cu at Brumby are sourced from minor mineralisation in the Proterozoic and their dispersion into the Mesozoic sediments is controlled by redox processes. Thus, ferruginous bands formed within sediments should be preferentially collected. These are more useful than structurally controlled ferruginous veins.

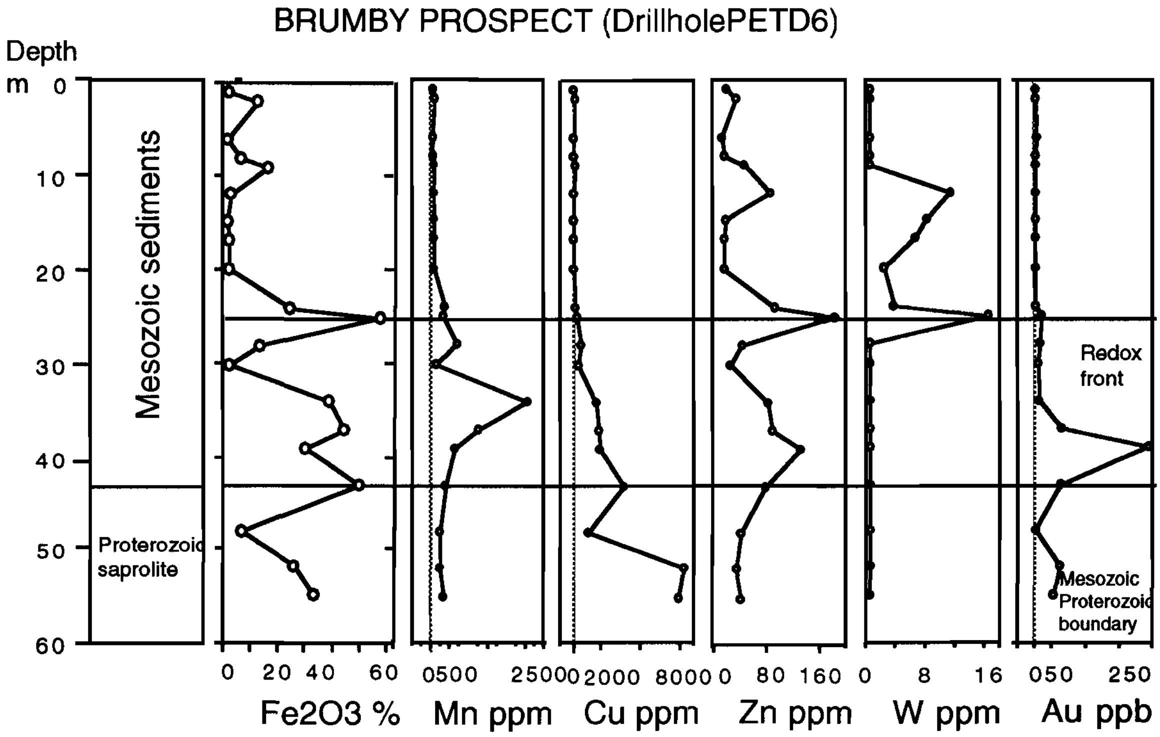

Figure 7.3. The distribution of Fe_2O_3 and trace elements, Brumby prospect (After Phang *et al.*, 1997 (429R)).

The Tringadee prospect, 7 km to the SE in a comparable area of Mesozoic sediments, has many similarities with Brumby (Anand *et al.*, 1996 (158R); Phang *et al.*, 1997 (429R)). Iron and Mn have accumulated Cu, Zn and Pb at old watertables marked by ferruginous bands in oxidised sediments. The Mn concentration is highest at 25 m where it reaches 47%; hollandite ($(Ba,K)Mn.Mn_7O_{16}$) was detected in the sample by XRD. Where the sediments have been preserved in reducing conditions, the old watertables are marked by horizontal black pyritic shales that also scavenge trace elements

(Figure 7.4). Drilling at Tringadee, has so far, not found a local source in the Proterozoic for the anomaly and it is assumed that the elements are derived hydromorphically from elsewhere.

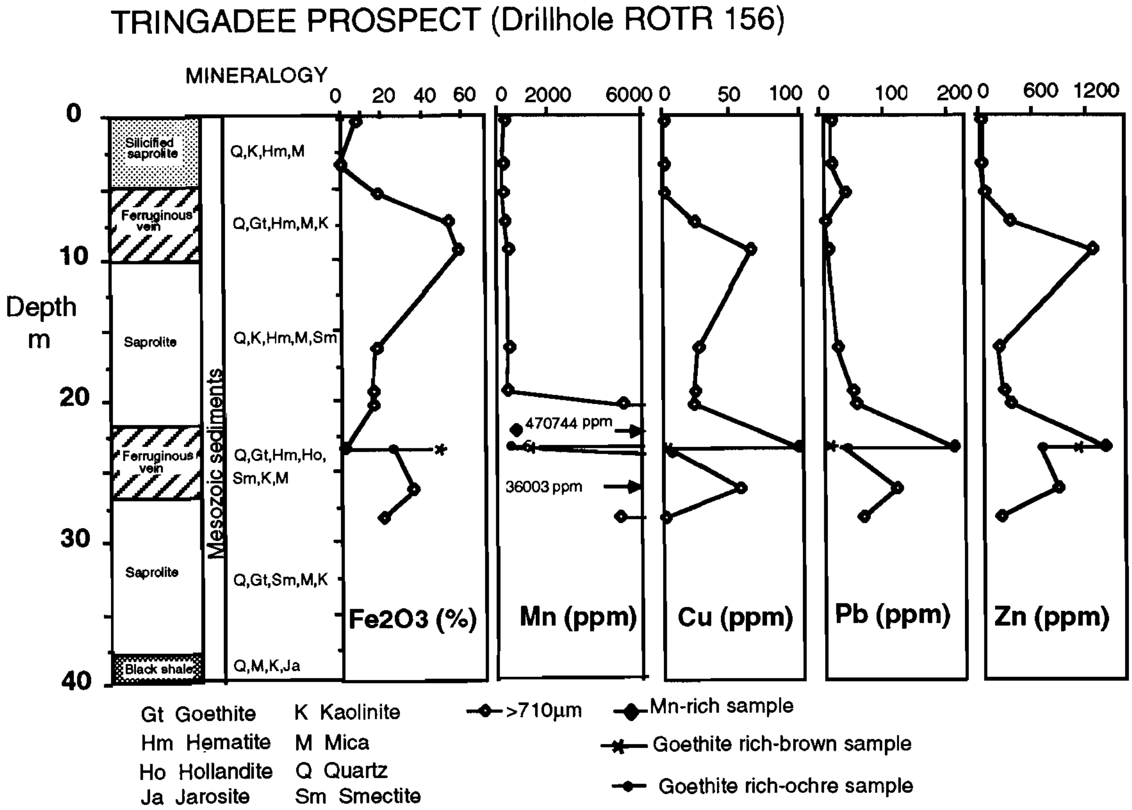

Figure 7.4. The distribution of Fe_2O_3 and trace elements, Tringadee prospect (After Anand *et al.*, 1996 (158R); Phang *et al.*, 1997 (429R)).

7.4 Mottling in recent colluvium

In many places, soils in alluvium have been subjected to pedogenic processes indicated by formation of mottles and incipient nodules. On valley floors, the watertable has fluctuated considerably, approaching the surface in wet months. The Fe of the mottles appears to scavenge pathfinder elements as at the Drifter prospect (Anand *et al.*, 1996 (158R)), where Fe occurs as ferruginous mottling. The sources of migrating Fe include lateral groundwater movement, *in situ* chemical breakdown of minerals and lithic clasts and hydromorphic dispersion from underlying bedrock either as a broad diffuse source, or as a localised source due to solutions moving along faults. Other elements (As, Sb, Cu) have been redistributed and concentrated with Fe as part of the mottling process. Hence, mottled alluvium has potential as a sampling medium for geochemical exploration.

7.5 Proterozoic ironstones

Proterozoic ironstones are linear and follow an underlying geological unit. This contrasts with lateritic duricrust formed in a weathering profile and essentially conformable to the landsurface.

The Cu-Au mineralisation at Selwyn occurs in massive Proterozoic magnetite bodies (Wildman, 1997 (341R)). Oxidation has produced goethite from primary chalcopyrite and altered magnetite to hematite. Most of the Cu has been leached to 50 m below the surface where it occurs as chalcocite and native copper. At the surface goethite after chalcopyrite contains 6,000 ppm Cu and the Au occurs as inclusions in quartz and hematite.

Pyritic shales at Grey Ghost contain Zn and Pb for a strike length of over 5 km. Goethitic gossan fragments form a ferruginous lag in many places and the anomaly shows in ferricretes in the immediate area.

7.6 Criteria to distinguish residual from transported duricrusts and other ferruginous materials

In assessing the origin of a particular ferruginous material, it is important to combine evidence from field relationships, chemistry, mineralogy and morphology. Preservation of bedrock structures, quartz veins or fabrics through the complete profile indicates an *in situ* origin of lateritic duricrust. In residual duricrust, there is generally a gradual transition between mottled saprolite and overlying duricrust. Nodules with angular shapes and diffuse external borders and those with similar framework grains within nodules and matrix materials have formed *in situ*. The nodules with thin goethite-rich yellowish brown cutans are believed to be confined to residuum or have undergone minimal transport. However, a large proportion of nodules and pisoliths with chipped or worn cutans may indicate transported materials.

Transported duricrusts (such as slabby and vesicular) formed by Fe impregnation of sands at seepages on edges of valley floors are goethite and Mn oxide-rich and generally lack kaolinite and hematite. The presence of quartz pebbles, zircon and heavy minerals may suggest their formation in distal alluvium.

The duricrust (e.g., pisolitic duricrust) formed by the local reworking (10-100 m) of residual duricrust is very similar to residual duricrust. However, the cement in locally reworked duricrusts is laterally derived goethite rather than a mixture of kaolinite, goethite and hematite.

Ferruginous bands are redox products the deposition of which are controlled by the watertable position within the profile. These redox products, dominantly goethite and /or Mn oxides-rich, occur as near horizontal layers and are related to fluctuations in the watertable and texture of the sediments. They are strongly developed in sandy sediments. The highly ferruginous nature of the Mesozoic/Proterozoic contact is due to the permeable layer of quartz-rich material, making the base of sediments a conduit for oxidising groundwaters for a long time. The extent of ferruginisation depends on the stability of the watertable and the availability of ferrous iron from local sources.

Ferruginous bands at watertables develop coarse textures possibly because the acid solutions transporting ferrous iron can dissolve kaolinite from the matrix of a saprolite or sediment but do not affect the coarse quartz.

The structurally controlled ferruginous veins in Mesozoic sediments follow tectonically induced partings that are at different angles to the bedding of sediments. The veining is hematitic and very low in Mn oxides, but contains significant amounts of kaolinite. Here, the solutions carrying ferrous iron were not acid enough to alter the mineralogy of host material except by dilution with Fe. This indicates a short term induration which might be expected in near vertical water movements.

Distinction between ferruginous veins and bands is essential because the latter is more useful as a geochemical sampling medium.

Proterozoic bedrock ironstones derived from magnetite generally have a characteristic microscopic martite pattern in the remnant hematite. For example, at Selwyn, the remnant hematite after magnetite ranged from blocky (5 cm) to sand sized (<1 mm) within matrix of quartz (Wildman, 1997 (341R)). At both Selwyn and Grey Ghost, the ironstones conform to the steeply dipping Proterozoic bedrocks and sufficient saprolite fabric remained to suggest that the iron was derived from the bedrock.

7.7 Conclusions

The ferruginous materials described from North Queensland have, in many cases, accumulated pathfinder elements from mineralisation, indicating their usefulness in exploration. However they occur sporadically in the landscape and are generally not sufficiently common to provide a consistent sample media. Where they occur, they have to be assessed relative to their landscape position and geological environment, to determine whether they are lateritic duricrust, gossans or fault ironstones or whether they were formed from watertables (ferruginous bands) or structurally controlled ferruginous veins. Dispersion can then be described in terms of bedrock, hydrology and landscape and an exploration strategy developed.

8. CHARTERS TOWERS-NORTH DRUMMOND BASIN REGION: GEOMORPHOLOGICAL LANDSCAPE PROVINCES AND LANDSCAPE EVOLUTION

8.1 Introduction

A variety of sedimentary cover sequences, including the Campaspe, Southern Cross and Suttor Formations, occurs in the Charters Towers-north Drummond Basin. Because of their widespread distribution, there is considerable interest in the use of these sediments as geochemical sampling media. However, sedimentary cover presents formidable challenges to exploration because of (i) its allochthenous origin (exploration strategy has relied on drilling through the cover into bedrock) and (ii) it has been subjected to post-depositional weathering and diagenesis. Notwithstanding this, older cover sequences might have potential for mechanical or chemical dispersion from underlying mineralisation.
Thus, it is necessary to understand the influences that weathering and landscape evolution in northeast Queensland have had on element dispersion into the regolith and use this to guide exploration programmes.

8.2 Regional setting

The study area (20° 04' 30" to 21° 36' 30" S; 145° 57' 30" to 147° 40' 30" E) covers parts of the Charters Towers, Bowen, Mt Coolon and Buchanan 1:250 000 scale map sheets (Figure 8.1).

The pre-Tertiary geology is sub-divided into the Ravenswood Arch, Anakie Inlier, Drummond Basin, Bulgonunna Block and the Galilee Basin. The rocks of the Anakie Inlier and Ravenswood Arch are essentially basement to the sediments of the Drummond Basin which are, in turn, overlain by volcanics (Bulgonunna Block) and younger sediments (Galilee Basin). Two Cainozoic sediment systems are developed within the area; an older system, the Southern Cross and Suttor Formations and, a younger system, the Campaspe Formation.

A large proportion of the region, comprising undulating hills of Palaeozoic rocks, is covered by a thin veneer of soil. Deep weathering and extensive Cainozoic cover occur across parts of the region, and are divided into two main landforms (Grimes, 1979; Henderson and Nind, 1994):

(i) dissected plateaux and mesas overlying sediments of the Southern Cross and Suttor Formations;

(ii) flat-lying sheets of fluviatile sediments, the Campaspe Formation, infilling areas of low topography.

There are several major catchments that dominate the landscape of the study area, all of which belong to the Burdekin River system. The Burdekin and Campaspe rivers are in the north; the Cape and Belyando Rivers are in the west and the Suttor river is in the south. These rivers have given the area dominant erosional characteristics, with a progressive lowering of base-level towards the east and north-east.

The climate of the region is tropical semi-arid. Annual rainfall is 550-750 mm; however, falls over the past ten years have been substantially less than normal. Most rain falls in the summer months, and is typically associated with coastal cyclonic disturbances. Daily temperatures range from 21-35°C in December, to 7-26°C in July. The vegetation over the area consists predominantly of open woodland and grassland savannah, dominated by eucalyptus, acacia and spear grass.

This section summarises the regional geomorphological provinces, characteristics and evolution of regolith developed on sediments (Southern Cross, Campaspe and Suttor Formations) and basement lithologies, based on studies at Red Falls, Featherby Walls, Waterloo, Pajingo, and Police-Creek-Mt Coolon (Figure 8.2). The studies included regolith mapping and regolith characterisation at local and district scales. It has been recognised by our research and that of Aspandiar *et al.*, (1997) that the landscape of the region is a product of several sedimentation and weathering episodes. In places, it is difficult to ascertain whether the sedimentary rocks are those of the Southern Cross or the Campaspe Formations. This report uses formal names for the sedimentary cover sequences for the sake of simplicity.

8.3 Mapped geomorphological provinces

The area has been subdivided, on the basis of landforms, into seventeen geomorphological provinces, each with particular regolith characteristics (Figure 8.2; Table 8.1). These geomorphological-regolith provinces were delineated using photoform, drainage and other textural features identified on processed Landsat TM imagery (Fraser, 1997 (366R)). The resulting interpretation is a broad-scale regional subdivision of the landscape. For explorationists, the map is a guide to assist in area-selection and formulating exploration strategies. For regolith researchers, the map provides a framework for more detailed investigation. For geochemical surveys at tenement or prospect scales, a more detailed subdivision of the landscape would be required than that presented here.

Because the nature of the landsurface is critical in determining an appropriate geochemical exploration strategy, the mapped geomorphological-regolith provinces were grouped into regolith-landform units, which broadly convey information regarding the nature of the surface, and the state of preservation of weathered material. Three terrain types have been identified: duricrust-dominated terrain, saprolite-dominated terrain and alluvium-and colluvium-dominated terrain.

8.3.1 Duricrust-dominated terrain

In this group (units UPS, RSm, RSc, UFP and Sil), ferruginous duricrust material is preserved. There is little evidence for widespread development of duricrust on basement lithologies (with the exception of the silcrete unit, Sil). Intact (nearly) weathering profiles are more common on the younger Tertiary sediments (units UPS,UFP, RSm and RSc).

Unit Sil represents a silcrete preserved as mesas capping granitic lithologies in rugged, dissected terrain, south of the Burdekin Dam.

8.3.2 Saprolite-dominated terrain

The saprolite dominated terrain (MRR, FeI, UCLG, LRSH, SUH1, TSBS-L and SEDS) have had their weathering profiles eroded or substantially stripped.

The rugged MRR province represents an end-member of this group characterised by moderate - to-high relief, with only relatively thin or localized vestiges of saprolite. Provinces FeI and UCLG represent the other extreme, with undulating, lower relief landscapes typically developed on "granitic" lithologies.

Provinces LRSH, SUH1 and TSBS-L tend to occur over basement lithologies. The LRSH and TSBS-L provinces occur over meta-sediments, with various basement structural trends evident on the Landsat imagery. Structural trends are less well preserved in province SUH1; its undulating, rounded appearance suggests that it is more eroded than either LRSH or TSBS-L.

The SEDS province represents Mesozoic sediments, which occur as inliers on the western side of the study area.

8.3.3 Colluvium and alluvium-dominated terrain

Provinces A/F, SW/SS, CDA, EUP and UC are dominated by alluvium and colluvium where Quaternary sediments have been deposited over older units. These more recent sediments are derived from erosion of the Southern Cross Formation, Campaspe Formation and basement lithologies.

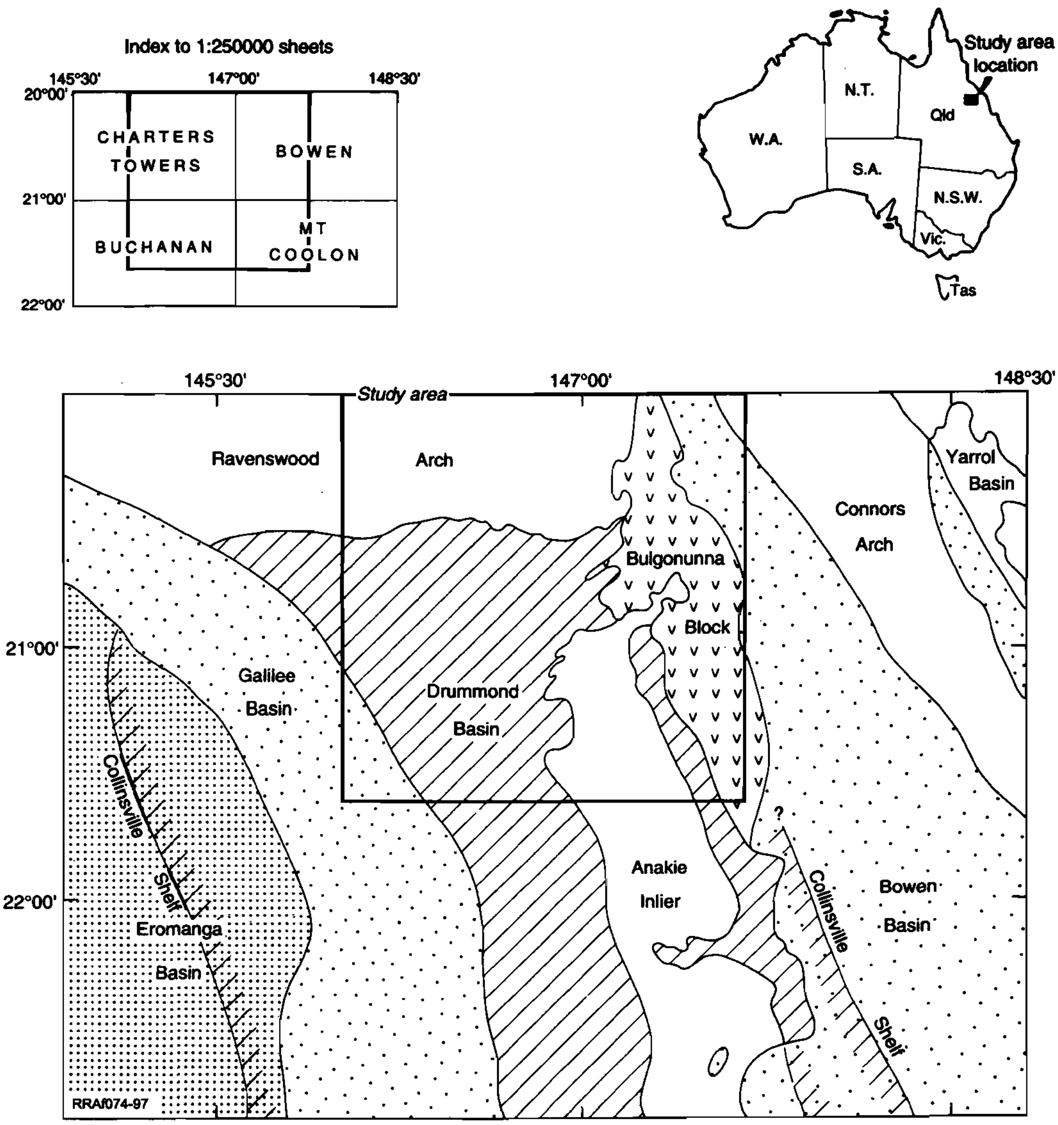

Figure 8.1 Location of the study area and structural setting, Charters Towers-North Drummond Basin.

LEGEND

Geomorphic Provinces

Duricrust Dominated

UPS
Undulating plateau surface, with moderate elevation, bounded by steep scarps

UFP
Undulating flat plains of sediments (Tertiary Campaspe Fm ?); now being reworked(sheetwash and bedload re-working of pre-existing sediments

RSm
Remnant sedimentary mesas, typically with plateau tops, bounded by scarps unless they abut higher ground (partially dissected UPS unit)

Sil
Silcrete developed as capping on granitic terrain

RSc
Remnant sedimentary cover, level or sloping terrain with low mesas or their dissected remains (strongly dissected UPS)

Saprolite Dominated

MRR
High-to-moderate relief, rugged terrain; bedrock characteristics evident

SUH1
Strongly undulating, rounded hilly terrain, low-to-moderate relief, exposed basement.

FeI
Strongly dissected low terrain with iron staining; mafic intrusives(?)

TSBS_L
Thin soils on basement sediments; low relief. (structure).

UCLG
Undulating, strongly dissected granitic terrain

SEDS
Slightly elevated, dissected sediments with trellis drainage patterns; flat-lying inlier

LRSH
Thin soils on basement sediments, moderate relief,strike ridges. (structure)

Alluvium and Colluvium Dominated

A_F
Alluvial plains associated with present day drainages; some sediment re-working

UC
Relatively flat undulating plains with low rises/hills, predominately relict transported surficial detritus, now being reworked

CDA
Rolleston River Catchment: an almost choked catchment with detritus derived from erosion of Tertiary sediments.

Sw_SS
Moderate to steep terrain; sheet wash areas & colluvium

EUP
Slightly elevated undulating plains, bounded by scarp margins

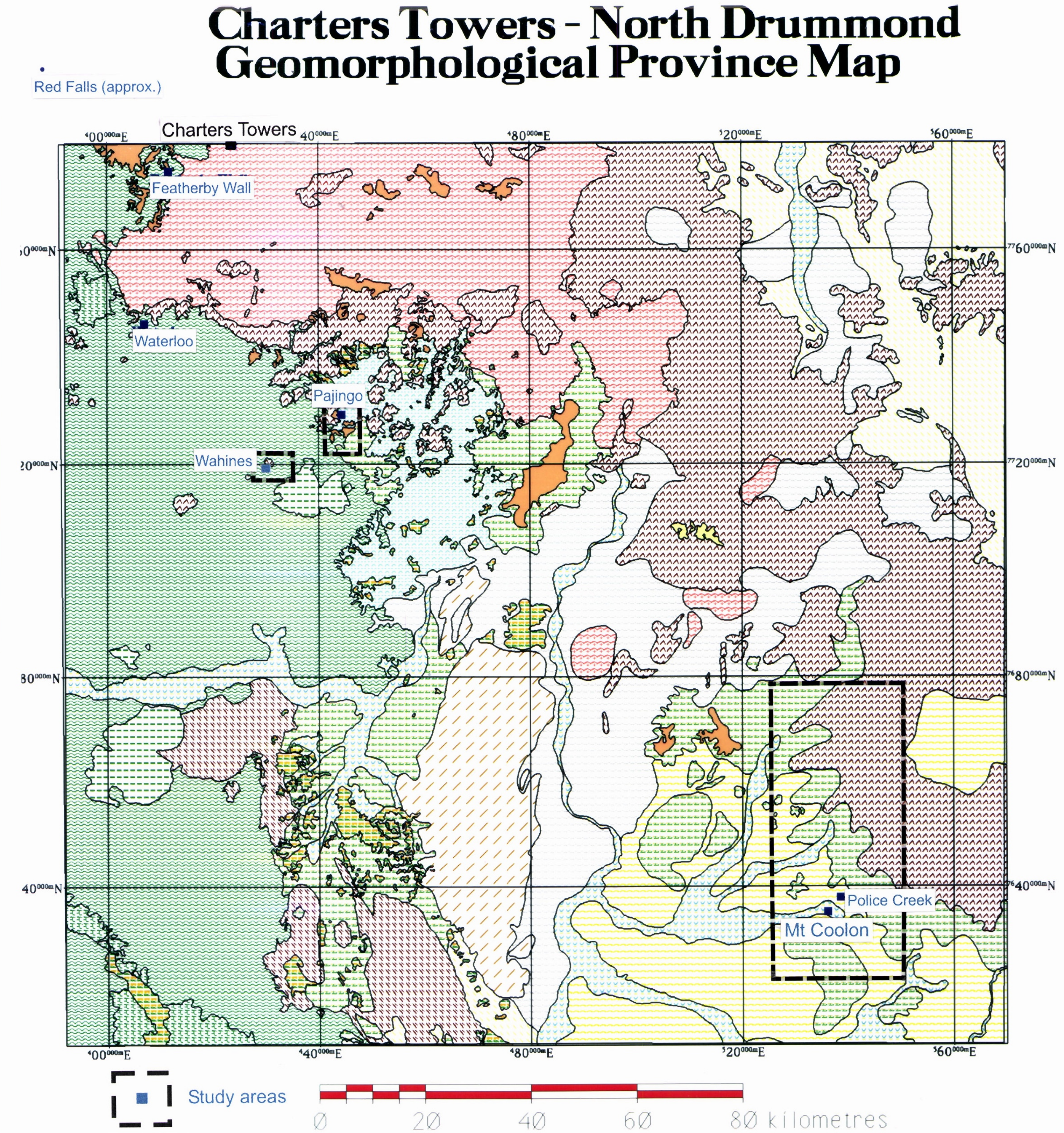

Figure 8.2 Map of geomorphological provinces-Charters Towers-north Drummond Basin (After Fraser, 1997 (366R)).

Table 8.1 : Geomorphological descriptions and regolith characteristics for the mapped geomorphological units belonging to the duricrust, saprolite, and alluvium and colluvium dominated terrains of the Charters Towers-north Drummond Basin (After Fraser, 1997 (366R)).

Duricrust Dominated Terrains

Province	Geomorphological Description	Regolith Observations
UPS	Undulating plateau surfaces, with moderate elevation, commonly bounded by scarps	Ferruginous duricrust present; some residual sand developed on mesas, plateaus, backslopes. (Southern Cross or Suttor Formations)
RSm	Remnant sedimentary mesas and benches, typically with flat plateau tops, bounded by steep scarps	Mesas commonly with preserved weathering profiles, but not everywhere; (may be related to either Campaspe or Southern Cross Formation)
RSc	Remnant sedimentary cover, level or sloping with low mesas and/or their dissected remains	Dissected sedimentary cover, may contain partially preserved weathering profiles; (may be related to either Campaspe or Southern Cross Formation)
UFP	Undulating flat plains of sediments (perhaps Tertiary Campaspe Formation); now being re-worked by cross-cutting streams and encroaching catchment expansion; sheetwash and bedload re-working of pre-existing sediments	Extensive plains, with surficial sheetwash and soil development. Sediments may include a layer of ferruginous nodules that overlie a buried, weathered profile. (Campaspe Formation ?)
Sil	Mesa(s) cappings on elevated terrain	Silcrete preserved as capping on elevated "granitic" ? terrain

Saprolite Dominated Terrains

Province	Geomorphological Description	Regolith Observations
MRR	Moderate-to-high relief, rugged terrain; strike-ridges evident.	Minor lithosols and colluvium on slopes, alluvium in valleys is removed with little accumulation, rate of sediment production approx. equals rate of sediment removal
FeI	Strongly dissected low terrain	Strongly weathered mafic intrusives, ferruginous soils and ferruginous saprolite preserved (?)
UCLG	Undulating country, consisting of strongly dissected (eroded) granitic terrain	Some preservation of saprolite on hills and topographically higher areas, thin lithosols.
LRSH	Moderate relief terrain, with linear strike ridges	Thin lithosols and colluvium on ridges and slopes; alluvium in valleys. Basement structural trends are evident. Remnant outliers of weathered basement preserved?
SUH1	Strongly undulating, rounded, hilly terrain, low-to-moderate relief with exposed basement	Lithosols and colluvium on slopes, alluvial material in valleys; Remnant outliers of weathered basement preserved?
TSBS_L	Thin soils on basement sediments; low relief; strike-ridges	Lithosols and colluvium on slopes. Thin cover as basement structural trends evident. Remnant outliers of weathered basement preserved
SEDS	Slightly elevated, dissected sediments with trellis drainage patterns; flat-lying (inlier within UFP unit)	Lithosols and colluvium on slopes, alluvium in valleys; rate of sediment production approximately equals rate of removal

Alluvium and Colluvium Dominated Terrains

Province	Geomorphological Description	Regolith Observations
A/F	Alluvial plains associated with present day drainages, some sediment re-working	Detritus derived from erosion of Palaeozoic, Mesozoic and Cainozoic lithologies
SW/SS	Moderate-to-steep terrain; sheet wash areas.	Areas with active erosion and detritus throughput; unlikely that weathered profile materials have survived
CDA	Rolleston River Catchment: complex landscape.	Recent alluvial and colluvial material; sediment production exceeds rate of removal; sediments derived from erosion of Tertiary sediments
EUP	Slightly elevated, undulating plains, commonly bounded by scarps,	Areas of black soil with gilgai development, - possibly remnant lake deposits, (caused by ponding within drainages)
UC	Relatively flat, undulating areas with low rises/hills.	Predominately recent alluvium and colluvium covering basement and overlying sedimentary units (Suttor /Southern Cross/Campaspe Formations)

8.4 Regolith

8.4.1 Southern Cross Formation

The Southern Cross Formation forms an extensive blanket over the northern Drummond Basin and the Lolworth-Ravenswood Block (Figure 8.2). It has been extensively dissected and is partly covered by younger sediments. The weathering profile on the Southern Cross Formation is variable. In some places, the Southern Cross Formation is partly eroded into breakaways, exposing underlying mottled sediments and mottled basement (Campbell, 1996 (286R)) (Figure 8.3A,B) but, in other areas, deep red or yellow earths are underlain by mottled sediments. Pisolitic duricrust is limited to the local high areas on the plateaus and mesas, where incision of the plateaux has increased drainage. Ferruginisation occurs throughout the top few metres of the profile but pisoliths are present in the top half metre. Some pisoliths are detrital, being derived from older profiles, and others have formed *in situ.* The duricrust exposed in breakaways appears thicker, due to recent Fe crusting of the outer 10 cm of mottled saprolite. In places, for example at Featherby Walls (Figure 8.2), the top of the megamottled zone forms a pock-marked surface due to removal of the soft clay material between the more Fe-rich areas.

The Southern Cross Formation at Pajingo consists dominantly of massive, kaolinitic clays and shales with cobbles of weathered volcanic material and vein quartz. Gross bedding of cobble rich horizons occur towards the top of the colluvium in the Scott Pit, but it seems that all fine sedimentary features, that may have originally existed, have been obliterated by weathering. The profile has been overprinted by several redox fronts where Fe oxides have precipitated as goethite and hematite.

The sediments forming the Southern Cross Formation in the Pajingo area are locally derived (Campbell, 1996 (286R)). The lateritised surface is bounded by escarpments to the north, south and east of the Mount Janet Range. Its relief and form suggests that the Southern Cross Formation surrounded the Mt Janet Range but did not cover them. Quartz veins of the Scott Lode probably were never completely covered by the Southern Cross Formation, so that these veins shed material into the Southern Cross Formation at several levels.

A palaeochannel, filled with Southern Cross Formation and incising the volcanics, is exposed at Scott pit. Sediments in the palaeochannel are dominated by kaolinite, weathered volcanic cobbles and pisoliths probably derived from breakdown of an earlier lateritic profile. The Southern Cross Formation is strongly mottled

8.4.2 Campaspe Formation

The Campaspe Formation is dominated by sands with a minor interbedded silts and clays and covers much of the northern Drummond Basin and the Lolworths-Ravenswood Block. In many areas, the Campaspe Formation has limited outcrop as it occurs in low, subdued parts of the landscape and it lacks breakaways.

The profile exposed at Red Falls (type section; Wyatt *et al.*, 1970) is one of the few places where the Campaspe Formation overlies the Southern Cross Formation (Figure 8.3C). Here, the Campaspe Formation is about 14 m thick and consists of yellow earths, ferruginous gravels, mottled quartz-rich sediments and sands within a clay-rich matrix. The sands unconformably overlie the red, mottled Southern Cross Formation and show bedding and cross-bedding (Figure 8.3D). Cementing of quartz-grains by Fe oxides occur at the top of the profile. This ferruginous horizon degrades to a lag composed mainly of 2-25 mm ferruginous gravel, mainly of Fe-stained and cemented sandstone with some large, angular quartz fragments, pisoliths and nodules which in places are cemented by goethite into nodular duricrust. In contrast, the mottled southern Cross Formation consists of gritty sandstone and lacks sedimentary structures.

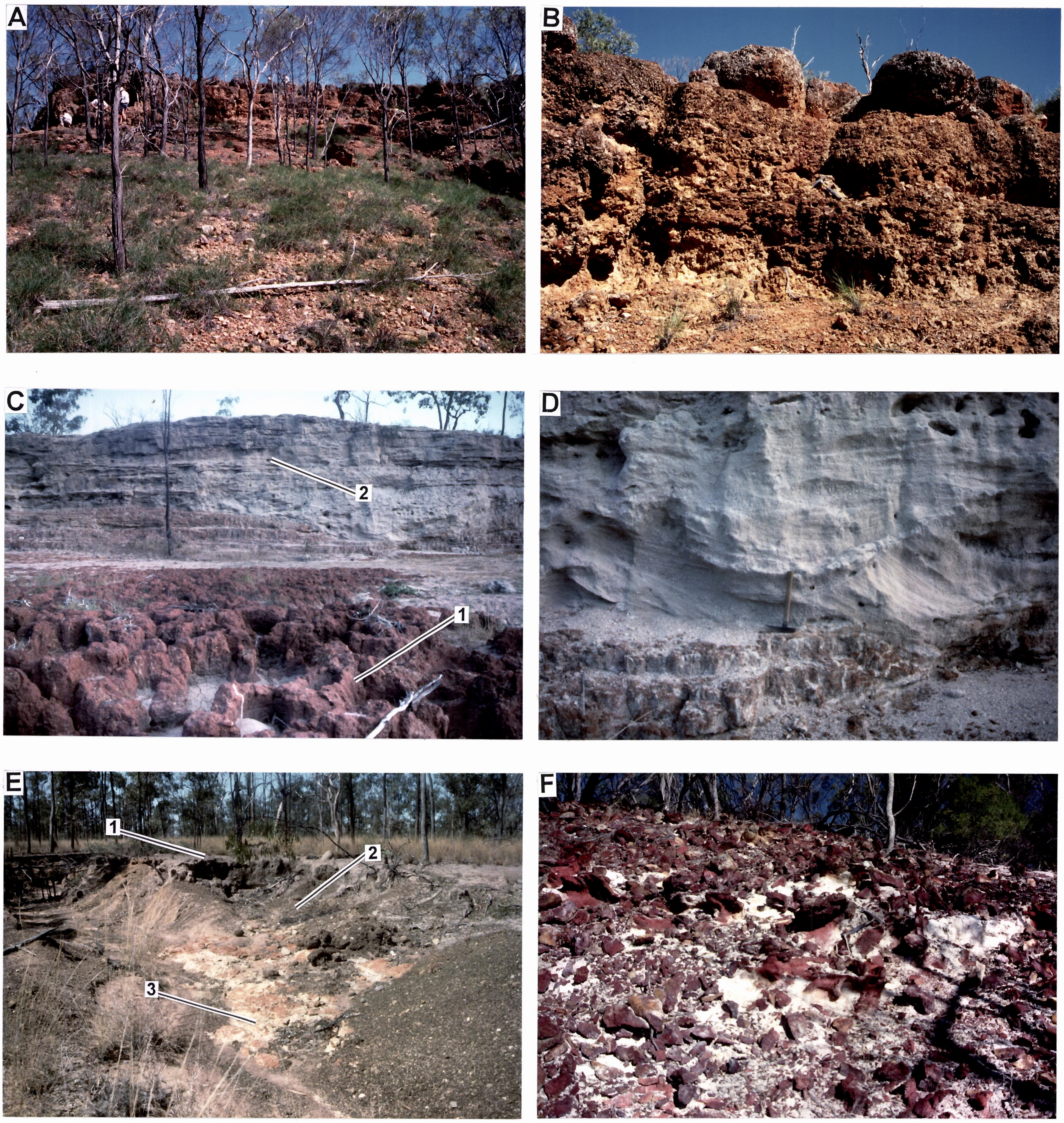

Figure 8.3. Regolith profiles developed on Southern Cross, Campaspe and Suttor Formations (A) Typical escarpment at the edge of Southern Cross Formation plateau. Most of the escarpment is of mottled sediments. Lateritic duricrust outcrops at the very top of escarpment, set slightly back from the edge, Pajingo area. (B) Breakaway on a lateritic profile developed on the Southern Cross Formation. Mottling increases towards the top of the profile and the top metre is of lateritic duricrust, Pajingo area. (C) At Red Falls, the Southern Cross Formation is deeply weathered and ferruginised (1) forming the channel bed. The Campaspe Formation is exposed in the valley wall (2). (D) Cross bedding at base of Campaspe Formation, Red Falls. (E) Erosion Gully at Waterloo prospect showing grey soil (1) over weakly cemented pisoliths which, in turn, overlies mottled sediments (3). (F) Mottling of the Suttor Formation sediments, Mt Coolon area.

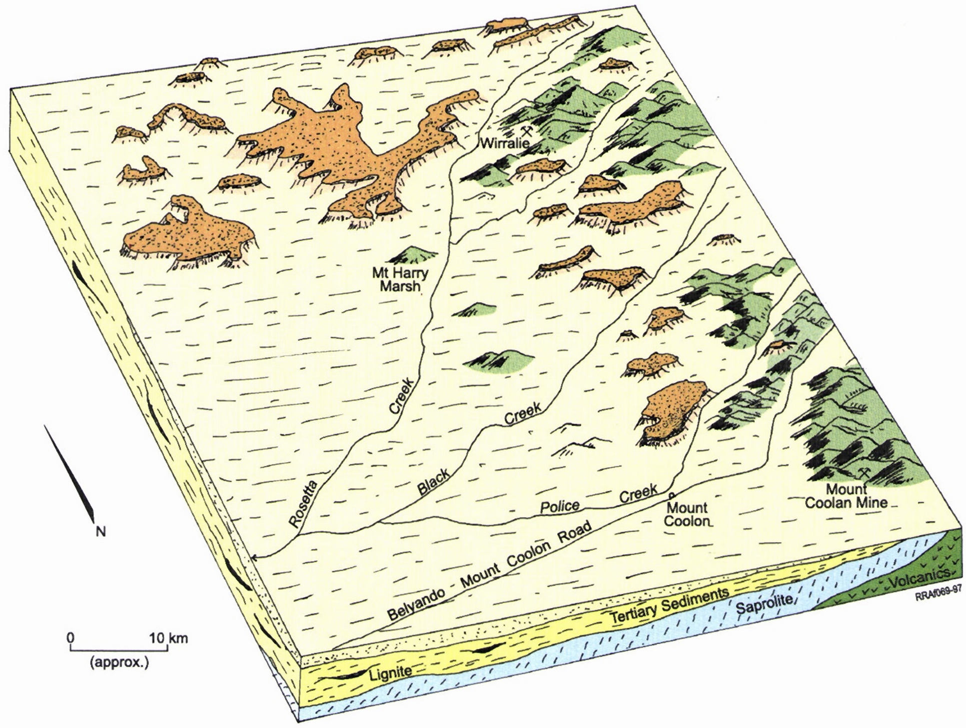

Figure 8.4. Block diagram showing landforms in the Mt Coolon area. A large part of the area is an alluvial plain formed by deposition of sediments brought down by Police Creek, Black Creek and Rosetta Creek. Ferruginised Tertiary sediments and saprolite on basement rocks form mesas. The eastern part of the area is dominated by hills of bedrock. (After Li Shu, 1997 (448R)).

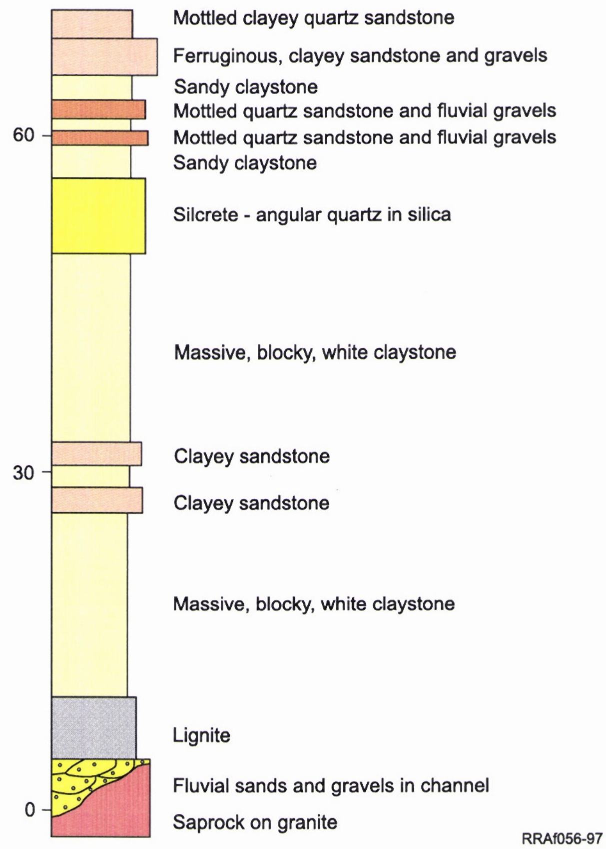

Figure 8.5. Type profile of Tertiary sedimentary units at Rutherfords Table, 25 km north of the Wirralie mine. The lower part of the profile can be seen only in the mine shaft. (After Li Shu, 1997 (448R)).

A similar profile in the Campaspe Formation occur at the Waterloo prospect, Pajingo and many parts of the Charters Towers-north Drummond Basin. For example in an erosion gully at the Waterloo prospect, grey brown soil (0.3 m) overlies weakly cemented nodules (0.5 m) which, in turn, overlie a conglomeratic greywacke with angular and sub-rounded quartz clasts and grains cemented by drusy silica (Figure 8.3E). The nodular and pisolitic material is cemented by Fe and Mn oxides. There appears to be two types of nodules and pisoliths. Some are detrital, with broken edges, but the majority were formed *in situ* in the soil or its substrate. The surfaces of nodules and pisoliths have goethite-rich cutans. In some places, massive duricrust has formed instead of pisoliths, over relatively fresh sediments, without any deep weathered profile. The minor weathering of the substrate suggests that Fe in these pisoliths and duricrusts came from the surrounding uplands, rather than from the basement below the Campaspe Formation.

At the Wahines prospect, the Campaspe Formation occurs in low, subdued parts of the landscape. It is about 30 m thick and is rich in detrital pisoliths derived upslope from erosion of lateritic profiles on the Southern Cross Formation (Campbell, 1996 (286R)). There are also zones of Fe concentration at palaeo-watertables where, the Campaspe Formation has been silicified to silcrete at a fairly consistent depth of 17-30 m. The silcrete shows several phases of silica precipitation following feldspars breakdown and etching of quartz grains. Initial silicification was by clean silica with little Fe, Al or Ti from an external silica and from local silica derived locally from feldspar weathering in the Campaspe Formation. Later silica was precipitated with Fe and Al; goethite and kaolinite are surrounded by later growths of silica. The last stage of silica precipitation was off-white, containing some Fe.

In the Wahines area, the Campaspe Formation is covered by up to a 4 m of black soil of smectite, quartz and kaolinite. The black soil directly overlies well-sorted coarse sands of the Campaspe Formation, with only a thin lithosol at the boundary.

8.4.3 Suttor Formation

The Drummond Basin contains a thick sequence of unlithified Tertiary sediments with lignite lenses, known as the Suttor Formation, interpreted to be an equivalent to the Southern Cross Formation in the Charters Towers area (see Li Shu, 1997 (448R)). The Suttor Formation was studied in the Police Creek-Mt Coolon area, where it forms discontinuous tracts of isolated mesas and low rises on alluvial plains, or infills valleys beneath younger alluvial material (Figure 8.4). The Suttor Formation can reach a maximum thickness of 120 m (Day, 1981; Strickland, 1993). Around Mt Coolon, it forms mesas 5-25 m high standing on saprolites of basement rocks. At Rutherfords Table, immediately to the north of the study area, the sediments are 73 m thick and form a large mesa (Figure 8.5). In the west, however, the Suttor Formation occurs beneath an alluvial plain.

The Suttor Formation has been intensely weathered (Li Shu, 1997 (448R)). Ferruginisation and silicification occur throughout the whole profile, with duricrusts developed at the top. At Black Creek, a fine to coarse cross bedded quartz sandstone with fluvial gravels forms a bluff about 7 m high (Figure 8.6)) where the Suttor Formation is highly ferruginised with mottles and megamottles developed (Figure 8.3F). Duricrusts have formed at the top part. A lag of ferruginous nodules, pisoliths and fragments of broken mottles occur at the top of the mesas or surround them.

Part of the fluvial sediments has been bleached to white clay (kaolinite). Where silica or iron has been moved hydromorphically, the bleached sediments have been converted to silcrete. Field evidence and petrography show that some silcretes have subsequently been de-silicified. The complicated weathering processes obscure the original sedimentary structures and make field identification of parent rocks difficult. Weathering of diverse parents, such as Devonian sandstones or granites, result very similar products.

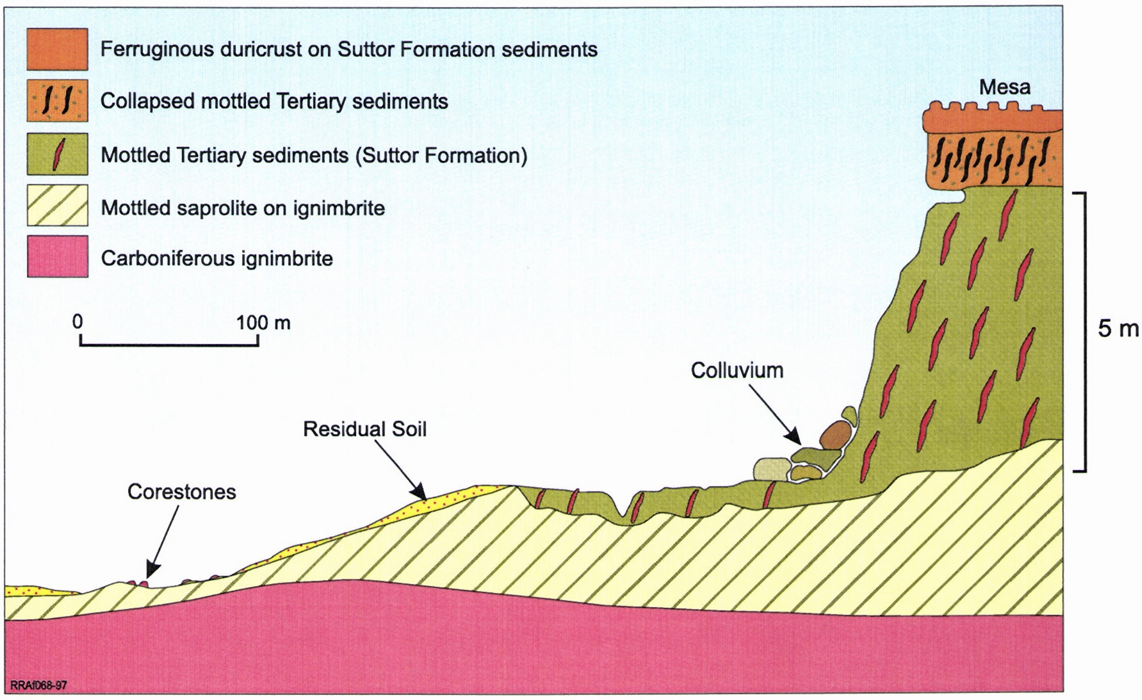

Figure 8.6. Section of duricrust-capped Suttor Formation at Black Creek. (After Li Shu, 1997 (448R)).

8.4.4 Recent sediments

Alluvium is extensive in low lying areas and ranges from boulder gravels to massive clays up to 4 m thick. Most exposures have basal gravels that fine upward to massive silts. The alluvium is well sorted but mineralogically immature, with common cobbles of weathered volcanics and vein quartz. Ferruginous pisoliths occur in the alluvium, presumably derived from erosion of the weathered volcanic and Tertiary sediments. It is likely that many of the cobbles in the alluvium are inherited from the Southern Cross Formation and are multicyclic. The size distribution in alluvium of the modern creeks is bimodal, with well-sorted coarse sands and cobbles of volcanics. This contrasts with the palaeo-alluvium exposed in the gully walls.

Soils are extensively developed on the alluvium. The dominant soil processes is eluviation of the clay fraction in the A horizon to the well-defined B horizon.

Weathering of Quaternary sediments also occurred at the Police Creek prospect and nearby Wirralie mine with small incipient mottles in the sediments under soil profiles. Recent sediments are also found silicified along the beds of many modern creeks, indicating the process of silicification is still active.

8.4.5 Basement rocks

In the Pajingo area, remnants of a poorly formed lateritic profile occur on the Devonian volcanics at a similar altitude as lateritic profiles on the Southern Cross Formation. The height concordance over small distances and the similarities of the profiles imply a single planation and lateritisation event. Its surface expression is an Fe-rich pisolitic duricrust similar to that developed on the Tertiary sediments but lacking in cobbles. The duricrust is dominantly hematite, with some goethite, gibbsite and kaolinite cementing the pisoliths. There is no natural sectional exposure, so its substrate could not be determined.

Mottled saprolite on volcanic rocks is equivalent to mottled Tertiary sediments. Mottles are confined to one horizon and the mottling is much more intense than on the Tertiary sediments. The mineralogy is similar to that of the mottled sediments and distinguishing between the two can be difficult; generally the vegetation on this unit tends to be more sparse than on the mottled sediments. In places, mottles have been broken into a very coarse lag.

In the Mt Coolon area, profiles on basement rocks, in particular the Ankie Metamorphic sandstone and siltstone have weathered to mottled saprolite or silcrete. Granite or ignimbrite, whose dark minerals are weathered and bleached are transformed into white, silicified saprolite. These deeply weathered saprolite as Tertiary sediments form mesas, which, where intensely weathered have similar characteristics and can be difficult to differentiate in the field. This provides a dilemma when mapping using aerial photographs.

8.5 Weathering geochronology

The deep weathering profiles exposed at the Scott Lode gold deposit were sampled in detail (Vasconcelos, 1997 (452R)). Manganese oxides and K-bearing sulphates (alunite and jarosite) occur throughout but only selected benches could be sampled due to safety reasons. No mineral suitable to $^{40}Ar/^{39}Ar$ geochronology occurred in the ferruginous channel deposits (Southern Cross Formation) overlying the mineralised volcanic rocks so only weathering of the underlying volcanic bedrock could be investigated. Manganese oxide samples were collected along the mine access road bench and at approximately 20 m and 60 m below the mine access road level. Thirty-eight grains from 13 Mn oxide samples were analysed by the $^{40}Ar/^{39}Ar$ laser-heating method and four grains from 2 jarosite hand specimens from approximately 20 m below the mine access road level.

Remarkably reproducible results were produced from the 13 Mn oxide samples analysed (in excess of 500 individual analyses) (Figure 8.7). Plateau ages ranged from 3.9 ± 0.1 Ma at the bottom of the pit to 16.2 ± 0.2 Ma at the uppermost part of the weathering profile at the western edge of the pit. The ages from jarosite were also remarkably reproducible. Only one jarosite grain yielded a plateau age (4.5 ± 0.1 Ma); the other three grains displayed a plateau-like series of steps at low temperatures, but the ages were unreasonably great at high temperature. The climbing spectra suggest that the jarosite grains are intermixed with unweathered or partially weathered hypogene silicates.

One Mn oxide sample from the Scott Lode was also dated by the K-Ar bulk method. The age (39.5 ± 2 Ma) is drastically different from the $^{40}Ar/^{39}Ar$ ages. The only explanation for the discrepancy is the presence of contaminants.

Weathering profiles overlying the Mount Leyshon and Kidston ore deposits were dated by K-Ar analysis of alunite (Bird *et al.*, 1990). The results for Kidston (1.85 ± 0.04, 1.61 ± 0.04, 1.52 ± 0.03, 3.91 ± 0.07, 4.1 ± 0.2 Ma) and Mount Leyshon (3.1 ± 0.2 and 4.1 ± 0.1 Ma) indicate Plio-Pleistocene ages, surprising given the long history of weathering in the region (Bird *et al.*, 1990). The $^{40}Ar/^{39}Ar$ ages for jarosite samples of this study (plateau age of 4.5 ± 0.1 Ma and plateau-like steps at 3.2 ± 0.1 and 2.7 ± 0.1 Ma) are consistent with these young ages.

However, Mn oxide $^{40}Ar/^{39}Ar$ ages indicate a longer history of weathering than suggested by $^{40}Ar/^{39}Ar$ jarosite or alunite ages. The Mn oxides dated in this study fill cavities and desiccation cracks in kaolinitised volcanic rocks, indicating that the host sequence was already strongly weathered at the onset of Mn oxide precipitation, at approximately 17 Ma. It is significant that Mn oxide ages are greater (10-17 Ma) at shallower horizons and younger precipitation ages are recorded at the bottom of the profile (4-6 Ma), indicating a downward propagation of the weathering front.

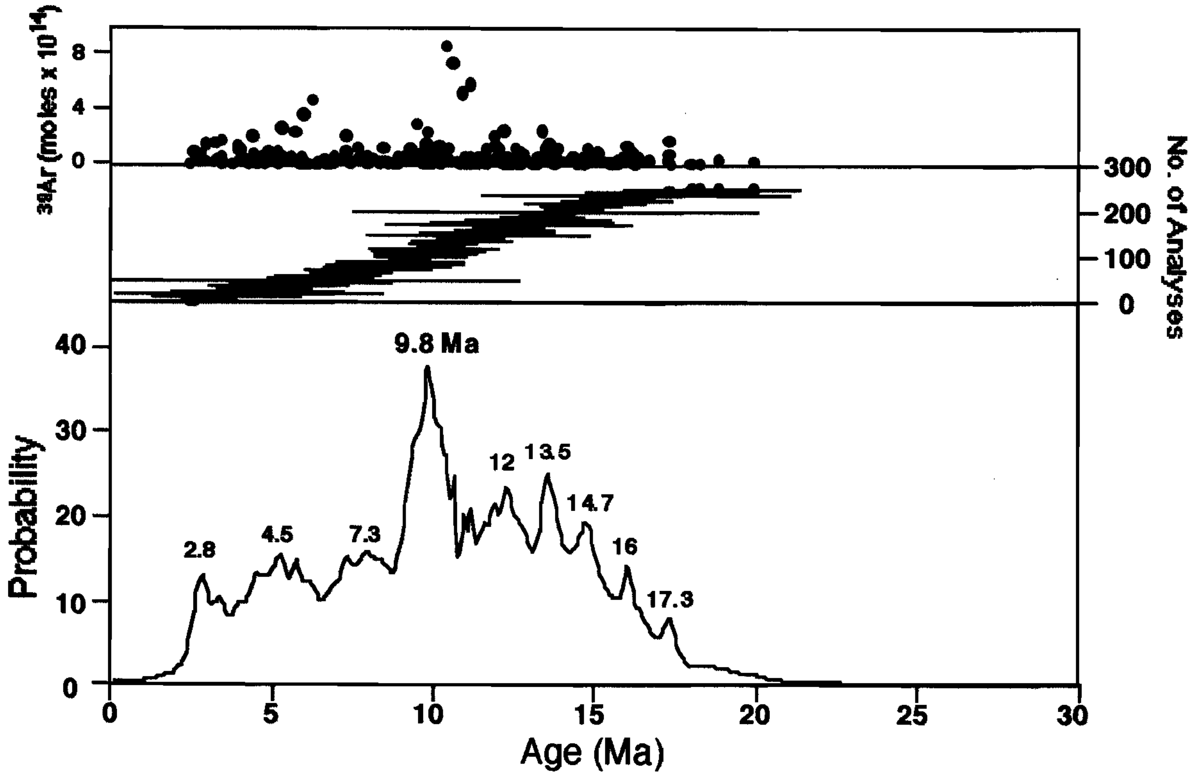

Figure 8.7 Ideogram for Charters Towers (n_{sample} = 15, n_{grains} = 42, n_{steps} = >500).

8.6 Regolith-landscape evolution

The landscape model of Grimes (1979, 1980) is based on cycles of development, where each cycle comprises an initial phase of tectonism, with active erosion and deposition, followed by planation and formation of deeply weathered terminal surfaces. The lateritised Tertiary sediments have been referred to as the 'Featherby Surface'. Although there was a planation surface developed on a local scale (*e.g.*, around Pajingo), marked by lateritised carboniferous volcanics and Tertiary sediments which is clearly visible on aerial photographs, regional extrapolation of such a surface and formal naming of surfaces is open to question. Correlating distant surfaces using duricrust development has been shown to be unreliable in many parts of Australia and the geomorphology in the northern Drummond Basin is too complex for a simplistic approach.

The dominance of a southerly flowing river system in the early Tertiary, the formation of a large lake system in the middle Tertiary, and the reversal of the river system in the late Tertiary are main episodes of landscape evolution in the north Drummond Basin (Li Shu, 1997 (448R)). In the modern landscape, there is a conspicuous breach through the Eastern Highlands by which the Burdekin River traverses the Highlands. Prior to the breach, however, the palao-drainage could only have found its way to the south. Major streams in the area, such as the Burdekin, the Cape, and the Campaspe rivers have a southeasterly flowing pattern. The upper reaches of the Suttor River and its tributaries of Police Creek and Rosetta Creek all flow towards the south. Following the general trend of the Campaspe River to the southeast, for instance, Tertiary sediments are found in a low and narrow corridor between the Scartwaters Salient and the Bulliwallah Syncline. Elevations of the top surface of the sediments decrease to the southeast from 245 m to 225, 214 and 194 m above sea level, indicating that the ancestral Campaspe River continued its southeasterly direction. To the west of the Bulliwallah Syncline, the pattern of Tertiary sediments suggests the ancestral Cape River ran southeasterly, swung around the southern limb of the Syncline and joined the ancestral Campaspe River.

Eruption of a large volume of basalts in the south and the breach by the Burdekin River through the Eastern Highlands in the north are the main causes of drainage reversal in the north Drummond Basin. The present divide between the Suttor and the McKenzie rivers is located on the Tertiary volcanics about 10 km northeast of Clermont. Tertiary basalts extruded from fissures and circular vents covering the sediment filled valleys, blanketed the sub-basaltic topography. A sediment-filled valley lies to the south under Tertiary basalts. The modern divide between the Suttor and the McKenzie rivers did not exist when basalts were erupted in the Tertiary. The Burdekin River system (the Burdekin, Cape, Campaspe and Suttor rivers) might have run through the sub-basaltic valley to the northeast of Clermont to join the McKenzie River and via the Fitzory River to enter the sea at Rockhampton (Figure 8.8A). Basalt eruption in the south choked the southerly flowing Burdekin River and a large lake formed (Figure 8.8B). Due to sedimentation in the Tertiary lake, flood waters in the Burdekin River eventually reached high enough to find a new course along a gap through the Eastern Highlands, diverting the river to the east (Figure 8.8C). Because of its large catchment and its high energy, the Burdekin River incised a deep gorge through the Highlands.

Deposition and erosion in the north Drummond Basin has been dictated by drainage changes. When the southerly drainage was choked rapid sedimentation formed the Suttor Formation in the south and the Southern Cross Formation in the north. An extensive blanket of Southern Cross Formation sediments were deposited during the early to mid Tertiary (Grimes, 1980; Henderson and Nind, 1994). As the uneven basement topography was 'drowned' in a rising tide of locally-derived fluvial material, colluvial detritus from the elevated basement was also incorporated. Cobbles of vein material at Pajingo were incorporated into the Southern Cross Formation at this stage. Some of the basement hills and ridges remained as 'islands', above the areas of active sedimentation.

The age of the Suttor Formation is controversial. Early Miocene pollens were reported from oil shales (Chaffee *et al.*, 1984). East of Mt Coolon, in the Byerwen area, basalts, reported to underlie the Formation, are dated at 23.1 to 29.2 Ma (Sutherland *et. al.*, 1977). This led Hutton *et al.*, (1991) to regard the Suttor Formation as mid-Tertiary. Later work has shown that the Suttor Formation is interbedded with these basalts, and a date of 53 Ma, obtained from basalt overlying silcrete of the Suttor Formation at Mt Dalrymple, indicates an early Tertiary age (Day *et al.*, 1983). All these data suggest that the Suttor Formation spans most of the Tertiary. In view of its extent and its fluvial nature, it may be more realistic if the Suttor Formation is regarded as deposited over a considerable time span and not restricted to a single event.

Subsequent deep weathering of both the fluvial sediments and the basement occurred during a time of relative stability which continued into the late Tertiary, forming the duricrust, red soils and, to a lesser extent, yellow earths. With the formation of the Burdekin Gorge, the base level of erosion for the Burdekin River was lowered rapidly, renewing rapid erosion within the river system (Li Shu, 1997 (448R)). The Southern Cross and Suttor Formations were dissected and largely removed, resulting in an undulating landsurface with mesas. Once the easterly drainage system was established, sediments were deposited and new floodplains were built up. In the areas less affected by the major change from the southerly to the easterly drainage, such as the upper reaches of the Burdekin River, Campaspe Formation sediments were deposited on the Southern Cross Formation. In areas where intense erosion of the Southern Cross or Suttor Formations occurred, Campaspe sediments were deposited in lower levels in the landscape.

Because the Campaspe Formation sediments are more quartz-rich and better sorted than those of the Southern Cross Formation, it is likely that the Campaspe Formation contains substantial re-worked detritus from the Southern Cross Formation. Attributes of the Campaspe Formation suggest dry phases punctuated with short, intense wet periods, and a lack of vegetation (Nind, 1988). Since its deposition, the Campaspe Formation has been dissected and weathered, and it currently forms extensive low plains. It is likely that much of the yellow and grey earths on the low plains are related to Campaspe sedimentation. Pedogenesis and sedimentation are likely to have operated alternately during the Pleistocene-Quaternary as indicated by palaeosols beneath the present shallow soils, between basalt flows and even within the Campaspe sediments (Nind, 1988).

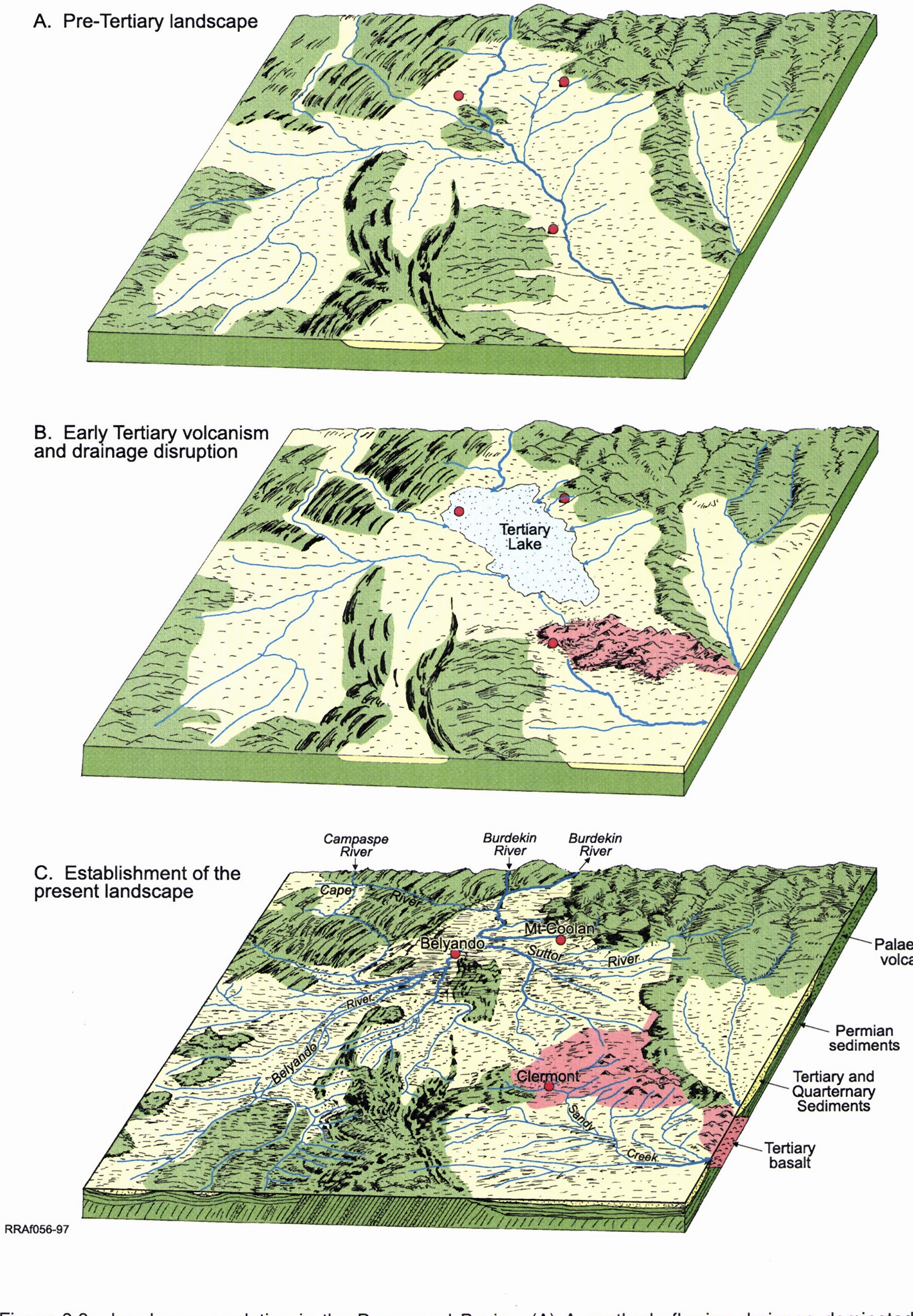

Figure 8.8. Landscape evolution in the Drummond Basin. (A) A southerly flowing drainage dominated the Basin prior to eruption of basalts northeast of Clermond. The Cape, Campaspe, Belyando and Suttor rivers all joined the Burdekin River tributary to the McKenzie River in the south; (B) Volcanic eruption and basalt emplacement choked the ancestral Burdekin River and consequently a lake system was formed around the Mount Coolon area; and (C) with the breach through the Eastern Highlands, the Burdekin River managed a new course to the east and northeast and established the modern drainage pattern and the present landscape (After Li Shu, 1997 (448R)).

Interspersed with sedimentation was the outpouring of basaltic lavas into existing valleys and drainage channels from the late Tertiary to present (5-0.13 Ma) to form the Nulla Basalt Province (Stephenson *et al.*, 1980). Volcanic activity suggests that tectonic instability and possible upwarping to the north initiated the main Campaspe cycle.

Coventry (1982) concluded, from his study at Torrens Creek, that development of red and yellow earths is dependent on the depth of sediment to bedrock which, in turn, determines the hydrological regime of the soil. Similar relationships have been observed for the Charters Towers area by Aspandiar *et al.*, (1997). Where unconsolidated sediment is thick over these rocks, red earth soils develop because of free profile drainage and greater oxidation of organic matter yields hematite. Where low porosity bedrock is close to the surface, drainage is impeded, shallow watertables develop, with goethite formed as the main Fe oxide in the yellow earths and kaolinite in the grey earths.

In the Mt Coolon area, Quaternary sediments are widespread, covering most of the Suttor Formation on the plain. The sediments are unconsolidated colluvium and alluvium brought down by the Rosetta, Black and Police creeks. They were derived from weathering of basement rocks and reworking of the Suttor Formation. Although the sediments are similar to the Campaspe Formation, further to the north around Charters Towers, at present they lack a formal name.

8.7 Distinguishing Southern Cross Formation from Campaspe Formation

The Southern Cross Formation lies stratigraphically below the Campaspe Formation, but can be topographically higher. The lateritic profile developed on the Southern Cross Formation generally provided the source material for the Campaspe Formation, yet it can be found under the Campaspe Formation in some drill holes. The time interval between the end of deep weathering of the Southern Cross Formation and the initiation of Campaspe deposition is unknown.

In drill spoil, the Southern Cross Formation is more clay-rich than the Campaspe Formation and contains clasts of the basement rocks. The Campaspe Formation tends to be sand-rich and more sorted than the Southern Cross Formation. The Campaspe Formation may contain detrital nodules and pisoliths throughout the sediment, whereas most of the pisoliths and nodules in the Southern Cross Formation are concentrated at its top.

8.8 Distinguishing sedimentary cover from weathered volcanics

There are no consistent mineralogical and geochemical criteria but hiatuses in feldspar and kaolinite abundances, rounding of quartz grains and geochemical parameters such as Ti/Zr ratios can be used to distinguish the Campaspe Formation from basement volcanics (Scott, 1997a (422R)). The Campaspe Formation is generally characterised by assemblages of quartz, plagioclase, orthoclase, smectite and kaolinite. Where it overlies weathered, altered and/or mineralised volcanics, very kaolinitic assemblages with no feldspars occur. In such areas, the abrupt change in the feldspar and kaolinite abundances readily define the Campaspe-basement unconformity. However, where the volcanics are unaltered, feldspars occur in the weathered volcanics and recognition of the unconformity must rely upon other criteria.

Where the volcanics are of intermediate to mafic composition, higher Si, Cl and lower Al and Ti/Zr ratios can be used to distinguish the Campaspe Formation from the volcanics. However, where the volcanics are felsic, as at Thalanga East, geochemical parameters such as Ti/Zr ratios do not discriminate between the sediments and volcanics. In such cases, fabric information (rounding of quartz grains) may provide the only means to locate the unconformity in drill-chip logging.

9. SUMMARISED CASE HISTORIES, CHARTERS TOWERS-NORTH DRUMMOND BASIN REGION

During the course of this project a number of sites were selected for detailed study. The objective is to relate geochemical dispersion patterns to underlying mineralisation, within a well-controlled regolith-landform framework. Here the various regolith types were characterised, where necessary mapped and samples were collected for detailed mineralogical and geochemical examination. Many of the sites had small to significant mineralisation (Pajingo, Police Creek, Wirralie, Waterloo). Towards the end of the project one additional mineralised site was offered (Brahman).

The case histories are summarised below; further details may be obtained from the project reports. Geochemical data are appended in a compact disc as Appendix III.

9.1 Pajingo Deposit

Location
The Pajingo deposits lie 53 km south-southeast of Charters Towers in the Janet Range (Figure 1.1B). Normandy Exploration and Battle Mountain (Australia) Inc. made the site available.

Geology and mineralisation
Several shallow, epithermal Au-mineralised veins, including the Scott and Cindy lodes, form part of a volcanic-hosted northwest trending, propylitically altered zone. The Scott Lode is boomerang-shaped, has a maximum width of 23 m and dips south at 70-80°. It consists of chalcedonic and microcrystalline quartz with goethite and hematite bands and shows massive, crustiform, colloform, cockade, vesicular and fibrous quartz fabrics, indicating multiple brecciation and resealing with silica. The Au-Ag mineralisation is associated with Hg, As, Sb, Cu, Pb, Zn, Te, Tl, Bi, W, Ba and F. The veins are hosted by relatively flat-lying Devonian andesites, tuffs, volcaniclastics and sandstones with chloritic subvolcanic intrusives.

Regolith
The Devonian volcanics vary from relatively fresh to saprolites on the high ground, but on the lower ground they have a lateritic profile having an Fe-rich duricrust of hematite, goethite and kaolinite with some gibbsite cementing the pisoliths (Campbell, 1996 (286R); Robertson (1997) (449R)). Here they form a complex pediment with an extensive cover of mottled and lateritised Tertiary sediments (Southern Cross Formation) and various colluvial scree and alluvium.

Pisolitic duricrust is developed in the top half metre of the Southern Cross Formation on the high parts of the pediment and, in places, this duricrust has broken down to a surficial pisolitic gravel. Most of the Southern Cross Formation, on the remainder of the pediment, consists of mottled clays covered with either a very thin lithosol or a veneer of proximal colluvium.

The Southern Cross Formation completely blankets the Cindy Lode with a thin basal conglomerate overlying mottled saprolite of the basement volcanics. This passes upwards into alternating conglomeratic and gritty layers with a thick mottled horizon at the top. The detritus has been derived from a variety of regolith horizons; there are pisolitic fragments, fragments coated with a thin cutan of yellow-brown clay and some contain preserved volcanic fabrics, although the feldspars are now completely kaolinised. At Scott Lode, the basement and the lode were exposed. The edge of a palaeochannel cuts into the southwest side of the pit, exposing an imbricate rudite of red-brown mottles, resting on a mottled clay basement. This is overlain by alternating mottled grits and gravelly clays with a thick wedge of red-brown clays with branching, rhizoform mega-mottles and further mottled gravelly sediments. The clasts of these sediments consist largely of deeply weathered saprolites of volcanic rocks with minor quartz, which are set in a clay matrix. It seems unlikely that many of these clasts would have survived transport in their deeply weathered form so at least the latter part of their weathering, including their mottling, was accomplished *in situ* within the Southern Cross Formation.

Alluvium is extensive in low-lying areas; it ranges from boulders, through gravels to massive clay deposits which are up to 4 m thick and upward fining. These materials are immature and contain ferruginous pisoliths from pre-existing lateritic profiles, vein quartz and weathered volcanics, much of which may have been inherited from the Southern Cross Formation.

Geochemical dispersion in the regolith
Dispersion within the Devonian basement was not investigated; dispersion studies were focused on the Souhern Cross Formation (Robertson, 1997 (449R)).

Regional and local background
Distant from known mineralisation, regional Au backgrounds are low (*e.g.*, <5-10 ppb at the Wahines Prospect) but, within 1 km of the Scott and Cindy mineralisations, Au reaches 31 ppb (local background). The background at Scott is very high (>100 ppb) because it was only partly covered and mineralised detritus from the lode has been shed into the palaeodrainage; it is less (16 ppb) at Cindy, where the bulk of the detritus was from up slope, beyond the mineralisation. Within the cover sequence, a Au background of >20 ppb may indicate a distal Au source; >35 ppb may indicate a proximal Au source. However, the source may not necessarily be economic. Significant dispersion may result from a large number of small auriferous veins.

Localised dispersions
Mechanical dispersion has produced localised anomalies in Au, W and Mo in the cover sequences (Robertson, 1997 (449R)). At Scott, the highest Au concentration (700 ppb) is not at the base of the channel but within gritty sediments just above a gravelly layer; concentrations of Au (200 ppb), As (80 ppm) and W (6 ppm) lie within gravelly sediments near but not at the base of the channel. Gold is locally concentrated (>500 ppb) down slope of the mineralisation at Cindy where it was cut by a small outflowing palaeodrainage. Again, it occurs near but not at the base of the sediments. Thus, dispersion is not necessarily at the base of the cover but may be at any level, requiring analysis of the whole sequence.

Exploration drilling, within 1 km of the mines, confirmed Au dispersion of 100-300 m (>70 ppb) both from the Scott and Cindy deposits or from areas of 'numerous auriferous quartz veins' nearby. Gold dispersion occur at the base of the cover and higher, indicating that auriferous sources remained exposed during sedimentation. All this supports a largely mechanical dispersion mechanism. Partial extraction experiments, however, indicated that a proportion of the Au is loosely attached (soluble in weak extractants; K-iodide and water) so some relocation of the Au by weathering is likely (Robertson, 1997 (449R)). A slightly greater proportion of the Au is held in the fine fraction (<100 μm) of the Southern Cross Formation at Scott (Campbell, 1996 (286R)).

9.2 Waterloo deposit

Location:
The Waterloo polymetallic sulphide deposit is located about 45 km south of Charters Towers (Figure 1.1B). RGC Exploration made the site available.

Geology and mineralisation
Polymetallic mineralisation outcrops in the Mount Windsor Subprovince within andesites and felsic volcanics of the lower Ordovician Trooper Creek Formation (Reward, Highway, Handcuff, Liontown, Magpie Waterloo, Agincourt, Brittania and Warrawee prospects) or in the stratigraphically lower rhyolites of the Mt Windsor Volcanics (Thalanga; Berry *et al.*, 1992). However, much of the prospective volcanic terrain is covered by sandstones of the Campaspe Formation. Although many of these deposits outcrop (Liontown and Highway), discoveries after 1972 were by geochemical exploration (gossan recognition or stream and soil geochemistry (Berry *et al.*, 1992)). However, in 1981, the East Thalanga deposit was found below 20-80 m of Campaspe Formation (Hartley and Alston, 1995). Here, a dispersion train of Cu, Pb and Zn was found within the Campaspe Formation (Granier *et al.*, 1989). These authors proposed that at least part of the geochemical halo in the Campaspe Formation is the result of chemical dispersion and recommended

systematic analysis of the Campaspe Formation because the position within the cover sequence could not be predicted a *priori*. A similar dispersion halo was identified at the Waterloo prospect (Hartley and Alston, 1995).

Regolith
Polymictic float (including pisoliths) occurs in red-brown and grey-brown soil of the pediment. Deeper in the profile, weathered Campaspe Formation overlies weathered volcanic basement. Weathering extends to about 50 m (Scott, 1995b (168R)).

The Campaspe-volcanic basement unconformity tends to be difficult to define from percussion drill cuttings and it had been misidentified in some sections at Waterloo. In mineralised environments the unconformity is marked by a lack of feldspar and smectite and appearance of kaolinite- dominated assemblages in the volcanics. However, barren profiles lack pyrite to generate acid conditions to facilitate feldspar destruction in the volcanics. Geochemical criteria, especially Ti/Zr ratios, are useful in differentiating the felsic-derived Campaspe Formation from weathered andesites and basalts. Where the Campaspe Formation overlies felsic volcanics, the geochemical differentiation criteria fail and only fabric (*e.g.*, morphology of quartz grains) can distinguish sediments from weathered Ordovician volcanics.

Geochemical dispersion in the regolith
If the position of the unconformity is defined accurately, the Pb dispersion anomaly is within the basal few metres of the Campaspe Formation (Scott, 1995b (168R)). Zinc and Cu dispersion may occur above the unconformity at least at the western end of the Waterloo deposit. There, elevated Zn and Cu are associated with dolomite and Fe oxides at least 10 m above the unconformity. It is postulated that the Zn-Pb-Cu mineralisation outcropped in the early to mid Tertiary and gossanous fragments were mechanically dispersed as a lag for several hundred metres prior to deposition of the Campaspe Formation. Subsequent leaching of the gossanous material followed and Zn and Cu were only precipitated in an alkaline environment associated with carbonates.

The sizes of the geochemical haloes at the base of the Campaspe Formation are at least 1 km across for Pb and 600 x 300 m for Zn.

9.3 Brahman prospect

Location
The Brahamn prospect is located 45 km west of Charters Towers area (Figure 1.1B). Normandy Exploration made the site available.

Geology and mineralisation
Basement geology at the Brahman prospect is characterised by magnetite-bearing and non-magnetic granites intruding biotite schists of the Charters Towers Metamorphics. Mesothermal mineralisation of the Charters Towers vein-style occurs at the boundary of the magnetic granite and the intruded schists. This is characterised by Au in quartz veins with pyrite, galena and sphalerite (Clarke and Pain, 1970). An intersection of 1.5 g/t Au over 4 m has been recorded in one drill intersection at Brahman.

Regolith
There is 1-2 m of recent alluvium overlying ferruginous pisoliths which are only exposed in shallow erosion gullies (Scott and Fraser, 1997 (434R)). Drilling indicates that the pisolitic unit may be up to 2 m thick. Below the pisolitic unit a zone of 5-20 m of silicified and ferruginous sandstone generally with coarse quartz lenses occurs and is considered to be derived from nearby granitoids (M. van Eck, 1997 pers. comm), *i.e.* it is mottled Campaspe Formation. Beneath these transported units is 5 to 10 m of sandy and puggy clay on ~30 m of saprolitic granite above relatively fresh magnetic granite at about 50 m.

Weathering proceeds by destruction of original hornblende, chlorite and feldspars to form clays and Fe oxides. The position of the unconformity between Campaspe and granite is marked, in a general way, by a change in kaolinite crystallinity. However, the species of the feldspars in the Campaspe Formation are influenced by those in the residual saprolite; plagioclase and orthoclase occur above and below the unconformity adjacent to mineralisation but only plagioclase occurs through the profile in barren area. This suggests that the unconformity should be investigated more thoroughly.

Geochemical dispersion in the regolith
Gold contents greater than 2 ppb occur at the top of the pisolitic unit in the Campaspe Formation and as a horizontal blanket at about 15-20 m within the saprolite and into the overlying clay zone (Scott and Fraser, 1997 (434R)). Mineralisation below that level is restricted to a narrow zone about the quartz lode but below 40 m, another horizontal zone of Au enrichment occurs at the base of the saprolite. A distribution (but with larger Au concentrations) in lateritic residuum above a depleted zone and lateral dispersion for hundreds of metres about the mineralized vein is similar to that encountered in parts of the Yilgarn of W.A. However, here, the surficial lateritic dispersion is within the Campaspe Formation. Arsenic, Cu and Pb contents are also elevated with Au in the surficial ferruginous material in an area at least 700 x 500 m about the mineralisation at depth.

In addition to the hydromorphic dispersion of Au, As, Cu and Pb, elements such as Mn, Ce, Co, La, Zn and, in places, Ba are also dispersed in the transported material as indicated by Mn staining, *i.e.* these elements move late in the regolith history.

9.4 Police Creek prospect

Location
Police Creek prospect is located 6 km northeast of Mt Coolon (Figure 1.1B). Ross Mining NL made the site available.

Geology and mineralisation
Within the northern portion of the Drummond Basin, Au mineralisation occurs at Yandan, Mount Coolan, Wirralie and in the Bimurra-Conway area, all within 50 km of Police Creek. All of these deposits have sericitic alteration assemblages generally overprinted by kaolinite. Adularia occurs locally, with minor pyrophyllite and alunite (Wood *et al.*, 1990). The Au:Ag ratio is ~10:1 at Yandan and between 2:1 and 3:1 at Wirralie and Mount Coolon, but Ag contents are much greater in the Bimurra-Conway area with ratios locally 1:10 or more (Wood *et al.*,1990; Seed, 1995a). The gold in these deposits tends to be fine grained, *e.g.* 50% of the gold at Yandan is less than 5μ and 92% less than 30μ in diameter (Seed, 1995a).

At Police Creek, the Silver Hills Volcanics host pervasive silica-pyrite alteration that contains discrete zones of quartz-pyrite±marcasite breccia (up to 10 m wide) and narrow, quartz-carbonate veins. This mineralisation grades up to 0.5, 3 and 10 g/t respectively (R. Mustard, pers. comm., 1994). The silica-pyrite alteration is surrounded by successive zones of illite and chlorite-carbonate, typical of epithermal mineralisation (*e.g.* Hayba *et al.*, 1986). Base metal sulfides are not obviously developed in the alteration zones.

Regolith
Alluvial and colluvial material, up to 6 m thick, overlies weathered basement volcanics (Scott, 1995a (157R); Scott (1997b) (323R)). Weathering commonly extends to 40 m. Complete weathering of sulphides occurs to a depth of 30 m, with partial weathering extending for another 10-20 m. Within the zone of partial weathering (transitional zone), there is some supergene Au enrichment to grades ~1 g/t. Gold is depleted in the saprolite above the supergene zone except where the gold is protected by quartz. It is, however, present in the transported material that overlies the mineralized Silver Hills Volcanics.

The alluvium and colluvium forms a pediment about 10 m below the top of a scarp of ferruginised Suttor Formation. The transported materials of the pediment have been weathered (mottling) since deposition. The pediment has been incised by present streams. Basement rocks form areas of outcrop up to several metres above the pediment but areas of coarse float suggest that the basement occurs beneath a very thin cover elsewhere, especially close to the Suttor Formation scarp. The extent of shallow residual soils is probably greater than originally estimated (Scott, 1995a (157R)).

Geochemical dispersion in the regolith

The original exploration in the area by Australian Consolidated Minerals Limited (ACM) used the <80 mesh (<180 μm) fraction of the alluvium to define a 1200 x 600 m anomalous Au zone above mineralisation in the basement rocks. Silver, As, Cu and Sb were also found to be anomalous within the anomalous Au zone (R. Mustard, pers. comm., 1994). Because the bedrock below the alluvium is depleted in Au, ACM believed that the transported material was up to 30 m thick. However, mapping of costean faces by Ross Mining revealed that quartz phenocrysts, derived from the basement, occur at 2-3 m depth above mineralisation and the transported material is less than 6 m thick.

Detailed investigation have shown that analysis of the <75 μm (*i.e.* kaolinite-rich) fraction of the soil results in a more intense Au anomaly than the <80 mesh (<180 μm) fraction (Scott, 1997b (323R)). However, in comparison, although As >50 ppm and Sb >5 ppm occur in the fine fraction, these elements are concentrated in the Fe rich >2 mm fraction of the soils. Thus, As >200 ppm, Sb >10 ppm and Mo >5 ppm in the coarse fraction also define the area defined by Au >40 ppb in the fine fraction. In addition, use of both the fine and coarse fraction of soils leads to identification of a second anomaly defined by Au >100 ppb, As >140 ppm and Sb >10 ppm in the coarse fraction. This second anomaly occurs in residual soil and was not obvious in the original <180 μm sampling. The association of As, Sb (and in places Au) with Fe in the coarse soil fraction is due to incorporation of rock fragments in residual soils. However, in soil developed in transported material, the ferruginous components include authigenic nodules and mottles as well as bedrock-derived ferruginous material that has been introduced into the soil by bioturbation.

Weathering profiles in different parts of the prospect reveal different alteration styles in weathered material in outcrop and subcrop. Alteration, in the main mineralised area, is Characterised by pyrite and its preservation as jarosite after weathering; the As/Sb ratio of the sulphides (~20) is retained. Alteration at Cicada East is characterised by K-feldspar and silification, which survive weathering, an As/Sb ratio ~ 40 and elevated Mo contents in fresh and weathered rock (as well as residual soils). Argillic alteration at Cicada Ridge contains dickite and pyrophyllite but the sulphide content is low. Dickite survives weathering and clearly reflects this style of alteration as does its low As/Sb (~1). Propylitic alteration was not sampled within the regolith but plagioclase and calcite, which reflect it at depth, might be expected to degrade to smectite in the regolith. Together, this suggests that the temperature (and probably depth of formation) decreases from the K-feldspar, As and Mo-rich assemblages (Cicada East) > pyrite-rich mineralisation (main mineralisation) > dickite ± pyrophyllite and Sb-rich assemblages (at Cicada Ridge) and these features can be seen in regolith materials.

9.5 Wirralie deposit

Location

Wirralie deposit is located 25 km north of Police Creek. Ross Mining NL made the site available.

Geology and mineralisation

Epithermal Au mineralisation at Wirralie crops out over a surface area of 600 x 600 m and was discovered in 1986 by BLEG (<6 mm fraction) and <180 μm As stream sediment anomaly (Fellows and Hammond, 1990). Although Cu, Pb, Sb and Zn were not useful pathfinders in the stream sediment programme, subsequent rock chip sampling found significant levels of pathfinder elements close to mineralisation, *e.g.* Hg up to 3370 ppb, As up to 1000 ppm and Sb up to 120 ppm (Seed, 1995b). Mining of an oxide resource of 3.65 m tonnes at 2.75 g/t Au by Australian Consolidated Minerals Limited commenced in 1988 and concluded in 1992 when Ross Mining N.L. acquired the property, extended the oxide resource and are considering leap leaching the sulphide-associated mineralisation (Seed, 1995b).

The gold of the deposit contains 16-33% Ag, averages 25 µm in size and is associated with up to 5% sulphides (mainly arsenical pyrite and lesser amounts of marcasite, sphalerite, arsenopyrite and chalcopyrite). Where weathered, Au occurs with Fe oxides along quartz boundaries.

Regolith
In the area of the deposit, a thin soil is developed on 20 m of Suttor Formation (Scott, 1997b (323R); Scott, 1996 (286R)). Locally derived material from the Mt Wyatt Formation, up to 0.5 m in size and including clasts containing epithermal quartz veins, are incorporated into the Suttor Formation. In the Wirralie area, the Suttor and Mount Wyatt Formations are weathered; much of the lateritic profile has been removed with only remnants preserved in mesas and plateaux. Ferruginous duricrusts and silcretes are developed on the Suttor Formation in the Wirralie area.

Although the weathering extends to about 40 m in the Mt Wyatt Formation and sulphides are destroyed, Au appears to be only locally redistributed, *i.e.* there is no supergene enrichment.

Geochemical dispersion in the regolith
Two profiles through the Suttor Formation have been studied, one is the southern face of the open pit and the other from drill hole W33, about 100 m to the northeast. The southern face consists of generally white sandstones with a clay matrix, although the top 5 m is weakly Fe stained. Clasts of silicified (and ferruginised) Mt Wyatt Formation occur in its basal portion. Samples consist of quartz, kaolinite and anatase. Excluding the ferruginous boulder, Au contents through the profile vary between 35 and 270 ppb (the latter being highly silicified) but As and Sb contents are generally low, reaching maxima of 20 and 12 ppm respectively. Barium contents are generally high, generally >350 ppm. The ferruginous boulder shows that As, Cr and Sb are strongly associated with Au and Fe. Mottled material from the top of the Mt Wyatt Formation is enriched in As, but is relatively poor in Au.

The W33 profile allows more systematic sampling through the Suttor Formation which here consists of sandstone, in places with clasts up to 5 mm, within a clay matrix. Its mineralogy is quartz, kaolinite ± trace illite, anatase ± ?alunite. Gold contents through the Suttor Formation are consistently greater than in the pit face with good ore grades between 8 and 13 m and at the base. Arsenic and Sb are also generally slightly greater in this section than in the pit face, with As being enriched at the base. Barium contents are lower than in the pit face.

The upper portion of the Mount Wyatt Formation is finer grained than the Suttor Formation and consistently contains illite in addition to quartz, kaolinite and anatase. Although Au contents are low (47-160 ppb) relative to those in the Suttor Formation, As contents are greater (~20 ppm). Such a lack of Au in the Mount Wyatt Formation suggests that the Au in the Suttor Formation reflect largely mechanical transport rather than hydromorphic dispersion.

10. DISPERSION MODELS AND EXPLORATION PROCEDURES FOR THE MT ISA AND CHARTERS TOWERS - NORTH DRUMMOND BASIN REGIONS

10.1 Introduction

This section presents concise recommendations for improved regolith geochemical exploration procedures, based on the outcomes of this project. Inevitably, regolith geochemistry will be used with geological and geophysical methods. This section draws upon and is cross referenced to other parts of the final report and to project reports. At the end of this section, the recommendations are tabulated (Table 10.1) in summary.

The Mt Isa and Charters Towers-north Drummond Basin regions have variable regoliths reflecting weathering from the late Cretaceous to the present day and have been variously eroded and exhumed. Relief inversion adds complexity of the present landscape. Different regolith materials require different sampling and interpretation strategies and require an understanding of their origins, the style of weathering, geomorphological processes and regolith-landform relationships. The Mt Isa and Charters Towers - north Drummond Basin regions are discussed separately as they have different regolith-landforms and cover sequences.

10.2 Mapping and tenement assessment

Appraisal of geomorphology and regolith at a district scale is an important pre-requisite for efficient exploration of a regolith-dominated terrain. Regolith-landform maps and regolith stratigraphy should guide the selection of sampling media, sample interval, sampling procedure, analytical method, element suite and data interpretation procedures. This is achieved by regolith interpretation from aerial photographs, satellite imagery and radiometrics, confirmed by field checking. A descriptive regolith 'fact map' is produced so that regolith materials can be described in a landform framework and be broadly divided into duricrusts, saprolites and sediments. Each, with the exception of alluvium and colluvium, are subdivided into Proterozoic and post-Proterozoic bedrocks (Wilford, 1997a (372R), 1997b (407R); Li Shu and Robertson, 1997 (405R); Phang *et al.*, 1997 (429R); Li Shu, 1997 (448R)). The bedrocks have different prospectivities and require different interpretation. The 'fact map' forms the basis for derivative maps, such as a geochemical sampling strategy map, which can be used for planning and interpreting geochemical surveys.

In areas that have been explored previously, where drill cuttings and cores are available, regolith stratigraphy, including depth of weathering, lithology, principal horizons, depth and nature of transported overburden (including weathering of transported overburden), soil type and nature of any lag, should be recorded. It may be necessary to drill for regolith stratigraphy, particularly in depositional areas.

Recommendation. Regolith-landform mapping, to understand regolith characteristics, stratigraphy and geomorphological processes, is essential to ensure appropriate sampling.

10.3 Regolith-landform environments - Mt Isa region

10.3.1 Regolith with ferruginous or siliceous capping on Proterozoic basement

Ferruginous materials (duricrust, nodules, ferruginous or mottled saprolite) or silcrete outcrop on mesas and palaeoplains or are buried beneath locally derived shallow sediments. Where residual ferruginous duricrusts occur, Pb, Sb and As exhibit enlarged dispersion haloes as shown by wide dispersion at Lady Loretta (>600 m) (Anand *et al.*, 1996 (158R)) (Figure 10.1A). However, the concentrations of these elements are low relative to underlying bedrock mineralisation, due to leaching. Other elements, such as Cr and V, accumulate residually in resistant minerals within the ferruginous horizon. Lateritic duricrust, nodules and pisoliths, should be sampled from surface outcrop or where buried and are good geochemical sampling, media. Pisoliths are rare in the Mt Isa region.

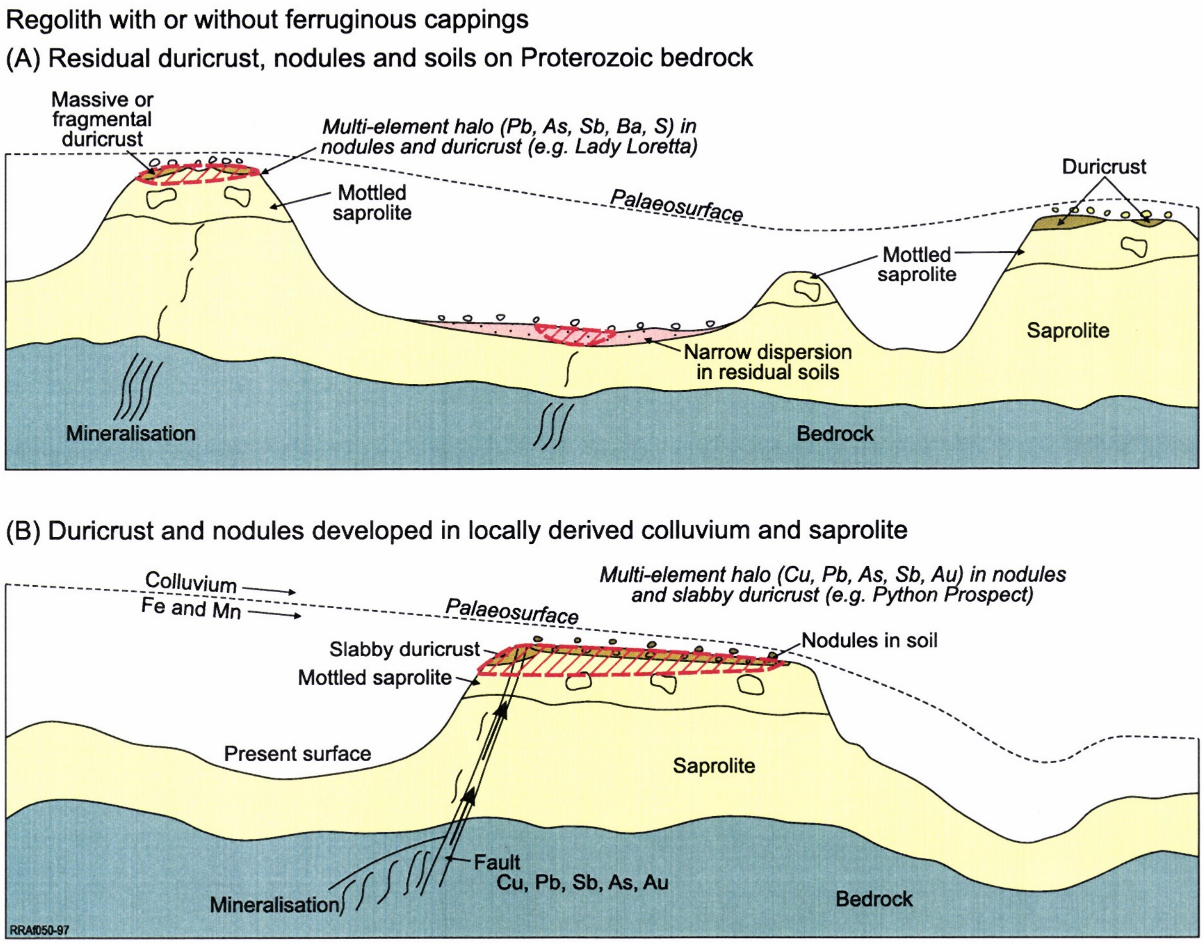

Figure 10.1. (A) Cross section showing dispersion of pathfinder elements in residual lateritic duricrust, nodules and pisoliths and soils developed on saprolite, Mt Isa region. (B) Cross section showing pathways of dispersion of pathfinder elements in duricrust developed in locally derived colluvium and saprolite. Enrichment in partly transported duricrust sourced largely from the fault with some contribution from a distal source .

Where lateritic duricrust and nodules are absent, mottles or ferruginous saprolite may be used but narrower dispersion haloes may be expected. Sample intervals for regional surveys, using lateritic duricrust and nodules, may be as wide as 500 m but they decrease to 50 m where mottles or ferruginous saprolite is used or for delineating drill targets. Ideally, they should be analysed for a wide range of indicator elements.

Ferruginous materials have formed in different ways and in different substrates (see Sections 2 and 7). Duricrusts occur both in residual and transported materials. Massive, fragmental, nodular duricrusts and their derived loose nodules are residual; slabby and vesicular duricrusts appear to have formed by lateral accumulation of Fe, precipitated from groundwater at seepages on valley sides and are not genetically related to underlying lithologies. Slabby duricrust is characterised by occurrence on plateau edges, micromorphology (platy), geochemistry (P-rich) and mineralogy (goethite-rich). However, both residual and transported duricrusts (Figure 10.1B) are enriched in Cu, As, Pb and Sb in places where they are associated with Au-Cu mineralisation (Python Prospect; Anand *et al.*, 1996 (158R) and Pb-Ag mineralisation (Lady Loretta; Anand *et al*, 1996 (158R); Cox and Curtis, 1977).

These enrichments are derived from local sources in the case of residual duricrust or from local and distal sources in the case of transported duricrust. Recognising the difference between residual and transported duricrust is essential to data interpretation.

All elements are diluted in silcrete, except for Si, Ti and Zr, so it is unlikely to be a useful sampling medium. However, mottling in silcrete may form a thin layer of ferruginous lag. The mottles could have adsorbed indicator elements but no case study in this project investigated this.

Recommendations. Residual ferruginous material, where it occurs, is a preferred sampling medium for district- to prospect-scale surveys. Based on the experience in the Yilgarn Craton, duricrust should be distinguished from ferruginous saprolite; these require separate treatment. Data from slabby duricrusts should be interpreted with care as their Fe and trace element (Cu and As) content may have been derived laterally.

10.3.2 Regolith on Proterozoic basement lacking ferruginous or siliceous capping

There was no case study for this situation so conclusions reached below are based on the experience in the Yilgarn Craton. Here, there has been either truncation of deeply weathered profiles or continuous erosion of weathering products that prevented formation of ferruginous or siliceous horizons. Lags of ferruginous materials (mottles or ferruginous saprolite) are common in these areas. Residual soils are produced by recent weathering of the substrate and are generally overlain by 10-20 cm of colluvium with abundant ferruginous gravels, lithic fragments and/or quartz (Buckley river area, Anand *et al.*, 1996 (158R)). Two situations are possible:-

1. Erosional plains of saprolite. Kaolinite is dominant and all weatherable primary minerals are destroyed.

2. Pediments and hill belts. Soils are developed on bedrock or on a thin saprock profile. Primary minerals (amphibole, feldspar, mica) are weathered to smectite, calcite and dolomite under the present climate.

These two regolith situations alternate over short distances and have different geochemical characteristics. Smectite and kaolinite have different affinities for trace elements. It is necessary to distinguish soils developed from the lower saprolite, saprock or bedrock from those developed from kaolinitic saprolite. Geochemical characteristics may vary over very short distances and require different sampling procedures and interpretations of element mobilities.

Recommendations. Sample soil and ferruginous lag. Size fraction, horizon to be sampled and treatment of samples should be determined by orientation survey.

10.3.3 Regolith on Proterozoic basement with shallow cover (1-5m)

This situation is common in the Mt Isa region where shallow colluvium and alluvium overlies saprolite and/or bedrock. The colluvium-alluvium contains polymictic gravels and may have been weathered (mottles and/or silicification) since deposition (Drifter, Anand *et al.*, 1996 (158R); Little Eva, Robertson *et al.*, 1995 (128R)). Soil (including mottles) is an appropriate sampling medium in areas where the sediments are up to 5 m deep (Figure 10.2), particularly where the sediments either are weathered or where bioturbation (ant and termite activity) has been important.

Copper, Zn and As have strong affinities with neoformed Fe and Mn oxides in soil mottles and form large, strong, hydromorphic dispersion haloes. Fine (<75 μm), kaolinitic soil fractions are richer in Pb and Sb, which probably indicates an early, possibly mechanical (bioturbation) dispersion into the soil (*e.g.*, Drifter, Anand *et al.*, 1996 (158R)). Copper and Au anomalies are an order of magnitude less in colluvium covered areas than in areas of residual soil on the basement (Little Eva, Robertson *et al.*, 1995 (128R)).

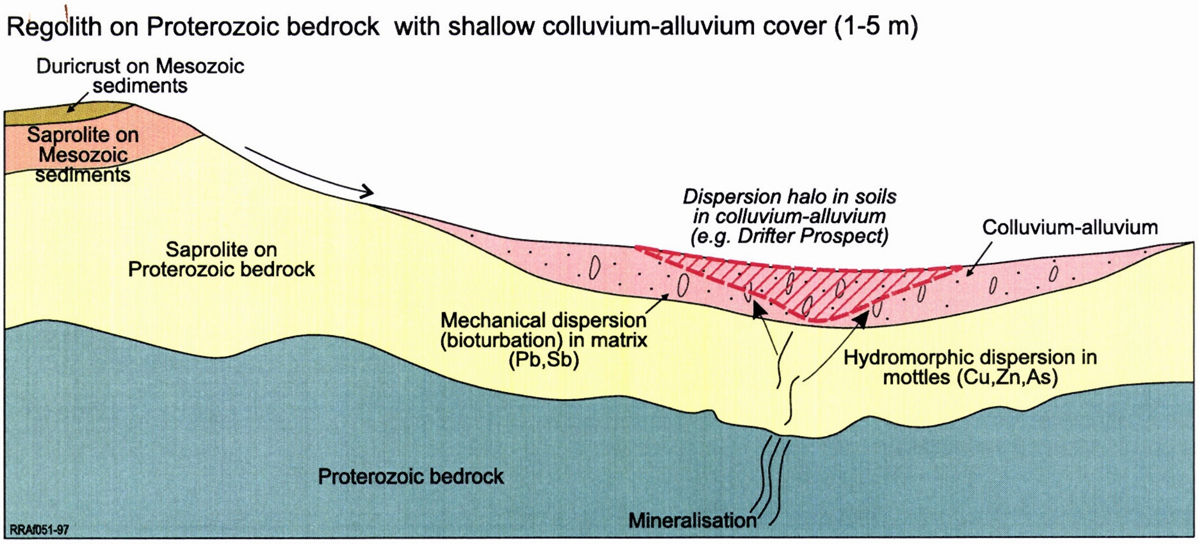

Figure 10.2. Cross section showing hydromorphic and mechanical dispersions of pathfinder elements in soils developed in colluvium-alluvium, Mt Isa region.

Recommendations. Soil sampling is effective in areas of shallow overburden (1-5 m). The best materials are mottles or the soil matrix rather than clastic grains. Where Fe and/or Mn oxides have adsorbed significant quantities of indicator elements (*e.g.*, Zn and Cu) multiple regression, followed by a residual treatment of these indicator elements would remove the effects of adsorption and draw attention to anomalies that would otherwise remain hidden. See Appendix II for a full discussion.

10.3.4 Regolith on Cambrian, Mesozoic and Tertiary sediments (>5m) overlying Proterozoic basement

Regoliths in Cambrian, Mesozoic and Tertiary sediments, overlying deeply or partly weathered Proterozoic bedrock, are common throughout the Mt Isa Region and may be overlain by up to 10 m of Quaternary sediments. This has provided a considerable challenge to exploration. Geochemical haloes in the basement may possibly extend into the cover but these are likely to be very different from those in the bedrock. Bedrock beneath thick Mesozoic sediments can be very fresh, so the extent of dispersion within basement and cover, due to weathering, is likely to be minimal.

Conclusions are limited because of limited access to study areas with known mineralisation. Some areas show no evidence of hydromorphic dispersion into the cover sequences (*e.g.*, Eloise, Li Shu and Robertson, 1997 (405R); *e.g.*, Maronan, Robertson *et al.*, 1997 (409R)) but mechanical dispersions as much as 100 m in size of Cu, Au, As and Sb occur in coarse sediments at or just above the Proterozoic-Mesozoic boundary at Eloise (Figure 10.3). The form of the palaeo-landscape governs dispersion directions.

Where there is no thick Mesozoic cover and a weathered profile on Proterozoic rocks occurs, there is dispersion of Au, Cu and Pb within the saprolite but the top 6 metres of the residual profile is leached (*e.g.*, Maronan, Robertson *et al.*, 1997 (409R)).

Where the cover sequence is weathered, hydromorphic leakage of Cu, Zn and Pb occurs in a basal Cambrian cherty breccia without known mineralisation (*e.g.*, Drifter, Anand *et al.*, 1996 (158R)). The source of these elements is from Drifter Fault and adjacent areas. The Zn and Cu is retained by Fe and Mn oxides in the cherty breccia.

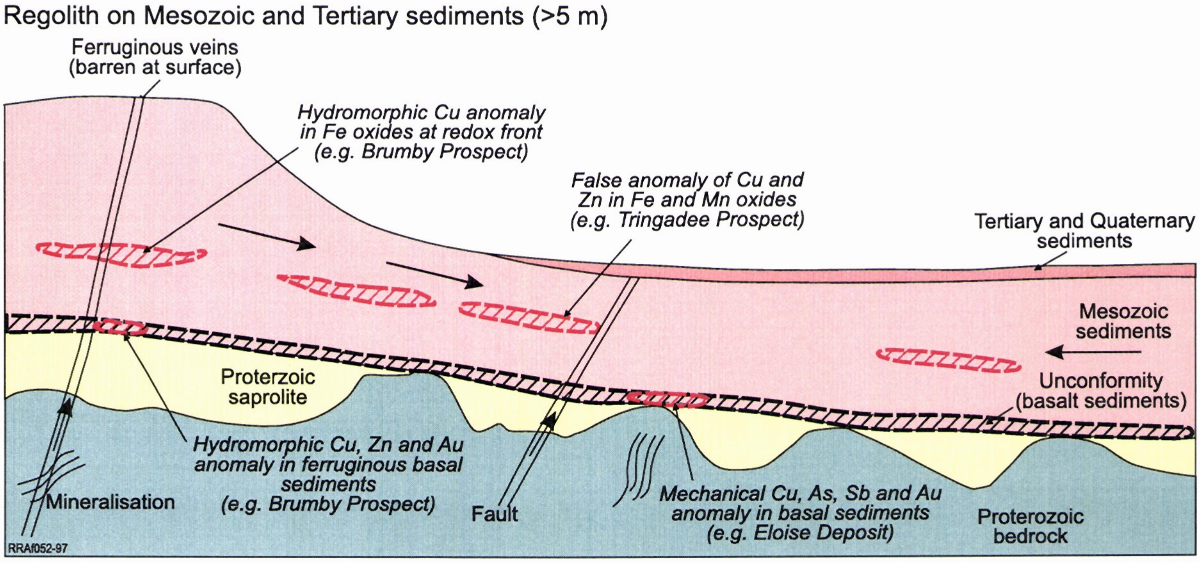

Figure 10.3. Cross section showing pathways of dispersion of pathfinder elements at the unconformity (between Mesozoic sediments and saprolite or bedrock) and at redox fronts dominated by Fe and Mn oxides, Mt Isa region. In places, false anomalies are developed.

A widespread and quite high-tenor hydromorphic dispersion of Zn occurs at Fe-Mn oxide-rich redox fronts within Mesozoic cover *without any known significant mineralisation beneath or in the vicinity* (Tringadee, Anand *et al.*, 1996 (158R); Phang *et al.*, 1997 (429R)). Although the Mesozoic sediments now occupy high ground, sedimentation is interpreted to have occurred low in the landscape when Fe, Mn and trace elements were moved laterally into the Mesozoic cover from external sources. Hydromorphic dispersion of Cu, Zn and Au, on the Proterozoic-Mesozoic boundary and at redox fronts within the Mesozoic sediments, is related to underlying mineralisation (*e.g.*, Brumby, Phang *et al.*, 1997 (429R)). There was no hydromorphic dispersion of Cu, Au or Zn into the structurally controlled ferruginous veins.

Recommendations. Coarse sediments should be collected at and just above the unconformity (interface sample) in areas of unweathered or slightly weathered Mesozoic cover to detect a near-miss when drilling a geophysical target. The form of the palaeo-landscape controls mechanical dispersion so accurate logging and surveying of drillholes are essential, perhaps augmented by geophysical methods to determine the palaeo-topography of the unconformity.

Where sediments have been weathered, buried ferruginous horizons at palaeosurfaces or at watertables may provide a continuous sampling medium. Ferruginous bands formed within sediments should be preferentially collected but careful interpretation of data is needed. These are more useful than structurally controlled ferruginous veins within the Mesozoic sediments.

10.3.5 Other sampling possibilities in the Mt Isa region

Several Cu-Au deposits and prospects, investigated within the Eastern Succession, are associated with substantial bodies of magnetite (Selwyn, Maronan, Eloise, Little Eva). Some of this magnetite has been affected by the mineralisation and differs geochemically from barren magnetite, *e.g.*, at Selwyn (Wildman, 1997 (341R)). Indicator elements such as Zn, Cu, Sn, W and Au, introduced by the mineralising fluids, may be incorporated into the magnetite (McQueen and Cross, in press). Even where weathering has oxidised the magnetite to hematite (martite), Cu, W and Sn minerals still may remain as inclusions (Wildman, 1997 (341R)).

Thus, magnetite and its oxidation product, martite, have potential as geochemical sampling media within streams in erosional regimes, and incorporated as placer concentrations within or along the base of cover sequences. Where the bedrock is essentially fresh, as along the unconformity at Eloise, a magnetic concentrate could be used but, where weathering has partly or completely oxidised the magnetite, as at Little Eva, Maronan and Selwyn, heavy mineral separation would be required. As magnetites of different origins would be expected to be mixed in such a situation, micro-analysis of individual grains may be required (McQueen and Cross, in press).

10.4. Regolith-landform environments - Charters Towers - north Drummond Basin

10.4.1 Regolith on Volcanics with shallow cover (1-5 m)

In the northern and central portions of the Drummond Basin, up to 5 m of colluvial-alluvial material, which has been weathered (mottling and nodules) but not lithified, occurs above a deeply weathered basement of weathered volcanics in a situation analogous to Drifter (Mt Isa Region). Hydromorphic and mechanical (bioturbation) dispersion has led to significant Au, As and Sb anomalies (1000 x 600 m) in the colluvium-alluvium (Figure 10.4) directly over mineralisation (e.g., Police Creek, Scott, 1997b (323R)). Although Au is concentrated in the <75 μm soil fraction, As and Sb occur with Fe in the >2 mm soil fraction. Separation of Au from its pathfinders could reflect the small primary Au grains (<30 μm) which remained small during weathering; As and Sb occur in neoformed Fe oxides of the mottles.

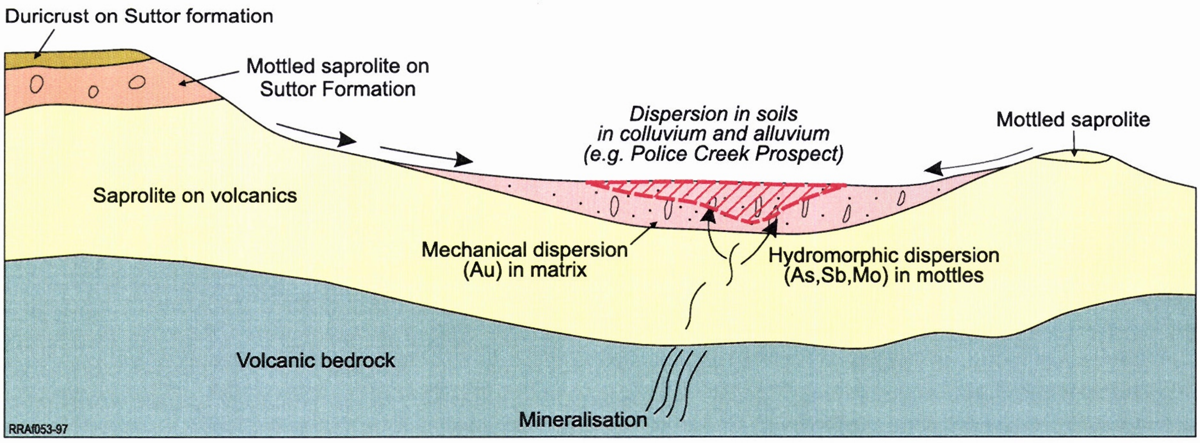

Figure 10.4. Cross section showing hydromorphic and mechanical dispersions of Au and pathfinder elements in soils developed in colluvium-alluvium, Charters Towers-north Drummond Basin.

Recommendations. Soil sampling (including specific sampling of mottles) would be effective in areas of shallow overburden (1-5 m). The probability of hydromorphic dispersion appears to be better in sediments that have been weathered since deposition.

10.4.2 Regolith on Campaspe Formation (>5 m) overlying volcanics or granite

Lead is mechanically dispersed in the base of the Campaspe Formation (Figure 10.5). Zinc and Cu form haloes at least 10 m above the unconformity where they are associated with dolomite and Fe oxides (e.g., Waterloo and Thalanga East, Scott, 1995b (168R); Scott, 1997a (422R)). The Pb halo is at least 1 km across, and the Zn dispersion is 600 x 300 m in size. In contrast to previous interpretations (Granier *et al.*, 1989), it is postulated that the Zn-Pb-Cu mineralisation appears to have outcropped in the early-mid Tertiary and gossanous fragments were mechanically dispersed for several hundred metres from the outcrop, prior to deposition of the Campaspe Formation.

Subsequent weathering of the gossanous clasts, incorporated into the base of the Campaspe Formation, leached Zn and Cu which were precipitated by nearby carbonates.

Ferruginous pisoliths occur in the top of the Campaspe Formation in large areas of the Charters Towers - Mt Windsor Subprovince. There has been hydromorphic dispersion for several hundred metres about Au mineralisation (Brahman prospect, Scott and Fraser,1997 (434R)) both in the granitic saprolite of the basement and in the ferruginous pisoliths of the Campaspe Formation (Figure 10.5). Arsenic, Cu, Pb and Au form a halo at least 700 x 500 m above the mineralisation in the ferruginous pisoliths.

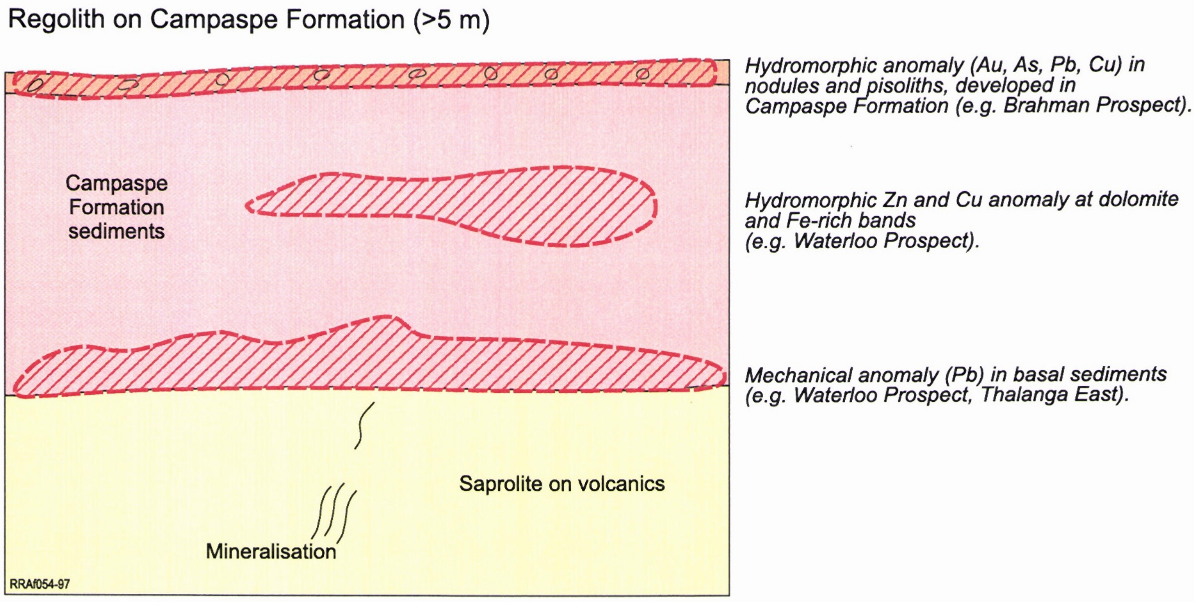

Figure 10.5. Cross section showing dispersion of pathfinder elements at unconformity between saprolite and Campaspe Formation and in Fe-rich bands and pisoliths developed in the Campaspe Formation, Charters Towers-north Drummond Basin.

Recommendations. The base of the Campaspe Formation and Fe oxides and dolomite bands within it should be sampled preferentially. The unconformity must be accurately located. Ferruginous pisoliths appear to be useful for locating underlying Au mineralisation but anomalies in these should be treated with caution; soils and the substrates in which pisoliths occur may be multicyclic and could inherit chemical signatures from past residence sites.

10.4.3 Regolith on Southern Cross Formation (>5 m) overlying volcanics

Regional Au backgrounds in the Southern Cross Formation are low (<5-10 ppb) distant from known mineralisation (*e.g.*, Wahines prospect, Campbell, 1996 (286R)) but, within 1 km of significant mineralisation (*e.g.*, Scott and Cindy lodes, Robertson, 1997 (449R)), the local background reaches 30 ppb. Local background is very high (>100 ppb) where mineralisation was only partly covered (Scott Lode) and mineralised detritus from the lode has been shed into the palaeodrainage; it is less (16 ppb) where the mineralisation is completely obscured by sediment (Cindy) and the bulk of the detritus was from up slope, beyond the mineralisation.

Mechanical dispersion has produced localised anomalies in Au, W and Mo in the base or above the base of the cover (Figure 10.6). Gold dispersions of 100-300 m diameter occur down slope of mineralisation (Scott and Cindy lodes) or near areas of numerous auriferous quartz veins. The highest concentrations occur in coarse sediments (Scott Lode). Gold is locally concentrated (500 ppb) down slope of the mineralisation where it was cut by a small outflowing palaeodrainage (Cindy). All this supports a largely mechanical dispersion mechanism. Partial extraction experiments, however, indicated that a proportion of the Au (~18%) is loosely attached so some hydromorphic relocation of the Au by weathering has taken place.

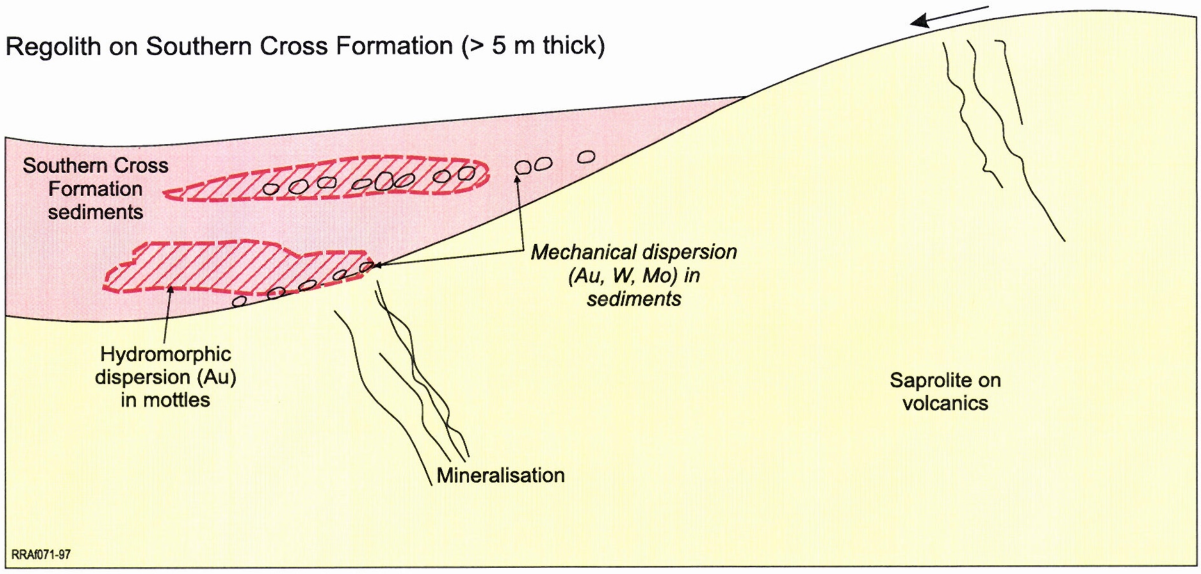

Figure 10.6. Cross section showing dispersion of Au and pathfinder elements at unconformity (between Southern Cross Formation and saprolite of volcanic basement) and mottling developed in Southern Cross Formation, Charters Towers-north Drummond Basin.

Recommendations. Within the Southern Cross Formation, a Au background of >20 ppb may indicate a distal Au source; >35 ppb may indicate a proximal Au source. However, the source may not necessarily be economic as significant dispersion may result from a large number of small, auriferous veins. Hydromorphic dispersion (~18%) of Au in Fe oxides of mottles has occurred. Dispersions occur not only at the base of the cover but higher in the sequence so the whole sequence should be analysed. Indicator elements are Au, W and Mo. Tungsten and Mo are likely to be distributed patchily. Arsenic and Sb should be used with care; adsorption onto Fe oxides of mottles occurs and a residual treatment may be necessary.

10.4.4 Regolith on Suttor Formation (>5 m) overlying volcanics

At Wirralie, the Suttor Formation sandstone contains locally anomalous, mechanically dispersed Au from topographically high, epithermal Au mineralisation in the basement (Figure 10.7) which reach ore grade in places. Siliceous fragments may contain epithermal quartz and Au. Subsequent weathering has redistributed As and Sb in Fe oxides of mottles.

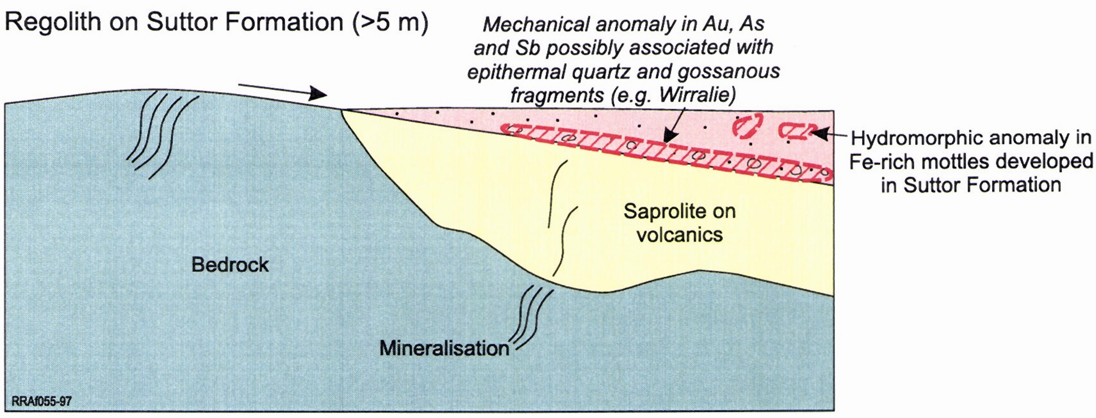

Figure 10.7 Cross section showing dispersion of Au and pathfinder elements at unconformity (between Suttor Formation and saprolite of volcanic basement) and mottling developed in Suttor Formation.

Recommendations. Sample basal sediments and ferruginous mottles developed in sediments.

Table 10.1. Recommended Sampling media

<table>
<tr><th colspan="2">Regolith-Landform Environments</th><th>Dispersion</th><th>Recommended Sampling Media</th><th>Case Studies</th></tr>
<tr><td colspan="5">Mt Isa Region</td></tr>
<tr><td colspan="2">Regolith with residual ferruginous capping on Proterozoic basement</td><td>Pb, As, Sb, and Ba anomaly (Residual, hydromorphic, mechanical) in duricrust</td><td>Lateritic duricrust, nodules and pisoliths</td><td>Lady Loretta deposit (Ag-Pb-Zn)</td></tr>
<tr><td colspan="2">Regolith with partly transported ferruginous capping on Proterozoic basement</td><td>Cu, Pb, As, Sb and Au anomaly (Hydromorphic, lateral chemical transport of Fe, Mn, Cu, As) in slabby duricrust, nodules and pisoliths</td><td>Slabby duricrust, nodules and pisoliths (care is needed in interpretation of data)</td><td>Python prospect (Cu)</td></tr>
<tr><td colspan="2">Regolith on Proterozoic basement lacking ferruginous capping</td><td></td><td>Soil and ferruginous lag</td><td>No case study (Recommendation based on the experience in the Yilgarn Craton)</td></tr>
<tr><td colspan="2">Regolith on Proterozoic bedrock with shallow cover (1-5m)</td><td>Cu, Zn, As, Pb and Sb anomaly (Hydromorphic, mechanical/bioturbation) in mottled colluvium - alluvium</td><td>Soil including specific sampling of mottles</td><td>Drifter prospect (Cu, Zn)
Little Eva (Cu)</td></tr>
<tr><td rowspan="2">Regolith on Mesozoic and Tertiary Sediments (>5m) overlying Proterozoic bedrock</td><td>Fresh Mesozoic and fresh basement</td><td>Cu, As, Sb and Au anomaly (Mechanical) at Proterozoic -Mesozoic boundary</td><td>Coarse basal or near basal sediments (interface sample)</td><td>Eloise deposit (Au-Cu)</td></tr>
<tr><td>Weathered Mesozoic and weathered basement</td><td>Cu, Zn and Au anomaly (Hydromorphic) in ferruginous bands at Proterozoic-Mesozoic boundary and within Mesozoic sediments</td><td>Ferruginous bands</td><td>Brumby prospect (Cu-Au)</td></tr>
<tr><td colspan="5">Charters Towers - North Drummond Basin Region</td></tr>
<tr><td colspan="2">Regolith on volcanics with shallow cover (1-5m)</td><td>Au, As and Sb anomaly (Hydromorphic, mechanical/bioturbation) in mottled colluvium-alluvium</td><td>Soil including specific sampling of mottles</td><td>Police Creek prospect (Au)</td></tr>
<tr><td colspan="2">Regolith on Campaspe Formation (>5m) overlying volcanics or granite</td><td>Pb anomaly (Mechanical) in basal sediments, Zn and Cu anomaly (hydromorphic) at dolomite and Fe-rich bands

Au, As, Cu and Pb anomaly (Hydromorphic) in ferruginous pisoliths developed in Campaspe Formation.</td><td>Basal sediments, Fe oxides and dolomite bands within the Campaspe Formation

Ferruginous pisoliths</td><td>Waterloo prospect (Cu-Pb-Zn)
Thalanga East (Cu-Pb-Zn)

Brahman prospect (Au)</td></tr>
<tr><td colspan="2">Regolith on Southern Cross Formation (>5 m) overlying volcanics</td><td>Au, W and Mo anomaly (Mechanical) in the base or above the base of cover, some Au (Hydromorphic)</td><td>Whole sequence</td><td>Scott and Cindy deposits (Au)</td></tr>
<tr><td colspan="2">Regolith on Suttor Formation (>5 m) overlying volcanics</td><td>Au (Mechanical) in basal sediments, Au, As and Sb in Fe oxides of mottles</td><td>Basal sediments; mottles developed in sediments</td><td>Wirralie deposit (Au)</td></tr>
</table>

11. CONCLUSIONS: MT ISA AND CHARTERS TOWERS-NORTH DRUMMOND BASIN REGIONS

11.1 Mt Isa region

Investigation of a broad spectrum of regolith-landform relationships and regolith from chosen districts, has contributed to an understanding of the distribution of regolith units, their stratigraphy, characteristics and evolution. The weathering geochronology implies that the Mt Isa region has been subject to some very wet periods, when dissolution, redistribution and reprecipitation of elements within weathering profiles was facilitated by abundance of meteoric water. It appears that the late Cretaceous - early Palaeocene, early to middle Oligocene, and early to middle Miocene were periods most conducive to dissolution and reprecipitation of elements. The provisional weathering history and implications for exploration for the Mt Isa region is summarised in Table 11.1.

The regolith-landform studies of the project have established the landscape evolution on regional and district scales and assessed the geochemical effectiveness of a variety of regolith materials. Geochemical dispersion of indicator elements and Au occur both in residual (*e.g.,* Lady Loretta) and partly transported duricrust (*e.g.,* Python prospect). The enrichment of indicator elements is derived from local sources in the case of residual duricrust or from local and distal sources in the case of transported duricrust. Recognising the difference between residual and transported duricrust is essential to data interpretation.

Useful dispersion into transported overburden occurs if the cover is less than 5 m thick. The dispersion is generally hosted by both pre-existing materials (*e.g.*, kaolinitic clay) and neoformed Fe and Mn oxides (*e.g.*, Drifter, Little Eva). Both hydromorphic and mechanical/bioturbation dispersion have taken place.

Areas dominated by thick Cambrian, Mesozoic and Cainozoic sediments present significant problems. Mechanical dispersion is limited to basal sediments (palaeosols, *e.g.*, Eloise) or hydromorphic dispersion to various Fe-Mn rich redox products (*e.g.*, Brumby). However, in places, there may be false anomalies that do not reflect known basement mineralisation. Where Fe and/or Mn have adsorbed significant quantities of indicator elements (*e.g.*, Zn and Cu) multiple regression, followed by a residual treatment of these indicator elements would remove the effects of adsorption and draw attention to anomalies that would otherwise remain hidden.

11.2 Charters Towers - north Drummond Basin region

Field relationships and geochronology indicate that evolution of landscape and weathering profiles involved repeated sedimentation and weathering episodes and spans the Tertiary, possibly extending into the Cretaceous. The weathering history of the region is summarised in Table 11.2.

The focus of most of the geochemical studies in the Charters Towers - north Drummond Basin region was on investigating dispersion in sedimentary cover. The trends appear to be similar to those of the Mt Isa region, with geochemical dispersions (hydromorphic and mechanical) in the sediments (Au, As, Sb at Police Creek) where the cover is shallow (1-5 m). Dispersion is predominantly mechanical near the base of the Campaspe (*e.g.*, Waterloo), Southern Cross (*e.g.*, Scott) and Suttor Formations (*e.g.*, Wirralie). In places, Zn and Cu are hydromorphically dispersed with Fe oxides and dolomite at least 10 m above the unconformity (*e.g.*, Waterloo). Gold, As and Pb have also hydromorphically dispersed in ferruginous pisoliths developed in the Campaspe Formation.

<table>
<tr><th colspan="3">Table 11.1 Provisional weathering history of the Mt Isa region and implications for geochemical exploration</th></tr>
<tr><th>Period</th><th>Event</th><th>Dispersion</th></tr>
<tr><td>Late Jurassic</td><td>Erosion of broadly undulating terrain produced plains of low relief on a local scale; deposition of basal conglomerates over the bedrocks in places; some Cambrian sediments preserved on topographic lows.</td><td>Mechanical dispersion during erosion.</td></tr>
<tr><td>Early Cretaceous</td><td>Marine incursion; widespread sedimentation; local relief reduced due to valley infilling and beveling of hills by erosion.</td><td>Mechanical dispersion.</td></tr>
<tr><td>Late Cretaceous</td><td>Marine transgressions; erosion and deep chemical weathering of Cambrian, Mesozoic and Proterozoic rocks.</td><td rowspan="2">Mechanical dispersion; leaching of ore and host rocks; accumulation and dispersion of Au and other elements in duricrusts and saprolites; weathering and possible dispersion in sediments in situations where underlying bedrock is also weathered.</td></tr>
<tr><td>Paleocene - Miocene</td><td>Continued deep chemical weathering on gently undulating surface; formation of residual massive, fragmental and nodular duricrusts and columnar silcretes possibly during Oligocene;transported slabby duricrust and some silcretes possibly during Miocene.</td></tr>
<tr><td>Pliocene - Quaternary</td><td>Instability and erosion, lowering of watertable, undulation of surface with formation of mesas, deposition of colluvium and alluvium, dispersion of lag and formation of black soils in poorly drained areas; continued weathering, including silification and ferruginisation, formation of vesicular duricrust and redox fronts within the cover sequences; local topographic inversion.</td><td>Mechanical dispersion in soils; hydromorphic dispersion at redox fronts within the thick cover sequences.</td></tr>
<tr><td>Quaternary to present</td><td>Continued erosion and weathering, silicification and ferruginisation of alluvium including formation of mottles.</td><td>Hydromorphic dispersion in mottles in shallow covered areas, clastic reworking in soils on exposed surfaces with bioturbation.</td></tr>
</table>

Note: Weathering and erosional processes have been continuous but their relative importance has changed over time.

Table 11.2 Provisional weathering history of the Charters Towers - north Drummond Basin and implications for exploration

Period	Event	Dispersion
Late Cretaceous-Palaeocene	Deep chemical weathering of basement and stripping.	Leaching of ore and host rocks, accumulation and dispersion of Au and other elements in duricrusts and saprolites.
Palaeocene - Oligocene	Instability, erosion of basement and deposition of Southern Cross and Suttor Formation sediments.	Mechanical dispersion in sediments.
Oligocene - Pliocene	Continued deep chemical weathering, formation of soils, mottling and duricrust on Southern Cross/Suttor Formation in places.	Possible hydromorphic dispersion in weathered sediments.
Pliocene - Quaternary	Instability, erosion and dissection of weathered mantle; deposition of Campaspe Formation; ferruginous pisoliths development on Campaspe Formation, local topographic inversion.	Mechanical dispersion; hydromorphic dispersion in ferruginous pisoliths and ferruginous bands developed within the Campaspe Formation sediments.
Quaternary - Present	Ongoing weathering and erosion of exposed units, deposition of colluvium and alluvium and their weathering.	Hydromorphic dispersion in mottles developed in colluvium and alluvium, clastic reworking in soils on exposed surfaces with bioturbation.

Note: Weathering, erosional and depositional processes have been continuous but their relative importance has changed over time.

12. RECONCILING PROJECT OBJECTIVES WITH OUTCOMES

The major objectives of this project as stated in the project proposal are compared below, with the findings.

12.1 Principal objective vs outcomes

To substantially improve 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) Charters Towers-north Drummond Basin region.

Regolith-landform frameworks for the Mt Isa region and Charters Towers-north Drummond Basin were established. Regolith-landform maps (factual and derivative) on a regional (1:250 000 - 1:500 000) to district (1:50 000 - 1:100 000) scales were prepared for ten regions and districts. Local scale maps (1:5 000 - 1:25 000) were also prepared in six locations. Within each of these districts, detailed multi-disciplinary studies were undertaken at one or more sites, including regolith-landform relationships, regolith stratigraphy with petrographic, chemical and mineralogical characterisation of regolith coupled with studies of geochemical dispersion from buried mineralisation in a range of regolith environments (where possible). Regolith models have been established for several districts in both the regions.

Methods of regolith mapping and enhancement of Landsat Imagery were developed to an operational stage and were made available to sponsors. Quaternary landscape processes were investigated in two areas, Kennedy Gap and Eloise-Maronan in the Mt Isa region. Weathering geochronology was undertaken both in the Mt Isa region and the Charters Towers north Drummond Basin region with emphasis on the Mt Isa region. One hundred and three $^{40}Ar/^{39}Ar$ laser step-heating and eleven K-Ar analyses of Mn oxides provided a substantial geochronological framework.

12.2 Specific objectives vs outcomes

1. *To establish sound operational procedures, within the finite resources of the project, for exploration geochemistry in the two regions based on generation of knowledge of dispersion patterns, dispersion processes and regolith-landform settings by:*

    - *a series of case studies;*
    - *establishing geochemical dispersion models based primarily on these case studies;*
    - *determining a field scheme for the identification and classification of sample type for use with exploration drilling and surface sampling, that takes into account regolith-landform setting and weathering history.*

Regolith-landform maps, regolith stratigraphy, characteristics of regolith and regolith-landform models were established for a number of districts (Table 12.1). The origin of specific materials such as ferruginous materials, silcrete and black soils was established. Examples of weathering profiles and sediments are illustrated in the Atlas of Regolith Materials, as an aid to identifying materials in hand specimens, drill cuttings and thin or polished sections (Phang *et al.*, 1997 (450R)). Criteria for distinguishing transported from residual regolith materials have been established. This remains critical to effective exploration, particularly for distinguishing weathered cover from weathered basement.

Geochemical dispersion was studied in a variety of regolith-landform settings, although some had no known mineralisation beneath. Element distributions were determined at each site and the probable dispersion mechanisms established. Several sample media were demonstrated to have specific application in exploration.

2. *To develop appropriate methods of regolith mapping (including remote sensing) for control of exploration geochemistry and geophysics that take into account weathering and geomorphological histories in the regions.*

The methodology for compiling regolith-landform maps was further developed. The processing and enhancement of landsat TM imagery using principle components and band ratios of separating weathered materials at the surface were also developed and provided to sponsors.

3. *To facilitate transfer of research findings into exploration practice through field trips, review meetings and substantial project reports.*

The following meetings and field visits addressed this objective:

Sponsors Meetings	***Field Excursions***	
28 November, 1994	26-28 May, 1995	Mt Isa region
25 May, 1995	23-25 July, 1996	Charters Towers- north Drummond Basin
22 July, 1996		
1 May, 1997 (Final meeting)		

12.3 Recommendations for future research

The following topics are important future research directions in the Mt Isa and Charters Towers-north Drummond Basin regions.

Mt Isa region

- Continued investigation of weathering, stratigraphic and sedimentology of recent and old cover sequences, particularly in the Mt Isa Eastern Succession.
- Continued investigation of regolith characterisation and weathering geochronology.
- Continued development of field-based criteria for distinguishing residual from transported regolith.
- Investigation of supergene enrichment and depletion of Au and base metals.
- Continued investigation of source and mechanisms of dispersion into transported cover and thus optimising sampling media. *To achieve this, it would be essential to have access to sites with known major mineralisation.*
- Testing of partial and selective extraction procedures for enhancing anomalies.
- Continued investigating origin of the cherty breccia at the base of the Cambrian and tracing the source of its anomalies.
- Determining procedures for identifying false from true anomalies with multivariate statistics.

Charters Towers-north Drummond Basin region

- Continued investigation of regolith characterisation, landscape evolution and weathering geochronology.
- Continued development of field-based procedures for distinguishing residual from transported regolith.

- Continued investigation of the origin of ferruginous nodules and pisoliths developed in the Campaspe Formation and their use in exploration. Regional sampling of ferruginous nodules should be carried out to delineate chalcophile corridors related to mineralisation.

- Continued investigation of source, mechanisms and size of dispersion into the cover sequences and thus optimising sampling media and sampling strategies.

- Developing methods/techniques to distinguish between mechanically and hydromorphically dispersed gold.

Table 12.1 Summary of regolith and geochemical dispersion study sites in project 417

MAPPING, REGOLITH CHARACTERISATION AND REGOLITH MODELS

- *Regional scale mapping-**1:500 000-1:250 000***
    - Regional regolith-landforms of Mt Isa region (84000 km^2)
    - Regional regolith-landforms Charters Towers-north Drummond Basin (30260 km^2)
    - AGSO-AGCRC Seismic Line (2600 km^2)

- ***District scale mapping (1:50 000-1:100 000)***
    - Buckley River-Lady Loretta (3220 km^2)
    - Selwyn (1806 $km^{2)}$
    - Eloise (480 km^2)
    - Maronan (645 km^2)
    - Tringadee (600 km2)
    - Little Eva-Dugald River (1200 km^2)
    - Police Creek-Mt Coolon (1250 km^2)

- ***Local scale mapping (1:5 000-25 000)***
    - Python prospect (4 km^2)
    - Grey Ghost prospect (18 km^2)
    - Little Eva prospect (1 km^2)
    - Tringadee prospect (12 km^2)
    - Police Creek prospect (2 $km^{2)}$
    - Pajingo deposit (30 km^2)

GEOCHEMICAL DISPERSION STUDIES

- Python prospect (Cu prospect)
- Lady Loretta deposit (Pb-Ag-Cu)
- Blinder prospect (Zn)
- Drifter (Zn)
- Eloise deposit (Cu-Au)
- Maronan prospect (Cu-Au)
- Selwyn deposit (Au-Cu)
- Little Eva prospect (Cu)
- Tringadee prospect (Zn)
- Brumby prospect (Cu-Au)
- Scott Lode and Cindy deposits (Au)
- Waterloo-Thalanga East prospects (Cu-Pb-Zn)
- Brahman prospect (Au)
- Police Creek prospect (Au)
- Wirralie deposit (Au)

GEOCHRONOLOGY STUDIES

- Mt Isa mines
- Lake Moondarra prospect
- Kennedy Gap- (Mesa 1 outcrop (324605E 7755409N), Gunpowder Creek Road prospect (301550E 7783000N)
- Century deposit
- Overhang deposit
- Selwyn deposit
- Pegmont prospect
- Cowie prospect
- Tringadee prospect
- Tick Hill region
- Scott Lode deposit

13. ACKNOWLEDGEMENTS

We wish to thank the sponsoring companies and their personnel for providing encouragement, financial and logistic support for this project over three years; without this the research would not have been possible. They also provided access to exploration sites and data; project geologists and staff provided hospitality and critical discussions. MIM Exploration is thanked for providing airborne radiometric data for the Buckley River and Selwyn regions.

Collaborative support of the Cooperative Research Centre for Australian Mineral Technologies is gratefully acknowledged. Thanks go to Matthew Dell who provided samples and field information for the Seismic Line.

Sample preparation was by Wayne Maxwell and Sheryl Derriman. XRD analysis was by Michael Hart. Chemical analyses were by Michael Hart (CSIRO), ANALABS (Perth) and Becquerel Laboratories. Thin and polished sections were prepared by Ray Blitz. Pearl Phillips and Jenny Porter assisted with document formatting and compilation. Diagrams were drafted by Travis Naughton, Angelo Vartesi and Colin Steel. All this assistance is acknowledged with appreciation.

Thanks go to Dr Charles Butt and Dr Leigh Bettenay who provided critical review of this manuscript.

14. REFERENCES

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. pp.207-215.

Anand, R.R., Smith, R.E., Phang, C., Wildman, J.E., Robertson, I.D.M. and Munday, T.J., 1993. Geochemical exploration in complex lateritic environments of the Yilgarn Craton, Western Australia. CSIRO Australia, Division of Exploration and Mining Report 442R. 297pp.

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 Australia, Division of Exploration and Mining Report 440R. 87pp.

Anand, R.R., Phang. C., Wilford, J.R., Wildman, J.E., Li Shu, Robertson, I.D.M. and Munday, T.J., 1996. Regolith-landscape characteristics, evolution and regional synthesis of the Mt Isa region - Progress Report. CSIRO Australia, Division of Exploration and Mining Restricted Report 158R/CRC LEME Restricted Report 1R. 142pp.

Anand, R.R., Wilford, J., Munday, T.J., Phang, C., Wildman, J.E. and Scott, K.M., 1995. Mt Isa field trip, 26-28 July, 1995. CSIRO Australia, Division of Exploration and Mining Restricted Report 156R. 41pp.

Aspandiar, M.F., Eggleton, R.A., Orr, T., Van Eck, M. and Taylor, G., 1997. An understanding of regolith and landscape evolution as an aid to mineral exploration-the Charters Towers experience. The Aus. IMM Annual Conference, Ballarat, pp.125-129.

Beams, S. D., 1993. Landform development in North East Queensland: The impact on geochemical exploration procedures. In: R.A. Henderson, (Ed), Guide to the economic geology of the Charters Towers region, North Eastern Queensland. Geological Society of Australia (Queensland Division), James Cook University of North Queensland, Townsville.

Beckman, G.G., Thompson, C.H. and Richards, G., 1981. Relationships of soil layers below gilgai in black earths. In: J.W. McGarity, E.H. Hoult and H.B. So (Eds), The properties and utilisation of cracking clay soils. Reviews in Rural Science, 5:64-72.

Berry, R.F., Huston, D.L., Stolz, A.J., Hill, A.P., Beams, S.D., Kuronen, U. and Taube, A., 1992. Stratigraphy, structure and volcanic-hosted mineralization of the Mount Windsor Subprovince, North Queensland, Australia. Economic Geology, 87:739-763.

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

Birot, S P., 1955. Morphologie Structural. Press 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.

Britt, A.F., 1993. Regolith, bedrock and geochemistry at Johnson Creek, Northwestern Queensland. Honours Thesis, Australian National University. 190pp.

Campbell, I.D., 1996. Pajingo area. In: K.M. Scott, Li Shu, S. Fraser, I.D. Campbell, R.R. Anand and I.D.M. Robertson, Charters Towers-North Drummond Basin Field Excursion. CSIRO Australia, Division of Exploration and Mining Restricted Report 286R/CRC LEME Restricted Report 11R. 74pp.

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.

Chaffe, E., Ekstrom, A., Fookes, C.J.R., Gilkson, M. and Loeh, H., 1984. An examination of the oil shale from the Mount Coolon deposit. In: Proceedings 2nd Australian Workshop on Oil Shale, Brisbane, CSIRO, Sutherland, pp.56-61.

Clarke, D.E. and Paine, A.G.L., 1970. Explanatory notes on the Charters Towers Geological Sheet, Queensland. BMR, Geology and Geophysics, 34pp.

Connah, T.H. and Hubble, G.D., 1960. Laterites. In: D. Hill and A.K. Denmead (Eds), The Geology of Queensland. Journal of Geological Society of Australia, 7:373-86.

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 (Eds), Geochemical Exploration, 1976. Journal of Geochemical Exploration, 8:189-202.

Coventry, R.J., 1982. The distribution of red, yellow and grey earths in the Torrens Creek area, Central North Queensland. Australian Journal of Soil Research, 20:1-14.

Craig, M.A. and Churchward, H.M., 1995. Wiluna regolith landforms. 1:250,000 Regolith Landform Map. AGSO.

d'Auvergne, P., 1984. IMC Authority to Prospect 3521m Mount Coolon oil shale project. Unpublished report held by Queensland Department of Resource Industries as CR13538.

Day, R.W., 1981. Oil shale in Queensland. Queensland Government Mining Journal, pp.214-222.

Day, R.W., Whitaker, W.G., Murray, C.G., Wilson, I.H. and Grimes, K.G. 1983. Queensland Geology. A companion volume to the 1:2,500,000 scale map (1975). Geological Survey of Queensland, Publication. pp.383-194.

Dell, M., 1997. Regolith-landform-Mt Isa geodynamic transect. CSIRO Australia, Division of Exploration and Mining Restricted Report 451R/CRC LEME Restricted Report 67R.

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

Fellows, M.L. and Hammond, J.M., 1990. Wirralie gold deposit. In: F.E. Hughes (Ed), Geology of the mineral deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy, Melbourne, pp.1489-1492.

Fraser, S.J. and Green. A.A., 1987. A software defoliant for geological analysis of band ratios. International Journal of Remote Sensing, 8:525-532.

Fraser, S.J., 1997. A regional overview of the Charters Towers - north Drummond Basin region: Geomorphic Landform Provinces. CSIRO Australia, Division of Exploration and Mining Restricted Report 366R/CRC LEME Restricted Report 39R, pp.28.

Gibson, D.L., 1996. Regolith-landform relationships from the Broken Hill area. Regolith 96, Second Australian Conference on Landscape Evolution and Mineral Exploration, Abstracts, pp.11.

Grainier, C., Hartley, J., Michaud, J.C. and Troly, G., 1989. Contribution de la geochimie tridemensionelle a la decouverte, sous couverture allachtone, d'extensions du gisement polymetallique de Thalanga (Queensland, Australie). Journal of Geochemical Exploration, 32:467-475.

Grimes, K.G., 1972. The Mesozoic and Cainozoic geology of the Cloncurry 1:250 000 Sheet area, Queensland. BMR Australia Record, 11972/57.

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 Northern Queensland. BMR Journal of Australian Geology and Geophysics, 4:33-46.

Grimes, K.G., 1980. The Tertiary geology of north Queensland. In: R.A. Henderson and P.J. Stephenson (Eds), 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 (Ed), Geology of the mineral deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy. pp.943-948.

Hartley, J.S. and Alston, T., 1995. Discovery history and geochemistry of the Thalanga East and Waterloo base metal deposits, Mt Windsor Subprovince. In: S.D. Beams (Ed), Mineral deposits of Northeast Queensland: Geology and geochemistry. Economic Geology Research Unit, James Cook University of North Queensland, Contribution 52:171-181.

Hayba, D.O., Bethke, P.M., Heald, P. and Foley, N.K., 1986. Geologic, mineralogic and geochemical characteristics of volcanic-hosted epithermal precious-metal deposits. In: B.R. Berger and P.M. Bethke (Eds), Geology and geochemistry of epithermal systems. Reviews in Economic Geology, Vol.2, Society of Economic Geology, pp.129-167.

Henderson, R.A. and Nind, M.A.P., 1994. Tertiary units, landscape and regolith of the Charters Towers region. In: R.A. Henderson and B.K. Davis (Eds), New developments in geology and metallogeny: Northern Tasman orogenic zone pp.17-21. James Cook University of North Queensland, Economic Geology Research Unit, Contribution No 50.

Hutton, L.J., Grimes, K.G., Law, S.R. and McLennan, T.P.T., 1991. Geology of the Mount Coolon 1:250 000 sheet area. Queensland Resource Industries Record 1991/19. 113pp.

Imasuen, O.I., Tazaki, K., Fyfe, W.S. and Kohyama, N., 1989. Experimental transformations of kaolinite to smectite. Applied Clay Science, 4:27-41.

Jones, M., 1997a. Alluvial landscapes of the North Kennedy Gap area, Mt Isa district, Queensland. CSIRO Australia, Division of Exploration and Mining Restricted Report 382R/ CRC LEME Restricted Report 48R. 37pp.

Jones, M., 1997b. Alluvial landscapes of the Maronan area, Cloncurry-McKinlay district, Queensland. CSIRO Australia, Division of Exploration and Mining Restricted Report 374R/CRC LEME Restricted Report 45R. 37pp.

Jones, P.A., 1994. Python Grid geology and drill hole locations. 1: 5000 scale, Drawing No., 1SA/276, Figure No. 25. Technical Report No 2231, MIM Exploration Pty Ltd.

Li Shu and Robertson, I.D.M., 1997. Surficial geology around the Eloise area and dispersion into Mesozoic cover from the Eloise mineralisation, NE Queensland. CSIRO Australia, Division of Exploration and Mining Restricted Report 405R/CRC LEME Restricted Report 56R. 71pp.

Li Shu, 1997. Landscape evolution and regolith development over the Mt Coolon area, Central East Queensland. CSIRO Australia, Division of Exploration and Mining Restricted Report 448R/CRC LEME Restricted Report 64R.

McQueen, K.G. and Cross, A.J., 1998. Magnetite as a geochemical sampling medium: application to skarn deposits. In R.A. Eggleton (Ed), Proceedings of Regolith 96 Conference, Australian Journal of Earth Sciences (in press).

Nind, M.A.P., 1988. Nature and origin of the Campaspe Formation: a Pliocene continental sedimentary assemblage for North Queensland. M.Sc. Thesis, James Cook University North Queensland (unpublished).

Nott, J., 1994. Long-term landscape evolution in the Darwin Region and its implications for the origins of landsurfaces in the north of the Northern Territory. Australian Journal of Earth Sciences, 41:407-415.

Paton, T.R., 1974. Origin and terminology for gilgai in Australia. Geoderma, 11:221-242.

Phang, C., Munday, T.J. and Wildman, J.E., 1997. Regolith-landform relationships and geochemical dispersion around Tringadee and Brumby prospects. CSIRO Australia, Division of Exploration and Mining Restricted Report 429R/ CRC LEME Restricted Report 59R.

Phang, C., Anand, R.R., Wildman, J.E., Rŏbertson, I.D.M. and Li Shu, 1997. Atlas of regolith materials, North Queensland. CSIRO Australia, Division of Exploration and Mining Restricted Report 450R/ CRC LEME Restricted Report 66R.

Rivers, C.J., Eggleton, R.A. and Beams, S.D., 1996. Ferricretes and deep weathering profiles of the Puzzler walls, Charters Towers, North Queensland. AGSO Journal of Geology and Geophysics, 16:203-212.

Robertson, I.D.M., 1990. Mineralogy and geochemistry of soils overlying the Beasely Creek gold Mine-Laverton, W.A. CSIRO Australia, Division of Exploration Geoscience Restricted Report 105R. 53pp.

Robertson, I.D.M., Phang, C. and Munday, T.J., 1995. Regolith geology and soil geochemistry of the Little Eva copper prospect, Quamby district, N.W. Queensland. CSIRO Australia, Division of Exploration and Mining Report 128R. 46pp.

Robertson, I.D.M., Li Shu and Wildman, J.E., 1997. Geochemical dispersion around the Maronan Cu-Au prospect, N.E. Queensland. CSIRO Australia, Division of Exploration and Mining Restricted Report 409R/CRC LEME Restricted Report 57R. 19pp.

Robertson, I.D.M., 1997. Dispersion into the Southern Cross Formation around the Scott and Cindy Lodes, Pajingo, N.E. Queensland. CSIRO Australia, Division of Exploration and Mining Restricted Report 449R/CRC LEME Restricted Report 65R, 41pp.

Scott, K.M., 1987. Geochemistry of ferruginous outcrop as a guide to mineralization at Mt Leyshon, N.E. Qld. CSIRO Australia, Division of Mineral Physics and Mineralogy Restricted Investigation Report 1683R.

Scott, K.M., 1995a. The geochemistry of transported soils and weathered bedrock at Police Creek, Drummond Basin, Qld - A Progress Report. CSIRO Australia, Division of Exploration and Mining Report 157R. 19pp.

Scott, K.M., 1995b. Secondary dispersion about the Waterloo polymetallic deposits, Mt Windsor Sub-province, N.E. Queensland. CSIRO Australia, Division of Exploration and Mining Restricted Report 168R. 30pp.

Scott, K.M., 1996. Wirralie case study. In: K.M. Scott, Li Shu, S.J. Fraser, I.D. Campbell, R.R. Anand and I.D.M. Robertson, Charters Towers - north Drummond Basin Field Excursion. CSIRO Australia, Division of Exploration and Mining Restricted Report 286R/CRC LEME Restricted Report 11R. 74pp.

Scott, K.M., 1997a. The significance of Campaspe-dominated terrains in exploration within the Mt Windsor sub-province, N.E. Queensland. CSIRO Australia, Division of Exploration and Mining Restricted Report 422R/CRC LEME Restricted Report 58R. 25pp.

Scott, K.M., 1997b. Soil, bedrock and profile geochemistry at Police Creek, Drummond Basin, NE Queensland. CSIRO Australia, Division of Exploration and Mining Restricted Report 323R/CRC LEME Restricted Report 25R. 40pp.

Scott, K.M. and Fraser, S.J., 1997. Mineralogical and geochemical aspects of the regolith at the Brahman Au prospect, Charters Towers area, N.E. Queensland. CSIRO Australia, Division of Exploration and Mining Restricted Report 434R/CRC LEME Restricted Report 60R. 19pp.

Seed, M., 1995a. Discovery history, geology and geochemistry of the Yandan gold deposit. In: S.D. Beams (Ed), Mineral deposits of Northeast Queensland. Geology and Geochemistry EGRU Contribution. 52, Townsville, pp.79-90.

Seed, M., 1995b. Discovery history, geology and geochemistry of the Wirralie gold deposit. In: S.D. Beams (Ed), Mineral deposits of Northeast Queensland: Geology and Geochemistry EGRU Contribution. 52: Townsville, pp.91-99.

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

Smith, R.E., Anand, R.R., Churchward, H.M., Robertson, I.D.M., Grunsky, E.C., Gray, D.J., Wildman, J.E. and Perdrix, J.L., 1992. Laterite geochemistry for detecting concealed mineral deposits. CSIRO Australia, Division of Exploration Geoscience Report 236R. 171pp.

Smart, J., Grimes, K. G., Doutch, H.F. and Pinchin, J., 1980. The Mesozoic Carpentaria Basin and the Cainozoic Karumba basin, North Queensland. BMR, Geology and Geophysics, Bulletin 202.

Stephenson, P.J., Griffin, T.J. and Sutherland, F.L., 1980. Cainozoic volcanisms in northeastern Australia. In: R.A. Henderson and P.J. Stephenson (Eds), The Geology and Geophysics of Northeastern Australia, pp. 349-374.

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.

Strickland, C. D., 1993. Ross Mining NL Yandan water bore programme. Unpublished report held by Yandan Mine.

Summerfield, M.A., 1983. Silcrete. In: A.S. Goudie and K. Pye (Eds), Chemical sediments and geomorphology, pp.59-61, Academic Press, London.

Sutherland, F.L., Stubbs, D. and Green, D.C., 1977. K-Ar ages of Cainozoic volcanic suites, Bowen-St. Lawrence hinterland, North Queensland. Journal of the Geological Society of Australia, 24:447-459.

Taylor, G.F. and Scott, K.M., 1982. Evaluation of gossans in relation to lead-zinc mineralisation in the Mt Isa Inlier, Queensland. Australia. BMR, Geology and Geophysics, Bulletin 7:158-159pp.

Taylor, G.F. and Ruxton, B.P., 1987. A duricrust catena in South-East Australia. Geomorphology, 31:305-310.

Thompson, C.H. and Beckman, G.G., 1982. Gilgai in Australian black earths and some of its effects on plants. Trop. Agric. (Trinidad) 59, No 2, 149-155.

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

Twidale, C.R., 1956. Chronology of denudation in Northwest Queensland. Bulletin of the Geological Society of America, 67:867-882.

Wells, K., Murray, A.M. and Cunneen, R.D., 1989. The geology and exploration of the Mt Coolon gold deposit. In: G. Broadbent, R. Fumell and G. Morrison (Eds), NQ Gold 1989 Conference. Australasian Institute of Mining and Metallurgy, pp.111-114.

Wildman, J.E., 1997. The geochemical discrimination of mineralised and barren ironstones from the Selwyn Au-Cu deposit, NW Queensland. CSIRO Australia, Division of Exploration and Mining Restricted Report 341R/CRC LEME Restricted Report 35R. pp.21.

Wilford, J., 1997a. Regolith-landform characteristics, evolution and implications for mineral exploration over the Selwyn region, Mt Isa. CSIRO Australia, Division of Exploration and Mining Restricted Report 372R/CRC LEME Restricted Report 44R. 83pp.

Wilford, J., 1997b. Regolith-landform characteristics, evolution and implications for mineral exploration over the Buckley River-Lady Loretta region, Mt Isa. CSIRO Australia, Division of Exploration and Mining Restricted Report 407R/CRC LEME Restricted Report 47R. 89pp.

Wood, D.G., Porter, R.G. and White, N.C., 1990. Geological features of some Paleozoic epithermal gold occurrences in Northeastern Queensland, Australia. Journal of Geochemical Exploration, 36:413-44.

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

Wyatt, D.H., Paine, A.G.L., Clarke, D.E. and Harding, R.R., 1970. Geology of the Townsville 1:250 000 sheet area, Queensland. BMR Report 127.

Vasconcelos, P., 1997. Geochronolgy of weathering profiles. CSIRO Australia, Division of Exploration and Mining Restricted Report 452R/CRC LEME Restricted Report 68R.

APPENDIX I

LIST OF REPORTS FOR PROJECT P417

APPENDIX I

REPORTS ISSUED BY P417 PROJECT

REPORTS

DEM No	CRC LEME No	Title	Author (s)
128R		Regolith geology and soil geochemistry of the Little Eva Copper prospect, Brumby district, NW Queensland (volume I and II)	I.D.M. Robertson, C. Phang and T.J. Munday
157R		The geochemistry of transported soils and weathered bedrock at Police Creek, Drummond Basin, Queensland - A Progress Report	K.M. Scott
158R	1R	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
168R		Secondary dispersion about the Waterloo polymetallic deposit, Mt Windsor Sub-province, NE Queensland	K.M Scott
323R	25R	Soil, bedrock and profile geochemistry at Police Creek, Drummond Basin, NE Queensland	K.M Scott
341R	35R	The geochemical discrimination of mineralised and barren ironstones from the Selwyn Au-Cu deposit, NW Queensland	J.E. Wildman
374R	45R	Alluvial landscapes of the Maronan area, Cloncurry-Mckinlay district, Queensland	M.R. Jones
382R	48R	Alluvial landscapes of the Northern Kennedy Gap area, Mt Isa district, Queensland	M.R. Jones
372R	44R	Regolith-landform characteristics, evolution and implications for the mineral exploration over the Selwyn region, Mt Isa	J. Wilford
407R	47R	Regolith-landform characteristic, evolution and implications for the mineral exploration over the Buckley River- Lady Loretta region, Mt. Isa	J. Wilford
422R	58R	The significance of Campaspe-dominated regolith profiles in exploration within the Mt Windsor Sub province, NE Queensland	K.M Scott
409R	57R	Geochemical dispersion around the Maronan Cu-Au prospect, NE Queensland	I.D.M. Robertson, Li Shu and J. E. Wildman
405R	56R	Surficial geology around the Eloise area and dispersion into Mesozoic cover from the Eloise mine, NE Queensland	Li Shu and I.D.M. Robertson
449R	65R	Dispersion into the Southern Cross Formation around the Scott and Cindy Lodes, Pajingo, NE Queensland	I.D.M. Robertson
450R*	66R	Atlas of Regolith materials, North Queensland	C. Phang, R.R. Anand, J.E. Wildman, I.D. M. Robertson and Li Shu
366	39R	A regional overview of the Charters Towers-North Drummond Basin Region: Geomorphic Landform Provinces	S.J. Fraser
451R	67R	Regolith-landforms - Mt Isa geodynamic transect	M. Dell
452R*	68R	Geochronology of weathering profiles, North Queensland	P. Vasconcelos
429R	59R	Regolith - landform relationships and geochemical dispersion around the Tringadee and Brumby prospects	C. Phang, T.J. Munday and J.E. Wildman
448R*	64R	Landscape evolution and regolith development over the Mt Coolon area, Central East Queensland	Li Shu
447R	63R	Geochemical exploration in regolith dominated terrain, North Queensland	R.R. Anand, S.J. Fraser, Li Shu, T.J. Munday, C. Phang, I.D.M. Robertson, K.M. Scott, P. Vasconcelos, J.E. Wildman, J. Wilford
434R	60R	Mineralogical and geochemical aspects of the regolith at the Brahman Au prospect, Charters Towers area, NE Queensland	K.M. Scott and S.J. Fraser

* Yet to be released.

APPENDIX I (CONTINUED)

FIELD GUIDES ISSUED BY P417 PROJECT

Field Guides

DEM No	CRC LEME No	Title	Author (s)
156R		Mt. Isa Field Trip.	R.R. Anand, J.Wilford, T.J. Munday, C.Phang, J.E. Wildman K. Scott,
286R	11R	Charter Towers-North Drummond Basin Field Excursion	K. Scott, Li Shu, S. Fraser, I.D. Campbell, R.R. Anand and I.D.M Robertson

APPENDIX II

RESIDUAL TREATMENT OF DATA

APPENDIX II

Some indicator elements (e.g., Zn and Cu) are strongly adsorbed by or are incorporated into Fe and/or Mn oxides. Thus, the content of Fe and/or Mn may have a profound effect on the content of the indicator element, which is unrelated to mineralisation. It is necessary to remove this effect to use the indicator element properly. The content of the indicator element is first predicted from the Fe and/or Mn content and this is subtracted from the actual content (residual treatment). A simple linear regression and residual treatment is illustrated in Figure A where Zn may be predicted as a function of Fe.

$Zn = fFe + x$

A background population is first used to determine the relationship (dashed line). Anomalous zinc concentrations at B and D deviate from this prediction; the significance of D (D-C) is greater than that of B (B-A) even though the absolute value of D is less than that of B. This can have a profound effect on data interpretation.

This method may be expanded to include two predictive (adsorptive) elements (Figure B), e.g., Fe and Mn, where the background data approximates a tilted plane and the anomalous Zn component of B is B-A. Here the plane is defined by;

$Zn = f_1Fe + f_2Mn + x$

which is a simple, trivariate case of multiple regression. Again, the parameters of the plane (f_1 and f_2) are determined from background data; the anomalous component of B is determined from B-A; A being the expected Zn content predicted from both Fe and Mn (on the plane). Blind application of multiple regression techniques is not recommended; anomalous values may distort the result. Care needs to be taken that only background data are included before the regression parameters (f_1, f_2 and x) are estimated; this can be achieved by examination of a rotating plot and systematic exclusion of any anomalous data.

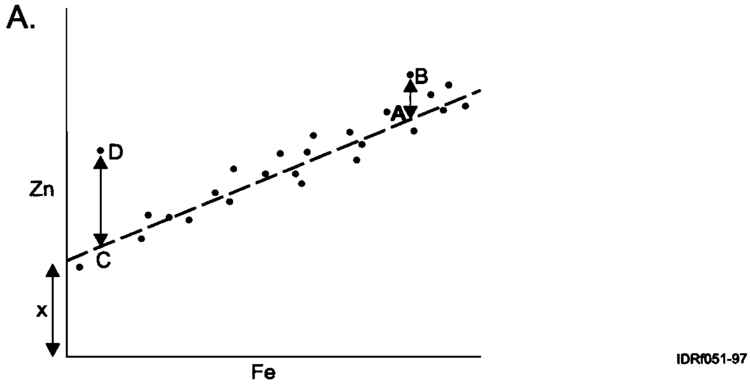

Figure A. A simple linear regression model for Zn adsorbed by Fe oxides. A background population, defined by A and C is used to predict the effects of adsorption. This is subtracted from actual values B and D to determine those parts of their Zn contents that are unexplained by the Fe oxide adsorption (B-A and D-C respectively).

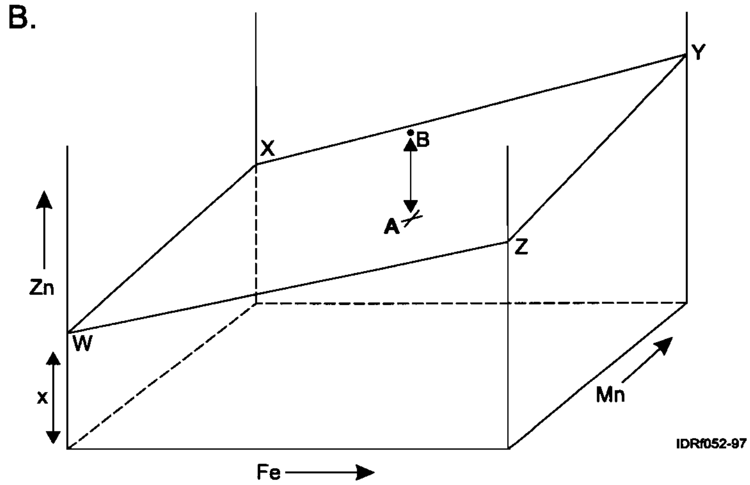

Figure B. Adsorption of an element (say Zn) on both Fe and Mn oxides defines an inclined plane WXYZ. Adsorption by these oxides may be predicted from background information at A and is then subtracted from a known value B to give that part unexplained by Fe and Mn adsorption.

APPENDIX III

REGOLITH MAPS AND GEOCHEMICAL DATA

DATASETS

Digital datasets used or created as part of the project are provided on three CD-ROM. The CD-ROM contain the following data types and formats;

1. regolith map datasets in Mapinfo and ArcInfo formats with attributes,

2. regolith maps as print-files in postscript and native HP650 RTL format, and

3. as geochemical datasets as ascii files.

Please be aware that with eleven companies, each wanting a diversity of products, we made a decision based on a survey of your dataset requirements that the above formats would be most appropriate. If your company requires additional data or in a particular format, a charge may have to be applied to cover conversion, printing or copying costs.

CD-ROM Volume 1

This CD contains Mapinfo and ArcInfo files from the Mt Isa and Charters Towers-north Drummond Basin study areas with the exception of Mt Coolon regolith-landform map which will be sent out separately. The CD also includes geochemical datasets and some postscript and RTL plot-files. Files are ordered in a hierarchical structure under the main directory called CRCDATA. The **CRCDATA** directory has the following sub-directories; Buckley, Charter, Selwyn, Tringadee, Eloise, Maronan, Geochem and Crcplots. Content and files formats under these sub-directories are described below.

Buckley sub-directory
Under the Buckley directory are two sub-directories called Mapinfo and ArcInfo. These directories contain Mapinfo and ArcInfo versions of the Buckley River-Lady Loretta regolith-landform map. Mapinfo files end with either l, P or A, which indicate a line, polygon and attribute feature file respectively. ArcInfo files are in arc export format (.e00) and as coverages with double precision. The regolith polygon coverage is called buckrego and the landform coverage is called buckland (see below for ArcInfo and Mapinfo data structure).

Selwyn sub-directory
Under the Selwyn directory are two sub-directories called Mapinfo and ArcInfo. These directories contain Mapinfo and ArcInfo versions of the Selwyn regolith-landform map. Mapinfo files end with either l, P or A, which indicate a line, polygon and attribute feature file respectively. ArcInfo files are in Arc export format (.e00) and as coverages with double precision. The regolith polygon coverage is called selwrego and the landform coverage is called selwland.

Charter sub-directory
Under the Charter directory are two sub-directories called Mapinfo and ArcInfo. These directories contain Mapinfo and ArcInfo versions of the Charters Towers regolith-landform map. Mapinfo files end with either l, P or A, which indicate a line, polygon and attribute feature file respectively. ArcInfo files are in Arc export format (.e00) and as coverages with double precision. The regolith polygon coverage is called charters.

Tringadee sub-directory
Under the Tringadee directory are two sub-directories called Mapinfo and ArcInfo. These directories contain Mapinfo and ArcInfo versions of the Tringadee regolith-landform map. Mapinfo files end with either l, P or A, which indicate a line, polygon and attribute feature file respectively. ArcInfo files are in Arc export format (.e00) and as coverages with double precision. The regolith polygon coverage is called Trinrego.

Maronan sub-directory
Under the Maronan directory are two sub-directories called Mapinfo and ArcInfo. These directories contain Mapinfo and ArcInfo versions of the Maronan regolith-landform map. Mapinfo files end with either l, P or A, which indicate a line, polygon and attribute feature file respectively. ArcInfo files are in Arc export format (.e00) and as coverages with double precision. The regolith polygon coverage is called Marorego.

Eloise sub-directory
Under the Eloise directory are two sub-directories called Mapinfo and ArcInfo. These directories contain Mapinfo and ArcInfo versions of the Eloise regolith-landform map. Mapinfo files end with either l, P or A, which indicate a line, polygon and attribute feature file respectively. ArcInfo files are in Arc export format (.e00) and as coverages with double precision. The regolith polygon coverage is called Eloirego.

ArcInfo and Mapinfo data structure
Items or attributes attached to the ArcInfo and Mapinfo formatted regolith map files vary in detail according to the geologist who compiled the map. However, all maps have as a minimum a label indicating the regolith and landform type and a description of the regolith-landform unit. An example of one of the more detailed attribute lists for the Selwyn regolith map is shown below. Although the example is a ArcInfo file similar feature items have been generated for mapinfo datasets.

Example of attributes or items for a AcrInfo coverage

Area
Perimeter
Sel_rego#
Sel_rego-id
IGDS-Text
Map_symbol
Regcolour
Sampcolour
Samp_code
Regolith
Landform
Bedrock
Rheading
Rdesc1
Rdesc2
Rdesc3
Rdesc4
Sdesc1
Sdesc2
Sdesc3
Sdesc4

Key items include the;

Map_symbol	- polygon label which appears on the map
Regolith	- describe regolith type
Landform	- describes landform type
Bedrock	- major bedrock type
Regcolour, sampcolour	

& samp_code - refer to various codes to colour the hard copy maps using AGSO shadesets.

Rdesc1,2 & 3 - legend description of regolith and landform features

Sdesc1,2 & 3 - legend description of geochemical sampling information

Geochem sub-directory
The geochem directory contains geochemical datasets. The datasets are organised by report number. Each report is a directory which contains the data and in most cases a README text files to explain content and format.

Directories named after P417 reports include;

128R
157R
158R
168R
323R
341R
405R
409R
422R
429R
434R
449R
451R

Each directory contains a number of files related to tabulated data within the report. Most files are in text (ascii) format, though a few are in Microsoft Word Version 6 format. The text files are all tab delimited which should make transfer to spreadsheets and data -bases easy. The MS Word files are tables. Some datasets do not have standard amgs and instead use local mine site coordinate systems.

Crcplots sub-directory
This directory contains postscript and native HP650 RTL files for printing hardcopy regolith maps of the Buckley River-Lady Loretta, Selwyn, Tringadee, Charters Towers, Maronan and Eloise regolith-landform maps at 1:100 000 scale. Postscript file have a '.PS' extension and HP 650 RTL files have a '.RTL' extension. The Mtisa directory contains the 1:500 000 regional regolith-landform maps over the Mt Isa region. Plot-files under these directories include;

Buckley
Brego100.ps and Brego100.rtl are print-files of the Buckley River-Lady Loretta regolith-landform map at 1:100 000 scale.

Bsamp100.ps and Bsamp100.rtl are print-files of the Buckley River-Lady Loretta geochemical sampling strategy map at 1:100 000 scale.

Selwyn
Sreg100.ps and Sreg100.rtl are print-files of the Selwyn regolith-landform map at 1:100 000 scale.

Ssamp100.ps and Ssamp100.rtl are print-files of the Selwyn geochemical sampling strategy map at 1:100 000 scale.

Charters
Charters.rtl is a print-file of the Charters Towers regolith-landform map at 1:250 000 scale.

Tringadee
Trinrego.ps and Trinrego.rtl are print-files of the Trindagee regolith-landform map at 1:50 000 scale.

Maronan
Marorego.ps is a postscript file of the Maronan regolith-landform map at 1:50 000 scale.

Eloise
Eloirego.ps and eloirego.rtl are print-files of the Eloise regolith-landform map at 1:50 000 scale.

Mtisa
Mtisa_r.ps and Mtisa_r.rtl are print-files of the regional regolith-landform map at 1:500 000 scale.

Mtisa_rt.ps and Mtisa_rt.rtl are print-files of the regional regolith-landform map superimposed over a digital elevation model (DEM) at 1:500 000 scale.

CD-ROM Volume 2

This CD contains postscript and native HP650 RTL files for printing hardcopy maps of the Buckley River-Lady Loretta study area (refer to report - 47R / E&M report 407R). Postscript file have a ".PS" extension and HP 650 RTL files have a ".RTL" extension. Files listed on the CD include;

Buckreg.ps
Buckreg.rtl
Bucktm5.ps
Bucktm5.rtl
Buck3tm.ps
Buck3tm.rtl
Bucksamp.ps
Bucksamp.rtl

Brief description of these files are provided below (for more detail see report 47R / E&M report 407R);

Buckreg is a print-file of the Buckley River-Lady Loretta Regolith-Landform map.

Bucktm5 is a print-file of Landsat TM band 5 with regolith polygons superimposed.

Buck3tm is a print-file of a enhanced Landsat TM image separating iron oxides, clays and silica materials with regolith polygons superimposed.

Bucksamp is a print-file of the Buckley River-Lady Loretta geochemical sampling strategy map.

CD-ROM Volume 3

This CD contains postscript and native HP650 RTL files for printing hardcopy maps of the Selwyn study area (refer to report - 44R / E&M report 372R). Postscript file have a ".PS" extension and HP 650 RTL files have a ".RTL" extension. Files listed on the CD include;

Sreg_rt.ps
Sreg_rt.rtl
Seltm_rt.ps
Seltm_rt.rtl
S3tm_rt.ps
S3tm_rt.rtl
Ssamp_rt.ps
Ssamp_rt.rtl

Brief description of these files are described below (for more detail see report 44R / E&M report 372R);

Sreg is a print-file of the Selwyn-River Regolith-Landform map.

Seltm is a print-file of Landsat TM band 5 with regolith polygons superimposed.

S3tm is a print-file of a enhanced Landsat TM image separating iron oxides, clays and silica material with regolith polygons superimposed.

Ssamp is a print-file of the Selwyn geochemical sampling strategy map.