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LATERITE GEOCHEMISTRY FOR DETECTING CONCEALED MINERAL DEPOSITS, YILGARN CRATON, WESTERN AUSTRALIA

P240 Summary Report

R.E. Smith, R.R. Anand, H.M. Churchward,
I.D.M. Robertson, E.C. Grunsky, D.J. Gray,
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November 1998

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RESEARCH ARISING FROM CSIRO/AMIRA REGOLITH GEOCHEMISTRY PROJECTS 1987-1993

In 1987, CSIRO commenced a series of multi-client research projects in regolith geology and geochemistry which were sponsored by companies in the Australian mining industry, through the Australian Mineral Industries Research Association Limited (AMIRA). The initial research program, "Exploration for concealed gold deposits, Yilgarn Block, Western Australia" (1987-1993) had the aim of developing improved geological, geochemical and geophysical methods for mineral exploration that would facilitate the location of blind, buried or deeply weathered gold deposits. The program included the following projects:

P240: Laterite geochemistry for detecting concealed mineral deposits (1987-1991). Leader: Dr R.E. Smith.
Its scope was development of methods for sampling and interpretation of multi-element laterite geochemistry data and application of multi-element techniques to gold and polymetallic mineral exploration in weathered terrain. The project emphasised viewing laterite geochemical dispersion patterns in their regolith-landform context at local and district scales. It was supported by 30 companies.

P241: Gold and associated elements in the regolith - dispersion processes and implications for exploration (1987-1991). Leader: Dr C.R.M. Butt.
The project investigated the distribution of ore and indicator elements in the regolith. It included studies of the mineralogical and geochemical characteristics of weathered ore deposits and wall rocks, and the chemical controls on element dispersion and concentration during regolith evolution. This was to increase the effectiveness of geochemical exploration in weathered terrain through improved understanding of weathering processes. It was supported by 26 companies.

These projects represented "an opportunity for the mineral industry to participate in a multi-disciplinary program of geoscience research aimed at developing new geological, geochemical and geophysical methods for exploration in deeply weathered Archaean terrains". This initiative recognised the unique opportunities, created by exploration and open-cut mining, to conduct detailed studies of the weathered zone, with particular emphasis on the near-surface expression of gold mineralisation. The skills of existing and specially recruited research staff from the Floreat Park and North Ryde laboratories (of the then Divisions of Minerals and Geochemistry, and Mineral Physics and Mineralogy, subsequently Exploration Geoscience and later Exploration and Mining) were integrated to form a task force with expertise in geology, mineralogy, geochemistry and geophysics. Several staff participated in more than one project. Following completion of the original projects, two continuation projects were developed.

P240A: Geochemical exploration in complex lateritic environments of the Yilgarn Craton, Western Australia (1991-1993). Leaders: Drs R.E. Smith and R.R. Anand.
The approach of viewing geochemical dispersion within a well-controlled and well-understood regolith-landform and bedrock framework at detailed and district scales continued. In this extension, focus was particularly on areas of transported cover and on more complex lateritic environments typified by the Kalgoorlie regional study. This was supported by 17 companies.

P241A: Gold and associated elements in the regolith - dispersion processes and implications for exploration. Leader: Dr. C.R.M. Butt.
The significance of gold mobilisation under present-day conditions, particularly the important relationship with pedogenic carbonate, was investigated further. In addition, attention was focussed on the recognition of primary lithologies from their weathered equivalents. This project was supported by 14 companies.

Although the confidentiality periods of the research reports have expired, the last in December 1994, they have not been made public until now. Publishing the reports through the CRC LEME Report Series is seen as an appropriate means of doing this. By making available the results of the research and the authors' interpretations, it is hoped that the reports will provide source data for future research and be useful for teaching. CRC LEME acknowledges the Australian Mineral Industries Research Association and CSIRO Division of Exploration and Mining for authorisation 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.

PREFACE TO THE SECOND IMPRESSION
R. E. Smith and R.R. Anand, 1st October 1998.

This summary report is one of two companion volumes (CRC LEME Open File Reports 50 and 58) which bring together the results of the CSIRO-AMIRA projects 'Laterite Geochemistry' and its extension 'Yilgarn Lateritic Environments' which, in total, ran from July 1987 to December 1993.

These summary and final reports synthesise 25 reports and three field guides which cover the project components, including multidisciplinary studies of several 'type' districts, across the Yilgarn Craton of Western Australia and many geochemical dispersion studies about concealed gold deposits.

Although the main focus of the project concentrated on gold exploration, the knowledge, regolith mapping methods, regolith stratigraphy, models and evolution are applicable to exploration for a wide range of commodities (including base metals, rare metals and diamonds) and the geochemical data are comprehensively multi-element.

In this second impression (second printing), the senior authors made the decision to produce the two reports as they were except for the correction of a small number of typographical errors, minor omissions and some additional acknowledgments.

We direct readers' attention to the following correlation of terms used for regolith-landform regimes developed in later work:

This Report		Terminology used in 1994 onwards
Residual regime	equivalent to:	*Relict regime*
As defined in Section 2.4.3, page 12, Open File Report 50		Anand and Smith (1993)

Comment on use of regolith-landform regimes

The first step is to make an objective map of the regolith-landform units present in an area, with little or no genetic bias. Such a factual map forms the basis of derivative or interpretative maps based on genetic grouping of the regolith and associated geomorphic features. It should also be pointed out that ferruginous materials have formed both in *in-situ* and transported materials. Laterite residuum, formed by residual enrichment in the weathering of parent rocks, is included with the relict regime. Iron cemented sands and gravels (ferricretes) are different because there is no direct genetic relationship between these ferricretes and the underlying bedrocks. Therefore, they are included with the depositional regime.

Although focus of the research presented here is on the Yilgarn Craton of Western Australia and its periphery, the research findings have wider application. Sponsors have used the research findings in other parts of Australia (Northern Territory and Queensland) and in appropriate terrain overseas, including western Africa, southern Asia and South America. However, having said this, we stress the importance of carrying out systematic research, including orientation studies, in each of these more distant areas.

We hope the approaches we have found helpful in the Yilgarn, translated generically, will be a guide to approaches that can be used in other lateritic terrains around the world.

Reference:

Anand, R.R. and Smith, R.E. (1993). Regolith distribution, stratigraphy and evolution of the Yilgarn Craton. In: P.R. Williams and J. A. Haldane (Compilers), An International Conference on Crustal Evolution, Metallogeny and Exploration of the Eastern Goldfields. Kalgoorlie 1993. Australian Geological Survey Record 1993/54. pp187-193.

Addresses and affiliations of authors

R.E. Smith
CSIRO Exploration and Mining
Private Bag, P.O. Wembley
WA 6014, Australia

E.C. Grunsky
Alberta Geological Survey
9945 108 Street
Edmonton, Alberta
Canada T5K 4G6
(Previously CSIRO Division of Exploration
Geoscience, Wembley, Western Australia)

R.R. Anand
CSIRO Exploration and Mining
Private Bag, P.O. Wembley
WA 6014, Australia

D.J. Gray
CSIRO Exploration and Mining
Private Bag, P.O. Wembley
WA 6014, Australia

H.M. Churchward
Glenarden Road
Balingup
WA 6253, Australia
(Retired, CSIRO Division of
Exploration Geoscience, Wembley,
Western Australia)

J.E. Wildman
CSIRO Exploration and Mining
Private Bag, P.O. Wembley
WA 6014, Australia

I.D.M. Robertson
CSIRO Exploration and Mining
Private Bag, P.O. Wembley
WA 6014, Australia

J.L. Perdrix
Editor, Australian Journal of Astronomy
P.O. Box 107
Wembley, WA 6014
Australia
(Retired, CSIRO Division of Exploration
Geoscience, Wembley, Western Australia)

EXECUTIVE SUMMARY

The objective of this four-year AMIRA study was to develop new and improved methods for mineral exploration based upon the use of multi-element laterite geochemistry. The project focussed upon using the knowledge that geochemical dispersion haloes in laterite greatly enlarge the target size in the search for concealed ore deposits. Laterite geochemistry was known to be applicable to a wide range of commodity types, including precious-, base-, rare-, and strategic-metal deposits. A multidisciplinary team was established with skills in regolith geology, geomorphology, soil science, exploration geochemistry, bedrock geology, numerical geology, hydrogeochemistry, and, through collaboration, remote sensing.

Orientation studies
Considerable emphasis was placed on establishing a regolith-landform understanding of four carefully-chosen orientation districts, within which geochemical dispersion from concealed Au deposits was studied. The orientation districts, Mt. Gibson, Bottle Creek, Boddington, and Lawlers range from 120 km^2 to 500 km^2 in area, represent a range of regolith and geomorphic settings distributed across the present-day rainfall gradient of the Yilgarn Craton. The Beasley Creek Au deposit was the focus of a subsidiary orientation study.

Specific themes
Research was also directed at the following specific themes: establishing (a) a workable scheme for terminology and classification of laterites for the Yilgarn Craton, (b) the siting and bonding of ore-associated elements in laterites, (c) processes of geochemical dispersion, (d) anomaly recognition methods for use with multi-element laterite geochemistry, (e) knowledge of regional variations in laterite geochemistry, (f) geochemical dispersion models, and (g) participating in exploration feasibility tests based on the research findings.

Exploration applications
Study of the chosen orientation districts allowed a substantially-improved understanding of the distribution of regolith units, regolith stratigraphy, the characteristics of regolith units, regolith evolution, and of geochemical dispersion patterns in laterite. This understanding is fundamental to effective exploration and has progressively been transferred to industry users through field trips, sponsors' meetings, project reports, and workshops.

Laterite classification and sampling methods
The major findings of the project concern the characteristics, origin and use of the lateritic residuum as a sample medium in exploration. The project's volume *Laterite types and associated ferruginous materials – terminology, classification and atlas* was an important practical outcome and is in widespread use amongst the sponsorship both in Australia and overseas.

Considerable attention was given to the question of where best to sample within the regolith stratigraphy. The spacing of samples and sampling patterns with regard to anomaly size have been integrated into general procedures. Knowledge of which parts of laterite blankets to sample is now well established from the results of this project. This knowledge has been extended, at pilot scale, to ferruginous material immediately underlying lateritic residuum, (materials such as mottled zone, ferruginous saprolite, and various iron segregations). Such media are important alternatives in areas where erosion has removed the lateritic residuum.

Data interpretation
The geochemical dispersion anomalies, studied within the orientation areas, have been comprehensively described. Sample type and geochemical characteristics are linked to the position within the regolith stratigraphy. These studies provide well-controlled reference geochemical data sets and thus provide important information on the geochemical characteristics for the settings and ore types studied. When coupled with knowledge of the background variation and thresholds for the target pathfinder elements, as provided in the CSIRO-AGE database, these data sets provide the essential components of a powerful exploration system. A discussion document on anomaly recognition methods for multi-element laterite geochemistry, complete with worked-through examples from the project, was produced and distributed to sponsors.

Areas of sedimentary cover
The use of laterite geochemistry in areas of sedimentary cover, particularly for exploration of substantial colluvial and alluvial outwash plains, was developed during the project. Application of these techniques, in collaboration with sponsors, proved the feasibility of exploration in sediment-covered areas by drilling for geochemical haloes in buried laterite, capitalizing on their far larger size than the source ore deposits. An important outcome of this phase of the project has been the recognition that, in the semi-arid and arid parts of the Yilgarn Craton, buried laterite profiles are widespread, and can occur even in areas where lateritic residuum has been largely stripped from the uplands.

Overall, it is clear that the level of expertise in laterite geochemistry used by industry is now substantially greater than when the project commenced in mid-1987. In collaboration with other researchers, project staff have played a major role in improving this expertise, developing application capabilities, and transferring these skills to sponsors.

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Note: At the time of going to press, the abstract of Report 246R (on the Boddington orientation study), with supporting diagrams, was awaiting clearance on confidentiality. It will be issued later as an addendum to Sections 4.6 and 9.2.

PROJECT LEADER'S PREFACE
R. E. Smith, 30 October, 1992

GENERAL

In January 1987, a programme of research, *Exploration for concealed gold deposits, Yilgarn Block, Western Australia* was proposed by CSIRO, through AMIRA, for sponsorship by companies from the mineral industry. The researchers who would carry out the projects which would constitute the program were within CSIRO's Division of Minerals and Geochemistry at Floreat Park in Perth and Division of Mineral Physics and Mineralogy at North Ryde in Sydney. In January 1988, all of the latter and much of the former were merged to form the present Division of Exploration Geoscience.

Initially, four research projects or modules were envisaged in this program. Three of these eventuated, the project reported upon here being one and each received substantial industry sponsorship. Their titles and pertinent dates are as follows:

Short title	AMIRA No.	Project Leader	Commenced	Ended	Extended Project	Completion date
Laterite Geochemistry	P240	R E Smith	1.7.1987	30.6.1991	P240A	30.6.1993
Weathering Processes	P241	C R M Butt	1.7.1987	31.12.1990	P241A	31.12.1992
Remote Sensing for Au Exploration, WA	P243	A R Gabell	1.9.1988	30.4.1992	-	-

The Laterite Geochemistry Project, AMIRA P240, was an evolutionary continuation of a project with the same name which had been under industry sponsorship since 1980.

SPONSORSHIP

During the AMIRA Laterite Geochemistry Project P240, a total of 30 companies have sponsored the research, Table 1. Although some sponsors had to withdraw (the October 1987 stock market collapse), several additional companies joined the sponsorship.

Table 1. Sponsors of the CSIRO-AMIRA Project P240

Australian Consolidated Minerals	Indian Ocean Resources Ltd
Analabs	F. Lubbock and Associates Pty Ltd
Battle Mountain Australia	Metana Minerals NL
Billiton Australia	Miralga Mining NL
BHP Minerals	Mt. Gibson Gold Project (Reynolds Australia,
BP Minerals/RTZ Ltd	Forsayth NL)
Centaur Mining and Exploration	Newmont Australia/Newcrest Mining
CRA Exploration	Pancontinental Mining Ltd
Eldorado Resources/Croesus Mining Ltd	Placer Pacific Pty Ltd
Dominion Mining Ltd/Southern Ventures	Poseidon
Geochemex Australia	Renison Goldfields Consolidated Ltd
Geoscan	Sons of Gwalia NL
Geopeko	Taurus Resources
Homestake Australia Ltd	Western Mining Corporation
Hunter Resources Ltd	Whim Creek Consolidated

This sponsorship funded substantial research by an interdisciplinary team. The AMIRA funding was augmented by funds for an additional study of the Lawlers district, a B.Sc. Honours project (two companies), and specific consultations to sponsoring companies. External funding for the Laterite Geochemistry Project is summarized in Table 2. The total of externally-derived project funds ($1.215M) marginally exceeded the total sought ($1.203M) in the original research proposal.

Table 2. Industry Funding for the Laterite Geochemistry Project P240

	$
Total funds for P240 to AMIRA	1,050,450
(As at 28 February 1992 and includes AMIRA administrative fees)	
Supplementary study, Lawlers District	38,000
Company support for a B.Sc. Honours study	14,000
Fees from consultancies to sponsoring companies	113,000
Total funding from sources external to CSIRO	**1,215,450**

Note: CSIRO more than matched these funds during execution of the project.

An important outcome has been the improved expertise of the exploration industry in exploring lateritic environments in Australia. Several discoveries of ore deposits (Au) were made by sponsors using methods developed during this project. At least five of these have been brought into production.

PROJECT PERSONNEL

Project staff:
R. E. Smith (Project Leader)
R. R. Anand (Deputy Leader)
H. M. Churchward
I. D. M. Robertson
J. Innes
E. C. Grunsky
D. J. Gray
J. L. Perdrix
J. E. Wildman
S. M. Llorca
H. van der Hyde

Collaborators:
M. J. Palmer, CSIRO Division of
    Mathematics and Statistics
T. J. Munday, CSIRO WA Remote Sensing
    Group/Curtin University of Technology
J. R. Gozzard, Geological Survey of WA

Support Staff:
A. J. Bowyer
G. Burkhalter
J. F. Crabb
M. K. W. Hart
C. Harris
A. Howe
A. Janes
J. Porter
B. W. Robinson
C. R. Steel
A. Vartesi
M. J. Willing

Visiting Scientists:
A. A. Levinson, University of Calgary,
    Alberta, Canada
R. Davy, Geological Survey of WA

Under Short-Term Contract:
P. English, Geochemex Australia
I. K. Butler, Consultant, Brisbane

B.Sc. Honours Student:
A. D. von Perger, School of Applied Geology,
    Curtin University of Technology

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1.0 INTRODUCTION

1.1 Background

The CSIRO-AMIRA Laterite Geochemistry Project P240 commenced 1 July 1987 as an expansion of a precursor project which had been funded by industry since 1980. The AMIRA funding period was for three years and has involved sponsorship by 30 companies. Since 1989, the project has been collaborative between CSIRO and the Bureau of Mineral Resources (BMR) through joint funding of one of the scientists and, more recently, with the Geological Survey of WA (GSWA) by participation of another scientist. For various reasons, including illness, the project period has run through until 30 June 1991, the period of four years covered by this report.

The project focuses upon use of the ferruginous upper zones of laterite profiles, particularly the lateritic residuum, as sample media for exploration geochemistry because (a) a multi-element geochemical anomaly is generally present in these materials above a concealed mineral deposit, and (b) the target size of such geochemical anomalies is commonly greatly enlarged in comparison with the corresponding mineral deposit itself. Emphasis of the project is on viewing geochemical dispersion patterns in laterite in their regolith-landform context – at both local and district scales. The project has been continually evolving by studying progressively more complex regoliths and building upon the accumulated experience of the research group.

Prior to the commencement of this AMIRA project, multi-element laterite geochemistry, incorporating methods developed through CSIRO research, was in operation with some exploration companies and discoveries of several ore deposits had resulted. The methods were being applied generally where lateritic residuum occurred at surface, or within a metre or so of the surface where sampling could be carried out by digging or by hand augering, the residual regime (1) of Fig. 1.1. Some deeper, subsurface laterite geochemistry was being carried out experimentally, the depositional regime (3).

At that time, exploration trials in the regional use of multi-element laterite geochemistry for exploration had been completed in the AGE Joint Venture, which consisted of Greenbushes Ltd, St. Joe Minerals Australia, and later, Sons of Gwalia NL. An integral part of that programme was sponsored research at CSIRO. These activities added to our knowledge of laterite geochemistry, which included orientation studies carried out earlier about the Golden Grove base metal sulphide deposits (Smith and Perdrix, 1983) and about the Greenbushes rare metal pegmatite field (Smith et al., 1987). In addition, the significance to exploration of chalcophile corridors had been recognized (Smith et al., 1989).
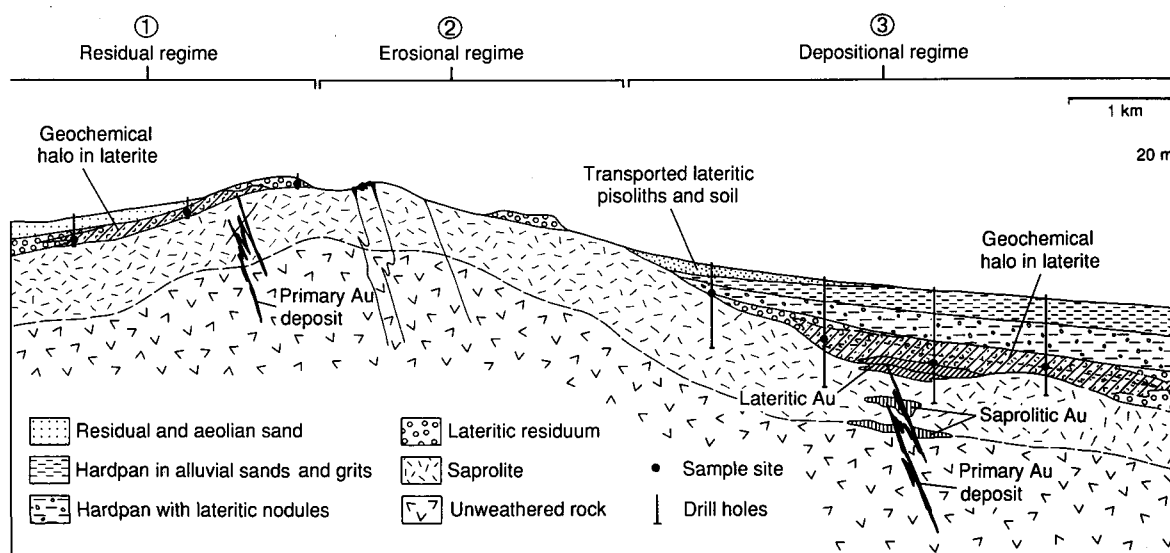
Figure 1.1 Generalized cross section showing some common Yilgarn regolith-landform situations. Modified from Smith and Anand (1988).

The chief barriers, at that time, to effective use of laterite geochemistry for the detection of concealed mineral deposits were:

- insufficient orientation data;

- insufficient knowledge of geochemical variation in laterites, hindering interpretation;

- insufficient knowledge of dispersion mechanisms of geochemical haloes in lateritic overburden;

- a lack of proven interpretative numerical methods;

- a lack of documentation and understanding of misleading laterite geochemical anomalies;

- an unfamiliarity with laterite geochemistry on the part of industry and a failure to realize its major potential advantages;

- inability to adequately interpret multi-element geochemical data; and

- perhaps disappointment with the results of initial exploration trials.

It was generally accepted that substantially more effective exploration would result if multidisciplinary research addressed these issues.

1.2   Objectives and strategy

The overall objective of the Laterite Geochemistry Project has been to develop new and improved methods for mineral exploration, based upon the use of multi-element laterite geochemistry.

This objective would be achieved through:

- continued execution of orientation studies of dispersion patterns in lateritic materials about concealed ore deposits;

- optimizing sampling methods with regard to sampling position, sample spacings, and sample patterns;

- understanding more about the characteristics and origin of the sample medium being collected;

- further development of methods for anomaly recognition, classification, and discrimination; and

- characterization of a selected series of anomaly types.

A major effort of the project was devoted to the study of four substantial *district-scale orientation areas*, each some 120 to 500 km^2 in area, distributed across the present-day rainfall gradient of the Yilgarn Craton, (Figure 1.2). To this was added subsidiary orientation studies, and research on *specific themes*. These themes are: the laterite classification scheme, the siting and bonding of elements of interest, dispersion processes, anomaly recognition methods, knowledge of regional geochemical variations, geochemical dispersion models, and feasibility tests for exploration. The above components of research are listed in Table 1.1.

Within each orientation district, the regolith-landform relationships of the area, at local and district scales, were established. Geochemical dispersion then could be interpreted within that regolith-landform framework. This approach has general application to exploration geochemistry and geophysics in deeply-weathered terrain. The approach has also been referred to as *landscape geochemistry*, particularly in the Soviet and Canadian literature (Perel'man, 1972; Fortescue, 1975, 1992).

1.3   Expected benefits

At the commencement of this project, laterite geochemistry already provided substantial benefits to exploration of poorly-outcropping terrain. It allowed more efficient detection of concealed ore deposits and significantly decreased exploration costs compared with close-spaced, systematic drilling. It was expected that the research project would considerably enhance these benefits and result in:

- more efficient laterite sampling both for reconnaissance and follow-up exploration;

- more confident interpretation of laterite geochemistry;

- improved knowledge of which particular parts of laterite blankets provide the most reliable samples for exploration; and

- a number of comprehensive orientation studies would be provided to assist interpretation.

Table 1.1. The main research components of the Laterite Geochemistry Project, 1987-1991.

- Orientation studies:
  - Mt. Gibson
  - Bottle Creek
  - Boddington
  - Lawlers
  - Beasley Creek

- Themes:
  - Laterite classification scheme
  - Siting and bonding of elements
  - Dispersion processes
  - Anomaly recognition methods
  - Knowledge of regional variations in laterite geochemistry
  - Representative models, syntheses

- Feasibility tests of research findings

- Experience transfer

1.4 Scope

Although the Laterite Geochemistry Project has focussed on the Yilgarn Block of WA and its periphery, the research findings have wider application. Use of the research by sponsors has included other parts of Australia (parts of NT and Qld) and appropriate terrain overseas, including western Africa, SE Asia and South America.

The scope of the project includes the development of methods for sampling, analysis, and interpretation of multi-element geochemical data from lateritic materials, predominantly lateritic residuum, and includes studies at several representative locations where Au mineralization occurs within or beneath laterite. Detailed studies of the mineralogical, textural, and geochemical characteristics of various laterite types form an important part of the research. Research during the last five years has focussed on exploration for Au deposits, yet the research has multi-commodity application. The research into the regolith-landform framework is applicable to most exploration commodities. Furthermore, the database used to geochemically characterize the regolith has involved analysis of more than 30 elements, and has provided comprehensive anomaly, threshold, and background information for a range of other commodities.

1.5 Purpose of this report

This report summarizes and synthesizes most of the research findings arising from this AMIRA research project. Although many individual research papers and reports have appeared during the last decade, this is the first major summary since the CSIRO Laterite Geochemistry Group was formed in the late 1970s.

Research progress has been presented to sponsors through periodic sponsors' meetings, in brief quarterly and semi-annual period reports, and in workshops and field trips. Substantial stand-alone reports have been issued as the major research topics were completed. These activities and reports are listed in Appendices I to V.

This summary report provides indexing and cross-referencing of individual reports and provides links with other research, including the AMIRA Projects Weathering Processes (P241) and Remote Sensing for Gold Exploration in Western Australia (P243). The report also provides an outlook on future direction of research and exploration.
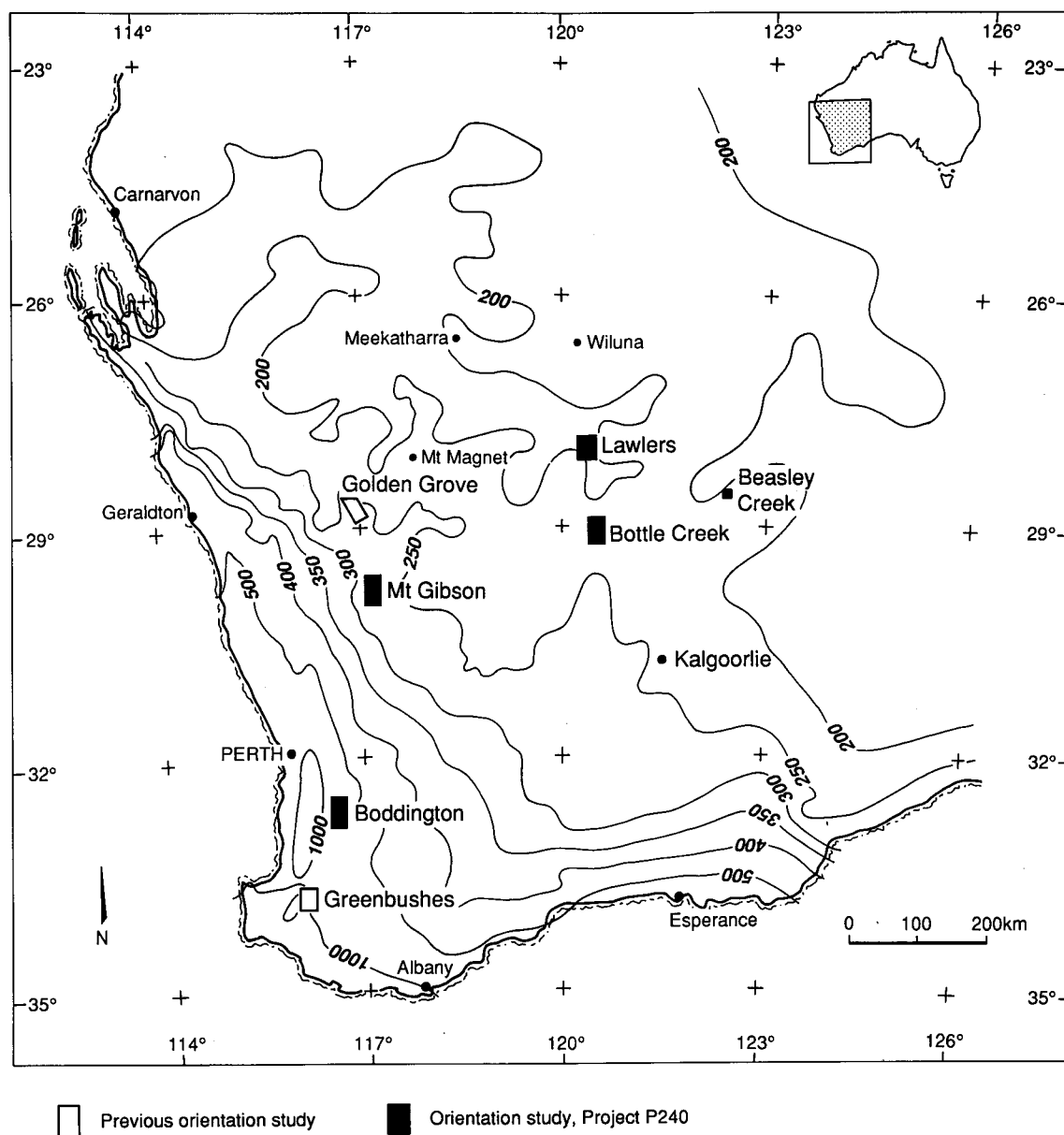
Figure 1.2. Map showing the locations of the four orientation districts which have been the foundations for the Laterite Geochemistry Project P240. Other orientation studies are also shown. Isohyets show the average rainfall in millimetres.

2.0   DEFINITIONS, STANDARDIZED TERMINOLOGY, AND CLASSIFICATION

2.1   Introduction

2.1.1   Purpose

Regolith profiles, some deeply weathered, and the terrain in which they occur, have been studied extensively by soil scientists, geologists, engineers, geomorphologists, and mining engineers. Each discipline or sub-discipline tends to develop its own terminology and classification schemes for its particular needs (Bardossy and Aleva, 1990). Therefore it should not be surprising to see a wide range of confusing or even contradicting terms in use. No one scheme is ever likely to be universally acceptable so it is important to keep in mind its purpose.

This section presents definitions of the main terms used in the project with commonality, where possible, with the Weathering Processes Project (AMIRA P241). It presents classifications of regolith materials, including relevant sample media, in terms of regolith stratigraphy. Their relationships to regolith-landform mapping units and regimes are also discussed.

2.1.2   Regolith, regolith stratigraphy and regolith units

Regolith is used as a general term for the entire cover, whether cemented or unconsolidated, that overlies unweathered bedrock, that has been formed by weathering, erosion, and sedimentary or chemical deposition. Regolith materials thus include residual weathered materials (e.g. saprolite, laterite, soils) and transported materials (e.g. colluvium, alluvium, evaporitic sediments, aeolian deposits).

The term *regolith stratigraphy* refers to units of weathering profiles as well as to those of the Cainozoic sedimentary succession. The use of the term stratigraphy, when dealing with regolith materials, is compatible with the International Stratigraphic Guide (Hedberg, 1976). A lithostratigraphic approach is used, namely systematic organization of rocks (in this case weathered rocks) and sediments based upon certain unifying characteristics, or attributes that distinguish each from the other layers.

The term *regolith unit* refers to the zones or horizons of weathering profiles such as soil, lateritic duricrust, lateritic gravel, mottled zone, saprolite, etc., as well as the subdivisions of the associated sedimentary sequences. Each regolith unit can vary spatially and changes can be gradual or sharp; subdivisions of a particular regolith unit are referred to as *regolith type* (e.g. gravelly soil, pisolitic duricrust).

A *regolith facies* is defined as the aspect, appearance and characteristics of a regolith type, properties which are usually related to the origin of the regolith type and especially distinguish it from its adjacent or associated types, as seen at the mesoscopic scale (hand specimen to continuous outcrop, cutting or excavation face) based upon descriptive parameters, using normal field aids (e.g. hand lens). Facies is thus used in the sense of Walker (1984).

2.2   Standardized terminology for lateritic regoliths

2.2.1   Lateritic weathering profiles

Figure 2.1 shows an example of a complete, lateritic weathering profile from the Yilgarn Craton using terminology proposed by the CSIRO Laterite Geochemistry (P240) and Weathering Processes (P241) Projects, see Anand and Butt (1988), Anand et al. (August 1989) and Butt et al. (1991). The profile can be compared with that for a typical laterite-saprolite profile of Bárdossy and Aleva (1990: Fig. 3-2). The lateritic residuum horizon is subdivided because of its importance in this project. Most of the other zones may also be subdivided using field, hand specimen, petrographic, mineralogical, or chemical criteria. Thicknesses of the whole profile and the component zones vary considerably; weathered profiles of 50 m or much more in total thickness are common.

Lateritic weathering profiles consist of two major components, the pedolith (the upper part of the profile where pedogenic processes have been dominant) and the saprolith (the lower part of the profile with fabric inherited from the parent rock). These are distinguished by their fabrics, which, in turn, reflect their genesis. Below are descriptions of the units, taken from Anand and Butt (1988), Anand et al. (1989) and Butt et al. (1991).

2.2.2   Pedolith

Pedolith is the upper part of the profile in which much of the fabric of the parent bedrock has been destroyed by one or more pedogenic processes, including non-isovolumetric weathering associated with soil formation,

Fig. 2.1. Regolith terminology for the deeply-weathered laterite profile (modified after Anand and Butt, 1988).

and/or the development of new fabrics. The pedolith is characterized by concentration of particular chemical components (e.g. Fe- and Al-oxides in lateritic profiles) and the presence of distinctive secondary structures such as mottles, pisoliths, and nodules.

Subdivision within the pedolith is based on fabric, particularly those of the secondary structures and/or on the concentration of particular elements. The principal units of the pedolith are the mottled zone, lateritic duricrust, lateritic gravel, and gravelly soil. Lateritic duricrust and the mottled zone may be absent. Generally, loss of fabric and the accumulation of Fe- and Al-oxides appear to coincide fairly closely, defining the mottled zone. Where such accumulations occur without substantial loss of fabric, the material remains classed as saprolite. Where loss of fabric occurs, without oxide accumulation, there is a transitional zone of settling and consolidation, the clay zone, which occurs just above the pedoplasmation front. Major structural features, such as quartz veins and lithological contacts, may still be preserved within the pedolith, generally with some change in orientation (dip).

Lag

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

Soil

Soil forms the uppermost horizon and is composed of the weathering products of the breakdown of the underlying lateritic residuum, mixed with plant remains and humic matter, and very small amounts of extremely resistant primary minerals (zircon, chromite, quartz, etc.). The soil is generally gravelly or sandy and acid although calcareous, red earths and other soils also occur.

The soil is readily removed by erosion as an early stage of dismantling of the weathering profile. Where dismantling is minimal, lateritic gravel commonly occurs at the surface. Further dismantling may expose lateritic duricrust. The duricrust commonly provides an armour for the softer, underlying regolith and further dismantling tends to be selective, for a variety of reasons, including duricrust thickness, hardness, Fe-content, and local geomorphology. Dismantling is discussed further in Section 4.2.4 (Orientation Studies – Mt. Gibson).

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

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

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

The sharpness of boundaries between the units described above is variable. The boundary between soil and lateritic gravel is generally not well defined. The transitions from lateritic gravel to duricrust can be gradational over 50 cm. However, in many cases, this boundary is relatively sharp. At the base of the duricrust, there is commonly a marked change in consolidation over a 1-10-cm interface to a heterogeneously mottled zone, to ferruginous saprolite, to a uniformly soft clay zone or, in some cases, directly to soft saprolite.

Mottled zone
The mottled zone represents the lower part of the ferruginous zone of the weathering profile and differs from the lateritic residuum above by lesser accumulation of Fe-oxides and lack of induration. The mottled zone has contrasting kaolinite-rich bleached domains and Fe-mottles, which may be distinguished easily in outcrops and in samples on a centimetre scale. The mottles are commonly red or reddish-brown and are dominated by hematite, goethite, and kaolinite. Many profiles show evidence that mottles evolve upwards in the profile into other secondary structures such as nodules and pisoliths and become upwardly more numerous. Nodule growth progressively destroys pre-existing fabrics, although lithic or saprolitic fabric may be preserved in their cores.

The lower boundary of the mottled zone is marked by the *cementation front*. This is a transformation front above which there is cementation by oxides and oxyhydroxides of Al, Fe, Mn, by silica and by carbonates of Ca and Mg. It is generally more planar than the pedoplasmation front and, in places, may extend below it, where saprolite fabrics may be cemented and thus preserved. The transition to the mottled zone, in places, may be gradational over 10 m or more. The mottled zone is generally softer than the overlying duricrust.

Clay zone
This zone generally occurs above the pedoplasmation front but may be absent. It consists of massive clays, commonly with a mesoscopically-homogenous clay fabric. The loss of lithic fabric is caused by solution and authigenesis of saprolitic kaolinitic clays and mechanical processes such as shrinking and swelling of clays.

2.2.3   *Saprolith*
Saprolith is the lower part of the profile that has retained the fine fabric of the parent bedrock; this was originally expressed by the arrangement of primary mineral constituents (e.g. mineral grain boundaries) and is now shown by relics and pseudomorphs. The definition may be extended to include weathered rocks in which only larger structures, including bedding, schistosity, veining, or lithological contacts, are preserved. The presence of these fabrics implies that weathering has been nearly isovolumetric and pseudomorphic. This zone is essentially characterized by alteration of weatherable primary minerals and by leaching of the most soluble elements (e.g.. alkalis and alkaline earths).

The saprolith is separated from fresh bedrock by the *weathering front*. This is a transformation front marking the commencement of weathering at the base of the regolith. Two saprolith horizons, saprolite and saprock, are recognized at present, in which the fabric and structure of the underlying bedrock are preserved. Even though their constituent minerals are weathered to varying degrees, they have not been affected by pedogenic processes.

Saprolite

Saprolite is weathered bedrock that retains much of the fabric and structure of the parent bedrock. Saprolite can be firm (rather than hard), soft, or friable. Isovolumetric weathering is commonly envisaged. Compared to saprock, more than 20% of the weatherable minerals have been altered. Saprolite may become more massive upwards as the proportion of clay increases and cementation by secondary silica, carbonates, and especially Fe oxides is common. The saprolite is lighter in colour than the overlying lateritic residuum. Its mineralogy is variable, depending upon the nature of the parent bedrock. The term "pallid zone" should not be used synonymously for saprolite as the latter exhibits a wide variety of colours. Although saprolites over felsic rocks are commonly white, over some felsic and over most mafic and ultramafic rocks, they are not; conversely, not all pale or white horizons are saprolite.

Saprock

Saprock is a compact, slightly-weathered rock of low porosity, with less than 20% of the weatherable minerals altered. Weathering is initiated along grain boundaries, intra-mineral fissures, exsolution lamellae, twin planes, cleavages, shears, joints and fractures and affects only a few individual mineral grains or mineral species. The boundary between bedrock and saprock is not generally a plane, but is very irregular and corestones of fresh rock may occur in the saprock and saprolite. The dominant secondary minerals of saprock are smectite, kaolinite and vermiculite after rock-forming minerals, with goethite and hematite after oxidized sulphides.

2.2.4 Other lateritic profiles

This section describes some other commonly-occurring weathering profiles in the Yilgarn Craton. Whilst saprolite is common to all the weathering profiles, the nature and thickness of the upper units may vary, depending upon bedrock type, present climate, and local drainage conditions. The Darling Range profile described below is an example of a saprolite overlain by a bauxite zone. At Lawlers, ferruginous saprolite, instead of a mottled zone, is extensively developed on mafic and ultramafic rocks.

Lateritic bauxite profiles - Darling Range, Boddington

In the Darling Range, the ferruginous zones are commonly bauxitic (Fig. 2.2). The lateritic weathering profile generally consists of a succession of zones: a gravelly, sandy top soil, a loose, nodular-pisolitic unit, a lateritic duricrust, a bauxite zone and a clay zone which passes through saprolite into fresh rock at depths that range from 2 to 50 m. The thicknesses of these zones vary considerably, depending upon the nature of the parent bedrock.

In the Darling Range laterites, a relative increase in Al_2O_3 has taken place in the upper parts of some profiles to the extent that gibbsite occurs in the lateritic residuum and the mottled zone. The mottled zone is dominant and is referred to as the bauxite zone or B zone by the local bauxite mining companies (Anand *et al.*, 1991). It is an earthy, porous, 2-6 m thick, yellowish-brown to dark reddish-brown layer which underlies the 1.5-3.0 m thick lateritic duricrust. The boundary between lateritic duricrust and bauxite zone is gradational. The bauxite zone consists of ferruginous fragments, incipient nodules and, in places, is mottled. Relict saprolitic fabrics, such as gibbsite pseudomorphs after feldspars, may be present in this zone. The dominant secondary minerals are gibbsite, goethite, and hematite. The bauxite zone is underlain by a 10-50 m thick, multi-coloured clay zone and saprolite. The saprolite merges into underlying parent rock through a 0.5-2.0 m thick saprock zone.

Lawlers profile

Although mottled zones are widespread, they are not developed everywhere in the lateritic profile. Mottled zones are generally most conspicuous in saprolite developed from felsic rocks. A mottled zone can even be developed in some Cainozoic and Permian sediments. At Lawlers, where the underlying rock is mafic/ultramafic, ferruginous saprolite is commonly developed. Here the upward sequence from the bedrock is saprock, a thick saprolite, ferruginous saprolite, collapsed ferruginous saprolite, nodular lateritic duricrust, and loose lateritic nodules (Fig. 2.3).
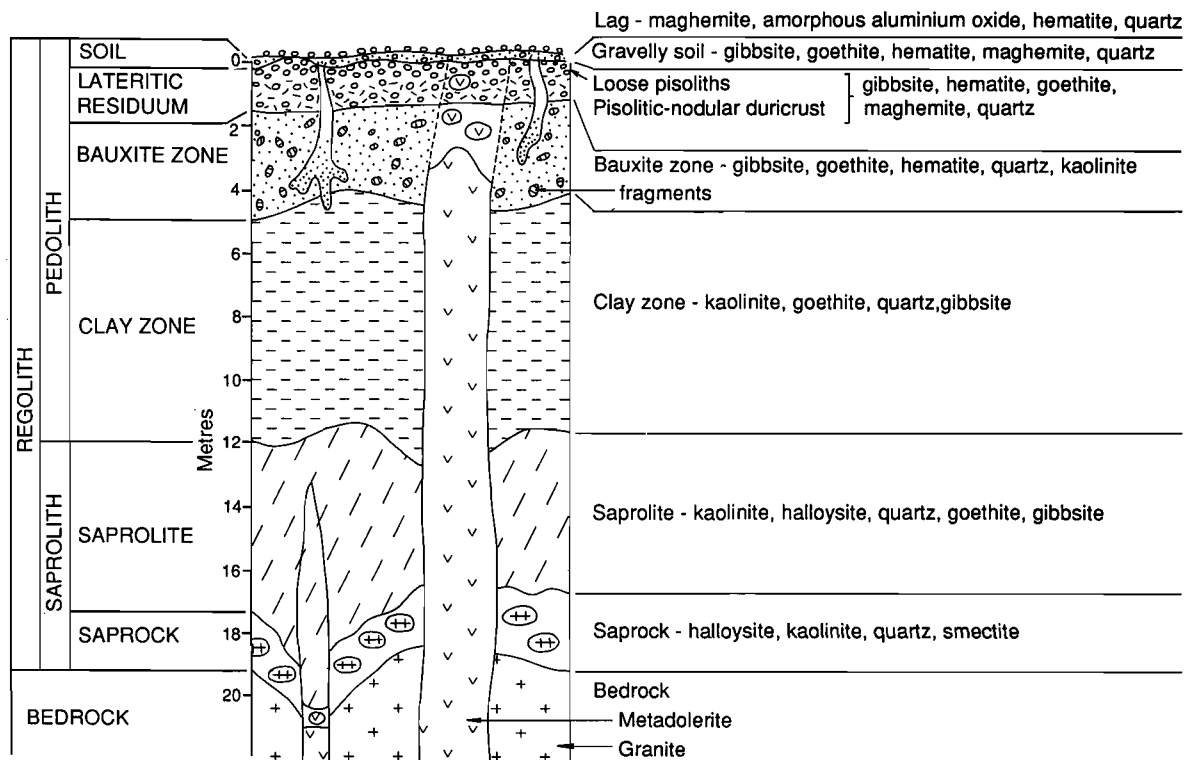
Figure 2.2. Typical weathering profile in the Darling Range (modified after Anand *et al.*, 1991).
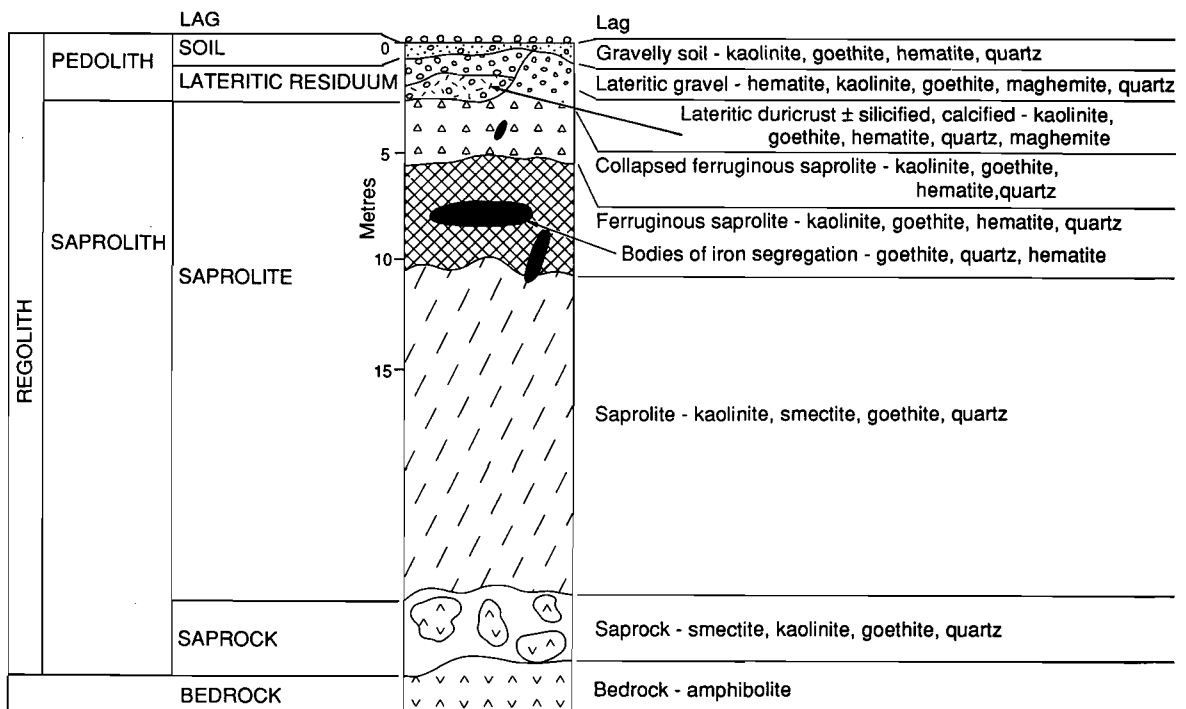
Figure 2.3. Typical weathering profile in the Lawlers area (after Anand *et al.*, 1991).

Ferruginous saprolite is formed by the infusion of clay-rich saprolite with goethite and, here, is hard, 5-15 m thick, massive to mottled, and is dominated by goethite and kaolinite. Fragments of ferruginous saprolite are yellow-brown, non-magnetic, irregular and have an incipient nodular structure. Fragment interiors may contain preserved relics of resistant primary minerals (e.g. talc, chromite) allowing limited identification of the underlying lithology. Where exposed in the McCaffery, North, and Turrett Pits (discussed later in Section 4.4), ferruginous saprolite forms a continuous blanket and is overlain by *collapsed ferruginous saprolite* where soft, soluble, less ferruginized material has been removed by leaching, causing the whole structure to collapse.

Lateritic residuum (embracing nodular duricrust and loose nodules) averages some 3-6 m in thickness. Duricrust is not present at all localities, but, where it is present, it varies in hardness, from weakly to strongly indurated. Nodular duricrust may lie directly on collapsed ferruginous saprolite with a gradual to sharp boundary. Lateritic nodules and pisoliths are associated with the fragmentation of ferruginous saprolite; both lithic and non-lithic nodules occur.

Various forms of iron enrichments (*iron segregations*) also occur within the ferruginous saprolite and lateritic duricrust. These iron segregations occur as pods, lenses, and large slabs. They are black, non-magnetic and are goethite rich. Fragments of iron segregations are subrounded to subangular and commonly range in size from 20 to 200 mm. It is significant that iron segregations do not have cutans. Cutan here refers to an outer layer, surface coating, or skin (Anand *et al.*, 1989).

2.2.5   *Laterite types and associated ferruginous materials*

Because of the focus of this project, the ferruginous upper parts of laterite profiles have received considerable attention. Whilst some materials such as pisolitic gravels and lateritic duricrusts are widespread and well recognized, the range of ferruginous materials confronted in exploration is more diverse, some of which have been described above. The chemical, mineralogical, and petrographic characteristics of these materials vary considerably as does their origin. This diversity can strongly influence their geochemical thresholds. The origin of sampling material also influences the shape and size of the expected dispersions.

To address this diversity of materials, an expandable, loose-leaf volume entitled *Laterite types and associated ferruginous materials, Yilgarn Block, WA - terminology, classification, and atlas* by Anand *et al.*, (Report 60R; hereafter referred to as the *Atlas*, an extract is in Appendix V) was produced in August 1989. Its objective was to provide a manual for use in exploration, which would standardize description and classification of the diverse range of laterite types seen in the Yilgarn Craton. Furthermore, it is important to place the different types of laterite in their regolith-landform setting. These issues are critical to proper design and execution of geochemical exploration in lateritic terrain. A method was needed that would encourage proper documentation of samples for entry into geochemical databases and for flexible retrieval and interpretation of the data. Coding of sample types was required in a way which would allow grouping of like samples, while still retaining the detailed characteristics of each sample.

It was recognized that linking sample type to regolith stratigraphy was fundamental; firstly, because it would indicate to explorationists what was actually being sampled. Secondly, position within the regolith stratigraphy may lead to estimation of the size, shape, element associations and thresholds of a useful anomaly. Linking regolith stratigraphy to regolith-landform models likewise allows better design of sampling and better interpretation of geochemical dispersion patterns.

The *Atlas* has four main sections; Regolith Models, Classification Tables, Fabrics and Microstructures (a colour photographic section), Glossary and Index.

As the Regolith Models section grows, it will form a logical first entry. The Classification Tables section summarizes all terms that are in use for a chosen sample medium and gives their corresponding codes. Photographs of cut surfaces of representative laterite types show their fabrics alongside their descriptions. These are arranged systematically, according to their classification codes. The main textural and classification terms are listed alphabetically in the Glossary/Index with standardized notes. Alpha-numeric codes are given for all the materials described and the scheme is expandable, hierarchical, and mnemonic. The codes provide linkages between the classification tables, the photographs and their descriptions, regolith stratigraphy, the regolith-landform models, and the glossary. The codes allow grouping of sample types into compatible categories for data interpretation whilst retaining 'high resolution' information of specific sample types for each sample.

It is hoped that future collaboration will link the laterite atlas and its incorporated concepts, with classifications of broader categories of regolith materials and extend laterite classification to other regions of

Australia. Within the extension of this project, additional regolith-landform models will be established as new orientation districts are studied. An international link has been established with the European CORLAT project which aims to provide a generalized handbook on laterites.

The *Atlas* and its concepts have gained acceptance in Australia and overseas and its content has survived well through some three years of exploration use.

2.3   Terminology used for associated Cainozoic sedimentary sequences, soils, and calcretes

In addition to subdividing the weathered profiles, units of the sedimentary cover (transported overburden), soils and carbonates, needed to be addressed and terminology was therefore adopted. At this stage, terms in use by the Laterite Geochemistry Group are: alluvium, colluvium, soils, and calcrete. These main categories are deliberately kept broad and simple, each is subdivided and classified hierarchically into field working terms in the *Atlas*.

Many of the sedimentary regolith units of the arid interior of the Yilgarn Craton are now indurated through cementation by silica (commonly hyalite or opal) and Fe-oxide cements to form a commonly porous, red-brown hardpan. This process of cementation is referred to as hardpanization which can also occur in residual regolith units, such as lateritic duricrust and saprolite, particularly in the first metre or so beneath the base of hardpanized sedimentary units. *Hardpanization* is used as a modifier, attached to the regolith material which has been indurated, e.g. hardpanized colluvium, hardpanized saprolite.

Calcification, the growth of authigenic calcite and dolomite, is also wide spread in the arid interior, and can infuse colluvium, soil, and lateritic residuum. Calcification is also used as a modifier coupled with the host regolith material, e.g. calcified lateritic duricrust.

2.4   Regolith-landform mapping

2.4.1   *The importance of regolith-landform control in exploration geochemistry*

In the Yilgarn Craton, the combined effects of prolonged deep, lateritic weathering under warm, humid conditions followed by differential erosion and chemical modification, particularly under arid or semi-arid conditions, have led to a great variety of materials exposed at the landsurface and to intricate regolith-landform relationships. It is important to understand the regolith-landform relationships in the wide variety of terrain types which have resulted from this complex regolith evolution within an exploration area for two purposes: (i) To design and execute the sampling programme properly; (ii) to present and interpret the data properly. Both of these need to include knowledge of regolith and landscape evolution, weathering, and dispersion processes. An overall flow chart for carrying out regolith mapping is given in Section 10.3, Fig. 10.3.

Regolith-landform control is provided by regolith-landform mapping, establishing the regolith stratigraphy within these mapped units, and synthesizing a regolith-landform model. Once the regolith-landform relationships for an exploration area or district are understood and regolith models are established, appropriate geochemical dispersion models can be sought from the research literature or from a company's past experience. Such models can be used predictively, obviating some of the need for repeating comprehensive orientation studies.

2.4.2   *Regolith-landform (mapping) units*

Air-photo patterns generally form the basis of regolith mapping. They are largely related to the interactions of bedrock, surficial geology, soil, vegetation, and landform. *Regolith-landform units* are defined as areas (usually delineated from airphoto-interpretation), within which a particular association of regolith materials and landforms occur which can be distinguished by mapping, at the scale chosen, from adjacent areas which have been differently defined, using similar principles. An area is thus mapped by delineating regolith-landform units from the interpretation of aerial photographs, satellite imagery (such as LANDSAT TM) and/or airborne multispectral scanner imagery and is verified with field traverses. The scale of airphotos or other imagery will influence the choice and definitions of regolith-landform units because of the practicalities of representing heterogeneous assemblages at these scales. The more detailed the scale becomes, the more the mapping units become regolith rather than landform-based.

Different geochemical thresholds may apply to different sampling media and to different regolith-landform mapping units. One purpose of producing a regolith-landform map is to delineate areas or units within which data may be treated uniformly. If the variation in sample characteristics is too great, true

geochemical dispersion anomalies will be lost among the natural variation in sample characteristics, related to changes in regolith-landform situations. Regolith-landform maps also identify and delineate areas characterized by complex surficial relationships which may require specialized exploration approaches in contrast with areas which require straight-forward soil sampling.

Regolith-landform units have been mapped within the individual orientation areas and districts of the project. This approach is being used increasingly by companies in their exploration tenements. However, a scheme is needed to classify such mapping units and allow proper linking across a region. One of the expected benefits would be to be able to transfer geochemical backgrounds and thresholds (of soils for example) to comparable units elsewhere. A classification scheme for regolith-landform mapping units for the Yilgarn region of WA is presently being developed through collaboration between CSIRO, BMR, GSWA, and Curtin University within the extension of this project, P240A.

2.4.3   Regolith-landform regimes

Fundamental to exploration in lateritic terrain is whether lateritic residuum is still present or has been removed by erosion. The boundary which marks the base of lateritic residuum and that which outlines areas having substantial sedimentary cover are both very important and they need to be clearly delineated.

For these reasons it has been found useful to consider regolith-landform relationships in terms of residual, erosional, and depositional regimes which are defined below. These regimes are broader terms than the regolith-landform units discussed in 2.4.2. They add a genetic interpretation to the regolith-landform relationships and delineation of regimes should be seen as an additional step to basic regolith mapping. However, the genetic interpretation should be carried out as field work develops.

Residual regimes, by our definition, are mappable areas characterized by widespread preservation of lateritic residuum. *Erosional regimes* are those areas where erosion has removed the lateritic residuum to the level where the mottled zone, clay zone, saprolite, or fresh bedrock are either exposed, concealed beneath soil, or beneath thin, locally-derived, associated sediments. *Depositional regimes* are areas characterized by widespread, substantial sediments which can reach many metres in thickness. The boundary between residual and depositional regimes can be gradational or sharp. Where the backslopes are long the changes are generally gradational. In contrast, where the backslopes abut alluvial floors the boundaries are more clearly expressed. The boundary between residual and erosional regimes can be sharp, commonly being marked by a local scarp or breakaway.

If the broad *regolith-landform regimes* are mapped in an area (such as in Section 4.2, Mt. Gibson), it usually becomes clear which geochemical sampling media to use. For example, in the erosional regimes, soil geochemistry, either conventional soil geochemistry, or bulk-leach cyanide-extractable gold (BLEG), is commonly very effective. However, in the residual regimes, laterite geochemistry is superior to soil geochemistry, where geochemical anomalies are relatively large or consistent. Moreover, soil sampling on a lateritic substrate may result in weaker contrast anomalies, erratic Au patterns, and imposes an extra weathering process to be understood. Much, however, depends on the size fraction used.

2.5   Regolith-landform models

Regolith-landform models are conceptual devices developed to represent regolith-landform relationships. They seek to have a predictive capability and often aim to convey clear genetic interpretations. Regolith-landform models are commonly presented as cross sections and block diagrams. These diagrams show (a) the main regolith-landform regimes (sometimes subdivided into regolith-landform mapping units), (b) the main units of the regolith stratigraphy, and (c) bedrock lithologies where known. The vertical scale is usually exaggerated to show units of the regolith stratigraphy. It is useful to link individual regolith profiles to the different regolith-landform regimes on a model, in effect expanding the vertical scale to show details of the regolith stratigraphy. (An example from the Mt. Gibson orientation study is shown in Fig. 4.5.) By adding information on geochemical dispersion processes and patterns, regolith-landform models become conceptual or idealized geochemical dispersion models, Section 9.0.

3.0 LATERITIC WEATHERING AND REGOLITH EVOLUTION

3.1 Introduction

Laterite weathering profiles are widely distributed over the Yilgarn Craton. Lateritic weathering is also an important process elsewhere in the world and is estimated to have affected about one third of the Earth's land surface, including much of Australia, India, Brazil, SE Asia, central and west Africa, and intertropical regions elsewhere (Gidigasu, 1976; Fig. 3.1). In these regions, the bedrocks are commonly weathered to depths of 10 to >100 m, depending upon the nature of bedrock, regional tectonic stability, and climate (McFarlane, 1976; Nahon *et al.*, 1977; Butt, 1981; Anand *et al.*, March 1989).

Weathering profiles in the Yilgarn Craton are commonly deep. Paleoclimate, particularly in the Mesozoic and early Tertiary, has played an important, if not dominant, role in the development of the lateritic regolith and resultant landforms and the patterns of geochemical dispersion. The importance of past climates and weathering episodes in the development of the regolith and landscape has been recognized by many workers, for example Michel (1973), Butt (1981), and Budel (1982). Two stages appear to have been important to the development of regolith and the dispersion of Au and ore-related elements within it.

1.   A long period(s) of deep lateritic weathering, under warm, humid climates occurred particularly during the early Tertiary. Lateritic profiles developed at this time are characterized by a residuum of Fe- and Al-oxides and kaolinite clays overlying deep clay and saprolite zones, which are depleted in alkalis and alkaline earths.

2.   In inland Australia, subsequent periods of aridity and semi-aridity occurred since the Miocene, continuing to the present, during which the weathering profiles have been modified (Bowler, 1976; Mabbutt, 1980). Because of the tectonic stability and generally low relief during this period, many of the products of weathering have been preserved.

During the course of Project P240, new observations have been made and new ideas have emerged, particularly made possible by the exposures of open pit mining. Study concentrated on four orientation districts. Like Mulcahy and Hingston (1961) in their pioneering investigation of a lateritized landscape near York, WA, the research has included a wide range of regolith materials in an area rather than working with isolated profiles. In the selected regolith relationships were mapped, the regolith stratigraphy was established, the regolith units characterized, regolith models erected, and the regolith evolution interpreted, all from an exploration perspective.

Lateritic weathering
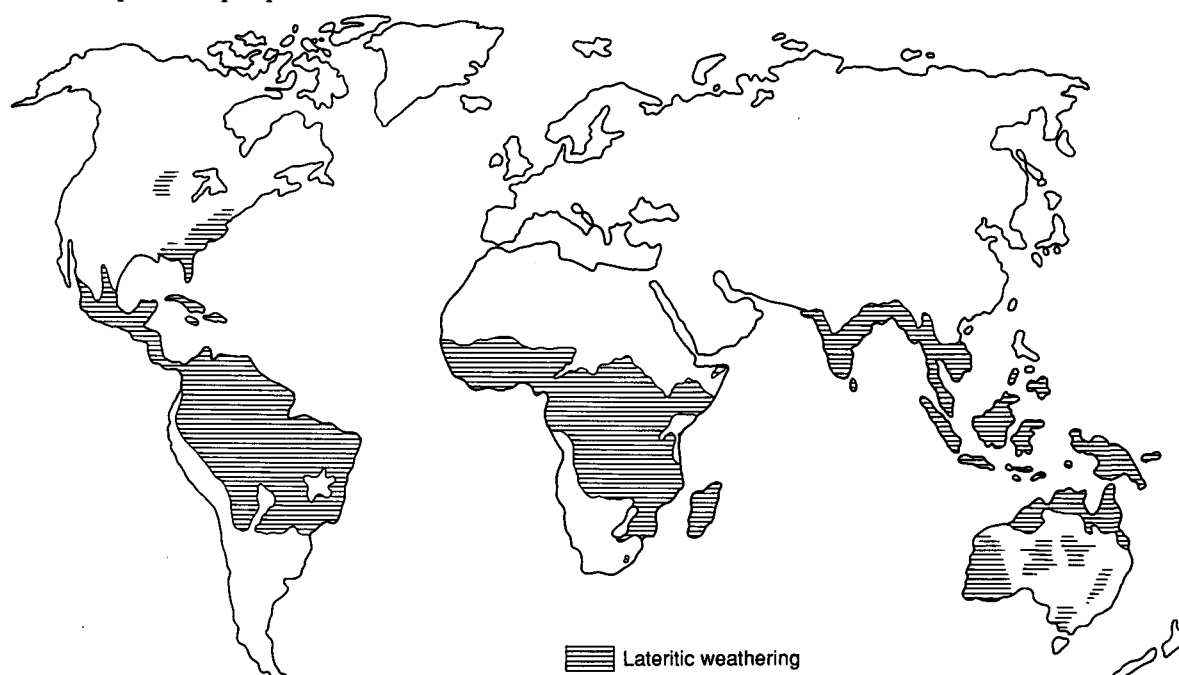
Figure 3.1. World distribution of lateritic weathering profiles. (Modified after Gidigasu, 1976.)

3.2   The main period(s) of lateritic weathering in the Yilgarn Craton

Development of the regolith and landscape of Western Australia has taken place over a long time-span. Paleogeographic reconstructions (Fig. 3.2) indicate that the Yilgarn Craton has been exposed since at least the mid-Proterozoic (Playford *et al.*, 1975). Subsequent stability is indicated by extensive linear, undeformed E-W Proterozoic dykes and the absence of deformed, younger sequences. Whilst stability enables deep weathering, it does not guarantee preservation of its weathering products. It would be overly simplistic to suggest that the present surface of the Yilgarn Craton was a weathering surface since the Proterozoic. Some kilometres of Proterozoic sedimentary cover are likely to have been removed from the northern margin of the Yilgarn Craton with at least some of the weathered mantle.

Glaciofluvial sediments, attributed to the Permian, are scattered over the Yilgarn Craton, particularly in the NE. Since the Permian, much of the Yilgarn Craton has been above sea level and weathered under a variety of climates (Ollier, 1988). Weathering commenced after the Permian glaciation. Erosion during the Jurassic and Cretaceous led to extensive plantation by the mid-Cretaceous. Thus, most of the tectonically-stable Yilgarn Craton has been weathered for at least 100 million years, initially under a warm, humid climate which was a global phenomenon, Australia and Antarctica then formed part of a low relief continent at higher latitudes than at present.

Where well exposed, such as in open cut pits of gold mining activities, glaciofluvial sediments are seen to be lateritized, and extensive lateritic mottling is common (e.g. the Telegraph Pit at Lancefield the Genesis pit at Lawlers, and the Beasley Creek pit at Laverton). Thus, at least some of the lateritic weathering is post-Permian.
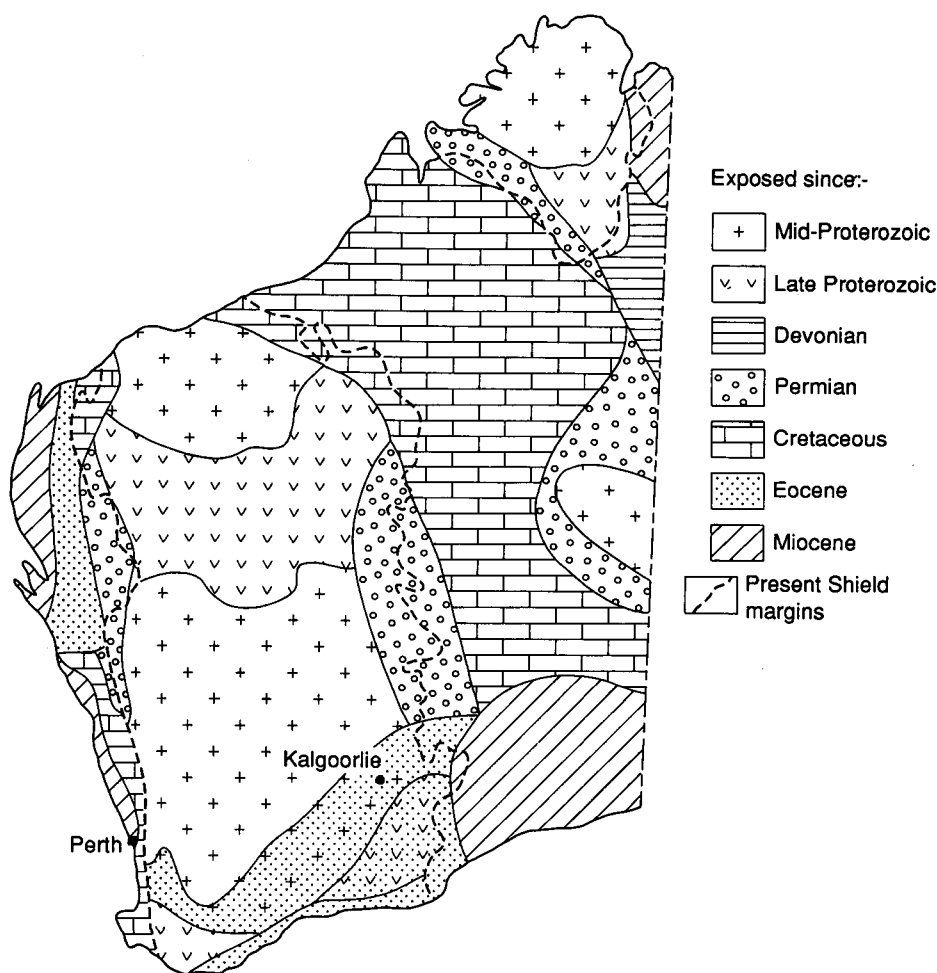
Figure 3.2. Periods of exposure to subaerial weathering, Western Australia.
(Taken from Daniels, 1975 & Playford *et al.*, 1975.)

The lateritic weathering mantle of the Yilgarn Craton is a patchwork of complete lateritic profiles co-existing with stripped and partly-stripped ones. As yet, no technique is routinely available for the absolute dating of these profiles. There are many difficulties in dating lateritic profiles. In the interior, the climate has modified the weathering profile by various post-lateritization processes. On the SW margin of the Yilgarn Craton, where an uplifted lateritized rim forms the Darling Range (Mulcahy, 1967), recent warm to humid climates have rejuvenated lateritic weathering (Bettenay *et al.*, 1979).

For relatively young weathering (i.e. Quaternary), a variety of techniques (radiocarbon, fusion track, and ^{10}Be dating) can be used to date the weathering. However, the ages of most of the regoliths of the Yilgarn Craton appear to be beyond this range. Previous attempts to date the age of the Australian regolith have relied upon localities where weathering is developed on, or is overlain by, a sedimentary or igneous unit which can be dated stratigraphically or isotopically. Such indirect methods usually only provide a maximum or minimum age, which may bear little relation to the actual age of weathering. Paleomagnetic measurements have provided age estimates for Cretaceous and Tertiary weathering events (e.g. Schmidt and Embleton, 1976). However, the relationship between the time of magnetization and the age of formation of the profile remains ambiguous (Idnurm, 1986). Oxygen isotopes have been moderately successful in dating weathering minerals (Bird and Chivas, 1989).

Although generally attributed to the early and mid-Tertiary, dating of Yilgarn laterites and the underlying regolith has not been carried out, for reasons given above. Nahon (1986) suggested that ferruginous zones, a few metres thick, overlying saprolite of several tens of metres in thickness, need several million years to form. The period will depend on the nature of the parent material, intensity of climatic changes, tectonic evolution, and other factors. The formation of the profile is not a single event, but rather takes place over a considerable period. Field relationships suggest that the ages of Yilgarn lateritic weathering profiles are variable and diverse; when these deeply-weathered lateritic profiles formed still remains uncertain.

Dating methods, mostly experimental, were discussed at an Integrated Cratonal Processes workshop at the University of California, Berkeley, in January, 1992. Some methods are based on exposure of minerals, such as quartz to cosmic rays. A wide range of nucleides are being studied, including ^{26}Al, ^{28}Si, ^{21}Ne, and ^{10}Be. Currently, the timing of events *within* units of laterite profiles, is being determined by Ar-Ar dating of authigenic (supergene) K-bearing Mn-oxides (Vasconcelos, 1987). These new methods are most likely to be meaningful where the regolith relationships and stratigraphy have been well studied, such as within the orientation areas studied in this project.

3.3   Evolution of lateritic weathering profiles

3.3.1   *Lateritic residuum and transported lateritic gravels*

Several types of laterite residuum, (pisolitic, nodular, fragmental, vesicular, etc.) several metres thick, are extensively distributed in each of the districts studied. Laterite not only occurs in the higher parts of the landscape, but is also widespread beneath colluvium and alluvium. It appears that laterite has developed as an undulating blanket across land surfaces at various levels. Laterite occurs on slopes of up to 8° and with a local relief of 60 m on the Darling Plateau. Thus extensive laterite sheets have not developed only on level land surfaces.

The *in situ* versus transported nature of laterite has been debated for many years. Are they the result of lateral transportation of Fe in solution, precipitating in host saprolite (Maignien, 1958; McFarlane, 1976), or are they formed from long-distance, mechanically-transported materials, so that they are entirely independent (Milnes *et al.*, 1985) of the surrounding rocks? The findings of this study are summarized as follows:

(a)   The materials recognized as lateritic residuum are largely *lithodependent* at a landscape scale. Detailed work in four areas (Section 4) has shown that lateritic nodules and pisoliths in lateritic residuum are formed by a combination of several processes, including fragmentation, ferruginization, and a multiple of phases of leaching, migration and deposition of Fe-oxides. Biological processes also contribute to this re-organization. Thus, formation of lateritic residuum is complex, consisting of numerous stages expressed by different facies.

Quartz and resistant minerals such as talc and chromite survive through much of the laterite and help identify the bedrock. Iron and some trace elements in lateritic residuum also reflect the composition

of the underlying bedrock. Laterites formed from granite, metadolerite, amphibolite and serpentinized ultramafics together with samples of mottled zone and ferruginous saprolite (low in Fe) from the Darling Range and from Lawlers are shown in Fig. 3.3. The latter are included in this figure to see if increasing ferruginization in laterite masks recognition of parent bedrock. The data show that these lateritic materials are lithodependent and remain so irrespective of the degree of ferruginization. The proportion of residual quartz, and the abundances of Fe, K, Ti, V, Mn, and Zr may be used to distinguish laterites formed from granite from those formed from mafic rocks. Laterites formed from granite are low in Fe due to the small abundances of original Fe. Laterites derived from ultramafic rocks are slightly Al poor but richer in Fe than many of those arising from the weathering of mafic rocks. The laterites derived from ultramafic rocks are, however, richer in Co, Ni, and Cr and these elements may be used to establish parentage (Fig. 3.3).

(b)   Laterites result initially from vertical diffusion and local scale lateral movement of Fe in ground water, followed by the precipitation of Fe-oxides in the upper profile. Landscapes evolve with time by a vertical lowering of the soil surface and of weathering fronts at depth.

Vertical diffusion is the dominant process in the formation of deep weathering profiles. Figure 3.4A shows an idealized section through a typical weathering profile on the Yilgarn Craton with the postulated direction of movement, during weathering, of an ion such as Fe^{2+}. This ion is released at the weathering front where its mobility is subject to combined upward diffusion and lateral migration (ground water flow). The diffusion of Fe is controlled by chemical concentration gradients (Mann, 1983). Iron is subsequently precipitated by oxidation (as Fe^{3+} oxides) and accumulates near the water table. This process, of oxidation and hydrolysis of Fe^{2+} is known as *ferrolysis*.

(c)   Broad scale lateral movement of Fe, over say hundreds of metres, contributes to the formation of other ferruginous materials (Fig. 3.4B). Iron, derived from laterite moves in solution laterally across the landscape. Where Fe is precipitated in favourable sites, considerable bodies of ferruginous material accumulate. Examples include bog iron, various iron enrichments in saprolite, and possibly some Fe-rich duricrusts. It is possible to differentiate between lateritic residuum and various discrete bodies of ferruginous materials (iron segregations) in that lateritic residuum consists largely of hematite, goethite, maghemite, and kaolinite, whereas iron segregations are dominated by goethite with sub-ordinate hematite. Lateritic residuum has goethite with high Al substitutions (15-30 mole %), whereas iron segregations have low Al substitutions (0-11 mole%) and generally higher Mn, Co and Cu abundances.

(d)   Horizons of ferruginous, lateritic gravel, consisting of nodules and pisoliths in a sandy clay matrix, are generally developed above, or are laterally associated with, indurated lateritic duricrust. This gravelly horizon commonly arises from *in situ* breakdown of the lateritic duricrust, followed by some downslope colluvial transport. The matrix of the duricrust breaks down by dissolution of its components which allows separation of nodules and pisoliths in a sandy clay matrix. Iron, Al, and Si, leached from the decomposing upper horizon, precipitate in a deeper horizon and may form Fe-rich zones below.

(e)   Mechanical dismantling of lateritic residuum from upland areas results in transported lateritic gravels occurring in low-lying areas of the landscape (Fig. 3.4C). The lateritic clasts become rounded and progressively lose their cutans on transport. These lateritic clasts are incorporated with other clasts, of diverse origin, within colluvial/alluvial units or occur as lateritic gravelly lenses and may be re-cemented by Fe-oxides. Transported gravels may be misidentified as residual laterite. Lateritic gravels, which have been transported long distances, may not be suitable media for geochemical sampling, at the prospect scale, because the provenance is likely to be in doubt. Therefore, it is important to distinguish lateritic clasts in sedimentary units from those in a buried residual laterite, see, for example, Section 4.4 (Lawlers district).

3.3.2   *Distribution of Al-goethite and Al-hematite in Lateritic Profiles*
The extent of aluminium substitution in goethite and hematite is a sensitive indicator of the environment of Fe-oxide formation and is dependent on the accompanying minerals. The Al substitution in goethite appears to have potential for the identification of the diverse types of ferruginous samples used in exploration. The amount of Al substitution in goethite generally increases upwards in lateritic weathering profiles (Anand,
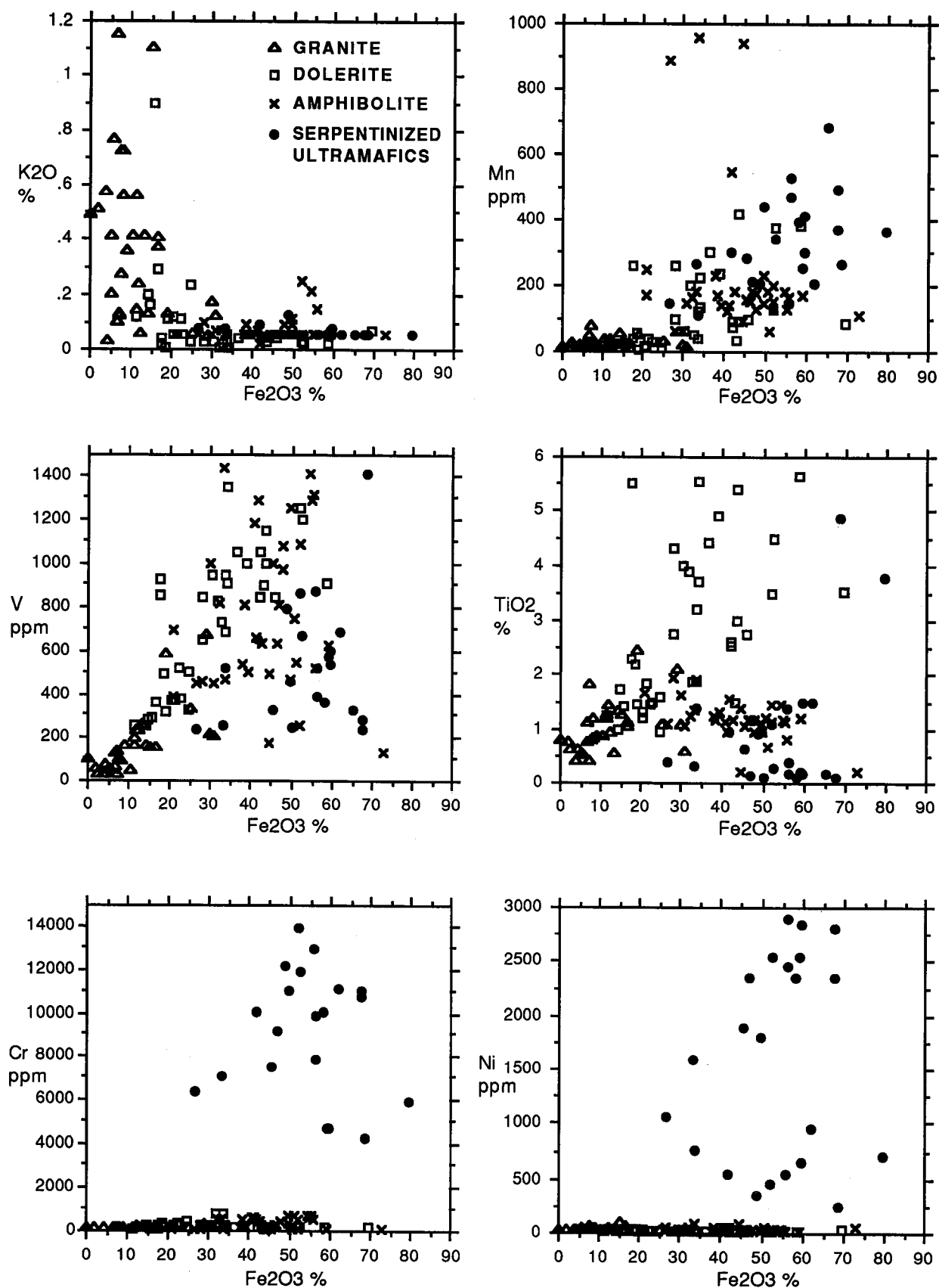
Figure 3.3. Examples of chemical compositions of lateritic materials (lateritic residuum, ferruginous saprolite, and mottled zone) developed from granite, mafic, and ultramafic rocks. The dependence of chemical composition on bedrock type is demonstrated.

A. Formation of lateritic residuum

Water table

Mottles (goethite-hematite-rich)

Saprolite

Fe^{2+}
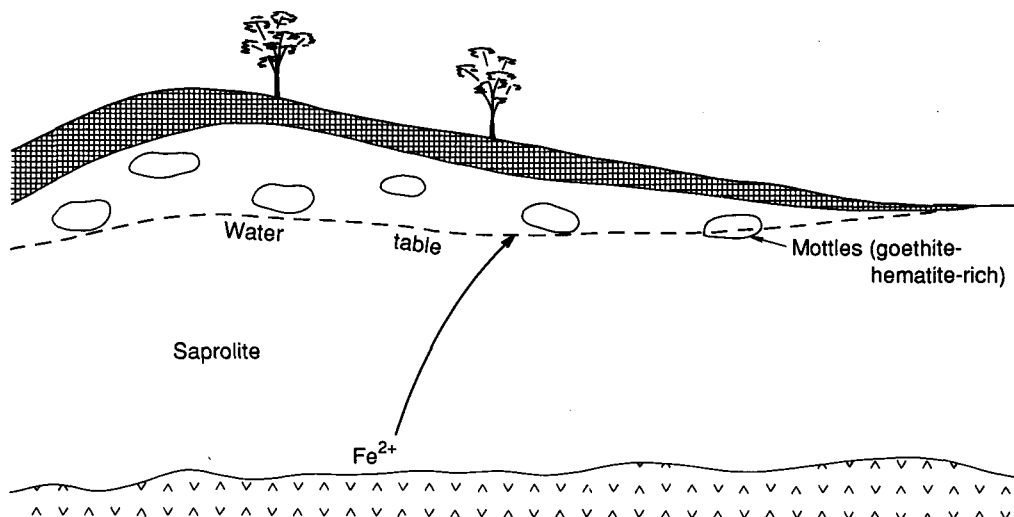
B. Lateritic residuum regression

Lateritic residuum
chemical dismantling

Lateral transport
of Fe and Al in solution

Bodies of ferruginous material
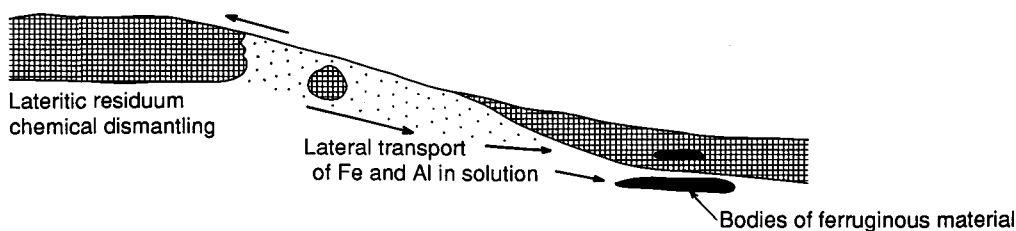
C. Lateral and mechanical transport by gravity after erosion

Lateritic residuum
mechanical dismantling

Lateritic pisoliths and
nodules without cutans
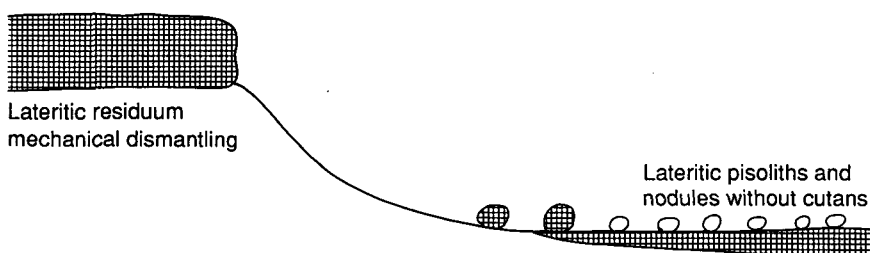
Figure 3.4. Various mechanisms of migration of Fe: (A) idealized section of a weathering profile showing the postulated trajectory of an Fe^{2+} ion released at the weathering front, under the combined influence of vertical diffusion and lateral ground-water flow, modified after Mann (1983); (B) lateral migration of Fe and Al in solution; and (C) lateral mechanical movements of disaggregated blocks of lateritic duricrust.

1984). Substitution of Al ranges from 6 to 28 mole % in goethites of laterites rich in kaolinite (Fig. 3.5A and B) as in the Mt. Gibson and Lawlers districts. In contrast, Al-substitution ranges from 20 to 35 mole % in goethites associated with gibbsite in Darling Range lateritic bauxites (Fig. 3.5C and D). Goethite in ferruginous saprolite has less Al substitution (8 to 23 mole%) than in the overlying lateritic residuum (Fig. 3.5E). Goethite in iron segregations shows the lowest Al substitution (0 to 11 mole%) where kaolinite is either absent or present in very small amounts(Fig. 3.5F). Hematite generally has less Al-substitution than co-existing goethite.
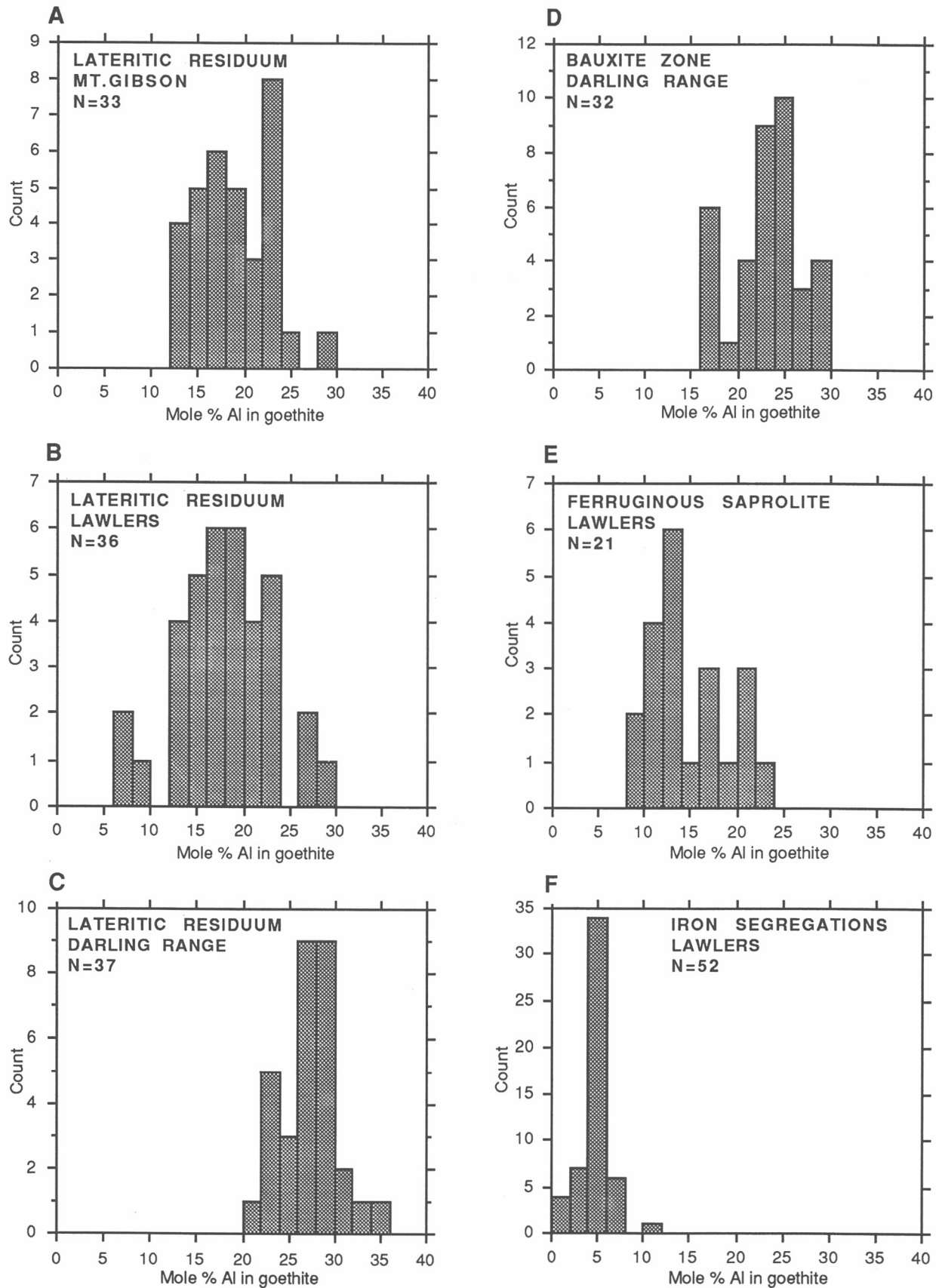
Figure 3.5. Values of mole % Al in goethite for lateritic residuum, bauxite zone, ferruginous saprolite, and iron segregations – Darling Range, Mt. Gibson, and Lawlers districts.

The differences in Al substitution in goethite between the regolith types suggests different environments and/or mechanisms of formation. Very low Al substitution in the goethite of iron segregations indicates an environment almost free of soluble Al. In contrast, the goethite in lateritic residuum has formed in an Al-rich environment, as indicated by kaolinite and even gibbsite.

3.3.3   *Regional variations in profile type*

Profiles, developed on similar rocks, exhibit some regional variations, though to what extent these reflect original lateritic rather than post-lateritic conditions is uncertain. These variations can only be demonstrated with certainty when the same rocks, with identical mineral assemblages and physical characteristics, are compared. Examples of the profiles developed over mafic lithologies in three study areas (Darling Range, Mt. Gibson, Lawlers) are described below.

In the Darling Range, the lateritic residuum is highly weathered and aluminous. The major secondary minerals in lateritic duricrust and lateritic gravels are gibbsite, hematite, and goethite. Feldspars and amphiboles have altered to kaolinite and to gibbsite high in the profile (Anand and Gilkes, 1984). Some feldspars have altered directly to gibbsite in the lower saprolite. Inland, the lateritic residuum tends to be more ferruginous and less aluminous and the major minerals are kaolinite, hematite, and goethite. Here feldspars have altered to kaolinite, amphiboles have commonly altered first to smectite and then to kaolinite. Gibbsite is absent or present in very small amounts which can be taken as an indicator of relatively-weak leaching conditions.

Smectite occurs in the upper saprolite at Lawlers. It is not certain whether this smectite is a product of lateritic or post-lateritic weathering. It is possible that smectite in the upper part of the profile may have formed from kaolinite. Kaolinite is generally a stable mineral that will persist in a neutral to alkaline environment. Thus, if kaolinite is formed under a strong leaching, acid environment and the climate subsequently becomes arid, kaolinite may persist and serve as an indicator of the former wet climate. However, in places, there is a suggestion that smectite may form from kaolinite in the soil-chemical system, where the activities of $Si(OH)_4$ and bases are high (Weaver *et al.*, 1971).

3.4   Modification of weathering profile, regolith distribution, and stratigraphy, Yilgarn Craton

3.4.1   *Post-lateritization Processes*

A number of processes have continued since the formation of the lateritic weathering profiles, (Fig. 3.6). Such as:

- dehydration and hardening of the lateritic residuum;
- weathering of the lateritic residuum;
- erosion of the whole or part of the weathering profile;
- deposition of detritus generated from this erosion;
- weathering of the newly-exposed regolith;
- silicification and calcification of both transported and residual regolith;
- leaching of the upper regolith; and
- chemical and mineralogical changes in the upper regolith.

The above processes may be related to a change to a drier climate for the inland Yilgarn; a change which has probably taken place since the mid-Miocene. Arid to semi-arid climates, which still prevail, have resulted in modifications of the pre-existing regolith by acid and highly-saline ground waters, lower watertable, and changes to, and decline of, chemical weathering. Vegetation started to take on its present-day aspect, and would in turn have affected the nature of weathering and effectiveness of erosion.

3.4.2   *Regolith distribution and stratigraphy*

For successful application of geochemical exploration in deeply-weathered terrain, it is important to have a detailed view of regolith evolution. It should include an understanding of the district-scale distribution of regolith units and their stratigraphic relationships. The regolith distribution and stratigraphy of the four orientation districts studied in this project are complex because of the cyclicity of erosion and deposition. This has resulted in a diversity of regolith types (Table 3.1).

Erosion of the lateritic weathering profiles has occurred in each of the districts. At Mt. Gibson, extensive areas of lateritic undulating sandplain with lateritic gravel at shallow depth (commonly within 1 m of the surface) in turn lying on nodular duricrust and the underlying thick (commonly 50 m) saprolite

A. LATERITIZATION PROCESSES
(Warm, seasonally wet)

Residual accumulation

Chemical reorganization with destruction of fabric

Lateritic residuum

Hematite-rich → Cutan

Pisolization (dissolution of irregularly shaped edges)

Formation of cutans → Goethite, kaolinite gibbsite-rich cutan

Magnetic (hematite-maghemite-rich)

Non-magnetic (hematite-goethite-kaolinite-rich)

Nodulization

Mottled zone

Mottle (hematite/goethite-rich)

Hematite-kaolinite rich

Mobilization and segregation of Fe

Fragment of ferruginous saprolite

Isovolumetric weathering

Saprolite

Void development, collapsing, ferruginization

Kaolinite and goethite pseudomorph after Fe-bearing primary mineral

Clay pseudomorph after feldspar

Fresh rock

Hematite   Goethite   Al in goethite   Kaolinite

B. POST LATERITIZATION PROCESSES
(Semi arid to arid climate)

Formation of loose lateritic gravelly layer and gravelly soils

Weathering of lateritic residuum (degradation and dissolution of matrix)

Dehydration and hardening of lateritic residuum

Slope instability

EROSION

Transport of material removed in dismantling the lateritic profile

DEPOSITION

Erosion of whole or part of the weathering profile, sediments generation

Gravity, water → Colluvium

Water → Alluvium

Wind → Aeolian

Lags

WEATHERING OF EXPOSED REGOLITH (Chemical)

Some leaching of alkali and alkaline earths

Eluviation and illuviation of Si and Al

Mobilization and segregation of Fe

Soil formation: Acid red plastic clays on saprolite/saprock, red earths in colluvium

Si/Si-Al -rich balls in matrix of lateritic residuum

Ferruginous granules in acid red plastic clays; pisoliths in colluvium, alluvium

MODIFICATION OF WHOLE PROFILE (Introduction of Si, Ca, Fe, Al)

Calcification — Ca-enrichment

Silicification — Si-enrichment

Hardpanization — Si, Al, Fe enrichment

Calcareous soil

Calcified lateritic duricrust

Silicified lateritic duricrust

Silicified saprolite

Hardpanized colluvium, alluvium

Hardpanized lateritic duricrust

Calcrete   Silcrete   Silcrete

Figure 3.6. Flow charts showing processes responsible for the evolution of the variety of regolith types in the Mt. Gibson district. A, lateritization processes. B, post-lateritization processes (modified after Anand *et al.*, 1991).

Table 3.1. Summary of the distribution of regolith units in four orientation districts studied.

Regolith	Boddington	Mt. Gibson	Bottle Creek	Lawlers
Residual regime (% of ground surface area)	40	40^1	25^1	15^2
Erosional regime (% of ground surface area)	45	25	40	45
Depositional regime (% of ground surface area)	15	35^1	35^1	40^2
Calcareous clays	-	Common	Trace	Trace
Pedogenic carbonates	-	Common	Trace	Trace
Colluvium/alluvium	Shallow	Deep	Deep	Deep
Hardpan in colluvium/alluvium	-	Deep, discontinuous	Deep, discontinuous	Deep, discontinuous
Lateritic gravel	Extensive, discontinuous	Extensive, discontinuous	Extensive, discontinuous	Extensive, discontinuous
Lateritic duricrust	Extensive, discontinuous (bauxitic)	Patchy (ferruginous)	Patchy (ferruginous)	Patchy (ferruginous)
Hardpan in lateritic duricrust	-	Common	Common	Common
Silicified/calcified lateritic duricrust	-	Common	Trace	Trace
Mottled zone	Extensive (bauxitic)	Extensive	Moderate	Very patchy
Ferruginous saprolite	-	Trace	Extensive	Extensive
Fe-rich duricrust	-	Patchy	Patchy	Patchy
Fe-segregations in saprolite	-	Few	Moderate	Abundant

Notes: [1] Buried complete laterite profiles occur.
[2] Buried complete laterite profiles are common.

characterize areas of essentially-complete laterite profiles. Dismantling has cut through lateritic residuum to varying levels of the saprolite. Removed material forms detritus which has commonly accumulated in low-lying areas. The Mt. Gibson district is thus an example of residual, erosional, and depositional regimes which are represented in each of the orientation districts studied (Table 3.1). Residual regimes constitute from 15% (Lawlers) to 40% (Mt. Gibson and Boddington) of the surface landscape. Partly-truncated saprolite forms 25-40% of the landscape, and, in places, fresh rock is exposed. Depositional regimes make up 15% (Boddington) to 40% (Lawlers) of the areas. In the latter, buried complete laterite profiles are common. In the Darling Range, depositional regimes are restricted possibly because of high relief coupled with high rainfall, which together cause sediments to be completely removed. Because of erosion and the amount of concealment by sediments, it is not known how extensively lateritic residuum was distributed originally. Was the landscape completely mantled by an undulating lateritic blanket, with a few monadnocks rising through? This research, which includes knowledge of stratigraphy beneath some sandplains (Golden Grove and Mt. Gibson) and colluvial and alluvial plains (Lawlers, Bottle Creek), suggests that lateritic residuum was indeed extensive in the Yilgarn. However, it is not known if laterite formed an almost continuous blanket.

The upper regolith stratigraphy in the districts studied comprises lag, acid and calcareous soils, colluvium, alluvium, lateritic residuum, mottled zone, ferruginous saprolite, calcrete, and silcrete (Table 3.1). Differences in regolith stratigraphy occur between the areas. At Mt. Gibson, both hardpan and pedogenic carbonate are extensively developed in both transported and residual materials. This contrasts with the Lawlers, Bottle Creek and Boddington areas, where pedogenic carbonate is either absent or present only in minor amounts. Ferruginous saprolite and iron segregations are major regolith units at Lawlers contrary to Mt. Gibson and Boddington.

A generalized cross-section of some important regolith-landform relationships in the Yilgarn Craton is shown in Fig. 3.7. The generalized regional distribution of some broad regolith types is summarized in Fig. 3.8. A zone of gravelly acid sand, commonly associated with laterite, is developed on granite. These
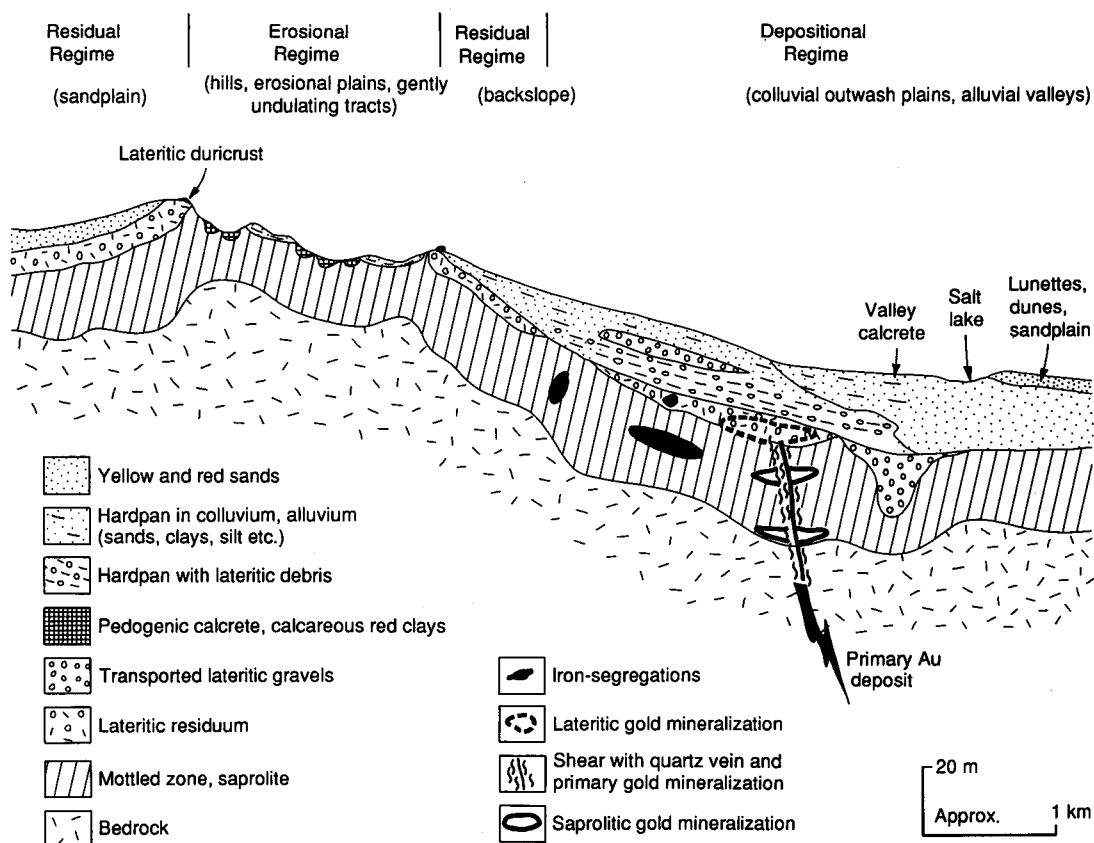
Figure 3.7. Generalized cross sections showing regolith-landform relationships and regolith-stratigraphy in the Yilgarn Craton.
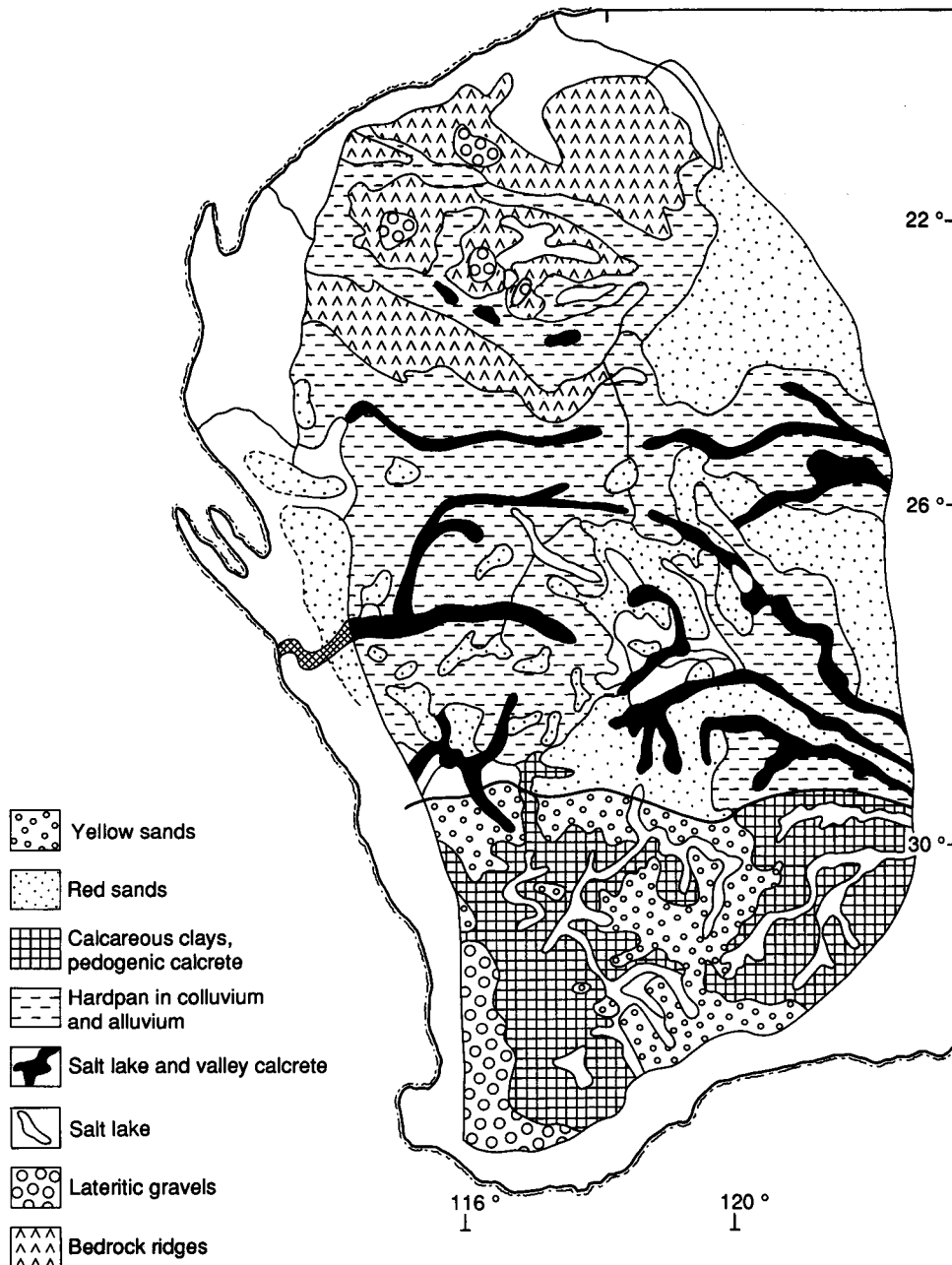
Figure 3.8. Generalized map showing the distribution of some broad regolith units in the Yilgarn Craton. (Modified after Churchward, 1983).

sands have largely formed in place and represent the upper part of the lateritic profile. In contrast, red earths are common within the greenstone belts. Red soils are uniformly Fe-stained and some contain ferruginous granules and lateritic debris. The present climate influenced the upper regolith. Extensive sandplains progress from yellow through orange to red with decreased, sporadic rainfall and increased temperature. The yellow sand is due to goethite, but redness implies hematite. High temperature and low moisture favour formation of hematite in the northern half of the Yilgarn Craton. Calcareous earths and pedogenic carbonates are extensive in the southern half of the Yilgarn Craton. In the north, there is little pedogenic carbonate, but valley calcretes are common along stream channels. Hardpan is extensively present, both in residual and transported materials, in the northern half of the Yilgarn Craton.

Lacustrine deposits of gypsum, halite, clay, silt, and sand along with saline soils occur in salt lakes and clay pans. Kopi dunes and lunettes form peripheral aeolian deposits. Dust from the salt lakes probably mantles valley sides and is likely to be incorporated in the soil.

3.4.3 *Formation of Hardpan, Calcrete and Silcrete*

Hardpan and carbonates of various forms occur extensively in the Mt. Gibson, Bottle Creek, and Lawlers districts. The morphology of carbonates vary significantly according to their position in the landscape (Fig. 3.9). In the depositional regimes, carbonates are present in a number of forms including powdery carbonates, nodular or platy calcrete, calcrete pods, and calcrete sheets. Calcareous clays up to 2 m thick occupy erosional regimes dominated by mafic lithologies. Carbonates in the calcareous clays occur as coatings on the soil matrix or as stringers. Hardpanization (cementation by amorphous Si, Al, Fe) have not only affected
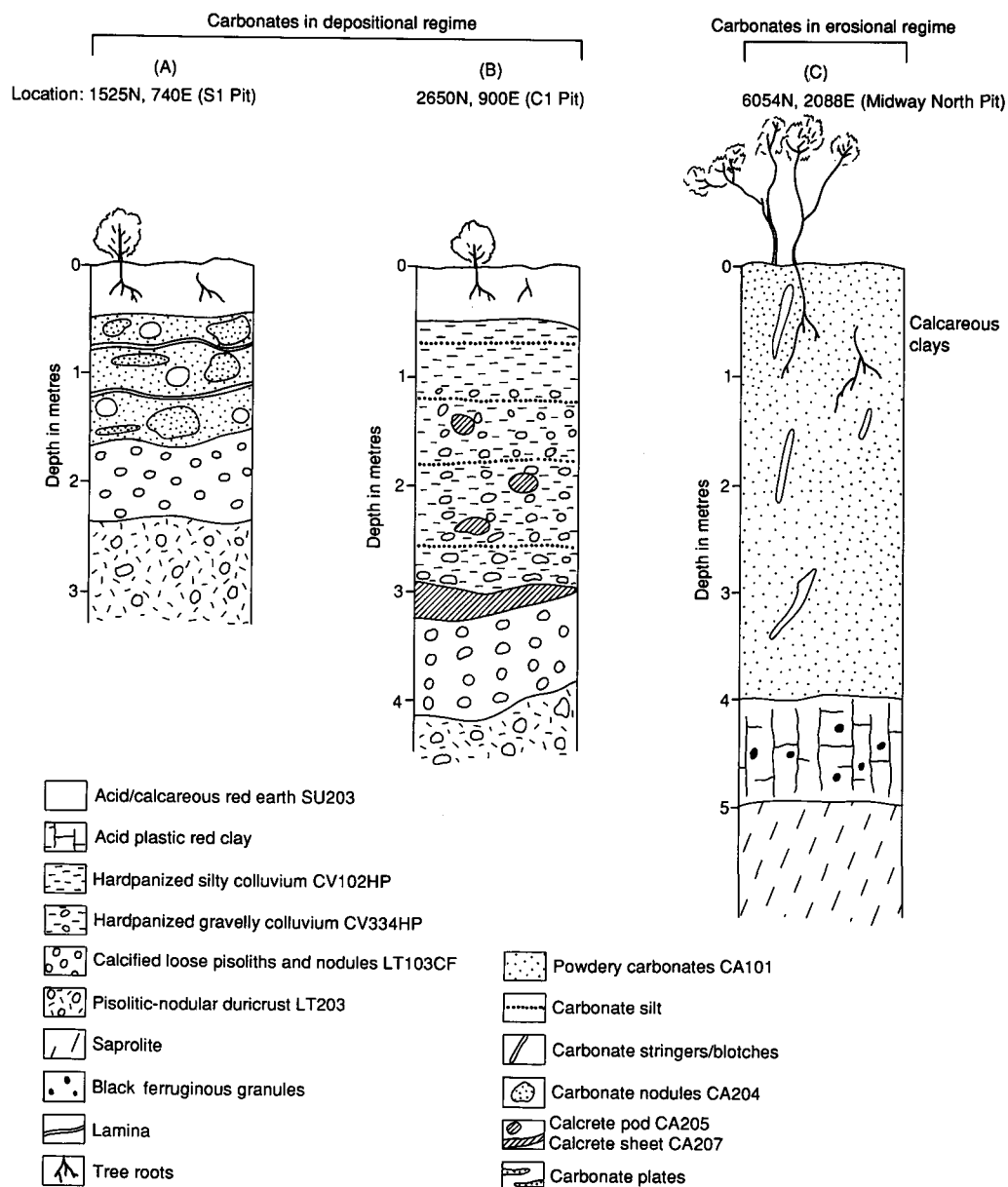
Figure 3.9. Diagrams showing the variation in morphology and facies of calcrete profiles (after Anand *et al.*, 1991 - Report 165R).

colluvium and alluvium but also lateritic residuum and in places, upper saprolite. Hardpanization commonly occurs within the top few metres of the regolith, particularly in wide past or present depressions. The maximum penetration of hardpanization is about 10 m. Well-developed hardpans are uncommon in erosional regimes which include active pediments and steep slopes. This suggests that land-surface stability is a prerequisite for hardpanization. Widespread hardpanization of many regolith units indicates mobilization and deposition of silica in the upper regolith. Hardpanization appears to have resulted from periodic waterlogging of the sediments and locally-underlying regolith followed by desiccation under semi-arid to arid conditions.

Hardpanization involves the infusion of dominant silica with lesser Fe and Al oxides. This is the result of a combination of the two processes, *viz lateral* movement and infusion of silica by ground water and eluviation as part of pedogenesis. Carbonates are common in hardpanized colluvium and appear to have been deposited after the hardpan had formed. Hardpanization seems a relatively-recent process, related to the present arid climate. It seems Fe-oxides formed in hardpans (mainly hematite and some goethite) probably by *in situ* breakdown of Fe-bearing silicates (e.g. amphiboles, biotite) and non-silicate grains (ilmenite and magnetite) by alkaline water. This weathering has also formed some smectite and illite in hardpan.

There can also be extensive chemical modification of lateritic duricrust, including precipitation of carbonates and silica. In some locations, the matrix, nodules, and pisoliths appear to have been replaced and/or displaced by carbonates and silica, with consequent formation of calcareous and siliceous duricrusts. If the process was taken to completion, calcrete and silcrete would result.

Hardpan and calcrete do not occur in the regolith of the Darling Range. Strong leaching of the upper horizons under a thick vegetative cover has given rise to a bauxitic horizon. This process is probably continuing, upgrading the Darling Range bauxite. The highest grades of bauxite correlate closely with present high rainfall. Leaching is taking place within nearby bauxitic laterite at Boddington (Davy and El-Ansary, 1986). At Del Park, some 60 km NW of the Boddington deposit, ground waters contain not only Na, Ca, K, and Mg ions, but also those of Al, Fe, Mn, Cu, and Zn. Some Al and Fe may be present as colloidal particles (Davy, 1976). Alternate wetting and drying, caused by winter rainfall and summer drought, provides conditions in which the products of summer oxidation may be flushed by winter rains. The measured soil pH is close to the value necessary for lateritization, calculated by Norton (1973), and lateritization, in the Boddington area, may still be active.

3.4.4   *Chemical and mineralogical changes*

Besides the physical effects of the dismantling of lateritic profiles, there have been chemical and mineralogical changes in response to changing climates.

The high rainfall of the SW of Western Australia supports a thick forest cover in which bush fires are common. Intense fires are regarded as responsible for the development of several high-temperature minerals such as maghemite and corundum (Anand and Gilkes, 1987) in the surface and near surface lateritic residuum. Maghemite formation requires heating of Fe-oxides and oxyhydroxides to about 230°C in a reducing environment which occurs during bush fires where burning logs provide high temperatures and localized oxygen-deficient conditions in contact with the soil. There are large amounts of maghemite in lateritic gravels in the Mt. Gibson, Bottle Creek, and Lawlers districts. It is most likely that thick forest extended inland during periods of sustained higher rainfall over the last 30 Ma, so some of these high-temperature related mineralogical changes may have been more widespread than in the SW of Western Australia. Maghemite is absent in ferruginous saprolite and iron segregations, but occurs only in lateritic gravels. This is compatible with the bush fire origin, since the ferruginous saprolite and iron segregations have been exposed at the landsurface only during the present-day arid erosional stage and a forest cover would be lacking.

3.4.5   *Clay mineral-soil-climate relationships*

Soil morphology and other soil properties can be used to infer past climates (Birkeland, 1984). Before paleoclimatic interpretations are possible, one has to ensure that the observed soil property was actually imparted to the soil by a past climate and is not related to other processes of soil formation. The study areas have shown that highly-weathered, acid, gravelly, kaolinitic soils occur on old, dissected plateau remnants (residual areas), whereas younger soils on colluvium and alluvial floors are much less leached and some of these contain smectites and carbonates and are alkaline. Three of the orientation districts have less than 300 mm annual rainfall. It seems unlikely that the highly weathered soils on residual areas could form under the present climate because it is doubtful if leaching occurs. A much wetter earlier, climate, extending back into the Tertiary, is postulated for the highly weathered soils.

Clay mineral formation and transformation in the regolith are slow processes in some environments and therefore clay mineralogy may be a useful tool in assessing past climatic influences on the regolith. The stability of a clay mineral in a changing, regolith-leaching environment is a function of the original clay mineral and the direction of the climatic change. Kaolinite, for example, is formed under a fairly strong leaching and relatively acid environment. As the climate becomes arid, kaolinite may persist in the regolith and serve as an indicator of a former wetter climate.

Palygorskite has been found to occur in close association with carbonates in the Mt. Gibson district. The presence of palygorskite in the regolith may indicate long-term aridity.

3.5 The significance of deep weathering and regolith evolution to exploration

The most obvious impact of lateritic weathering on exploration is the masking of ore deposits by the products of weathering. This may be through formation of deep saprolites and gossans followed by lateritization of gossans, and by concealment beneath lateritic residuum or by soils and sands of the lateritic plains. Recognizing the *physical appearance* of an ore deposit will be easier after truncation of the weathering profiles has taken place. Weathering also disperses minerals and chemicals from the weathered ore deposits. Most ore deposits cause geochemical anomalies within their host sequences, which comprise several pathfinder elements, either from the mineralization or its alteration halo, so that multi-element dispersion anomalies generally result.

Lateritic weathering results in oxidation of sulphides at or close to the weathering front, strong leaching of alkali and alkaline earth elements from the saprolite zone, retention and concentration of Fe and elements with an affinity for Fe-oxides, and accumulation of relatively-immobile elements occurring within resistant minerals. The main processes of lateritic weathering, hydromorphic dispersion, mechanical dispersion, and residual accumulation, generally result in usable geochemical dispersion patterns from concealed ore deposits. The anomalies in lateritic residuum tend to be large relative to the source mineral deposit and its primary halo (Table 5.1), but commonly have relatively low element abundances.

In general, dispersion tends to be greater at the top of weathering profiles, because of enhanced mechanical dispersion and greater hydromorphic dispersion. An important exception is supergene dispersion of Au and base metals which can take place deep within the saprolite, close to the saprolite-bedrock interface.

One important side-effect of lateritic weathering has been to simplify the extractive metallurgy of Au from saprolite and lateritic Au deposits.

A near-surface Au depletion zone in the saprolite above a bedrock Au deposit has a significant effect on Au exploration and mining and is attributed to modification of the laterite profile. Very low Au abundances can be encountered in the top 10 to 50 m of saprolite, beneath the lateritic residuum. Such a depletion zone is commonly associated with a deep supergene zone. We need to understand under what conditions such depletion zones occur and be able to predict where they occur.

Weathering imposes a sub-horizontal layering of alteration processes and products upon the bedrock. In the undissected state, the mineralogical and geochemical characteristics change vertically. In reality, varying degrees of truncation and preservation of the weathered layer complicate the situation, which is made much more complex by deposition of sediments derived from dismantling of weathering profiles in uplands and deposition of chemical sediments in arid regions. Still further complexities result from precipitation of authigenic carbonates, chlorides, sulphates, and amorphous silica within the landscape.

Thus, in general, materials found on the surface are a heterogeneous assemblage of weathering products. Thus, there are different element abundances, associations, and dispersion geometries. It is therefore important to map domains, units or regimes which divide the landscape into comparable areas and to develop an understanding of the regolith-landform dynamics, regolith stratigraphy, genesis and evolution of the regolith-landform system. This should complement systematic bedrock mapping and studies of ore genesis.

The following questions frequently arise in exploration for Au using laterite geochemistry:

1.   Under what circumstances should a Au anomaly occur in lateritic residuum above a Au deposit?

2.   How much are multi-element laterite anomalies affected by post-lateritization changes?

3.   If Au is leached from a laterite geochemical anomaly, arising from a Au deposit, which elements remain?

4.   How confidently can we interpret laterite geochemical anomalies?

The research presented below addresses these questions. It also provides necessary documentation which contributes to confidence in exploring in lateritic terrain. However, the scope of some of these issues extends beyond the time frame of this project.

4.0 ORIENTATION STUDIES

4.1 Introduction

The initial foundations of the Laterite Geochemistry Project, during the period covered by this report, are four substantial, district-scale, interdisciplinary geochemical orientation studies: Mt. Gibson, Bottle Creek, Lawlers, and Boddington. These studies focus on important Au deposits in differing lateritic regolith-landform situations, covering a range of climatic types and geographic locations (Figs 1.2 and 4.1). In each case geochemical dispersion from concealed Au deposits has been studied by understanding the regolith-landform and bedrock relationships both near the ore deposits and distant from them (at district scale). A regolith-landform framework has been established for each orientation study, within which samples and their associated geochemistry are tightly controlled.

Representative regolith-landform dispersion models have been established from this information. The models, which are presented in Section 9.0, are important in summarizing knowledge of multi-element geochemical dispersion and are essential for predicting comparable dispersion characteristics, both in the Yilgarn and elsewhere.

The orientation studies vary in extent from 120 km^2 to 500 km^2 and are distributed across the present-day rainfall gradient of the Yilgarn Craton, Fig. 1.2.

The orientation studies provide the data and observations from which specific research themes (Section 1.2) draw. By mapping the districts it was possible to understand the regolith-landform relationships in each. This approach results in a much more complete perspective than from studying idealized situations or isolated vertical profiles.

The CSIRO Division of Soils had carried out regolith-landform studies, resulting in a series of Soils Publications. A prominent example in the Yilgarn Craton is that of the York-Quairading area by Mulcahy and Hingston (1961). Previously the CSIRO Laterite Geochemistry Group had carried out orientation research in the Golden Grove base metal sulphide district (Smith and Perdrix, 1983) and in the Greenbushes rare metal pegmatite district (Smith et al., 1987). Regolith-landform approaches to exploration geochemistry in Australia, part of which focussed on the Yilgarn Craton, were presented in a series of idealized models and supporting case studies by Butt and Smith (1980). The Laterite Geochemistry Project reported here extended these exploration geochemical approaches.

These substantial orientation studies, made possible by collaboration between mining, exploration, and research, are intended to be type examples to assist exploration in lateritic environments. Findings from the main orientation studies are summarized in the following sections and their implications to exploration are tabulated at the end of each sub-section. Readers should refer to the substantial individual reports (listed in Appendix I, Section 15) for comprehensive information and documentation. Following an introduction, in general, only abstracts of these reports are presented here, together with several key diagrams.

Rainfall	Status of lateritic residuum:					
	Truncated		At surface	Near surface (beneath soil or sand)	Buried	
	Extensively	Sporadically			Shallow cover 0 - 10m	Deep cover 10 - >20m
Regular winter rain 500 to >1000mm		Greenbushes				
		Boddington				
250 to 500mm		Mt. Gibson				
		Golden Grove				
<200 to 250mm		Bottle Creek			Bottle Creek	
	Lawlers					
Arid interior		Beasley Creek				

Figure 4.1. Orientation studies carried out by the Laterite Geochemistry Group showing the status of lateritic residuum, and arranged according to average annual rainfall. Orientation studies are located in Fig. 1.2.

4.2   Mt. Gibson

4.2.1   Introduction

The Mt. Gibson district is typical of the complex lateritic sand plains of the semi-arid Perenjori-Ninghan region, where an essentially-complete undulating lateritic peneplain is undergoing dismantling by erosion. Burial of complete and partly-truncated laterite profiles by erosional detritus has taken place on some of the slopes and in the low-lying areas. These dynamic erosional and depositional processes are continuing.

Outcrop of bedrock is scarce in much of the low-relief parts of the Perenjori-Ninghan landscape, which is typical of much of the Yilgarn Craton. Thus regolith units are the most used sampling media for initial geochemical exploration. A study of the geochemical expression of a concealed Au-base metal mineralized system here would be valuable for exploration of poorly-outcropping parts of the region and of comparable areas elsewhere.

The Mt. Gibson Gold Project, a joint venture between Forsayth (Gibson) Ltd and Reynolds Australia Mines Pty Ltd, is located (117°45'E; 29°45'S) some 300 km northeast of Perth and some 200 km from the coast. At the commencement of CSIRO research at Mt. Gibson in November 1986, the areas destined for mining were little disturbed. The area has a semi-arid to arid, hot Mediterranean climate with a 250-mm average annual rainfall, most of which falls during the cooler months of May to August. However, there is a significant component of summer rainfall from erratic thunderstorms. The gold mining locations, upon which this study is based, are distributed along strike of the shear zone system and host lithologies. The
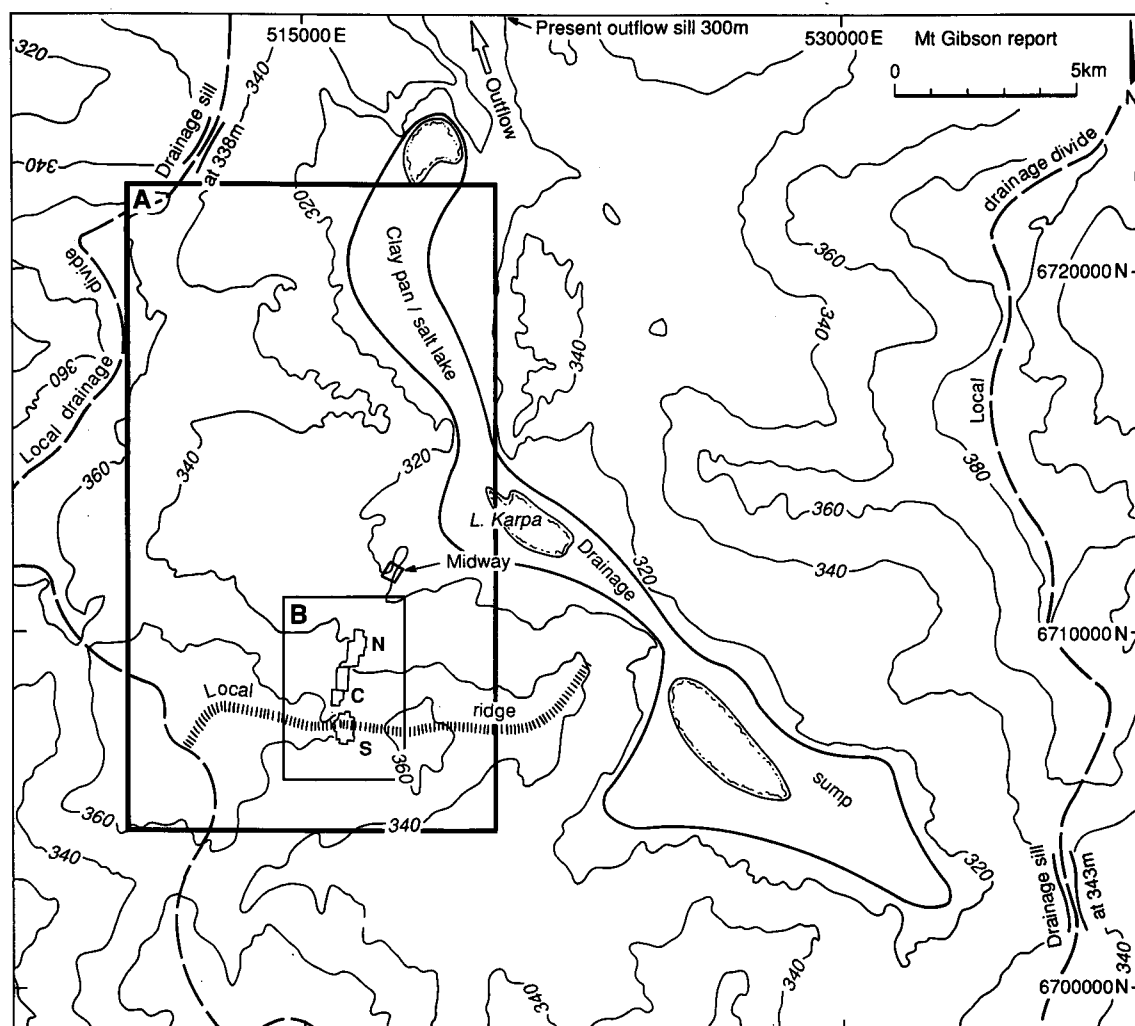
Figure 4.2. Map showing the district scale topographic setting of the Mt. Gibson Au mining areas (the S,C,N Pits and the Midway North locations) upon which the orientation studies are based. The outer rectangle, A, shows the area covered by Report 165R, the inner rectangle, B, shows the focus of Report 20R.

bedrock assemblage in the Mt. Gibson area comprises a suite of mafic volcanic and hypabyssal rocks, felsic volcanics, and felsic meta-sedimentary rocks. Primary mineralization occurs in the form of mineralized veins, mineralized shear zones, and stratabound sulphides. The location of the South Pit (S Pit) lies on a subdued ridge, the Central (C) and North (N) Pits on a mid-slope position and the Midway North Pit is located on a toe slope, Fig. 4.2.

The area is mantled by thicket communities of various species of acacia which are prominent amongst the sand-plain communities in both the uplands and lowland. Eucalypt woodlands, largely of salmon gum, York gum, and mallee, together with some native pine occur on the finer textured soils in local erosional tracts and along valleys.

4.2.2   Objectives

The overall objectives of the Mt. Gibson study were to first establish a well-controlled regolith-landform framework and, within which, to carry out a geochemical orientation study about the concealed Au deposits.

To do this it was necessary to:

1.   Understand the regolith-landform relationships around the S, C, and N Pit areas which, in the initial stages of research, contained the main Au reserves.

2.   Carry out an orientation geochemical survey of the S, C, and N Pit areas concentrating on multi-element dispersion patterns in the upper, lateritic parts of the weathering profiles.

3.   Establish, at reconnaissance scale, the regolith-landform relationships of the district.

As the study progressed, exploration by the joint venture in the Midway North area discovered the Hornet Zone. This is a bedrock Au deposit which is now being open-cut mined. Objective 4 was added to take advantage of the research opportunity which arose at Midway.

4.   Extend the findings from 1 and 2 by establishing regolith-landform control at Midway North and determine the extent of geochemical dispersion into laterite and hardpan.

5.   Establish the gross ground water regimes in the district and to investigate dispersion from the ore system into these ground waters.

6.   Organize the multi-element geochemical data from this study into reference data sets which would be used, along with data from other orientation areas for multivariate data interpretation.

4.2.3   Research components and reports produced

The multi-disciplinary research at Mt. Gibson has a number of inter-related components. The results have been presented progressively, with supporting documentation, as five substantial reports. Arranged by the research topics these are:

• Regolith-landform relationships (detailed area*)	Report 20R
• Geochemical dispersion (detailed area*)	Reports 20R, 157R and 165R
• Geochemical dispersion (Midway North)	Report 165R
• Regolith-landform relationships (district**)	Report 165R
• Ground water geochemistry (detailed area* and district**)	Report 120R
• Siting and bonding of elements, dispersion processes	Report 165R
• Characteristics and origin of carbonates in regolith	Report 165R
• Orientation geochemical data sets	Report 157R
• Classification of laterite types, regolith-landform models	Report 60R (*The Atlas*)
• Overview and synthesis	This Summary Report

*   A 15-km^2 area containing the S, C, and N Pits.

**   A 170-km^2 area which contains Midway North (Hornet zone) and the Lake Karpa drainage sump.

Summaries of these results follow with abstracts of reports where appropriate.

4.2.4   Exploration geochemistry about the Mt. Gibson Au deposits. R.R. Anand, R.E. Smith, J. Innes and H.M. Churchward. March, 1989, Report 20R, 93p. (Data sets on floppy disks in Report 157R.)

Abstract

A regolith, landform, and geochemical orientation study about the S, C and N lateritic Au deposits at Mt. Gibson clarifies landscape evolution and geochemical dispersion in terms of the dynamics of formation, preservation, and dismantling of the undulating lateritic weathering mantle [Fig. 4.3].

The relatively complex regolith and vegetation patterns are explained in terms of the distribution of (i) sub-areas of erosion of the lateritic mantle to the level of saprolite, (ii) sub-areas of essentially-complete lateritic mantle, and (iii) sub-areas characterized by depositional accumulation of detritus provided by the dismantling of the lateritic mantle upslope, commonly burying the essentially complete laterite weathering profile in the local foot slopes and lowlands [Figs 4.4 and 4.5].

The regolith units were mapped over the central 3-km by 5-km area, the regolith stratigraphy established, and units of the upper regolith were characterized in field profiles petrographically, mineralogically, and chemically. An idealized regolith-landform facies model [Fig. 4.6] has been erected for use in prediction in appropriate terrain, and for planning and integrating follow-up research.

Geochemical analyses of samples of the loose pisolitic, nodular laterite unit collected systematically both from surface and from pit walls, where the unit occurred sub-surface, document the characteristics of the lateritic Au deposits. These and earlier results of the orientation study show that the lateritic Au ore and the area peripheral to it is a multi-element, chalcophile, geochemical anomaly, measuring 1 to 1.5 km across and greater than 4 km in length, with a Au Ag Pb As Bi Sb W association.

Within the loose lateritic gravel unit, and in the underlying duricrust, coincident highs of several of these elements in centres within the overall anomaly suggested a close genetic link with bedrock sources, now verified by occurrences of gold-bearing quartz-hematite veining in saprolitic bedrock revealed by exploration and mining.

Geochemical results of 37[*] samples of the underlying lateritic duricrust show similar strengths and associations of elements as seen for the unit consisting of loose lateritic pisoliths and nodules. Close comparisons of the geometry of the dispersion patterns of these two closely related regolith units await the result of current research on more extensive sampling of the duricrust.

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[*] Note: Sampling of the lateritic duricrust was extended to a total of 112 samples in the detailed S, C, and N Pit areas. Results (presented in Report 157R) now clearly show that the multi-element dispersion pattern in the pisolitic-nodular gravel unit of the lateritic residuum is coincident with, yet broader than, the dispersion pattern in lateritic duricrust (Section 4.2.7).
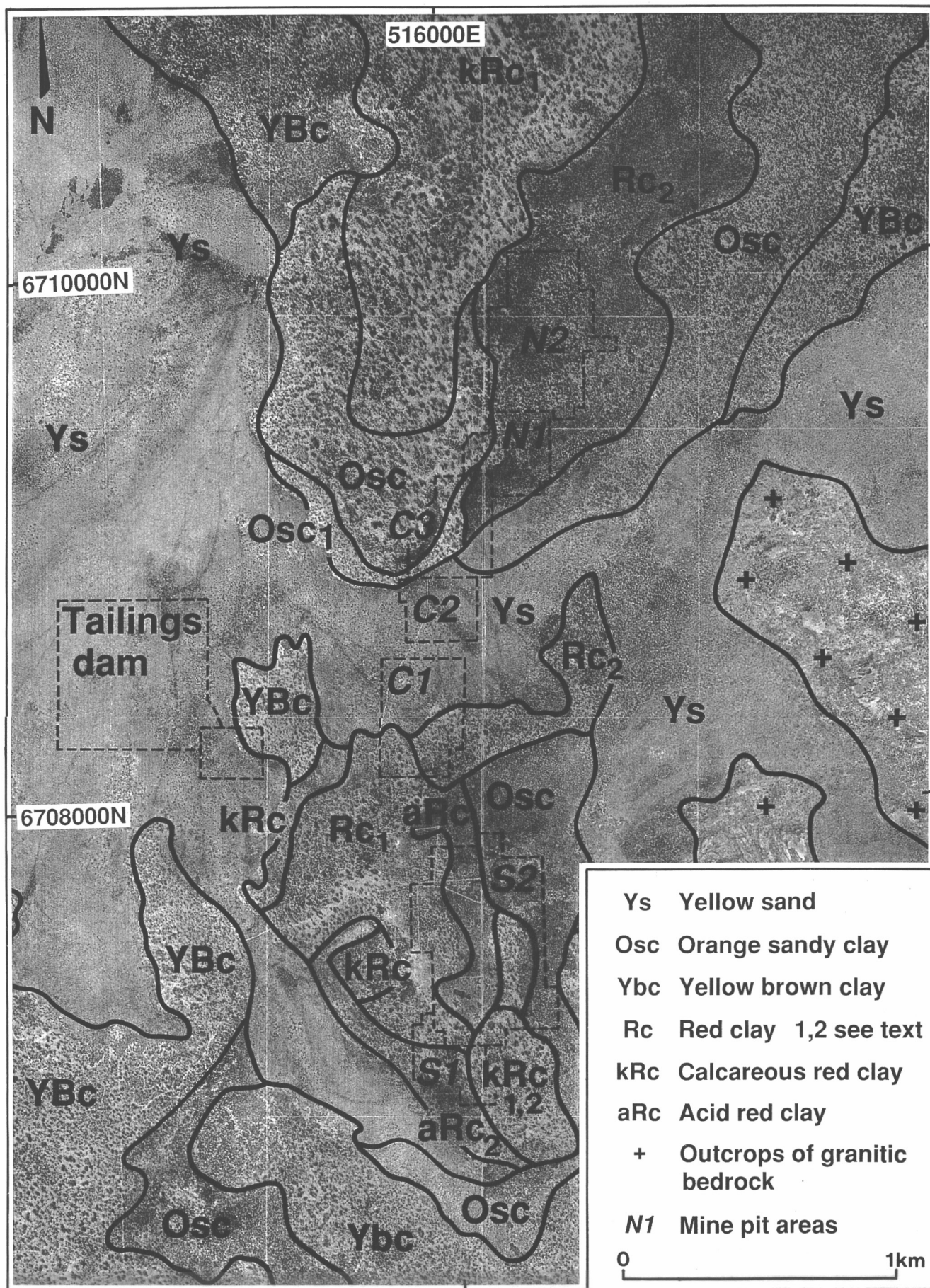
Figure 4.3. Map showing the surface distribution of regolith units and vegetation patterns for the Mt. Gibson detailed orientation area as an overlay to the black and white air photograph (Ninghan run 11,5239, Sept. 1980) from CRC LEME Open File Report 35. DOLA Copy Licence 543/98 WA1992, Run 11, Frame 5239, Project 790020.
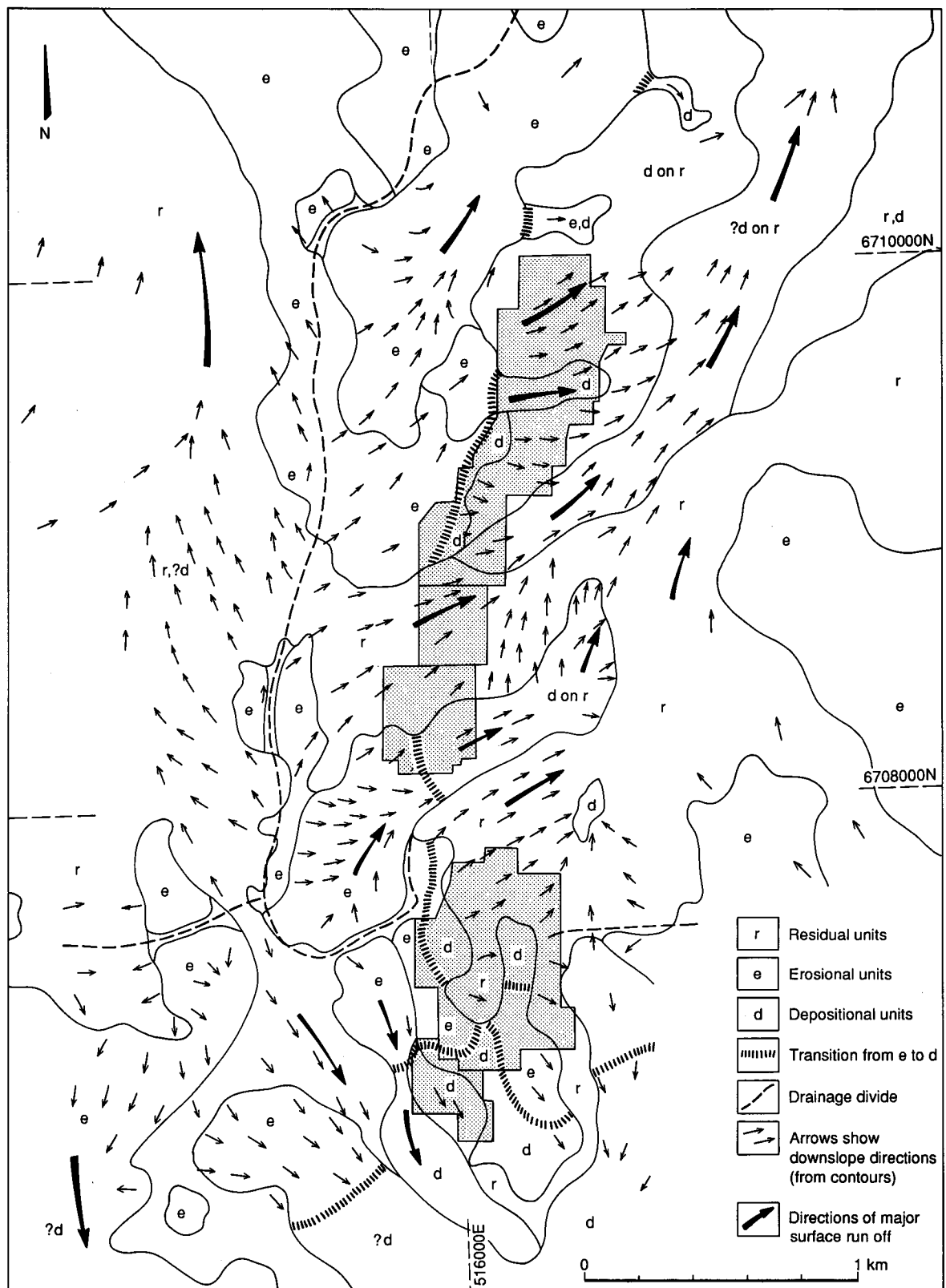
Figure 4.4. Map of the Mt. Gibson detailed orientation area showing
a synthesis of regolith-landform dynamics, Report 20R.
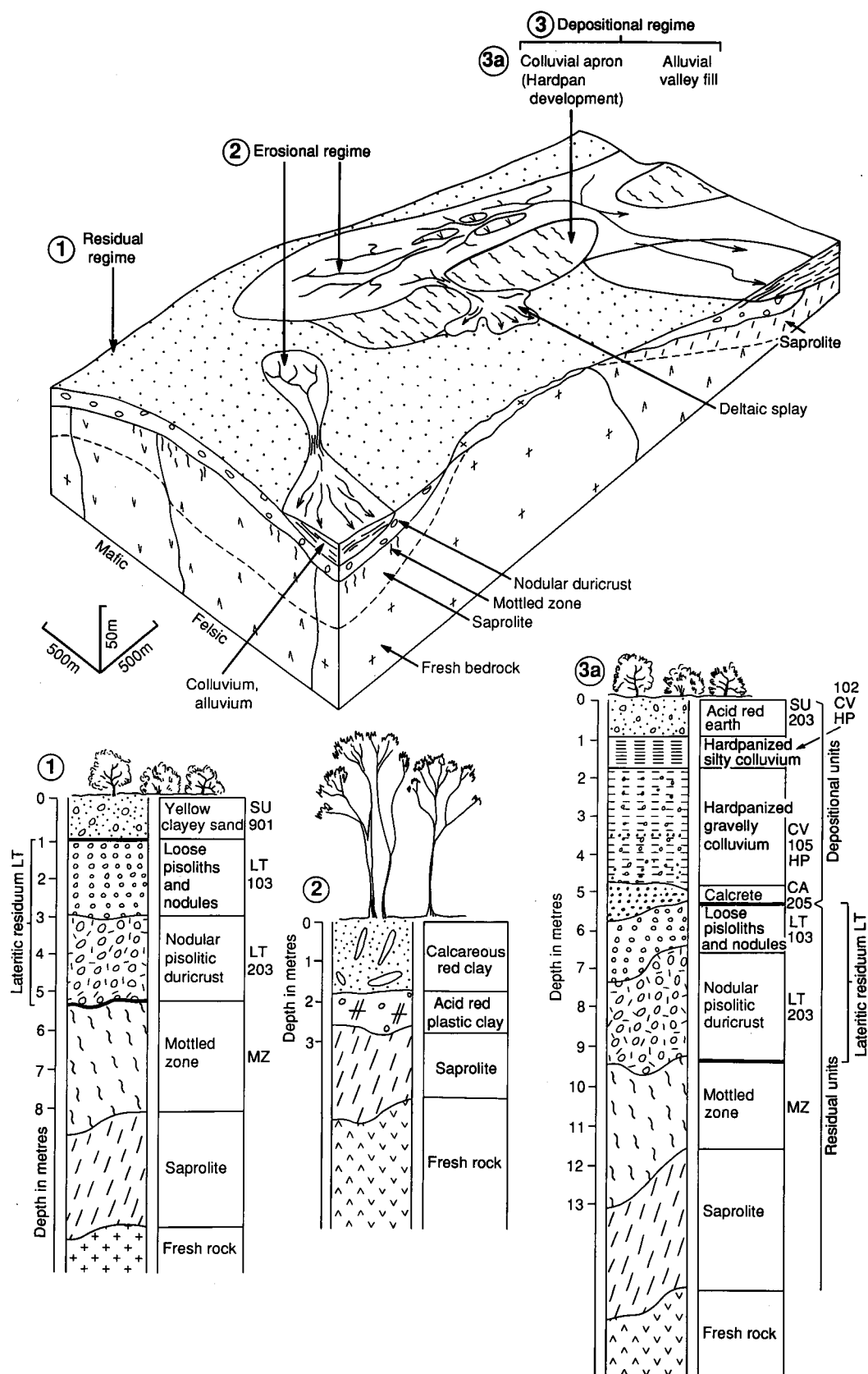
Figure 4.5. Regolith-landform model for the Mt. Gibson oreintation area, columns show units of the regolith stratigraphy together with classification codes for selected regolith materials, Reports 20R and 165R.

DURICRUST FORMATION AND DISMANTLING
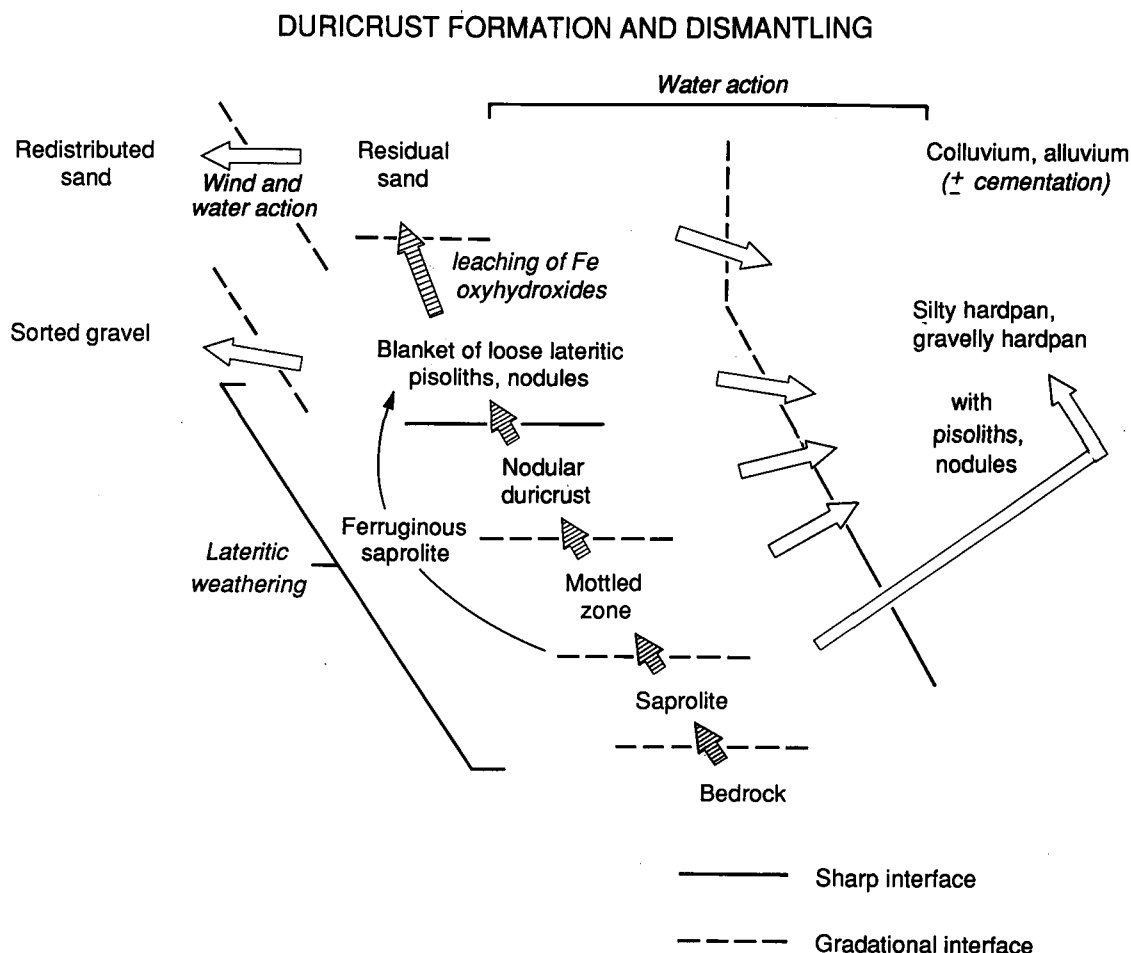
Figure 4.6. Schematic facies model for the formation of the lateritic weathering mantle and its subsequent dismantling at the Mt. Gibson orientation area, Report 20R.

4.2.5 *Regolith-landform development and siting and bonding of elements in regolith units, Mt. Gibson district. R.R. Anand, H.M. Churchward and R.E. Smith. September, 1991, Report 165R, 95p, data on floppy disk.*

Abstract

Regolith-landform relationships

The complex regolith of the Mt. Gibson district is explained in terms of the distribution of: (a) regimes where the essentially-complete laterite profile is preserved, commonly forming broad crests and upper gentle slopes, (b) regimes of erosion of the laterite profile to the level of saprolite/saprock/bedrock resulting in terrain characterized by low to medium hills, and (c) regimes characterized by depositional accumulations of detritus provided by the erosion of the laterite profile, commonly burying the complete and partly-truncated lateritic weathering profile in the lower slopes and valley floors. In the latter, sediments reach 30 m in thickness and residual laterite up to 6 m thick was observed to occur under the sediments [Table 4.1].

The regolith units were mapped over a 17-km x 10-km area, the regolith stratigraphy established, and the regolith units were characterized. A regolith-landform model for the Mt. Gibson district describes relationships in terms of erosion and burial of complete and partly-truncated profiles. Lateritization and post-lateritization processes responsible for the formation of a variety of regolith types are discussed.

Midway North Area

The pattern of regolith at Midway North, which characterizes the district, relates closely to the erosional and depositional modification of the deeply-weathered mantle. A total of 25 samples representing various regolith units were characterized petrologically, mineralogically, and geochemically. Systematic mineralogical and geochemical differences occur between transported and residual regolith units. For example, the colluvial units (soils and hardpanized colluvium) contain higher amounts of kaolinite and quartz relative to the underlying residual regolith units. Hematite increases upwards in the residual weathering profile. The Al content in goethite also tends to increase towards the top of the residual profile.

Lateritic residuum is enriched in Cu, Pb, Zn, As, W, Ag, and Au which are associated with hematite and goethite [Figs 4.7 and 4.8]. The calcareous clays overlying acid, plastic clays largely consist of dolomite, kaolinite with small amounts of hematite, calcite, halite, and palygorskite. These clays have low contents of chalcophile elements, but contain significant amounts of Au. However, the amounts of Au are very low in clays relative to the lateritic residuum. The upper saprolite is depleted compared to the lower saprolite in Au and chalcophile elements. Acid, red plastic clays developed from the weathering of underlying saprolite are also low in Au.

Carbonates

Scanning electron microscopic studies of calcareous soils and nodular calcretes from the Mt. Gibson Au deposits reveal a fossilized community of soil micro-organisms dominated by filamentous structures preserved in fine detail by calcite. The calcite forming the filaments has a variety of crystal habits. Calcified filaments observed in samples of nodular calcrete suggest that biological activity could have played a significant role in the formation of the carbonates in the regolith.

Siting and Bonding of Elements and Dispersion Processes

The bulk samples of soils, lateritic residuum, hardpanized colluvium (red-brown hardpan), and calcareous soils were separated into various morphological groups, such as magnetic vs. non-magnetic nodules/clasts, matrix vs. clasts, calcareous fragments vs. ferruginous clasts, and cores vs. cutans. The petrological, mineralogical, and geochemical characteristics of these materials were established. Non-magnetic lateritic nodules/clasts are the dominant fraction of both soils and lateritic residuum. The magnetic and non-magnetic nodules/clasts have different internal fabrics. The cores of magnetic nodules/clasts are black and massive, whereas those of non-magnetic nodules/clasts are yellowish brown and porous. Hematite is a dominant mineral in both magnetic and non-magnetic lateritic nodules/clasts. The non-magnetic lateritic nodules/clasts contain higher amounts of goethite and kaolinite relative to the magnetic lateritic nodules/clasts, while maghemite is present in the magnetic nodules/clasts. The cutans of nodules and pisoliths are dominated by goethite. Goethite in the lateritic residuum is highly Al-substituted (17 mole %).

Iron, Cr, V, Pb, As, W, Sb, Bi, and Zn are enriched in magnetic lateritic nodules/clasts relative to the non-magnetic lateritic nodules/clasts. By contrast, Al, Si, Cu, Ag, Au, and Ni are relatively more abundant in non-magnetic lateritic nodules/clasts. Cores of both groups of nodules/clasts contain higher amounts of Au than cutans.

The matrix of hardpanized colluvium (red-brown hardpan) consists of kaolinite, quartz, and amorphous silica. The mean values of Au and Ag for the matrix of hardpan are higher than, or very similar to, those for lateritic nodules.

Carbonate fractions separated from nodular calcrete are anomalous in Au. The magnitude of the anomaly is, however, smaller than that of lateritic nodules and pisoliths.

The possible associations of Au, Pb, Zn, As, Cu, Ni, Cr, and V with various secondary mineral species are discussed. Chromium, V, Ga, Pb, As, and Sb are strongly associated with hematite. Goethite and kaolinite appear to have strong affinities for Cu, Ni, Ag, and Au. Hydromorphic dispersion appears to be the major dispersion process that extended the geochemical halo in the upper part of the regolith.

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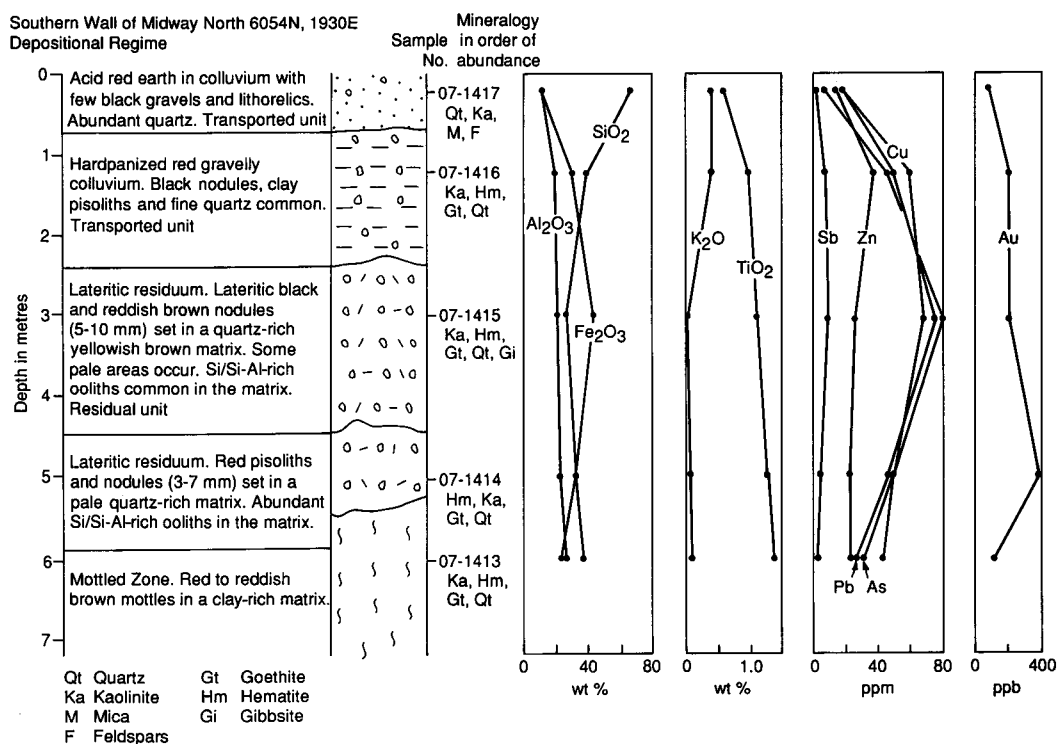
Figure 4.7. Vertical profiles showing the stratigraphy, mineralogy, and geochemistry of residual and transported regolith units for the depositional regime, southern wall, Midway North Pit, Report 165R.
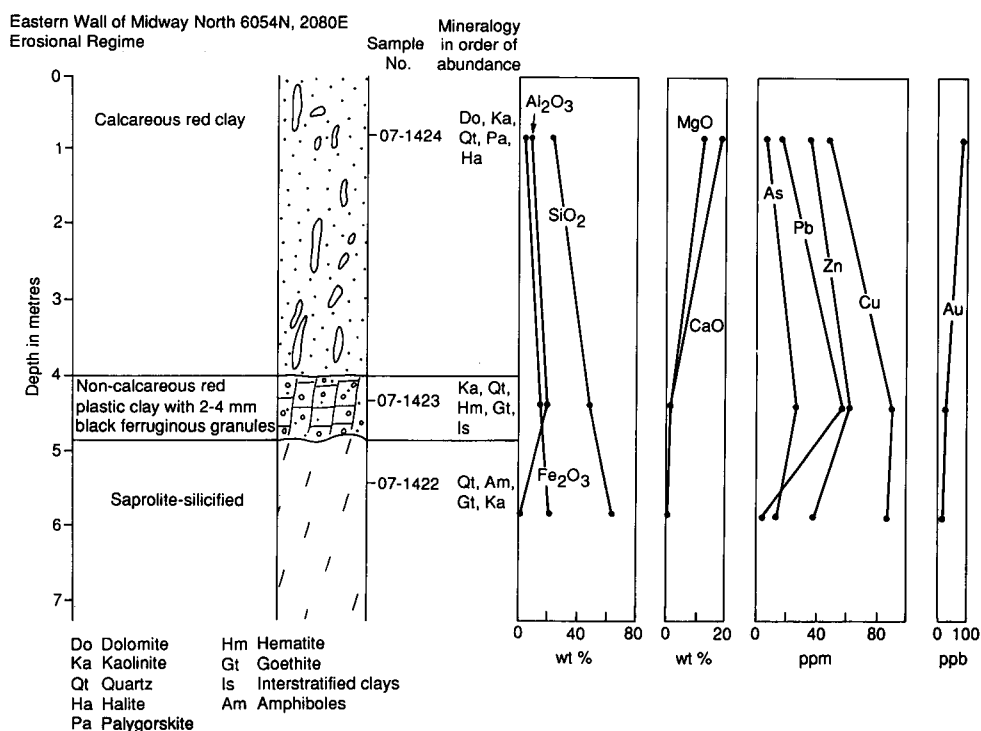
Figure 4.8. Vertical profile showing the stratigraphy, mineralogy, and geochemistry for the erosional regime, eastern wall, Midway North Pit, Report 165R.

Table 4.1. Summary of regolith stratigraphy and characteristics of regolith units, Mt. Gibson district, Report 165R.

REGOLITH MAPPING UNIT	RESIDUAL REGIMES		EROSIONAL REGIMES		DEPOSITIONAL REGIMES		
	(3 Subdivisions)	(2 Subdivisions)	(2 Subdivisions)	(2 Subdivisions)	(2 Subdivisions)		(2 Subdivisions)
REGOLITH DERIVED FROM	GREENSTONE BELT	FELSIC ROCKS	GREENSTONE BELT	FELSIC ROCKS	GREENSTONE BELT	FELSIC ROCKS	MIXED
LANDFORMS	Crests and slopes		Undulating hills	Breakaways, domes.	Slopes and valleys	Floors	Major drainage
VEGETATION	Acacia	Casuarina/acacia	Eucalyptus	Eucalyptus	Mallee, eucalyptus	Eucalyptus	Salt bush
LAG	Lateritic nodules and pisoliths		Saprolite/saprock/bedrock		Ferruginous granules		— — —
SOILS	Gravelly earths	Gravelly sand/ yellow sand	Calcareous clays	Sandy	Red earths	Red earths	Brown clayey sand
COLLUVIUM	Minor	Minor	Minor	— — —	Red sandy clay	— — —	— — —
CO-ALLUVIUM	— — —	— — —	— — —	— — —	Extensive	Extensive	Extensive
CARBONATES	— — —	— — —	— — —	— — —	Some calcrete	Some, soft carbonates.	
HARDPAN	Minor or absent	Minor or absent	Minor or absent	Minor or absent	With or without hardpan		
LATERITIC RESIDUUM	Pisolitic nodular duricrust		Absent by definition of regime		Duricust can be buried		
MOTTLED ZONE	Sporadic	— — —	— — —	— — —	Sporadic	?	?
SAPROLITE	Variable thickness	Pallid		Pallid	Variable thickness	?	?
BEDROCK	Mafic,metaseds, felsic.	Granitic	Mafic,metaseds, felsic.	Granitic	Mafic,metaseds	Granitic	Mixed

4.2.6   Hydrogeochemistry in the Mt. Gibson Au district. D.J. Gray. March, 1991, Report 120R, 80p.

Abstract

Research was conducted into the hydrogeochemistry of ground waters within the Mt. Gibson mine area and in the surrounding district [Fig. 4.9]. This work involved determination of field parameters such as pH and Eh, laboratory analysis of water samples for major and trace elements, isotope determinations (D and O^{18}), computer speciation of analytical data, and statistical analysis of the water data.

The ground-water system is dominated by a northward saline drainage system. Ground-water flow along this drainage appears to be restrained by an underground sill about 7 km north of the mine area, resulting in highly saline ground waters within the mine region. This saline ground-water appears to flow back into the mine area at depth. Thus, the north section of the mine area has fresher waters (about 3% TDS) overlying hypersaline water (> 13% TDS).

Based on the major element and isotope analyses, the mine ground waters were resolved into a number of hydrogeochemically distinct water masses. Waters west of the major area of supergene Au mineralization at Midway were identified as originating from contact with granitic rocks, whereas the other mine ground waters appear to be associated with mafic or ultramafic systems.

Waters within the Midway area showed highly-anomalous characteristics, being high in dissolved Au, Fe, Mn, Co, Cd, Ba, and I, and having low HCO_3 concentrations, probably due to weathering of sulphide minerals. Downgradient of the Midway area, the ground-water becomes acidic, due to oxidation/hydrolysis of the dissolved Fe. This has led to major dissolutions of many metals, particularly (in order from least to most enriched) Cd, Co, Ni, Zn, Cu, Cr, Al, and Ag. This enrichment is related to the base affinity of the metals.

Soluble Au was below the detection limit (0.05 g/L) outside the mineralized area. Within the mineralized area two major anomalies were recognized: the first, within the Midway area, may represent dissolution of Au by thiosulphate; while a second anomaly within the N2 pit area may represent dissolution by chloride.

On the basis of this work, soluble Au analyses could be used at this site to indicate areas of Au mineralization at both a district and a mine scale. Thus, measurements of dissolved Au may represent a useful adjunct to drilling during Au exploration, particularly with respect to buried mineralization.

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Discussion of the research findings – Mt. Gibson waters

Research focussed on the opportunity for systematic study of changing environments: upland, well-drained, with relatively fresh ground-water at depth and infiltration by rainwater at one extreme to low-lying area immersed in highly saline ground waters at the other, Fig. 4.9. The objectives of this study were as follows:

(i)   to establish the flow paths for ground waters in areas of interest;

(ii)   investigate the gross characteristics of ground waters in and about the geochemical dispersion halo in laterite and about the associated ore environments, following the flow path from uplands, to mid slope, lower slope, and saline sump regimes;

(iii)   inquire into the role of Fe-cycling and ferrolysis in the regolith situations at Mt. Gibson and in the formation of the geochemical haloes;

(iv)   inquire into the role of carbonate in the geochemistry of Au in the regolith environments;

(v)   determine the ground-water concentration of Au and of other chalcophile elements and estimate the importance of the potential complexes of Au and other elements;

(vi)   investigate the impact of differing ground-water regimes on the multi-element characteristics of the dispersion haloes; and

(vii)   consider to what degree we can understand the past ground-water regimes at Mt. Gibson from our knowledge of today's conditions.

The waters within the evaporative sump are at or near saturation for calcite, gypsum, celestine, barite, and halite. Ground-water flow along this drainage appears to be partially or wholly constrained by an underground sill about 7 km north of the mine area. Recirculating ground waters increase in salinity with evaporation and mineral dissolution and form the saline sump system.

At the mine area, ground-water is suggested to originate at the drainage divide at Tobias' Find, via rainfall, and then travel in a north-northeast direction before reaching the drainage sump system about 2000 to 3000 m to the north-east of Midway (Fig. 4.9). There is a general increase in TDS along the northward flow direction. The data indicate the presence of two aquifer systems: a shallow system of recent origin of "low" salinity (TDS < 4 %) and a deeper system of higher salinity (TDS > 13 %), probably due to back-flow of the waters from the regional drainage sump south into the mine area, at depth. This situation is demonstrated in Fig. 4.10, as modified from Smith (1987). The Midway area lies in a region where saline waters from the regional system are back-flowing at depth (Fig. 4.10).

Based on major element and isotope analyses, the ground waters were resolved into a number of hydrogeochemically distinct water masses, which seem primarily to be under the control of bedrock lithologies.

The high Mn and Ba in the Midway waters may indicate release from carbonate associated with the mineralization. Iodide is very strongly enriched (0.8 - 1.7 mg/L) in the Midway area, consistent with other work suggesting iodide to be enriched in mineralized areas (Chitayeva *et al.*, 1971; Fuge *et al.*, 1988). The high dissolved Au values (up to 1 μg/L) are consistent with the supergene Au enrichment in this area. The generally neutral character of the Midway waters suggests that the first stage of pyrite weathering is occurring under neutral conditions and that appreciable $S_2O_3^{2-}$ could be produced during sulphide oxidation (Goldhaber, 1983). Additionally, the presence of high levels of Fe^{2+} precludes the Au being present as $AuCl_2^-$, as this species would be readily reduced in such an environment (Mann, 1984b). These observations suggest that the Au is present as $Au(S_2O_3)_2^{3-}$ (Mann and Webster, 1990).

Downgradient of the Midway area, the ground-water becomes acidic, due to oxidation/hydrolysis of the dissolved Fe (ferrolysis).

$$2Fe^{2+} + \tfrac{1}{2}O_2 + 5H_2O \rightarrow 2Fe(OH)_3 + 4H^+$$
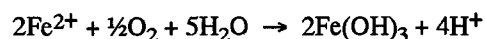
This has led to major dissolution of many metals, in a manner related to the base affinity of the metals. The sequence for mobilization (going from higher to lower pH) was observed to be Ba,Sr,Ca > Mn,Cd > Co,Ni,Zn > Cu,Cr,Al, consistent with other field and laboratory observations (Blowes and Jambor, 1990; Dubrovsky, 1986; Gray, 1986).
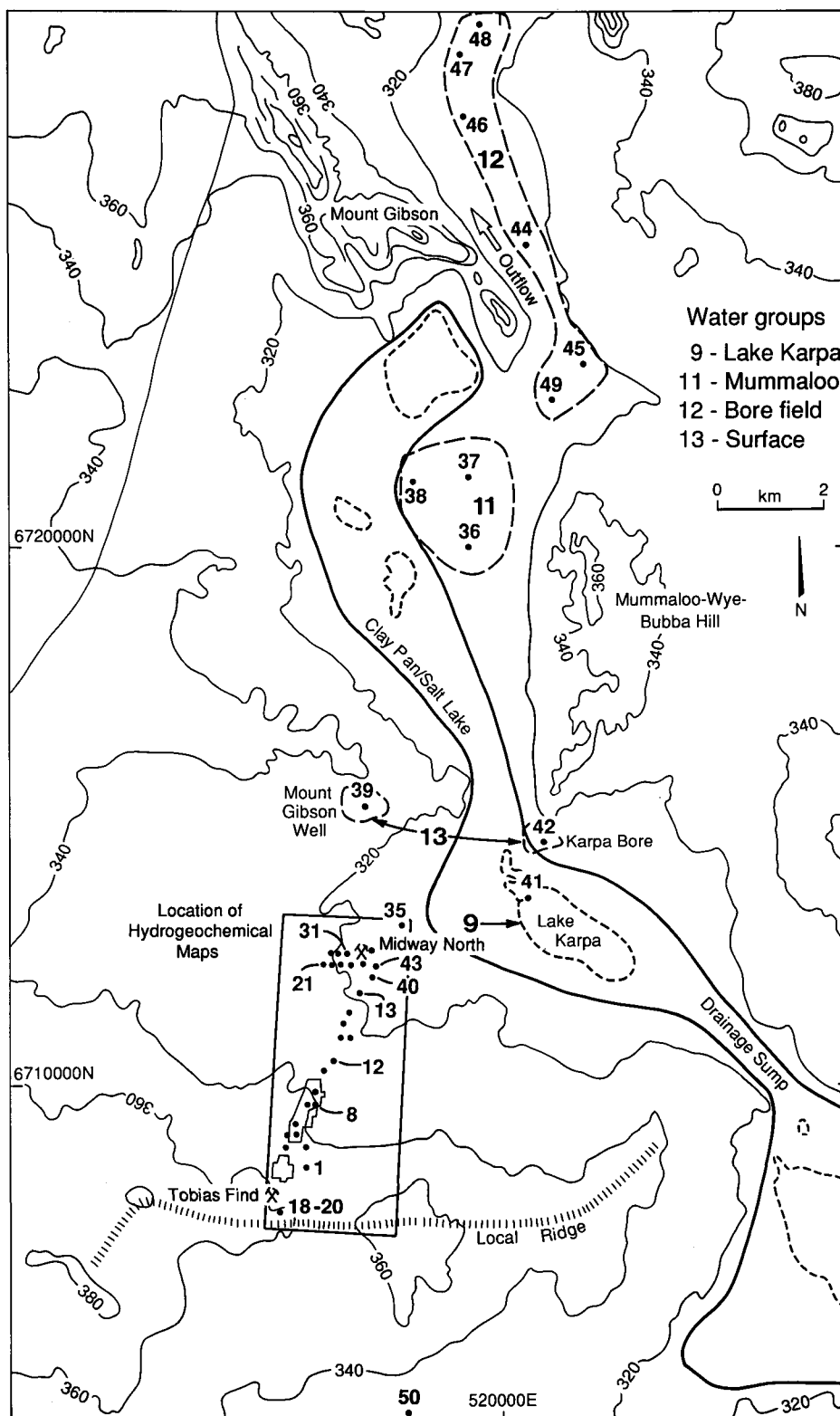
Figure 4.9. Map showing the distribution of drill hole locations used in water sampling for hydrogeochemistry, Mt. Gibson orientation district. Topographic contours in metres above mean sea level are also shown. From report 120R.
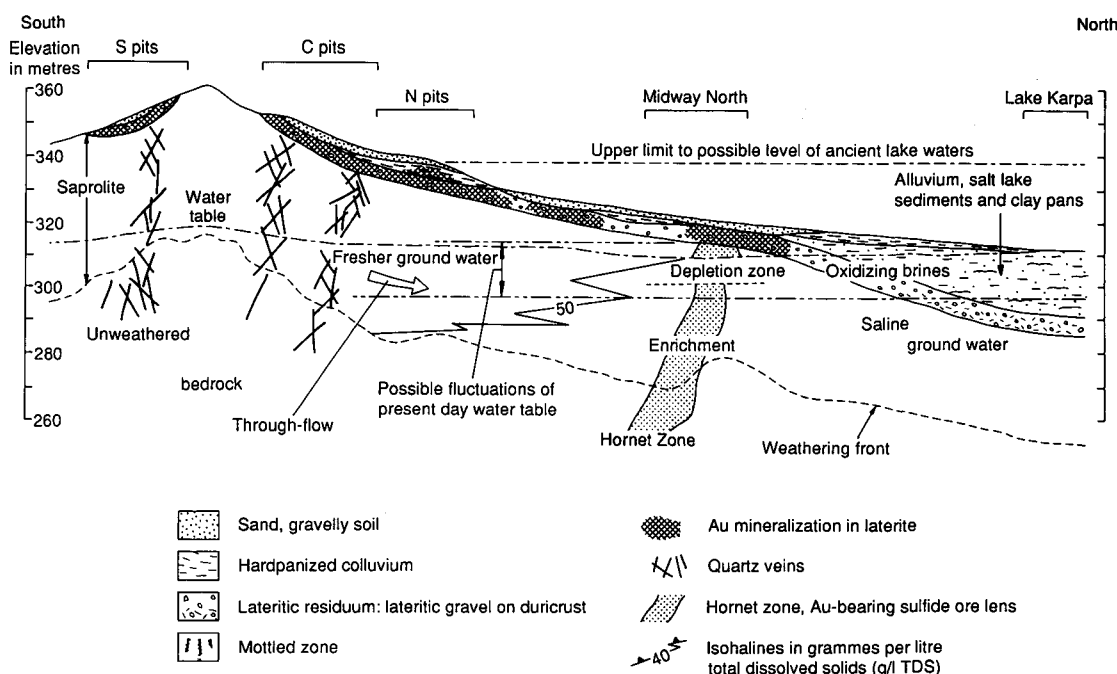
Figure 4.10. Conceptual longitudinal section from the ridge in the vicinity of the S Pits to the saline sump at Lake Karpa, based upon topographical contours and ground waters from drillholes, modified from Smith (1987) and Report 120R.

The acid water had low soluble Au in comparison with the relatively high levels at Midway. This is consistent with Au mobilization at Midway being due to thiosulphate or other thio compounds, as such ligand complexes would be decomposed by acidification. Gold thus precipitated would not redissolve as $AuCl_2^-$, as oxidizing potentials for the acid water, though high, are not sufficient for the reoxidation of Au metal. This implies that ferrolysis, by generating acidic conditions, can act to precipitate Au occurring as thio- (or other) complexes. Such a scheme can explain the common presence of secondary Au in laterite.

Implications to exploration – Mt. Gibson waters
The area of Au mineralization investigated in this report includes many interesting features, which may be relevant to exploration strategies:

(i)   the mineralized area is upgradient to a saline sump system and brines have been refluxing underneath the area over long-time periods;

(ii)   soluble Au values were only above detection within the mine area;

(iii)   there appear to be two major soluble Au anomalies, one in N2 Pit and the other in the region of the Midway Pit, which roughly correlate to the two areas of economic Au in bedrock; and

(iv)   these two anomalies have distinct characteristics and may contain differing Au complexes, with $AuCl_2^-$ in the N2 anomaly and $Au(S_2O_3)_2^{3-}$ in the Midway anomaly.

The different forms of the soluble Au at the two anomalies may, at least, partially explain the difference in the supergene expression of Au at the two sites. Supergene mineralization at the N2 anomaly is restricted, consistent with a low mobility of $AuCl_2^-$ under all conditions except highly acid and oxidizing environments (Gray, 1989). If the Midway Au is in the form of $Au(S_2O_3)_2^{3-}$ or as Au complexed by any other ligand(s) such as HS^- of CN^-, then the Au may be more highly soluble and will form more extensive supergene deposits and associated depletion zones. Gold under these conditions will be strongly immobilized by acid or oxidizing conditions, such as those produced by ferrolysis-type reactions, as observed at MG35, down gradient from Midway.

The presence of the hydrogeochemical Au anomaly at Mt. Gibson suggests that water sampling could give information on the location of buried mineralization. Separate samples would be taken for Au analysis and for water quality measurements. The later sample could be sent for commercial analysis for TDS, pH, and a suite of elements of interest, such as Cr, Mn, Fe, Co, Ni, Cu, and Zn. Such a procedure could provide a low cost adjunct to petrological information, giving water data that could be interpreted in a manner analogous to that given above.

4.2.7   Reference geochemical data sets from the Mt. Gibson orientation study. R.E. Smith, J.E. Wildman, R.R. Anand and J.L. Perdrix. 31 March, 1992, Report 157R, 109p. data on floppy disks.

Abstract
Data sets from the Mt. Gibson geochemical orientation study have been organized into reference groups based upon the regolith stratigraphy for the area. The data sets (with the numbers of samples making up each set in brackets) consist of *soils* (17 or, with gravelly red earths included, 31), *colluvium* (58), *lateritic gravel* (55), *lateritic duricrust* (112), *mottled zone* (13), and *saprolite* (25). In addition, some data are presented for calcretes, iron segregations, mineralized veins, and lag. The total number of samples included in this report is 296.

The main information required to support the geochemical data is presented in concise and accessible form [Fig. 4.11]. This includes maps of the surface regolith relationships, bedrock geology, and sample sites for each sample set, together with a regolith-landform model and a schematic diagram of the regolith stratigraphy. Listings of chemical analyses for each sample, grouped according to sample type, are included, and summary statistics are presented. Box plots show the distribution of levels for each element, or oxide, for units of the regolith stratigraphy. Histograms for colluvium, lateritic gravel, and lateritic duricrust are presented for each element and oxide. Separate maps [Figs 4.12 and 4.13] showing the geochemical dispersion patterns for Au, Pb, As, and Bi in colluvium, lateritic gravel, and lateritic duricrust allow the sampling to be seen in terms of the shape of the geochemical dispersion anomaly. Scales used for maps in this report are common to a previous report (20R) which comprehensively discussed the regolith relationships at Mt. Gibson. Correlation webs highlight relationships between some elements for several of the sample media and a Si-Al-Fe triangular diagram shows the main characteristics of laterite samples.

The use of standardized formats for data presentation allow the characteristics of each data set to be appreciated, and comparisons to be made between the data sets. Furthermore, Mt. Gibson data, as they arise, can then be readily compared with data sets whether from other orientation studies, or from company exploration data. A floppy disk of the geochemical data together with sample type and location is included in standard format to enable users to have easy access and readily manipulate the data for their required purposes[*].

Data sets, such as those presented, which are controlled within a regolith-landform framework, are being generated from other orientation studies within the Laterite Geochemistry Project. Collectively, these reference data sets will form an essential part of a growing interpretational data system.

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[*] Also included on the disk is a demonstration data set with examples of dynamic, three-dimensional rotations, colour-coded and in animation.

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Correlation plot matrix

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Lateritic gravel　　LT100
Lateritic duricrust　　LT200

Available for reference at CSIRO or plot from floppy disk

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Floppy disk in pocket

Animated data interpretation demonstrations

Floppy disk in pocket

Figure 4.11. Index to the Mt. Gibson Data Sets Report, 157R. Icons show the ways in which the data sets are arranged for ease of reference.
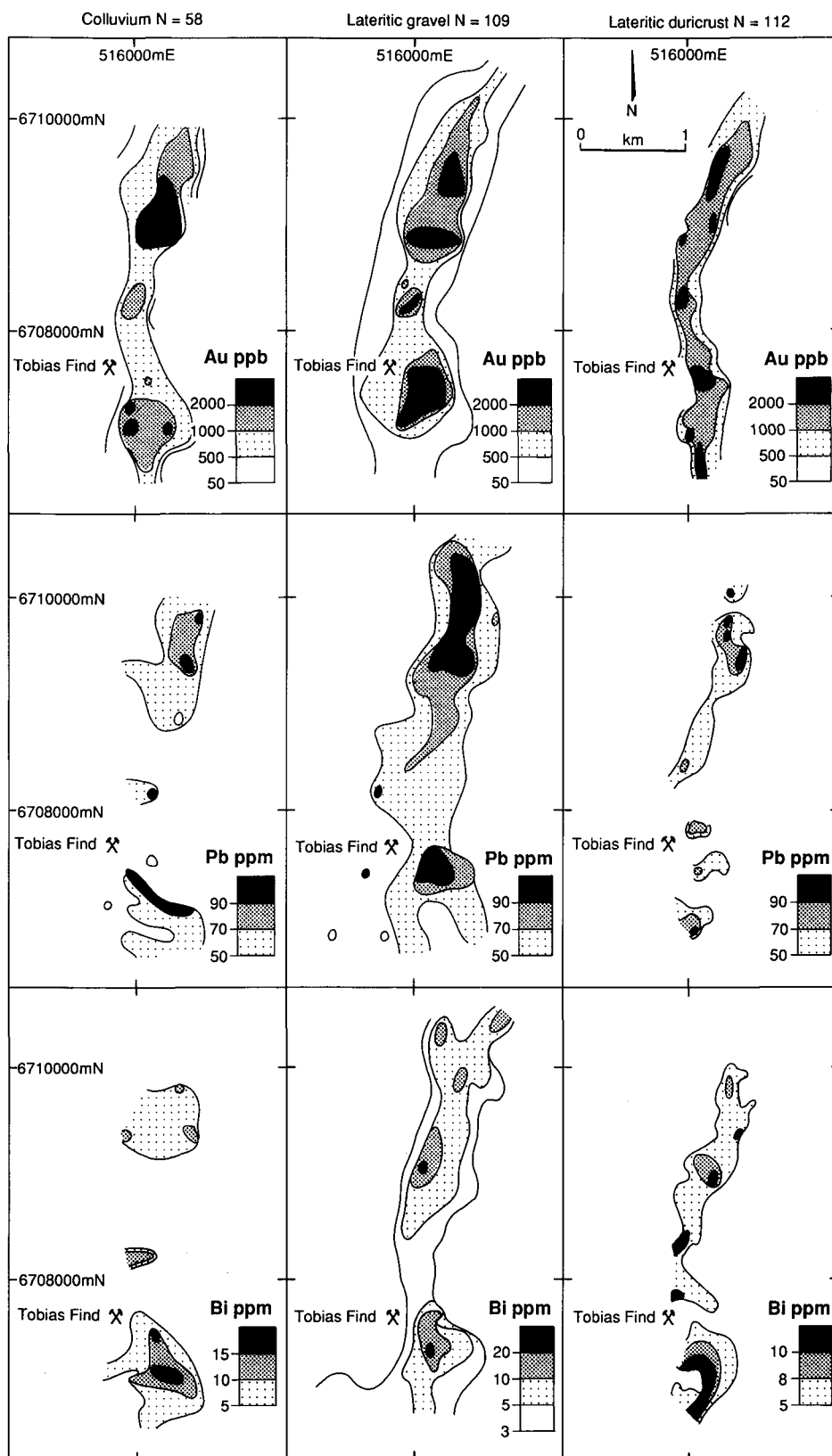
Figure 4.12. Maps showing the dispersion patterns for Au, Pb, and Bi for three sample media - colluvial lateritic gravel, gravelly lateritic residuum, and lateritic duricrust (narrowest dispersion), from Report 157R.
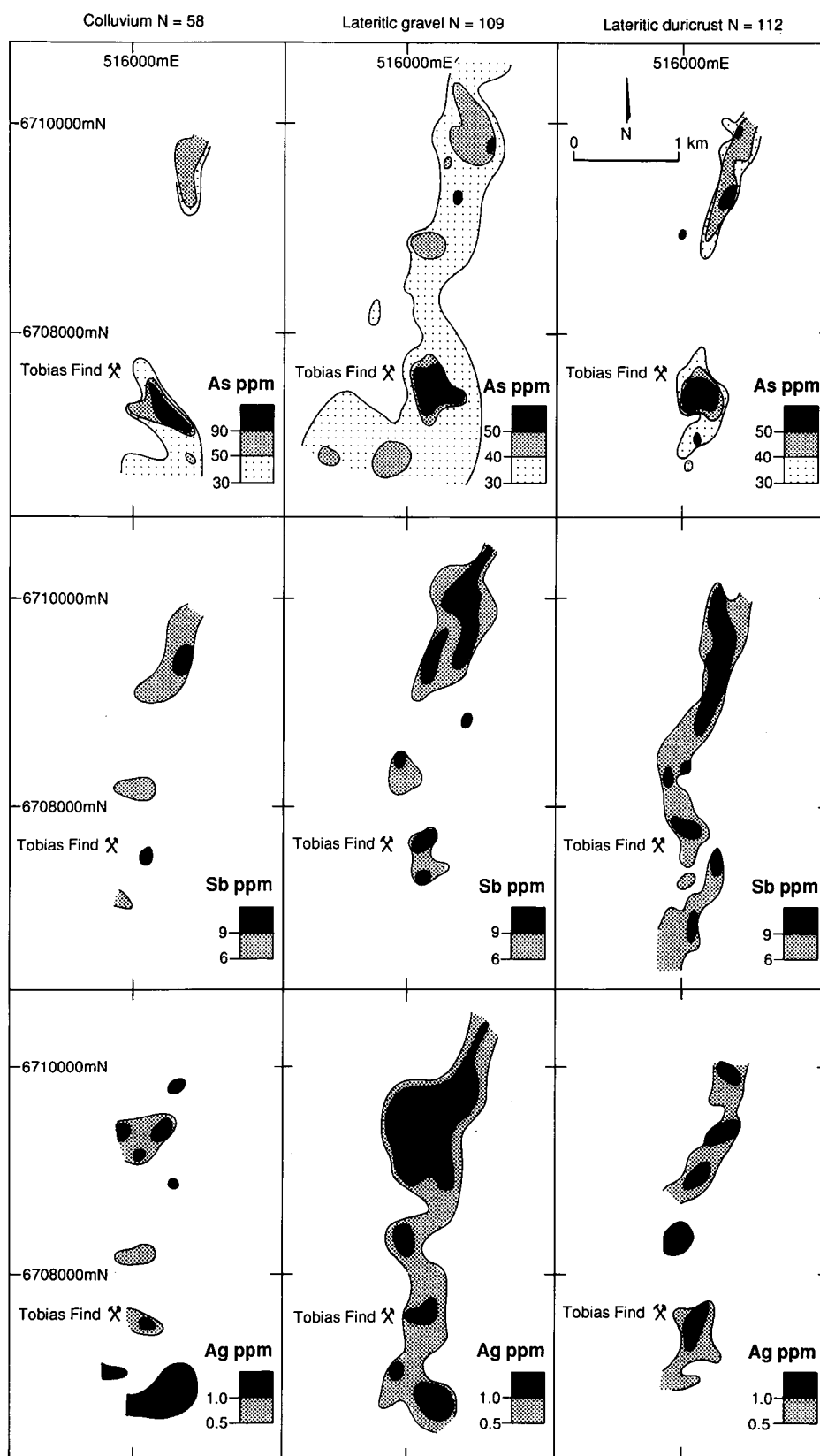
Figure 4.13. Maps showing the dispersion patterns for As, Sb, and Ag for three sample media - colluvial lateritic gravel, gravelly lateritic residuum, and lateritic duricrust (narrowest dispersion), from Report 157R.

4.2.8   Implications of the Mt. Gibson research in exploration

Some of the most important implications of the Mt. Gibson orientation research in exploration are listed in Table 4.2.

As summarized in the Table, the Mt. Gibson orientation study has shed light on a number of exploration issues. However, some important questions remain:

- Why is the Au anomaly in lateritic residuum so extensive and why is it so internally consistent? Why are the chalcophile and base metal anomalies relatively narrow in comparison with Au? This contrasts with the large, near-surface geochemical anomaly at Boddington where the reverse is seen.

- Can use of lower limits of detection (e.g. for Bi, Sb, In, Mo, Ag, Sn, Ge, Se) enlarge the width of the multi-element anomaly?

- By what methods is/was Au dispersed and concentrated in the Mt Gibson weathering environments? This would require further knowledge of the ground-water and regolith relationships.

- What would be the geochemical expression in laterite of a Au or base metal deposit completely immersed within the hypersaline ground-water environment? (At Midway North the geochemical anomaly in lateritic residuum was above the standing water table, Fig. 4.10.)

- To what extent can remote sensing methods (such as LANDSAT TM) be used in regolith mapping of this type of terrain? This topic forms part of the project extension, P240A. Pilot investigation shows considerable promise for the erosional and residual regimes. Will it be possible to delineate the distribution of carbonates at surface in the landscape using remote sensing?

- Can ground geophysical methods delineate the distribution of buried laterite in the alluvial sump areas?

- How effective will airborne electromagnetics (AEM) be in delineating the hypersaline ground water masses? This will be important in the use of AEM in the detection of sulphide deposits. Recent research shows succesful mapping of salinity using apparent conductivity from an AEM survey in the Yornaning Catchment of WA, carried out for environmental purposes (Street, 1992).

- How is Au dispersed in hardpan units? Does Mn staining contain more Au and base metals than the surrounding clay matrix?

Table 4.2.   The implications in exploration listed against the research findings, Mt. Gibson orientation study.

Research findings	Implications in exploration
■ Multi-element geochemical dispersion patterns have been established and are tied to the regolith stratigraphy and a regolith-landform model for the S, C and N Pits and Midway North areas. Details of geochemical dispersion were established for lateritic duricrusts, lateritic gravel and for gravelly colluvium derived from laterite. Includes Au and chalcophile elements. (Reports 20R, 157R, 165R)	- Sets expectations for geochemical dispersion for this style of ore deposit. - Allows prediction to similar terrain elsewhere.
■ Regolith-landform relationships have been explained in terms of the dynamics of dismantling laterite profiles. (Reports 20R, 165R)	- Provided key to understanding the complex lateritic sandplain of the region.
■ In detail, the multi-element dispersion anomaly is broader in pisolitic-nodular laterite than in the lateritic duricrust substrate. Anomalous element assemblages are similar in both media. (Report 157R)	- Pisolitic-nodular laterite should be used for reconnaissance exploration, lateritic duricrust for follow-up and for defining drilling targets. Data from both units are broadly compatible.
■ District-scale regolith-landform relationships were established. (Report 165R)	- Provides control for interpretation of LANDSAT TM for regolith mapping.
■ Complete laterite profiles can be buried - e.g. by alluvium, colluvium, brown clays.Reports 20R, 165R)	- Is advantageous to drill for buried laterite geochemical haloes beneath alluvium and colluvium.
■ Geochemical data sets were established for several sample media. (Report 157R)	- Provides well-controlled 'target' reference data sets for use in multivariate interpretational procedures.
■ Ground water regimes vary from hypersaline (ponded drainage sump) to relatively fresh (drainage divides and through-flow valleys). (Report 120R)	- Weathering environments vary systematically, with implications to mobility of Au and depletion zones. Salinity variation also has implications to the use of electromagnetics in exploration for concealed sulphide bodies.
■ Well-documented project material has been generated.	- Provides material for education and training of explorationists.
■ Exploration trials and synthesis led to the seeking of a project area with more complex buried laterite situations (viz. Lawlers district). (Report 166R)	- Increased ability to work with buried laterite profiles and the opportunity for buried geochemical haloes.

4.3   Bottle Creek

4.3.1   Introduction

The Bottle Creek Au deposits were discovered in 1983 by the Electrolytic Zinc Company of Australia Limited. It was one of several 'greenfield' discoveries in the Yilgarn Craton which resulted from the 1980s gold boom (1979 to 1988). Discovery of the Bottle Creek deposits resulted from strategic planning, geological concepts of ore genesis, and the use of multi-element geochemistry of lateritic pisoliths and nodules, collected from the ground surface, initially at 1-km spacing (Legge *et al.*, 1990).

Bottle Creek was chosen for an orientation study because of the importance of multi-element geochemistry in its discovery, because of the extent of prospective greenstone sequences which are largely concealed by laterite, alluvium, and colluvium, and to provide comparisons and contrasts with the project's other orientation areas. Except for some cleared grid lines and several small exploration costeans, crossing the strike of the mineralized zone, the area was essentially undisturbed.

The Bottle Creek area is also the focus of collaborative activity. Gossans and saprolite profiles have been studied by the Weathering Process Project (AMIRA P241) and unweathered bedrock from the ore environments has been examined (R A Binns, unpublished results).

The Bottle Creek gold deposits, held by Geopeko Limited, are located 210 km NW of Kalgoorlie on the MENZIES 1:250,000 sheet (SH 51-3). The Bottle Creek area has an arid climate with an average annual rainfall of 180 to 190 mm, much of which falls between January and April. Summers are hot to very hot; winters are cool and frosts are common. The vegetation is largely mulga (*Acacia aneura*), with various types of poverty bush and turpentine (*Eremophila spp*). On the major depositional surfaces, mulga communities are a scrub, while there are tall shrub communities on the steeper slopes and breakaways. Thickets of eucalypts mark erosional tracts, but there are scattered trees on sandy, gravelly soils of long gentle slopes.

4.3.2   Objectives

The overall objectives of the Bottle Creek study were to carry out a geochemical orientation study about the generally-concealed Au-ore deposits within a well-controlled regolith-landform framework.
To do this it was necessary to:

1.   Establish the regolith-landform framework of the upper Bottle Creek catchment.

2.   Establish the patterns and processes of multi-element dispersion in the lateritic, colluvial, and lag units of the upper regolith at the Emu, VB, and Boags deposits.

3.   Carry out regolith-landform mapping around the Bottle Creek Au deposits at district and regional scales.

4.   Reconcile the results of the company's exploration geochemistry with the regolith-landform setting and the processes of dispersion in the project extension, P240A).

4.3.3   Research components, Reports produced and underway

Research on the Bottle Creek district and its included mineral deposits has been carried out over several years. Some components are continuing within AMIRA Project P240A. The topics covered and the corresponding reports are:

* Regolith-landform relationships
  (detail to district scale) H M Churchward, R E Smith and I K Butler
  Report 247R (in press, November 1992).

* Gossans and wall rocks
  G F Taylor
  Report 36R July 1989, 35pp, AMIRA Project P241.

* Geochemical dispersion
  I D M Robertson
  Report in preparation for AMIRA Project P240A.
  Summary of progress, this report, Section 4.3.6

* Honours student thesis underway, R Wills, Curtin University, 1992, as part of project extension, P240A.

4.3.4   Regional and local geology

The Bottle Creek Au deposits are located in the NW tip of the Mt. Ida Greenstone Belt (Fig. 4.14), which is the most westerly greenstone sequence of the Kalgoorlie subprovince of the Western Australian Shield (Griffin, 1990). The Mt. Ida Greenstone Belt comprises a NNW striking, E dipping succession surrounded by variably-deformed adamellitic rocks. The western part of the belt is marked by a laterally extensive sequence of banded iron formations and interspersed coarse-grained mafic rocks. The remainder of the belt is dominated by high magnesian basalts that are intercalated with interflow sedimentary rocks (black shales and cherts). To the N, a prominent tholeitic unit in the centre of the belt changes along strike to an intensely-sheared and brecciated black shale with felsic porphyries to the south. This is informally referred to as the Emu complex, or Emu formation, and hosts the mineralization.

The Bottle Creek Au ore zones occur in the lower saprolite, and are the weathered expression of silicified, sulphidic, black shales in biotite-altered mafic volcanics, which are part of a high magnesian basalt sequence. In areas of greater mineralisation, the volcanics, and the ore zone itself, have been intruded by quartz-feldspar porphyry, which is now a quartz sericite schist. The mineralized zone has been affected by strong potash and carbonate metasomatism and silicification. The mineralized zones dip steeply and have undergone intense, ductile deformation followed by later, brittle deformation (Binns, 1988). There are two types of ore; one within the main mineralized zone and the other, a stockwork ore within the adjacent porphyries and altered volcanics. Micron size gold (electrum) and a species of silver-bearing tetrahedrite are intimately associated with pyrite in the unweathered mineralized zones. In addition, sphalerite, pyrrhotite, arsenical pyrite, arsenopyrite, and chalcopyrite have been recognized. A total of 908,273 tonnes of ore had been mined until November 1989, with an average grade of 2.25 g/t Au and 7.82 g/t Ag.

Legge *et al.*, (1990) considered the Emu formation, host to the Au mineralization, to be a volcanic-related auriferous exhalative horizon of sulphidic, graphitic shales, chert, and felsite which now contains massive pyrite and pyrrhotite. They concluded that Au concentration in bedrock took place during a period of strong deformation and intrusion by quartz-feldspar porphyry.

4.3.5   Regolith-landform Relationships in the Bottle Creek Orientation Study. H M Churchward and I K Butler and R E Smith. In press, November, 1992, Report 247R.

Abstract

Regolith-landform relationships

A framework of regolith stratigraphy and landforms was established for the district surrounding the Bottle Creek Au deposits, located some 200 km north west of Kalgoorlie, as a basis for geochemical dispersion studies. An early phase of broad reconnaissance provided several sites at which the regolith was examined in detail, and the landform-regolith relationships were defined. A regolith-landform map (scale 1:10,000) was developed for the upper Bottle Creek catchment [Figs 4.15, 4.16, and Table 4.3]. In order to test the general application of the detailed investigations, a reconnaissance study of the regolith was carried out in an area of approximately 450 km² surrounding the detailed study. A map of the regolith relationships at 1:25,000 scale was produced.

Several well-defined regolith types were identified as a result of these studies and they relate, directly or indirectly, to a deeply-weathered mantle and to its modification by weathering and landform processes. These regolith materials were either horizons of a deep profile developed by *in situ* weathering of basement rock or transported debris derived from it by erosion. Generally, they form extensive surface and subsurface bodies so that the regolith, at any particular location, commonly comprises several strata.

The nature of the regolith stratigraphy is strongly related to the landforms with which they are associated[Fig. 4.17], so that a framework of landform regimes provides a useful concept for considering the regolith in this area. Thus, regolith-landform units of relatively-stable, deeply-weathered tracts were recognized as relics of a once more extensive landsurface that has been fragmented by fluvial action and then replaced by erosional and depositional regimes.

At Bottle Creek, regolith types associated with the ancient, deeply weathered landsurface (the residual regimes) are mainly various expressions of the (upper) ferruginous horizon of the laterite profile, as well as the mottled zone, the pallid saprolite, and the saprock. Several transported types, of colluvial and alluvial origin, were recognised in both erosional and depositional regimes.
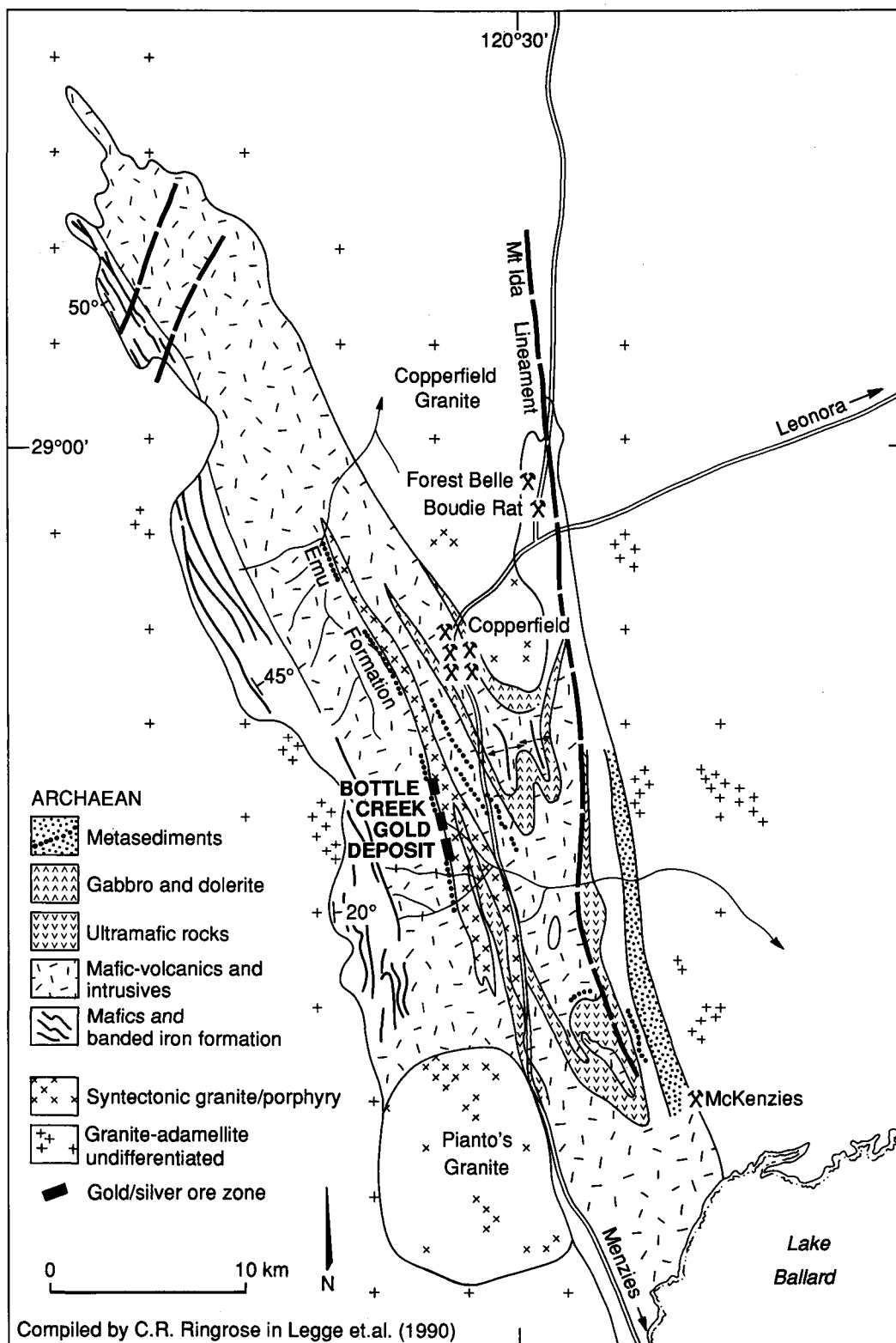
Fig. 4.14. Map showing the geological setting of the Bottle Creek orientation area.

Ferruginous horizon(s)

The ferruginous horizon comprises various types of lateritic residuum, but the more common are duricrusts having abundant pisoliths, usually with yellow-brown clay skins, set in a brown to red-brown clayey matrix. At depth, this material merges with the more ductile clays of the mottled zone. In addition, large irregular to lensoid bodies occur in the upper part of the regolith. The rock-like nature of these masses contrasts with the surrounding brittle, pisolitic lateritic residuum. Some of these masses are Fe-rich, having a dusky red matrix and dark brown to black nodules that can be magnetic. Such materials have been placed in the broad class of Fe-rich duricrusts. Another rock-like mass is diffusely mottled brown to pale brown, and can have vermiform voids. Depending upon the nature of these attributes, such materials can be classed as ferruginous saprolite, vermiform duricrust, or fragmentary duricrust. Other Fe-rich bodies in the upper regolith are goethite-rich pods which often have box-work textures. At Bottle Creek, these gossan-like bodies can occur in close proximity to a carbonaceous, previously pyritic shale member of the greenstone sequence.

Residual regimes

The residual regimes at Bottle Creek form gently-undulating tracts that are extensive on the divide between the Raeside and Ballard drainages. The location for the regolith stratigraphy of this regime is at the Emu test pit [Fig. 4.18] within this undulating tract. Most crests in this terrain are slightly stripped with consequent exposure of an array of ferruginous materials from the upper parts of the regolith. These are predominantly ferruginous saprolite, but there are also some pisoliths and pieces of Fe-rich duricrust, as well as clay and sand released by weathering. Such materials contribute to the colluvial mantles that extend downslope from the crest, covering the pisolitic lateritic residuum, the latter forming the more extensive substratum of this regime. On the mid- and upper slopes colluvium is less than 1m thick, whilst beneath lower slope sites and local drainage floors, it can be as much as 4 m. The lag also changes with topographic position; coarse fragments of ferruginous saprolite dominate the crests. Some yellow-brown cutan-coated pisoliths also occur here and this is generally indicative of some subcropping pisolitic lateritic residuum. On surfaces down-slope from these crests, lags of dark brown to black granules are dominant; there is little quartz or lithic material. The soils are acid and have developed in a fine sandy loam colluvium, which has granules of similar composition to the lag. Hardpans appear at a depth of 1 m and continue for 3 to 8 m.

Erosional regimes

The landforms and the regolith types in the erosional regimes [Fig. 4.19] present a more complex picture reflecting active geomorphic processes. Deeper units of this weathered mantle, as well as the country rock, are exposed. This regolith is dominated by shallow soil, often calcareous, and a lag of lithic fragments; there are some outcrops of vein quartz and goethitic Fe-segregations. Gentle slopes occur as pediments below low breakaways. These slopes are mantled by acid red earths, developed in a pedisediment, and have a lag dominated by coarse ferruginous saprolite, lithic fragments and quartz. Erosion is active in such areas.

Depositional regimes

The most extensive depositional regimes or tracts [Figs 4.17, 4.19, 4.20] are mantled by a friable clay, being an alluvium of sheet flood origin; acid red earths have developed on this material. The lags are dark brown to black granules of mixed origin, with medium-sized (20-40 mm) lithic and ferruginous saprolite fragments, and quartz clasts, as a minor, though characteristic component. This alluvium overlies pallid saprolite and saprock at a depth of 1 to 1.5 m, but it can also mantle pockets of pisolitic lateritic residuum, or coarse deposits of paleo-channels. Some of the depositional tracts are being further modified by erosion resulting in land surfaces having regolith types comparable with those in other erosional regimes.

Regolith evolution and a framework for geochemical dispersion

The topographic relationships and regolith stratigraphies revealed by this study indicate a polyphase, multi-process history [Fig. 4.21]. Many of the regolith types resulting from this complex array of processes have a distinctive pattern. The residual regimes at Bottle Creek are dominated by a regolith that is the result of intense *in situ* weathering, some of the uppermost regolith has been deposited by local colluviation. These areas have had a relatively-stable geomorphic history. In contrast, depositional regimes here represent areas that have received fluvial detritus from much further afield and this material varies from highly weathered to relatively fresh and is generally of diverse lithological origin. Prior to deposition, these areas can have been subjected to widespread, though incomplete, stripping of the more weathered regolith types. The regolith in erosional regimes is, in detail, complex with exposure of a variety of variably-weathered lithologies. Understanding this general geomorphic framework assists our appreciation of geochemical dispersion and thus it provides a basis for the developing sampling strategies for this weathered terrain.

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Land form regime	Mapping Unit	Abbreviated characteristics
Stable		
	1	Lateritic crests and slopes
	2	Local valley floors and lower slopes
Erosional		
	3	Pale saprolite outcrops
	4	Pediments with pedogenic carbonate
	5a	Low hills, red earths, calcareous earths
	5b	Low rises, calcareous earths, shallow acid earths
	6	Pediments with pedisediment, acid red earths
	7	Minor calcareous alluvial tracts
Depositional		
	8	Alluvial plains
	9a	Alluvium, minor tributaries
	9b	Alluvium, medium-sized tributaries

Fig. 4.15. A regolith-landform map of the upper Bottle Creek catchment, Report 247R.
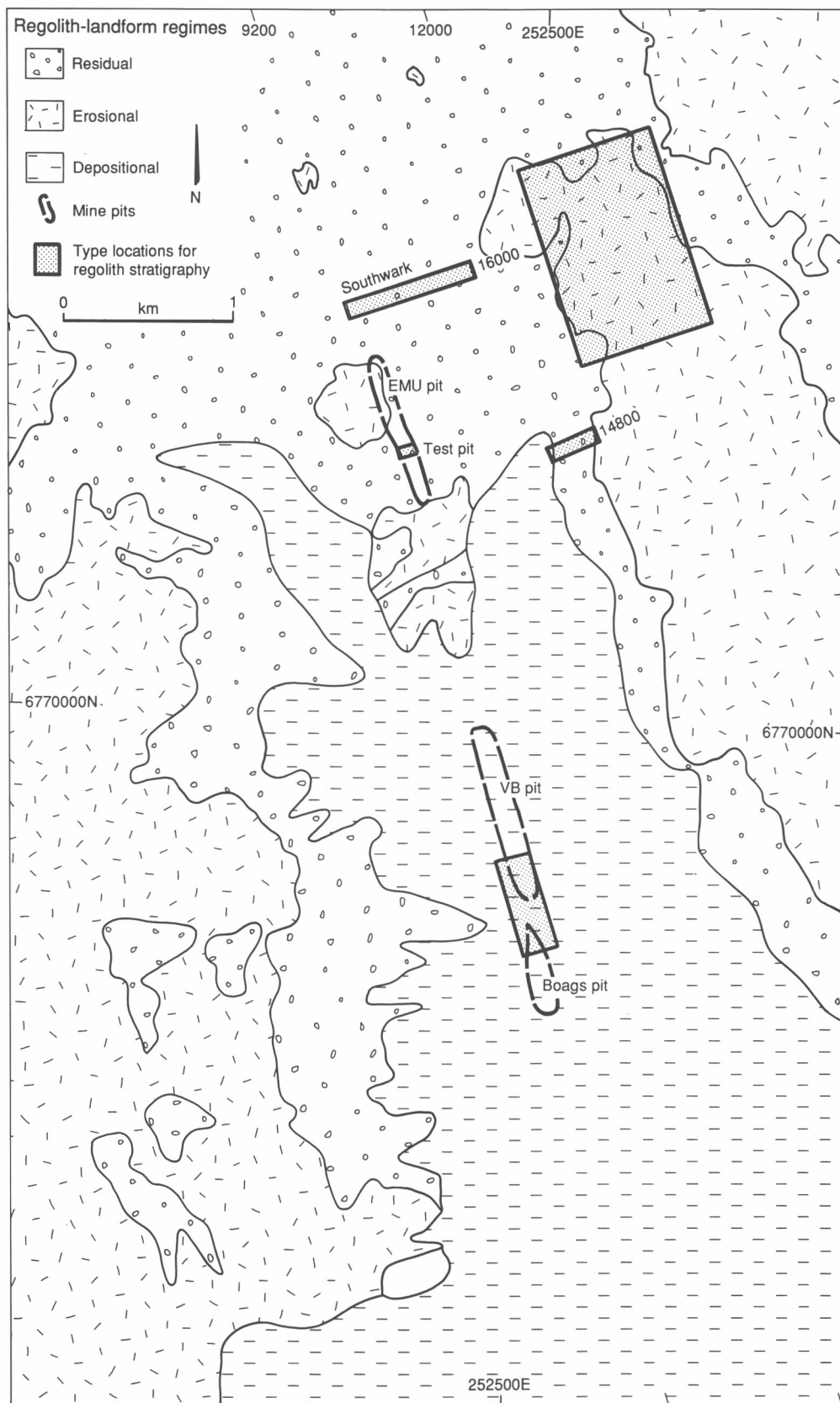
Fig. 4.16. Location of sites for the detailed regolith study in the upper Bottle Creek catchment. Active drainage tributaries have been removed in order to emphasize substrates, Report 247R.

Table 4.3. Regolith-landform mapping units for the upper Bottle Creek catchment.

Geomorphic Regime	Mapping Unit	Landforms	Regolith
Residual	1	Smoothly rounded crests and flanking upper and mid slopes.	Crests: *Lag:* mainly fragments of ferruginous saprolite; few Fe-rich duricrust (<50 mm); trace gossan. *Outcrop:* some blocks of above types; a few gossanous ironstones; some yellow-brown lateritic pisoliths and nodules. *Soil:* acid, shallow, stony, very friable, light brown, fine sandy loam. Gradual change to flanking slopes. Slopes: *Lag:* fine (<15 mm) dark brown and black ferruginous fragments; trace lateritic pisoliths and nodules. *Outcrop:* none. *Soil:* acid, gravelly, very friable, light brown to reddish brown, fine, sandy loam. Substrate of pisolitic-nodular, argillic, lateritic residuum.
	2	Long, very gentle, lower slopes and broadly concave floors.	*Lag:* fine (less than 10 mm dia) dark brown to black ferruginous fragments; trace pisoliths. *Soil:* acid, red, very friable, fine sandy clay loam to light clay.
Erosional	3	Steeply sloping, breakaway faces; some gently bevelled, crests.	*Lag:* coarse, iron-stained saprock with coarse quartz fragments. *Soil:* very thin, stony calcareous earths. *Saprolite:* extensive exposure.
	4	Steeply concave, pediments.	*Lag:* coarse fragments of saprock, Fe-segregation and vein quartz. *Outcrop:* widely scattered, of weathered rock; some quartz veins and calcrete pockets. *Soil:* grey-brown, calcareous earths common.
	5a	Low hills and shallow vales.	*Lag:* usually coarse and of variable composition. *Outcrop:* scattered saprock; some iron-stained saprock; quartz and calcrete. *Soil:* red earths and calcareous, grey-brown earths.
	5b	Low rises and gently concave slopes.	*Lag:* generally coarse; variable composition. *Outcrop:* few, saprock and ferruginous saprolite, quartz and calcrete. *Soil:* calcareous, grey-brown earths, and some red earths.
	6	Gently concave, pediments.	*Lag:* ferruginous saprolite. *Outcrop:* none. *Soil:* uniform cover of acid, red earths in clay loam colluvium.
	7	Narrow, alluvial tracts.	*Lag:* sparse. *Soil:* calcareous, grey-brown earths.
Depositional	8	Upper, tributary plains	*Lag:* ferruginous types, mainly saprolitic; some iron-stained saprock; mantled by co-alluvium. Quartz always present. Finer fractions dominant but some medium sizes always present. *Soil:* acid, red earths in friable, light clay.
	9a	Alluvial tract, 50 to 120 m wide.	*Lag:* none. *Soil:* brown, silty to sandy loam.
	9b	Alluvial tract, 120 to 350 m wide.	*Lag:* none. *Soil:* brown, silty to sandy loam.

Fig. 4.17. Regolith-landform model of the Bottle Creek orientation area.

4.3.6　*Geochemical dispersion*

The upper regolith was sampled to provide geochemical orientation to complement the original exploration data. Some 464 samples have been collected which include material from the surface (prior to disturbance) and from shallow costeans which crossed the main ore zones prior to mining. The geochemical dispersion reported here is based upon 340 of the total samples spread across three mineralized zones, and is discussed in terms of two sub-areas.

The northern area, which includes the Emu deposit, lies mostly within the main residual regime and is characterized by a largely-complete laterite profile, with thin, locally-derived lateritic colluvium in places. Dispersion patterns presented here for the Emu area are based upon 128 samples of lateritic lag and lateritic residuum. Their detailed characteristics have been logged separately, but they are presented together as a compatible family of sample media. The Emu deposit remains unexploited, with a test pit exposing the upper regolith in its southern end. The area is mantled by calcareous to acid red earths. A local alluvial tract contains calcareous sediments.

The southern area covers the Boags and VB ore deposits which have now been largely mined out. This area lies within the broad depositional regime of the upper Bottle Creek catchment. The area is characterized by erosional truncation of the weathering, generally to the base of the lateritic residuum, but isolated pockets remain. The area is mantled by ferruginous, gravelly, colluvial sheet wash, typically 1 m to 3 m thick cut by a network of present-day narrow, shallow, drainage channels. The orientation geochemistry is based upon 212 samples which consist of gravelly ferruginous lag and gravelly colluvium. They form a largely-compatible family of sample media which are derived from mottled zone and ferruginous saprolite. The geochemical dispersion patterns are mostly compatible with a local origin for at least some components of the gravelly colluvium (or colluvium/alluvium).

Bottle Creek regolith stratigraphy	Type location: Stable regime (mid to lower gentle slope)
	Emu Test Pit: 15050N 9400E Mine grid

Depth	Graphical column	Regolith unit	Description of regolith units, facies
Metres 0		Lag	Ferruginous clasts, some lateritic nodules, pisoliths. Yellow cutans are rare. (LG203, LG104)
1*		Soil	Acid red earth in colluvium. (SU100)
		Colluvium	Red-brown sandy loam with ferruginous clasts. (CV106HP)
2*		Lateritic residuum - hardpanized	Lateritic pisoliths/nodules set in a brown to red-brown clayey matrix with yellowish grey mottling. Pisoliths/nodules form up to 40% of residuum at top, decreasing to rare at 5m. Superimposed is a white, coarse (10 cm scale) reticulate tree root mottling. (LT203, LT203HP, LT241)
5		Mottled zone	Brown and yellowish brown subrounded to irregular mottles on a 10 cm scale set in a pale brown to yellow-grey clay-rich matrix. The pale material dominates.
10		Saprolite	Pale brown-grey clay-rich.
		Saprock	Pale brownish-grey, brittle with coarse rock fabrics visible
50		Bedrock (not exposed)	

1* 〜〜 Hardpanization:
*Laminar and curviplanar conspicuous due to cementation, dominantly by silica.
Mn staining (⌇) in soil and in colluvium.
Hardpanization also conspicuous in upper part of lateritic residuum.*

2* ◈ *Irregularly distributed competent masses up to several m across within lateritic residuum:*

- *Fe-rich pebbly duricrust. (LT228)*
- *Hard mottled (LT241) and vermiform (LT231) duricrust*
- *Gossans and gossanous pods comparable to LT229 and IS101*

Australian Map Grid Coordinates:

Fig. 4.18. Regolith stratigraphy for the stable regime at Emu test pit.

West   East

| Geomorphic regimes | Depositional Regimes | | | Residual Regimes | | Erosional Regimes | | | |

Landform/regolith mapping units: 8   9a   8   2   1   3   6   5a   7   5b

Legend:
- Fine lag
- Fine and medium lag; some quartz float
- Alluvium
- Colluvium - sandy loam
- Colluvium - clay loam
- Coarse irregular lag - ferruginous saprolite
- Silty sandy alluvium
- Coarse channel deposits
- Pisolitic lateritic residuum
- Duricrust blocks and coarse lag
- Fe-rich duricrust in pisolitic residuum associated with some gossan pockets
- Mottled zone
- Ferruginous saprolite
- Pallid zone and saprock
- Fresh rock
- Hardpan in regolith
- Calcrete

Horizontal scale: 0   200 m

Inset mapping units: 3   4   6   4   5a   5b   7   5b

Fig. 4.19. Conceptual east-west cross section for the Bottle Creek orientation area showing regolith and landforms.

Regolith Stratigraphy - depositional regime

VB west wall

BOAGS east wall

Section 1

Section 2

N

S

Ramp

Ramp

Bench

Lag: ferruginous saprolite pebbles (LG203) and minor ferruginous cobbles (LG206), ferruginous lithic fragments (LG231) and quartz grains, some quartz pebbles.

Colluvium: red clay with gravels (CV104) similar to lag.

Stone line: coarse lithic fragments in a sandy clay matrix.

Channel deposits: crudely stratified gravelly alluvium; ill-defined coarse laminae of ferruginous cobbles and granules, (AV305).

Lateritic residua: fine nodular, very gravelly mass in firm to friable yellow-brown matrix (LT204).
: fine and coarse nodules in yellow-brown clayey matrix; weakly indurated (LT203).

Mottled zone: clay, coarsely mottled yellow-brown, red and olive grey.

Soil: acid red earths.

Hardpan: hard brittle; rough fracture faces; coarse irregular laminae, and black manganese staining.

Fe-rich duricrust: very hard, dense; black to brown nodular and pisolitic, some magnetic; slabs, lenses and coarse pods; some gossan pockets

Pallid saprolite: pale brownish grey clay.

Saprock: pale grey brown brittle weathered rock.

Fresh rock

0   200 m

Horizontal scale

Fig. 4.20. Cross section showing regolith stratigraphy of the depositional regime at the Boags and VB Pits.
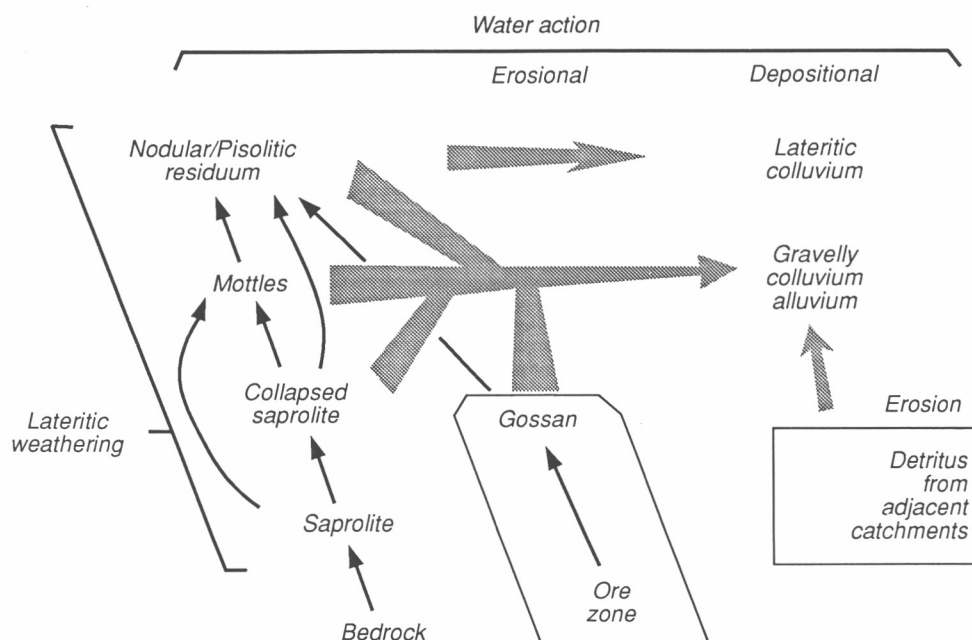
Fig. 4.21. Schematic facies relationship diagram for the formation of the lateritic weathering mantle at Bottle Creek and its subsequent dismantling.

The orientation geochemistry is being further studied as part of the project extension (P240A). Included in that extension, during 1992, is an Honours project on the regolith setting and geochemical dispersion (R. Wills, Curtin University).

Comparative lithology-related and pathfinder element geochemistry

To widen the distribution of samples and make the dispersion geochemistry easier to interpret, merging the colluvium and lag at Boags-VB and the laterite and lag at Emu was investigated. Comparison of the major element-abundances for these data sets showed that the merger of lag and colluvium at Boags-VB was questionable, as the colluvium was significantly different from the lag, but appeared to be quite valid for the merger of laterite with lag at Emu. This is illustrated by the ternary plots of Si-Al-Fe for the two areas (Fig. 4.22). The lag and laterite samples from Emu are intimately mixed on the plot and show a very clear trend at a relatively constant Al:Si ratio of 54:46. This ratio corresponds to that of kaolinite. The lag tends to be slightly enriched in Fe (with a median value of 53% Fe_2O_3) relative to the laterite (median 40% Fe_2O_3), although there is considerable overlap. It is suspected that the lag evolved from the laterite by pedogenic and/or surficial dissolution of kaolinite. A particular group of lag and laterite samples have an anomalously-high Al:Si ratio and all these are rich in gibbsite (established from X-ray diffraction). Those with a low Al:Si ratio are very quartz rich. The lag from the Boags-VB area shows a very similar trend to the Emu lag, with increasing Fe and loss of kaolinite. The colluvials, however, are more siliceous. Thus, the lag and the colluvials at Boags-VB are distinct on a major element basis.

The Ti/Zr ratios demonstrate the residual nature of the laterite and the lag at Emu, Fig. 4.23. Low ratios (13-35) tend to be concentrated over the felsic rocks, to the NE of the test pit, and high ratios (>50) occur to the NW, over mafic rocks. In contrast, the Ti/Zr ratios from the Boags-VB lag and colluvials do not show a consistent relationship to the underlying lithology, appearing to confirm that the regolith here is no longer residual. However, materials derived from the upper part of the pedolith (lateritic zone) have less reliable Ti/Zr ratios than those of the saprolite.

The distributions of the chalcophile elements (As, Pb, Sb, and Zn) are similar in the lag and in the laterite at Emu. Despite their major element differences, the chalcophile elements are not particularly different in their distributions among the lag and colluvium from Boags-VB either, thus they have been pooled at Boags-VB to enhance the coverage of ground for these chalcophile elements.
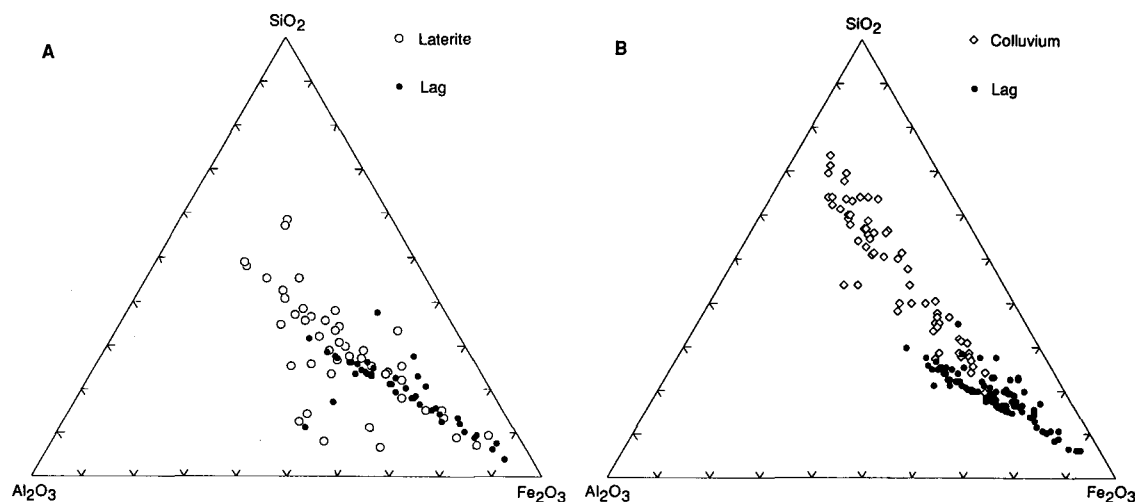
Fig. 4.22. A. Ternary Si-Al-Fe diagram showing a clear trend corresponding to loss of kaolinite, the lag is enriched in Fe relative to the laterite. Samples below the trend contain gibbsite. The two populations show considerable overlap. B. Ternary Si-Al-Fe diagram of lag and colluvials from the Boags-VB area. The lag tends to follow the kaolinite trend shown in A, but the colluvials are more siliceous. The two populations show only slight overlap.

Geochemical backgrounds

Generalized geochemical backgrounds for exploration in the Yilgarn Craton can be obtained from Tables 7.1 and 7.2 in Section 7.3. Using the 98th percentile for the laterite family of sample media in the AGE database, gives thresholds of 173 ppm for As, 9 ppm Sb, 93 ppm Pb, and 40 ppb Au. For gravelly colluvium and associated lag, thresholds of 242 ppm As, 13 ppm Sb, 82 ppm Pb and 23 ppb Au would be used. Locally-derived thresholds could be applied; however, the large width and strike extension of the dispersion anomaly at Bottle Creek cause this to be hazardous at this stage. Establishment of local backgrounds for Bottle Creek is being investigated during the project extension. Whilst the use of thresholds aims to outline anomalies, lower levels are commonly significant in delineating geochemical patterns.

Geochemical anomalies – Emu area

Arsenic, Sb, and Pb show distinct anomalies, some 300 m to 500 m in width lying within a strong As-Sb pattern 1.5 km wide (Fig. 4.24A), aligned along the mineralized trend; the strongest anomalies lie 150-300 m N and S of the test pit. Gold anomalies are similar, Fig. 4.24A, but an additional anomaly lies 600 m further N. The Au and Ag data are spiky. Bismuth, Cu, and Se show randomly-located, rather spiky, anomalies in the general region of the mineralization, but do not define it well. These may be combined with the As and Sb data, using either a CHI-6*X or some of the other empirically-designed indices (Section 8.3), to show the general area of mineralization. By far the best pathfinders are As, Sb, Pb, and Zn and these are better than Au.

Geochemical anomalies – Boags-VB area

Very clear anomalies overlay the Boags and VB deposits (Fig. 4.24B). These anomalies are some 250-300 m in width and are defined by the combined lag and colluvium samples. The geochemical association is As (peak of 3000 ppm against a background of 100 ppm), Sb (500 ppm against a background of 20 ppm), Au (2000 ppb against a background of 20 ppb), Pb (300 ppm against a background of 30 ppm) and, to a lesser extent, Se (14 ppm against a background of 2 ppm), Ag (0.9 ppm against a background of 0.2 ppm) and Zn (150 ppm against a background of 50 ppm). Also present were very weak and inconsistent anomalies in Cu and Bi, which may be combined with the other elements in empirical indices such as CHI-6*X.

In some of the early, shallow exploration trenches, which crossed the mineralized zone at Boags and VB, clear evidence was seen for incorporation of clasts, derived from the upper units of the lateritic weathering profile into the colluvial cover. The geochemical dispersion anomalies at Boags-VB, at least in part, would have formed by mechanical incorporation of such clasts (including gossan clasts) into the thin colluvial cover. It is also possible that some of the chalcophile elements may have been mobile through hydromorphic processes during the post-depositional weathering period.
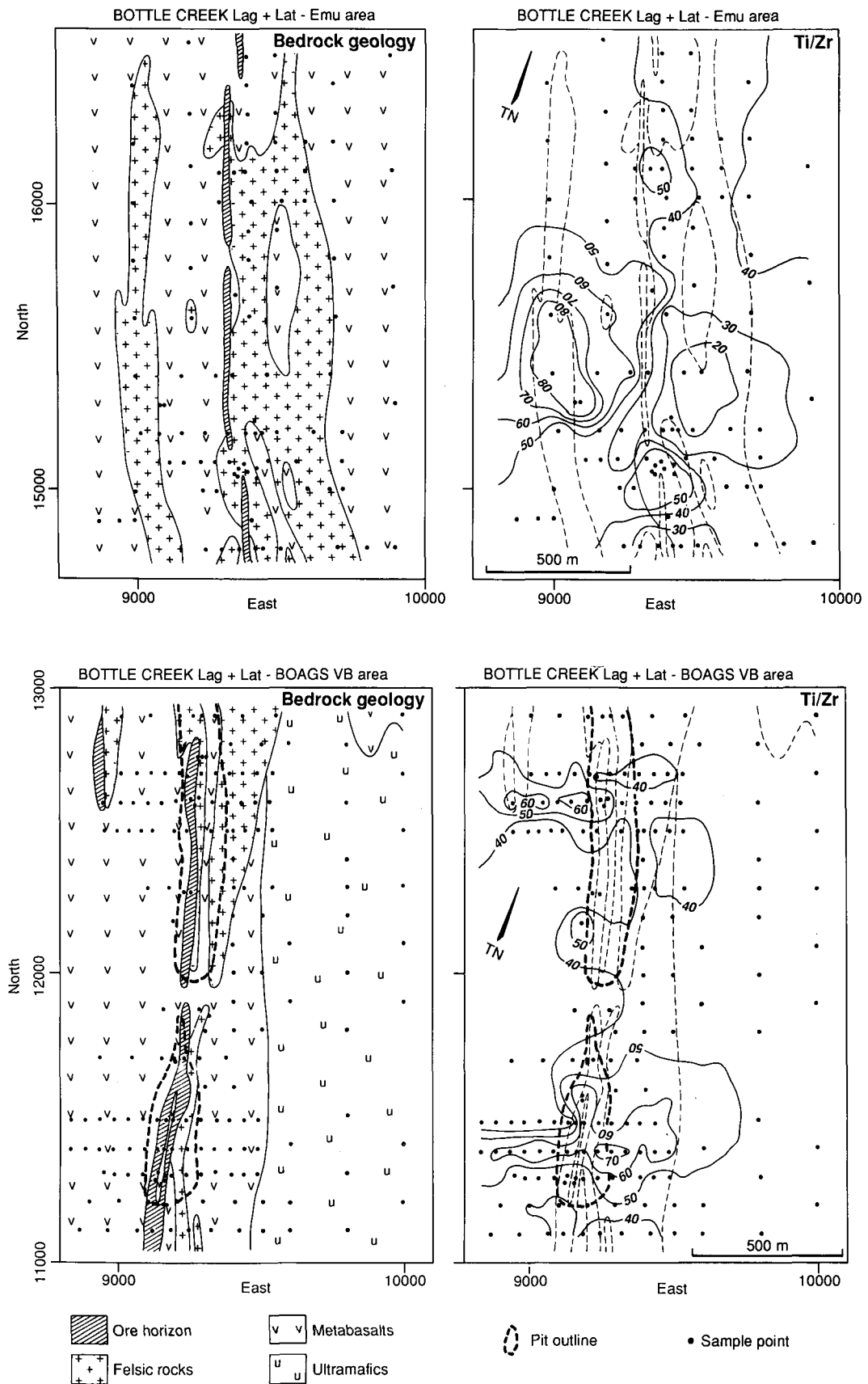
Fig. 4.23. Bedrock geology and Ti/Zr ratios in surficial material in the Emu and Boags-VB areas.
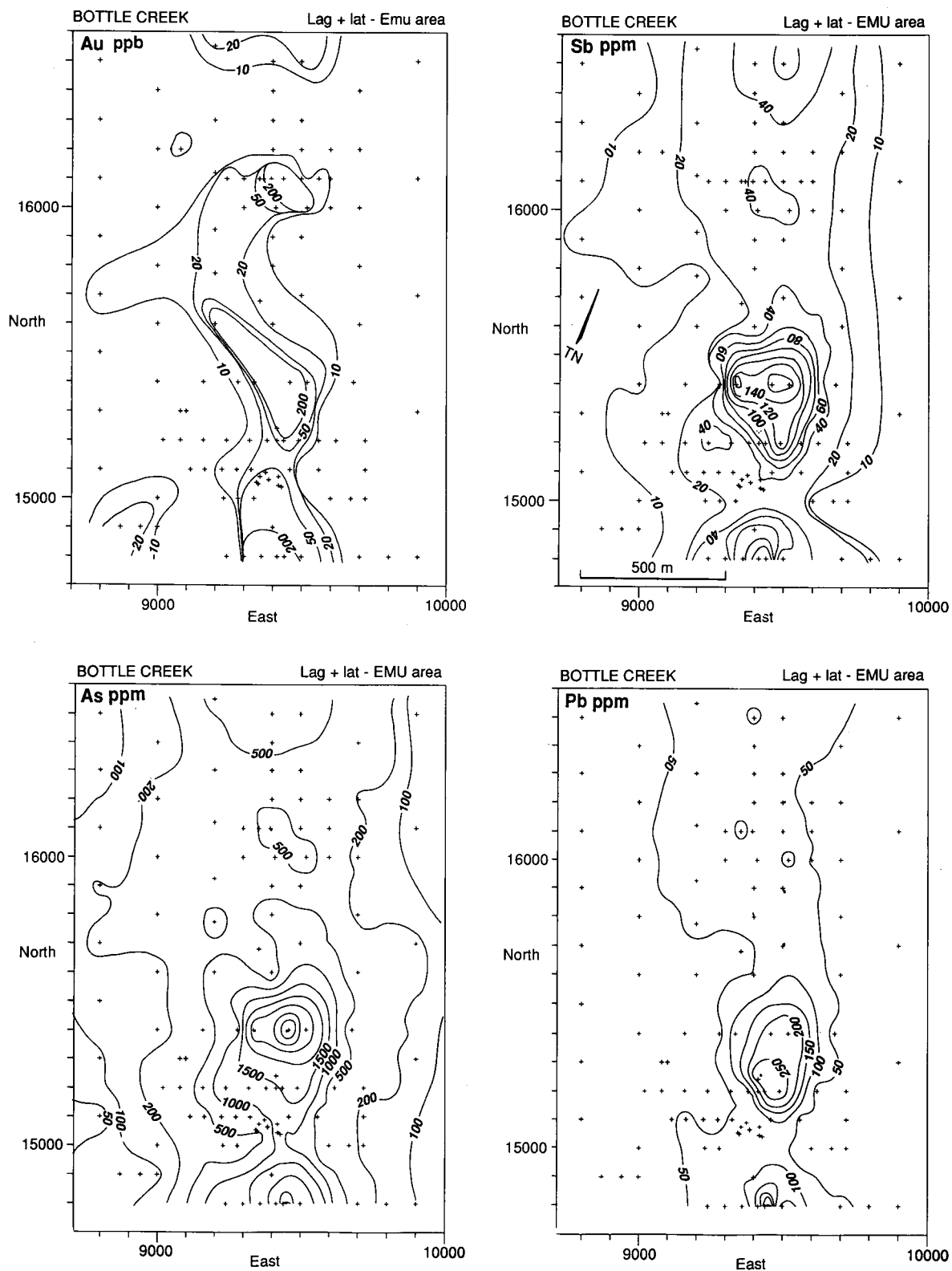
Fig. 4.24A. Map showing the distributions of Au, Sb, As, and Pb in lateritic lag at the Emu area.
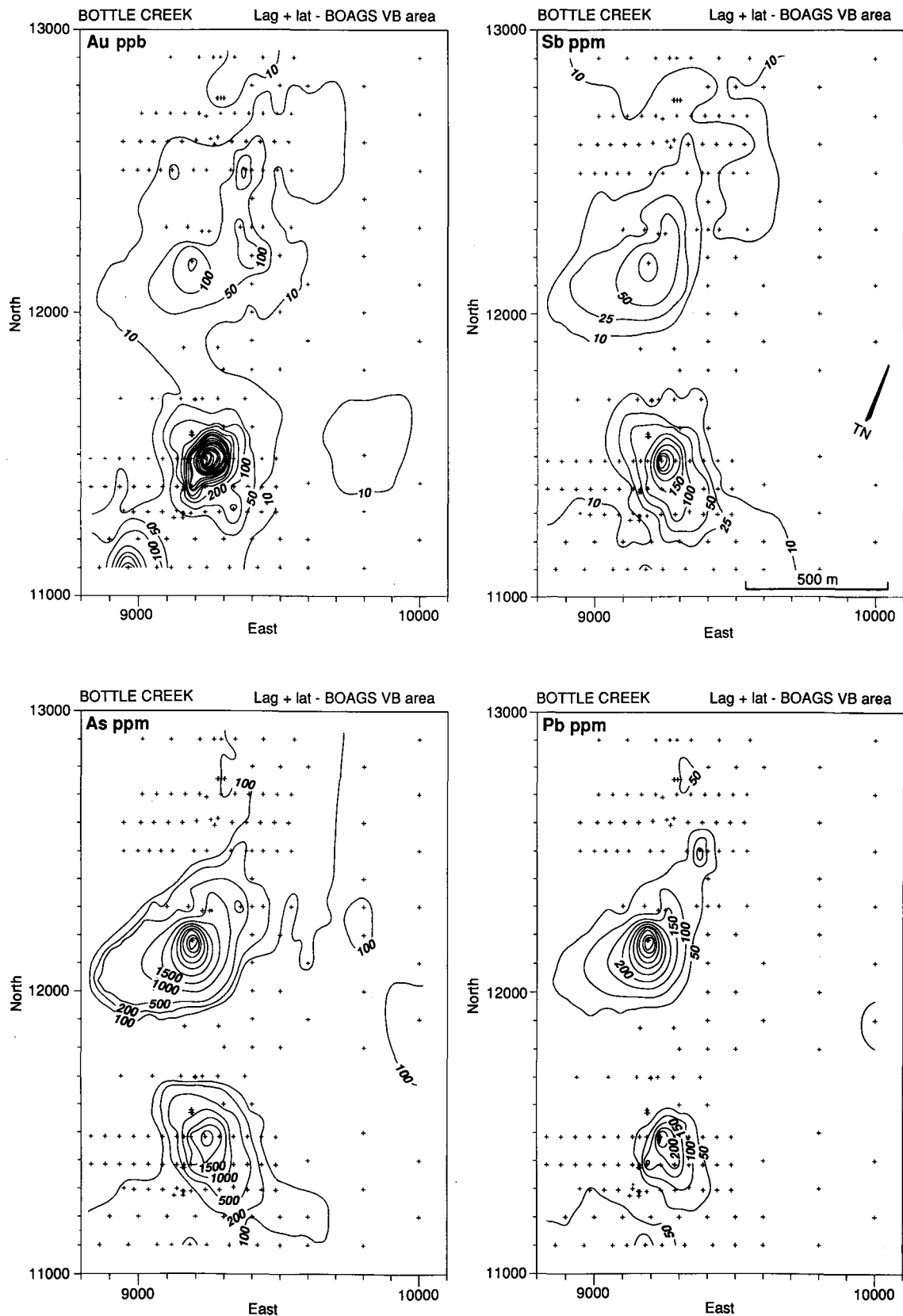
Fig. 4.24B. Map showing the distribution of Au, Sb, As, and Pb in lag and colluvium at the Boags-VB area.

Bottle Creek
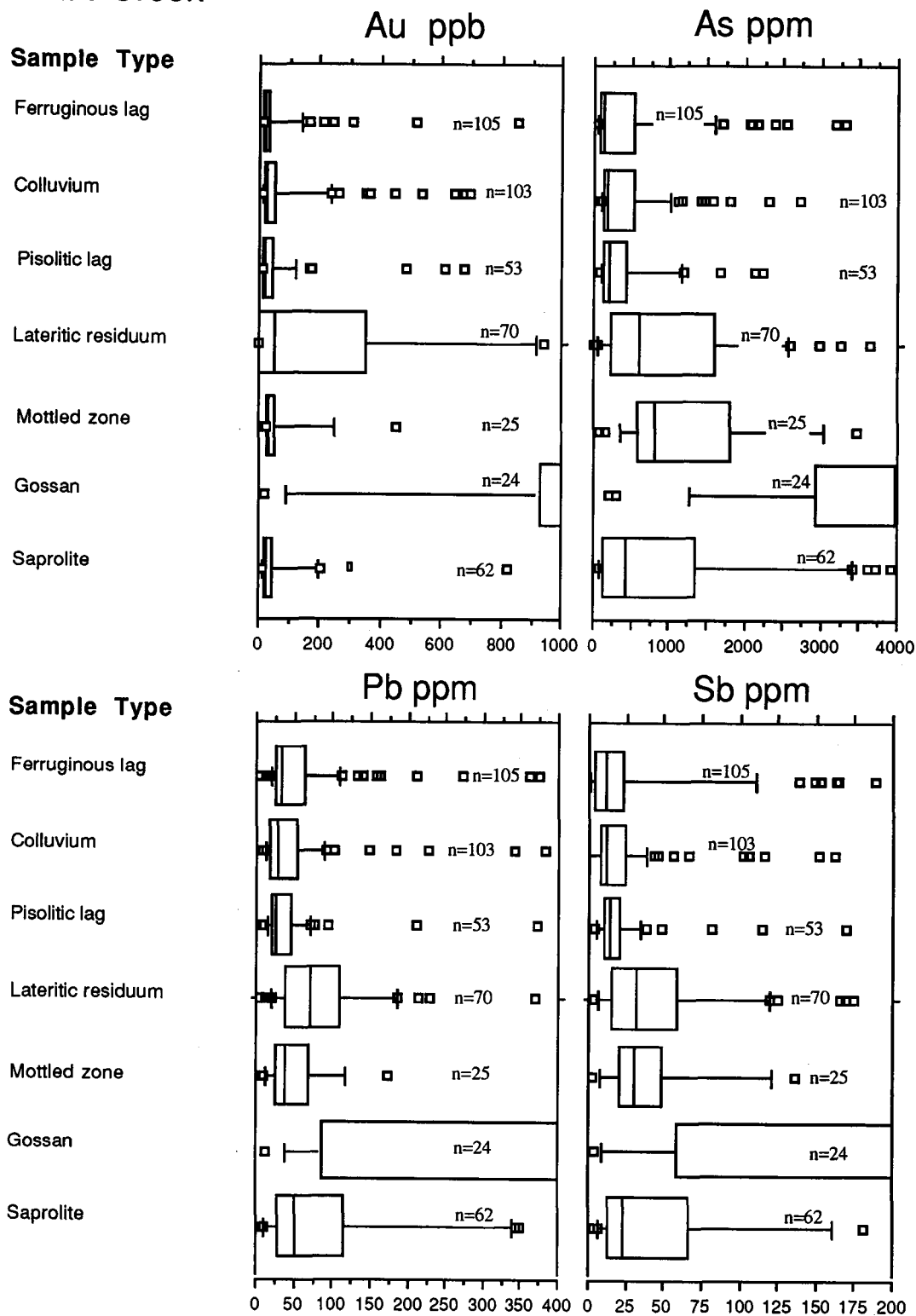
Fig. 4.25. Box plots showing the distribution of Au, As, Pb, and Sb in regolith types from
Bottle Creek arranged vertically in order of regolith stratigraphy.

The gap in the geochemical anomalies between 11700 and 11900 m N corresponds closely with an E-flowing alluvial tract, where background abundances only have been recorded.

Conclusions from the initial findings on Bottle Creek geochemistry

Sampling lateritic residuum and lag, locally derived from it, defines a large, strong anomaly with an association of As, Sb, and Pb with supporting Au (Fig. 4.25). In the broad depositional regime, sampling gravelly colluvium or the associated ferruginous lag also defines substantial geochemical anomalies with a similar element association, which coincide with the mineralized horizon and peak over the known Au deposits. The geochemical anomaly in colluvium appears to have been formed, at least in part, by mechanical incorporation of clasts from the upper parts of the lateritic profile. This profile has been truncated to the base of lateritic residuum, the mottled zone, and zone of ferruginous saprolite. The regolith-landform situations are summarized in the dispersion models of Section 9.3.

4.3.7   Implications in exploration

The geochemical dispersion study at Bottle Creek has clarified the processes of dispersion and anomaly characteristics. By establishing regolith-landform control, the study shows why geochemical exploration worked so well, both in the areas of lateritic residuum and in the depositional area of gravelly colluvium. The study also shows why, in detail, the geochemical expression in surface gravelly lag is discontinuous. The main implications in exploration of the Bottle Creek research are listed in Table 4.4.

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Table 4.4.   The implications in exploration listed against the research findings for the Bottle Creek orientation study.

Research findings	Implications in exploration
■ Multi-element geochemical associations and dispersion patterns have been established, based on the Emu, VB and Boags locations. Section (4.3.6)	- Sets expectations for geochemical dispersion for sulphidic shale mineralization. Allows extrapolation to similar terrain elsewhere.
■ Regolith-landform relationships are explained by polyphase dismantling of laterite profiles and consequent burial. (Report 247R)	- Provides a useful training area for regolith-landform mapping and regolith stratigraphy.
■ Confirming the exploration data, a large chalcophile anomaly is present at surface in lateritic residuum or the lag derived from it. The anomaly for As and Sb reaches 2 km in width and extends over 5 km of strike length. (Section 4.3.6)	- The exploration and research data show that 1-km spaced surface samples were effective in locating the concealed Au deposits.
■ An As-Sb-Au anomaly is also present at surface in the broad depositional regime (gravelly colluvium). The anomaly is narrower where colluvium overlies mottled zone than where it overlies lateritic residuum. (Section 4.3.6)	- Anomaly expectations need to be based upon regolith-landform control. - Shows importance of regolith-landform in interpreting anomaly characteristics.
■ Locally shallow, present-day and palaeochannel gravels and sands interrupt continuity of the geochemical dispersion anomaly in the colluvial unit and lag derived from it. Section 4.3.5, Fig. 4.20, and Report 247R)	- Careful mapping of present-day channels and palaeochannels will assist interpretation.
■ Complete and partly truncated profiles can be buried by colluvium.	- Exploration can be directed at buried geochemical haloes in laterite. However, where cover is shallow, mechanical mixing within colluvium allows surface sampling to be effective.
■ Geochemical data sets were established for several sample media.	- Provides well-controlled 'target' reference data sets for use in multivariate interpretational procedures.
■ District-scale regolith-landform relationships were established.	- Provides control for interpretation of satellite imagery (e.g. LANDSAT TM) for regolith mapping.
■ Well-documented project material has been generated.	- Provides material for education and training of explorationists.

4.4   Lawlers District

4.4.1   Introduction

The Lawlers district, an area of some 500 km^2, contains truncated laterite profiles on uplands and lateritic residuum buried under thick, transported sequences, marked by extensive plains.

The sparse vegetation, due to the arid climate, allows us to see and interpret processes of regolith and landscape evolution not visible in thickly-vegetated, high-rainfall regions. The Lawlers district is an example of some important exploration problems in the Yilgarn Craton and particularly in the Norseman-Wiluna Belt.

Geochemex Australia commenced a regolith geochemical exploration programme over the Lawlers district for Forsayth N.L. in 1987. An early phase of that work was a district-scale surface and near-surface laterite sampling programme. Regolith-landform control was regarded as essential to guide the programme and for interpretation of the results, so Geochemex Australia carried out regolith-landform mapping with the geochemical sampling, from August 1988 until February 1989. Mapping of the regolith was at 1:25,000 scale, using colour air photography (Butler *et al.*, 1989).

The CSIRO research at Lawlers, which commenced in November 1988, provided an improved understanding of the regolith and this, with the Geochemex studies, became an integral part of the exploration. The CSIRO work included regolith mapping, regolith stratigraphy, characterization of regolith units, regolith evolution, and mechanisms of geochemical dispersion in type areas. This provided the basis for regolith-landform and geochemical dispersion models of the Lawlers district.

A satisfying result of the collaboration at Lawlers was the discovery of the Turrett and Waroonga Au deposits as a direct result of the experimental exploration programme. Both were discovered by drilling and recognizing buried geochemical haloes in laterite. The halo of the Waroonga deposit was beneath 7 m of hardpanized transported sediments. Open pit mining commenced at these deposits in the latter half of 1990 and has provided exposure of both the cover sequences and the buried laterite profiles. These locations have been included in sponsors' field trips.

The Lawlers district lies some 300 km N of Kalgoorlie (see Fig. 1.2). It has a hot, arid climate with an erratic median annual rainfall of approximately 200 mm. Rain may fall in both summer and winter, mostly in late summer, from cyclonic rain-bearing depressions. The mean daily maximum January temperature is 36°C, 18°C for July and frosts are common in winter. The area is characterized by sparse, low acacia woodlands with dominant mulga (*Acacia aneura*). The shrub layer is dominated by poverty bush and turpentine (various *Eremophila sp*) and rattle bush (various *Cassia sp*). More shrubby individuals of the same species dominate the hills and are noted in a shallow, stony soil.

4.4.2   Objectives

The objectives of the Lawlers study were to provide a regolith-landform framework for the district and, within this, to carry out multi-element, orientation, geochemical dispersion studies about concealed Au deposits.

Specific objectives were:

1.   To extend the regolith-landform study by Geochemex Australia.

2.   To establish the regolith-landform relationships in the Agnew-McCaffery, Brilliant, and Meatoa areas which are examples of important variations within the district.

3.   To find methods to reliably identify laterite types and thus regolith stratigraphy from drill spoil.

4.   To carry out a concise orientation study at the concealed North and Turrett Pit Au deposits.

5.   To characterize and establish the origin of various massive ironstones, ferruginous pods, and iron segregations, which occur widely in the ferruginous saprolite, and contribute to coarse lag on the partly-truncated landforms.

6.   To determine whether Fe-segregations are suitable for geochemical exploration in partly-truncated areas.

7.   To establish the relationships of lag and regolith types (in the Meatoa area).

8.   To carry out pilot investigations into the siting and bonding of Au and chalcophile elements in samples from the laterite geochemical anomalies at the Turrett and North Pit deposits.

4.4.3   Research components and reports
Research at Lawlers has been directed at the following:

• Establishing the regolith-landform framework	Report 166R
• Characterizing relevant regolith materials	Report 166R
• Discrimination between sample types	Report 166R
• Generating models of regolith evolution	Report 166R
• Carrying out geochemical dispersion studies	Sections 4.4.5, 4.4.6
• Generating geochemical data sets for several sample media	Report 166R
• The siting and bonding of elements	Report 166R

The WA Remote Sensing group at CSIRO (AMIRA Project P243) began collaboration in June 1989 in order to take advantage of the well-controlled regolith relationships established by the Laterite Geochemistry Group. The sparseness of the vegetation was recognized as an important factor which would facilitate regolith recognition and delineation. This collaboration has focussed on developing methods for regolith mapping using remote sensing.

Another phase of current research at Lawlers, as an adjunct to this AMIRA study, concerns the application of geophysics, particularly ground geophysical methods, for defining and delineating regolith stratigraphy. This research is being carried out through collaboration with the Department of Geophysics at Curtin University. Investigation of airborne radiometric surveys of the Lawlers district is also underway.

4.4.4   Regional and local geology
The Lawlers district lies within the Agnew supracrustal belt of the Archaean Yilgarn Craton. The Lawlers greenstone sequence is up to 3 km thick and consists of interlayered high-Mg basalt, ultramafic rocks, gabbro and differentiated gabbro-pyroxenite-peridotite sills, thin, fine-grained sedimentary and silicic, volcanogenic layers (Platt *et al.*, 1978). Some ultramafic units show spinifex textures. The gabbroic sills are up to 300 m thick; they are concordant to the stratigraphy and are laterally very extensive. Volcanic and sedimentary units are interlayered with sills throughout the sequence which is also intruded by tonalite. The most prominent structural feature in the area, a major north plunging upright fold, is the Lawlers Anticline (Fig. 4.26). A later leucogranite has been mapped in the area cutting both the tonalite and greenstones.

The Lawlers greenstone sequence is overlain on the west side of the Lawlers Anticline by the Scotty Creek sedimentary sequence (Fig. 4.26). This is about 1500 m thick and consists of a basal conglomerate derived from mafic and ultramafic units within the Lawlers greenstone sequence (Platt *et al.*, 1978). The Scotty Creek sequence faces westwards and grades into quartz-felspathic sandstones with tonalitic clasts and sporadic chert and shale horizons. North and E of Lawlers, the Lawlers greenstone sequence is also overlain by the Vivien sedimentary Sequence of sandstone, siltstone, shales, conglomerates, and cherts. Cudahy (Personal Communication) considers the Vivien clastic sequence to be stratigraphically equivalent to the Scotty Creek Sequence. Partington (1986) and Eisenlohr (1989) have argued that the Scotty Creek Sequence has an angular unconformable relationship with the Lawlers greenstone succession. West of the Scotty Creek Sequence lies the Waroonga Gneiss. The contact lies within a major ductile shear zone (Waroonga Shear zone); the original relationship of the gneiss to the supracrustal sequence is not clear.

Gold deposits in the Lawlers district fall into the following broad categories.

(i)   Disseminated Au within alteration haloes ± quartz vein systems in shear zones (e.g. Great Eastern, McCaffery, Weight Hill, North Pit, and Turrett).

(ii)   Laminated Au-bearing quartz veins in fractures or shear zones (e.g. Donegal, Bellevue).

(iii)   Altered and sulphidic shoots with little or no quartz in major shear zones (e.g. Emu, Redeemer).

(iv)   Quartz stockworks and ladder veins in metasediments (e.g. Genesis).

Gold from any of the primary categories has been redistributed and concentrated by secondary weathering into the saprolite and, in places, to the overlying lateritic residuum. This secondary Au mineralization forms a new category. It is important as it forms low to medium tonnages of low-grade Au resources which are easily mined and processed, examples are the laterite ore at North Pit, Turrett, and Waroonga.
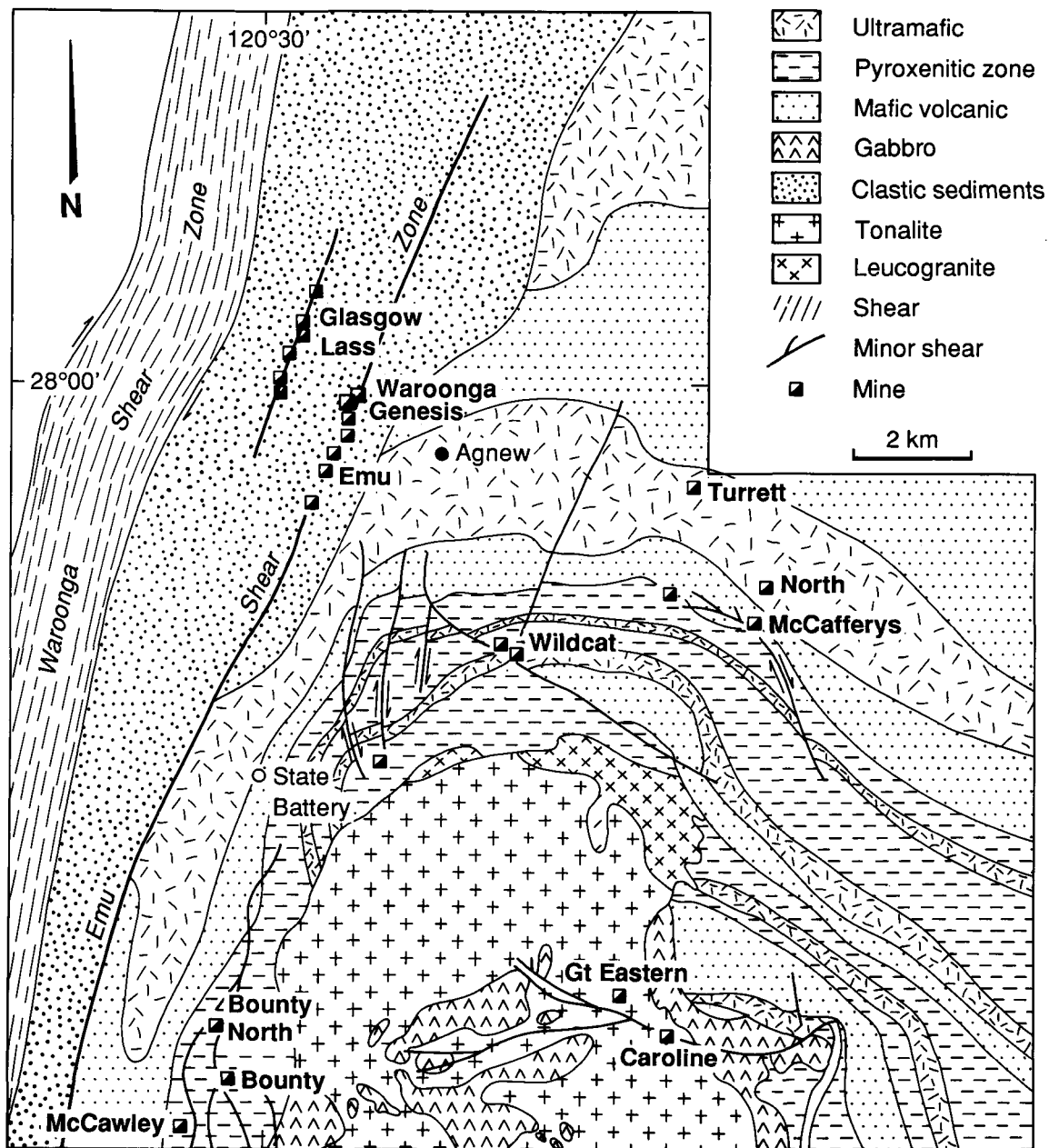
Fig. 4.26. Detailed geology in the vicinity of Agnew and Lawlers, modified after Aoukar and Whelan (1990) and Eisenlohr (1987), Report 166R.

4.4.5   *Regolith-landform development and consequences on the characterization of regolith units, Lawlers district. R.R. Anand, H.M. Churchward, R.E. Smith and E.C. Grunsky. August, 1991, Report 166R, 160p, data on floppy disk.*

Abstract

Regolith-landform relationships
The regolith patterns observed in the Lawlers district are explained [Fig. 4.27] in terms of the distribution of (a) regimes of erosion of the laterite profile to the level of saprolite/saprock/bedrock resulting in terrain characterized by low hills, (b) regimes where the essentially-complete laterite profile is preserved, commonly forming small ridge crests and backslopes, and (c) regimes characterized by depositional accumulations of detritus derived by erosion of the laterite profile, burying the partly-truncated, and in places complete, laterite profile in the lower slopes of colluvial/alluvial outwash plains. The sediments reach up to 30 m in thickness in the depositional areas. Buried residual laterite profiles are widespread beneath the colluvium and alluvium.

The three type areas (Agnew-McCaffery [Figs 4.28 to 4.30], Meatoa [Fig. 4.31], and Brilliant) provide an understanding of regolith relationships, stratigraphy and the origins of its units. Criteria have been established for distinguishing residual regolith from transported regolith [Fig. 4.32, Table 4.5] using drill hole logging. The regolith-landform model, for the Lawlers district, presents relationships in terms of erosion and burial of complete and partly-truncated lateritic profiles [Figs 4.33 and 4.34, Table 4.6].

Soils
The soils on truncated regimes, overlying mafic or ultramafic rocks are predominantly red light clays and red, sandy clay, loams. They are generally acidic and are underlain by a red-brown hardpan. Most red clays contain pseudomorphic grains of goethite and kaolinite after amphiboles, further evidence of their mafic origin. Occurrence of pedogenic calcrete, at shallow depths, in the erosional regimes, generally indicates a mafic lithology. Soils on felsic lithologies are acidic, yellowish-brown, sandy loams. Residual regimes are mantled by acidic, brown, gravelly, sandy loams and sandy, clay loams; red-brown hardpan is generally not developed. The soils, within the depositional regimes, are developed in colluvium or alluvium and are acidic, gravelly sandy clay loams and light clays.

Lags
The distribution and characteristics of lag gravels have been compared with the regolith-landform framework. Black, ferruginous cobbles of iron segregations, fragments of ferruginous saprolite and vein quartz occur largely on erosional areas (Units 2a, 2b). Lag of lateritic pisoliths and nodules occurs on residual areas which have been planed down to below the base of the laterite (Units 1a, 1b) overlying complete or nearly-complete laterite profiles. A lag of mixed origin, comprising lithic fragments, quartz, lateritic pisoliths, nodules and fragments of ferruginous saprolite is abundant on colluvial/alluvial outwash plains.

Lateritic residuum
The top of the residual laterite profile is composed of a layer of lateritic residuum averaging some 3 to 8 m in thickness. It consists of layer of loose pisoliths and nodules which may be underlain by a layer of nodular duricrust. The laterite residuum, in turn, is underlain by a zone of ferruginous saprolite characterized by bodies of iron segregations. Ferruginous saprolite forms a blanket deposit, up to several metres thick, in many areas, in the Lawlers district, and is preferentially developed over mafic and ultramafic lithologies. Ferruginous saprolite grades downwards into a thick saprolite zone, which extends to vertical depths of 50 to 70 m.

Nodules and pisoliths in lateritic residuum are formed from the fragmentation of ferruginous saprolite. Fragmentation of bodies of iron segregations can also yield nodules and pisoliths, which become incorporated within the lateritic residuum.

The Fe-rich duricrusts were probably formed by absolute accumulation of Fe. One possible explanation is that Fe-oxides originally impregnated the soils and sediments in small valleys, which because of inversion of relief now occur as ridge crests in the present landscape.

Note: The map uses an uncontrolled photomosaic as its base; some minor distortion occurs.

Depositional units

Alluvium
- Note: Alluvium in upper tributaries is omitted
- 7b — Alluvium in lower tributaries
- 7c — Alluvium in braided-wash valleys

Colluvium
- 6 — Colluvium as sheetwash

Calcrete
- 8 — Interpreted as valley-form calcrete

Residual units

Lateritic residuum
- 1 — Loose lateritic pisoliths and nodules / Nodular lateritic duricrust

Erosional units

Mottled zone
- 3a — Contains outcrop and scree of mottled zone and saprolite after mafic rocks
- 3b — Mottled zone and saprolite after felsic rocks

Saprolite
- 11 — Saprolitic outcrops and sediments, a mafic, b felsic

Outcrop, rubble, lithosols
- 5 — Bedrock lithologies exposed or beneath veneer of regolith

Stony soil
- 2 — Red-brown soil, ironstone lag and saprolite after mafics Pedogenic calcrete

- Areas of detailed mapping
- – – – Road
- .... Track
- ✗ Past or present Au mine

0 km 1

N

Fig. 4.27. Map showing the surface distribution of regolith-landform units for the Lawlers district, Report 166R.
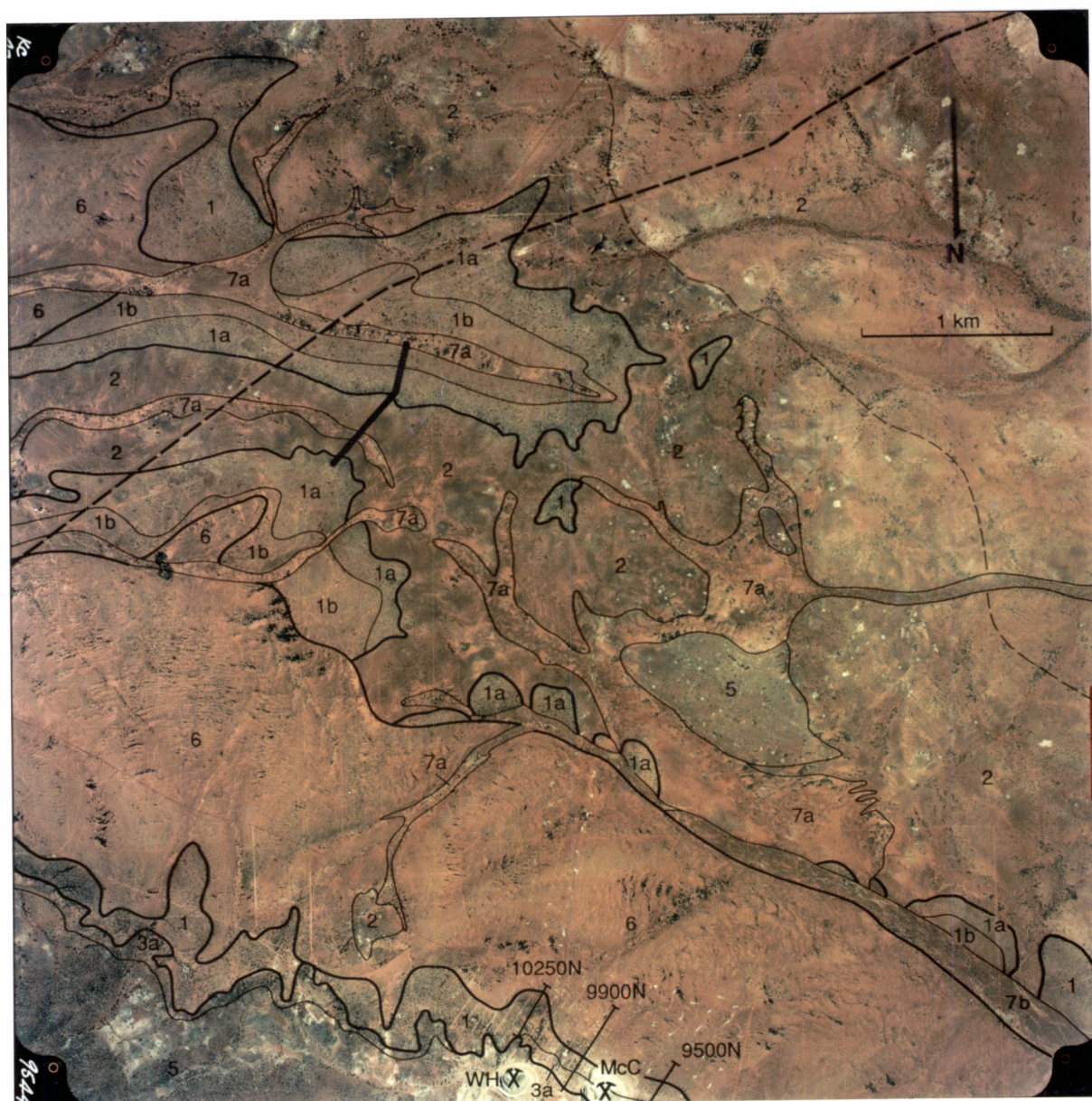
EROSIONAL REGIMES

2	Soil, lag, on saprolite
3a	Mottled zone saprolite
5	Subcrop of bedrock

RELICT REGIMES

| 1 | Lateritic residuum |

| 1a | duricrust |
| 1b | gravel |

- - - Gradational subdivision within Unit 2

DEPOSITIONAL REGIMES

| 7 | Alluvium |

| 7a | in minor tributaries |
| 7b | in major tributaries |

| 6 | Colluvium as sheet wash |

Traverse

Regolith cross sections from Anand et al (1989)

McCaffery and Weight Hill mine pits

Agnew-Leinster road

Fig. 4.28   Map showing the surface distribution of regolith units and vegetation for the Agnew-McCaffery area as an overlay to the colour air photograph (4/9544, 6.12.88). Bedrock lithologies are mafic and ultramafic.

Aerial photograph, 4/9544, 6.12.88, Kevron Aerial Surveys, published with permission of Homestake Gold of Australia Limited.

Lawlers regolith stratigraphy	Type location - depositional regime North Pit - hole 783, 5296E 9899N		
	Terminology	Description	Mineralogy
	Colluvium (transported)	Brown sandy loam with lateritic nodules, pisoliths, lithic and quartz fragments	H, K, Go, Q, Ma, R, Il
	Hardpanized colluvium (transported)	Hardpanized red-brown sandy clay loam to clay with lateritic nodules, pisoliths and lithic fragments. Mn staining (#) in colluvium. Nodules to 15mm maximum without yellow cutans	K, H, Go, Q, Ma, R, Sm
	Transported lateritic debris	Reddish brown silicified lateritic nodules without cutans	K, H, Ma, Go, R, Q
	Lateritic residuum (residual)	Loose nodules, pisoliths and nodular-pisolitic duricrust. Nodules to 35mm maximum with yellowish brown or greenish cutans	K, H, Go, Gi, Ma, Q
	Collapsed ferruginous saprolite	Yellow-brown fragments of ferruginous saprolite	Go, K, Q
	Iron segregations	Black, non-magnetic, massive competent iron-rich bodies	
	Ferruginous saprolite	Yellow-brown saprolite with black, non-magnetic iron segregations	Go, K, Q
	Saprolite	Pale clay-rich	K, Sm, Go, Q

Depth in metres: 0, 5, 10, 15, 20, 25

K	Kaolinite	Sm	Smectite
Go	Goethite	R	Rutile
H	Hematite	Il	Ilmenite
Ma	Maghemite	Gi	Gibbsite
Q	Quartz		

Fig. 4.29. Vertical profile showing the regolith stratigraphy and mineralogy of the regolith units for the depositional regime, North Pit, Report 166R.

Hardpan

At Lawlers, hardpan has developed within both *in situ* regolith and detritus resulting from the erosional modification of the old surface. Cementation of these materials by Si and Fe to form the hardpan, is a relatively recent process.

Discrimination between sample types

The 181 samples collected from the McCaffery-North Pit area were separated into four broad groups, based mainly upon their morphological characteristics and their position in the regolith-landform framework. These include materials from both surface and sub-surface units of the weathering profiles. The four groups recognized are: colluvium, lateritic residuum, ferruginous saprolite and iron segregations. These groups have different morphological, mineralogical and geochemical characteristics. Iron segregations can be recognized by their irregular, black, non-magnetic pitted surfaces. Some interiors of iron segregations show goethite and/or hematite pseudomorphs after sulphides. Lateritic pisoliths and nodules of lateritic residuum typically have 1 - 2 mm thick, yellowish-brown to greenish cutans around black/red nuclei. The presence of cutans may be used to recognize nodules and pisoliths derived from the breakdown of lateritic residuum.

A
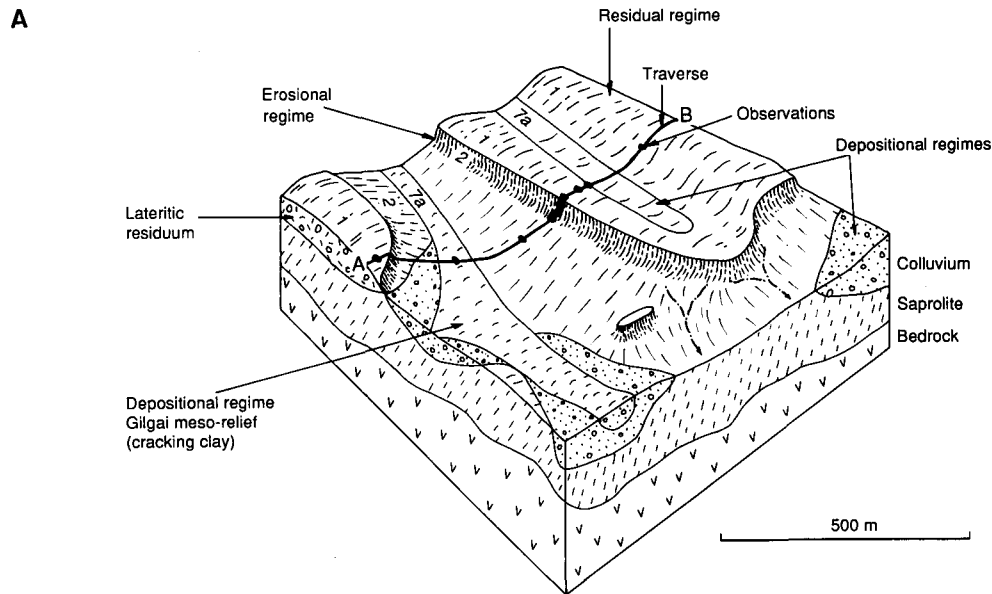
Fig. 4.30A. A generalized regolith-landform model based upon the Agnew-McCaffery study area, Report 166R.

B
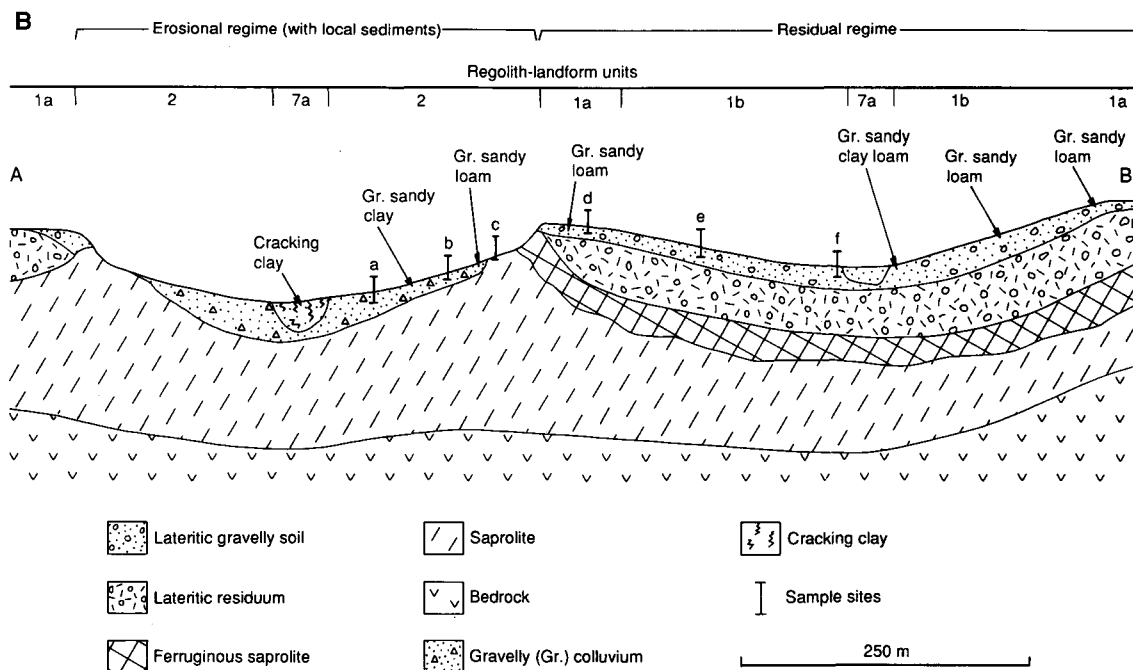
Fig. 4.30B. A schematic cross section of trends in soil and regolith stratigraphy for the traverse shown in Fig. 4.30A, Report 166R.
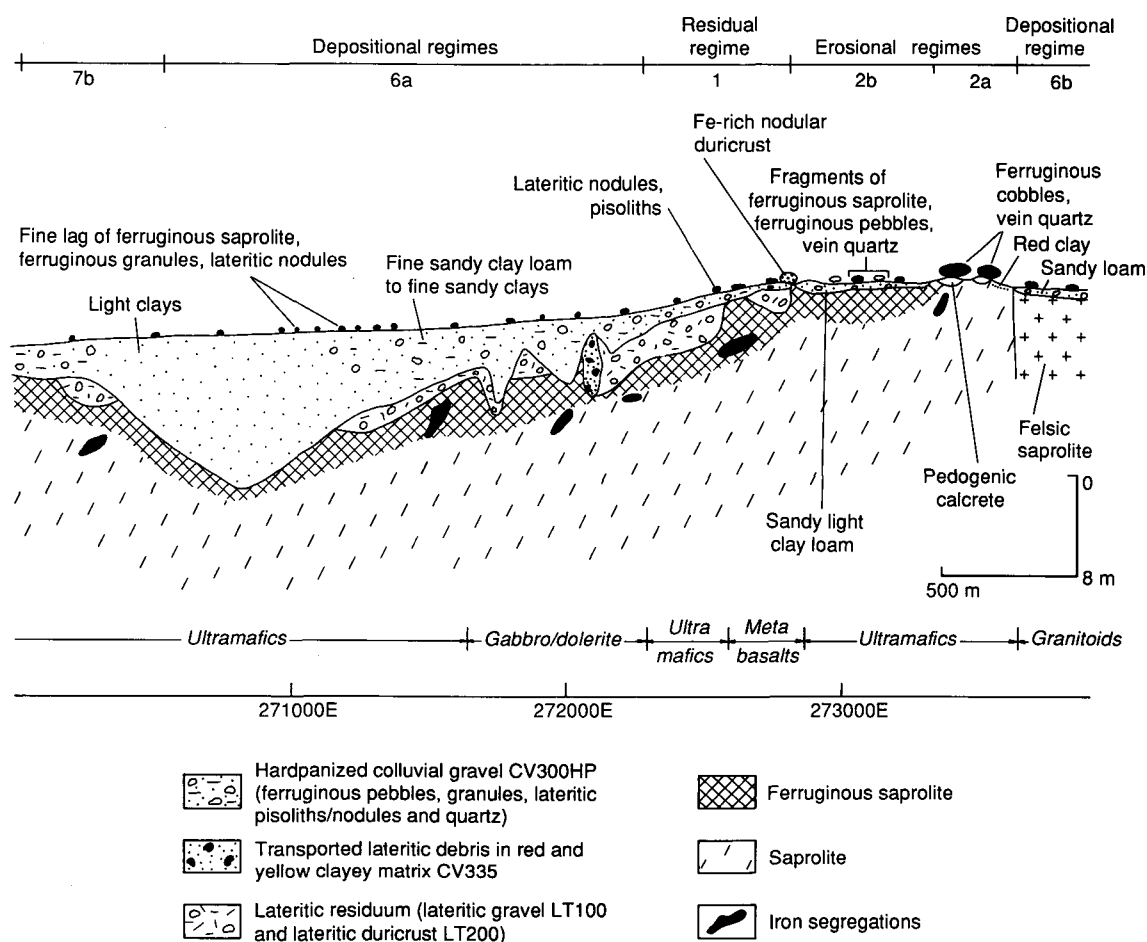
Fig. 4.31. Cross section showing the regolith stratigraphy for line 6891600 N, Meatoa area, Report 166R.

Mineralogy has been used to identify which part of the weathering profile that are exposed at the surface. Iron segregations differ from lateritic residuum by having abundant goethite and less hematite and kaolinite. Maghemite is typically absent in iron segregations. Lateritic residuum can be distinguished from ferruginous saprolite by having abundant hematite and less kaolinite. Colluvium differs from the other groups in having abundant quartz, kaolinite and some heavy minerals. The four sample media show differences in the degree of Al-substitution in goethite. This appears to be related to degree of maturity of the regolith, level of truncation and may also reflect the environments in which the particular regolith unit has formed. Identification of various sample media by the degree of Al substitution in goethite seems very promising [Fig. 4.35].

Iron segregations are dominated by Fe_2O_3, Mn, Zn, Co and Ba these elements can also be used to discriminate iron segregations from lateritic residuum, ferruginous saprolite, and colluvium. Many of the chalcophile elements and Au occur at lower abundances in the iron segregations to those in lateritic residuum and ferruginous saprolite. Despite this, the prominent regional distribution of iron segregations, generally as scree on pediment surfaces in partly-stripped profiles, offers potential for use as a geochemical sampling medium, provided these differing elemental abundances are considered in setting thresholds.

Lawlers regolith stratigraphy	Type location - depositional regime western wall of Waroonga Pit	
	Terminology	Description
	Colluvium (transported)	Red sandy clay loam with ferruginous clasts
	Hardpanized colluvium (transported)	Hardpanized red-brown sandy clay loam to clay with lithic fragments, quartz and ferruginous clasts, Mn staining, (※) white fine silica along partings
	Colluvial red clay (transported)	Red clay with few black ferruginous granules. Irregular pale mottles superimposed on a red matrix
	Lateritic residuum (residual)	Nodular-pisolitic duricrust. Red-brown 5-10mm nodules and pisoliths with yellow-brown, 1mm cutan, set in a red matrix
	Mottled zone	Pale to brown large mottles in a clay rich matrix

Depth in metres: 0, 2, 4, 6, 8, 10

Fig. 4.32. Vertical profile of the regolith stratigraphy at Waroonga, located within a depositional regime, Report 166R.

Table 4.5. Regolith stratigraphy and characteristics of units, Agnew area, Report 166R.

SAMPLE SITES (See Fig. 4.30B)	a	b	c	d	e	f
REGOLITH UNIT AT SURFACE	2	2	2	1a	1b	1b
TYPE OF REGIME	Erosional	Erosional	Erosional	Residual	Residual	Residual
LANDFORM	Valley floor	Upper pediment	Breakaway scarp	Broad smooth crest	Smooth gentle slopes "back slopes"	Valley floor
LAG	Lag of mixed origin (ferruginous pebbles/ granules, lateritic nodules)	Fragments of ferruginous saprolite	Fragments of ferruginous saprolite	Lateritic nodules, pisoliths	Lateritic nodules, pisoliths	Lateritic nodules, pisoliths
SOILS	Gravelly red fine sandy clay	Reddish-brown gravelly fine sandy loam	-	Gravelly reddish-brown fine sandy loam	Gravelly reddish-brown fine sandy loam	Gravelly brown fine sandy clay loam
COLLUVIUM	Gravelly colluvium	Gravelly colluvium	-	-	-	Gravelly colluvium
HARDPAN	Present within a metre of surface	Present within a metre of surface	-	-	Some	Some
LATERITIC RESIDUUM	-	-	-	Nodular duricrust	Nodular duricrust	Nodular duricrust
SAPROLITE	Ferruginous and clay-rich saprolite (?)	Ferruginous and clay-rich saprolite	Ferruginous and clay-rich saprolite	Ferruginous and clay-rich saprolite (?)	Ferruginous and clay-rich saprolite (?)	Ferruginous and clay-rich saprolite (?)

Although the Fe_2O_3 contents of the ferruginous saprolite are comparable to those of the lateritic residuum, there are strong geochemical differences between the two. Lateritic residuum has relatively higher abundances of Cr, V, Ni, As, and Pb. Conversely, ferruginous saprolite carries significantly higher levels of Cu, Sb, Bi, and Au. The concentrations of SiO_2, MgO, TiO_2, Zr, and Nb are higher in colluvium than in lateritic residuum and ferruginous saprolite. These differences may be due to the degree of weathering, mineralization, mechanism of accumulation of the secondary weathering products, and origin.

Group separation, using canonical variate analysis and all possible-subset calculations, has indicated that effective separation of the four sampling media exists. A combination of 14 elements (Fe, Mn, Cr, V, Pb, Zn, Ni, Co, As, Sb, Bi, W, Zr, Nb) would seem to be the most useful for separation of the groups at Lawlers [Fig. 4.36].

Siting and bonding of elements
Gold in lateritic nodules from the North Pit location occurs as grains (<15 μm in diameter), in cracks, and as relatively large, dendritic grains (which reach 70 μm in diameter), attached to the surface of goethite. Both occurrences of Au appear to be secondary and are almost free from Ag (<1% Ag). In the lateritic nodules, As and Mn are strongly associated with Fe oxides but Cu is associated with kaolinite.

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W

EROSIONAL REGIMES

RESIDUAL REGIME

DEPOSITIONAL REGIMES

RESIDUAL REGIME

EROSIONAL REGIME

DEPOSITIONAL REGIME

E

Pediplain	Convex hills	Breakaway and pedimented slopes	Crests, back-slopes	Long gentle slopes	Alluvial floors	Calcreted drainage lines	Alluvial floors	Long gentle slopes	Crests, back-slopes	Low hills	Long gentle slopes
Regolith units 11	5	3	1	6	7	8	7	6	1	2	6

Lag of mixed origin
(lithic fragments, ferruginous granules after iron segregations and ferruginous saprolite, lateritic pisoliths/nodules and vein quartz)

Pedogenic calcrete
Red clay

Calcrete mound

Lag of mixed origin

Felsic lithologies

Coarse black ferruginous cobbles after iron segregations and yellowish brown ferruginous saprolite, vein quartz

Lense of transported nodules and pisoliths

Saprolite (clay-rich)

Lateritic nodules, pisoliths with yellowish brown cutans

Cracking smectitic clay

Mafic, ultramafic bedrock

Hardpanized gravelly (ferruginous pebbles, granules, lateritic pisoliths/ nodules, lithic fragments and quartz) colluvium

Nodular-pisolitic Fe-rich duricrust

Bodies of iron-segregations

Hardpanized alluvium with lateritic nodules and pisoliths

Lateritic residuum:
Nodular-pisolitic duricrust and loose lateritic gravelly layer

1 km

Silty alluvium

Ferruginous saprolite - may be collapsed

Fig. 4.33. Schematic cross section for the Lawlers district showing regolith stratigraphy and landforms, Report 166R.
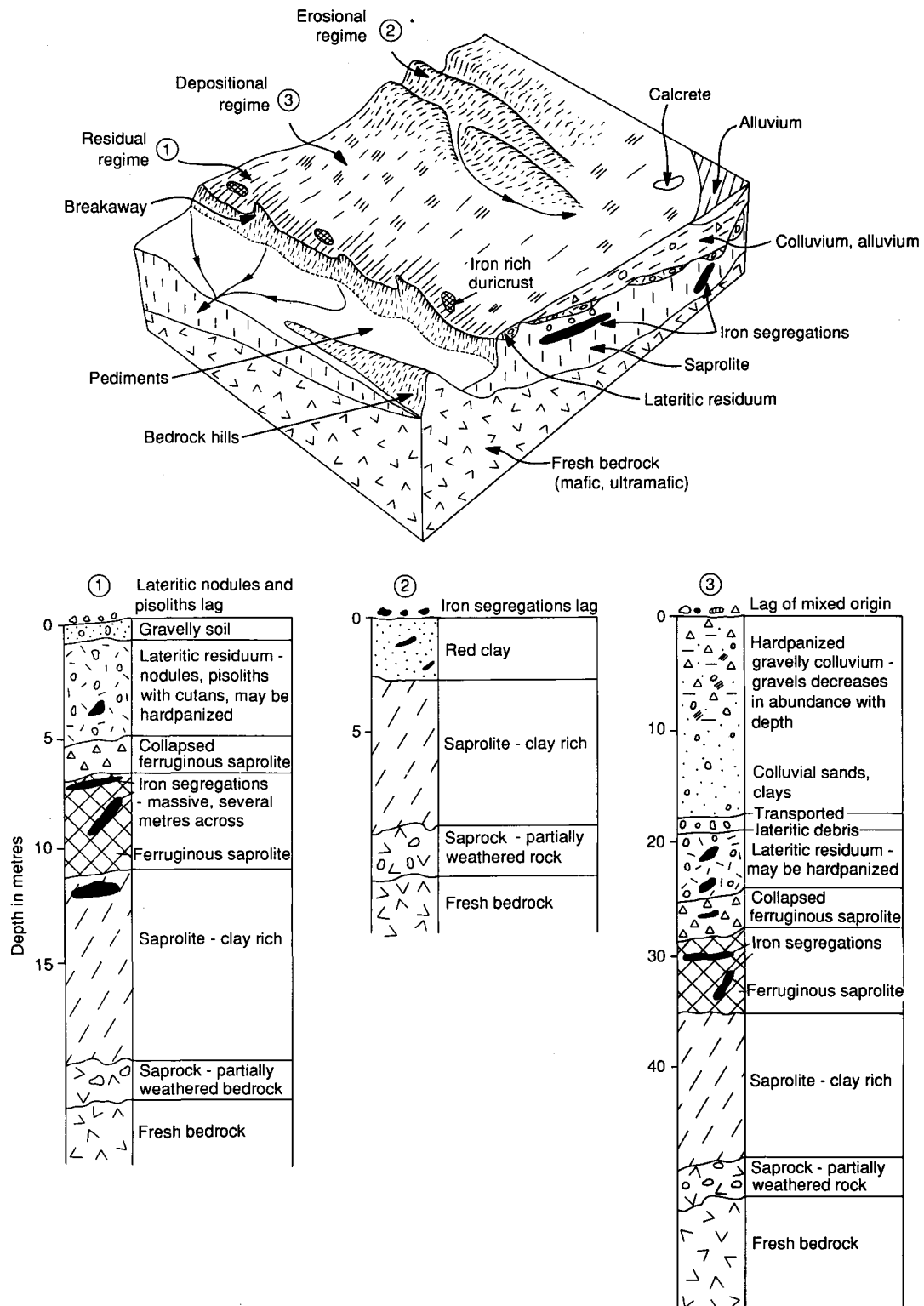
Fig. 4.34. Regolith-landform model for the Lawlers district. Columns show units of the regolith stratigraphy in the regimes.

Table 4.6. Summary of regolith stratigraphy and characteristics of regolith units, Lawlers, Report 166R

TYPE OF REGIME	RESIDUAL REGIMES	EROSIONAL REGIMES	DEPOSITIONAL REGIMES
REGOLITH-LANDFORM MAPPING UNIT	(2 units)	(6 units)	(6 units)
LANDFORM	Crests and backslopes	Breakaway, pediment slopes, low hills.	Slopes, valleys,major and minor drainages.
VEGETATION	Mulga	Mulga	Mulga and shrubs.
LAG	Laterite nodules, pisoliths.	Iron segregations, Fe-saprolite, saprolite, quartz.	Mixed ferruginous granules, pebbles
SOILS	Sandy loam to sandy-clay loam	Sandy-clay loam to light clay.	Light clay.
ALLUVIUM	—— —— ——	—— —— ——	Extensive
COLLUVIUM	Minor	Minor	Extensive
HARDPAN	Minor to absent.	—— —— ——	Extensive
CALCRETE/ CARBONATES	—— —— ——	Pedogenic carbonate.	Calcreted drainage lines.
LATERITIC RESIDUUM	**Nodular duricrust, Fe-rich nodular duricrust.**	—— —— ——	**Commonly beneath colluvium and alluvium.**
FERRUGINOUS SAPROLITE	Present	Present	Present
SAPROLITE	Multicoloured clay-rich mafic/ultramafic saprolite.	Granitic/mafic/ultramafic saprolite.	Multicoloured clay-rich mafic/ultramafic saprolite.
BEDROCK	Mafic, ultramafic.	Felsic, mafic, ultramafic.	Mafic, ultramafic.

Discussion: distinguishing residual regolith from transported regolith

Transported regolith embraces materials of redistributed origin such as alluvium, colluvium, sheetwash gravels, and aeolian clay that blanket fresh or weathered bedrock. Areas of alluvial/colluvial outwash plains are widespread in the Yilgarn Craton and are common in the Lawlers district. In these landform situations, seeking geochemical haloes in buried residual laterite can be of great advantage in exploration. This requires accurate, sub-surface sampling of the lateritic materials and knowledge of the regolith stratigraphy. However, the colluvial/alluvial units may include materials, such as lateritic gravels (nodules, pisoliths) and clays derived from erosion of lateritic profiles. These may be misidentified as residual lateritic materials. Pisoliths, developed *in situ* in transported regolith, may have different geochemical and mineralogical characteristics from those in a lateritic residuum. Thus, the transported regolith may have been lateritized – hence its identification can pose problems. Lateritic gravels which have been transported long distances may not be a suitable medium for geochemical sampling at the prospect scale. In sampling for exploration geochemistry, it is therefore important to distinguish between transported nodules and pisoliths in alluvial/colluvial units and those of a buried residual laterite profile.

Criteria for identification of regolith units in drill spoil or in exploration pits
The following criteria, taken conjointly, are believed sufficient to establish the characteristics of residual and transported regolith in a field situation, although ambiguous cases arise.

♦   *Hardpanized colluvium/alluvium*

- Red-brown, non-hardpanized colluvium may have variable colours.
- Hard, brittle, irregular dull fracture faces, very fine porosity.
- Abundant Mn staining.
- Glassy, botryoidal opal in pores or along partings.
- Soft carbonates along partings.
- Exhibit coarse subhorizontal lamination.
- Presence of large amounts of sandy/gritty clays and/or exotic lithorelics.
- Presence of polymictic gravels - exotic lithorelics, lateritic gravels, quartz.

♦   *Lateritic residuum*

- At Lawlers, the presence of nodules and pisoliths with yellowish-brown/olive green cutans are believed to be confined to residual laterites or those with minimal transport (less than say 50 to 100 m).
- Presence of small fragments of lateritic duricrust in drill spoil.

♦   *Transported lateritic gravels*

- Large proportion of nodules/pisoliths which are fractured or the abundance of chipped cutans would be indicative of transport. Conversely, the presence of coherent (not disaggregated) clusters of nodules and pisoliths in drill hole pulps indicates residual material.
- Layers of well-sorted and well-rounded lateritic gravel may indicate transported laterite.
- Presence in a profile of cyclic bands of packed lateritic debris alternating with layers of colluvial/alluvial clays/loams indicates a transported regolith.

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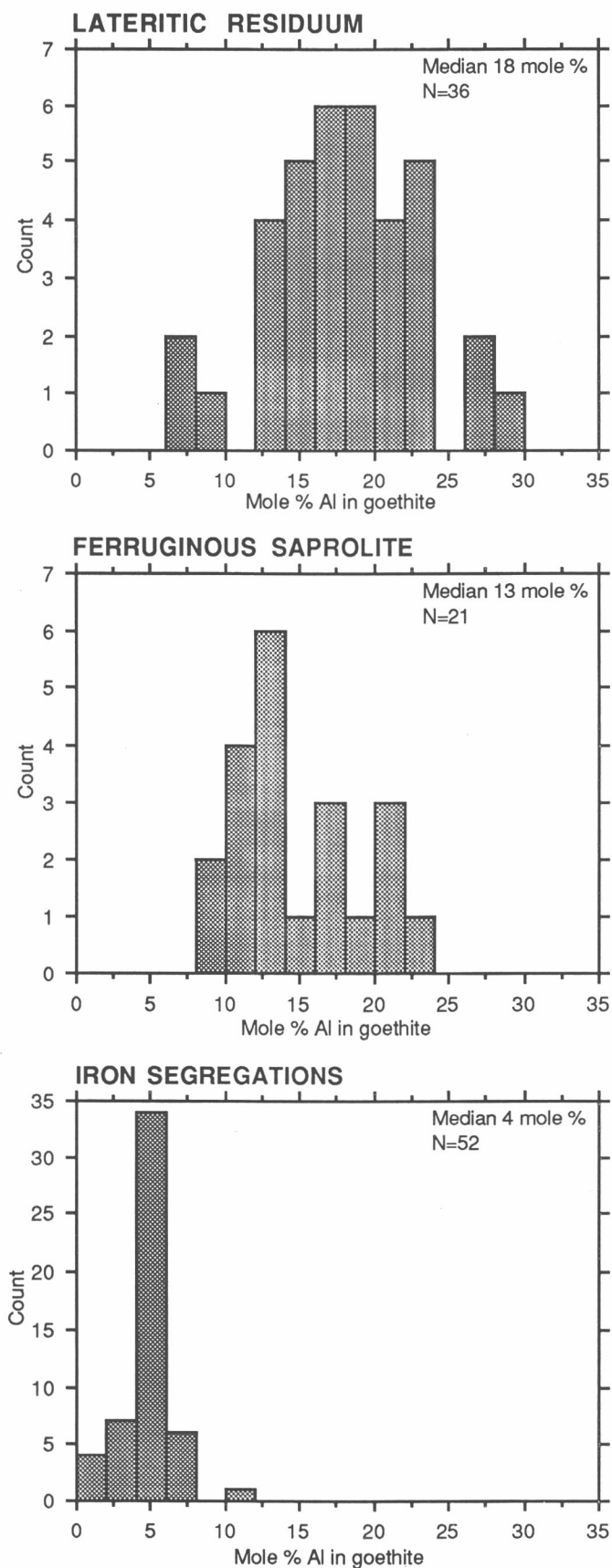
Fig. 4.35. Histograms of the values of mole % Al in goethite for the three categories of sample media, Report 166R.

Table 4.7. Some summary statistics on element concentrations in four sample media, North Pit area, Report 166R.

Sample Type	Colluvium n = 33	Lateritic residuum n = 48	Ferruginous Saprolite n = 26	Iron Segregations n = 74
	Median	Median	Median	Median
wt.%				
SiO2	40.00	18.80	25.10	11.60
Al2O3	16.70	14.93	14.16	3.10
Fe2O3	34.31	52.20	47.12	73.67
Mgo	0.265	0.154	0.137	0.081
CaO	0.214	0.089	0.113	0.095
Na2O	0.046	0.017	0.034	0.014
K2O	0.102	0.020	0.020	0.020
TiO2	1.343	1.128	1.125	0.236
ppm				
Mn	288	205	238	2820
Cr	554	5640	238	47
V	814	847	502	236
Cu	60.0	70.0	195.0	130.0
Pb	14.0	14.0	0.7	3.0
Zn	22.0	35.0	57.0	320.0
Ni	62	210	68	69
Co	20.0	28	35	84
As	46.0	127.5	55.5	33.0
Sb	4.0	5.0	6.5	4.0
Bi	0.7	0.7	6.5	0.7
Mo	2.0	3.0	2.0	2.5
Ag	0.20	0.20	0.10	0.10
Sn	2.0	2.0	2.0	0.7
Ge	1.3	1.3	2.5	1.3
Ga	44.0	45.0	17.5	4.0
W	8.0	10.0	4.5	1.3
Ba	105	38	72	147
Zr	110	100	74	20
Nb	10.0	7.0	3.5	2.0
Se	0.7	2.0	0.7	0.7
Be	1.0	1.0	1.0	1.0
ppb				
Au	64	110	365	17

Lawlers CVA scores for colluvium, lateritic residuum, iron segregations, ferruginous saprolite (Al, Ga, Cr, Si, Bi, Pb, V, Au, Nb, Zn, As, Sb, W, Ni)
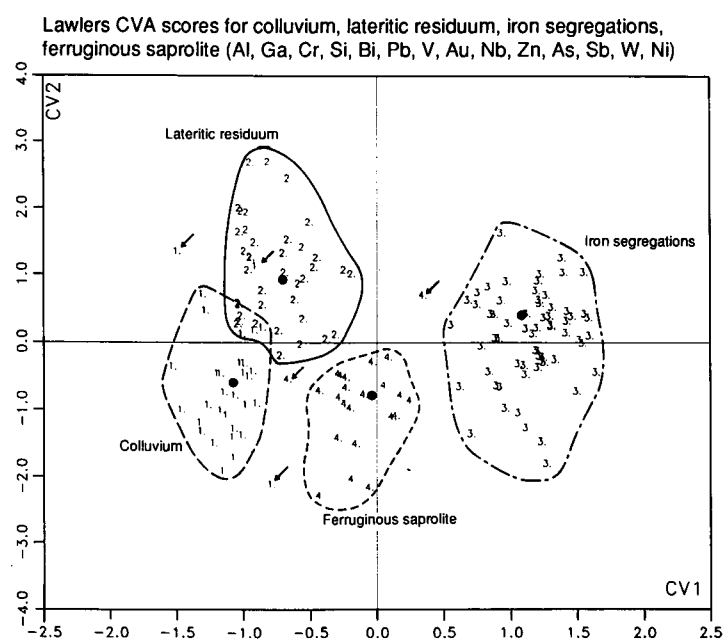
Fig. 4.36. Plot of CVA scores (CV1 vs. CV2) for colluvium, lateritic residuum, ferruginous saprolite, and iron segregations from the North Pit area, Report 166R.

4.4.6   Geochemical dispersion

North Pit, Turrett and McCaffery deposits

Introduction
Here the multi-element geochemical dispersion patterns in the regolith units (particularly lateritic residuum and colluvium) overlying the deposit were studied (Fig. 4.37).

The area is dominated by gravel-strewn colluvial outwash plains, sloping E at about 1° towards a local drainage axis, and truncated to the W by a NW trending line of breakaways (Fig. 4.28). An extensive, but discontinuous, horizon of essentially-residual laterite is overlain unconformably by a varying thickness (5-30 m) of colluvium. The colluvium contains components derived by partial or complete stripping of lateritic residuum and ferruginous saprolite elsewhere. Detailed field relationships and regolith stratigraphy of the North Pit area are covered in report 166R.
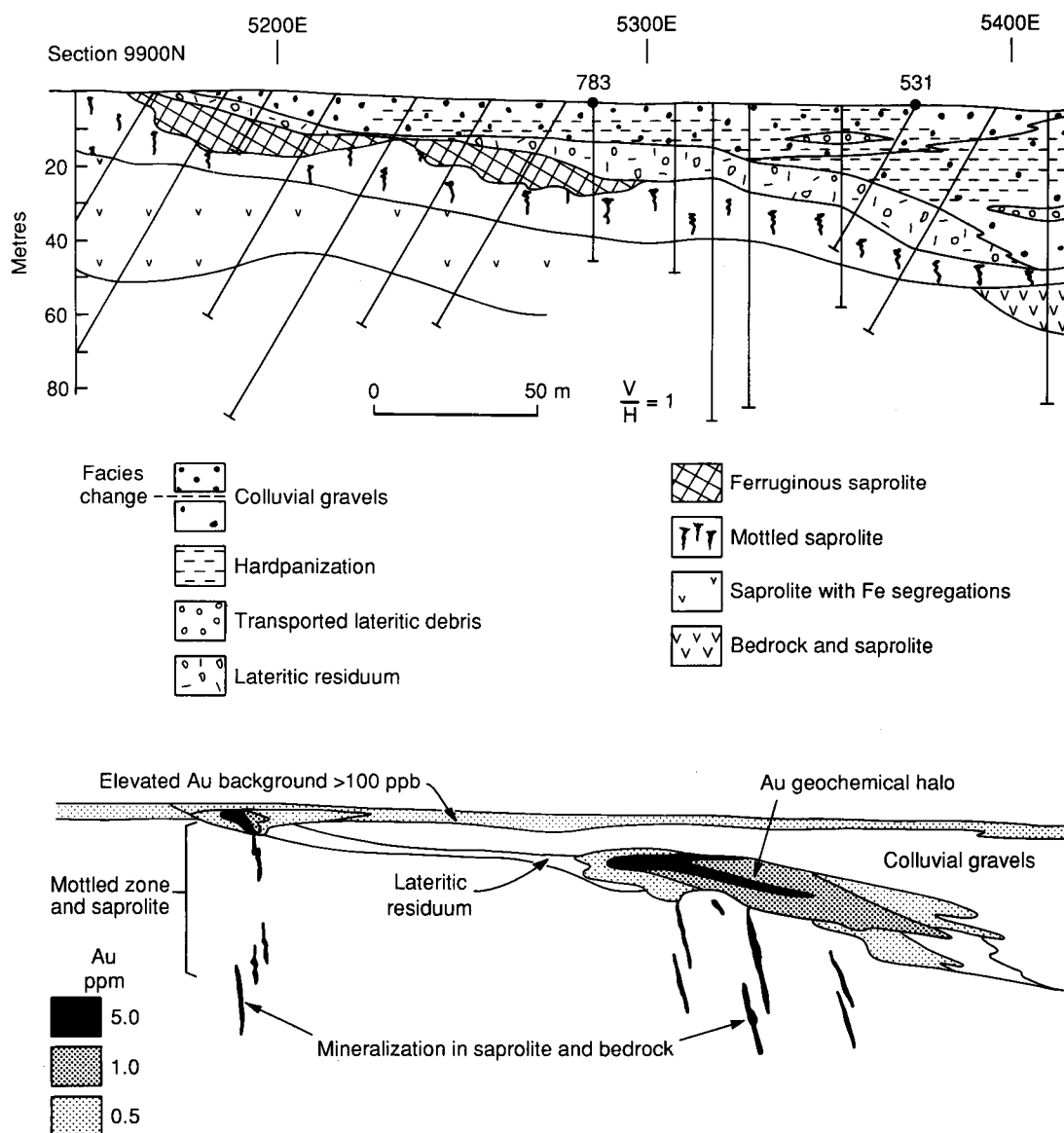
Fig. 4.37. Diagrammatic cross section along line 9900 n in the North Pit area showing regolith stratigraphy and dispersion of Au in lateritic residuum.

Prior to mining at North Pit, lateritic and saprolitic Au resources lay beneath 10 to 20 m of hardpanized colluvium. The bedrock mineralization continues to the S within the McCaffery Pit. Gold from this source has been redistributed and concentrated by secondary weathering effects into the saprolite and, in places, into the overlying lateritic residuum. In the North Pit orientation area, eight percussion drill holes were sampled to assess variations in the geochemistry of the regolith units which include unconsolidated colluvium, hardpanized colluvium, loose lateritic nodules and pisoliths, nodular duricrust, saprolite, and iron segregations. The results showed that the North Pit lateritic Au deposit forms the high-grade part of a chalcophile multi-element (Au, As, Cu, W, Sb and Bi) geochemical anomaly (Figs 4.37 and 4.38). The results are summarized below.

Unconsolidated colluvium: The inhomogeneity of samples of colluvium with varying amounts of gravels, sands, and clays, imparts a wide variation in major-element chemistry. Manganese abundance is greatest in the upper part of the colluvium, reaching several thousand ppm within 10-40 cm of the surface, a function of pedogenic processes. This enrichment is generally visible in exposures as coatings of black Mn-oxides on pebbles within the near-surface zone.

Detailed sampling from drill holes showed high relative abundances of Fe, Mn, Cr, V, and Ni in the loose, near-surface colluvial gravels due to a higher content of lateritic debris and fragments of iron segregations in the upper part of the profile. Gold, Ag, Pb, and Sb are also moderately abundant in the near-surface colluvium.

Hardpanized colluvium: Most chalcophile elements have similar abundances to those in the unconsolidated colluvium, but As (to 640 ppm) and Au (to 140 ppb) are significantly higher. Detailed profiles show a strong correlation between the content of Si, Mg, Ca, Na, and K and the development of hardpan. The same detail shows a trend of increasing As downward in the colluvium, the highest As abundances being below the hardpan zone.

Loose nodules and pisoliths: Loose nodules and pisoliths are enriched in SiO_2 and Al_2O_3 and depleted in Fe_2O_3 relative to the underlying lateritic duricrust. Copper, Pb, and Bi are enriched in loose nodules near the base of residual laterite, below the nodular duricrust in this area. Arsenic, Ag, and Au give a stratigraphically-confined response associated with the laterite horizon, generally with a very sharp drop off in the underlying saprolite and overlying colluvium.
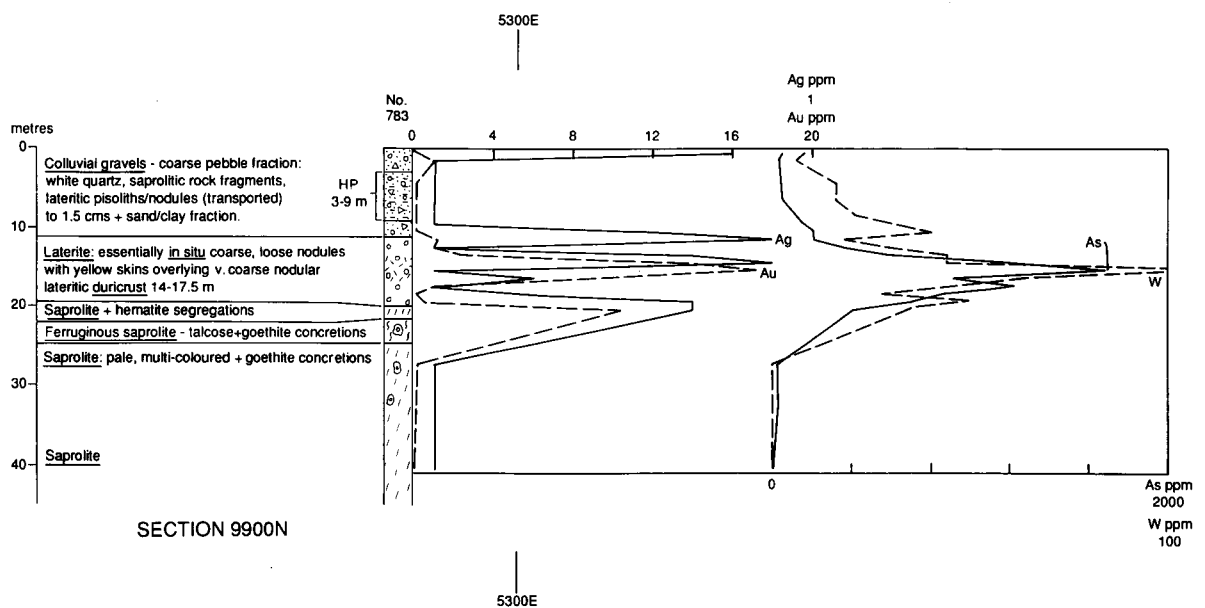
Fig. 4.38. Vertical profile of regolith stratigraphy and geochemistry of regolith units intersected by drill hole 783, North Pit area.

Nodular duricrust: Analyses of duricrust indicate that highly-anomalous Au (to 18 ppm), Ag (to 0.8 ppm), As (to 1680 ppm), W (to 110 ppm) are associated with the duricrust horizon of the residual laterite profile. It appears that there are significant geochemical differences between the residual loose, nodular/pisolitic unit and the duricrust in the North Pit orientation area. A greater number of samples taken elsewhere would be required to extend the study so as to establish sample backgrounds and thresholds for the whole Lawlers district.

*Ferruginous saprolite.* Many of the ore-related elements (Cu, As, W, Ag) in ferruginous saprolite exhibit similar or higher abundances to those in the overlying nodular duricrust and in the layer of loose pisoliths. However, Au is relatively low.

Saprolite. Major-element chemistry of the saprolite can be expected to vary greatly according to parent rock type (whether mafic, ultramafic, etc.), the extent of development of a mottled zone, and the presence or absence of iron segregations. This is reflected in the large range of abundances of SiO_2, Al_2O_3, TiO_2, CaO, MgO, Na_2O, and K_2O. The high levels of Mn, Ni, Co, Cu, and Zn probably reflect significant amounts of iron segregations in the saprolite.

Iron segregations. One of the objectives of the research was to assess iron segregations as a suitable sampling medium for geochemical exploration in areas where lateritic residuum is stripped. This was carried out in the immediate vicinity of the McCaffrey-North Pit, where iron segregations are common. Iron segregations occur as pods, slabs, or lenses, within the upper part of saprolite or ferruginous saprolite, and form a dominant coarse, black lag on erosional surfaces on partly-stripped profiles. This is a common feature in the Lawlers district and, indeed, in other orientation areas, such as Bottle Creek. The external appearance of fragments of iron segregations is generally black and subrounded to subangular. They commonly range in size from 20 to 200 mm. Iron segregations are typically non-magnetic and consist dominantly of goethite.

   Samples of iron segregations collected from surface over an area of 1.5 km by 0.5 km, and from pit walls, document the multi-element characteristics of the McCaffery-North Pit Au deposits, including dispersion during lateritic weathering of the hosting mafic and ultramafic lithologies. The mineralization is depicted by a multi-element anomaly in Au, As, Cu, Zn, W, Mn and to some extent in Bi, Ag, and Sb (Figs 4.39 to 4.41). The ore-related elements in iron segregations, with the exception of Mn and Zn, are similar in abundances to those in the lateritic nodules and pisoliths. Gold has, however, a relatively-low abundance. The geochemical pattern for Au is consistent over the 200 to 300 m width of the anomaly for a strike length in excess of 700 m. From experience in the Yilgarn Craton, the geochemical compositions of iron segregations may be compared with statistics for the non-lateritic ferruginous cobbles and pebbles from erosional regimes, Table 7.2 in Section 7.3. A background for Au between 3-5 ppb with a threshold of 10 to 20 ppb would seem appropriate in reconnaissance exploration.

   Arsenic, Zn, Cu, and Mn show more consistent and widespread distributions than those of W, Bi, and Sb. The As, Zn, and Cu patterns are strong and extensive, some 300 m wide and more than 1 km long. However, caution is needed because Mn and Zn are highly mobile during weathering and can be easily adsorbed by goethite, which is the dominant mineral. The most marked As pattern is NE of the McCaffery Pit, coinciding with the North Pit.

   The W and Bi patterns lack the continuity of Cu, Zn, and As. Localized patterns of W and Bi reach 1100 and 250 ppm respectively. High values of Au (62 ppm) coincide with the high Bi (250 ppm) and are related to mineralized veins. The Sb anomaly is weak.

Turrett Pit
The objective was to establish the multi-element dispersion patterns in ferruginous saprolite and lateritic residuum over the deposit.

   The Turrett Pit, 2 km N of the McCaffery-North Pit area, is located in a broad depositional regime. At Turrett, colluvium is shallow and reaches a maximum thickness of 5 m. Gravelly colluvium overlies a 3 m to 5 m thick residual laterite. A zone of ferruginous saprolite, which forms a continuous blanket, underlies the residual laterite and is yellowish to reddish-brown in colour. Development of lateritic nodules and pisoliths in residual laterite is associated with fragmentation of ferruginous saprolite.

   Three percussion drill holes were sampled to assess the variations in geochemistry of the regolith units (Fig. 4.42). The units sampled include colluvium, loose nodules, nodular duricrust, and ferruginous saprolite. The ferruginous saprolite and loose nodules are dominated by goethite and kaolinite. These samples contain high concentrations of Cr, Ni, and Co, suggesting an ultramafic origin.
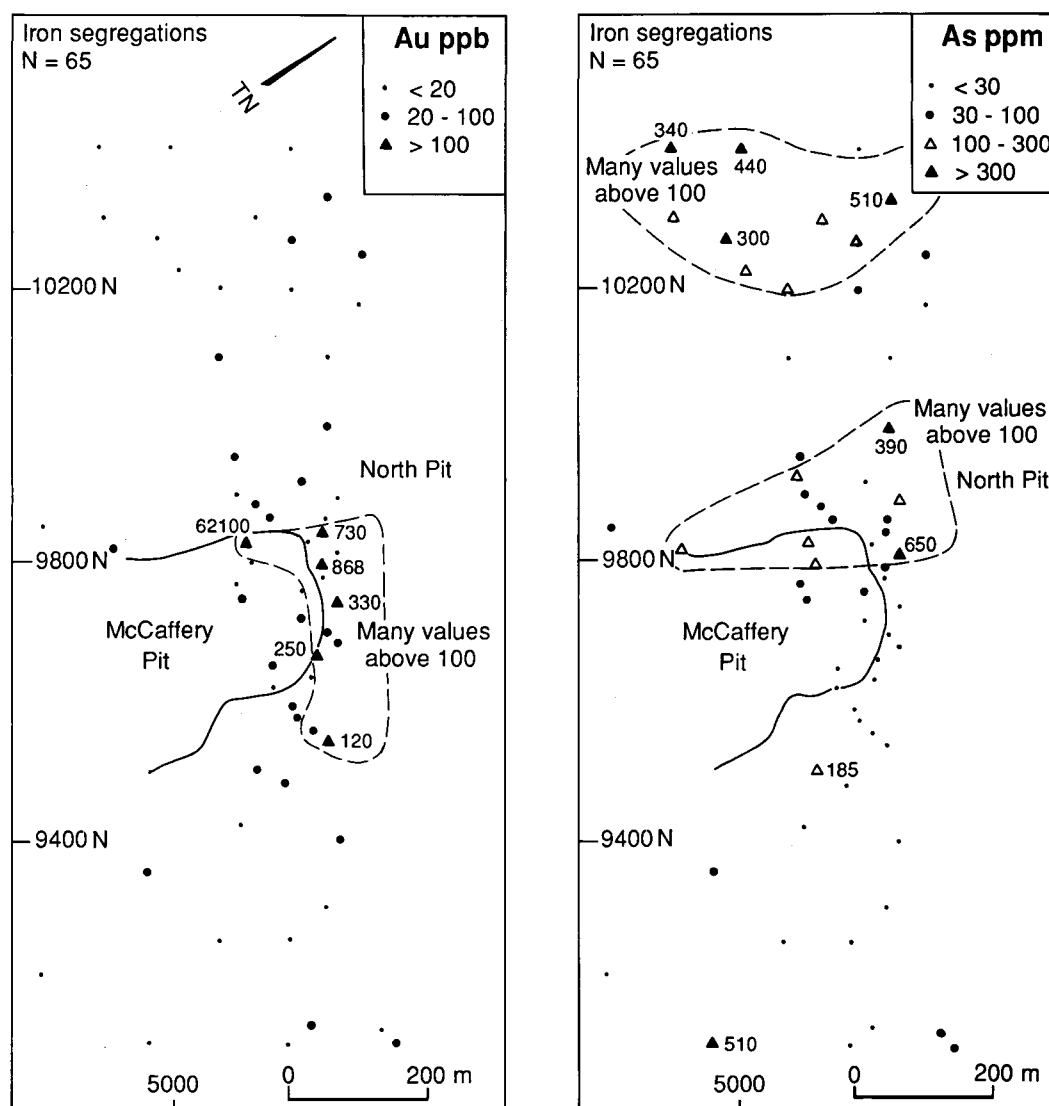
Fig. 4.39. Maps of the distribution of Au and As in iron segregations, North Pit area.

Colluvium: Gold is anomalous, reaching 72 ppb. Colluvium also shows significantly-higher values of As (to 190 ppm) and Sb (to 17 ppm).

Lateritic residuum: Gold is distinctively-anomalous, reaching 9 ppm. Apart from Au, the ore body is also depicted by strong As, Cu, Sb, Bi, and W anomalies. Caution: the scale used in Fig. 4.42 suppresses the anomalous As abundances.

Ferruginous saprolite: Gold is highly-anomalous (to 5.5 ppm). Arsenic (to 2200 ppm), Cu (to 80 ppm), and Bi (to 145 ppm) giving a stronger expression of mineralization in ferruginous saprolite than in the overlying laterite. Tungsten is relatively low in abundance in ferruginous saprolite. Antimony (to 30 ppm) in ferruginous saprolite is similar in abundance to its level in lateritic residuum. Silver is very low in abundance.
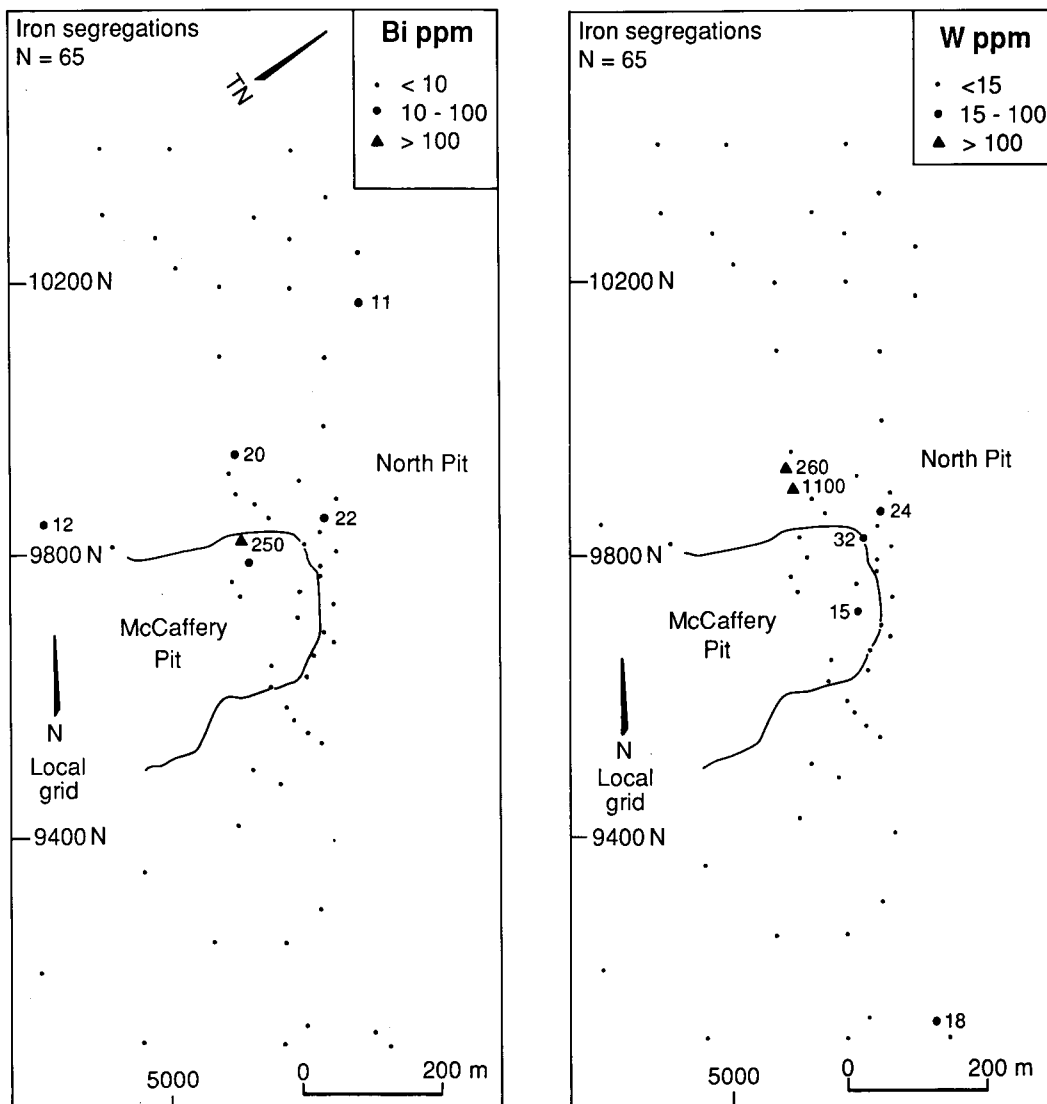
Fig. 4.40. Maps of the distribution of Bi and W in iron segregations, North Pit area.

4.4.6   Implications in exploration

The Lawlers research is particularly important to exploration because, as far as we know, it is the first research-documented case of exploration in a district where extensive areas of complete laterite profiles occur buried beneath widespread alluvial and colluvial plains. The extent of buried laterites is in marked contrast with the restricted area of lateritic residuum exposed at surface, the latter being about 15% of the total area. Exploration beneath the plains at Lawlers carried out by Forsayth and Geochemex, with research support by CSIRO, has clearly demonstrated the effectiveness of drilling for buried geochemical haloes in laterite. These principles have been applied successfully by sponsors in other parts of Australia.

There is likely to be continued systematic testing of exploration methods and associated research at Lawlers in the foreseeable future, because of the attributes of the district (regolith, landform, and bedrock relationships and occurrences of conceleated ore deposits), the research, and exploration documentation which has accumulated.   Continued testing of airborne geophysical methods and remote sensing will be particularly relevant. The Lawlers district also provides excellent opportunities for training explorationists in regolith geology.
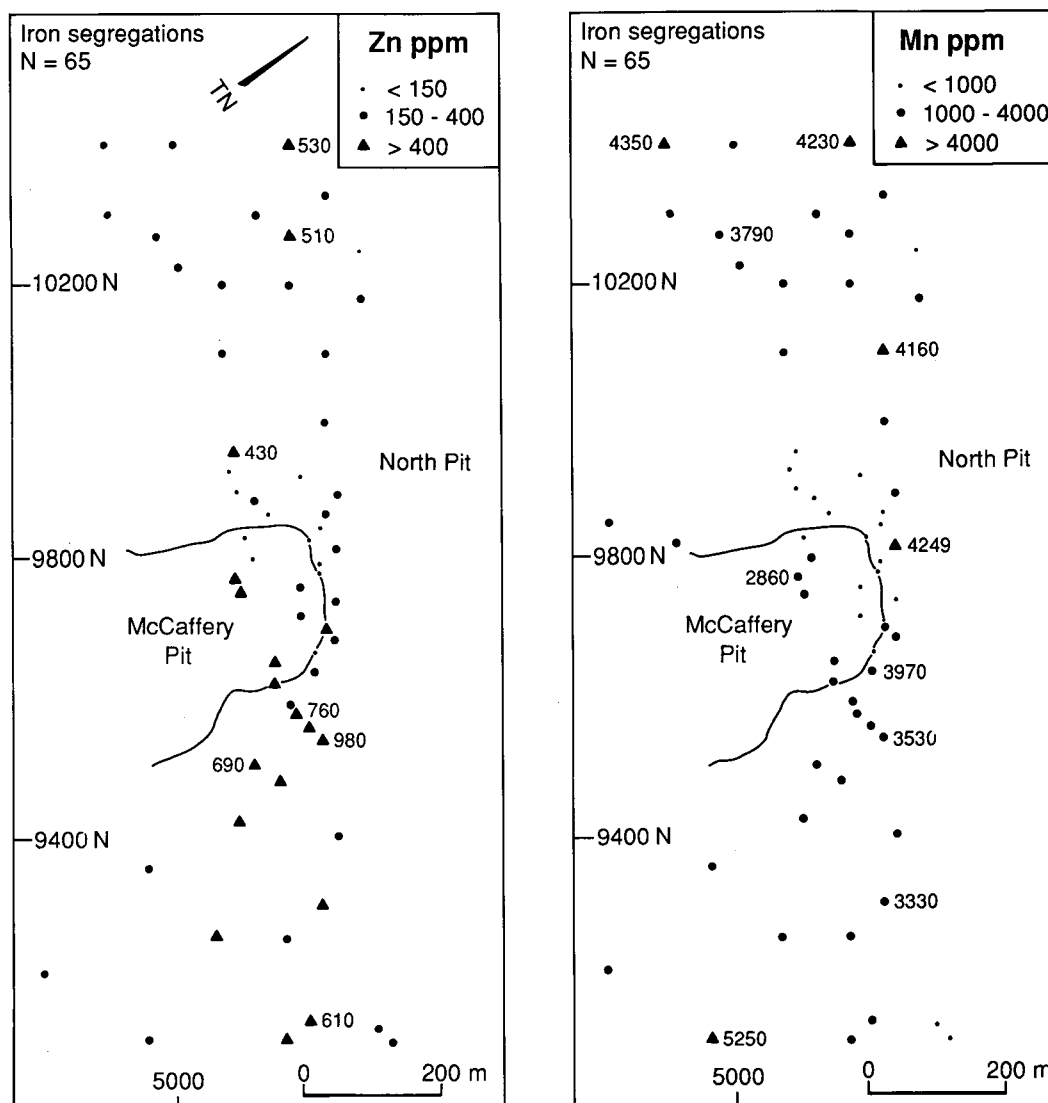
Fig. 4.41. Maps of the distribution of Zn and Mn in iron segregations, North Pit area.

Broad Au anomalies and anomalous concentrations of other ore-associated elements, such as As, Cu, Bi, Sb, and W in the lateritic residuum and ferruginous saprolite at North and Turrett Pits are effective indicators of primary and supergene Au mineralization.. Compared with lateritic residuum, the ferruginous saprolite is less weathered and is closer in geochemical characteristics to the mineralization. However, more data are required to establish the geometry of dispersion patterns in ferruginous saprolite.

The iron segregations, and the lag derived therefrom, are appropriate sampling media in partly-truncated areas of the Lawlers district, in lieu of lateritic residuum and ferruginous saprolite. Elevated levels of Au, As, Cu, and to some extent Bi and Sb, form anomalous geochemical associations in the iron segregations. The colluvium and hardpanized colluvium are also anomalous in Au, while As and Sb have only moderate abundances in the near-surface colluvium.

The main implications in exploration of the Lawlers research and collaboration are listed in Table 4.8.
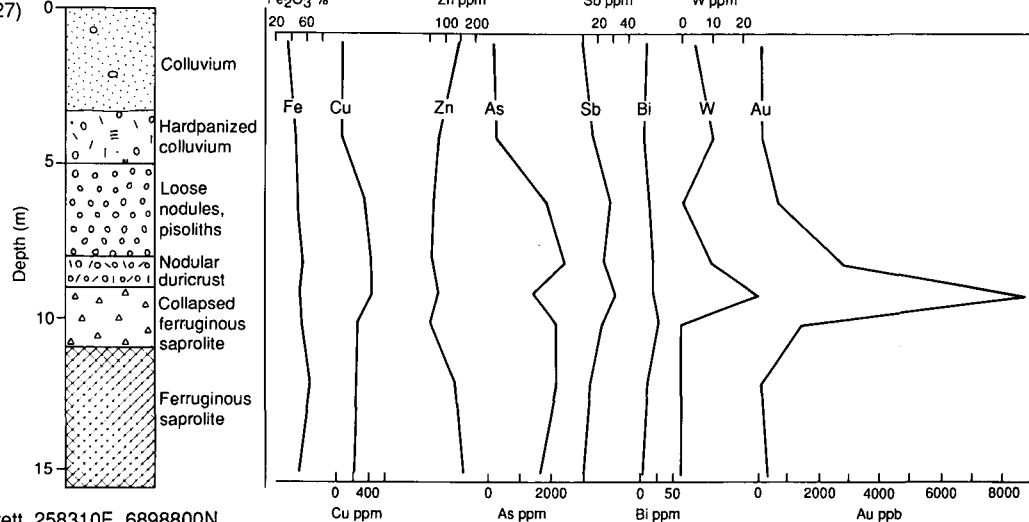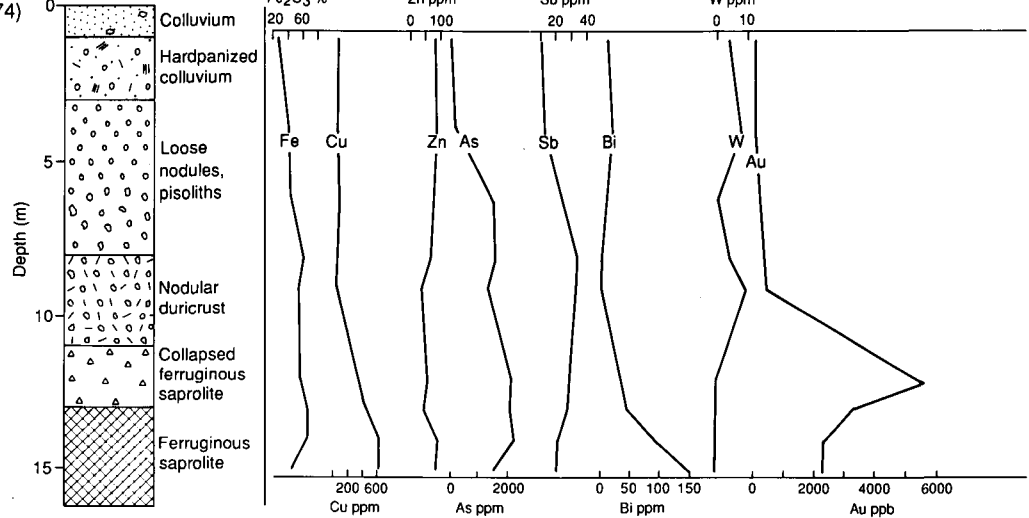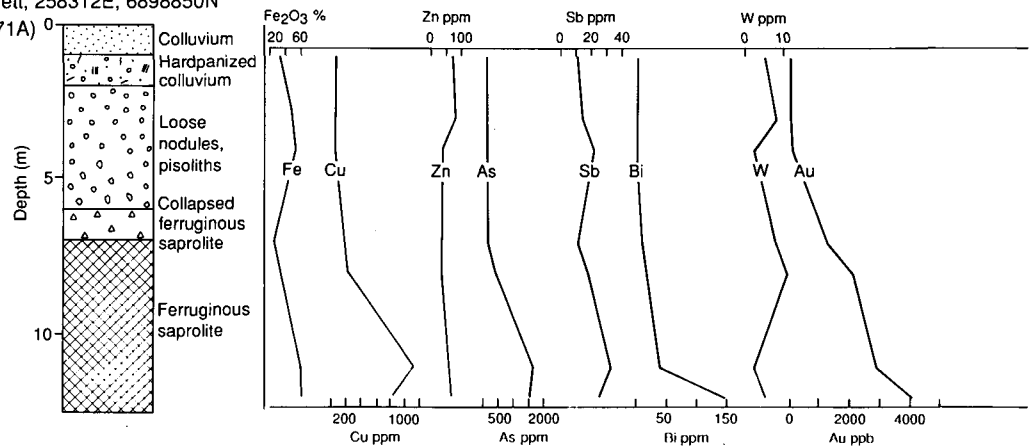
Fig. 4.42. Vertical profiles showing the regolith stratigraphy and geochemistry of the regolith units intersected in the drill holes T327, T274, and T271A, Turrett Pit area.

Table 4.8.   The implications in exploration listed against the research findings, Lawlers orientation district study.

Findings from research and collaboration	Implications in exploration
. Geochemex, Forsayth and CSIRO showed the extent of buried laterite in terrain characterized by largely eroded uplands and alluvial-colluvial plains. (Report 166R)	- Showed potential for exploration based on drilling for buried geochemical haloes to locate concealed mineral deposits beneath alluvial and colluvial plains.
. Regolith-landform patterns are explained in terms of erosional, residual and depositional regimes. (Report 166R)	- Appropriate geochemical exploration methods can be chosen according to regolith-landform mapping units or regime.
. Regolith-landform models were established. (Report 166R)	- Enables prediction into appropriate terrain elsewhere.
. Criteria were established for recognizing and discriminating buried lateritic residuum from sedimentary units containing gravel lenses with abundant transported lateritic nodules and pisoliths. (Report 166R)	- Enabled accurate logging of drill spoil (RAB, air core, and RC drilling) and identification of regolith stratigraphy. Made reliable sampling feasible.
. A wide range of laterites and associated ferruginous materials were categorized with regard to their petrographic and chemical properties and genesis. (Report 166R)	- Enabled sample types to be discriminated, thus improving the reliability of sampling and data interpretation.
. Showed it was possible to separate Fe-segregations, ferruginous saprolite and lateritic residuum based upon geochemical and mineralogical characteristics. (Report 166R)	- This is an important step towards routine geochemical screening of exploration samples into sample types. (However, this should not be seen as replacing routine logging.)
. The multi-element characteristics of dispersion in laterite at the North Pit and Turrett deposits were established. (Report 166R)	- Adds confidence that chalcophile trends in laterite can be followed leading to discovery of concealed ore deposits.
. Colluvium shows an association of Au, Ag, Pb, and Sb, with As where hardpanized. Lateritic residuum, ferruginous saprolite, and iron segregations show anomalous Au, As, Cu, Sb, Bi, and W associations, with lateritic residuum being broadest.	- Shows potential of alternate media for sampling where lateritic residuum is missing, e.g. iron segregations in erosional regimes.
. Geochemical data sets were established for several sample media. (Report 166R)	- Provides well-controlled target data sets for use in multivariate interpretation.
. Lag types have been linked to regolith-landform units. (Report 166R)	- Demonstrates the need for regolith-landform control in lag sampling.
. Mapping the regolith-landform units and understanding the relationships. (Report 166R)	- Increased efficiency in regolith-landform mapping using remote sensing, particularly LANDSAT TM. (Amira Project P243)
. Detailed regolith mapping, regolith stratigraphy, other field relationships, and project material.	- Provides readily accessible training areas for regolith mapping in exploration.

4.5   Beasley Creek

4.5.1   Introduction

An comprehensive study of the Beasley Creek Gold Deposit, held by Western Mining Corporation Ltd, has been carried out within the CSIRO/AMIRA Yilgarn Gold Research Programme. The area has a hot arid climate, similar to Lawlers, with a median annual rainfall of approximately 200 mm. This deposit lies about 12 km WNW of Laverton at 122° 18'E, 28° 34'S. Here, Archaean rocks occupy a small window in the surrounding Permian glacial sediments. Both the Archaean and Permian rocks have been deeply weathered, but only the saprolite of the Archaean rocks outcrops in a few places. The ore body lies in a black shale zone, some 15-40 m thick, which dips at 45° to the E. It strikes generally N, but swings to the W at its southern end and flattens. This black shale unit is intensely weathered to considerable depth (>200 m) and Au is associated with ferruginous zones within it. The black shale is enclosed in a narrow, north-striking basaltic, amphibolitic schist, which is less intensely weathered (40 m), particularly were distant from the black shale. Small porphyry, granitoid, and metadolerite lenses intrude the stratigraphy and are associated with north-west striking faults and shears. The amphibolite schist is in turn enclosed in komatiitic lithologies of the Mt. Margaret Anticline. Proved and probable ore reserves of 2.1 million tonnes at 2 g/t have been outlined by Western Mining Corp. Ltd. The CSIRO research commenced prior to disturbances by mining which began at the end of 1987. The open pit is now well advanced and mining halted.

Mining at Beasley Creek has provided an opportunity for an integrated study of the surficial materials and the saprolite at Beasley Creek, involving all three of the CSIRO-AMIRA Yilgarn Projects referred to in the Preface. Surficial materials were mapped and soil and lag samples were collected along two transects over the mine site and into the background. The landscape around the Beasley Creek Gold Mine leaves a first impression of simplicity but, in actuality, it is quite complex (Fig. 4.42). Surface geochemical media are part of this landscape, so it is essential to understand them in order to select the best materials and interpret the results.

The site of the Beasley Creek Gold mine lies on a small rise 3.5 m above the surrounding wash plains which, together, form a low, tabular divide between broad drainage floors to the north and south. The rise is asymmetric, with a very gentle western slope, marked by calcrete and sparse, small, saprolite outcrops. The crest has sporadic outcrops of iron segregations in saprolite, and a steeper, eastern slope, protected by lateritic duricrust. The regolith at Beasley Creek has been partly stripped. A ferruginous, lateritic duricrust closely follows the upper surface of an ore-bearing black shale unit and it seems likely that Fe, in the shale, probably originally as sulphides, was the source of Fe in the lateritic duricrust. Pods of iron segregations and associated lag overlie both the ore-bearing black shale and metadolerites.
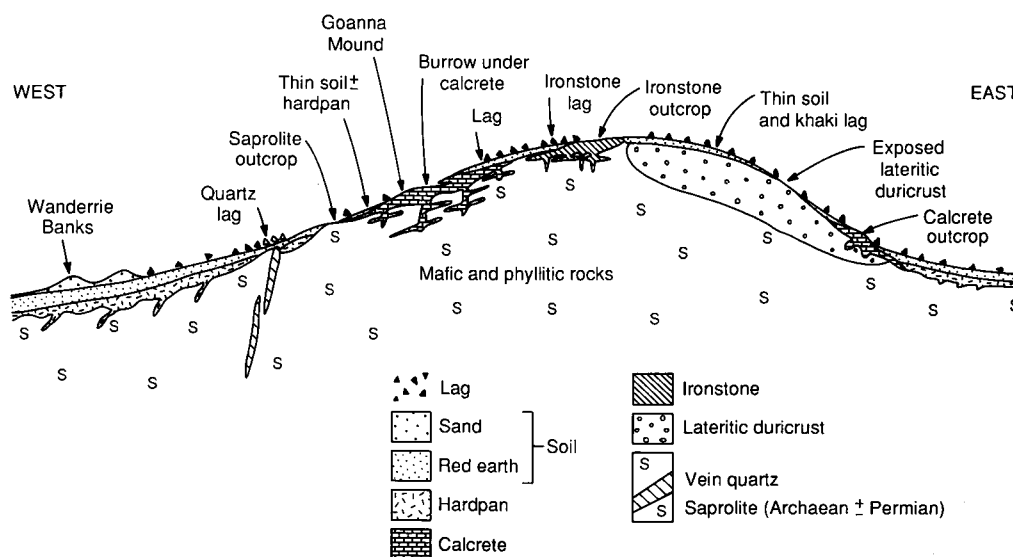
Fig. 4.43. Sketch cross section of the hill at Beasley Creek showing relationships between major surficial materials (not to scale).

The whole area, including the rise, is mantled by red, friable clay soil and strewn with a multi-component lag. This was derived by selective removal of the fine fractions of the soil by sheetwash and deflation. The soils on the low-lying areas are deeper (0.3-4.5 m) than on the rise, are generally acid and are underlain by hardpan, but become alkaline and thin (0.1-0.2 m) on the rise where they are underlain by saprolite and calcrete. The distribution of the duricrust-related khaki lag closely follows the hangingwall of the black shale orebody. A coarse, black, ferruginous lag has a wide distribution, but seems associated with the subcrop of the host black shale, and its contained iron segregations, and is concentrated within 200 m of its source. A finer, brown ferruginous lag has a wider distribution and its finest fractions have been partly separated by downslope colluvial sedimentation. Quartz lag is dispersed around small quartz veins, unrelated to ore.

Considerable multi-element geochemical, mineralogical, and petrographic detail has been gathered from the surface and near-surface regolith materials. This information is essential for meaningful multivariate statistical interpretation of geochemical data. Ultimately, the Beasley Creek orientation study will provide geochemical reference groups for a broader phase of research, that of establishing multivariate data interpretation procedures, appropriate to Yilgarn lateritic weathering environments.

4.5.2 Objectives

The overall objective was to carry out a geochemical orientation study about the Au deposit, which, at commencement of the study, was largely undisturbed.

Specific objectives were:

1. To map the regolith-landforms surrounding the deposit.

2. To delineate multi-element geochemical dispersion patterns in the coarse and fine ferruginous lags which mantle the deposit and its vicinity.

3. To delineate the multi-element dispersion patterns in the soil overlying the deposit to ascertain which soil components were the best geochemical media and to compare these with the lag.

4. To provide well-controlled target geochemical data sets for these sample media.

4.5.3 Research components and reports produced

CSIRO research at Beasley Creek is being carried out as an integrated regolith and bedrock study within this project and AMIRA Project P241 (Weathering Processes). Components of research have been reported as follows:

•	Regolith-landform relationships and surface geology I.D.M. Robertson and H.M. Churchward	Report 26R July, 1989
•	Orientation geochemistry of ferruginous lag I.D.M. Robertson	Report 27R November, 1989
•	Orientation geochemistry of soils I.D.M. Robertson	Report 105R September, 1990

The geochemical dispersion within saprolite is being studied as part of AMIRA Project P241. In addition, the field spectral properties of selected surface materials (lag and soil) are being determined within AMIRA Project P243 (Remote Sensing for Au, WA).

4.5.4 Lag

The fine (0.2-4.0) and coarse (10-50 mm) fractions of the black ferruginous lag were studied physically, petrographically, mineralogically, and geochemically. The fine lag was split into magnetic and non-magnetic components.

Mineralogy and petrography
The black ferruginous lag consists mainly of goethite and hematite with minor kaolinite, illite, quartz, and interstratified clay. The hematite and goethite contents appear to be complementary. Background lag samples are richer in kaolinite, quartz, and hematite and poorer in goethite than those nearer ore.

The lag contains ferruginized lithorelics with relict and pseudomorphed minerals and fabrics inherited from the underlying primary lithology, the saprolite, and the plasmic horizon. The phyllitic host rock is indicated by relics of slightly K-deficient mica and kaolinite. The mafic and ultramafic rocks are shown by fingerprint fabrics after saprolitic clays. Goethite pseudomorphs kaolinitic accordion structures which, originally, were either saprolitic or plasmic fabrics rather than fabrics of the fresh rock. The Permian glacials are reflected by polymictic breccia fabrics.

The lithorelics are surrounded by several phases of secondary goethite and hematite, which have obliterated much of the original fabric. Hematite appears to be a dehydration product of goethite. Later history is shown by skins and complete nodules of ferruginous clay, which have undergone several cycles of solution, clay precipitation, and permeation by Fe-bearing solutions. The fine lag contains additional minor components of calcrete, quartz, and fragments of a geochemically very important cellular ironstone or gossan (Robertson, 1989:Appendix 7).

Fabric information from the coarse lag may be used to help determine the underlying lithologies of lag-covered areas, without the need for drilling. Although the fine lag has similar fabrics, the information is fragmentary and its clasts more widely dispersed, so that elucidation of the original rock type is difficult.

Geochemistry
Lag derived from the orebody is anomalous in Au, As, Ba, Co, Cu, Fe, Mn, Mo (weak), Pb (possible), Sb, W, and Zn. The cellular ironstone appears to be responsible for much of the anomalous As, Au, Co, Cu, Mn, Sb, Se, and Zn. Gold is the best indicator of mineralization and shows strong anomalies (1000 ppb over a 10 ppb background) which are 600-900 m wide. Other elements show narrower dispersions. Superimposed on these broad Au anomalies are narrow, subsidiary peaks (>10,000 ppb), specifically in the coarse lag, which accurately locate the ore. The wide dispersion of gold reflects dispersion in the underlying rocks, prior to mechanical surface dispersion of the lag. The very distinctive Mn and Ba anomalies are thought to be related to the ore host rather than to the ore itself.

Both the coarse and the fine lags are effective geochemical media as key indicator elements are readily adsorbed by goethite, which is their major component. Intense Au spikes in the coarse lag locate the orebody more precisely than the more mechanically-dispersed fine lag. The fine lag gave better results for Sb, W and Zn; the non-magnetic component of the fine lag was geochemically superior to the magnetic component as it contains gossanous fragments. As the non-magnetic component makes up about 75% of the total lag, only a slightly-improved performance could be gained by analysing it separately. The geochemical signal could be considerably improved if the minor, cellular ironstone could be extracted and analysed separately, but use of such a specific material would then be entirely dependant upon sufficient gossan fragments reaching the surface. The adsorbed metals on other goethitic materials should be not ignored.

Dispersion and origin
The fine lag is readily transported by surface water, even down a very slight gradient, but the coarse lag requires either a significant gradient or introduction into a drainage to move any distance. In general, the finest fractions of the fine lag show the greatest dispersion and the coarser fractions show progressively lesser dispersion. The more dispersed fine lag is better for defining the general area of mineralization in a first pass survey; the coarse lag should be used for follow-up. The distribution of the khaki lag and the ironstone lag are not sufficiently universal at Beasley Creek for them to be used effectively as geochemical sampling media.

The potential of a lag as a geochemical sampling medium depends upon its geomorphic setting and on the underlying geology. Lag derived from weathered Permian glacial sediments would have a severely-reduced potential as would lag derived from a thick blanket of recently-transported overburden. Lag derived from underlying duricrust and from the saprolite of partly-eroded areas has the best potential. It is therefore necessary to map the geomorphology and, as far as possible, the underlying geology in order to subdivide the geochemical data prior to statistical treatment.

4.5.5 Soil

Composition
The soil consists of three contrasting fractions. There is a coarse, saprolite-derived fraction (>710 μm; petrographically indistinguishable from the lag) of dense, goethitic granules (some magnetic), slightly less-

dense, ferruginous, clay pebbles and granules, a few quartz grains, fragments of calcrete, hardpan and rare cellular gossan. The proportion of gossan fragments is significantly greater close to the orebody. The intermediate fraction (75-710 μm) consists largely of hematite-coated, wind-blown quartz sand, which acts as a geochemical diluent, and minor grains of feldspar. The fine fraction (<75 μm) consists of quartz grains and smaller kaolinite and Fe-oxide particles (1 μm), partly locally derived by breakdown of clay pisoliths and granules and partly wind-blown.

The goethitic granules are analogous to the lag and consist of reveal mica relics, goethite pseudomorphs after kaolinitic lithorelics, and vermicular accordion structures, set in a variety of secondary goethite phases. The clay-rich granules consist largely of hematite- or goethite-stained kaolinite and some include goethite-rich lithorelics.

Soil fractionation and mineralogy

Wet sieving and an efficient clay sedimentation technique, using pH control, were used to separate the soil into the ferruginous (710-4000 μm), the relatively quartz-rich (<75 μm) and the clay- and Fe oxide-rich (<4 μm) fractions.

The complete soil and its constituent size-fractions were analysed to assess their value as sampling media. The largely aeolian 75-710 μm fraction was discarded. The <4 μm fraction shows maximum abundances in both kaolinite and sericite over the ore, probably related to the phyllitic host rock. The geochemical expression of mineralization in the different size-fractions of the lag and soil are compared in Table 4.9.

Table 4.9. Comparison of anomaly widths and peak to background ratios.

| | COARSE LAG | | FINE LAG | | | | | | |
| | | | All | | Magnetic | | Non-magnetic | | |
	Peak P/B	Width (m)	Peak P/B	Width (m)	Peak P/B	Width (m)	Peak P/B	Width (m)	Possible Source
Au1	5	100							
Au2	100	900	100	900	5	600	7	700	Supergene
As	3	100	2	100	?		2.5	100	Ore
Sb			1.5	300	?		1.5	100	Ore
Se	2	100	1.5	100	-		2	100	Ore
Cu	2	100	2	200	-		1.5	200	Ore
Pb	2	100							Ore
Cd	-		-		-		-		Ore
Zn	?		1.5	100	-		1.5	100	Ore
Co	2	100	1.5	100			1.5	100	?
W	?		3	100	?		2	300	Ore
S									?
Ba	5	300	7	300	8	300	6	300	Host Rock
Mn	15	200	6	200	?		7	200	Host Rock

| | SOIL | | | | | | | | |
| | Complete Soil | | 710-4000 μm | | <75 μm | | <4 μm | | |
	Peak P/B	Width (m)	Peak P/B	Width (m)	Peak P/B	Width (m)	Peak P/B	Width (m)	Possible Source
Au1	5	200	30	300	5	100	3	200	Supergene
Au2	6	900	30	300	5	900	8	900	Supergene
As	3	100	3	200	3	100	3	100	Ore
Sb	1.5	200	1.5	200	-		-		Ore
Se	2	200	1.5	300	-		-		Ore
Cu	2	200	2	200	-		2	200	Ore
Pb	-		-		-		-		Ore
Cd	3	300	6	200	?		4	100	Ore
Zn	1.5	200	2	200	1.5	200	1.3	200	Ore
Co	-		?		-		-		?
W	?	100	4	200	?		3	200	Ore
S	4	300	3	300	6		5	200	?
Ba	2.5	200	15	300	?		?		Host Rock
Mn	3.5	300	3.5	200	2.5	300	5	300	Host Rock

Notes: Au1 Relatively narrow gold anomaly, closely defining target.
Au2 Broad gold anomaly giving a locally high background.

Geochemistry

The geochemical characteristics of the 710-4000-μm fraction and the fine lag are virtually identical. Gold is distinctively anomalous, giving a very broad peak of >20 ppb but locally reaching 200-300 ppb. The 710-4000 μm fraction is the most effective medium with the highest Au anomalies and the greatest anomaly to background contrast. The orebody is also depicted by anomalies in As, Cd, Cu, Sb, Se, W, and Zn and the host rock by Ba and Mn. A maximum in S over the ore is related to a subcropping gypsiferous horizon. Although As is concentrated in the 710-4000-μm fraction, the anomaly to background contrast is better in the fine fractions. There is a small Pb anomaly (50 ppm in a background of 30 ppm) in the coarse lag, but no corresponding anomaly in the fine lag or in the soil. Sulphur is anomalous in all fractions. Increased geochemical noise in Co, Ni, and V over the rise at Beasley Creek reflects the saprolites of Archaean rocks buried under a shallow, residual soil. This may be contrasted with the lesser geochemical noise in these elements, over weathered Permian rocks, possibly buried under a slightly-deeper, colluvial soil. There is a decrease in the Si abundance over the ore host rock, whereas Fe in the lateritic duricrust shows a complementary increase.

4.5.6   *Exploration implications*

Gold anomalies in this arid region, and particularly their contrast, are greatly improved by the use of the coarse, ferruginous 710-4000-μm fraction, in preference to the complete soil. Apart from Au, anomalies in As, Cd, Cu, W, and Zn comprise the useful multi-element signature of Beasley Creek. The effectiveness of the various sampling media are summarised in Table 4.9 in terms of peak background ratio, anomaly width, and clarity of the anomaly.

The soil has been diluted by wind-blown sand and, in its complete form, is less effective than certain of its fractions. The quartz-rich 75-710-μm fraction should be removed, by sieving, prior to analysis. The most effective media are the coarse, ferruginous 710-4000-μm soil fraction and its analogous fine lag, followed by the <4-μm soil clays. The <75-μm silty soil fraction also contains a significant wind-blown, sandy component and is the least effective size fraction together with the clearly wind-blown 75-710-μm fraction. Preferential use of the coarse and fine fractions, where aeolian dilution has occurred, is a similar conclusion to that reached by Barbier (1987), Salpeteur (1985) and Salpeteur and Sabir (1989) where aeolian dilution is more severe. Mazzucchelli (1980) was able to achieve a similar improvement by partial extraction (acetic acid) of the fine (<175 μm) soil fraction (presumably extraction from Fe oxides).

Fine lag is an excellent sampling medium. Only a very marginal improvement may be gained by using the non-magnetic portion of the fine lag, but it is doubtful if the improvement would be worth the extra cost of separation. The coarse lag fraction (10-50 mm) will find use in follow-up work and for assisting geological mapping. The enhanced dispersion of Au in the soil clay fraction, together with proven responses in As, Cd, and Cu, suggests that it could be used for drainage surveys in areas of low relief. Its separation from the soil does not present any great technical difficulties.

Size fractionation and microscopic examination of the components of both soil and lag during orientation surveys and during the exploration process will contribute to an understanding of the history of these materials. Information gleaned from this will ensure that the correct media are collected, detect gossan fragments, and help with interpretation of results.

The main implications in exploration of the research at Beasley Creek are listed in Table 4.10.

Table 4.10.   The implications in exploration listed against the research findings, Beasley Creek orientation study.

Research Findings	Implications in Exploration
■ Regolith-landforms mapped on regional and prospect scale; showed erosional regime on hill, with colluvial, depositional regime on surrounding wash plains. Distribution of lag types mapped. (Report 26R)	- Appropriate exploration medium chosen to suit regolith-landform regime and availability.
■ Petrography of lag revealed relics and pseudomorphs of some primary minerals but largely saprolitic material. Permian glacials showed clear clastic fabric. Much fabric obliterated by secondary goethite and hematite. (Report 27R)	- Some potential for coarse lag petrography to aid mapping. Necessary to take several samples at one site to find useful fabric.
■ Fine lag gives most reliable Au anomalies but coarse lag accurately located ore location. (Report 27R)	- Fine lag appropriate for first pass geochemical survey with coarse lag useful for follow-up of specific anomalies.
■ Non-magnetic fraction of lag better for multi-element geochemistry. (Report 27R)	- Use of magnetic fraction, though yielding consistent sample medium, very questionable practice.
■ Soil composed of three major components; a coarse fraction of ferruginous granules, analogous to fine lag, a silty-sandy fraction of largely wind-blown quartz, a ferruginous clay component. Some minor gossan fragments included with coarse fraction. (Report 105R)	- Importance of well-executed orientation survey paramount. This must include physical examination of sample media as well as chemical.
■ The corse soil component gave best Au and multi-element anomalies, the clay component also good; silty-sandy component least effective. (Report 105R)	- Removal of wind-blown diluting material important in areas of aeolian action. - Clay fraction shows promise for drainage sampling in areas of very low relief.
■ Usable anomalies in Au, As, Cd, Cu, Sb, Se, W, Zn depict the lag for orebody. Ba and Mn depict the host rock. (Report 27R)	- This type of orebody has a strong multi-element signature.
■ Geochemical data sets established for several sample media. (Reports 27R and 105R)	- Provides well-controlled reference data for use in multivariate interpretation procedures.

4.6 Boddington

4.6.1 *Introduction*

Discovery of the Boddington Au deposits (Davy and El-Ansary, 1986) was particularly significant to exploration in WA because it is a world class deposit of a new type, close to Perth, located within a relatively-small greenstone belt and had remained undetected despite more than 100 years of prospecting within the state. The presently-mined Au deposits, which are distributed along 5 km of strike length, are located within the saprolitic part of the lateritic mantle and were formed by supergene enrichment during weathering of a Cu-Au porphyry system (Monti, 1987, Symons, *et al.*, 1990).

The Boddington research, part of which is discussed here, provides an important orientation study of geochemical dispersion in a relatively-high rainfall part of the state. It also will allow comparison with orientation studies carried out inland. When the proposal for the AMIRA Laterite Geochemistry Project was being drafted, mining operations were about to commence. It was essential, for future exploration and research, that such a study of geochemical dispersion be carried out before the opportunity was lost. Sampling of the surface material was therefore an early priority. Through collaboration, Worsley Aluminium carried out the required systematic sampling on a close grid over areas that were to be disturbed. Sampling of profiles followed as the mining pits were developed.

The Boddington Gold deposit occurs within the northern part of the Saddleback greenstone belt, which is centred at 32°50'S and 116°57'E, approximately 100 km SSE of Perth (Fig. 1.2). The climate is Mediterranean, with mild, wet winters and warm, dry summers and mean maximum temperature ranging between 12 and 28°C. Rainfall is 810 mm (Davy and El-Ansary, 1986).

The dominant vegetation is scherophyll forest. Varying proportions of *Eucalyptus marginata* and *Eucalyptus calophylla* form the upper storey on the ridge crest and slopes. The middle and lower storey is dominated by *Banksia grandis*, *Persoonia longifolia* and *Xanthorrhoea preisii* and *Macrozomia riedlei*. *Eucalyptus calophylla* and *Melaleuca preissianan* dominate the upper storey of the valley floors, where the lower storey contains *Xanthorrhoea preisii*, *Kingia australis* and *Hypocalymma angustifolium*.

The first significant event for Au and base metals exploration in the region was recognition of the relatively-small greenstone belt by Wilde (1976). A geochemical prospecting programme, seeking Au, Cu, and Zn mineralization in the Saddleback greenstone belt, instituted by the WA Geological Survey followed. This led to the discovery, in 1979, of an area of anomalous Au, As, Cu, Pb, Mo, and Zn (Davy, 1979). In 1980, Reynolds Australia Mines Pty Ltd commenced an exploration programme for commodities other than bauxite in the area (El-Ansary, 1980). Surface laterite sampling, followed by systematic reassaying of bauxite drill samples, led to the discovery of the Boddington Au deposit (44 million tonnes of lateritic ore at 1.8 g/t Au, (Symons *et al.*, 1990).

A study of the mineralogy and geochemistry of four drill holes and geochemical patterns in the lateritic profile at the Boddington Au deposit had been carried out by Davy and El-Ansary (1986). The primary mineralization has been described by Symons *et al.* (1988).

4.6.2 *Objectives*

The overall objectives of the Boddington study were to provide a well-understood regolith-landform framework over the district and within this, to carry out multi-element, orientation, geochemical dispersion studies about the concealed Au deposits.

Specific objectives were to:

- Establish regolith-landform relationships,
  - including the regolith stratigraphy,
  - characterization of regolith units, and
  - generating a model of regolith-landform evolution.
- Elucidate the origin and evolution of lateritic pisoliths and nodules.
- Examine the variation in geochemistry, petrology, and mineralogy of regolith units developed on (a) the intermediate to felsic rocks and (b) the mafic rocks.
- Examine the variation in behaviour of ore-associated elements, including Au, and mineralogy of various laterite morphologies.
- Provide a multi-element orientation geochemistry database.

4.6.3   Research components and report

During this AMIRA project, research at Boddington has been directed at the following interrelated components:

- the regolith-landform framework;
- laterite classification;
- geochemical dispersion studies;
- siting and bonding of elements of interest; and
- integration of research.

Research results are presented in Report 246R, which, at the time of summarizing here, was still within the confidentiality period. A summary of that report will be an addendum to this report once cleared by the tenement holders.

Prior to commencing the Boddington orientation study, the Laterite Geochemistry Group had carried out reconnaissance of laterite geochemistry over the Saddleback Greenstone Belt. That work is summarized below.

4.6.4   Regional laterite geochemistry of the Saddleback Greenstone Belt

The geochemistry of surface laterites of the Saddleback greenstone belt was studied by the Laterite Geochemistry Group during 1980, prior to discovery of the Boddington Au deposit. The purpose was to investigate the geochemical characteristics of lateritic cover of a greenstone sequence in a high rainfall area. A total of 140 samples of lateritic pisoliths and nodules (categories LT102, LT103) and some pisolitic or nodular duricrust (LT202 and LT203) were collected. This was a pilot study with samples spaced between 1 km and 3 km. The study identified a regional chalcophile anomaly and a smaller yet substantial coincident multi-element anomaly, later seen to lie over the Boddington Au deposit (Davy and El-Ansary, 1986).

Some of the patterns shown by the distribution of elements of importance in Au, base metal and rare metal exploration are shown in Figs 4.44 and 4.45, together with a figure showing the interpreted bedrock relationships from Wilde (1976). One of the most striking features is the large anomaly shown by the chalcophile index CHI-6*X, Fig. 4.44B. This is an additive, weighted linear combination of As, Sb, Bi, Mo, Ag, Sn, W, and Se (Section 8.3) but does not include Au in this version. The Au patterns shown by this pilot study show anomalies at surface, yet they are not striking on a regional scale.

Separate patterns for As, Bi, Sn, and W are also shown. Each is markedly anomalous (Yilgarn thresholds are shown). The 'proximity index' NUMCHI-1 (Section 8.3) is also shown. This index adds up the number of elements which exceed their corresponding pre-selected thresholds. This index delineates a strong, large (3 km by 5 km) anomaly centred on Boddington.

The reconnaissance study clearly showed the Cu, Bi, Mo, Sn, W, Au association of the Archaean Cu-Au Boddington porphyry system as well as the regional chalcophile geochemical anomaly and its culmination.

The relationship between the detailed geochemical orientation study (Section 4.6.6) and the regional sampling is shown in Fig. 4.44A. The regional sampling was also used for lithological discrimination studies (Section, 4.6.5).

4.6.5   An investigation of geochemical composition of pisolitic laterite as an indicator of gross bedrock type in the Marradong-Duncan Area (Saddleback Greenstone Belt). R.D. Birrell,* 1985. Preliminary Thesis, Master of Science, University of WA.

Abstract

Recognition at the surface of potentially-mineralized "greenstone" belts in the Archaean Yilgarn Craton of Western Australia is often difficult or impossible due to a lateritic weathering profile or its remnants.

This study has investigated geochemical relationships between gross bedrock type and surficial pisolitic laterite developed over an area encompassing the Saddleback greenstone belt, the host of the substantial Boddington Au deposit.

A broad distinction between greenstone and granite/migmatite lithologies is shown by levels of Si, Fe, Ti, V, Mn, Cu, Zn, Ni, Zr, and Nb in pisolitic laterite, while elevated As and complimentary Sb levels are indicators of acid volcanics within the greenstone belt.
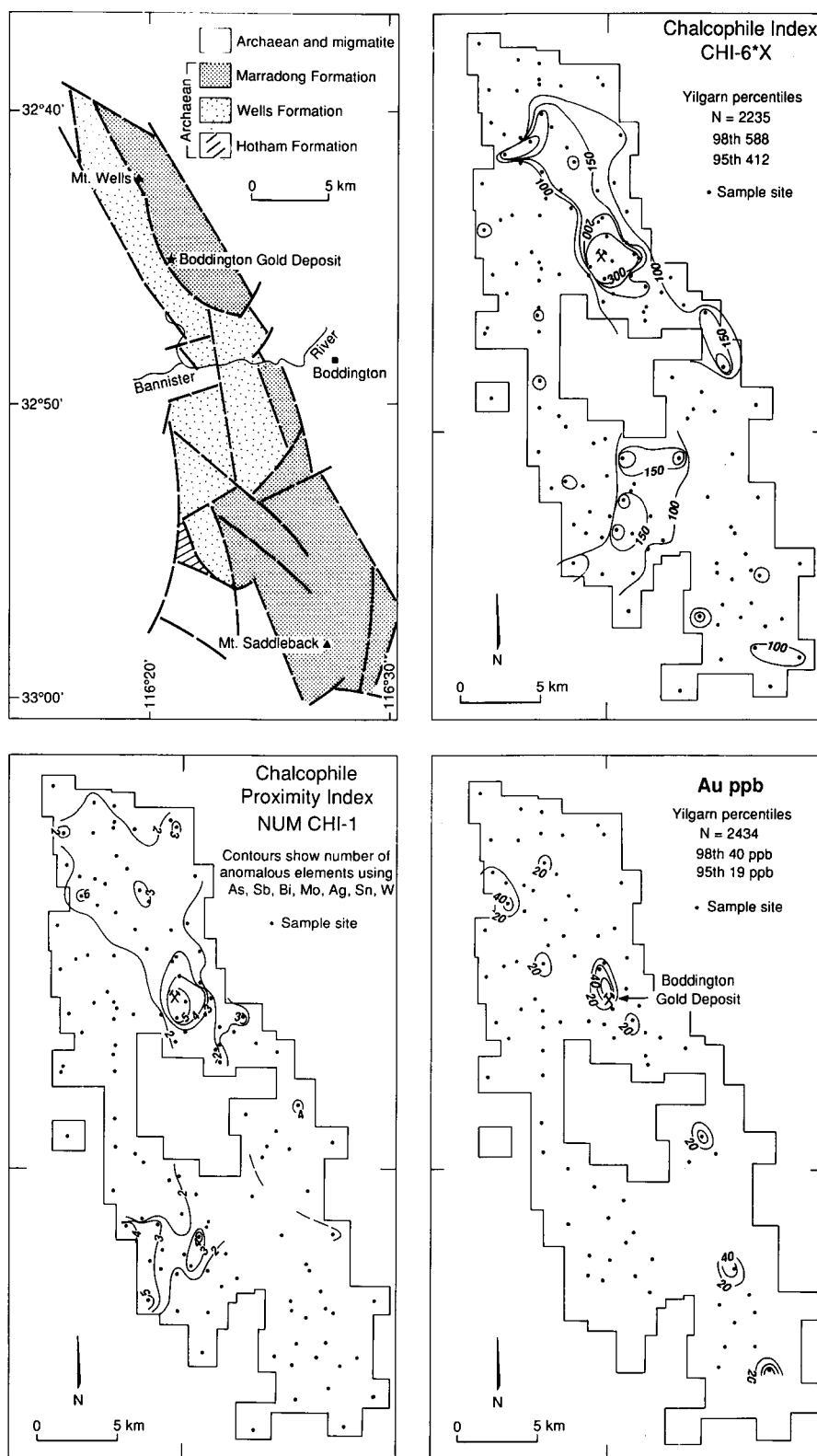
Fig. 4.44. Maps of the Boddington district showing, A the interpreted bedrock relationships of the Saddleback Greenstone Belt (Wilde, 1976), B large anomaly indicated by chalcophile index CHI-6*X, C anomaly shown by the NUMCHI-1 index (see section 8.3), D small Au anomalies at surface. (Data from Innes *et al.*, 1988). All of the geochemical maps are based upon pisolitic laterite collected from the surface.
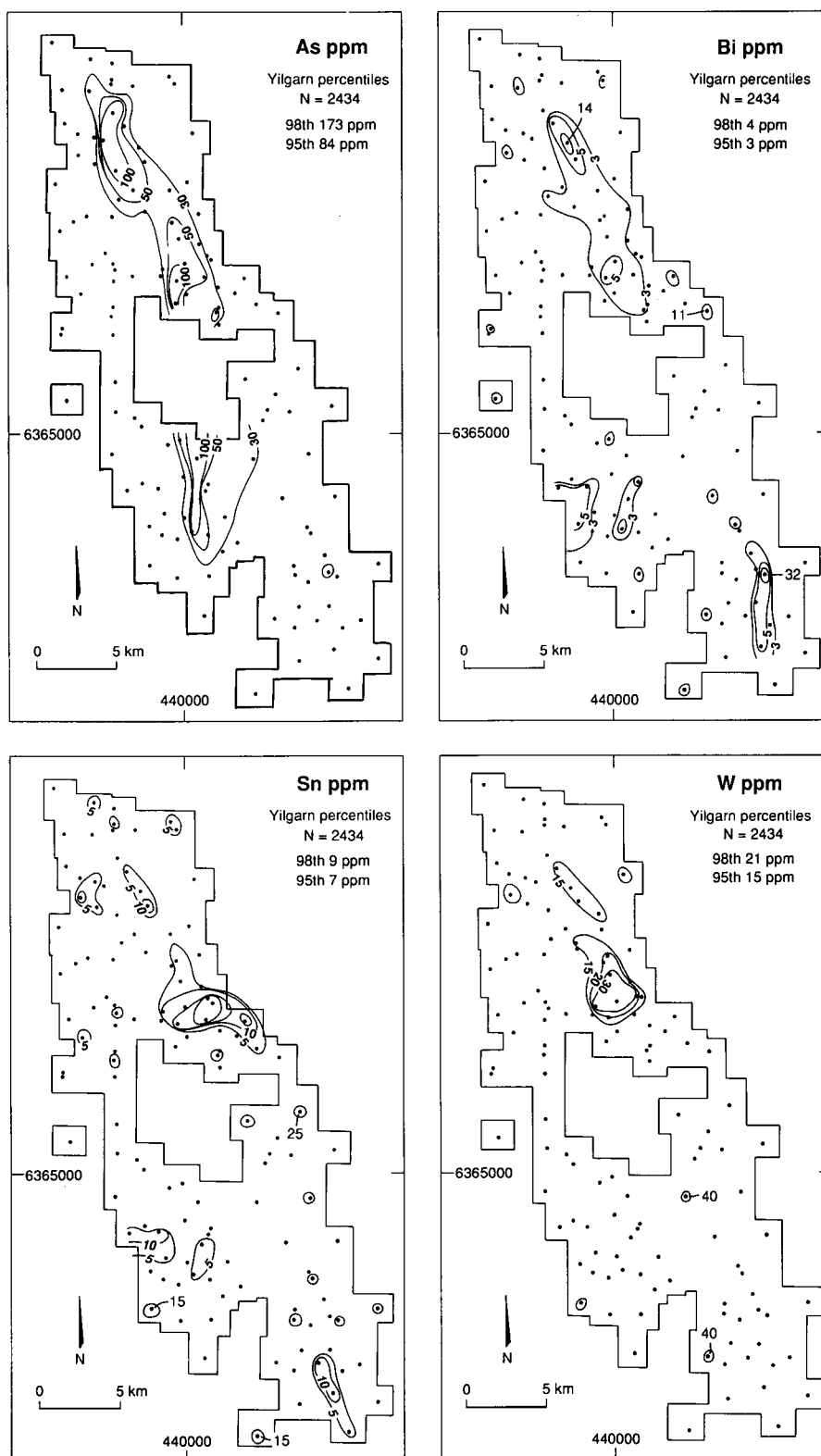
Fig. 4.45. Maps of the Saddleback Greenstone Belt showing the regional distribution of As, Bi, Sn, and W in surface pisolitic laterite (Data from Innes *et al.*, 1988).

Anomalous levels of chalcophile elements (As, Sb, Bi, Sn, Mo, W, and Au) are associated with the Boddington Gold Deposit.

Univariate and bivariate data interpretation techniques were used for investigation of geochemical relationships between pisolitic laterite and gross bedrock type. The methods employed enabled a broad definition of the basic volcanic component of the greenstone belt, while elevated values of the As/Mo ratio reliably defined acid volcanic lithologies.

Although empirical techniques had been useful, an improvement in gross bedrock definition, particularly over the Saddleback Group, was achieved using more sophisticated multivariate statistical procedures. Canonical variate analysis, applied to four gross bedrock reference groups, was successful in separating all groups, including the acid and basic volcanic components of the greenstone belt, using the following 14 elements: Si, Al, Na, K, Ti, Mn, Cr, Cu, Zn, As, Mo, Sn, Ga, and Nb [Fig. 4.46].

The study suggests that the prediction of gross bedrock type, including a mineralized acid volcanic lithology, is possible using the geochemical composition of *in situ* pisolitic laterite and multivariate statistical techniques.

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* GEOCHEMEX Australia, 280 Hay Street, Subiaco, Western Australia.
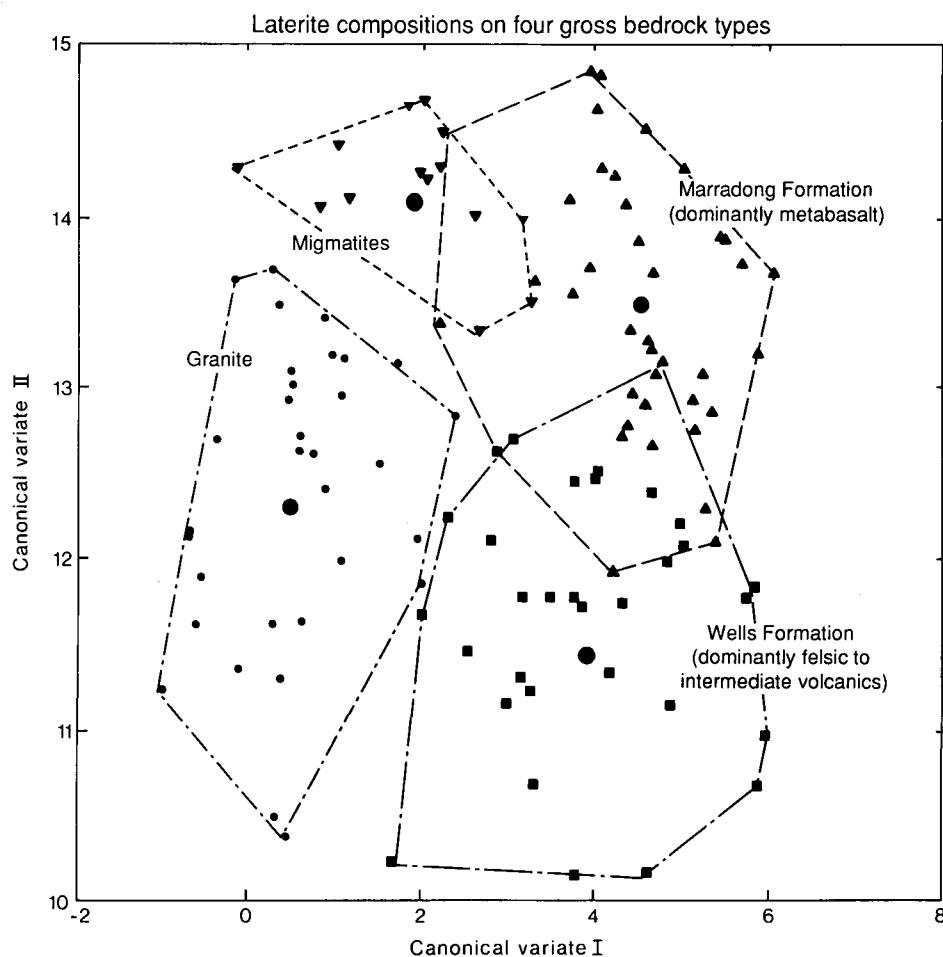
Fig. 4.46. Plot of CVA scores for laterite compositions on four gross bedrock types, after Birrell (1985).

4.6.6   *Regolith-landform evolution and geochemical dispersion from the Boddington Au deposits.   R.R. Anand.   Report 246R, submitted to tenement holders, November 1992.*

Note: Abstract with supporting diagrams will be issued as an addendum to this report once cleared by the tenement holders.

4.6.7   *Implications in Exploration*

Full comments on the implications of the Boddington orientation study in exploration have to await the clearance of Report 246R through the confidentiality requirements. However some important implications can be made from the reconnaissance study, from general findings of a non-sensitive kind, and from published work. These implications are listed in Table 4.11.

Table 4.11.   The implications to exploration listed against the research findings, Saddleback greenstone belt and the Boddington orientation study (as cleared at this stage of confidentiality requirements).

Research findings	Implications in exploration
■ Reconnaissance laterite geochemistry shows a large (30 km long) chalcophile pattern passing through the Boddington Au deposit. The patterns are seen in laterite and owe their origins to geochemical features in bedrock. (Section 4.6.4)[*]	- Reconnaissance exploration should seek and follow-up of large chalcophile patterns, in this case recognized in laterite. - Such chalcophile patterns or corridors can also be recognized using other sample media.
■ Coincident, strong, multi-element, geochemical anomalies occur in laterite directly above and adjacent to the Boddington Au deposit. (Section 4.6.4)[*]	- Exploration can have confidence in large, coincident, multi-element, chalcophile anomalies. - A large geochemical anomaly can mean a large mineral deposit.
■ Au in laterite and lateritic gravel at surface is relatively weak. The main distribution of anomalous Au is subsurface, at a depth of 3 m and below the base of duricrust and within the underlying bauxite zone also (Davy and El-Ansary, 1986; Monti, 1987[*]). Perhaps leaching is due to relatively high rainfall compared with inland areas (cf Mt. Gibson, Section 4.2).	- Realize that Au may be depleted from surface materials, perhaps due to high rainfall. Again place confidence in multi-element, chalcophile anomalies even if Au is not anomalous or only weakly anomalous.
■ Chalcophile elements (As, Sb, Bi, Mo, Sn, W) are strongly anomalous at surface. (Section 4.6.4)[*]	- Chalcophile anomalies appear to be more robust, when exposed to sustained weathering than Au under the prevailing moderately-high rainfall conditions.

[*] These relationships have been expanded and new relationships established in Report 246 (Anand, 1992).

5.0   SITING OF ELEMENTS AND DISPERSION PROCESSES

5.1   Introduction

Studying the processes of geochemical dispersion enables a better understanding of the circumstances under which anomalies will form, be recognizable, and, ideally, their multi-element characteristics may be predicted. Understanding the siting of anomalous elements is a necessary part of establishing dispersion processes. It can also shed light on the stability of expected anomaly characteristics, such as element abundances and associations in different surficial environments. The term *target-associated elements* is used to refer to elements which are associated with ore deposits. These include elements that are ore forming and those which occur at minor and trace levels in the deposits (this is a collective term for ore elements and pathfinder elements). In this report, reference is particularly made to target-associated elements of Au, base metal, and rare or strategic metal deposits.

Table 5.1 summarizes the main characteristics of the anomalies studied. Most of the information in this section was derived from the orientation studies in Section 4.

It is clear from this table that geochemical anomalies in lateritic residuum are much larger in area than the generally concealed ore deposits which are being sought. Most of the laterite geochemical anomalies are characteristically multi-element. For Au and base metal sulphide deposits target-associated elements contribute important information on dispersion. In general, geochemical anomalies are strongest and are characterized by the widest range of elements closest to the ore deposit source. In lateritic residuum, this generally directly overlies the weathered mineralized system.

In this section, the siting of these target-associated elements is discussed, and is followed by a discussion of interpretation of dispersion processes, and the implications of the research findings to exploration.

5.2   Siting and partitioning of target-associated elements

Research in this subject had to be selective, based upon the importance of likely outcomes and was limited by the practicalities of study, including the lower limits of detection of analytical methods (e.g. the electron microprobe).

The objectives were to:

(i)   establish the siting and bonding of target-associated elements in the strongest parts of anomalies within some of the orientation areas;

(ii)   deduce the stability or robustness of anomalies related to the studied ore types in a variety of surficial environments; and

(iii) establish general predictive guides for anomaly expectations.

These findings have been incorporated into geochemical dispersion models, as the project developed, and are reported in Section 9.0.

5.2.1   *Mt. Gibson siting and bonding investigations*

Introduction

The specific objectives were to establish (a) the siting of target-associated elements within selected samples from various upper regolith units, in order to establish any relationships of these elements to Fe-oxides, clay minerals, or carbonates; and (b) the morphology of Au. This research should lead to an improvement of geochemical sampling methods and a better understanding of the mobility and behaviour of target-associated elements in weathering profiles. It should provide information on the circumstances under which chalcophile anomalies, from which Au is leached, arise (as at Boddington) and aid the understanding of the genesis of nodules.

A total of 53 samples of various regolith units, including soils, lateritic residuum, hardpanized colluvium (red-brown hardpan), and calcrete were collected from the S, C, and N Pits. Bulk samples were separated into sub-samples which were analysed separately. Such sub-samples include magnetic and non-magnetic clasts of soils, magnetic and non-magnetic nodules and pisoliths from lateritic gravels, cores and cutans from lateritic pisoliths, matrix and gravel fractions from hardpan, and calcareous fragments and the associated gravel fraction from nodular calcrete. These sub-samples were analysed geochemically, mineralogically and examined petrographically.

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108   *Section 5: Siting of elements and dispersion processes*

TABLE 5.1.   Summary of anomaly characteristics for orientation studies referred to in this report.
Also shows status of lateritic residuum and interpreted dispersion processes.

Orientation district or area	Average annual rainfall mm	Ore deposit type	Bedrock lithologies	Size of deposit. Production and present resources	Ore-element association	Horizontal dimensions of bedrock source in metres	Anomalous element association	Area of laterite anomaly sq km	Number of times ore deposit size	Extensively	Sporadically
Greenbushes	953	Rare metal pegmatite Sn Ta Nb Li	Amphibolite, migmatite	13.5Mt[4] 0.15% Sn 0.06% Ta₂O₅ 5.9Mt 4% LiO	Sn Nb Ta Li As Sb	>3300x200	Sn As Sb Nb Ta Li B Be W Mn	>150	230	In Blackwood River Valley	✓
Boddington	810	Archaean[2] Au-rich porphyry system. Disseminated sulphides in diorite, dacite, andesite	Diorite, dacite, andesite adjacent mafic volcanics	118t Au[1] oxide zones. Also has bedrock resources	Cu Au Mo Bi W	Intermittent within 4500x1000	As Sb Bi Mo Sn W (Au)	60 to 175	50 to 130	In major valleys	✓
Mt. Gibson	250	Au in laterite, disseminated sulphides in complex shear zones[3]	Metasediments, amphibolite quartz-porphyry	8.5t Au in[3] laterite, plus 11t Au. Hornet zone mostly basement	Au Ag Cu Zn Bi As Sb	Intermittent lenses within 7000x20	Au As Sb Bi Ag W (Pb)	15	250	In some adjacent regimes	✓
Golden Grove	260	Volcanogenic massive sulphides Cu Zn Pb Au.	Felsic-intermediate-mafic volcanogenic sediments, felsic pyroclastics		Cu Zn Pb Au Ag As Sb Bi Sn W Co					Along strike to north	✓
Gossan Hill				13.5Mt 3.7% Cu with Au 10.5Mt 1.2% Cu 11.7% Zn 1.1gt Au		700x40	As Sb Bi Mo Ag Sn W Au	3	100		✓
Scuddles					Cu Zn (Au)	600-40 blind	As Sb Bi	2	70		✓
Kalgoorlie	240	Brittle ductile shear zones with quartz stockworks in dolerite. Quartz stock-works in mafic granophyre	Dolerite/basalt mafic granophyre		Au Ag Te W	Individual bodies within zone 3000x1000	Au As Sb W	>15 Remnants only	?60	✓	
Golden Mile				1225t Au							
Mt Charlotte				98t Au	Au Ag W	300x70					
Bottle Creek	220	Au in saprolite, sulphidic shale protore	Sulphidic shale mafic volcanics quartz porphyry	6t Au resource	Au Ag As Sb	Intermittent within 5000x20	As Sb Pb Zn Ag Au	10	200 to 400	Adjacent regimes	✓
Lawlers McCaffery, North Pit, Turrett. Waroonga, Genesis	200	Quartz veins and sulphidic shear[5] zones in mafics Quartz veins in quartz-rich metasediments	Differentiated mafics Metasediments	3t Au (Not released)	Au As W Au As	Individual bodies to 300x50	As Sb W Ag Au Bi Au As (?W)	0.5	30	✓	
Beasley Creek	200	Black shale host	Black shale amphibolite schist	4t Au	Au As	700x40	Au As Cu Zn (Mn)	Isolated remnant	Insufficient data	✓	

References: 1. Groves and Bennett (1990); 2. Roth, Bennett and Symons (1990); 3. Gee, 1990; 4. Hatcher and Clynic (1990) 'hard rock' reserves given; 5. Stokes *et al.* (1990).

Results

The chemical abundances of Au for the separated fractions are shown in Fig. 5.1. Detailed results of this study are given in Report 165R and are now summarized.

Magnetic and non-magnetic gravel fractions of soil

The magnetic and non-magnetic gravel fractions of soil consist of ferruginous granules and lateritic pisoliths/nodules, all of which are referred to as clasts. The non-magnetic, lateritic, gravel fraction is dominant. The magnetic clasts are generally smaller than the non-magnetic. Although the external appearances of both the magnetic and non-magnetic gravel components are similar, their internal fabrics are different. The cores of magnetic clasts are black and massive, whereas those of non-magnetic clasts are yellowish-brown and porous. Hematite is the dominant mineral of both gravel components, but there are significant differences in mineralogy. Non-magnetic clasts contain higher amounts of goethite and kaolinite, relative to the magnetic clasts and maghemite is present only in the magnetic clasts. Cutans in both clast types are dominantly goethite. Small quantities of gibbsite indicate weak leaching conditions.

Both the magnetic and non-magnetic gravel fractions consist dominantly of Fe_2O_3. The magnetic fraction has a higher mean Fe_2O_3 content, and lower SiO_2 and Al_2O_3 relative to the non-magnetic fraction. Iron shows a wide range in the non-magnetic fraction reflecting variable clay and Fe-oxide content. The minor oxides CaO, MgO, Na_2O, and K_2O are strongly depleted relative to Fe, Al, and Si. The non-magnetic gravel fraction contains slightly less TiO_2 than the magnetic fraction. The magnetic fraction is richer in Mn, Cr, V, Pb, Zn, As, W, and Ga than the corresponding non-magnetic fraction. In contrast Au, Ag, Cu, and Ni are enriched in the non-magnetic fraction relative to the magnetic fraction. The levels of Co, Sb, Bi, Mo, Sn, and Se show no significant differences between magnetic and non-magnetic fractions.

Status of Lateritic Residuum				Landform setting	Laterite relative to present water table	Groundwater			Dispersion Processes			Orientation district or area
At surface	Near surface (beneath soil or sand)	Buried				Essent. fresh	Intermed	Hyper-saline	Residual accumulation	Mechanical dispersion	Hydro-morphic dispersion	
		Shallow cover 0 - 10m	Deep cover 10 - 20m									
✓	✓	✓	-	Uplands part dissected plateau	above	✓			Cassiterite, columbo-tantalite, tourmaline	Cassiterite, columbo-tantalite, tourmaline	As ?Sb	Greenbushes
✓	✓	✓	-	Uplands and mid slopes	above	✓			?Cassiterite, fragments of lateritized bedrock	Fe-oxy-hydroxides	?As	Boddington
✓	✓	✓	In district	Uplands, mid slopes, toe slopes	Generally above	✓	✓	✓	Au	Au in lateritic nodules	Au	Mt. Gibson
✓	✓	✓	In southern drainage ✓	Hill top plain	Generally above	?✓			Cassiterite, gossan fragments (with Cu Zn As Sb Bi Sn Au)	Cassiterite, gossan-fragments (with Cu Zn As Sb Bi Sn Au)	Fe As Sb Cu Zn Au	Golden Grove
✓	✓	✓	-									Gossan Hill
✓	✓	-	-									Scuddles
✓	-	-	-	Hill and uplands	Above		?	?✓	?Au	?Au	?Au	Kalgoorlie / Golden Mile / Mt Charlotte
✓	✓	✓	-	Uplands, mid slope and broad valley	Above		?✓		Gossan fragments (with As Sb)	Gossan fragments (with As Sb)	?As Sb	Bottle Creek
✓ about 15% of district	✓ some	✓	✓ common	Sheet wash plains within table lands	Above	✓			?Au	Fe-oxy-hydroxides	?Au	Lawlers McCaffery, North Pit, Turrett, Waroonga, Genesis
Remnant	-	Not known	Not known	Erosional window through sheet wash plain	Above		?✓					Beasley Creek

Magnetic and non-magnetic nodules and pisoliths from lateritic residuum

The mineralogical compositions of the magnetic and non-magnetic nodules and pisoliths are similar to those of soil. However, gibbsite occurs in greater quantity in both magnetic and non-magnetic nodules of the lateritic residuum, in contrast to its minor content in gravel fractions of soils. The distributions of major, minor and trace elements, including Au, in magnetic and non-magnetic nodules are similar to those of soil. However, actual abundances of these elements are different. For example, the mean abundances of Fe_2O_3, Mn, Pb, Zn, As, and Ba are relatively low in magnetic nodules of lateritic residuum and higher in the corresponding magnetic gravel of soil. In contrast, magnetic nodules of lateritic residuum show higher mean concentrations of Au and Ag than the magnetic gravel fraction of soil. Similar relationships apply to non-magnetic nodules.

Cores and cutans of loose pisoliths

Cores and cutans could only be separated where the pisoliths were large and their cutans thick. The pisoliths, which were studied, were round, 20-50 mm in diameter and contained black to red cores and are dominated by hematite and maghemite with lesser amounts of goethite, kaolinite, quartz, and gibbsite. The cutans were generally 2-15 mm in thickness, have light- and dark-red banded zones and consist largely of kaolinite, hematite, and gibbsite with small amounts of goethite and quartz. Maghemite is typically absent from cutans.

The cores are relatively rich in Fe_2O_3 and are poor in SiO_2 and Al_2O_3. In contrast, cutans have similar mean abundances of Fe_2O_3, Al_2O_3, and SiO_2. Both cores and cutans are rich in TiO_2 (up to 4.6%) which are significantly more Ti-rich than nodules of lateritic residuum. This suggests that the large pisoliths, with thick cutans at the studied location, have developed from weathered Ti-rich, mafic rocks.
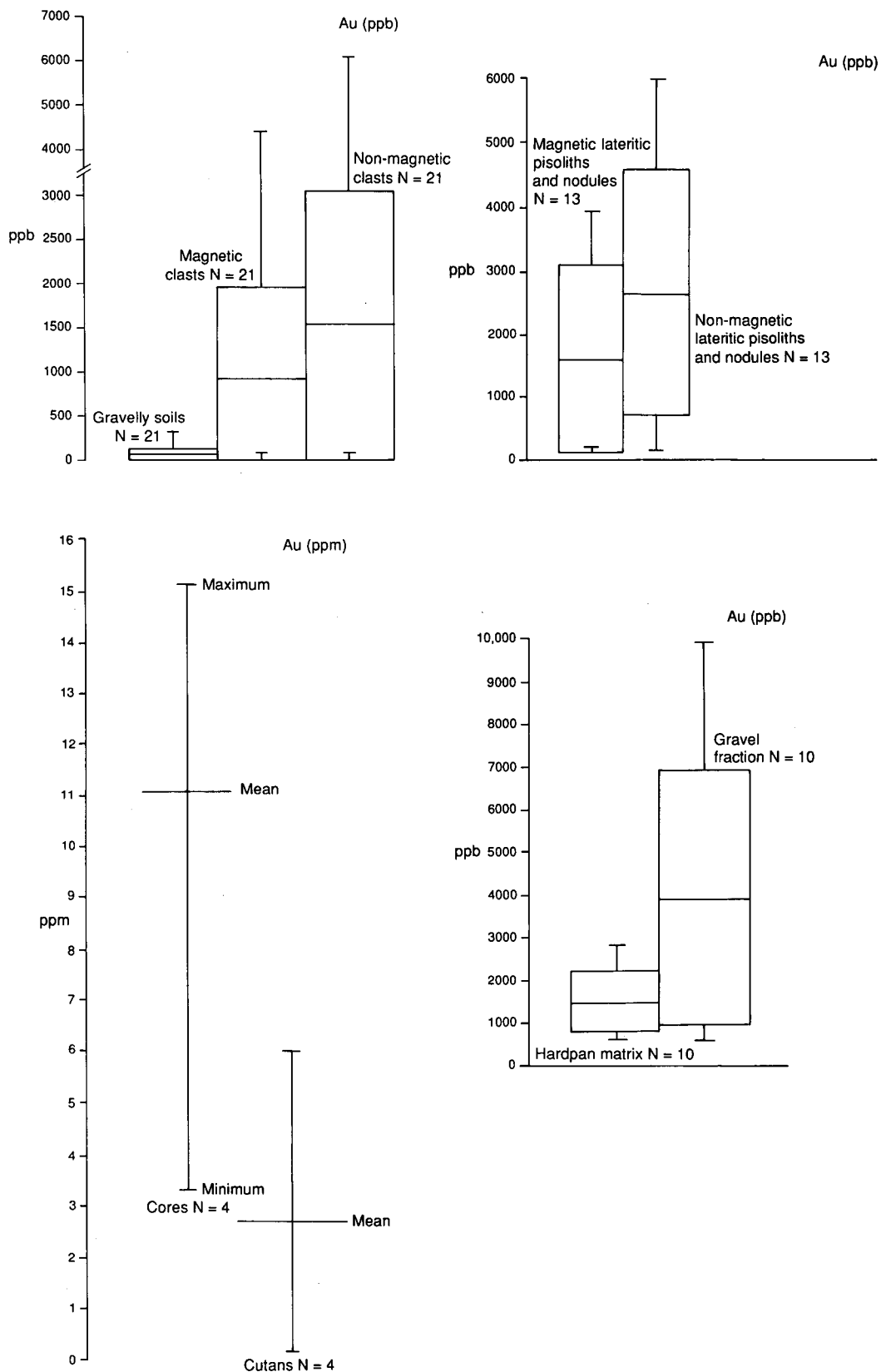
Figure 5.1. The distribution of Au in magnetic and non-magnetic clasts/nodules, cores, and cutans of pisoliths, hardpan matrix, and gravel fraction separated from soils, lateritic residuum, and hardpanized colluvium. Samples are from the Mt. Gibson orientation study, Report 165R.

Chromium, V, Pb, Zn, As, and Ga are enriched in the cores relative to the cutans. The cores show very high concentrations of Au, averaging about 11 ppm, compared with 2.7 ppm for the cutans. In contrast, Ag is more abundant in the cutans than the cores. The cutans were probably formed by deposition from Al and Fe-rich solutions around black nuclei and therefore may not have a direct genetic link with the formation of the cores. This suggests that Au enrichment in the cores and cutans did not occur at the same time and that Au has been mobile.

The gravel fraction and silicified matrix of hardpanized colluvium (red-brown hardpan)

Hardpanized colluvium consists of varying amounts of a ferruginous clay to sandy matrix and lenses of lateritic gravel. The hardpan matrix is a brittle, dull, earthy red to dark red or red-brown (2.5YR 4/6 - 4/8 or 5/6 - 5/8, moist) silicified mass of kaolinite, with some fine quartz, infused with Fe-oxides, carbonates, and Si. Accumulations of Mn-oxides characteristically occur on fracture and parting surfaces within the hardpan.

The gravel fraction, when separated from hardpanized colluvium, largely consists of various amounts of lateritic nodules, pisoliths, and hardened mottles, which are most abundant in the lower and middle parts of the hardpan unit. Amorphous silica and carbonates may coat these ferruginous clasts, which largely consist of hematite and kaolinite, with varying amounts of goethite, quartz, gibbsite, and calcite.

Chemically, the silicified matrix is richer in SiO_2 and Al_2O_3 than the Fe-dominant gravel fraction. The matrix is richer in CaO and MgO which occur as calcite and dolomite.

The mean concentrations of Au, Mn, Cr, V, Pb, As, Sb, Bi, Ag, and W are much higher in the gravel fraction than in the matrix. These abundances of Zn and Cu do not significantly differ in the two fractions. Nickel, Co, and Ba are enriched in the matrix relative to the gravel component. Care is needed in the interpretation of Ba below about 250 ppm because Ba is an impurity in the alumina disk grinding plates and a small amount (about 50 ppm on average) may be introduced into samples prepared this way. The matrix shows significantly higher values of Ba (to 900 ppm), confirmed by scanning electron microscopy which shows the presence of barite.

The mean concentrations of Au and Ag in the matrix of harpanized colluvium are higher than, or very similar to, those for nodules of lateritic residuum and the gravel fractions of soil. Gold enrichment in the hardpan matrix may reflect the original abundances of Au in the eroded materials from the upper part of the weathering profile, in upland, source areas. Introduction of Au into the hardpan matrix at a much later stage is also a possibility.

Separating the ferruginous gravel fraction and calcareous clasts from calcrete

The calcareous fragments and calcrete are platy, cream to pinkish in colour and vary from 1 to 5 cm in diameter. The gravel fraction consisting of lateritic nodules, pisoliths, and ferruginous granules separated from calcrete are reddish brown to black and are infused with carbonates.

As expected, the calcareous fragments have higher mean levels of CaO and MgO and lower Fe_2O_3, SiO_2, and Al_2O_3 than the lateritic nodules and pisoliths. Relative to the calcareous fragments, the lateritic gravel is enriched in all the trace elements analysed, including Au. Although the mean concentration of Au (931 ppb) is relatively low in the calcareous fragments, it is still highly significant. The low levels of Fe_2O_3 (4.2%) in calcareous fragments would lead one to suggest that most of the Au is in the calcareous fraction.

In the samples studied at Mt. Gibson, carbonates have replaced or displaced pre-existing regolith fabrics in the soil so that the Au, which now occurs in carbonates, may represent Au that was originally in soil. It is also possible that Au-enrichment in calcrete has taken place during the formation of carbonates.

Conclusions drawn from the Mt. Gibson siting and bonding investigations

- Both the magnetic and non-magnetic gravel fractions of the soil and lateritic duricrust are anomalous in chalcophile elements. However, the magnetic lateritic nodules and pisoliths are richer in Fe_2O_3, As, W, Sb, Bi, Cr, V, Pb, and Zn than their non-magnetic equivalents which, in turn, are richer in Au, Ag, Al_2O_3, SiO_2, Cu, and Ni.

- The non-magnetic lateritic nodules and pisoliths are richer in Au relative to the magnetic ones. The differences in the amounts of Au may be due to differences in the mineralogy of the two fractions.

- The cores of lateritic nodules and pisoliths contain more Au than their cutans.

- The matrix of the hardpan is highly anomalous in Au and Ag which possibly reflects the original Au abundances in the eroded source material. However, introduction of Au into the hardpan, through hydromorphic dispersion, is also possible.

- The carbonates studied are anomalous in Au. This needs further investigation.

- Gold, found in the lateritic nodules and pisoliths, occurs as irregular subhedral to anhedral crystals in cracks which are either filled with goethite and kaolinite or are empty. Gold crystals also occur on the surfaces of goethite.

5.2.2   *Lateritic residuum at Lawlers*

The morphology of Au and the siting of target-associated elements were investigated in laterite samples from the North and Turret Pits at Lawlers. Cores of the nodules have compositions ranging from 56.0-82.4% Fe_2O_3, 2.5-26.0% SiO_2 and 3.1-26.2% Al_2O_3. Cutans have lower Fe_2O_3 contents (34.0-57.8%) and higher Al_2O_3 (25.0-50.4%) and SiO_2, (1.1-14.5%) contents. The Cr and Ni contents of the cores generally allowed prediction of underlying bedrock types. Chromium occurs both as the chromite and associated with Fe-oxides. Arsenic and Mn in lateritic nodules were strongly associated with goethite and hematite. Kaolinite-rich areas of nodules generally contained only small amounts of As. The distribution of Cu within nodules was erratic, but it tends to be concentrated in kaolinite-rich areas. Surface adsorption of Cu by kaolinites has been observed by McBride (1978) and by McLaren and Crawford (1973). Bismuth and Sb were below the detection limit ($\approx$40 ppm) of the microprobe.

The Au in the nodules occurs as irregular, subhedral to anhedral crystals and as delicate wire forms in voids or cracks, which are either filled with kaolinite and goethite or are empty. Gold crystals also commonly occur on the surfaces of residual or colloform goethite and range in size from 15 to 80 μm. Energy dispersive microprobe analysis shows that Ag in the Au grains is below the detection limit of the technique ($\approx$1%).

5.2.3   *Lateritic residuum at Bottle Creek*

Data from a limited number of samples suggest that magnetic nodules are more ferruginous than co-existing non-magnetic nodules. The pathfinder elements As, Sb, and Pb, have higher abundances in magnetic nodules. Conversely, Cu and Ni are enriched in non-magnetic nodules. Magnetic nodules do not seem to be enriched in Au. These findings are similar to those for magnetic and non-magnetic nodules studied from Mt. Gibson.

5.2.4   *Lateritic residuum at Gossan Hill, Golden Grove*

Smith and Perdrix (1983) showed anomalous levels of Cu, Zn, and As in Fe-oxides of cutans of lateritic nodules within the multi-element dispersion anomaly around the volcanogenic massive sulphide deposits at Gossan Hill. These observations indicate hydromorphic dispersion. Mechanical dispersion has also taken place as interpreted from finely-distributed detrital cassiterite (which is also incorporated in cutans), gossan fragments which have been incorporated into lateritic residuum as the cores of lateritic nodules, and the movement of fragments and nodules of Fe-oxides carrying anomalous As and probably Cu, Zn, and Sb.

Analyses of 100 samples of 2 cm-sized lateritic nodules from the strongest part of the geochemical anomaly on the SW flank of Gossan Hill shed further light on the distribution and siting of target-associated elements. Histograms for the main target-associated elements show that each of these nodules, which were collected at random over a 10 m radius, is anomalous. The nodules, with their well-developed cutans, appear to be lateritized gossan. Their relatively-homogeneous abundances of Au and elements with an affinity for Fe-oxides possibly are due to hydromorphic dispersion during gossan formation and lateritic weathering.

These results provide insight into the sighting of target-associated elements at the nodule and pisolith scale. The results indicate why a laterite geochemical anomaly is internally consistent. At this location, the lateritic residuum is composed of nodules and pisoliths, which are themselves relatively consistent. Thus, taking a 0.5 to 1.0-kg sample of 2 to 5-g pisoliths more than adequately allows for local variability.

This study of individual pisoliths appears to be the only one available. Much more needs to be done before generalizations can be made. It would be relevant to know the homogeneity or heterogeneity at other positions within the Gossan Hill anomaly, as well as within significant anomalies from other orientation studies.

5.2.5 *Conclusions on siting of target-associated elements in lateritic residuum*

Native gold

Native Au was observed in lateritic residuum at Mt. Gibson and Lawlers as platelets and veining on a microscopic to hand-lens scale. Gold grains, observed in the lateritic nodules and pisoliths, occurred largely in voids or cracks, which are either filled with secondary goethite and kaolinite or are empty (Fig. 5.2A). Some grains also occurred on the surfaces of a goethite-rich area (Fig. 5.2B). Gold grains also showed dissolution features and surface pitting. Where studied, the Au has a high purity (Ag < 1 %), which is in keeping with observations by others on authigenic Au in oxidized weathering profiles (e.g. Mann, 1984a). These relatively-coarse forms of Au, however, are only a small proportion of the total Au.

Gossan Fragments

Incorporation of gossan fragments into lateritic residuum (Gossan Hill at Golden Grove and Bottle Creek) or into locally-derived gravelly colluvium (Bottle Creek - VB) and into lag (Beasley Creek) has been recognized and clearly can be an important contributor to the geochemical dispersion patterns. Although they are likely to have the highest contrast in target-associated elements compared with geochemical backgrounds, gossan fragments are fragile and can be expected to be geochemically modified, in comparison with their parent gossans, by the further weathering processes involved. Even so, where studied at Gossan Hill, the compositions of gossan nodules in lateritic residuum are very clearly anomalous in the wide range of target-associated elements which characterize the gossan. Likewise, chemical analysis of several rounded, ferruginous clasts in gravelly colluvium at the VB location at Bottle Creek confirm them to be clearly fragments of the nearby gossan. The contribution to the formation of the anomaly by incorporation of gossan fragments in lateritic residuum at Gossan Hill could probably be modelled with existing data to give a semi-quantitative estimate of the importance of that process. Incorporation of gossan fragments into lateritic residuum will not apply to some types of ore deposits, e.g. disseminated sulphide deposits, sulphide-poor or non-sulphide Au deposits, and rare metal pegmatites.

Mineralogical sites

Certain resistant minerals are important sites for target-associated elements in the generation and preservation of multi-element dispersion haloes in lateritic residuum. Cassiterite preserves the Sn imprint in laterite at the Gossan Hill anomaly at Golden Grove, at Boddington, and at the Greenbushes rare metal pegmatite system. Also at Greenbushes, columbo-tantalite carries the Nb and Ta imprint in laterite (Nb and Ta are also carried as columbo-tantalite inclusions within cassiterite). Resistant mineral grains of tourmaline carry boron. The chemistry of resistant chromites, as in laterites, has substantial research potential. To date, the abundance of Cr in laterites has been used extensively to indicate mafic or ultra-mafic bedrock affinity. Extremely-high abundances of Cr in laterites have led to the location of chromite-bearing rocks.

Lateritic weathering profiles are dominated by the three elements Fe, Al, and Si in the forms of Fe-oxides (goethite, hematite, maghemite), kaolinite, and quartz. Iron-oxides, mainly goethite, hematite, and maghemite, are the most important hosts for a range of trace elements in laterites. At Mt. Gibson and Lawlers, several significant correlations occur between elements and minerals. From these correlations and electron-microprobe analysis of mineral particles, the following affinity groups were recognized:

Fe, Ti, As, Pb, Sb, Cr, V, Ga, Zr with hematite and maghemite;
Al, Cu, Ni, Ag, Au with goethite and kaolinite

The relatively-high level of a given trace element in an Fe-oxide may be due to surface adsorption, co-precipitation, or isomorphous substitution. Iron, in its octahedral position in the structure of Fe-oxides, can be replaced by other metals. Aluminium is the best known example of this substitution, although Mn, Co, Cr, Ni, and V, may also substitute for Fe. Arsenic, Sb, and Bi co-precipitate readily with Fe-oxides over a wide pH range and tend to be retained throughout the weathering process.

Manganese oxides are also well-known absorbents of trace elements and this is expressed by the common correlation of Mn with Zn and Co.

5.3 Dispersion processes

As discussed in Section 2, material referred to as lateritic residuum in this project is a residual, or almost residual, intensively-weathered blanket with a long history of formation. It consists of, in varying proportions: (i) material derived by lateritic weathering of underlying or adjacent parent rocks, through

leaching of chemical components and alteration of the original mineral assemblages; (ii) resistant minerals derived from the parent rock; and (iii) authigenic minerals which have grown by alteration of other minerals or mineral assemblages or from chemical components brought in by solution.

In addition, there may be some minor addition, at the top of the profile, of detrital material, washed from adjacent areas, and clay, silt and sand brought in by aeolian transport. These exotic materials can be carried downwards into the residuum, by eluviation, or by the back filling of decayed plant roots or animal and insect burrows, even to the level of the upper saprolite.

Where laterite profiles are complete, the upper lateritic residuum may degrade by slow dissolution of Fe-oxides to a layer of sand, sandy soil or clay soil, which is typically yellow over felsic rocks or orange to red over mafic rocks. Where erosional processes are active, mechanical transportation can effect the exposed parts of the profile. Disaggregation of lateritic residuum by vegetation, by collapse, and by other phenomena is also common.

The processes of lateritization thus involve residual accumulation, as well as mechanical and hydromorphic dispersion. The processes continued throughout long periods of lateritic weathering, believed to have been at least from the Palaeocene to the Miocene (Section 3.2), and involved progressive lowering of the land surface. Post-lateritization leaching, erosion, diagenetic alteration, and burial have also taken place over a long period and continue today.

It is within this setting that geochemical dispersion from ore deposit sources should be examined. Dispersion processes observed in the orientation areas studied by the Laterite Geochemistry Group to date are listed in Table 5.1. In the following text, the features and processes which are common to these areas are discussed first, followed by discussion of variations from the common observations and interpretation.

5.3.1   *Residual accumulation*

Accumulation of resistant minerals, derived from an ore deposit, can be an important mechanism in developing a recognizable geochemical halo in lateritic residuum. Residual accumulation of Au is an example. The primary Au, however, commonly undergoes leaching of its Ag content (Mann, 1984) from the margins inwards. Gold can be chemically mobile and both dissolution and precipitation fabrics have been described (Wilson, 1984; Colin *et al.*, 1989; Lawrance, 1988). Cassiterite is an important resistant mineral in the development of geochemical haloes in laterite about a range of deposit types. Examples include Gossan Hill at Golden Grove (VMS deposit), Boddington, (porphyry Au-Cu deposit), and Greenbushes (rare metal pegmatite). At Greenbushes, columbo-tantalite and tourmaline are also important resistant minerals which contribute (Nb, Ta, B) to the geochemical anomaly in laterite, through residual accumulation. Chromite, which, generally, is relatively stable in the weathering environment, can be particularly useful in forming haloes associated with ultramafic bodies in exploration for Cr and PGEs. The composition of chromites in laterite would also be important in exploration for diamond-bearing kimberlites.

Accumulations of Fe-oxides derived from ferruginous saprolite, mottles form the mottled zone, fragments of various iron segregations, and iron-rich gossan fragments are fundamental processes in laterite formation. These evolutionary trends are discussed in Section 6. Although the geochemical characteristics of such material can be modified by the processes involved, accumulation of these materials is important in the generation of laterite geochemical haloes. During weathering, formation of Fe-oxides takes place through alteration of pre-existing minerals and by precipitation from solution. In both cases, opportunities are created for close associations to develop between a wide range of trace elements, particularly the transition elements, with Fe. Where originally dispersed hydromorphically, once Fe-oxides formed, these element associations can be relatively stable in common weathering environments (Nickel, 1984).

Weathered rock fragments, covered by their cutans, commonly form the centres of lateritic nodules. Such nodules represent a common form of residual accumulation. However, the processes involved in lateritic weathering alters their compositions (Section 6.0).

5.3.2   *Hydromorphic dispersion*

An essential step in forming saprolite is the saturation of a relatively-permeable, porous, weathering zone with ground water. Dissolved ions diffuse across concentration gradients, or move by through-flowing ground water or by convection (Mann, 1984a, 1984b and Section 3.3.1). Thus an ore system, undergoing lateritic weathering, would contribute to the processes of early hydromorphic dispersion, which, under favourable conditions, would lead to enlargement of the exploration target. With periodic saturation of the lateritic residuum, through a rise in the water table during periods of high rainfall, hydromorphic dispersion into the lateritic residuum would occur. Conditions are likely to have been particularly favourable for hydromorphic dispersion during gossan formation.
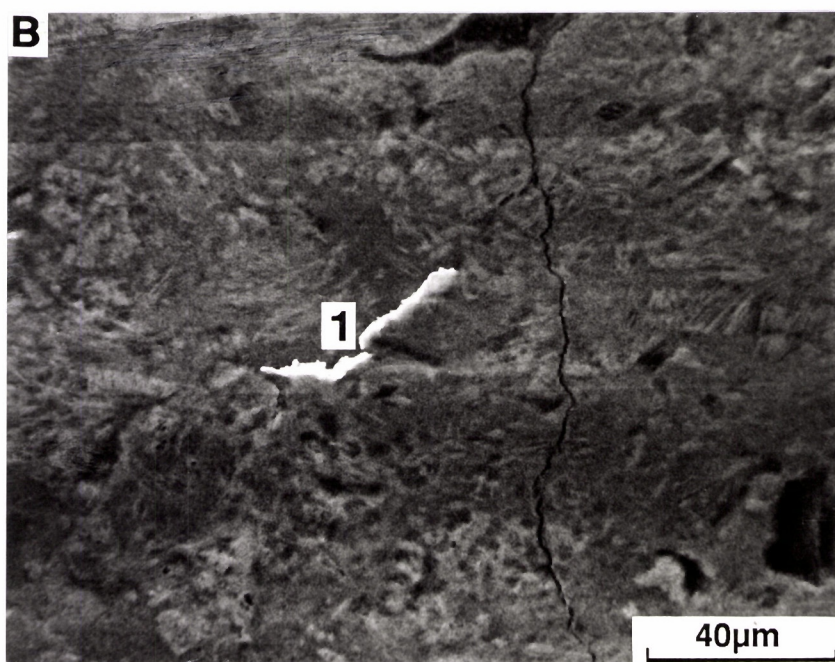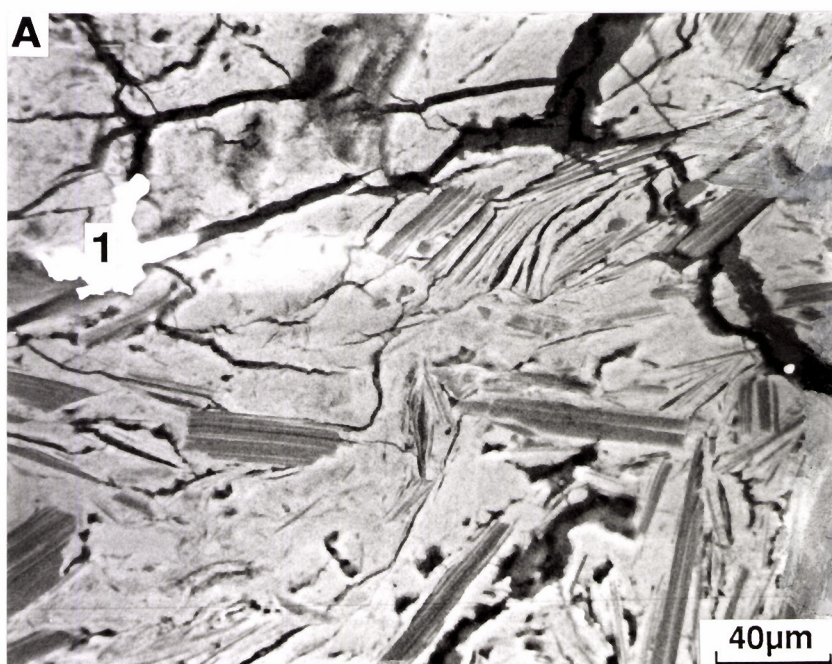
Fig. 5.2A. Scanning electron micrograph of part of a lateritic pisolith showing an angular, anhedral crystal of Au (1) in a void. Matrix of pisolith shows goethite and kaolinite pseudomorphs after muscovite: Location 1510N 775E, sample 07–0508, S! Pit, from Report 165R (CRC LEME Open File Report 61).

Fig. 5.2B. Scanning electron micrograph of part of a lateritic pisolith showing a wire-shaped crystal of Au (1) attached to the goethite-rich surface: Location 1510N, 775E, sample 07-0508, S! Pit, from Report 165R (CRC LEME Open File Report 61).

During saprolite formation, hydromorphic dispersion, arising from the weathering of an ore deposit or its primary halo, is a normal early step in the formation of a geochemical halo in laterite. Trace elements migrating from an ore source form a dispersed pattern within the Fe-oxides, particularly within the upper saprolite. As the landsurface is lowered, these Fe-oxides then become important parent materials for the overlying lateritic residuum. Hydromorphic dispersion can continue (or re-commence) during evolution of the lateritic residuum as evidenced by the cutans of pisoliths at Gossan Hill, containing anomalous levels of Cu, Zn, and As (Smith and Perdrix, 1983). Hydromorphic dispersion is believed to be a significant contributing process in making relatively-homogeneous and consistent geochemical anomalies in laterite.

5.3.3   *Mechanical dispersion*

The incorporation of gossan fragments into lateritic residuum accompanied by mechanical dispersion has been observed at Gossan Hill, Bottle Creek, and Beasley Creek. Although difficult to observe, because it requires good exposure and detailed studies, this process probably is common in forming geochemical haloes in laterite for those ore types which tend to form gossans.

Mechanical dispersion of loose pisoliths and nodules within the upper lateritic residuum is very common. This would have been inherent in soil formation during the Tertiary (or earlier) weathering period and would have been caused by vegetation, down-slope soil creep, and sheet wash from heavy rains. Arid periods would have aided mechanical dispersion when vegetation became sparse. During lateritization, dispersion of resistant minerals as silty detritus is likely to have been common at the top of the profile.

5.4   Implications in exploration

The accumulation of target-associated elements held in Fe-oxides during lateritic weathering is fundamental in anomaly formation. Elements held in these minerals form, or contribute to, geochemical patterns that are resistant to further weathering unless reducing conditions occur. Hydromorphic and mechanical dispersion, both being inherent in lateritic weathering, tend to enlarge the size and contribute to the homogeneity of laterite anomalies. Understanding of dispersion processes is essential as it indicates which units of the regolith are best to sample and enables, to some extent, some prediction of the geometry of an anomaly.

Lateral mechanical and hydromorphic dispersion in the loose upper, pisolitic and nodular laterite result in a wider anomaly than in the underlying lateritic duricrust. Thus sampling pisolitic-nodular laterite is generally more appropriate to reconnaissance exploration because wider-spaced samples can be taken close to the surface. Conversely, sampling lateritic duricrust is more appropriate for delineation of targets for drilling, the basal duricrust having the closest relationship to the saprolitic and, in turn, to bedrock substrates.

From the anomalies studied to date, there appears to be no special geochemical advantage in sampling magnetic nodules or pisoliths. On the contrary, the non-magnetic materials in some cases are more useful. Clasts separated from hardpanized transported overburden can also be used as a first pass sampling medium.

Some unanswered questions for future research to address are:

* How robust are multi-element anomalies in lateritic residuum where exposed to hypersaline ground waters?

* Under what circumstances is Au leached from a multi-element anomaly in laterite (Boddington) versus where it is retained (e.g. Mt. Gibson)?

6.0 EVOLUTION OF LATERITIC PISOLITHS, NODULES AND SOME ASSOCIATED FERRUGINOUS MATERIALS OF LATERITIC PROFILES

6.1 Introduction

A wide variety of ferruginous materials occur as clasts and outcrops in the lateritic landscapes of the Yilgarn Craton. Common types include lateritic pisoliths and nodules from lateritic duricrusts, hardened mottles, fragments of ferruginous saprolite, and cobbles of iron segregations. They may occur, for example, as outcrop or subcrop of large lateritic bodies, outcrops of ferruginous bedrock, gossans, or occur as loose surface aggregates or lag, and as gravelly components within soils, stream sediments, colluvium, and alluvium. Important patterns of geochemical dispersion from mineral deposits can be preferentially contained or preserved within many of these ferruginous materials. Exploration geochemistry has to deal with these materials frequently. Consequently, it is important to classify the different types and understand their evolution, internal and external characteristics, mineralogy and chemistry, and distribution within the landscape. Their origin is relevant to both research and exploration. The purpose of this section is to show their key features, to clarify relationships between some of the main types of ferruginous materials, and to summarize their evolutionary pathways.

6.2 Formation of lateritic residuum

The evolution of lateritic weathering mantles developed from mafic, ultramafic, and felsic bedrocks, is shown in Fig. 6.1, which summarizes relationships found in the Lawlers, Mt. Gibson, and Bottle Creek orientation districts. The left hand side of the figure shows a profile commonly developed from mafic and some ultramafic bedrocks, with a characteristic ferruginous saprolite, that on the right hand side shows a profile with a strongly developed mottled zone common on felsic bedrocks. Figure 6.2 is a detailed block diagram showing the transition from ferruginous saprolite to laterite residuum, based mainly upon observations at the McCaffery Pit in the Lawlers district. Two modes of formation of lateritic residuum have been identified in the orientation districts studied; these are described below. Various other forms of Fe enrichment (iron segregations) also occur within the saprolite and ferruginous saprolite. These iron segregations, representing zones of intense ferruginization, occur as pods, lenses, and large slabs.

Fragmentation of ferruginous saprolite

Many nodules and pisoliths develop by fragmentation of ferruginous saprolite (Fig. 6.1). Ferruginous saprolite is a yellowish-brown, indurated mass which was produced by the infusion of Fe-oxides into clay-rich saprolite. Higher in the profile, soft, clay-rich masses in the ferruginous saprolite dissolved, leading to the development of numerous irregular voids. These voids weaken the whole saprolite structure, eventually leading to its complete collapse. Fragments are then further broken down into small nodules with a yellowish-brown/olive-green cutan. As the sphericity of nodules increases, up the profile, by dissolution of irregular edges, some nodules develop progressively into pisoliths. The deposition of Fe and Al around the nucleus forms a cutan.

Local-scale migration and accumulation of Fe as mottles

This represents the more classical model of pisolith formation described in the literature (Fig. 6.1). Pisoliths are developed by local-scale migration and accumulation of Fe. As weathering progresses, high in the profile (mottled zone), Fe is mobilized and precipitated as spots, blotches, and streaks, leading to mottles and a mottled clay zone. Here, the major difference between mottles and matrix is the Fe content of the mottles which are dominated by hematite, goethite, and kaolinite. The areas within the mottled zone from which the Fe is moved in solution, essentially as soluble Fe^{2+} become progressively more pallid until they consist predominantly of relict kaolinite and quartz. These changes are generally accompanied by increased microporosity, leading to voids and tubules. The voids, left by dissolution of the matrix, may be occupied by secondary kaolinite, goethite, hematite, and fine grained quartz so becoming indurated masses.

Mottles evolve progressively upward in the profile into nodules and pisoliths with further mobilization and concentration of Fe where hematite generally replaces some of the goethite. In the duricrust, the nodules become more indurated and their boundaries with the matrix becomes distinct.

As the matrix dissolves, nodules and pisoliths become increasingly abundant towards the top of the profile. As the sphericity of the nodules increases, by dissolution of irregular edges, nodules develop into pisoliths. Thus pisoliths are relatively more abundant in the upper portion of the lateritic residuum. Near to the land surface, dissolution of the Fe-oxides of lateritic nodules and pisoliths, through leaching by infiltrating rain water, results in the orange to red clay soils and yellow quartz-rich sands which overlie lateritic residuum.

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WEATHERING PROCESSES

Former land surface

DEGRADATION AND
DISSOLUTION of matrix
(Fe-oxides and kaolinite)

HARDENING

FRAGMENTATION
(void development,
collapsing by removal of
Fe-oxides and kaolinite)

FERRUGINIZATION
Formation of goethite,
hematite

NEARLY
ISOVOLUMETRIC
WEATHERING
Weathering of smectite
and vermiculite to kaolinite,
local precipitation of
goethite and hematite

FRAGMENTATION of rock,
weathering of primary minerals
to smectite, kaolinite, vermiculite

Lateritic residuum

LATERITIC FAMILY

Present land surface

Soil

Loose nodules,
pisoliths

Duricrust (fragmental, nodular)

Collapsed ferruginous
saprolite

Ferruginous saprolite

Leaching
of Fe

Formation of voids and accumulation
of Fe-oxides and kaolinite in voids

Loose nodules
and pisoliths

Duricrust (nodular, pisolitic)

Mottled zone

Lateral migration
of Fe as Fe^{2+}

Iron
segregations

Fe^{2+}

MIGRATION AND
ACCUMULATION
OF Fe AS MOTTLES

Saprolite

Fe^{2+}

Saprolite

Gossan

Local precipitation of
Fe-oxides

Saprock

Fe^{2+}

Saprock

Fe^{2+}

Mafic, ultramafic

Felsic

Maghemite

Hematite

Al in goethite

Goethite

Kaolinite

Fig. 6.1. A schematic diagram of the differences in the nature of the weathering mantle developed
from mafic, ultramafic and felsic bedrocks. This diagram is based on findings in the Darling Range
and the Mt. Gibson, Lawlers and Bottle Creek districts.
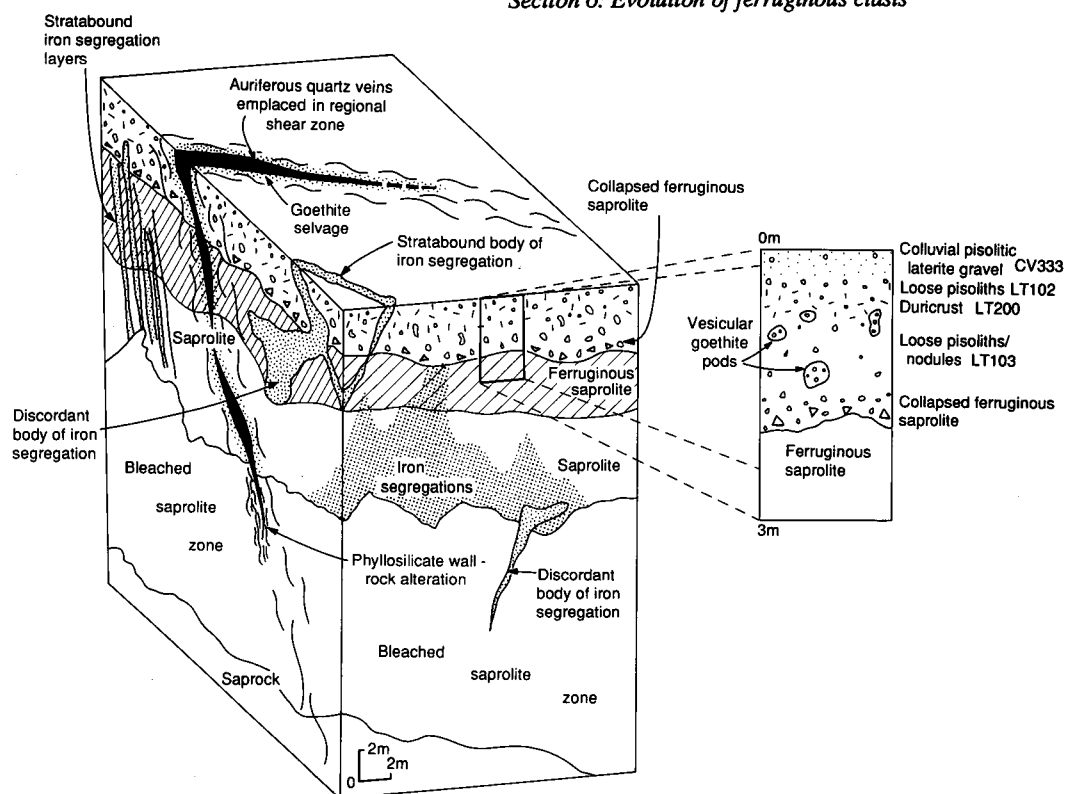
Fig. 6.2. Detailed block diagram showing field relationships for several categories of lateritic materials and iron segregations, based upon the Lawlers orientation study.

During lateritic weathering, the base of the lateritic residuum progresses continually downward (as do the other boundaries, Fig. 6.1) This proceeds by removal of the clay matrix from the mottled and clay zone. Where the saprolite is pervasively ferruginized, such as is common with mafic and some ultramafic rocks, the base of the residuum surface is lowered through fragmentation and collapse, apparently accompanied by removal of substantial amounts of Fe-oxides and kaolinite by dissolution.

6.3 Subdivision of ferruginous materials into two major families

For the purposes of geochemical exploration, two major families of ferruginous regolith materials are recognized, based upon their mesoscopic characteristics, position within the regolith stratigraphy, and within the regolith-landform framework as well as their chemical characteristics. These are the *lateritic family* and the *iron segregation family*. Figure 6.3 summarizes their major types and subdivisions. The characteristics of the lateritic and iron segregation families are listed in Table 6.1 and examples are shown in Figs 6.2, 6.4 and 6.5.

The lateritic family results from ferruginization and residual accumulation in the upper lateritic profile. A large part of their Fe is derived from the weathering of underlying bedrocks, they are yellowish-brown to dark reddish-brown and largely consist of kaolinite, hematite, goethite, and maghemite. Original rock texture may be partly preserved or completely destroyed.

The very diverse iron segregation family results from extreme ferruginization and has developed predominantly within saprolite. Its members are not confined to a single unit of the regolith stratigraphy. Their Fe is derived from a variety of sources, including weathering of Fe-rich lithologies, gossans, leaching from upper horizons and upland areas. Iron segregations are black and are dominated by goethite, with variable amounts of hematite and quartz. The members of the iron segregation family can also be distinguished chemically from the members of the lateritic family. Iron segregations have generally higher Fe, Mn, Zn, Co, Cu, and Ba and lower Al_2O_3, TiO_2, Cr, V, Ga, and Zr contents than the laterite family. Although the majority of both families are distinctive, there is a transitional subdivision of the lateritic family which extends downwards, to include mottles of the mottled zone and the commonly yellow-brown, ferruginous, upper saprolite, characteristic of weathering profiles derived from mafic bedrocks. Some of the most important ferruginous materials in exploration geochemistry are now discussed.

LATERITIC FAMILY

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                         ┌────────────────────────┴──────────────────────────┐
                  Lateritic residuum                                  Transitional types
                         │                    ┌──────────┬───────────┬──────────────────┬────────────────┐
                  Lateritic nodules      Hardened mottles   Mottled saprolite   Collapsed ferruginous   Ferruginous saprolite
                  and pisoliths                                               saprolite fragments          fragments

                  (Yellowish brown to
                  black, hematite-rich
                  core with goethite-        (Dark reddish brown to red, hematite-    (Yellowish brown, goethite-kaolinite-rich,
                  rich cutans; both          kaolinite-rich, non-magnetic)            non-magnetic)
                  magnetic and non-
                  magnetic)
```

```
          ┌──────────────┴─────────┐
       Lithic                   Non-lithic
    (rock fabric               (secondary
     preserved)                  fabric)

  ┌──────────┴────────┐            │
Pseudomorphic    Litho-relics -   Homogeneous
e.g. gibbsite    (rock fragment   (featureless,
pseudomorphs      in core)          massive)
after feldspar
```

Other important features
of the lateritic family -
concentric pisoliths and nodules,
compound pisoliths and nodules,
syneresis pisoliths and nodules

Ferruginous materials in residual regime   Ferruginous materials at transition

IRON SEGREGATION FAMILY

```
      ┌──────────┬──────────┴───────────┬──────────────────┬────────────────┐
  Gossans     Goethite      Stratabound      Other forms of        Extremely
              pods            bodies         Fe-enrichments        ferruginized
                                              (as lenses,         bedrock/saprolite
                                              slabs etc.)
```

(Dark reddish brown to black, goethite-rich, generally non-magnetic)

Ferruginous materials in erosional regimes

Fig. 6.3. Subdivision of common ferruginous weathering materials into two major families.

6.4   The lateritic family

The lateritic family includes lateritic pisoliths and nodules and various types of lateritic duricrust. A transitional subdivision of the lateritic family includes mottles, fragments of ferruginous saprolite, collapsed ferruginous saprolite, and mottled saprolite. These categories are described below.

6.4.1   Lateritic nodules and pisoliths

Lateritic nodules and pisoliths commonly form a loose or cemented blanket, up to a few metres thick. They also occur as lag on broad crests and backslopes. Yellowish-brown or greenish, goethite-kaolinite-rich cutans, 1-2 mm thick, are typical of residual lateritic pisoliths and nodules which commonly occur in a size range of 2-15 mm and are sub-angular to sub-rounded (Fig. 6.5A and B). Two main types are recognized, *lithic* and *non-lithic* and they may occur in equal proportions in the same location. Lithic lateritic nodules and pisoliths contain recognizable pseudomorphs after primary minerals (e.g. feldspar, mica, talc) or relics of BIF, gossan, amphibolite, and mica schist. The non-lithic nodules show no relict rock textures but several generations of Fe-oxides, impregnated or disseminated through the clay, sand, or gibbsite matrix. Where there has been extreme ferruginization, lithic and non-lithic nodules become similar and the distinction between the two is difficult.

A. MAFIC/ULTRAMAFIC WEATHERING PROFILE

Cutan

Accumulation
of kaolinite
and Fe-oxides

Lithic nodules
Non-lithic
nodules

Bodies of iron-
segregations

Litho structure

Gravelly soil

Loose nodules and pisoliths

Nodular, pisolitic duricrust
(weakly to strongly indurated)

Collapsed ferruginous
saprolite

Ferruginous saprolite

Saprolite

Saprock

Bedrock
(mafic, ultramafic)

B. FELSIC WEATHERING PROFILE

Non-lithic
nodules

Lithic nodules

Accumulation
of kaolinite
and Fe-oxides

Litho structure

Gravelly soil

Loose nodules and pisoliths

Nodular, pisolitic duricrust

Mottled zone

Clay zone

Saprolite

Saprock

Bedrock (felsic)

These boundaries are being lowered with time

C. LITHIC NODULES,
PISOLITHS

Ferruginization

Pisolith

Cutan
Nodule

Fragmentation

Iron segregation

Primary fabric
(pseudomorphic,
lithorelic)

NON-LITHIC
NODULES, PISOLITHS

Cutan
Pisolith

Nodule

Mottle

Ferruginization

Secondary fabric
(massive clays,
sands)

Fig. 6.4. Schematic diagram showing the evolutionary sequences of lithic and non-lithic nodules and pisoliths in lateritic profiles formed from the weathering of (A) mafic and (B) felsic bedrocks. Details are shown in (C).

Table 6.1. Important characteristics of the lateritic and iron segregation families.

Lateritic Family	Iron Segregation Family
▪ Ferruginous materials in residual regimes and at transition to erosional regimes.	Ferruginous materials in erosional regimes
▪ Extensive distribution	Extensive distribution
▪ Yellowish-brown to dark reddish brown	Dark reddish brown to black
▪ Clasts irregular to round	Clast sub-rounded to sub-angular
▪ 2-50 mm in size common	30-300 mm in size common
▪ Magnetic and non-magnetic	Non-magnetic
▪ Lateritic pisoliths and nodules typically have 1-2 mm thick yellowish-brown or greenish cutans.	Lack cutans
▪ Kaolinite, hematite, goethite, maghemite, quartz.	Goethite, quartz, hematite
▪ High Al-substituted low crystalline goethite.	Low Al-substituted highly crystalline goethite
▪ Low in Fe_2O_3, Mn, Zn, Co, Cu, Ba relative to iron segregations	High in Fe_2O_3, Mn, Zn, Co, Cu, Ba, As, relative to lateritic family
▪ High in Al_2O_3, TiO_2, Cr, V, Ga, Zr	Low in Al_2O_3, TiO_2, Cr, V, Ga, Zr
▪ Good sample medium	Good sample medium where lateritic family is absent.

Both magnetic and non-magnetic varieties occur together in the lithic and non-lithic nodules and pisoliths. Those that are magnetic are either black or steel grey; those that are yellow, red or brown are not magnetic. Magnetic nodules are dominated by Al-hematite and maghemite with small amounts of Al-goethite and kaolinite. In contrast, Al-hematite, Al-goethite, and kaolinite are the dominant minerals of non-magnetic nodules. Magnetism is due to maghemite.

(a)   *Lithic nodules and pisoliths*
Two types of lithic nodules and pisoliths are recognized:
Pseudomorphic nodules and pisoliths. These can have a variety of internal fabrics, depending upon the nature of the host material. The internal fabric is closely related to the fabric of the primary minerals that have been pseudomorphed. Pseudomorphic fabric relationships are seen in their yellow, red or black cores: examples are gibbsite pseudomorphs after feldspars in duricrust (Boddington), kaolinite and goethite after mica (Mt. Gibson, Bottle Creek, Beasley Creek), goethite after sulphides or magnetite (Bottle Creek), goethite after talc (Lawlers) and fine, kaolinitic booklets after amphiboles (Lawlers). Duricrust with an abundance of nodules with pseudomorphic fabrics relates directly to the underlying rock. Pseudomorphs are not readily recognized in hand specimen, though a few larger grains are visible under a hand lens; they are best recognized by petrographic examination, generally under high power, of polished blocks.
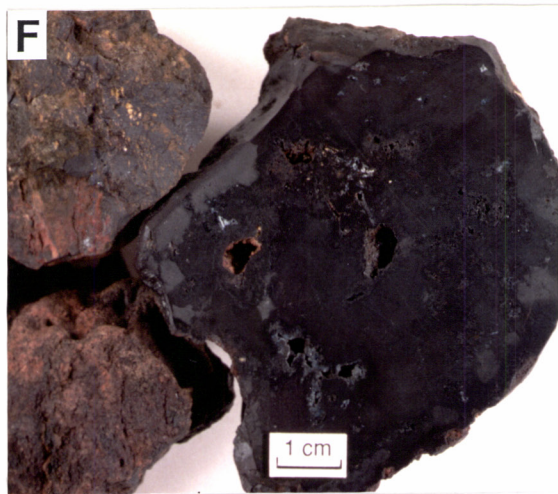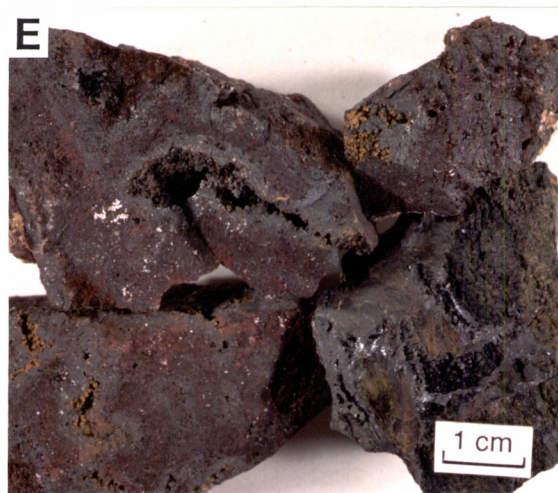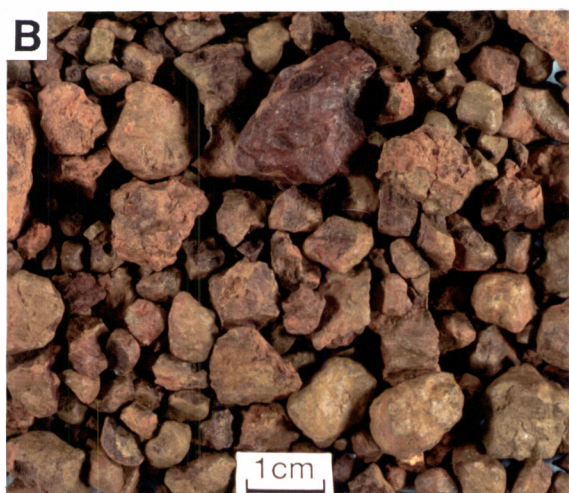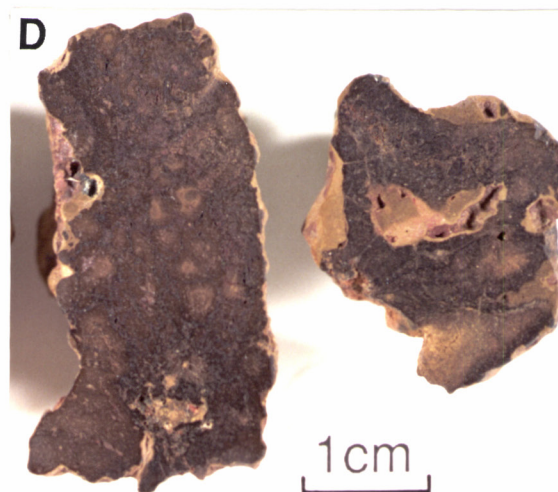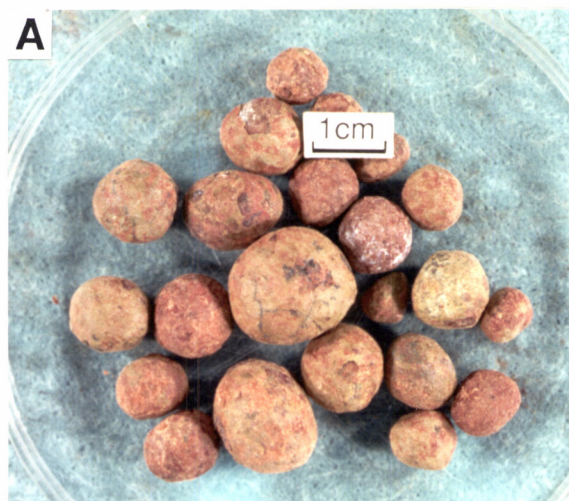
Fig. 6.5. Some examples of the lateritic (A to D) and iron segregation (E and F) families. (A) Lateritic pisoliths with yellow/yellowish-brown cutans. (B) Lateritic nodules with yellowish-brown/greenish cutans. (C) Hardened mottles. (D) Fragments of ferruginous saprolite. (E) Iron segregations showing boxwork texture after sulphides. (F) Ferruginous cobbles of iron segregations.

Lithorelic nodules and pisoliths. These are clasts which have a rock fragment as their core. Thus, nodules of former BIF are layered, with layers still composed largely of quartz or Fe-oxides. Relics of former schist retain their schistose fabric. Alteration rims may be visible within rock fragments when broken or sliced. These lithorelic clasts are generally yellow or red and are irregular, platy or circular in shape.

(b)   *Non-lithic nodules and pisoliths*

Homogeneous nodules and pisoliths. They are uniformly fine-grained, largely porous and are composed generally of kaolinite impregnated with fine-grained Fe-oxides. Homogeneous nodules and pisoliths do not show pseudomorphic or lithorelic fabrics in their cores. They are yellow or red and are generally rounded, elongate or irregularly shaped with smooth to rough surfaces.

(c)   *Other important features of the lateritic family*

Concentricly-structured pisoliths and nodules. These include pisoliths and nodules with abundant concentric cutans. Cutans may reach 20 mm in thickness. The cores are generally black, reddish-brown or red and are Al-hematite- and/or maghemite-rich. Some pisoliths are entirely banded without any Fe-oxide-rich core. Where alternate darker and lighter cutans are seen under the petrographic microscope, the lighter cutans have higher Al and lower Fe content and are kaolinite-gibbsite-rich. Concentric cutans may include micro-lenses of detrital or residual quartz grains suggesting a complex history of depositional and accretionary events.

Compound pisoliths and nodules. These contain a variety of earlier generation pisoliths and nodules in their cores and may have cutans. The matrix within each core is indurated kaolinite, Al-goethite, and Al-hematite. In some samples, their mineralogy and the characteristics of Fe-oxides of earlier pisoliths and nodules are variable suggesting multiple origins.

Syneresis in pisoliths and nodules. These are characterized by intricate cracks, commonly radiating and irregular in places crossed by other concentric cracks. In many specimens the cracks are filled with kaolinite and Al-goethite.

6.4.2 Mottles
Mottles may occur either within the mottled zone or as a lag where the mottled zone has been exposed by erosion. Yellowish-brown to dark red, irregular, non-magnetic Al-hematite- and kaolinite-rich, mottles in the 10 to 60 mm size range are common (Fig. 6.5C). They show numerous dissolution cavities.

6.4.3 Ferruginous saprolite fragments.
Ferruginous saprolite is typically developed over mafic and ultramafic rocks. Where it occurs, it generally underlies lateritic residuum. Fragments of ferruginous saprolite may occur as a lag in erosional areas such as breakaway and pediment slopes. They are yellowish-brown, irregular to platy, with a common size-range of 10-50 mm (Fig. 6.5D). The matrix shows relict rock fabrics. They are typically non-magnetic and are largely composed of kaolinite and Al-goethite. Ferruginous saprolite differs from the iron segregations (described below, Section 6.6.5) in that it has yellow-brown colour, less Fe and may have diffuse mottling and incipient nodular structures. Ferruginous saprolite is generally overlain by *collapsed ferruginous saprolite* where the soft, soluble matrix of the ferruginous saprolite has been removed by leaching, causing collapse.

6.4.4 Mottled saprolite fragments
These are similar to ferruginous saprolite but are irregularly to incipiently mottled in their interiors.

6.5   The iron segregation family
Apart from the materials described above, there are other types of ferruginous material which occur within a lateritic profile. These materials include *goethite pods, gossans, stratabound Fe-rich bodies, highly-ferruginized bedrock and highly-ferruginized saprolite* (as distinct from ferruginous saprolite) and are referred to as *iron segregations*. Although formed by weathering, their development is not confined to a single unit of the lateritic profile. Iron segregations commonly occur as pods, ovoid bodies, lenses and large slabs; they range in size from a few centimetres to several metres. As erosion proceeds, some of these materials are progressively exposed at the surface, where they disintegrate and contribute to the lag. They are generally dark brown to black and non-magnetic (Fig. 6.5E and F). Iron segregations are invariably rich in

Fe, Mn, Zn, Cu, and Co and are dominated by low Al-substituted goethite, with variable amounts of hematite, kaolinite, and quartz. It is significant that the iron segregations do not have cutans. Where gossanous, they show boxworks and goethite pseudomorphs after sulphides. Their interiors are riddled with solution cavities, filled with brownish-yellow, highly-crystalline, secondary goethite and traces of kaolinite. Some cavities are lined with chalcedony.

6.6   Evolutionary pathways

Figure 6.4 illustrates the evolution of lithic and non-lithic nodules and associated ferruginous materials in weathered mafic, ultramafic, and felsic profiles. This is based on findings from the Mt. Gibson, Lawlers, and Bottle Creek orientation studies.

6.6.1   *Lithic nodules and pisoliths*

Lithic nodules are Fe and Al accumulations in which the original structure of the parent rock can be seen. Rock fabrics include those of mica schist, andesite, dolerite, BIF, gossan, amphibolite, and serpentinite. These nodules developed by fragmentation and ferruginization of saprolite. Their formation was initiated lower in the saprolite. Some of the Fe required for ferruginization may have been derived, at an early stage, from patches of sulphides and ferromagnesian minerals. Lithic nodules over mafic lithologies form by direct ferruginization of the parent rock where hollow pseudomorphs of former ferromagnesian minerals pressure the original fabric. Leaching of ferromagnesian minerals has removed all but Fe, the Fe-oxides then retain the form of the primary minerals.

6.6.2   *Non-lithic nodules and pisoliths*

These nodules are generally formed higher in the mottled zone or ferruginous saprolite and result from pedogenetic activity in the vadoze zone. Non-lithic nodules and pisoliths are formed by leaching, migration and accumulation of Fe in voids or clay matrix. This is not a singular event, but involves multiple Fe leaching and precipitation events and leads to the generation of mottles. With further mobilization and concentration of Fe, mottles and incipient nodules evolve into true nodules and thence into pisoliths.

6.6.3   *Origin of magnetic nodules*

Magnetic nodules and pisoliths are more ferruginous than co-existing non-magnetic nodules and pisoliths. Their magnetism is due to maghemite which formed by the heating of goethite on the surface by bush fires. There is no evidence for maghemite below the lateritic residuum (except where magnetite from bedrock is weathering). Corundum can also form from heating of other minerals and has also been identified in pisoliths (Anand and Gilkes, 1987). The high temperatures in forest fires can easily explain these transformations. It is also probable that extensive forests previously extended into the areas that are now arid.

6.6.4   *Development of cutans*

Most lithic and non-lithic nodules and most pisoliths have thin (1-2 mm) cutans which are goethite-kaolinite rich and were formed by the deposition of Fe and Al around a nucleus. Some pisoliths are strongly banded. Where alternating dark and light cutans occur, the light coloured cutans are rich in Al, are in Fe and are kaolinite-rich. Milnes *et al.* (1987) suggested that the differing laminae reflected varying pedogenic environments. Nahon *et al.*

6.6.5.   *Iron segregations*

Systematic differences between the lateritic and iron segregation families occur in morphology, mineralogy, and geochemistry. These suggest that the conditions under which these families formed were different for the two families. It is possible to interpret the conditions of their formation by considering the regolith stratigraphy, the mineralogy, the chemistry, and their petrographic detail.

Gossans

Iron segregations, formed from the weathering of sulphides, are gossans, which may show goethite and subordinate hematite boxworks. These Fe-oxides developed *in situ*, by pseudomorphic replacement of pyrite or pyrrhotite or were deposited in solution cavities left by dissolution of sulphides. A delicate boxwork fabric may result where pyrite dissolution is accompanied or followed by silicification

### *Slabs, lenses and zones of intense ferruginization*

These were formed by residual accumulation of Fe-rich lithologies (e.g. pyritic shales) or as exotic accumulation of Fe-oxides along preferred pathways, such as fractures, faults, and lithological contacts. In the latter, Fe may have been derived from gossans, Fe-rich source rocks, upland areas or by weathering of the

country rocks, with precipitation occurring in a chemically-favourable zone. These iron segregations have formed under reducing conditions in a relatively Al-free environment which is shown by the low level of Al substitution in goethite and absence of kaolinite. It, therefore, seems likely that some of the iron segregations formed under some past hydromorphic concentration of Fe within the saprolite horizon, although they may occur today in areas which are freely drained. Some iron segregations in this category (zones of intensely-ferruginized bedrock or saprolite) may result from replacement of secondary minerals by goethite and hematite. A network of fractures may have provided access for incoming Fe-rich solutions and allowed removal of alkalis, Si, and Al from the breakdown of clays. The formation of either goethite or hematite is influenced by local conditions; lower temperature, high water activity and reducing conditions favour goethite (Schwertmann, 1985).

In reducing conditions, Fe and Mn are mobile as Fe^{2+} and Mn^{2+}. Zinc and Co, released from primary minerals and gossans, also occur as divalent ions in reducing conditions and may substitute for Fe^{2+} and Mn^{2+} (Tiller, 1963) which may explain the abundance of Mn, Zn, and Co in iron segregations.

Goethite pods
Small pods of iron-segregations, which occur in the base of lateritic residuum and collapsed ferruginous saprolite, are probably the result of redeposition of Fe (with Mn, Zn, and Co) leached from the upper parts of the profile. Mobilization of Fe and Mn from surficial units is possible under conditions of low pH and high CO_2 activity, provided by organic matter. Furthermore, the conversion of Fe^{3+} to Fe^{2+} is also favoured by the considerable porosity of the lateritic residuum and soil where open pores provide favourable conditions for bacterial, plant or animal growth. Thus, local and/or temporary strongly-reducing conditions might convert Fe^{3+} to Fe^{2+}. This environment also favours the reduction of Mn^{4+} to Mn^{2+}. Colloidal Mn^{4+} complexes are highly mobile and can be transported as sols over great distances (Tiller, 1963). The distribution of Co is controlled by similar physico-chemical conditions as Mn. It is initially adsorbed by negatively charged Mn^{4+} colloids and later incorporated into Mn oxides. Transport of Fe^{2+} takes place in solution and at the point of iron oxidation, ferrolysis occurs according to the reaction:

$$4Fe^{2+} + 6H_2O + O_2 \rightarrow 4FeOOH + 8H^+$$
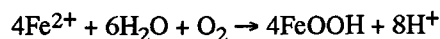
Manganese, Zn, and Co, in iron-segregations, coprecipitate with Fe^{+3} on oxidation, during the formation of iron segregations.

6.7 Summary and conclusions

- Two major families of common ferruginous materials are recognized, namely the lateritic family and the iron segregation family. The lateritic family forms a continuous blanket deposit, whereas iron segregations occur as pods, lenses and large slabs, and, whilst commonly occurring in saprolite, are not confined to a single regolith unit. The lateritic family includes lateritic nodules and pisoliths from lateritic duricrust, hardened mottles, fragments of collapsed ferruginous saprolite and ferruginous saprolite. The iron segregation family includes fragments of gossans, goethite pods, stratabound iron segregations, extremely-ferruginized bedrock, saprolite, and other forms of iron enrichment.

- Materials of the lateritic family are formed from ferruginization and residual accumulation in the upper part of the lateritic profile. By contrast, iron segregations are formed by hydromorphic accumulation of Fe, derived from a variety of sources, including gossans, Fe-rich lithologies, upper weathering horizons, and by lateral water from upland areas.

- The distinction between the lateritic family and iron segregations can be made on regolith-landform settings, position within the regolith stratigraphy, colour, and presence or absence of cutans. Iron, Mn, Zn, Co, and goethite can also be used as indicators in order to discriminate iron segregations from lateritic nodules, pisoliths, mottles and ferruginous saprolite fragments.

- A close genetic relationships exists between the members of the lateritic family. Lateritic nodules, developed over mafic rocks, are associated with the fragmentation of ferruginous saprolite while lateritic nodules formed over felsic rocks are associated with mottles in the mottled zone. The genesis of members of the lateritic family as well as extensive sampling for chemical characteristics indicates that they are geochemically compatible.

- The mottled zone is restricted in distribution and, in places, appears conspicuous mostly over felsic rock; where the underlying rock is mafic or ultramafic, mottling may be less evident. Ferruginous saprolite and collapsed ferruginous saprolite are strongly developed over mafic and ultramafic bedrocks.

- A variety of nodules and pisoliths can form from the same source rock. Nodules and pisoliths are derived from both lithic and non-lithic sources. Lithic nodules are derived directly from bedrock or from saprolite. In the areas studied, lithic fabrics include those of andesite, BIF, mica schist, dolerite, serpentinite, and gossan. Preservation of rock fabric in lithic nodules allows prediction of the underlying lithology. Non-lithic nodules are massive and featureless and are formed higher in the mottled zone.

- On the whole, formation of lateritic nodules and pisoliths has been complex. They are formed by a combination of fragmentation, ferruginization and a series of phases of leaching, migration and deposition of Fe-oxides.

- Both magnetic and non-magnetic varieties of nodules occur together. Non-magnetic nodules and pisoliths generally dominate the gravel fraction. Magnetic nodules are more ferruginous than co-existing non-magnetic nodules, the magnetic properties are due to maghemite.

- Cutans (goethite- and kaolinite-rich) are formed by deposition of Al and Fe around a nucleus.

6.8   Implications in exploration

- Understanding the evolution of lateritic and associated ferruginous materials enables recognition of geochemically-compatible family types which may give similar expressions of mineralization. The lateritic family includes lateritic nodules, pisoliths and lateritic duricrust. The laterite family can be extended (with caution) to include transitional materials, namely, hardened ferruginous mottles, fragments of collapsed ferruginous saprolite, and massive ferruginous saprolite. The iron-segregation family includes goethite pods, gossans, stratabound Fe-rich bodies, highly-ferruginized bedrock, and saprolite.

- Understanding the formation of lateritic nodules and pisoliths suggests possible changes in expression of mineralization within compatible samples. Some are more representative of primary mineralization and bedrock than others, probably due to the differences in the degree of evolution and modification. Ferruginous saprolite is less weathered and least modified than the overlying lateritic residuum and is, therefore, more representative of mineralization. Conversely, lateritic residuum shows far larger geochemical anomalies.

- Iron segregations and the lag formed from them may be used as a geochemical medium, but different threshold for Mn, Co, Zn, and As should be applied from those used for the lateritic family.

7.0   THE CSIRO-AGE LATERITE GEOCHEMICAL DATABASE

7.1   Introduction
Regional geochemical databases have been, or are being, developed for a variety of purposes in several countries. Commonly, one of their ultimate aims is to define geochemical provinces, some of which assist in recognizing mineralized provinces.

This section discusses a reconnaissance-scale programme that resulted in the CSIRO-AGE Laterite Geochemical Database. The database contains data on samples that cover wide areas of the Yilgarn Craton and forms part of the foundations for current research into laterite geochemistry in mineral exploration. The project involved sampling and analysis of the laterite cover and other residual materials that are extensively, but variably, developed over many greenstone belts, and granitoid terrain of the Yilgarn Craton.

The CSIRO orientation studies at the Golden Grove (volcanogenic base metal sulphide) and Greenbushes (rare metal pegmatite) deposits were followed by testing relatively-wide-spaced laterite sampling techniques from 1980 to mid-1986. Sample coverage of parts of the Yilgarn Craton largely followed the strategy and tactics of the companies in the AGE joint venture (Greenbushes Ltd, St Joe Minerals, and later, Sons of Gwalia NL), whilst the regolith and geochemical concepts were developed by CSIRO. To some extent sample coverage was dictated by ground availability, exploration potential, and the feasibility of follow up exploration. The CSIRO Laterite Geochemistry Group provided guidance on sampling techniques, data presentation, and interpretation. The priorities for choice of sample media are shown in Fig. 7.1. The abundance of laterite cover was one of the most important factors in choosing areas for sampling.

During the AGE reconnaissance sampling, it was not generally feasible to sample beneath areas of hardpanized colluvium to seek buried laterite profiles. Neither hand augering nor drilling (using the AGE programme's light trailer-mounted auger rig which was used where access allowed) were successful. Thus there are gaps within the AGE sampling, which could now be effectively explored using the findings of this project.

Besides generating numerous geochemical anomalies, the testing of which will continue for years to come, the CSIRO-AGE database provides knowledge of backgrounds, regional variation, and element levels in laterite, linked where feasible, to bedrock type. This information complements data from this project's orientation areas and is of relevance both to research and exploration.

7.1.1   *Objectives and scope*
The purpose of the CSIRO-AGE research and application activity was to establish laterite sampling as a practical technique for routine mineral exploration.

The research objectives were:

- to study regional variations in laterite geochemistry, which may be due to regional changes in climate or landform characteristics;
- to establish the variation in laterite composition in areas away from known ore deposits;
- to relate laterite composition to both regional and local geological variation; and
- to test and develop efficient sampling methods for cost-effective exploration.

The exploration objectives were:

- to identify laterite geochemical anomalies due to mineralized provinces or districts; and
- to recognize, particularly through follow-up sampling, laterite geochemical anomalies due to previously-unrecognized mineral deposits.

This section provides an overview of the CSIRO-AGE sampling programme and its geochemical database. Readers are referred to the individual reports arising from this project (Appendix I) in order to pursue the geochemical characteristics of the areas covered and the nature of individual anomalies.

7.2   Distribution of samples and Reports produced
The strategy upon which the AGE programme was based centred on reconnaissance laterite geochemistry to (a) provide information on geochemical provinces within the Yilgarn Craton, and (b) detect haloes about previously-unrecognized mineral deposits.

Fig. 7.1. Conceptual diagram showing the sampling priorities used in the CSIRO-AGE trial sampling exploration programme. Also shown are the original CSIRO-AGE sample codes and their equivalents.

A 3-km spaced, triangular sampling grid was used over much of the sampled area, with limitations caused by the distribution of access roads, the extent of erosion of the laterite cover, the extent of cover by alluvium/colluvium, and the extent of mining and exploration tenements. Follow-up and fill-in samples were taken in areas of interest so closing the sample spacing to 1 km and in some cases, to 330 m. The locations of follow-up sampling is obvious in plots showing sample sites, for example, at 1:250,000 scale or more detailed. Samples are coded according to the stage of exploration; reconnaissance (R), follow-up (F2), or detailed exploration (F3).

The intention was to sample lateritic residuum, either as duricrust or as loose lateritic pisoliths and nodules which had been released from the duricrust by natural disaggregation. Nodules and pisoliths in the

range of 1 cm to 2 cm were sought to avoid the possibility of introducing an unacceptable sampling error if very coarse material were collected and to aid sample preparation by providing direct feed for the disk grinder (to avoid coarse crushing). Where possible, 1 kg samples were collected over a 10 metre radius to suppress any unforeseen local variation. A separate 1-kg sample was collected for permanent reference. Other sample types were collected where lateritic residuum was not available (Fig. 7.1). Photomosaics (1:50,000 scale) were used, where available, in selecting sample sites and for recording sample locations. All samples were allocated AMG coordinates.

The classification developed during the CSIRO-AGE study was retained in the AMIRA project reports on the CSIRO-AGE database. Cross referencing with the terminology and classification scheme developed in this AMIRA project (the *Atlas*, Anand *et al.*, 1989) is shown in Fig. 7.1. Many categories in the 'lateritic family' used in the AGE study translate directly to the standardized terminology and classification. However, some of the categories in the 'ferricrete family' would require re-logging of the reference material and identification of the local regolith situation before translation to the *Atlas* scheme is possible. This has not been done.

Results were presented in six AMIRA reports with data for each on accompanying floppy disk. An index is shown in Fig. 7.2. In total, there are in excess of 7500 samples in the database.
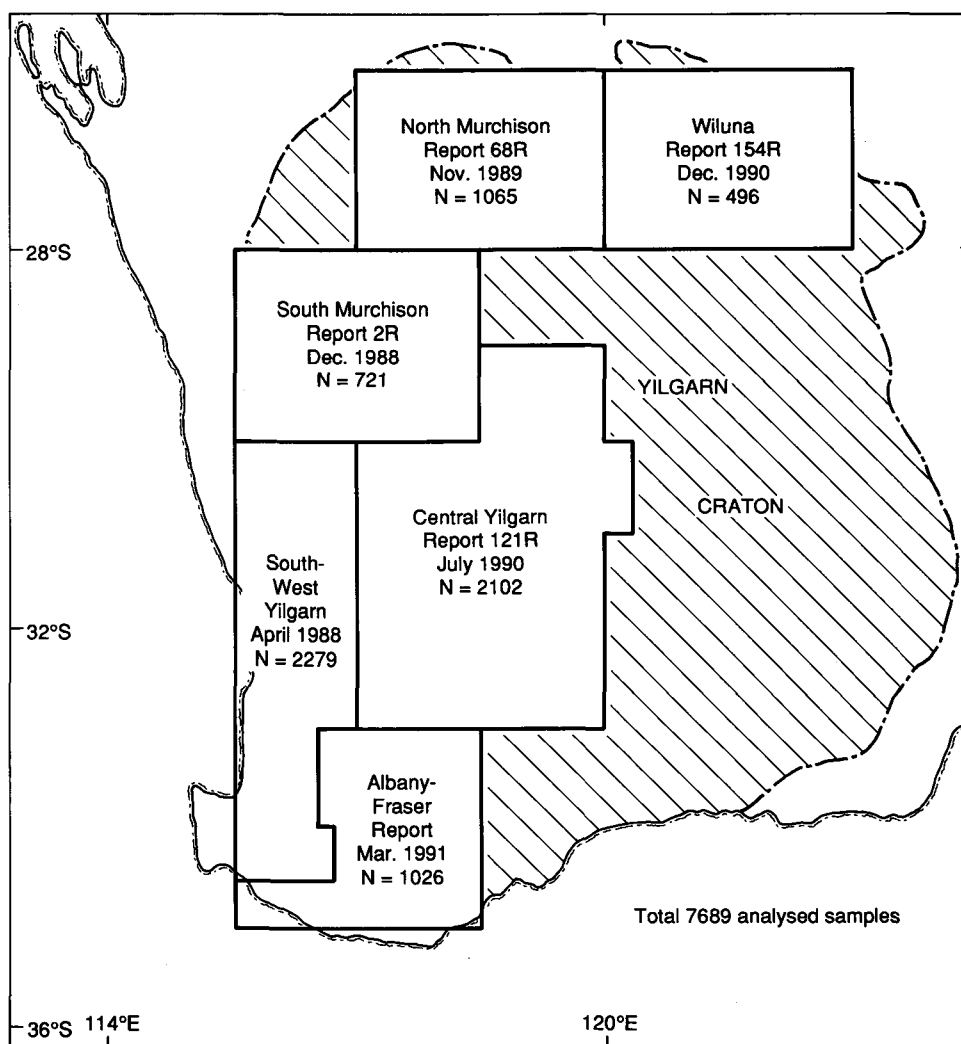
Fig. 7.2. Index of reports on blocks of data in the CSIRO-AGE Yilgarn laterite geochemical database. The number of analysed samples in each block is shown.

Table 7.1. Summary statistics from the CSIRO-AGE Yilgarn Geochemical Database, Reconnaissance sampling (R). **Lateritic family of samples.**
Sample types included: loose lateritic pisoliths, nodules and lateritic duricrusts (LP, LN, CP, CN, using CSIRO-AGE 1983-1986 Codes).
Number of samples in group: 2434.

Oxides	Units	Lab.	Method	LLD	No. of Samples	Percentiles 5	10	25	50	75	90	95	98	99	Min.	Max.	Mode	Mean	Std.Dev.	Element
SiO_2	Wt.%	CSIRO	ICP-FS	0.6	1078	9.8	13.2	21.7	37.9	49.9	56.2	60.3	63.5	67.6	2.2	75.9	51.9	36.0	16.2	SiO_2
Al_2O_3	Wt.%	CSIRO	ICP-FS	0.6	1078	12.3	15.0	18.2	22.0	26.5	33.7	39.6	44.6	48.1	1.7	57.9	21.2	23.3	8.0	Al_2O_3
Fe_2O_3	Wt.%	AMDEL	AAS-HF	0.1	2434	8.2	10.3	14.4	26.2	43.5	58.8	66.1	71.0	76.1	1.57	86.1	11.6	29.9	18.5	Fe_2O_3
MgO	Wt.%	CSIRO	ICP-FS	0.1	1078	0.02	0.04	0.06	0.08	0.10	0.13	0.15	0.23	0.30	0.02	2.37	0.02	0.09	0.09	MgO
CaO	Wt.%	CSIRO	ICP-FS	0.1	1078	0.02	0.02	0.05	0.06	0.07	0.09	0.11	0.15	0.19	0.02	1.56	0.02	0.06	0.08	CaO
TiO_2	Wt.%	CSIRO	ICP-FS	0.001	1078	0.44	0.51	0.64	0.96	1.43	2.01	2.38	2.88	3.38	0.08	5.83	0.85	1.13	0.66	TiO_2
Elements																				
Mn	ppm	AMDEL	AAS-HF	5	2434	10	16	30	65	140	270	409	1064	1308	1	9999	16	144	438	Mn
Cr	ppm	AMDEL	XRF	10	2434	103	127	184	305	732	1874	4231	8221	9999	33	9999	180	903	1734	Cr
V	ppm	AMDEL	XRF	10	2434	120	162	255	425	812	1220	1520	1877	2125	3	4811	314	585	468	V
Cu	ppm	AMDEL	AAS-HF	2	2433	2	4	6	14	48	120	190	260	319	1	2033	4	44	82	Cu
Pb	ppm	AMDEL	XRF	4	2434	6	11	19	30	45	62	74	93	118	1	235	1	35	24	Pb
Zn	ppm	AMDEL	AAS-HF	2	2434	6	8	10	16	26	41	57	122	153	1	380	10	23	27	Zn
Ni	ppm	AMDEL	AAS-HF	5	2434	5	10	20	31	52	100	175	315	510	1	2016	25	57	110	Ni
Co	ppm	AMDEL	AAS-HF	5	2433	2	2	2	5	10	20	33	53	60	2	150	2	10	13	Co
As	ppm	AMDEL	XRF	2	2434	6	9	14	22	33	53	84	173	274	0.7	2375	14	35	89	As
Sb	ppm	AMDEL	XRF	2	2434	0.7	0.7	0.7	0.7	3	6	6	9	13	0.7	175	0.7	2	6	Sb
Bi	ppm	AMDEL	XRF	1	2434	0.3	0.3	0.3	0.3	1	2	3	4	6	0.3	35	0.3	1	1.5	Bi
Cd	ppm	AMDEL	AAS	1	2434	0.3	0.3	0.3	0.3	0.3	0.3	0.3	1	2	0.3	8	0.3	0.4	0.3	Cd
Mo	ppm	AMDEL	XRF	2	2434	0.7	0.7	0.7	3	5	7	9	14	17	0.7	57	0.7	4	4	Mo
Ag	ppm	AMDEL	OES	0.1	2434	0.03	0.03	0.03	0.03	0.03	0.2	0.3	0.6	0.8	0	4	0	0.1	0.2	Ag
Sn	ppm	AMDEL	XRF	1	2434	0.3	0.3	0.3	2	4	6	7	9	10	0.3	38	0.4	2.5	2.5	Sn
Ge	ppm	AMDEL	OES	1	2434	0.3	0.3	0.3	0.3	0.3	0.3	1	2	2	0.3	10	0.3	0.4	0.4	Ge
Ga	ppm	AMDEL	OES	1	2434	6	8	15	20	25	30	30	35	40	1	80	20	19	9	Ga
W	ppm	AMDEL	XRF	10	2434	3	3	3	3	3	12	15	21	30	3	1483	3	6	31	W
Ba	ppm	CSIRO	ICP	100	1072	33	33	33	79	118	190	306	750	1088	3	3067	35	118	200	Ba
Zr	ppm	CSIRO	ICP-FS	100	1078	212	237	296	370	469	612	756	1000	1140	150	24175	305	430	746	Zr
Nb	ppm	AMDEL	XRF	3	2434	1	1	8	12	16	23	28	36	41	1	125	2	12.8	8.5	Nb
Ta	ppm	AMDEL	XRF	1	2434	1	1	1	1	1	1	3	5	6	0.3	13	1	1.2	1	Ta
Se	ppm	AMDEL	XRF	1	2380	0.3	0.3	1	2	4	6	7	8	10	0.3	73	0.3	2.9	3	Se
Be	ppm	AMDEL	OES	1	2434	0.3	0.3	0.3	0.3	0.3	0.3	1	1	1	0.3	4	0.3	0.4	0.2	Be
Au	ppb	ANALAB	AAS-CR	1	1193	0.3	0.3	1	3	6	11	19	40	170	0.3	3100	0.5	15.6	142	Au

Table 7.2. Summary statistics from the CSIRO-AGE Yilgarn Geochemical Database, Reconnaissance sampling (R). Non-lateritic family (iron segregation family).
Sample types included: ferruginous pebbles, cobbles (much derived from iron segregations), MF, FF, PF and PE (using CSIRO-AGE 1983-1986 Codes).
Number of samples in group: 500.

Oxides	Units	Lab.	Method	LLD	No. of Samples	Percentiles									Min.	Max.	Mode	Mean	Std.Dev.	Element
						5	10	25	50	75	90	95	98	99						
SiO2	Wt.%	CSIRO	ICP-FS	0.5	325	7.2	8.0	11.0	15.2	22.3	41.0	55.2	75.0	82.3						
Al2O3	Wt.%	CSIRO	ICP-FS	0.5	325	1.6	2.3	3.5	6.1	8.4	14.1	17.8	21.2	25.9						
Fe2O3	Wt.%	AMDEL	AAS-HF	0.1	500	25.6	39.5	54.6	65.5	73.4	79.2	82.2	84.7	88.8	5.6	95.5	65.0	61.6	17.2	Fe2O3
MgO	Wt.%	CSIRO	ICP-FS	0.1	325	0.02	0.05	0.08	0.11	0.14	0.22	0.34	0.84	1.34	0.02	8.67	0.02	0.18	0.58	MgO
CaO	Wt.%	CSIRO	ICP-FS	0.1	325	0.05	0.06	0.08	0.09	0.12	-0.17	0.23	0.55	0.99	0.02	4.71	0.09	0.14	0.29	CaO
TiO2	Wt.%	CSIRO	ICP-FS	0.001	325	0.11	0.16	0.35	0.60	1.07	1.81	2.47	3.92	5.49	0.02	9.74	0.54	0.93	1.14	TiO2
Elements																				
Mn	ppm	AMDEL	AAS-HF	5	500	53	95	228	540	1700	3100	4000	4502	5760	2	9999	62	1155	1377	Mn
Cr	ppm	AMDEL	XRF	10	500	127	175	323	695	1404	2705	4805	8153	9999	35	11896	302	1261	1711	Cr
V	ppm	AMDEL	XRF	10	500	138	224	381	575	914	1318	1629	2110	2496	3	6406	434	719	588	V
Cu	ppm	AMDEL	AAS-HF	2	500	22	44	100	175	250	330	390	489	660	2	971	140	188	127	Cu
Pb	ppm	AMDEL	XRF	4	500	2	2	6	15	32	54	82	121	198	1	507	1	26	42	Pb
Zn	ppm	AMDEL	AAS-HF	2	500	21	27	48	160	310	460	610	837	1000	4	1500	31	214	209	Zn
Ni	ppm	CSIRO	AAS-HF	5	500	10	20	55	130	270	530	847	1388	1700	2	2400	6	232	314	Ni
Co	ppm	AMDEL	AAS-HF	5	500	5	6	15	45	110	170	220	244	330	2	612	5	71	78	Co
As	ppm	AMDEL	XRF	2	500	3	4	9	20	51	165	242	425	764	1	2595	9	67	192	As
Sb	ppm	AMDEL	XRF	2	500	1	1	1	2	5	8	13	23	44	0.3	212	1	5	14	Sb
Bi	ppm	AMDEL	XRF	1	500	0.3	0.3	0.3	0.3	2	3	4	6	9	0.3	58	0.3	1.5	3.3	Bi
Cd	ppm	AMDEL	AAS	1	500	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	1	0.3	2.0	0	0.4	0.2	Cd
Mo	ppm	AMDEL	XRF	2	499	0.7	0.7	0.7	0.7	3	5	8	18	29	1	73	0.7	2.7	5.6	Mo
Ag	ppm	AMDEL	OES	0.1	500	0.03	0.03	0.03	0.03	0.03	0.2	0.4	0.8	1.0	0.03	2	0.04	0.1	0.23	Ag
Sn	ppm	AMDEL	XRF	1	500	0.3	0.3	0.3	3	5	7	9	11	13	0.3	71	0.4	3.4	4.3	Sn
Ge	ppm	AMDEL	OES	1	500	0.3	0.3	0.3	0.3	0.3	1	1	2	3	0.3	20	0.3	0.5	1.0	Ge
Ga	ppm	AMDEL	OES	1	500	0.3	1	3	6	15	20	25	30	30	0.3	60	9	9.5	8.4	Ga
W	ppm	AMDEL	XRF	10	500	3	3	3	3	11	18	22	30	35	3	290	3.4	7.8	15	W
Ba	ppm	CSIRO	ICP	100	325	99	138	186	296	575	1002	1334	2005	2616	33	6464	196	494	623	Ba
Zr	ppm	CSIRO	ICP-FS	100	325	177	192	210	236	283	370	470	650	708	47	1032	235	267	113	Zr
Nb	ppm	AMDEL	XRF	3	500	1	1	6	13	16	21	27	34	71	1	86	1.5	12.6	10.2	Nb
Ta	ppm	AMDEL	XRF	1	499	1	1	1	1	1	1	4	6	9	1	195	1	1.8	8.8	Ta
Se	ppm	AMDEL	XRF	1	498	0.3	0.3	0.3	2	4	6	7	8	10	0.3	13	0.4	2.7	2.3	Se
Be	ppm	AMDEL	OES	1	499	0.3	0.3	0.3	0.3	0.3	0.3	0.3	1	2	0.3	6	0	0.4	0.3	Be
Au	ppb	ANALAB	AAS-CR	1	190	.3	1	2	3	5	12	23	30	120	0.3	183	2	7	18	Au

Regional statistics

7.3   Overall statistics

Overall statistics of the geochemical analyses from the AGE sampling are given in Table 7.1, for the laterite family of samples, and Table 7.2, for cobbly and pebbly ferruginous lag derived from partly truncated profiles (the ferricrete family of the AGE programme). These statistics use only the reconnaissance phase of sampling so as to avoid biasing the results with follow-up sampling about identified anomalies. Results from orientation sampling were also excluded from these two statistical tables. Use of the upper percentiles (95th and 98th, for example) of target-associated elements provides useful thresholds for reconnaissance exploration in the Yilgarn Craton.

7.4   Use of the CSIRO-AGE database in exploration

The CSIRO-AGE database has a number of uses in exploration and research.

- The data contribute to the identification of geochemical provinces in the Yilgarn Craton.

- Numerous individual geochemical anomalies, believed to be (or suspected of being) related to previously-unrecognized ore deposits or ore systems, have been identified. Far more anomalies were identified than could be followed up by the AGE exploration programme. We understand that follow-up of AGE anomalies by sponsors of this AMIRA project continues.

- The data provide information on thresholds for geochemical exploration.

- The data show regional variation in some element abundances suggesting broad regional variation in bedrock characteristics.

- The recognition of a number of "chalcophile corridors" within the Yilgarn Craton by Smith et al. (1989) was an important outcome in terms of the ability to recognize mineralized provinces or districts.

   This was based on the regional distribution of As and Sb, in places together with Bi, Mo, Sn, W, and Au. Chalcophile corridors are believed to be strategically important in mineral exploration and have been providing stimulus for some sponsors' exploration activities. Chalcophile corridors have now been recognized in other continents (Plant *et al.*, 1989).

8.0 DATA INTERPRETATIONAL METHODS

8.1 Introduction

Laterite geochemistry achieves its full potential when it is used in a multi-element mode. Information can then be obtained on the potential for a wide range of concealed mineral deposits, their likely element associations, and on the main bedrock types. To realize this potential requires effective forms of data presentation and data interpretation. Whilst single element interpretation is fundamental (for example, the abundance levels of Au, As, Sb, ...), interpretational methods which condense the amount of data being presented or interpreted are important and necessary tools.

In this section several interpretational methods are discussed. These range from simple to sophisticated. It is emphasised that when individual samples or groups of samples are highlighted by an interpretation procedure, a geological or geochemical reason should always be sought. The question should be asked: "Do the unusual relationships make sense?" Thus it is highly advisable that there be very close collaboration between those doing data analysis and those involved in the field study. With methods of interactive interpretation becoming easier to use, it is now practical to have geoscientists who are involved in the field sampling participate in data interpretation. An interpretation is reinforced if several adjacent samples show similar anomalous behaviour. In many cases this may require follow-up sampling.

It is fundamentally important in exploration geochemistry to be able to compare similar materials. For this reason, it is paramount that information on sample type, for each sample, to be included in the database. The classification tables and descriptions developed within the project (Section 3.2, and Anand *et al.*, August 1989) enable the detailed characteristics of sample types to be included in the database in a way that may be manipulated easily.

In extracting data from the database and in subsequent interpretation, it is common to group data in terms of compatible sample types. For example, all types of lateritic gravel may be grouped together using the intermediate level code LT100, rather than a specific code (e.g. LT102, *etc.*). Broader groupings, such as bringing together all samples of lateritic duricrust and lateritic gravel as the broadest term, lateritic residuum (code LT), can be useful, particularly at the reconnaissance stage.

The use of graphical procedures is perhaps one of the most important aspects of geochemical data interpretation. Many of the numerical procedures are difficult to interpret from the numerical results alone. If the interrelationships between the samples and elements can be shown graphically, the nature of the relationships may can be easily observed.

The use of dynamic interactive graphical interpretation of multi-element geochemical data was the focus of a workshop for sponsors in March, 1991. On-screen demonstrations emphasized the ability to interpret clouds of sample points plotted in rotating 3-dimensional space. The ability to interrogate any sample in a sample cloud in terms of sample type, prospect location, bedrock type, sample number (and so on), or to show the level of any chosen element value was demonstrated.

In exploration, the ultimate goal of the investigation of geochemical data is commonly the detection of a spatially-continuous zone which has elevated abundances of target-related elements and which may host mineral deposits. A zone of unusually-elevated abundances (or ratios, etc.) is usually referred to as an anomaly. However, the definition of an anomaly is one of the most contested definitions in current exploration geochemical concepts. An important assumption is that the background and target populations are adequately represented. In regional sampling programmes, this may not always be the case. Sampling strategies are crucial and the design of sampling strategies must be carefully considered prior to collecting samples (Garret, 1983:Chapter 4). Data interpretation can be enhanced significantly if the design of the sampling strategy ensures an adequate representation of geochemical characteristics.

8.2 Discussion paper on the interpretation of laterite geochemical data

Much of the text in Section 8.0 is taken from the report *Strategies and Methods for the Interpretation of Geochemical Data - Discussion Paper Applied to Laterite Geochemistry*, (Eric Grunsky, 1991) which was prepared as part of this AMIRA project.

The Discussion Paper uses five geochemical data sets to provide contrasting examples of regional background data and data from precious metal and base metal massive sulphide settings. The data sets and supporting summary tables are used to provide graphic examples, together with various methods of interpretation.

The data sets used are listed below. All consist of samples of lateritic residuum.

1.   Murchison Greenstone Belt: Regional background data, N=868
2.   Yilgarn Block granite-gneiss terrain: Background group Albany-Fraser region, N=451
3.   Mt. Gibson Au deposit: Target group, N=173
4.   Golden Grove Cu-Zn-Au deposit: Target group, N=100
5.   Lawlers Au deposit: Target group, N=48

8.3   Suitable empirical methods for data interpretation

Some examples of simple methods for data presentation are given in Report 157R on the Mt. Gibson data sets by Smith *et al.* (1992). Use of summary statistics, box plots, histograms, correlations, and stacked maps are shown.

Some simple geochemical indices can be very effective. An example is the use of chalcophile indices. An additive index, based upon the abundances of several chalcophile elements was used by Smith and Perdrix (1983) at Golden Grove. A similar index CHI-6*X was used in Report 20R for Mt. Gibson (Anand *et al.*, March, 1989). Here CHI-6*X = As + 3 Sb + 10 Bi + 3 Mo + 30 Ag + 30 Sn + 10 W + 3 Se, where element abundances are in ppm and each element is weighted. It is clear that a high value for any one element will cause a high score for the index overall. Hence caution needs to be used and the reason for high values needs to be investigated.

Indices which are based upon the number of anomalous elements in each sample (NAE indices) are also useful. One of these types, the NUMCHI index, is a useful adjunct to the additive chalcophile indices. The NUMCHI index is the *number* of anomalous elements that are present in each sample. The NUMCHI index is a proximity indicator, based on the reasoning that, as an ore system is approached, the number of anomalous target-associated elements typically increases. Thresholds are generally decided for an area or region, although application of Yilgarn-wide statistics (Section 7.0) can be useful in broad reconnaissance. The NAE family of indices are not 'driven off scale' by a very high value in any one element, but they should be used in conjunction with element abundances or indices more closely related to quantitative information. Two examples of NUMCHI indices used at Mt. Gibson are given in Report 20R (Anand *et al.*, March 1989).

In all forms of data interpretation, knowledge of orientation situations is a decided advantage, and, for some interpretational methods discussed below, is absolutely essential. It is therefore important for those engaged in data interpretation to become familiar with orientation data sets arising from the project, Table 8.1, as well as those arising from their own exploration and those in the literature.

Sample populations that represent the anomalies produced by the ore deposits being sought are termed "**Target**" populations. These populations may be obtained from orientation studies over known mineral deposits or areas of specific interest. Homogeneity of the target populations is important for correct application of statistical procedures.

Sample populations that represent the regional geochemical background are termed "**Background**" populations. Separation of the background population into similar subsets that represent homogeneous multivariate normal populations is important and forms the basis of the modelled approach of geochemical data analysis. This can be achieved using components analysis, spatial analysis, chi-square plots, etc.. Typical background populations would be obtained from regional geochemical sampling over greenstone or gneiss terrains. Background populations must be checked for atypical observations, outliers, anomalous values, or any trends that do not represent typical regional values. Some of these atypical values could represent mineralized zones and should be closely scrutinized. Target populations should represent samples collected over mineralized zones and their associated alteration haloes. The geochemical characteristics of such a population would be distinctly different from the regional background population and thus a statistical distinction can be made between them.

8.4   Exploratory data analysis

Exploratory Data Analysis (EDA) analyses geochemical data to recognize and enhance any trends or structures, many of which are not immediately obvious. These trends, structures, or patterns provide insight into the geochemical and geological processes that have occurred. There are a great many methods and procedures that can be used with geochemical data which enable the investigator to discover patterns in the data. Some of the most important (principal components analysis, cluster analysis, and chi-square plots) are presented in the Discussion Paper.

Table 8.1. List of data sets of samples analysed from the main orientation studies carried out within the project and the CSIRO-AGE database, showing the corresponding project reports.

Orientation study	Number of samples analysed	Report number
Boddington	284	246R
Mt. Gibson	374	157R 165R
Bottle Creek	490	247R
Lawlers	248	166R
Beasley Creek	222	27R 105R
CSIRO-AGE	7689	Un-numbered report (SW Yilgarn, April 1988) 2R
Total	9307	68R 121R 154R 161R

The first stage of data analysis involves the examination of the frequency distributions, univariate statistics (parametric, non-parametric, and robust methods), bivariate plots, correlation coefficients, plus other numerical or graphical methods that assist in understanding the nature of the data. *It is at this stage that outliers should be identified and generally be eliminated. Failure to remove or compensate for outliers can have profound and adverse effects on any statistical interpretation of data.*

The usefulness of multivariate data analysis methods applied to geochemical data has been well documented (Howarth and Sinding-Larsen, 1983:Chapter 6). Methods such as principal components analysis, cluster analysis, multidimensional scaling, and projection pursuit provide numerical and graphical means through which the relationships of elements and samples can be studied. These techniques reduce the number of dimensions required to describe the variation of the data. An interpretation of the systematic relationships of 30 elements is almost impossible without applying some form of dimension-reducing technique. The outcome of these dimension-reducing techniques usually provides significantly-fewer "new variables", that describe variation and can be related to specific geochemical and geological processes. The use of robust estimates for the correlation coefficient or covariance matrix assists significantly in assessing multi-element relationships. Otherwise, the presence of outliers can distort the resulting linear relationships that are obtained in methods such as principal components analysis. There are several good reviews that discuss the basics of multivariate data analysis techniques (e.g. Joreskog *et al.*, 1976; Davis, 1986; Howarth and Sinding-Larsen, 1983). Mellinger (1987) provides a systematic approach to the application of multivariate methods in geological studies.

8.5   Modelled approaches to anomaly recognition

Modelled investigations of geochemical data are based upon the knowledge that certain geochemical patterns reflect particular geological processes (such as ore deposits) and are recognizable through data analysis. Through orientation studies, geochemical characteristics can be obtained for specific geological environments which, in interpretation, can be used as models. This information can lead to the definition of background

and target groups, which can then be used as the models with which unknown samples can be compared using a variety of statistical methods. *Background groups* are composed of data that represent regional background variation. *Target groups* are composed of data that characterize the geochemistry around selected mineral deposits.

Both strategies, exploratory data analysis and modelled approaches, can be important for a successful exploration programme and they are commonly carried out in parallel. However, the interpretation of the results of these strategies must be based upon a thorough understanding of the geology of the region(s) being investigated.

Once structures and systematic processes can be recognized within the data, additional numerically-based and statistically-based methods can be applied to further enhance the data interpretation. Methods such as regression analysis, canonical variate analysis (discriminant functions), and classification procedures can be applied to separate target from background populations.

8.6   Log-log anomaly display diagrams

Log-log diagrams, as presented by Smith (1979) and Smith *et al.* (1979), are useful for displaying the multi-element characteristics of laterite geochemical anomalies, Fig. 8.1. Thresholds for each element to be displayed are shown along the vertical axis. These thresholds can be established from statistical treatment of analyses in the CSIRO-AGE database, as has been done here for instance. In the diagrams, the range of values in each target group or anomaly is shown by the horizontal bar for each element. Such log-log diagrams readily allow the multi-element characteristics of many anomalies and orientation targets to be compared. They are particularly useful where plotted to the same size and overlain in a stacked or pad form.

8.7   Recommended steps for anomaly recognition

Following an Association of Exploration Geochemists workshop on *Thresholds and Anomaly Interpretation*, an appendix was assembled by Mellinger *et al.* (1984) which provided a suggested sequence of investigation for anomaly interpretation, based on the integration of geochemical, geographical, and geophysical data.
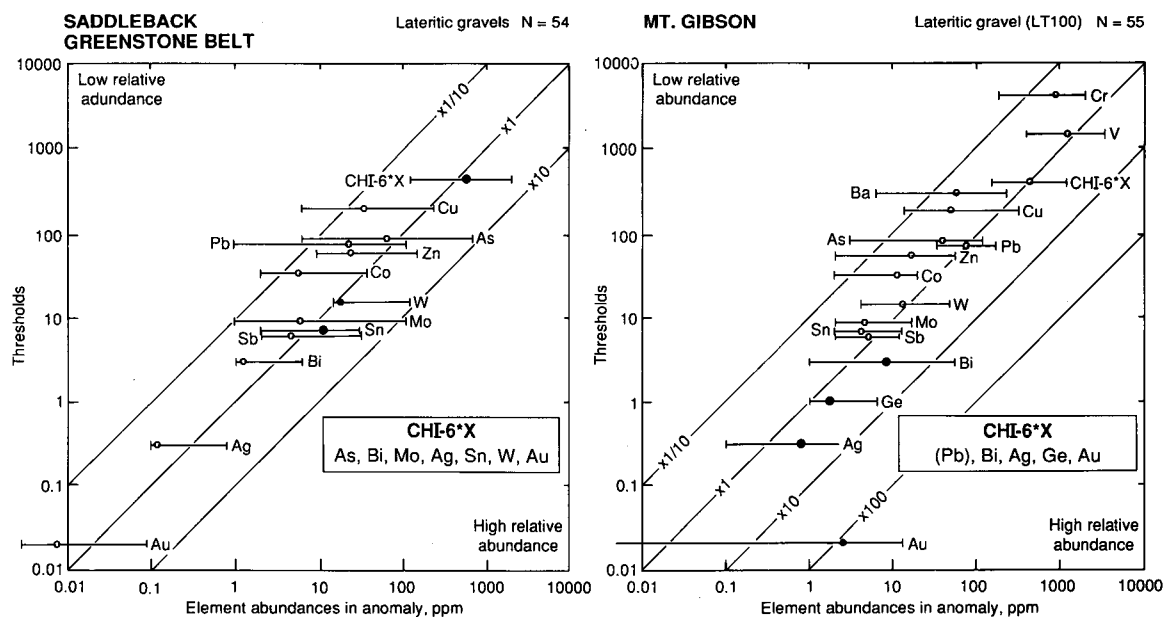
Fig. 8.1. Log-log diagrams comparing different anomalies with CSIRO-AGE database thresholds. (The diagrams use the 95th percentiles, for each element shown, from Table 7.1.) The main element associations are shown in the boxes.
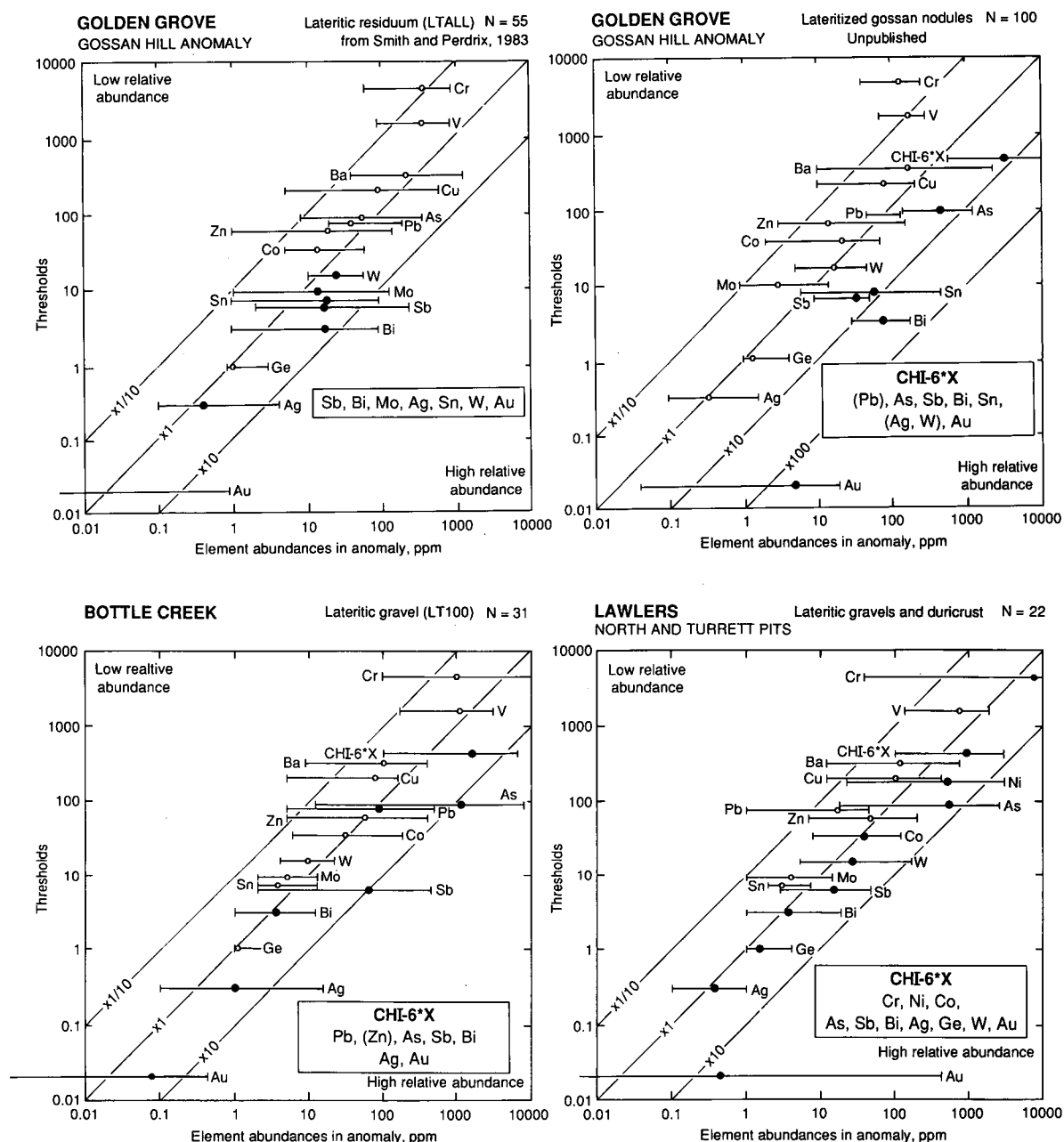
Fig. 8.1 continued. Log-log diagrams comparing different anomalies with CSIRO-AGE database thresholds. (The diagrams use the 95th percentiles, for each element shown, from Table 7.1.)

Three critical steps were defined: preliminary data analysis, descriptive multivariate analysis, and specific multivariate analysis. For the evaluation of lateritic geochemical data, the following detailed sequence of investigation (Grunsky, 1991) is recommended:

(1)   Preliminary data analysis
   •   Examine each element with histograms, box and whisker plots, Q-Q plots, scatter plot matrix, data ranking.
   •   Prepare summary statistical tables, plot data onto maps for each element.
   •   Trim the distribution of each element of gross outliers.

- Investigate outliers for each element; analytical error or atypical abundance?
- Use simple chalcophile and other indices here, see group (3) below.
- Adjust data for censored values if required.
- Transform each element with Box-Cox power transformations using samples below the 95-98th percentile. (This depends upon a prior, visual examination of Q-Q plots or histograms to ensure that estimates are made for single populations, as far as is practical.)
- Create a scatter plot matrix for transformed data. Look for trends/associations.
- Techniques such as PROBPLOT (Stanley, 1987) or the Gap statistic (Miesch, 1981) can be used to dissect multiple populations.
- Set thresholds for elements after transformation.

(2)   Exploratory multivariate data analysis

- The use of robust estimates to compute means and covariances to enhance the detection of outliers.

- Application of dimension-reducing techniques, such as principal components analysis to show systematic linear relationships of the variables and the samples. The use of robust methods on transformed data assists in detecting outliers. Dimension-reducing techniques also indicate which elements are associated with the commodity elements being sought. Maps of the component scores can assist in outlining regional lithological variation and areas that are anomalous.

- The use of methods to delineate structure in the data. Methods such as cluster analysis, multidimensional scaling, non-linear mapping, and projection pursuit isolate groups of samples with similar characteristics and delineate structure in the data. Atypical samples stand out as single outliers. Target groups generally can be isolated using these methods. Maps of the locations of the groups can help to isolate mineralized areas.

- The use of chi-square plots on the transformed data isolate outliers based on all of the elements of interest. The use of Ξ^2 plots assists in the elimination of outliers for the creation of background and target groups which can subsequently be used in canonical variate analysis and for allocation/typicality procedures. Maps of large Mahalanobis distances (>95th percentile) may identify anomalous areas.

(3)   Specific multivariate data analysis and modelled multivariate analysis

- The calculation of empirical indices can be used as methods which are specifically tailored to areas in which multi-element associations are well understood. The indices are based on a linear combination of pathfinder elements with coefficients that are selected for each area and the commodity being sought. Samples representing areas with high indices can be investigated for mineralization potential.

- The use of multiple regression can be applied to areas where a linear model of the multi-element association can be computed with good results (high R^2 coefficients). Residuals can be examined for potential association with mineral deposits.

- Once target and background groups have been established, the use of analysis of variance and canonical variate analysis test the statistical uniqueness of the groups. Groups that are statistically distinct can be used as reference groups against which unknown samples may be compared.

- The use of all possible subsets can be applied to compare the reference groups with each other and determine which group of elements most enhances the group separations.

- Application of allocation and typicality procedures can test the samples used to make the reference group populations. Additionally, unknown samples, from a regional exploration programme can be used to assign the probability of belonging to one of the reference groups and its typicality of that group. Maps of typicality or posterior probability can be made to indicate group membership.

9.0   GEOCHEMICAL DISPERSION MODELS

9.1   Introduction

Although the weathering of each ore deposit and its host bedrock is unique, the weathering products and dispersion characteristics are commonly similar within regions of similar weathering history. Idealized dispersion models are therefore used by explorationists. These models summarize geochemical dispersion from ore deposits in terms of the local regolith, landform, bedrock, and environmental relationships.

The purpose of this section is to bring together patterns and processes of geochemical dispersion, which have been established in the orientation areas with the corresponding models of the regolith-landform relationships. The intent is that the geochemical dispersion models which result (a) will allow ease of reference to generalized patterns of dispersion, and (b) can be used predictively in areas of comparable regolith, landform, and environmental characteristics.

Previous examples of dispersion models, which are relevant to lateritic terrain of the Yilgarn Craton, were given in the volume *Conceptual Models in Exploration Geochemistry – Australia*, by Butt and Smith (1980). A more recent and comprehensive series of dispersion models is presented in *Regolith Exploration Geochemistry in Tropical and Subtropical Terrains* by Butt and Zeegers (1992).

The Laterite Geochemistry Project has focussed upon geochemical dispersion within the upper, commonly ferruginous, part of the laterite weathering profile, particularly within lateritic residuum, the top of the mottled zone and, to a lesser extent, the upper-most ferruginous saprolite. These materials have been the target of sampling whether they be at surface, near surface, or buried beneath more recent sediments.

9.2   Dispersion models

Models used in this report are arranged in Fig. 9.1. The classification scheme is that of Butt and Zeegers (1992) and is primarily based upon the extent of preservation of the original weathering profile. Further subdivision takes into account the continuity of recent alteration of the profile and finally (right hand side) the nature of any overburden. Models based upon complete or near-complete preservation of lateritic weathering profiles are presented in this report. Examples taken from the project's orientation studies are shown within the classification.

9.2.1   *A-type models in semi-arid to arid climates*

Figures 9.2 and 9.3shows the main A-type dispersion models established for the orientation studies in this project from the semi-arid to arid climates of the Yilgarn Craton. Table 9.1 lists the element associations observed in the A-type models from the orientation studies of this project. In the cases studied, where Au is either the ore commodity at depth or is an ore-associated element, Au is retained in the lateritic residuum (Mt. Gibson; Turrett, North Pit, Waroona at Lawlers; Golden Grove; and Kalgoorlie). This is true for lateritic duricrust and any overlying lateritic gravel, including lateritic pisoliths and nodules at the present landsurface (Golden Grove, Mt. Gibson). Landforms where Au is retained in lateritic residuum include hill tops, gentle ridge crests, upper slopes, mid-slopes, and toe slopes. Gold is also retained where lateritic residuum is buried, in places by up to 15 m of hardpanized colluvium. In all the situations studied to date, the lateritic residuum containing the undisturbed geochemical dispersion anomaly lay above the standing water table. It is not known if and how the Au anomaly (and any associated chalcophile anomalies) might be effected if immersed or periodically immersed in ground waters with a high range of salinities.

Longitudinal sections through the Bottle Creek ore zones (Legge *et al.* 1990:Fig.5) show redistribution of Au and Ag in saprolite at 30-60 m. It is not clear whether the upper saprolite is depleted relative to the protore and whether the relatively-low Au levels in lateritic residuum reflect derivation from depleted saprolite.

At Mt. Gibson, hypersaline ground waters occur in the Lake Karpa drainage sump. These subsurface hypersaline waters coincide with a zone of supergene enrichment of Au with an overlying depletion zone. Gold is retained in the lateritic residuum which lay above the position of the standing water table prior to mining.

Figure 9.4 shows 'half models' of geochemical dispersion anomalies from the areas studied. These are one half transverse slices through centres of the respective anomalies, shown in generalized form. The multi-element associations, as judged against appropriate background information, are shown for horizons of the regolith stratigraphy. Five of the diagrams show the substantially-wider dispersion anomaly in lateritic residuum in comparison with the concealed mineral deposit.

Pre-existing
weathering
profile

Profile modification

Accumulation or
neoformation

Leaching

O: None
Al: Al-silicates
   or oxides
Ca: Ca and Mg
   carbonates
Fe: Iron oxides
Si: Silica
Sm: Smectites

Overburden on
pre-existing
profile

[Code in brackets]

Examples

Minor: A0
(All Yilgarn examples
considered greater
alteration than minor)

None: A1 _ _   [0]   Golden Grove (Gossan Hill)
                            Greenbushes

Residual soil: A1 Si _   [1]   Bottle Creek (Emu)
                               Greenbushes
                               Mt Gibson (Part S & C Pits)

Low: A1
Amounts of modification

Semi residual: A1 Si Ca   [2]   Bottle Creek (VB), Boags)
                                Greenbushes
                                Mt Gibson (S, C, N Pits, Midway N)
                                Golden Grove (Gossan Hill, Scuddles)

Transported: A1 Ca Si   [3]   Mt Gibson (N Pit, Midway N)
                              Bottle Creek (VB, Boags)

A-type models
Weathering profile
mostly preserved

None: A2 _ _   [0]   Lawlers (McCaffery)

Residual soil A2 Al _   [1]   Boddington

Moderate: A2
Modification

Semi-residual: A2 _ _   [2]

Transported: A2 Si Sm   [3]   Lawlers (Turrett, N Pit, Waroonga)

Strong: A3
Modification (Not yet observed)

Minor: B0

B-type models
Partly truncated
weathering profile

Low: B1   None: B1   [0]   Beasley Creek

                                    [1]   Mt Gibson (part)
Moderate: B2   Residual soil: B2 Si Sm   [1]   Lawlers (McCaffery)

Fig. 9.1. Part of the classification scheme for geochemical dispersion models from Butt and Zeegers (1992),
with examples of orientation studies referred to in this report.

The A1-1 models, Figs 9.4 A to C exemplify geochemical dispersion patterns into lateritic residuum
for the S, C, and N Pits at Mt. Gibson and the Emu location at Bottle Creek. Where the complete lateritic
profile is buried, the A1-3 model applies, Figs 9.3 and 9.4B. At the VB location at Bottle Creek (Model B2-
1), erosion has resulted in truncation of the profile to the extent that lateritic residuum has been removed,
leaving the units immediately beneath it in tact. The lag and colluvium contain clastic material from the
upper, mottled zone and ferruginous saprolite and a mechanically-enhanced dispersion anomaly is developed.
At VB, the B2-1 model is transitional to the A-1 model.

In Fig. 9.4B, a complete laterite profile is buried by colluvium derived locally, by erosion of
adjacent laterite profiles. The model is classified as an A1-Ca Si-3. Silicification has resulted in
hardpanization and growth of authigenic calcite has formed pockets of calcrete. Buried laterite profiles, such
as those studied at Lawlers, are depicted in Fig. 9.4E as A1-3 and A2-3 models. The figure shows that, where
transported cover is thick (say 5 m to more than 50 m), sampling can be carried out by drilling for buried
laterite geochemical haloes.

Table 9.1. Element associations observed in A-type models linked to sample media.

Sample media	Greenbushes	Boddington	Mt. Gibson	Golden Grove	Kalgoorlie	Bottle Creek	Lawlers (McCaffery, North Pit, Turrett)	Beasley Creek
Soil	As Sb Sn Nb Ta in pisoliths	Cu As (Sb) Bi Mo Sn W (Au) in pisoliths	Au (Pb As Sb Bi Ag W) Pedogenic carbonates:Au	Not known	Missing		Transported cover Au Cu As (Sb) Ag W	Lag: Au As Cd Cu W Zn
Lateritic gravel	As Sb (Bi) Sn W Nb Ta B Mn Li Be	Cu As (Sb) Bi Mo Sn W (Au)	Au Pb As Sb Bi Ag Ge W	Cu As Sb Bi In Mo Sn Au (W)	Au As Sb W	As Sb Au Cu Pb Zn Bi (Mo Ag W)	Au Cu As Sb (Bi Ag)	Au Zn As (W) (Cu)
Lateritic duricrust	As Sb (Bi) Sn W Nb Ta B Mn Li Be	*	Au Pb As Sb Bi Ag Ge W	Cu As Sb Bi In Mo Sn Au (W)	Au As Sb W	As Sb Au Cu Pb Zn Bi (Mo Ag W)	Au Cu As Sb W (Bi Ag)	Au Zn As (W) (Cu)
Ferruginous mottles from mottled zone	-		Au Bi (Pb As)			As Sb Au Bi Ag W		
Ferruginous saprolite	-						Au Cu As Sb Bi (W)	
Iron segregations	-						Au Cu Zn As Ba (Sb W)	
Gossans	NA			Cu Pb Zn As Sb Bi In Mo Sn Se Te Au (W)		Au (Cu) Pb As Sb Bi Ag Se Ba		
Upper saprolite		*	Au Cu Pb Bi (Ag)			Pb As Sb		
Lower saprolite						Pb As Sb Au		
Supergene zone	NA			Au				
Mineralization	Sn Nb Ta Li B Be W	Cu Mo W Au As Zn Sn	Au As Sb Bi Ag (Cu Pb)	Cu Pb Zn As Sb Bi In Mo Sn Se Te Au	Au As Sb Te W	Cu Pb Zn As Sb Ag Au	Au Cu As Sb Bi W	Au

NA = Not applicable.

* Additional information will be available from Report 246R once free from confidentiality.

A-type models, semi-arid to arid terrains

A1-3
Depositional regime

Colluvial apron
(Hardpan
development)

Alluvial
valley fill   **A2-3**

B2-1
Anomaly in soil
(relatively localized)

A1-1

Broad anomaly in soil
on laterite

Erosional regime

Broad anomaly in
lateritic residuum

Residual regime

Ferruginous
saprolite

Saprolite

Weathering
front

Deltaic splay

50m

500m   500m

Anomaly in
mottles,
in ferruginous
saprolite

Ore system

Primary halo

Displaced anomaly in colluvium

Colluvium, alluvium

Nodular duricrust

Mottled zone

Saprolite

Fresh bedrock

A1-1

Broad soil
anomaly
Laterite
anomaly
breadth
increases
upwards

Orange
earth   SU
              202

Loose
pisoliths
and   LT
nodules   103

Nodular-
pisolitic
duricrust
LT203

Mottled
zone,
ferruginous
saprolite

Saprolite

Fresh
bedrock

B2-1

Lateritic
residuum

Soil
anomaly

Calcareous
red clay

Acid red
plastic clay

Saprolite

Fresh
bedrock

A1-3

Depth in metres

0
1
2
3
4
5
6
7
8
9
10
11
12
13
>20

Acid red
earth   SU
              203

Hardpanized
silty colluvium   CV102HP

Hardpanized
gravelly
colluvium
CV105HP

Transported
units

Calcrete CA205

Loose
pisoliths   LT103
and nodules

Nodular
pisolitic
duricrust
LT203

Mottled
zone,
ferruginous
saprolite

Saprolite

Fresh
bedrock

Locally displaced anomaly

Lateritic
residuum
Buried
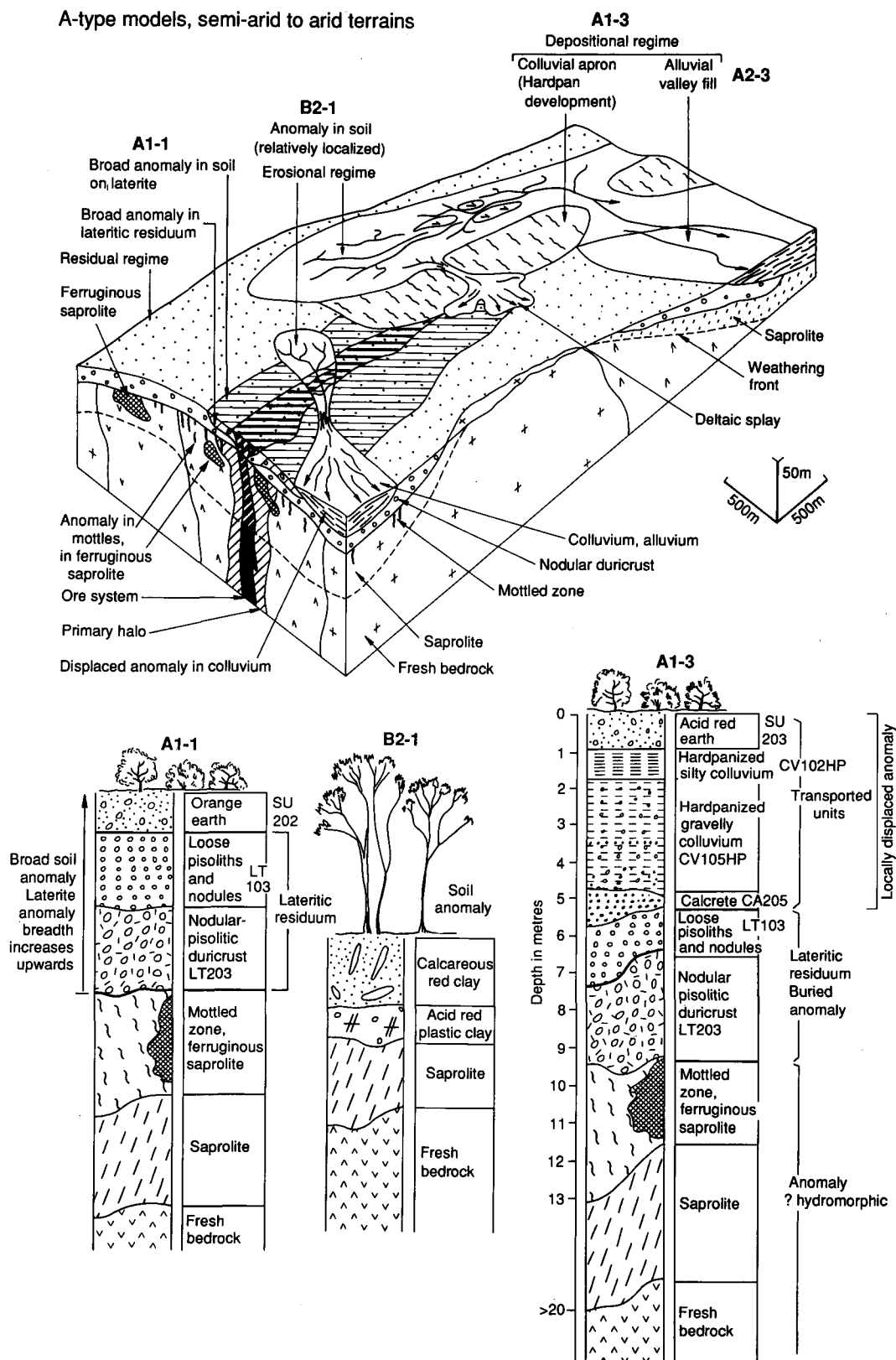anomaly

Anomaly
? hydromorphic

Fig. 9.2. Block diagram showing mostly A-type dispersion models (with a subsidiary B2 model), based upon
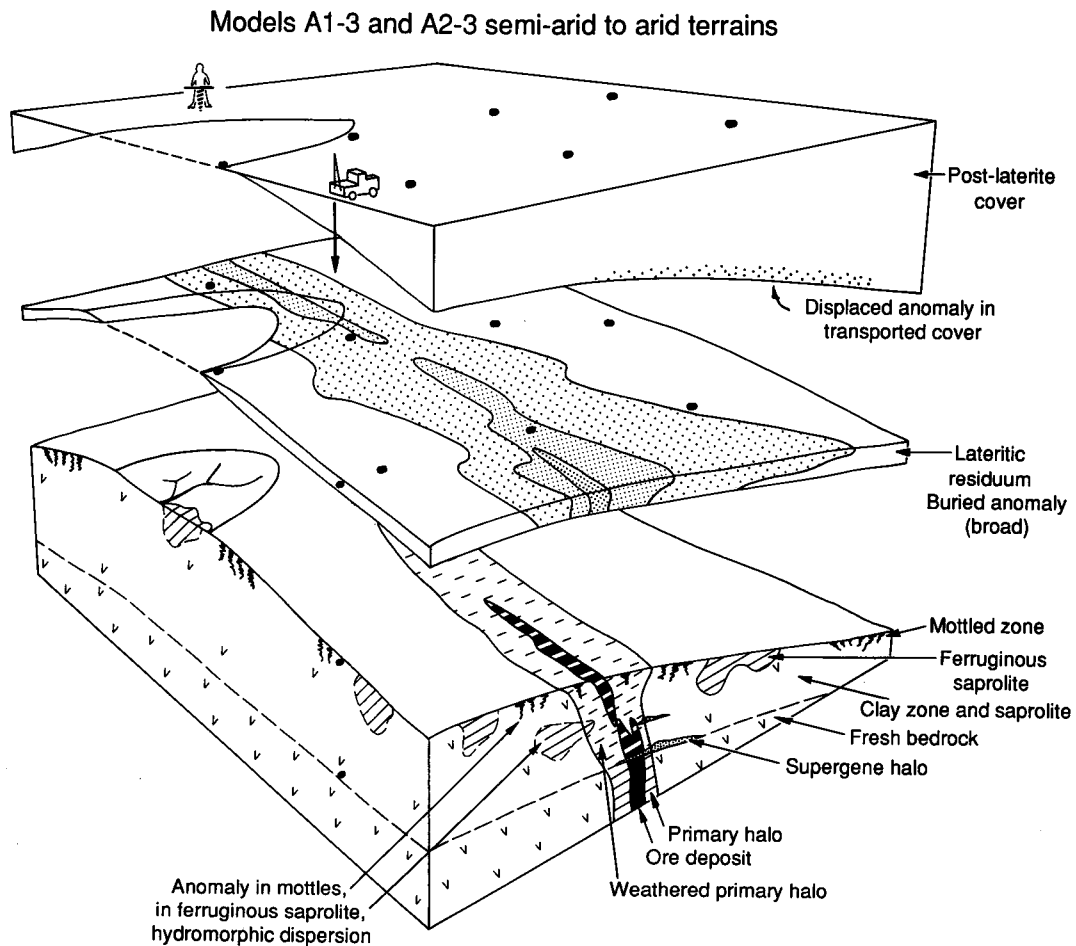the Mt. Gibson orientation study, Section 4.2.

Models A1-3 and A2-3 semi-arid to arid terrains

Post-laterite cover

Displaced anomaly in transported cover

Lateritic residuum
Buried anomaly
(broad)

Mottled zone
Ferruginous saprolite
Clay zone and saprolite
Fresh bedrock
Supergene halo

Primary halo
Ore deposit
Weathered primary halo

Anomaly in mottles,
in ferruginous saprolite,
hydromorphic dispersion

Fig. 9.3. Block diagram showing A1-3 and A2-3 dispersion models, based largely upon the Lawlers orientation studies, Section 4.4.

9.3   Discussion

A wide range of target-associated elements (Au, Cu, Pb, Zn, Ni, Co, As, Sb, Bi, In, Mo, Ag, Sn, Ge, Se, W, Cr, ...), from a variety of ore types, form dispersion anomalies in lateritic residuum, throughout the climatic range of the Yilgarn Craton.

Gold can be mobilized downwards in the profile as at Boddington (Davy and El-Ansay, 1986; Monti, 1987; Anand, 1992), but the factors which govern the behaviour of Au in lateritic residuum in a high seasonal rainfall are poorly understood. Although a strong Au anomaly in lateritic residuum will always be important in exploration, it is unwise to expect Au to dominate, in every case, the dispersion anomaly in lateritic residuum above a Au deposit. A large, strong, consistent, multi-element, chalcophile envelope or anomaly, with or without Au, seems to be the best and most reliable indicator of large Au, base metal, and rare metal deposits.

Although the dispersion models for each of the orientation studies have been linked to the respective regolith-landform mapping units for its district, a classification framework which would allow correlation of regolith-landform mapping units (and hence dispersion models) from one part of the Yilgarn to another has yet to be developed. This aspect of research is being addressed in the continuation project (AMIRA Project P240A.

So far no case study of a multi-element geochemical halo in lateritic residuum that is immersed in hypersaline ground water is yet to hand. The halo in lateritic residuum at the Midway North location at Mt. Gibson (Fig. 4.10), for instance, though from a hypersaline area, was situated above the standing water table.
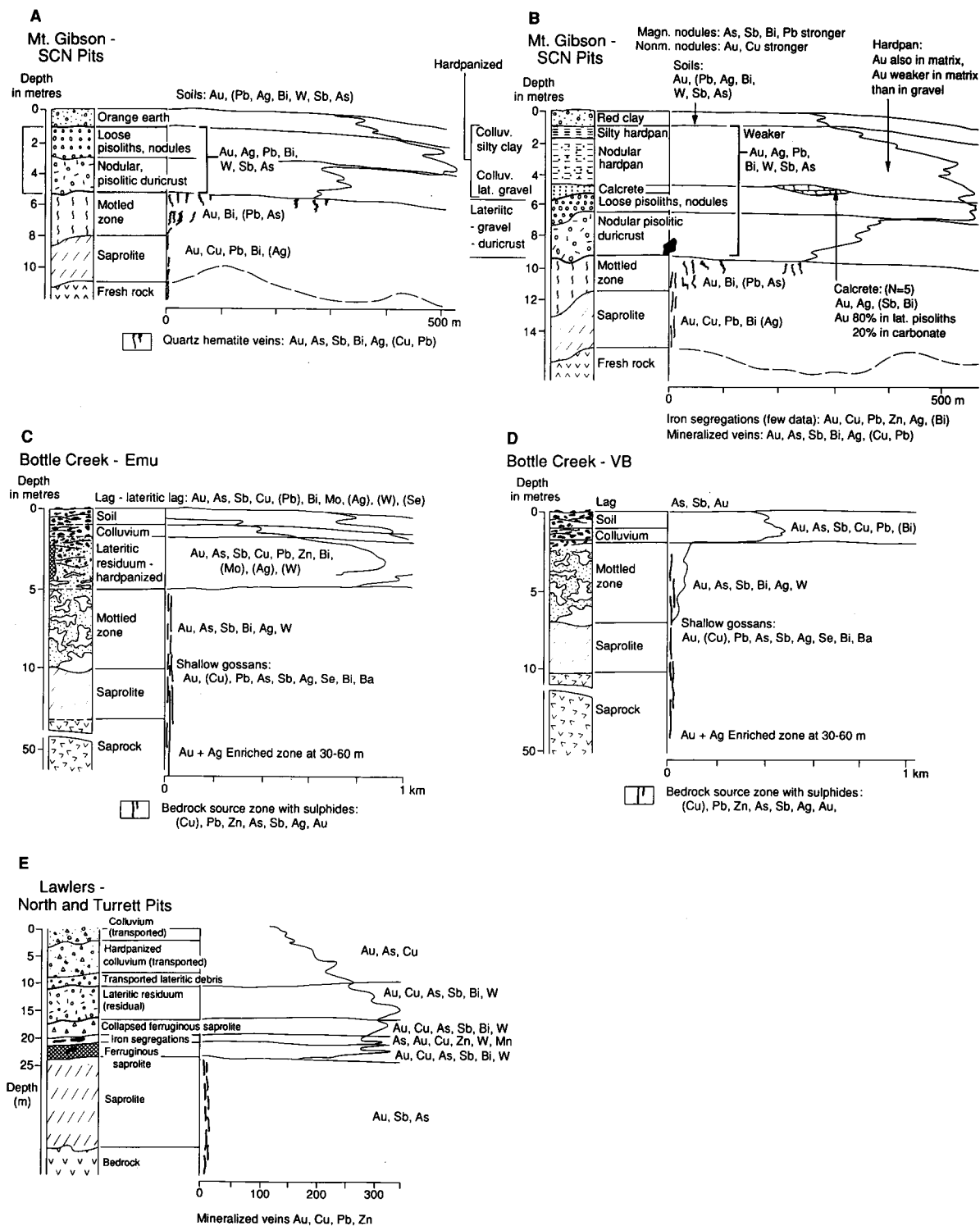
A

**Mt. Gibson -
SCN Pits**

Depth
in metres

Soils: Au, (Pb, Ag, Bi, W, Sb, As)

Hardpanized

Orange earth

Loose
pisoliths, nodules

Nodular,
pisolitic duricrust

Au, Ag, Pb, Bi,
W, Sb, As

Motled
zone

Au, Bi, (Pb, As)

Saprolite

Au, Cu, Pb, Bi, (Ag)

Fresh rock

0   500 m

Quartz hematite veins: Au, As, Sb, Bi, Ag, (Cu, Pb)

B

**Mt. Gibson -
SCN Pits**

Magn. nodules: As, Sb, Bi, Pb stronger
Nonm. nodules: Au, Cu stronger

Soils:
Au, (Pb, Ag, Bi,
W, Sb, As)

Hardpan:
Au also in matrix,
Au weaker in matrix
than in gravel

Depth
in metres

Colluv.
silty clay

Colluv.
lat. gravel

Lateriitc
- gravel
- duricrust

Red clay
Silty hardpan
Nodular
hardpan

Weaker
Au, Ag, Pb,
Bi, W, Sb, As

Calcrete
Loose pisoliths, nodules
Nodular pisolitic
duricrust

Mottled
zone

Au, Bi, (Pb, As)

Calcrete: (N=5)
Au, Ag, (Sb, Bi)
Au 80% in lat. pisoliths
20% in carbonate

Saprolite

Au, Cu, Pb, Bi (Ag)

Fresh rock

0   500 m

Iron segregations (few data): Au, Cu, Pb, Zn, Ag, (Bi)
Mineralized veins: Au, As, Sb, Bi, Ag, (Cu, Pb)

C

Bottle Creek - Emu

Depth
in metres

Lag - lateritic lag: Au, As, Sb, Cu, (Pb), Bi, Mo, (Ag), (W), (Se)

Soil
Colluvium

Lateritic
residuum -
hardpanized

Au, As, Sb, Cu, Pb, Zn, Bi,
(Mo), (Ag), (W)

Mottled
zone

Au, As, Sb, Bi, Ag, W

Shallow gossans:
Au, (Cu), Pb, As, Sb, Ag, Se, Bi, Ba

Saprolite

Saprock

Au + Ag Enriched zone at 30-60 m

0   1 km

Bedrock source zone with sulphides:
(Cu), Pb, Zn, As, Sb, Ag, Au

D

Bottle Creek - VB

Depth
in metres

Lag   As, Sb, Au

Soil
Colluvium

Au, As, Sb, Cu, Pb, (Bi)

Mottled
zone

Au, As, Sb, Bi, Ag, W

Saprolite

Shallow gossans:
Au, (Cu), Pb, As, Sb, Ag, Se, Bi, Ba

Saprock

Au + Ag Enriched zone at 30-60 m

0   1 km

Bedrock source zone with sulphides:
(Cu), Pb, Zn, As, Sb, Ag, Au,

E

**Lawlers -
North and Turrett Pits**

Colluvium
(transported)

Hardpanized
colluvium (transported)

Transported lateritic debris

Lateritic residuum
(residual)

Au, As, Cu

Au, Cu, As, Sb, Bi, W

Collapsed ferruginous saprolite
Iron segregations
Ferruginous
saprolite

Au, Cu, As, Sb, Bi, W
As, Au, Cu, Zn, W, Mn
Au, Cu, As, Sb, Bi, W

Depth
(m)

Saprolite

Au, Sb, As

Bedrock

0   100   200   300

Mineralized veins Au, Cu, Pb, Zn

Fig. 9.4A to E. Half models of geochemical dispersion based upon some of the orientation
studies of this project.

10.0 EXPLORATION PROCEDURES

10.1 Introduction

The purpose of this section is to present, in concise form, the procedures for effective exploration, using laterite geochemistry, based particularly upon research carried out within this project. Laterite geochemistry will commonly be used in combination with other geochemical, geological, and geophysical methods. The mix of exploration methods will depend upon terrain type, ore deposit characteristics, stage of exploration, budget, and the experience and preferences of exploration personnel.

This section draws upon other parts of the summary report and from project reports to which cross-referencing is made. The feasibility of using laterite geochemistry for mineral exploration in various regolith-landform settings is first discussed. This is followed by flow charts for some of the main exploration stages.

10.2 The Feasibility of laterite geochemistry in mineral exploration

The use of laterite geochemistry for mineral exploration was pioneered by Mazzucchelli and James (1966), extended by Smith and Perdrix (1983) and underwent considerable growth and further development during the 1980s (Smith, 1989). Laterite geochemistry is now used, in appropriate terrain, by most exploration companies. Numerous ore deposits have been found and mineralized prospects have been located in which laterite geochemistry played a substantial exploration role.

On a broader scale, laterite geochemistry has delineated geochemical provinces (Section 7.0) and defined chalcophile corridors (Smith et al., 1989) which are of strategic importance in exploration for major ore deposits.

10.2.1 Regolith-landform settings

Provided it is properly carried out, laterite geochemistry provides an effective means of exploration wherever lateritic residuum is present, whether at or near the surface, (Fig. 1.1) as a *residual regime* (1), or buried, *depositional regime* (3). Furthermore, where truncation of the lateritic residuum has been erratic, lateritic remnants may be sufficiently abundant for relatively wide-spaced sampling of some *erosional regimes* (2). Pilot research has also shown that there is merit in sampling ferruginous saprolite, ferruginous mottles, and iron segregations in areas where lateritic residuum has been removed by erosion (Section 4.4.5).

It is necessary first to recognize where lateritic residuum is present and then to obtain appropriate samples. Recognizing the presence and distribution of lateritic residuum requires regolith mapping supplemented by information on regolith stratigraphy, particularly in areas of sandplain, soil cover, colluvium, alluvium, and also in areas of variable truncation of the weathering profile.

In depositional regimes, it is difficult to determine where lateritic residuum is buried and where it has been removed prior to burial. Drilling for regolith stratigraphy and experienced interpretation of regolith-landform relationships will help. However, only systematic drilling, which can be wide spaced, will provide certainty. Currently, as an adjunct to AMIRA Project P240A, research is underway into the use of ground geophysical methods to assist in establishing regolith stratigraphy, including the distribution of buried laterite.

Drilling for buried geochemical haloes in laterite can be a particularly-effective method of exploring sediment-covered areas because the laterite dispersion haloes are much larger than the ore deposit targets. Table 5.1 shows that geochemical haloes in laterite (whether at surface or not) can be 100 to 400 times larger in area than their corresponding deposits.

Some Cainozoic sediments in the Yilgarn Block have developed mottling in response to weathering and this mottling can be confused with mottling developed through lateritic weathering of Archaean bedrock). In drilling to sample buried laterite, it is important to recognize and distinguish between the two forms of mottling. Failure to do so can lead to drilling being terminated in the cover sequence, with the erroneous conclusion that the profile has been truncated and the main mottled zone intersected even though a complete laterite profile may occur at depth. Regolith stratigraphy in the North Pit at Lawlers provides a classic example of strongly developed mottling in a cover sequence which overlies a complete laterite profile.

Figure 10.1A shows some alternative sample media for situations where truncation has removed lateritic residuum. Useful information on geochemical dispersion can be provided by sampling these materials. Some research is available on their element characteristics and on possible processes of dispersion (Section 4.4.5). The CSIRO-AGE data base (Section 7) has shown that these alternate media have much merit in geochemical surveys.
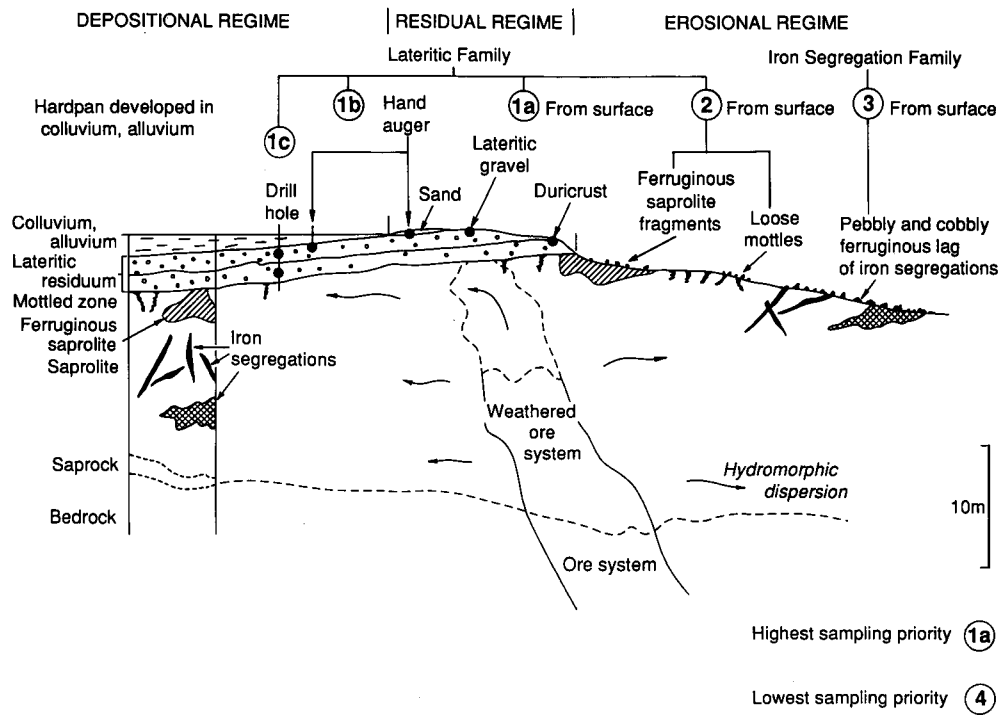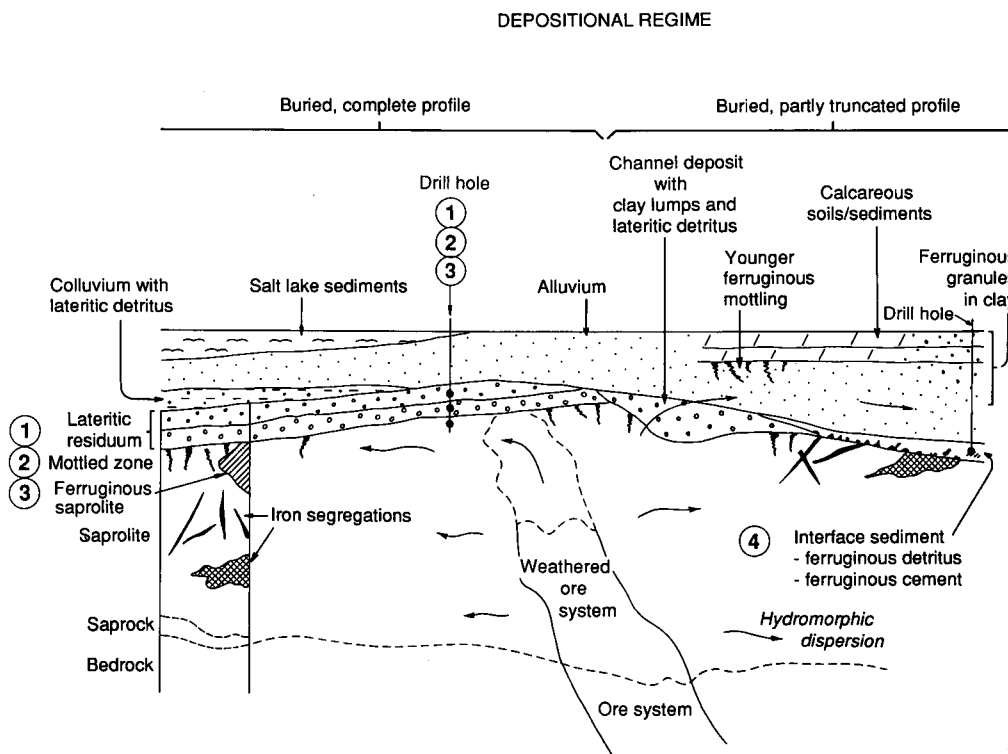
145

A. Laterite at or near the surface

B. Laterite subsurface

Fig. 10.1. Choice of sample media, in situation A, laterite at or near surface, B, laterite is subsurface, based upon the orientation studies of this project.

10.2.2   Types of suitable ore deposit targets

Laterite geochemistry is applicable to most ore deposit types. The essential ingredients are geochemical or mineralogical contrast against the host rocks and adjacent sequences, the ability for key elements to accumulate or be preserved in lateritic residuum (e.g. within relict minerals or through bonding within lateritic minerals, particularly Fe-oxides), sufficient size of the source (the ore deposit, its primary halo or alteration zone), and that the source has been intersected by the interface or transition, which is gradually being lowered, between the base of the lateritic residuum and upper saprolite. Alternatively, the source may have been intersected by the weathering front (the saprock-bedrock interface) and a halo of hydromorphic dispersion then forms the link between the ore deposit and the lateritic residuum.

Leachable elements can also form useful anomalies. This was shown by the recognition and delineation of a Li anomaly in laterite at Greenbushes (threshold 20 ppm) which outlined an important extension of a substantial spodumene resource.

Because, in general, the ground surface was gradually being lowered during lateritization, lateritic residuum progressively incorporates residues from the immediately-underlying zone upon which it 'feeds'. Thus, in a dynamic sense, it has inherited the geochemical characteristics of regolith units which were perhaps tens of metres above its present position. Consequently, ore zones and root zones of ore deposits now removed, may have left their imprint in the lateritic residuum. These possibilities need to be considered in interpretation.

Provided an ore system comes within the influence of lateritic residuum, as discussed above, the dispersion haloes in the lateritic residuum over a large ore deposit would be larger and more easily recognizable than haloes arising from small deposits. Furthermore, some and perhaps most (more case studies are needed) large Au, base metal, and rare metal ore systems have a chalcophile envelope and this is well expressed as a multi-element laterite anomaly.

Alteration zones, imprinted in lateritic residuum, can provide useful enlargement of targets, as at Greenbushes. This rare metal (Sn, Nb, Ta, Li) pegmatite deposit has an As-Sb zone of alteration in the hosting amphibolites. This alteration zone appears to provide a pronounced envelope within which dispersion patterns arising from the pegmatite-related elements are contained.

10.2.3   Other recognizable features

Laterite geochemistry can provide information on a number of other types of features which can be used in exploration beside anomalies related to individual ore deposits. These features become particularly relevant to reconnaissance exploration (e.g. $\geq$ 3-km sample spacing) as many ore deposit haloes would not be detected at this scale. Where lateritic residuum is abundant, such wide-spaced sampling provides a means of geochemical mapping comparable to a regional stream sediment survey at a similar cost.

Multi-element laterite geochemistry can lead to recognition of enlarged, targets such as geochemical provinces (some of which may be the combined geochemical expression of numerous small mineralized occurrences) and the recognition of chalcophile corridors (Smith *et al.,* 1989). The strategic significance of chalcophile corridors has not been adequately capitalized upon in exploration. From present understanding, they form curvilinear loci, at a district to regional scale, within which certain types of ore deposits lie. Some chalcophile corridors are perceived as delineating cratonal fault zones or geosutures. One of the most prominent examples recognized to date passes NNW through Greenbushes. Regional-scale laterite geochemistry delineates the distribution of chalcophile elements in bedrock, which in turn are interpreted as an imprint of the passage of mineralizing fluids. On a more local scale, a chalcophile trend in buried laterite at Lawlers was used in Au exploration by Forsayth and Geochemex. This trend, at the McCaffery and North Pit deposits, was followed northwards, leading to discovery of the Turrett deposit.

Laterite geochemistry can be used to locate and show the distribution of likely host rocks. Either specific rock types or associations may be sought or where bedrocks are little known, unusual rock types may be lighted. For example, the CSIRO-AGE database has been used to identify granitic intrusives with an As-Sb-Nb-(Ta) association in a region of granitic gneiss and migmatite at Wannamal (Perth Sheet).

Reconnaissance laterite sampling can provide data on regional background variations for specific elements. Many examples are evident in the project reports on blocks of sampling contained in the CSIRO-AGE data base. Information on geochemical backgrounds of ore-associated elements and their natural variations are crucial in establishing district and regional thresholds.

If sufficient lithologically-dependent elements are analysed, the geochemistry of lateritic residuum can also provide information on bedrock relationships as an important adjunct to the recognition of dispersion haloes. For example, higher levels of Fe, Mn, Ti, Cr, V, Cu, Ni, and Cr are seen in laterites associated with

mafic lithologies whereas Si, Nb, and Zr abundances relate to more felsic lithologies. Even greater Ni and Cr contents characterize lateritic residuum derived from ultramafic lithologies. Besides defining targets, simple Number of Anomalous Elements (NAE) indices, Section 8.3, have been widely used in exploration for predicting the distribution of concealed mafic sequences. Thresholds for each element are commonly based upon local area statistics and the index designated accordingly, e.g. NUMBAS-af, an index to predict the distribution of concealed mafic lithologies in the Albany-Fraser province.

Multivariate statistical methods can be applied where training sets of laterite geochemistry for each bedrock lithology are available. Birrell (1985) used canonical variate analysis for classification of bedrock types from laterite geochemistry in the Saddleback Greenstone Belt.

It is possible to integrate airborne magnetic and radiometric data with laterite geochemistry, provided the coverage of each is adequate and sufficient elements have been determined. An important application in exploration of lateritic terrain is reconciling surface geochemistry with features on maps derived from airborne magnetic surveys. Where essentially continuous coverage of laterite geochemistry is available and where sufficient elements have been analysed, a very powerful capability is possible. These data should be supplemented by bedrock information where available. Uses include lithology prediction, location and delineation of chalcophile trends, the distribution of dispersion haloes that are possibly related to concealed mineral deposits and linking of chalcophile trends to significant structural discontinuities (seen in the airborne magnetics information). In this way, so-called 'smart geological maps' can become smarter.

10.3   Flow charts for laterite geochemistry in mineral exploration
Detailed procedures for laterite geochemistry are covered in the various reports arising from this project, in published papers, in other parts of this summary report, and in this section. The procedures are presented as a series of flow charts with steps keyed to corresponding reports for more details. An overall flow chart is shown in Fig. 10.2. Some further details are given in Fig. 10.3.

10.3.1   Deciding sampling issues
Once the regolith-landform relationships for an area are understood, the details of the geochemical sampling programme can be designed. The merits of the wide range of exploration methods available and the choice of sample media are beyond the scope of this report. The effectiveness and low cost of laterite geochemistry would mostly make it a first choice where it is feasible.

The hierarchies of choice of specific lateritic and associated ferruginous media are shown in Fig. 10.1A for laterite at or near the surface, and in Fig. 10.1B where laterite is likely to occur subsurface. Sampling of lateritic residuum is the first choice in both the diagrams. This is generally straight forward for the situations shown in A. The buried situations, as depicted in B, clearly require skill in recognizing the different units of the regolith stratigraphy (for example, Sections 4.4 and Fig. 10.1B and Report 166R,).

Sampling basal lateritic duricrust will provide information most closely related to the substrates. This is most appropriate when deciding the position of drill holes to test the sources of individual laterite geochemical anomalies (follow-up work). Conversely, sampling the nodular or pisolitic gravel unit of lateritic residuum capitalizes on the probability of wider dispersion, perhaps yielding more homogeneous anomalies, and is generally more appropriate to reconnaissance exploration than is sampling of underlying duricrust (Figs 4.12 and 4.13 this report and Report 157R, Figs. 53 to 64).

Where lateritic residuum is missing, ferruginous mottles or ferruginous saprolite may be sampled, both of which can form a coarse lag. Pilot research (Section 4.4.5) shows that iron segregations and their lag have potential as sample media.

Sample spacing will depend on factors such as the size and shape of expected anomalies, the likely shape and attitude of expected ore deposits, the dip of the bedrock sequence, and the known ore potential, whether it is the first exploration programme in a district or region, etc. For reconnaissance, 3-km sampling can be appropriate for a first pass, however, spacings of about 1 km are more appropriate for Au and base metal exploration in the Yilgarn Craton because of the extent of exploration coverage and the likely size of dispersion haloes. Spacings of 800 m and 400 m closing to 200 m, are commonly effective in Au exploration in the Yilgarn Craton.

In general, it is only necessary to sample lateritic residuum closely (e.g. at 100 m or 50 m spacing) in the strongest parts of anomalies to delineate the source(s) in the substrate. Initial sampling should be designed to incorporate logical sample spacing for follow up. Where the strike of sequences or the trend of expected mineralization are unknown or variable, triangular spacing of samples, or off-setting of samples along alternate grid lines, is particularly effective.
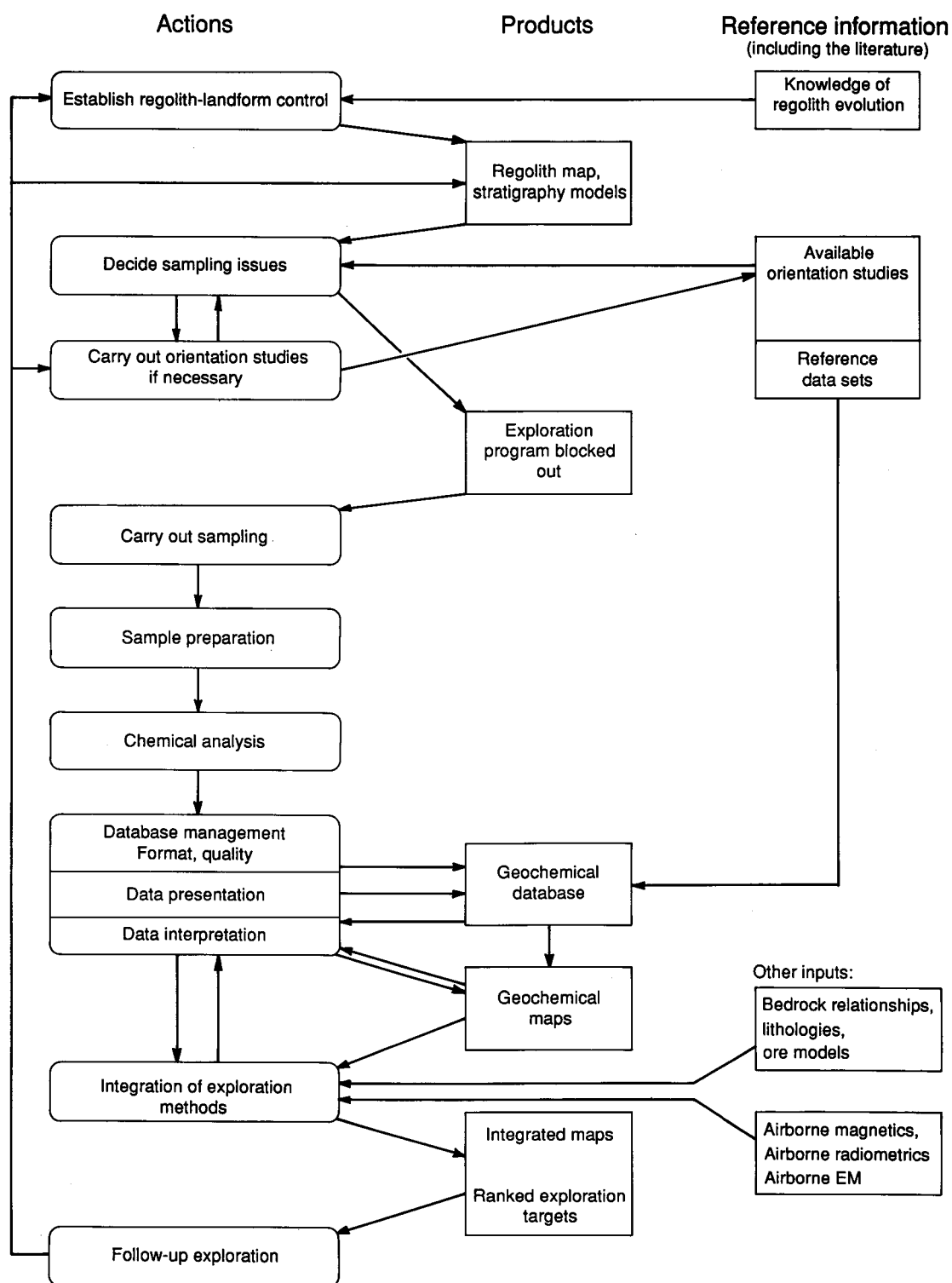
Actions

Products

Reference information
(including the literature)

Establish regolith-landform control

Knowledge of
regolith evolution

Regolith map,
stratigraphy models

Decide sampling issues

Available
orientation studies

Carry out orientation studies
if necessary

Reference
data sets

Exploration
program blocked
out

Carry out sampling

Sample preparation

Chemical analysis

Database management
Format, quality

Geochemical
database

Data presentation

Data interpretation

Geochemical
maps

Other inputs:

Bedrock relationships,
lithologies,
ore models

Integration of exploration
methods

Integrated maps

Airborne magnetics,
Airborne radiometrics
Airborne EM

Ranked exploration
targets

Follow-up exploration

Figure 10.2. Flow chart for the use of laterite geochemistry in mineral exploration.

Start with:
- Air photography
  (3D topography - stereo essential)
- LANDSAT TM
- Airborne radiometrics
- Airmag
- Aircraft scanner
- Digital elevation model

Pattern delineation

From references in literature:
- Regolith/terrain maps
- Orientation districts
- Classification of mapping units
- Sets of models
- Classification of materials
- data sets

Image processing

Photo pattern map

Field work
Partial interpretation

Working model for mapping

Regolith map

Full interpretation

Regolith stratigraphy

Genetic map
Regolith-landform regimes:
e.g. Residual
     Erosional
     Depositional

Regolith models

Decide exploration approaches

Fig. 10.3. Flow chart for providing regolith-landform control in exploration geochemistry.

10.4   Discussion

Some of the most fundamental points concerning laterite geochemistry are grouped here:

1.   No one exploration method is likely to provide an exploration panacea, so emphasis needs to be placed on integration of exploration findings.

2.   For laterite geochemistry to be effective, all the necessary steps shown in Section 10.3 need to be carried out properly.

3.   Aerial photography, satellite and airborne scanner mapping, and airborne radiometrics all provide essential information for regolith mapping – *but* there is no substitute for field work.

4.   Close interaction is needed between the geologist-geochemist who designs the sampling programme and the personnel carrying out the sampling. Details of regolith control and sampling may need to be revised as sampling progresses. In some programmes, particularly in reconnaissance, it is quite practical to have the geologist, who is providing regolith control, working together with samplers.

5.   The analytical schemes (and sample preparation) need be appropriate to laterite geochemistry as well as cost effective and care and thought are necessary in their design.

6.   Not all anomalies will be due to ore deposits. Other explanations can be unusual rock types, unusual environmental conditions, and natural variation. However, large, multi-element chalcophile anomalies in laterite always require careful assessment. They may be arising from a concealed world-class deposit. The anomalies at Boddington (Section 4.6.4) and Greenbushes (Smith *et al.*, 1987) are prominent examples.

7.   When exploring an area, it is important to spend time to understand the multi-element geochemical data, their internal structure and to relate the characteristics and outliers to the regolith and bedrock geological setting. Above all, you must have confidence that the data are worthy of the effort. The data must be shown to be reliable and worthy of the cost and effort of collection.

8.   Close collaboration between staff engaged in statistical investigations of the resulting data and field staff is essential, to gain the maximum benefit of this time-consuming, but potentially very productive, approach.

11.0 OUTLOOK

This report is a summary of research findings mostly from this AMIRA project over the period 1987 to 1991. Although individual research papers and reports have appeared during the last decade, this is the first major summary since the CSIRO Laterite Geochemistry Group was formed in 1978. Research on laterite geochemistry continues and some of the main activities are now discussed.

11.1 Project extension, P240A: Yilgarn lateritic environments

Research during the period reported herein has led to the present 2-year extension (AMIRA Project P240A) which continues until 30 June, 1993. The following topics are being addressed during this extension:

1. The research group's activities are being broadened to form a comprehensive regolith-landform approach to the Yilgarn lateritic environments, with increasing emphasis on areas of sedimentary cover (transported overburden). In so doing, closer links are being forged with the CSIRO Weathering Processes Group and the AMIRA Weathering Processes Project (P241A). This collaboration also involves topics 2, 5, and 9.

2. The orientation research is being extended by studying a 100-km by 100-km region centred on Kalgoorlie. The extent of variably-truncated profiles, areas of sedimentary cover, and the abundance of calcareous upper members of the regolith column complement the orientation districts investigated already within the project.

3. Completion of orientation research in the Boddington, Bottle Creek, and Davyhurst districts.

4. Establishing the framework for *regolith-landform mapping units* for the Yilgarn Craton. This topic is distinct from the classification of *lateritic materials* which had been previously done within the project (the *Atlas*).

5. Pilot investigation of variably-truncated, buried weathering profiles.

6. Data interpretative methods – extending the suite of reference data sets arising in particularly from the project's orientation districts. Also to include examples of data interpretation using the reference data sets.

7. Continued integration of research findings.

8. Research into the use of remote sensing for regolith mapping, in collaboration with the CSIRO WA Remote Sensing Group. This research will focus on reconciling LANDSAT TM imagery, in particular, and field relationships in the project's orientation districts, including those within the Kalgoorlie Region.

9. Extending the classification of regolith materials, where appropriate in collaboration with the AMIRA Weathering Processes Project (P241A).

10. Workshops and field trips will continue to be an important aspect of interaction with sponsors and of the transfer of research findings to industry users.

11.2 Yilgarn developments in areas of sedimentary cover (transported overburden)

Both the project extension (P240A) and the extension of the AMIRA Weathering Processes Project (P241A) are concerned, in part, with various aspects of sedimentary cover in the Yilgarn Craton. It is intended to pool the expertise of the two research groups. An interdisciplinary team with a wide and relevant skill-base would then be brought to bear on areas of sedimentary cover in the Yilgarn Craton. These activities would be collaborative with research activities within the Cooperative Research Centre in Australian Mineral Exploration Technologies. An AMIRA research proposal on this topic has been developed in consultation with industry. The aim is to commence the new AMIRA project as the present extensions, P240A and P241A are completed during the first half of 1993.

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11.3   Transferring the Yilgarn findings elsewhere

A strategic decision has been made to transfer the broad regolith-landform and geochemical expertise of the regolith and geochemical groups of the Division of Exploration Geoscience to appropriate regolith-dominated terrain in other parts of Australia. Discussions are underway with industry and with research collaborators with a view to initiate some pilot activities during 1993. Some of this activity will be in Queensland and New South Wales, and will build upon extensive previous CSIRO geochemical research carried out from the North Ryde laboratories.

12.0 CONCLUSIONS

12.1 Reconciling project outcomes with objectives and expected benefits

The findings of the research project are tabulated below with the objectives stated in the Project Proposal, January 1987.

1. *Overall objective:*
The objective of the project was to develop new and improved methodologies for mineral exploration based upon the use of multi-element laterite geochemistry.

> **Outcomes:**
> • The science and technology of laterite geochemistry, as applied to exploration for concealed mineral deposits, were advanced substantially during the project through interdisciplinary research, made possible by the considerable level of AMIRA sponsorship.
>
> • A broad spectrum of regolith-landform relationships, based on the chosen orientation districts, has allowed a greatly-improved understanding of the distribution of regolith units, their stratigraphy, characteristics, and regolith evolution. These findings are fundamental to effective exploration and have been transferred progressively to industry through field trips, sponsors' meetings, reports, and workshops.
>
> • Within this regolith-landform framework, dispersion patterns in lateritic residuum (and associated ferruginous materials in upper saprolite), whether at surface or buried beneath some tens of metres of cover and knowledge of dispersion processes, arising particularly from concealed Au deposits, have been established within the project and have taken on general application. These dispersion patterns form much larger targets (commonly 100 to 400 larger in area) than the concealed mineral deposits from which they arose.
>
> *The overall objective would be achieved ...*

2. *Objective: ... through continued execution of orientation studies of dispersion patterns in lateritic materials about concealed ore deposits;*

> **Outcomes:**
> • Orientation studies have been carried out about the Mt. Gibson, Bottle Creek, Lawlers, Boddington, and Beasley Creek Au deposits. In each of these, detailed studies of geochemical dispersion and regolith relationships have been placed in their district-scale regolith-landform context.
>
> • Each of the orientation studies shows a large dispersion anomaly in lateritic residuum (except for Beasley Creek where only a small patch of lateritic residuum remains and, therefore, anomaly size is unknown). The anomalies are all multi-element, with an assemblage of Au, As, Sb, Bi, Mo, and W being common, supported by Sn at Boddington. The largest anomalies at Boddington (from regional sampling) are for As, Bi, and Sn at surface (not Au), at Mt. Gibson are Au supported by As, Bi, Ag, and Pb, at Bottle Creek are As, Sb, Pb, and Au, and at Lawlers (McCaffery-North Pit-Turrett locations) are Au, As, Bi, and Sb.
>
> • At Mt. Gibson, it was shown that the non-magnetic lateritic nodules and pisoliths have higher abundances of Au relative to the magnetic nodules and pisoliths.

3. *Objective: ... through optimizing sampling methodology with regard to sampling position, sample spacings, and sample patterns;*

> **Outcomes:**
> • Considerable attention in each of the orientation studies was given to the position of samples within the regolith stratigraphy. The relationships between anomaly size and sampling intervals/patterns have been integrated into general exploration procedures.

• Orientation studies confirm the view that pisolitic and nodular laterite, the common upper unit of the lateritic residuum, is particularly appropriate for regional and district-scale exploration. In that regolith unit, anomalies tend to be wider than in the commonly underlying lateritic duricrust. In arid environments, element associations in both units of the lateritic residuum are generally the same. However, in the seasonally-humid, relatively-high rainfall region of the SW of the Yilgarn Craton, Au tends to be depleted in surface lateritic residuum, possibly because of leaching by rainfall, whilst chalcophile and some other target-associated elements tend to remain. However, further orientation studies in the high rainfall areas are needed.

4.   *Objective: ... through understanding more about the characteristics and origin of the sample medium being collected;*

Outcomes:
• Some of the major findings of the project concern the characteristics and origin of the lateritic residuum, and the use of this knowledge to guide sampling methods in exploration. The project's volume on terminology, classification and atlas of laterite types, and associated ferruginous materials (Report 60R) was an important practical outcome, and is in widespread use amongst the sponsorship, both in Australia and overseas.

• Besides lateritic residuum, use of sampling media was extended to include ferruginous mottles from the mottled zone, ferruginous saprolite, and iron segregations. These additional media are important in landform situations where lateritic residuum has been removed by erosion and the upper saprolite or equivalent zones are exposed.

• These additional media are also relevant in areas of sedimentary cover. Practical methods have been established for their recognition in drill spoil, particularly criteria for discriminating between the various ferruginous materials.

5.   *Objective: ... through further development of methods for anomaly recognition, classification, and discrimination;*

Outcomes:
• A discussion document (Grunsky, 1991), giving through examples of data interpretation for anomaly recognition, has been distributed to the sponsor and is in wide use. Its title is: *Strategies and Methods for the Interpretation of Geochemical Data – Discussion Paper Applied to Laterite Geochemistry*, by Eric Grunsky, August 1991.

• A workshop on multi-element data interpretation was held, March 1991, with demonstrations using data sets from the project. Follow-up demonstrations were arranged for interested sponsors.

• A demonstration disk on data interpretation accompanied the Mt. Gibson data sets report (Report 157R).

6.   *Objective: ... characterization of a selected series of anomaly types.*

Outcomes:
• The geochemical dispersion anomalies studied within the orientation areas have been well characterised with sample type and geochemical characteristics linked to positions within regolith stratigraphy. (Reference geochemical data sets from Boddington await clearance of confidentiality requirements for the Boddington Research Report. The Bottle Creek data sets are being incorporated into a report which is scheduled for completion during early 1993)

7.   *Expected benefit: More efficient laterite sampling strategies both for reconnaissance and follow-up exploration.*

7.   ***Expected benefit:*** *More efficient laterite sampling strategies both for reconnaissance and follow-up exploration.*

Outcomes:

• The research has clearly shown the fundamental importance of regolith-landform control in exploration geochemistry and has provided several well-documented examples in the orientation studies, ranging from detail- to district-scale.

• Efficient sampling strategies must include adequate regolith-landform control.

• For all scales of exploration, part of this control can be provided by reference to the regolith-landform models. Furthermore, the project's volume *Laterite types and associated ferruginous materials - terminology, classification and atlas* provides a framework for consistency in sample collection and data control.

• For regional and tenement-scale exploration, separation of terrain into broad regolith-landform regimes, such as residual, erosional, and depositional regimes is an important early exploration step in regolith control and hence to choice of exploration methods.

• Regolith control leads to choice of exploration methods and, in turn, to a hierarchy of sample priorities established in the project and its precursor.

• Sampling methods and strategies have been demonstrated by research and transformed to exploration practice through reports, workshops, project review meetings, and field trips.

8.   ***Expected benefit:*** *More confident interpretation of laterite geochemistry, particularly concerning types of anomalies that relate to ore deposits – and those that do not.*

Outcomes:

• Considerably greater confidence has been achieved in the general interpretation and application of laterite geochemistry. Accumulation of experience in assessing anomaly types will continue for decades.

• Data sets from the orientation studies provide knowledge of *target* situations and the CSIRO-AGE data base provides knowledge of *backgrounds*.

• The Discussion Paper (mentioned in 7) on data interpretation methods provides worked through examples for multi-element laterite geochemistry. The paper presents exploratory data analysis as well as modelled approaches using reference data sets for defined targets and backgrounds.

9.   ***Expected benefit:*** *A sound knowledge of which particular parts of laterite blankets provide the most reliable samples for exploration.*

Outcomes:

• Knowledge of which parts of laterite blankets to sample, which specific media are most appropriate to reconnaissance and which for follow-up surveys are now well established. This knowledge has been extended, at pilot scale, to ferruginous materials immediately underlying lateritic residuum (e.g. mottled zone, ferruginous saprolite, and various iron segregations).

    – For regional and district-scale exploration the established hierarchy is:
      -   lateritic pisoliths or lateritic nodules(Highest priority)
      -   lateritic duricrust, various types
      -   mottles from mottled zone
      -   ferruginous saprolite
      -   iron segregations   (lowest priority).

– For anomaly assessment:
-   lateritic duricrust, becoming basal duricrust
    for delineation of the anomaly source.
    (sampling basal lateritic residuum was shown to be appropriate for anomaly
    assessment because it provides closer delineation of subsurface relationships than the
    upper pisolitic unit of the lateritic residuum.

10.   *Expected benefit: A series of comprehensive orientation studies would be provided as part of the foundations for interpretation.*

Outcomes:
• Comprehensive orientation studies have been produced for the Mt. Gibson, Bottle Creek, Lawlers, and Boddington districts and the Beasley Creek location. (The Boddington study is passing through its confidentiality requirements as this report goes to press.)

12.2   Additional outcomes

An aspect, not originally listed but developed during the project, was to extend the use of laterite geochemistry to areas of sedimentary cover, particularly in exploration of substantial colluvial and alluvial outwash plains. Collaboration with Geochemex Australia at Mt. Gibson and, subsequently, with Forsayth and Geochemex at Lawlers, proved the feasibility of exploration in sediment covered areas by drilling for buried geochemical haloes in laterite. In so doing, a satisfying outcome was the discovery of the Turrett and Waroonga deposits at Lawlers, underlining the feasibility of this approach in exploration. Both deposits have been opened by mining activities, and this has provided excellent exposure of the regolith stratigraphy and have been the subject of sponsors' field trips.

An important outcome has been the recognition of widespread buried laterite profiles in the semi-arid and arid parts of the Yilgarn Craton, even in areas where lateritic residuum has been largely stripped from the uplands. Furthermore, in Au exploration, provided the cover is not too deep and the abundance of Au is adequate, buried laterite geochemical haloes can form readily-treatable ore in their own right.

12.3   Finale

Overall, the level of expertise in laterite geochemistry used by industry is now substantially greater than when the project commenced in mid-1987. Often in collaboration with other researchers, project staff have played a major contributing role in lifting this level of expertise and in developing application capabilities.

13.0 ACKNOWLEDGEMENTS

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15.0   APPENDICES

APPENDIX I   Reports issued by the laterite geochemistry Project P240

Report No.   Title, Author(s), etc.

Un-numbered   Laterite geochemistry in the Moora, Perth, Pinjarra, Collie and Pemberton sheets.
                      J. Innes, R.E. Smith, and J.L. Perdrix, April 1988.
                      21 pages with data on diskette.

2R   Laterite geochemistry in the CSIRO-AGE database, South Murchison Region (Yalgoo,
                      Kirkalocka, Perenjori, Ninghan Sheets).
                      E.C. Grunsky, J. Innes, R.E. Smith, J.L. Perdrix, December 1988.
                      92 pages with data on diskette.

4R   The aqueous geochemistry of gold in the weathering environment.
                      D.J. Gray, December 1988, (jointly with Project P241).

20R   Exploration geochemistry about the Mt. Gibson gold deposits, Western Australia.
                      R.R. Anand, R.E. Smith, J. Innes and H.M. Churchward, March 1989, 93 pages.

26R   Geomorphology and surface geology, Beasley Creek orientation study.
                      I.D.M. Robertson and H.M. Churchward, July 1989, 39 pages.

60R   Laterite types and associated ferruginous materials — *Terminology, Classification, and
                      Atlas.*
                      R.R. Anand, R.E. Smith, J. Innes, H.M. Churchward, J.L. Perdrix and E.C. Grunsky,
                      August 1989.
                      Expandable, loose-leaf format.

68R   Laterite geochemistry in the CSIRO-AGE database for the Northern Murchison region
                      (Cue, Belele, Glengarry, Sandstone Sheets).
                      E.C. Grunsky, R.E. Smith, J.L. Perdrix, November 1989.
                      148 pages, with data on diskette.

27R   Beasley Creek Orientation Study: Geochemistry, petrography and mineralogy of
                      ferruginous lag overlying the Beasley Creek Gold Mine - Laverton W.A.
                      I.D.M. Robertson, November 1989.
                      Vol. I, 75 pages; Vol. II, 98 pages; with data on diskette.

121R   Laterite geochemistry in the CSIRO-AGE database for the Central Yilgarn Region
                      (Barlee, Bencubbin, Corrigin, Hyden, Jackson, Kalgoorlie, Kellerberrin, Southern Cross
                      Sheets).
                      E.C. Grunsky, July 1990. Vol. I, 114 pages; Vol. II, 162 pages with data on diskette.

Un-numbered   Eastern Goldfields Trip: Introduction and Bottle Creek orientation study, field guide,
                      October, 1990, 24 pages.

Un-numbered   Eastern Goldfields Trip: Lawlers orientation study, field guide.
                      R.R. Anand, R.E. Smith, H.M. Churchward, and J.L. Perdrix, compilers, October 1990, 30
                      pages.

154R   Laterite geochemistry in the CSIRO-AGE database for the Wiluna region (Duketon,
                      Kingston, Sir Samuel, Wiluna)
                      E.C. Grunsky, December 1990, 161 pages with data on diskette.

105R   Beasley Creek Orientation Study: Mineralogy and Geochemistry of soils overlying the Beasley Creek gold mine - Laverton, W.A.
                  I.D.M. Robertson, December 1990. Vol. I, 53 pages; Vol. II, 99 pages.

161R   Laterite geochemistry in the CSIRO-AGE database for the Albany-Fraser region (Collie, Dumbleyung, Mount Barker, Pemberton sheets)
                  E.C. Grunsky, April 1991. Vol. 1, 61 pages with data on diskette; Vol. 2, 145 pages.

120R   Hydrogeochemistry in the Mount Gibson gold district.
                  D.J. Gray, April 1991, 80 pages.

Un-numbered   Strategies and Methodologies for the Interpretation of Geochemical Data - Discussion Paper Applied to Laterite Geochemistry.
                  E.C. Grunsky, August 1991, 160p, data on diskette.

166R   Regolith-landform relationships and consequences on the characteristics of regolith units, Lawlers District, Western Australia.
                  R.R. Anand, H.M. Churchward, R.E. Smith and E.C. Grunsky, August 1991, 160p, data on diskette.

165R   Regolith-landform development and siting and bonding of elements in regolith units, Mt. Gibson district, Western Australia.
                  R.R. Anand, H.M. Churchward and R.E. Smith, September 1991, 95p, data on diskette.

157R   Reference geochemical data sets from the Mt. Gibson orientation study, Western Australia.
                  R.E. Smith, J.E. Wildman, R.R. Anand and J.L. Perdrix, March 1992, 105p, data and animated demonstrations on diskettes.

236R   Laterite geochemistry for detecting concealed mineral deposits, Yilgarn Craton, Western Australia.
                  R.E. Smith, R.R. Anand, H.M. Churchward, I.D.M. Robertson, E.C. Grunsky, J.E. Wildman and J.L. Perdrix, November 1992. Summary Report for the CSIRO/AMIRA Project P240.

247R   Regolith-landform relationships in the Bottle Creek Orientation Study, Western Australia.
                  H.M. Churchward, I.K. Butler and R.E. Smith, November 1992. 73 pages, fold-out map.

APPENDIX II   **Reports issued to tenement holders**

22R	Laterite geochemistry, Lawlers district, W.A.; Progress report to Geochemex Australia and Forsayth Mining Ltd. R.R. Anand, J. Innes and R.E. Smith, April 1989, 57 pages.
106R	Regolith/landform relationships and the characteristics of lags, Lawlers district, W.A. R.R. Anand, H.M. Churchward, R.E. Smith, April 1990, 105 pages. (Reports 22R and 106R have been reformatted into Report 166R for sponsors).
120R	Hydrogeochemistry in the Mount Gibson gold district. D.J. Gray, June 1990, 91 pages.
246R	Regolith-landform evolution and geochemical dispersion from the Boddington Gold deposits, Western Australia. R.R. Anand, November 1992, 149 pages.
247R	Regolith-landform relationships in the Bottle Creek orientation study Western Australia, November 1992, 65 pages. H.M. Churchward, I.K. Butler and R.E. Smith.

APPENDIX III   **Progress Reports**

	Period	Date report produced
-	Oct-Dec, 1987	19 February 1988
-	Jan-March, 1988	31 May 1988
-	April-June, 1988	12 August 1988
- -	July-Sept, 1988 $\Big\}$ Oct-Dec, 1988	13 January 1989
- -	Jan-March, 1989 $\Big\}$ April-June, 1989	23 June 1989
- -	July-Sept, 1989 $\Big\}$ Oct-Dec, 1989	25 January 1990
- -	Jan-March, 1989 $\Big\}$ April-June, 1990	16 August 1990
236R	Summary and Synthesis (this report) July 1987-June 1991	November 1992

APPENDIX IV   Meetings held with sponsors

2 July 1987	Launching of the project
3 November 1987	Workshop on laterite sample types
4 November 1987	Project review meeting
11 April 1988	Project review meeting
8 September 1988	Joint meeting with Weathering Processes Project P241 Included discussions on terminology of regolith materials
16 December 1988	Project review meeting
15, 16 August 1989	Project review meeting Workshop on laterite types Launching of *Terminology, Classification, and Atlas* (Report 60R) Field trip to Mt. Gibson, including terminology and classification
15 November 1989	Project review
26 July 1990	Project review
11 October 1990	2nd Field trip to Mt. Gibson
30 October to 2 November 1990 }	Summary field trip, Kalgoorlie, Bottle Creek, Lawlers
13 March 1991	Project review meeting and demonstration of computing for graphical interpretation of geochemical data
10 September 1991	Final meeting

APPENDIX V   **Extract From Report 60R,** *Laterite Types and Associated Ferruginous Materials -*
*Terminology, Classification and Atlas.* **R.R. Anand et al., (August 1989)**

Classification Tables and Codes

LT
Example: LATERITIC RESIDUUM

|		
	LT100	LT101 loose ooliths
	Lateritic	LT102 loose ooliths
	gravel	LT103 loose pisoliths and nodules
		LT104 loose nodules
		LT164 loose lateritized gossan-nodules
		LT166 loose lateritized gossan-cobbles
LT	LT200	LT201 oolitic duricrust
LATERITIC	Lateritic	LT202 pisolitic duricrust
RESIDUUM	duricrust	LT203 pisolitic-nodular duricrust
		LT204 nodular duricrust
		LT205 fragmental duricrust
		LT211 packed oolitic duricrust
		LT212 packed pisolitic duricrust
		LT213 packed pisolitic-nodular duricrust
		LT214 packed nodular duricrust
		LT221 Fe-rich oolitic duricrust
		LT222 Fe-rich pisolitic duricrust
		LT223 Fe-rich pisolitic-nodular duricrust
		LT224 Fe-rich nodular duricrust
		LT228 Fe-rich pebbly duricrust
		LT229 Fe-rich massive duricrust
		LT231 vermiform duricrust
		LT232 cellular duricrust
		LT241 mottled duricrust
		LT242 massive duricrust

APPENDIX V (cont'd)
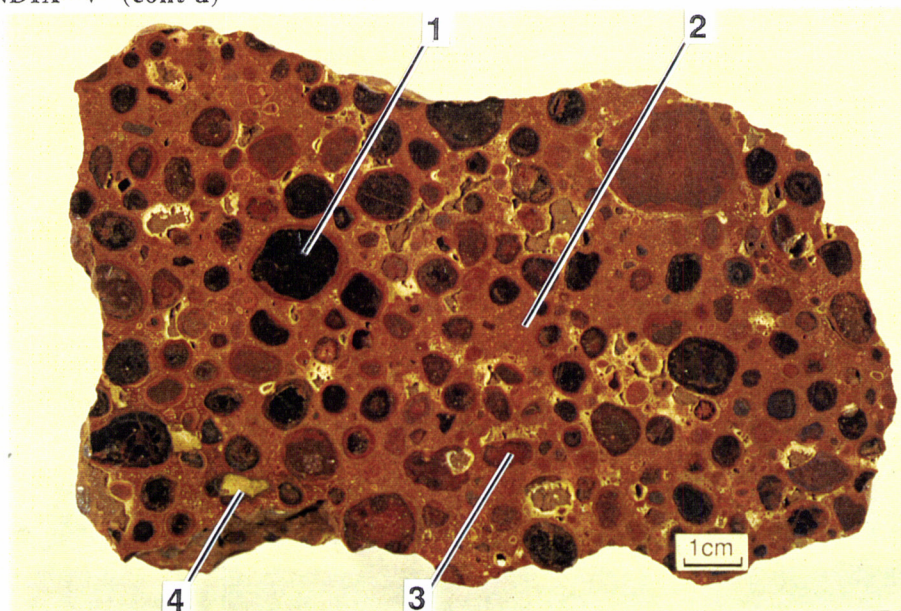
LT202
pisolitic
duricrust
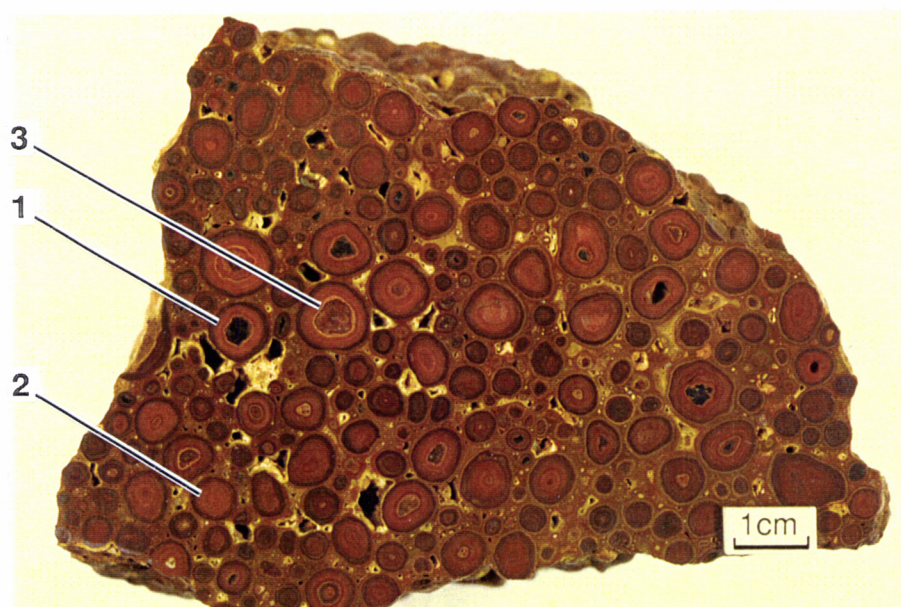
LT202
pisolitic
duricrust
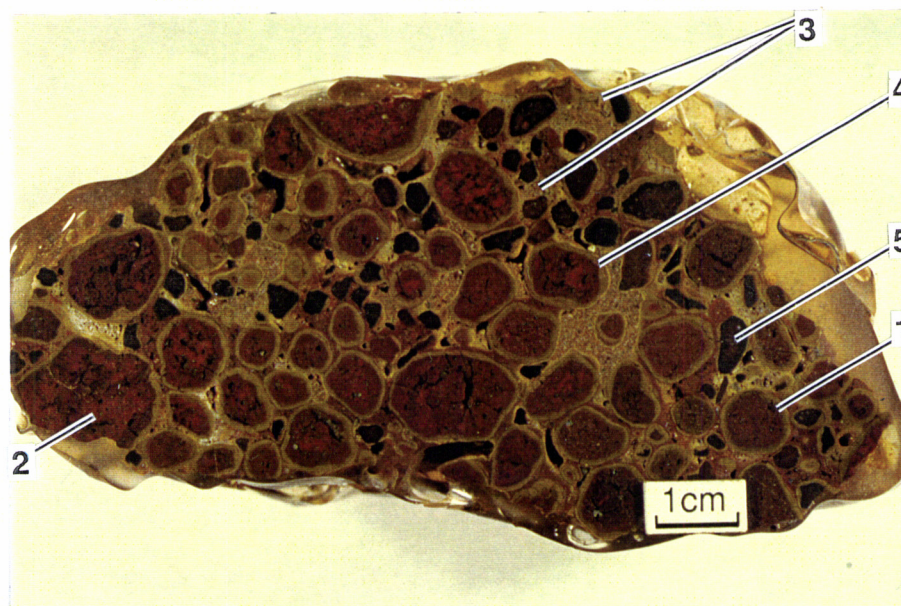
LT203
pisolitic-
nodular
duricrust

APPENDIX V (cont'd)

PISOLITIC DURICRUST LT202
Sample 07-0385, Darling Ranges

This pisolitic duricrust occurs on a midslope position overlying a fragmental and mottled duricrust. It consists predominantly of 3-15 mm sized reddish brown and black Al-hematite-rich pisoliths (1), cemented by a red, fine-grained gibbsite-rich matrix (2). In addition to gibbsite, Al-goethite, Al-hematite, kaolinite and anatase also occur in matrix. Maghemite is not a constituent of the matrix. The ratio of pisoliths to matrix is approximately 50:50. The cores of the black pisoliths are uniformly dense, non-porous, and magnetic due to the presence of maghemite. By contrast the cores of red pisoliths are porous, non-magnetic and do not contain maghemite. Al-goethite is either absent or present in small amounts in magnetic pisoliths whereas it occurs in significant amounts in non-magnetic pisoliths. Gibbsite in small to moderate amounts is present both in magnetic and non-magnetic pisoliths. Maghemite- and hematite-rich areas of black pisoliths show patchy alteration to a reddish brown phase (probably hematite) which is very similar to the cores of the reddish brown pisoliths. A few irregularly shaped nodules (3) are also present. The pisoliths are well rounded and sub-spherical in shape. Pisoliths by definition are spherical or sub-spherical, whereas nodules are irregular in shape with rounded edges.

The cores of the black pisoliths and red pisoliths have 1-2 mm thick hematite and gibbsite rich cutans in a succession of layers (light red-dark red). The matrix as well as some pisoliths contain voids which appear to be the result of dissolution (4). Voids are lined with a yellowish cutans of gibbsite and have a partial filling of kaolinite, gibbsite and Al-goethite.

Goethite in this sample is highly Al substituted. However the levels of Al substitution vary between pisoliths ($\approx$30 mole %), pisolith cutans ($\approx$20 mole%) and matrix ($\approx$25 mole %). The level of Al-substitutions in hematite ($\approx$10 mole%) is much lower.

PISOLITIC DURICRUST LT202
Sample 07-1304, Cobiac Pit, Jarrahdale

This pisolitic duricrust differs from the sample shown above in the nature and thickness of cutans and the ratio of pisoliths to matrix which here is approximately 70:30. The duricrust is characterized by concentric pisoliths with thick light and dark red cutans (1) which are set in a gibbsite-rich clayey matrix. Some pisoliths are entirely concentrically banded (2). Light red cutans are generally thicker ($\approx$2mm) than the dark red cutans (< 1mm). The innermost cutan (3) around some cores of pisoliths is yellow which is goethite-gibbsite-rich. Micro-vermiform voids occupy about 10% of the matrix and are lined with yellow gibbsite and kaolinite. Some pisoliths comprise a hematite-maghemite rich black core while others have cores of detrital quartz or gibbsite pseudomorphs after feldspar. Lighter cutans contain more Al (gibbsite rich) and less Fe (hematite) than the darker cutans. The complex nature of concentric cutans suggests a long history of weathering and accretionary events.

PISOLITIC-NODULAR DURICRUST LT203
Sample 07-0333, Mt. Gibson Orientation Area

This weakly indurated duricrust occurs in a lowslope position. It overlies a mottled zone and in turn is overlain by yellow sands. The duricrust consists predominantly of red earthy Al-hematite-rich spherical pisoliths (1), and irregular shaped nodules (with well-rounded corners) (2), cemented in a pale-coloured sandy quartz and kaolinite rich matrix (3). The pisoliths and nodules are non-magnetic. The cores of the red nodules and pisoliths are rimmed with a yellow goethitic cutan (4) of relatively uniform thickness ($\approx$1 mm). Other nodules consists of a sub-angular to rounded hematite rich core (5) again with thin yellow goethite cutans. The red pisoliths and nodules are porous and show the development of cracks and contain angular quartz grains up to 1 mm in size. The matrix comprises well sorted angular to rounded quartz ($\approx$0.5 mm) and has a pale colour. The relatively low Fe content of the matrix possibly results from leaching of Fe during the later stages of weathering. Microvermiform voids occur in the matrix.

Figure (opposite) and descriptions (above): Extract from *Laterite types and associated ferruginous materials, Yilgarn Block, WA - terminology, classification, and atlas* by Anand *et al.* (August, 1989) Report 60R.