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GEOCHEMICAL EXPLORATION IN AREAS OF TRANSPORTED OVERBURDEN, YILGARN CRATON AND ENVIRONS, WESTERN AUSTRALIA

FINAL REPORT

C.R.M. Butt, D.J. Gray, I.D.M. Robertson, M.J Lintern, R.R. Anand, A.F. Britt, A.P.J. Bristow, T.J. Munday, C. Phang, R.E. Smith and J.E. Wildman

CRC LEME OPEN FILE REPORT 86

January 2001

(CRC LEME Restricted Report 36R/
CSIRO Division of Exploration and Mining Report 333R,
2nd Impression.)

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CRC LEME is an unincorporated joint venture between The Australian National University, University of Canberra, Australian Geological Survey Organisation and CSIRO Exploration and Mining
Headquarters: CRC LEME c/o CSIRO Exploration and Mining, Private Bag No 5, PO Wembley, Western Australia, 6913.

RESEARCH ARISING FROM CSIRO/AMIRA YILGARN REGOLITH GEOCHEMISTRY PROJECTS 1987-1996

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" 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 commenced with 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 (1991-1993). 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.

Most reports related to the above research projects were published as CRC LEME Open File Reports Series (Nos 1-74), with an index (Report 75), by June 1999. Publication now continues with release of reports from further projects.

P252: Geochemical exploration for platinum group elements in weathered terrain. Leader: Dr C.R.M. Butt.
This project was designed to gather information on the geochemical behaviour of the platinum group elements under weathering conditions using both laboratory and field studies, to determine their dispersion in the regolith and to apply this to concepts for use in exploration. The research was commenced in 1988 by CSIRO Exploration Geoscience and the University of Wales (Cardiff). The Final Report was completed in December 1992. It was supported by 9 companies.

P409: Geochemical exploration in areas of transported overburden, Yilgarn Craton and environs, WA.
Leaders: Drs C.R.M. Butt and R.E. Smith.
About 50% or more of prospective terrain in the Yilgarn is obscured by substantial thicknesses of transported overburden that varies in age from Permian to Recent. Some of this cover has undergone substantial weathering. Exploration problems in these covered areas were the focus of Project 409. The research was commenced in June 1993 by CSIRO Exploration and Mining but was subsequently incorporated into the activities of CRC LEME in July 1995 and was concluded in July 1996. It was supported by 22 companies.

Although the confidentiality periods of Projects P252 and P409 expired in 1994 and 1998, respectively, the reports have not been released previously. CRC LEME acknowledges the Australian Mineral Industries Research Association and CSIRO Division of Exploration and Mining for authority to publish these reports. It is intended that publication of the reports will be a substantial additional factor in transferring technology to aid the Australian mineral industry.

This report (CRC LEME Open File Report 86) is a second impression (second printing) of CSIRO, Division of Exploration and Mining Restricted Report 333R, first issued in 1997, which formed part of the CSIRO/AMIRA Project P409.

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PREFACE

Areas with substantial transported overburden present some of the most significant exploration problems in the Yilgarn Craton and its environs, as well as in many other parts of Australia. It is estimated that such overburden conceals as much as 50% of the prospective terrain in the region, and greatly exceeds this in some districts. The previous and current AMIRA projects, Yilgarn Lateritic Environments (projects P240 and P240A) and Weathering Processes (P241, P241A), have shown that research can result in markedly improved methods of exploration in areas of transported cover and this project developed these further by studies of geochemical dispersion in a range of different depositional environments. Geochemical techniques are perceived to have considerable, but largely untested, potential in these environments. This project sought to investigate this potential. The aim has been to develop, if possible, suitable exploration geochemical methods for sediment-covered areas based upon an improved knowledge of the nature of the cover sequences and by reaching a better understanding of the mechanisms of element dispersion that may occur within them. To reach this end, a number of districts and sites were selected with the aid of the sponsoring companies and, following further selection based on some pilot studies, detailed investigations made at those that best typified many of the problems being encountered. The outcomes of these specific studies are given in the various investigation reports issued during the project; the purpose of this report is to summarize these results and to develop some more general conclusions and recommendations.

C.R.M. Butt
R.E. Smith
Project Leaders
January 1997

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Exploration issues

The presence of a thick regolith is recognized as a major impediment to mineral exploration in the Yilgarn Craton and adjacent regions, as well as in many other parts of Australia. The processes of deep chemical weathering, erosion and sedimentation have served to conceal ore deposits in the underlying rocks, such that their geological, geochemical and geophysical expression in the regolith is greatly altered, weakened or buried. The emphasis of research and exploration prior to this project had largely been in areas of residuum, where *in situ* weathered rocks outcrop or have only a very shallow cover of transported overburden. However, it is estimated that as much as 50% of the prospective terrain in the Yilgarn, and substantially more in some districts, is concealed by transported overburden, which itself commonly overlies highly weathered residuum. It is the exploration problems posed in these areas that have been the focus of the project.

The sedimentary cover ranges in age from Permian to Recent and in thickness from a few centimetres to many tens of metres. The sediments include marine, glacial, colluvial, alluvial, estuarine/deltaic, organic, evaporitic and aeolian types and several may be present in the sequence at a given site. The various types of sedimentary overburden are commonly poorly characterized and difficult to recognize, and their stratigraphy poorly defined. Consequently, they have not only been inadequately mapped, but their potential as geochemical sample media, or even as hosts to secondary mineralization, is poorly known. The overburden varies in character according to region, geomorphological setting and age, with each variant potentially presenting different problems and opportunities to mineral exploration. Upland areas are mantled by colluvium and, especially over sedimentary and granitic rocks, aeolian sands, which commonly overlie complete or partly truncated lateritic regoliths. In addition, considerable areas are occupied by major drainages that form broadly dendritic systems on the Precambrian Shield and adjacent sedimentary basins. The drainage systems may date from the early Mesozoic or earlier and are now represented by broad colluvial-alluvial plains, generally with deeper "palaeodrainage" channels within them. Some of these sediments may similarly overlie complete or truncated lateritic regoliths, whereas others may be contemporaneous with or pre-date lateritic weathering.

Transported overburden accordingly presents formidable problems and challenges to exploration. On the one hand, because of its exotic origin, it has commonly been considered unsuitable as a sample medium; on the other hand, because many of the sediments are ancient and have been subjected to diagenesis and post-depositional weathering, it has been thought that there is potential for their composition to be influenced by chemical dispersion from underlying mineralization. Exploration in depositional areas has proceeded according to both precepts, with some groups proceeding to drill through all transported and in some cases, residual regolith materials, whereas others have continued to collect and analyse shallow samples of clearly transported material in the belief that they will indicate the presence of concealed mineralization.

Previous research in areas of transported overburden had already confirmed that the nature of the geochemical expression, if any, of concealed mineralization varied according to the type and post-depositional history of the overburden. The following situations have been noted.

(a) Although extensive chemical and physical dispersion occurred during an initial deep weathering phase, there has been no significant later dispersion into the sediments. Nevertheless, successful exploration may be carried out by drilling to specific horizons in residuum: *e.g.*, to lateritic horizons: Lawlers district (Anand, 1995).

(b) Partial erosion of previously weathered residuum and deposition in the overburden has given a clastic dispersion halo in the sediments.

(c) Chemical dispersion, whether past or presently active, during post-depositional evolution of the regolith has resulted in the enrichment of adjacent or overlying regolith, both residual and transported (*e.g.*, Thalanga, Q (Granier *et al.*, 1989) and Dalgaranga, WA (Butt, 1992). Such enrichments may be largely confined to specific horizons in soils, developed on apparently barren sediments: *e.g.*, Au in pedogenic carbonates, southern Yilgarn Craton (Lintern and Butt, 1993; Dell and Anand, 1995).

(d) Presently active physical dispersion may give distal anomalies, in sheetwash (including lag) and stream sediments, derived from erosion of previously weathered residuum. Proximal anomalies may be produced by churning, caused by seasonal wetting and drying of smectitic soils (*e.g.*, in black soil plains).

(e) Presently active chemical dispersion may give rise to subtle anomalies best revealed by selective or partial analytical procedures (*e.g.*, Kadina, SA; Mazzucchelli *et al.*, 1980).

(f) Physical and, in particular, chemical accumulation of various metals in sediments may reach ore grade, either derived from a specific mineralized source or concentrated from diverse sources, thus themselves becoming exploration targets, *e.g.*, Au associated with palaeochannels (Devlin and Crimeen, 1990); U in calcrete, Yilgarn Craton and adjacent basins (Butt, 1988; Butt *et al.,* 1977); U and base metals, Au and REE in lignites (Douglas *et al.*, 1993).

The full potential and applicability of exploration techniques based on these examples can only be realized through a thorough understanding of the mechanisms involved, set in the appropriate geological and geomorphological context. Accordingly, the project undertook multi-element geochemical dispersion studies around deposits in a variety of geomorphological and sedimentary environments, paying particular attention to the distribution, characteristics and probable origin of the sediments themselves. The project sought to establish further criteria for identifying sediments and for distinguishing them from residual overburden, and to evaluate different units as sample media. Where possible, these studies included groundwaters and vegetation, with respect both to their roles in dispersion and their potential as sample media. Similarly, the use of different partial extraction procedures has been examined, both with regard to their value in indicating geochemical processes and as a means for enhancing the expression of possible active dispersion form concealed mineral deposits. From these investigations, recommendations for appropriate exploration procedures for some of the more common environments and sediment types have been developed.

Although the initial intention of the project scientists and the sponsors had been to study deposits of commodities other than gold, in the event, only gold deposits were offered. None of these was particularly enriched in other metals, although most had As, Sb and/or W associated with them.

1.2 Objectives

The initial objectives of the project were as follows:

1.2.1 Principal Objective

To develop geochemical methods for mineral exploration in areas having substantial transported overburden in the Yilgarn Craton and its environs, through investigations of the processes of geochemical dispersion from concealed mineralization.

1.2.2 Specific Objectives

1. Determine the characteristics of the principal types of surficial sediments and sedimentary environments in the region and to develop a system for the identification and classification of sedimentary overburden.

2. Determine the geochemical expression, in the regolith, of concealed gold and base metal deposits in selected geomorphological settings, such as playas and highly saline environments, and plains dominated by colluvial, alluvial and/or aeolian sediments. Investigations include determination of the mechanisms of dispersion and the potential for these deposits being revealed by labile ions in surficial materials.

3. Determine the genesis of sub-horizontal supergene gold deposits, particularly those apparently associated with palaeodrainage channels, and their relationship to primary sources.

4. Develop methods of sampling, analysis and data interpretation for mineral deposits concealed within and beneath transported overburden and establish appropriate geochemical exploration models.

5. Establish the relative timing and significance of dispersion events in terms of regolith and landscape evolution.

6. Transfer research findings and skills to the industry through seminars and field excursions, and by one-on-one discussions with individual sponsor companies.

Some of the specific objectives were slightly modified during the course of the project. In particular, no base metal deposits were offered for study, nor were there any suitable sites within playas or in areas dominated by aeolian sediments (Specific Objective 2). Following discussion, it was decided to greatly reduce the emphasis on supergene gold deposits (Specific Objective 3), restricting this to some minor laboratory experiments. However, greater emphasis was placed on the investigation of the use of labile ions in exploration, determined by partial extraction procedures, including a comparison between some in-house techniques and three available commercially. Based on these changes in the objectives, the Work Plan was modified and is outlined in Section 1.4.

1.3 Benefits

The benefits from the research, following the modification to the objectives, include:

(i) A series of geochemical case studies from a range of environments that typify many of those on the Yilgarn Craton. These provide strong evidence as to the nature of any geochemical expression of concealed mineralization, in buried residual regolith, transported overburden, groundwaters and vegetation.
(ii) A much improved understanding of the extent and mechanisms of geochemical dispersion that have influenced the composition of various units of the overburden.
(iii) Significantly greater knowledge of the nature, distribution and classification of sedimentary overburden, including the documentation of important types and characteristics that may serve as criteria for the recognition and identification of transported regolith units and distinguishing them from residual units.
(iv) Further studies of the regional composition of groundwaters, an important basis for understanding active chemical dispersion processes and for the interpretation of hydrogeochemical exploration data.
(v) An improved knowledge of the aqueous chemistry of gold, including some of the processes possibly involved in the formation of supergene gold deposits.
(vi) Development of analytical procedures that assist in identifying the mineralogical occurrence/association of gold in residual and transported regolith.
(vii) Further development of partial and selective analytical procedures for extracting labile ions, and an assessment of the value of these and commercially available procedures in exploration.
(viii) Recommendations regarding the most appropriate sampling, analytical and interpretational procedures for areas having extensive transported overburden.

(ix) Improved efficiency and confidence in exploration, leading to reductions in the overall cost of exploration.

(x) Transfer of information concerning regolith-landform relationships and regolith exploration geochemistry to industry geoscientists through informal discussions, one-on-one meetings, seminars, field excursions, reports and sponsorship of Honours projects.

1.4 Work plan

1.4.1 Themes

To meet the original objectives, it had been proposed that research would proceed under three main themes, as follows:

A. The surface and subsurface expression of concealed mineral deposits, including studies aimed at establishing the existence, detection and use of labile ions, and the determination of relevant dispersion mechanisms.

B. Geochemical dispersion in, and exploration methods appropriate to, highly saline environments.

C. The genesis of sub-horizontal supergene deposits of gold.

Following the modification of the objectives noted in Section 1.2, themes A and B were combined. The emphasis on theme C was greatly reduced to studies of the stratigraphy of some mineralized palaeochannels and experiments of possible mechanisms of gold mobility and precipitation. Four principal *disciplines* were applied to achieve the objectives.

1.4.2 Research disciplines

1. ***Regolith characterization***. This comprised investigations of the distribution, stratigraphy, facies and other properties of the principal types of transported overburden in the regolith. The topic includes regolith-landform mapping at local to district scales using remote sensing imagery, aerial photography and field traverses, determining regolith stratigraphy from drill cuttings, core and field exposures, and mineralogical and micromorphological studies of residual and transported regolith. Careful characterization of regolith materials is essential to ensure reliability if selected as sample media. Such studies lead, *inter alia*, to the development of criteria for the identification and classification of overburden and provide the geomorphological basis for geochemical exploration models. The petrographic, mineralogical and geochemical characteristics of some important sediment types have been compiled in a reference atlas of transported overburden.

   These activities were augmented at selected sites through collaboration with the Cooperative Research Centre for Australian Mineral Exploration Technologies, for investigations of the application of geophysical techniques (particularly ground electromagnetics) to define regolith stratigraphy.

2. ***Multi-element geochemistry***. Multi-element geochemical studies comprised a fundamental aspect of the research and provided information not only concerning the distributions of elements associated with mineralization, but of those that may control such distributions in the regolith (*e.g.*, Fe, Ca, Mn) or are diagnostic in determining regolith stratigraphy or parent lithology (*e.g.*, Al, Si, Fe, Cr, Ti, Zr). Dispersion studies at individual sites included analysis of fresh and weathered rocks, transported overburden and soils, and selected fractions of these materials. Vegetation was analysed at some sites, principally to investigate the role in active processes, but also to assess the potential of biogeochemistry. A variety of analytical procedures was used, including partial extraction procedures to determine the association of particular elements with specific mineral (or organic) phases. These multi-element studies

are the basis for establishing the nature of geochemical dispersion patterns in various residual and transported regolith units, the probable mechanisms involved and recommendations for exploration procedures.

3. ***Hydrogeochemistry***. Hydrogeochemical studies were conducted principally to assist in determining the nature of currently active dispersion processes, including those that contribute to the genesis of secondary mineralization. However, they also provided further important background data that will enhance the potential of groundwater sampling as an exploration procedure and are fundamental to understanding active processes that may be giving rise to anomalies of extractable labile ions. Although the most profound weathering of the Yilgarn and its environs probably took place under humid climates in the early Tertiary, the process is still continuing, albeit under changed conditions. It has particular relevance in alluvial, commonly saline, areas low in the landscape, where water-tables are higher and there is a greater interaction between groundwater and the regolith.

4. ***Solution - solid interactions***. These studies concentrated on the development and interpretation of selective extraction procedures, with the objective of determining the distribution of elements between various solid phases. Information regarding the sorption of elements on soil minerals and the role of organic matter in element mobilization and precipitation are crucial to understanding geochemical processes, particularly those that are currently active. Partial extraction analyses were also used to determine whether they could detect subtle anomalies in transported materials - a study that was extended to include some commercially available procedures that seemed to offer greater potential. Experiments to simulate possible mechanisms of gold mobilization and precipitation were developed in the last year of the project, particularly to investigate the genesis of supergene gold deposits associated with palaeochannels.

1.4.3 Research sites

The activities of the project ranged from some *district scale* investigations, with more detailed studies at specific *sites* (mines or prospects). In general, individual sites were selected to address specific problems and, where possible, studies were extended to place these within their geomorphological context by regolith and landform mapping at appropriate scales. A wide range of districts and sites for study were proposed during discussions with sponsors, based on the nature and importance of the transported overburden and the perceived exploration significance. These were then visited by members of the project team and pilot geochemical studies were undertaken at some of the most promising, particularly in the Kalgoorlie region. Decisions to continue or terminate the investigations were made on the basis of the field inspections or the results of the pilot studies, in consultation with sponsors. A number of environments that were deemed important were not studied due to a lack of suitable sites, specifically deposits beneath playas and those overlain by aeolian sediments; sites where harpanized colluvium overlies leached saprolite are also inadequately represented. One site (Curara Well) was selected specifically to investigate the strong surface expression shown by partial extraction analysis. The outcome contributed to the decision, late in the project (January 1996), to undertake the comparative study of a range of such procedures at a number of carefully characterized orientation sites. Similarly, also late in the project, a specific request was made to sponsors for a site in the Eastern Goldfields at which there was a seemingly unequivocal surficial anomaly in calcareous soils, over mineralization concealed by 20 m or so of transported overburden. No such site was offered and an approach was made to Resolute-Samantha Ltd., who are not sponsors of the project, to investigate the anomalies reported over their Higginsville palaeochannel deposits. This was the final site study, commencing in November 1995; field mapping was completed in May, 1996.

One or more of the following was undertaken at each of the sites:

(i) Geochemical pilot study;

(ii) District or local regolith-landform mapping; determination of regolith stratigraphy;
(iii) Petrographic, mineralogical and geochemical characterization of residual and sedimentary regolith materials;
(iv) Detailed geochemical and mineralogical studies of dispersion from mineralization into residual and transported regolith;
(v) Investigation of surface or near-surface expression of mineralization, including that of labile ions shown by partial extraction analysis;
(vi) Sampling and analysis of groundwaters close to deposits to determine the nature of any present-day dispersion. Modelling of groundwater chemistry and associated mineralogy;
(vii) Sampling and analysis of vegetation to determine the biogeochemical response, if any;
(viii) Development of exploration guidelines.

The locations of the districts and sites studied during the course of the project are shown in Figure 1.1. The nature of the investigations undertaken at each is listed in Table 1.1. Some sites from which material for the Atlas of Transported Overburden was obtained are not shown. No further work was undertaken after the pilot studies at Kurrawang and Versailles (Lake Cowan). Kurrawang has little or no transported overburden and gave a very strong anomaly in semi-residual calcareous soils, despite strong depletion to 30 m depth. At Versailles, only limited samples were available and many of those from the near-surface were subject to cross-hole contamination. However, the role of reducing sediments in Au precipitation in this area is worthy of investigation. The pilot sudy at Lady Bountiful indicated that there was no geochemical response in calcareous soils but, because of the advanced state of mining, there were limited opportunities for this to be followed-up. However, the exposures in the pits provided an excellent opportunity for a stratigraphic-sedimentological study. Research at Lawlers and Granny Smith was restricted to hydrogeochemical investigations, supplementing work undertaken in previous projects. Geophysical studies, principally to evaluate the use of EM and shallow seismic surveys in determining aspects of regolith stratigraphy, were carried out in collaboration with the Cooperative Research Centre for Australian Mineral Exploration Technologies (CRC AMET).

1.5 Sponsors and duration

The project commenced with 15 sponsoring companies, increasing to 22 in the third year.

Aberfoyle Resources Ltd	Acacia Resources (formerly Billiton Australia Ltd)
Aurora Gold Ltd	Aztec Exploration
BHP Exploration	Copperfield Gold NL
CRA Exploration Pty Ltd	RGC Exploration Pty Ltd
Homestake Gold of Australia Ltd	Mines and Resources Australia Ltd (formerly AFMECO Pty Ltd)
Mining Project Investors Pty Ltd	M.I.M. Exploration Pty Ltd
Mt. Kersey Mining NL	Newcrest Mining Group
Normandy Exploration	North Ltd
Pancontinental Mining Ltd	Pegasus Gold Ltd (formerly Zapopan NL)
Plutonic Operations Ltd	Sabminco NL
Western Mining Corporation Ltd	Wiluna Mines Ltd

The project commenced on 1 June 1993, with the first sponsor's meeting held on 18 June 1993. The project formally concluded with the Final Meeting on 4 July 1996.

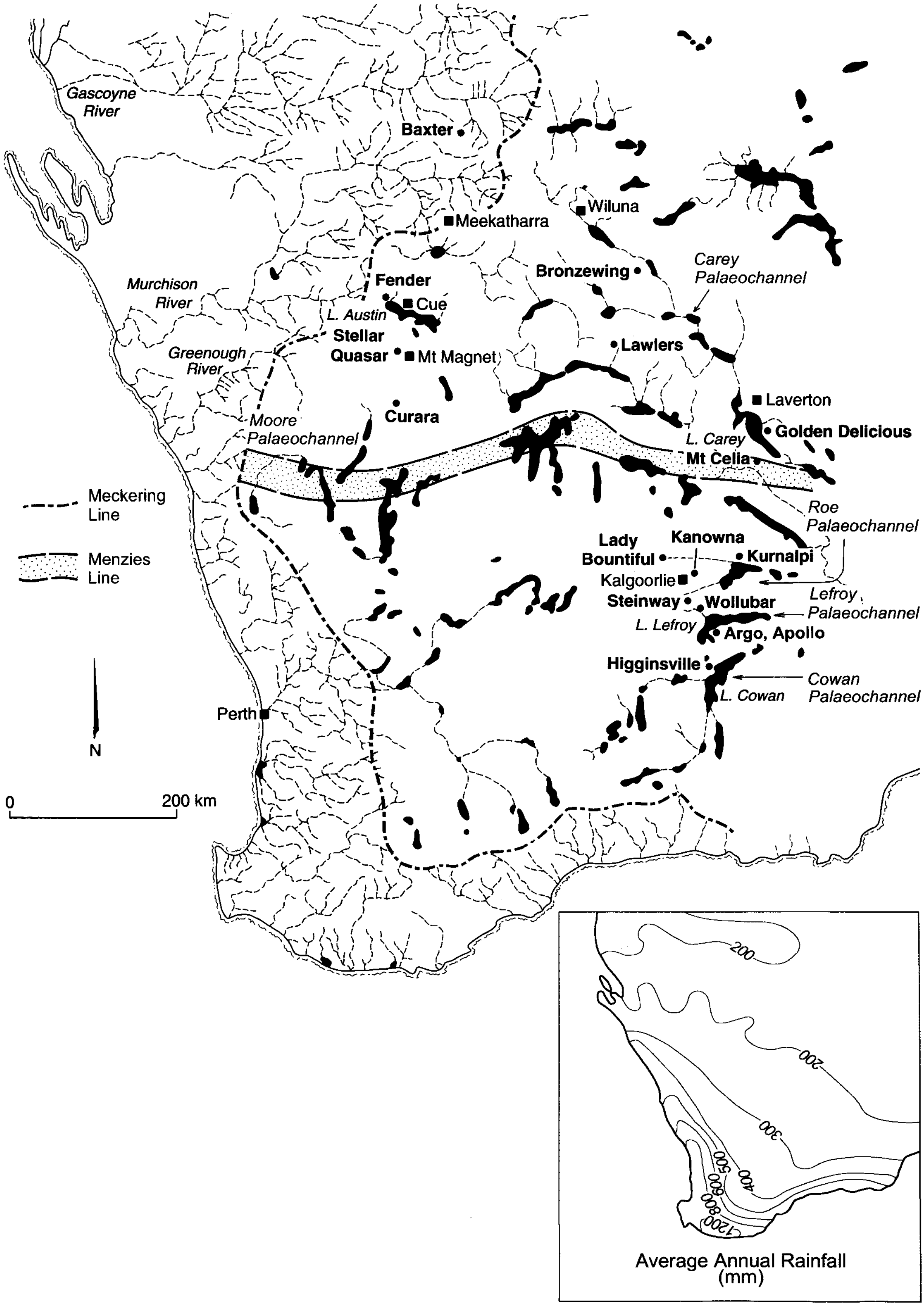


Figure 1.1: Locations of study sites

1.6 Project staff

The project brought together the Laterite Geochemistry and Weathering Processes groups in the then CSIRO Division of Exploration Geoscience (now CSIRO Exploration and Mining), Floreat Park. These research groups had extensive experience in geomorphology, regolith geology and exploration geochemistry in the Yilgarn Craton and the project was a successor to those commenced in 1987, namely Yilgarn Lateritic Environments (P240 and P240A), Dispersion Processes (P241, P241A) and Exploration for Platinum Group Elements (P252). Some research was undertaken as Honours projects supervised by members of the research group, thereby linking training of new graduates in regolith geology and geochemistry with project activities. In addition, the project group collaborated with the Cooperative Research Centre for Australian Mineral Exploration Technologies at sites of mutual interest. After formation of the Cooperative Research Centre for Landscape Evolution and Mineral Exploration (CRC LEME) in July 1995, the regolith geochemistry activities of CSIRO Exploration and Mining have been undertaken within CRC LEME. The project was formally transferred to CRC LEME in October 1995. The following staff have been involved in the project:

Project Leaders
Dr. C.R.M. Butt
Dr. R.E. Smith

Professional Staff
Dr. R.R. Anand
Dr. D.J. Gray
Ms. A. Koning (from September 1995, part time)
Mr. C. Phang
Mr. Z.S. Varga (from July 1995)
Mr. A.P.J. Bristow (from November 1994)
Mr. J.D. King (until May 1994)
Mr. M.J. Lintern
Dr. I.D.M. Robertson
Mr. J.E. Wildman

Support Staff
Ms. G. Ashton (from August 1995)
Mr. K. Lim (from August 1995 until February 1996)
Mr. W. Maxwell (until March 1995)
Ms. S. Derriman (from March 1996)
Mr. G.D. Longman

Honours Students

Regolith geology-geochemistry	
Ms. N. Gardiner	University of Western Australia
Mr. R. Ward	Curtin University
Mr. Z.S. Varga	University of Tasmania
Mr. R. Crawford	University of Tasmania
Ms. N.K. Woolrich	Curtin University
Regolith geology-sedimentology	
Mr. M.E. Dusci	Curtin University
Mr. B. Ladhams	Curtin University
Regolith geophysics	
Mr. R. Fowler	Curtin University (CRC AMET)
Mr. M. Cooper	Curtin University (CRC AMET)
Ms. T. Roberts	Curtin University (CRC AMET)
Mr. J. Lowe	Curtin University (CRC AMET)

Table 1.1 Investigations undertaken as part of Project 409, Yilgarn Transported Overburden.

Site	*Pilot study*	*Regolith landform map*	*Geochemical orientation*	*Partial extraction test*	*Hydro-geochemistry*	*Biogeochemistry*	*Other studies*	*Report*
Baxter (Harmony)	Yes	District	Yes		Yes			EM 169R/LEME 3R, EM194R/LEME 5R
Fender			Yes	Yes				EM 313R/LEME 22R
Mt. Magnet Stellar Quasar		District	Yes Yes					} EM 48C }
Curara				Yes				EM 210R/LEME 9R
Bronzewing		District	Yes	Yes				EM 308R/LEME 18R
Lawlers		*	*	*	Yes	-		EM 26R, Thesis: Ward, 1993
Granny Smith			**	**	Yes	-		EG 383R
Golden Delicious		Reconnaissance	Yes		Yes			EM 280R/LEME 15R
Mt. Celia - Safari	Yes	Reconnaissance	Yes	Yes		Yes		EM 281/LEME 13R
Lady Bountiful	Yes	District					Sedimentology	Thesis: Dusci, 1994
Panglo			**	Yes	**	**		EM 251R/LEME 10R
Gindalbie	Yes							
Kurnalpi	Yes	District	Yes					EM 97R
Kanowna		District	*				Sedimentology	Thesis: Ladhams, 1994
Kurrawang	Yes							
Runway								EM 250R, LEME 26R
Steinway		District	Yes	Yes	Yes	Yes		Thesis: Gardiner, 1993, EM 95R, EM 252R/LEME 27R
Versailles - L. Cowan	Yes							
Wollubar	Yes	District	Yes	Yes	Yes; **			EM 98R
Argo-Apollo		District	Yes	Yes	Yes	Yes	Stratigraphy	Thesis: Woolrich, 1994, EM 96R, EM274R/ LEME 30R
Higginsville		District	Yes	Yes		Yes		EM 275R/LEME 28R

*: undertaken as part of AMIRA Projects 240, 240A; **: undertaken as part of AMIRA Projects 241, 241A; EM=Exploration & Mining, EG=Exploration Geoscience

2. NATURE AND DISTRIBUTION OF TRANSPORTED OVERBURDEN ON THE YILGARN CRATON

2.1 Introduction

The development of the regolith and landscape of Western Australia has occupied a long period of geological time. An erosional history derived from palaeogeographic reconstructions indicated that some of the Western Australian craton has been exposed to sub-aerial conditions since the late Proterozoic (Figure 2.1). Glaciations in the late Proterozoic and early Permian probably removed most traces of pre-existing regoliths. Some landforms, however, may have been preserved. For example, the present surface of the Yilgarn plateau is only a few tens of metres below the essentially flat-lying, sub-Proterozoic unconformity, and the overall flatness of the landscape suggests that the plateau may represent a Proterozoic erosion surface. This view was also expressed by Finkl and Fairbridge (1979), although van de Graaf (1981) and Clarke (1994) have estimated that up to 400 m of erosion has been necessary to generate the sediments infilling the surrounding basins. Similarly, some of the major drainages in the north eastern Yilgarn contain Permian glacigene sediments, hence the broad valleys and deeper channels may be inherited. The generally low relief and tectonic stability during the long period of exposure since the Permian have permitted the widespread development and preservation of a thick regolith, formed under a range of different climates.

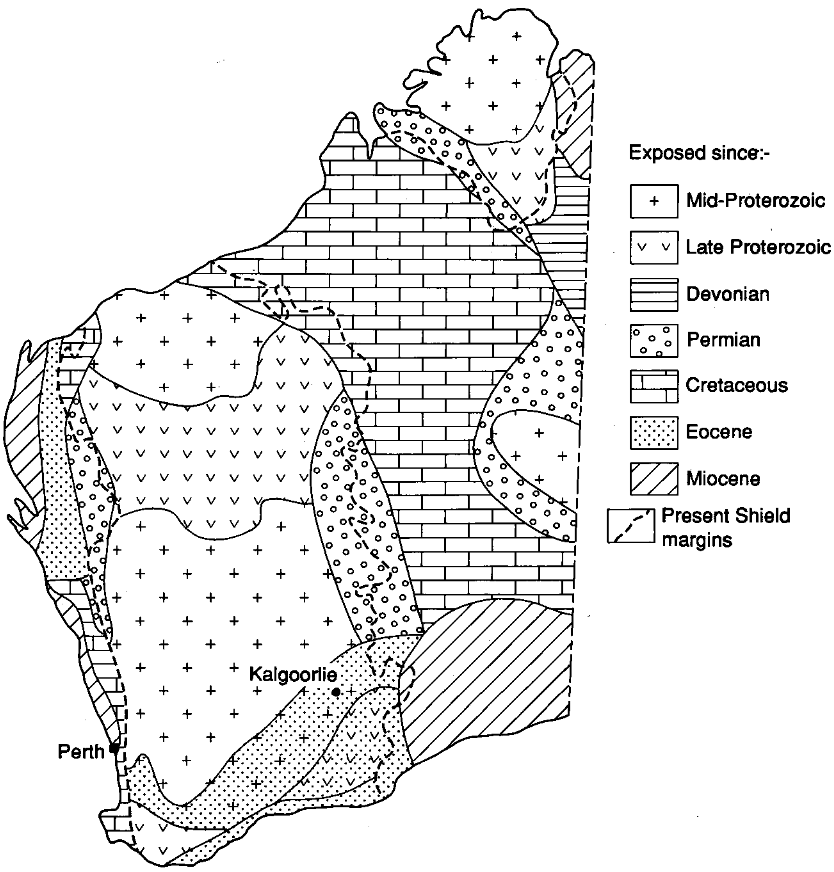


Figure 2.1: Periods of exposure to subaerial weathering, Western Australia. The Precambrian shields was subjected to glacial erosion during the Permian. Subsidence during the Eocene caused sedimentation in valleys in the south. (From Butt, 1989).

The climatic history since the Permian is very imprecisely known. There is little direct evidence of temperatures and amount or seasonality of rainfall. Furthermore, in most instances, neither the residual regoliths nor the sediments derived from, or burying, them can be readily dated. However, the following general conditions probably prevailed in the now semi-arid inland parts of the Yilgarn Craton.

Period	*Age (Ma)*	*Climate*
Quaternary	0-1.8	Cool, semi-arid to arid during glacial maxima. Temperate to warm, mainly semi-arid, during interglacials, continuing to present
Pliocene to Mid-Miocene	1.8-15	Warm to sub-tropical; aridity increasing. Cooler after 2.5 my
Mid-Miocene to Palaeocene	15-65	Warm to sub-tropical; seasonally humid (savanna or Mediterranean)
Mesozoic	65-230	Temperate to warm; humid
Lower Permian	270-280	Glaciation

Contemporaneous erosion and deposition, with more significant events probably triggered by climatic change, have resulted in variable retention of the regolith and an extensive veneer of sediments. These sediments thus have a wide range in age, from Permian to the present. In addition to those of continental origin, marine and estuarine sediments of late Eocene age are present in some of the major drainages south of Kambalda. The characteristics of the sediments reflect the conditions under which the material was initially formed, the erosional and depositional events under which they were deposited and the environments under which post-depositional modifications, due to diagenesis and/or weathering, have occurred. The sediments should, therefore, hold the key to interpreting the evolution of the regoliths and landforms of the Yilgarn Craton and, the mechanisms of element dispersion during this evolution. However, because of the number of these successive events and the complexity of the resultant overprints, such interpretation is at an early stage and largely beyond the scope of this project. Nevertheless, a number of different sedimentary sequences can be recognized and several of the more important of these have been investigated with a view to determining their characteristics, depositional and weathering history and the most appropriate geochemical exploration procedures for concealed mineralization.

2.2 Sedimentation and weathering episodes

The relative timing of continental sedimentation and the principal weathering events potentially has considerable significance for exploration. The possibility for chemical dispersion of ore-related elements into the sediments from concealed mineralization is likely to be greater for older sediments, *i.e.*, those deposited before or during the main phases of deep weathering in the Mesozoic and early Tertiary, since these will have been subjected to more post-depositional alteration than younger sediments. On this basis, the sedimentary environments can be classified into the following categories:

Sediments pre-dating deep weathering under humid, temperate to sub-tropical conditions
Permian glacial sediments

Sediments deposited contemporaneously with deep weathering.
(a) Colluvium
(b) Palaeochannel sediments

Sediments deposited during semi-arid to arid periods.

(a) Colluvium
(b) Alluvium
(c) Aeolian sands and clays
(d) Evaporites

This last group of sediments is the most widespread and most variable. It may overlie not only fresh and weathered basement, but also the sediments of the other groups, and consists of their physical and chemical weathering products.

2.3 Sediments pre-dating deep weathering

Excluding remnants of the mid-Proterozoic Glengarry Formation, which overlap the northern margin of Yilgarn Craton and occur as outliers such as Mt. Yagahong, 40 km SSE of Meekatharra, and Kaluweerie Hill, 40 km ENE of Agnew, the only known sediments of this type are the glacial deposits of the Lower Permian Paterson Formation. These are found near Laverton and Lawlers, and become increasingly abundant to the north and east. Glacial and fluvioglacial deposits at Laverton consist of boulder clays, grits and sandstones (Clarke, 1919-20; Hobson and Miles, 1950; Gower, 1976). The boulder clays consist of rounded, smooth boulders, cobbles and pebbles of chert, quartzite, granite, gneiss, metavolcanics, gneiss and BIF in a clay matrix (Figure 2.2). The deposits occur dominantly in channels, commonly following ultramafic lithologies, some over 80 m deep; one shallow channel is exposed in the wall of the Beasley Creek pit. Some of the deeper deposits are unweathered and carbonaceous material within them has been dated palynologically as Permian (J. Hronsky, WMC. Ltd., personal communication, 1996). In many places, the sediments have been deeply weathered after deposition. Boulder clays exposed in the Lancefield South pit, for example, have clay-rich saprolites in which the fabrics of the boulders and matrix are well preserved, overlain by mega-mottled horizons in which the fabric is partly or wholly destroyed. In the Agnew-Lawlers district, flat-lying sediments locally over 12 m thick, thought to be Permian glacials, occupy gentle erosional hollow developed over steeply dipping Archaean bedrock (A. Milne, written communication, 1976) The basal unit is a boulder clay, with granitic, ultramafic and quartz clasts in a clay-rich matrix, and is overlain by laminated siltstone and claystone. A thin cover of these sediments is present above the Genesis pit, 6 km west of Agnew.

2.4 Sediments deposited contemporaneously with deep weathering

2.4.1 Sedimentary environments

Weathering under humid, probably seasonal conditions, is thought to have taken place in the very long period from the Mesozoic through to the mid-Tertiary. There were, undoubtedly, numerous changes in weathering conditions and weathering rates during this time, which encompassed the break-up of Gondwanaland. Erosion and sedimentation would have been continuous throughout this period as weathering proceeded, with major environmental changes triggering particular erosional events. Sediments related to the continuous erosion that contributes to the gradual downwasting of the land surface are probably best represented by colluvium that accumulates on footslopes and valley floors within a weathering toposequence. Sediments related to more specific environmental changes are represented by the alluvial, presumed lacustrine and estuarine/marine sequences that have been deposited in palaeochannels. Both types of sediment were subjected to weathering themselves, following deposition, under continuing humid conditions.

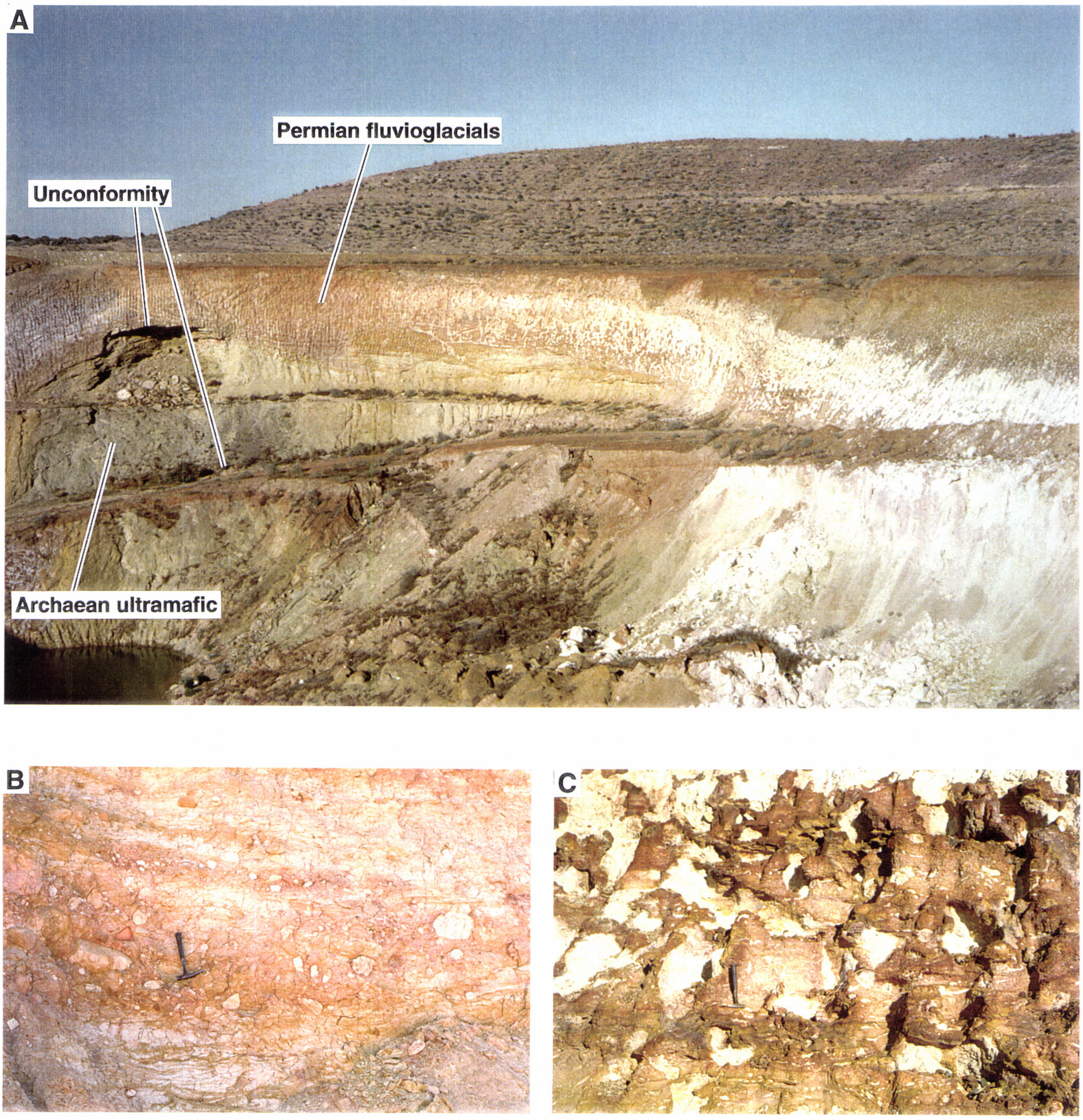


Figure 2.2: Permian glacial deposits, Lancefield South Pit, Laverton.
(A) Strongly mottled saprolite of Permian fluvio-glacial sediments, overlying saprolite and saprock developed in Archaean ultramafic rocks.
(B) Saprolite of Permian conglomerate or till. A wide variety of water-worn mafic and felsic clasts in a similar matrix. Clasts and matrix are all strongly weathered.
(C) Mottled saprolite of Permian sediments. Original bedding features are well preserved.

2.4.2 Colluvium

Sedimentary processes. Colluvial movement on slopes is an inherent aspect of the weathering process. Rain splash, mass flow and sheetwash contribute to the downslope movement of soil components, even in deeply weathered terrain of low relief. Depending on factors such as the relief, bedrock geology and the maturity of the landscape and regolith, the eroded material will vary from essentially unweathered minerals derived directly from outcrop to minerals typical of intense weathering, such as kaolinite, gibbsite and secondary Fe oxides. The latter may be as fine particles, or in secondary structures such as pisoliths. The eroded materials may form a minor component of soils on gentle gradients, but tend to accumulate at the base of slopes and lower parts of the landscape. They become part of the regolith in this new site and an inherent part of the weathering profile. Any regolith profile, therefore, and particularly those in low-lying parts of the landscape, will contain transported, colluvial material at the surface. In valleys, where thick colluvial deposits may accumulate, the regolith may have lower horizons developed in residuum and upper horizons in colluvium.

Regoliths with minor colluvial cover. Minor colluvial transport during deep weathering contributes to the effectiveness of laterite geochemistry, by broadening the dispersion haloes hosted by lateritic residuum. Geochemical anomalies in lateritic residuum comprised of elements residually accumulated in stable primary minerals, and chemically dispersed elements hosted by secondary minerals, which may also accumulate residually. This horizon has developed by partial collapse, which entails both vertical and lateral movement, following chemical wasting. It may be regarded as essentially residual if movement due to collapse and colluviation amounts to only a few tens of metres (or even 100 or so, depending on the scale of exploration). It is this feature that makes laterite sampling such a powerful exploration tool, subject to correct identification of the origin and provenance of the material. The use of sampling lateritic residuum in Au exploration has been demonstrated in earlier projects (Smith *et al.*, 1992; Anand *et al.*, 1993), which included its effectiveness in sites where the lateritic residuum is buried by later sediments (*e.g.*, at Mt. McClure). Similar situations, in which lateritic residuum is patchily preserved, have been examined in this project at Bronzewing, Stellar, Harmony and Fender, although in the latter two, the cover is less than 3 m thick over mineralization. An important aspect of exploration procedures aimed at sampling buried lateritic residuum is the need to distinguish between residual and transported lateritic materials. Transported lateritic debris is a common feature of the sedimentary cover and may directly overlie either lateritic residuum (*e.g.*, at Bronzewing) or saprolite (*e.g.*, Golden Delicious, Quasar). Such debris may be genetically unrelated to the underlying material (*e.g.*, where the distance of transportation is considerable) and hence is generally less useful as a sample medium. It can usually be identified by its polymictic nature, the lack of pale, goethite-rich cutans on pisoliths and nodules and angularity of fragments. Where deposited directly over saprolite, the abruptness of contacts, possibly with mineralogical changes (*e.g.*, absence of resistant minerals such as talc and muscovite present in saprolite) are additional criteria. However, pisoliths and nodules that have developed in the sediments themselves, after deposition, may have prominent multiple cutans, a feature commonly observed in palaeochannels. Multiple cutans suggest a complex formational history and are rare in lateritic residuum.

Regoliths with thick colluvial cover. If colluvial sediments deposited during, or between, phases of deep weathering have attained thicknesses greater than a few metres, a seemingly complete, mature profile may develop, in which lower horizons have formed in residuum and upper horizons in colluvium. No such sites have been investigated in this project, but this situation does, however, occur over the Mt. Keith Ni deposit (Brand and Butt, 1995) and North Pit, Lawlers (Anand *et al.*, 1991).

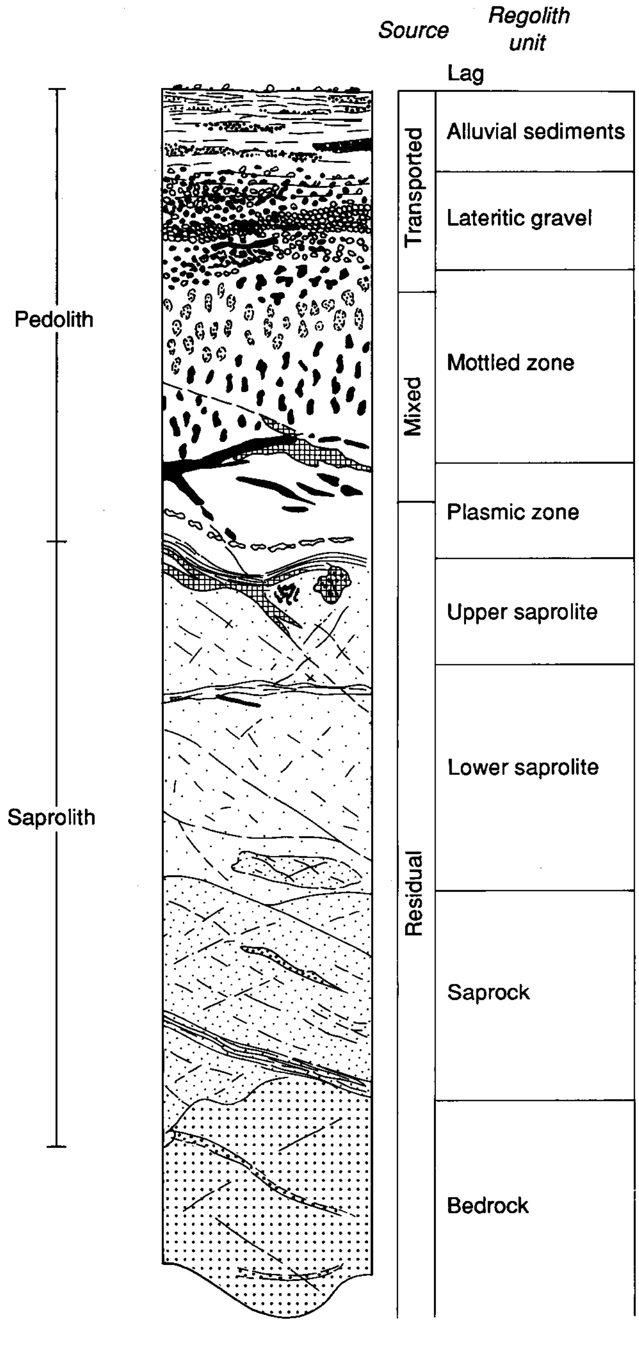


Figure 2.3: Generalized regolith stratigraphy developed over the MKD5 deposit, Mt. Keith (from Brand and Butt, 1995).

The Mt. Keith Ni deposit comprises disseminated Ni sulphides hosted by a serpentinized dunite, within a larger, lenticular peridotite-dunite komatiite body, the Mt. Keith Ultramafic Complex. The Complex is steeply dipping, approximately 1000 m thick, within a volcaniclastic sequence. The regolith, which has residual and transported components, is thickest over the mineralized dunite (to 120 m); the transported component is deeper here also and has units of differing provenance, composition and age. The unconformity between the residual and transported components is clear on the margins of the ultramafic unit, but indistinct in the centre and is apparently transgressed by the lateritic profile (Figure 2.3). A zone averaging 15 m thick, corresponding to the plasmic and mottled zones, has the signature of both the underlying ultramafic rocks and the overlying sediments. For example, there are marked increases in Fe_2O_3, Al_2O_3, Cu, Zn, Cr, As, Ti and Zr contents compared to the underlying saprolite that cannot be due wholly to residual concentration by textural collapse. In contrast, the MgO content decreases to less than 2%, marking the destruction of most serpentine. Nickel, Co, Mn and SiO_2 peak in the lower part of the plasmic zone and decrease markedly upwards, close to the contact with the mottled clay zone. Their mineralogy is dominated by goethite, hematite and kaolinite, with minor smectites, silica and Mn oxides. The distribution and thickness of the mottled zone suggest bedrock control on its development. It is thickest above the serpentinites compared to talc-carbonates and the wallrocks. The abundances of Ni, Cu, Co, Fe and Cr decrease progressively upwards, whereas those of Ti, Al_2O_3 and Zr increase upwards through the zone and reach their maximum concentrations close to the boundary with the overlying lateritic gravels. The lateritic gravels and duricrust are also thickest over the ultramafic rocks, but abundances of elements such as Al, Ti, Zr (high) and Cr (low) indicate a dominantly mafic or felsic origin.

The provenance of materials in the mottled zone and, locally, the upper plasmic zone, is enigmatic, since they have morphological, geochemical and mineralogical features consistent with both transported and residual components of the regolith. In comparison, the lateritic gravels have no geochemical signature of either the dunite or the Ni sulphides. It appears that the plasmic and mottled clay horizons have developed across the residual/colluvial unconformity and that the materials of which they are composed have become mixed by post-depositional processes such as slumping and churning.

2.4.3 Palaeochannel sediments

Occurrence and significance. The presence of palaeochannels (or "deep leads") has long been recognized as a feature of the regolith on the Yilgarn Craton. Good descriptions of the stratigraphy, and the occurrence of gold in deep leads of the Bulong-Kanowna district east of Kalgoorlie were given by Gibb-Maitland (1919). Palaeochannels are present at several sites studied during this project. They overlie mineralization at Bronzewing (Central Zone), Stellar and most sites in the Kalgoorlie-Norseman region (Lady Bountiful Extended, Kanowna QED, Kurnalpi, Steinway, Wollubar, Argo, Challenge-Swordsman). They also occur adjacent to the Harmony (Baxter) and Quasar deposits. The channels have importance because they may:

1. directly overlie and conceal primary or supergene mineralization in bedrock;

2. host supergene deposits of gold (and other commodities including uranium, base metals and industrial minerals);

3. contain geochemical or mineralogical dispersion products from mineralization in their catchment;

4. provide evidence for the age and evolution of the regolith and landscape.

The major channels are also very important aquifers, for potable and stock water north of the Menzies line and for processing of Au ores in the south.

The channels are of different ages and dimensions. The major trunk drainages may be of considerable antiquity, perhaps Permian or older, and are largely followed by the present systems, although there is some evidence for drainage capture and drainage reversal over this period (*e.g.*, van de Graaf *et al.*, 1977; Kern and Commander, 1993). Tributary drainages, however, may follow quite different courses and, although most occur in lower parts of the landscape, some, mostly smaller, channels are in more upland sites. Palaeochannels within the present drainage systems remain as aquifers where suitable sedimentary units (*e.g.*, calcrete, sands and gravels) are present. Detailed study of the regional distribution, stratigraphy and hydrology of these channels is beyond the scope of this project, although a number of contributory site investigations have been made. These sites are in several of the palaeodrainage systems, as follows (those in parenthesis studied in previous projects):

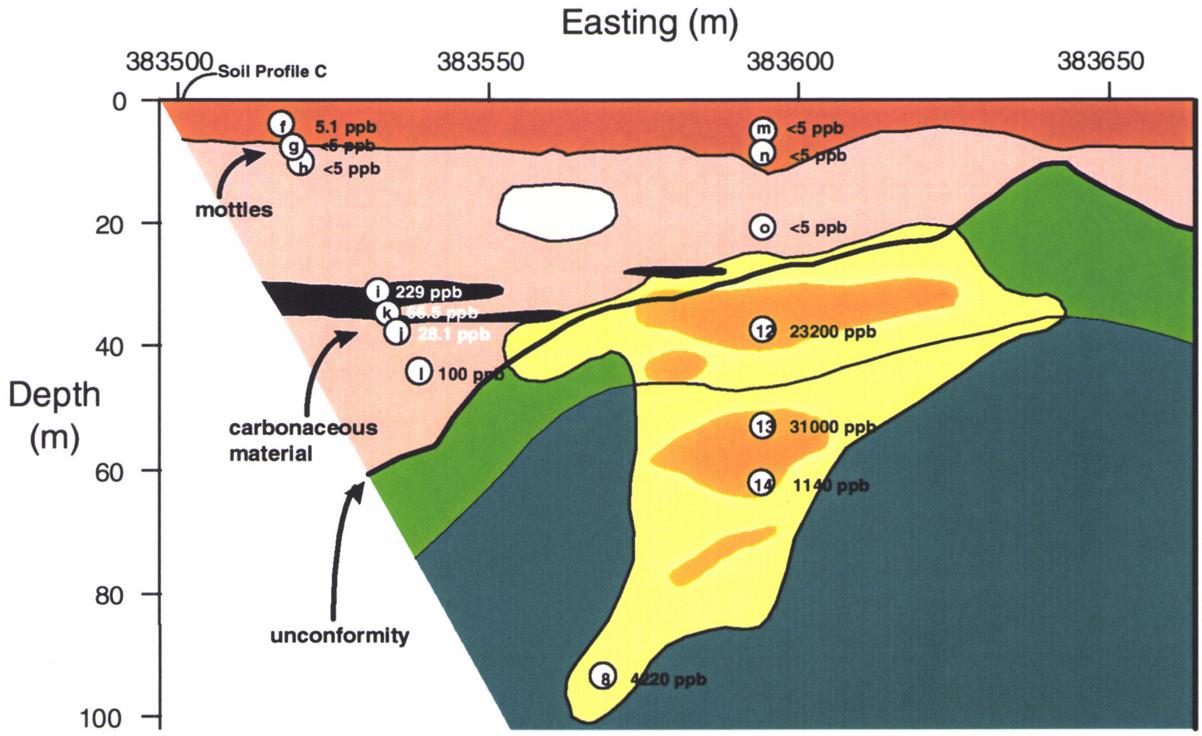
Cowan	Challenge-Swordsman
Lefroy	Argo
Roe:	Steinway, Wollubar, Kurnalpi, Kanowna, Lady Bountiful Extended, (Zuleika, Mulgarrie)
Carey	Bronzewing, (North pit, Lawlers)
Gascoyne	Harmony
Moore	Stellar, Quasar

An important feature of the channels and their sediments is their relationship with the deeply weathered regolith developed on the basement rocks. Most of the channels appear to be steeply incised into pre-existing residual regolith. Some overlie lateritic residuum, others contain detrital pisoliths and nodules in the basal sediments. In addition, the sediments themselves have been deeply weathered since deposition. They have strongly leached lower horizons (saprolite after reduced clay-rich sediments) and strongly mottled upper horizons, locally cemented to form duricrusts, which contain pisoliths formed *in situ*. The channels and sediments thus appear to date from a period (in the Eocene) between two episodes of deep weathering.

Lefroy and Cowan palaeodrainages

Palaeochannels in these districts are characterized by the presence of marine sediments and the widespread occurrence of reduced, commonly lignitic units. Investigations at Argo (Lefroy palaeodrainage) and the Mitchell and Challenge-Swordsman (Cowan palaeodrainage) within this project have largely confirmed the stratigraphic relationships established in the Lake Lefroy system by Clarke (1993).

The Argo palaeochannel crosses the southern part of the Au deposit. It has a maximum depth of 60 m and width of 400 m and appears to be flowing WSW towards L. Lefroy. The stratigraphy of the channel is shown in Figure 2.4 and Table 2.1. Dating of the sedimentary units is by analogy with the apparently equivalent units described by Clarke (1993, 1994). Gold mineralization at Argo is largely confined to the saprolite, with some lateral dispersion at the unconformity. Gold particles in the basal sands are Ag-rich, with Ag-poor rims and are thought to be detrital, eroded from then outcropping primary mineralization (Woolrich, 1994). A similar origin is considered probable for Au-enrichment in the lignites higher in the sequence, although these have not been studied in detail. Primary mineralization is shallow dipping and it is uncertain whether or not the sub-horizontal enrichments at the weathering front, and higher in the saprolite, are supergene. Weathering to form the saprolite is assumed to be pre-Eocene but, given the reducing nature of the organic, sulphidic sediments, post-depositional Au mobilization in either the saprolite or lower sediments is unlikely. Accordingly, a direct surface expression of the mineralization would seem improbable - as borne out by detailed studies at the site (Section 3.2).



Calcareous red-brown sandy clay, becoming non-calcareous with depth. Siliceous hardpan commonly at base.

Puggy lacustrine clays of various colours (yellow, red and/or grey), with lenses of lignite and/or spongolite. Quartz sands and gravels form basal unit in deepest part of channel.

Spongolite

Lignite

Saprolitic clays with some partially weathered rock.

Fresh rock/saprock dominated by dolerite.

Moderately mineralized (Au 1-10 ppm)

Strongly mineralized (Au >10 ppm)

Sample points

Figure 2.4: Regolith stratigraphy, Au mineralization and Au contents of selected samples, section 52560N at Argo (after Lintern and Gray, 1995b).

Table 2.1: Stratigraphy of the Argo palaeochannel (after Woolrich, 1994; Lintern and Gray, 1995b). Formation names, dates and depositional environments interpreted from Clarke (1993, 1994).

Depth (m)	Formation	Age	Description	Environment
0-0.2		Quaternary	Sandy soil, probably aeolian	Semi arid
0.2-5.0		Pliocene to Holocene	Red calcareous clays and sands, with diffuse impregnations and nodules of carbonate	Semi-arid
5.0-8.0	Revenge	Oligocene to Miocene	Fine to medium grained ferruginous sands, locally cemented by Fe oxides	Fluvial and fan systems
8.0-13.0			Grey green clays, moderately to intensely mottled	Shallow lake sediments
13.0-18.0	Princess Royal Spongolite (Tuketja marine transgression)	Late Eocene	Spongolite. White-pink silt with 50-60% siliceous sponge spicules	Tidal channel or estuary
18.0-21.0			Pale grey to white silty clay, locally lithified	
21.0-27.0			Spongolite. White silt with 50-60% siliceous sponge spicules	
27.0-49.0	Pidinga	Early to Late Eocene	Pale to dark grey plastic clays with abundant carbonaceous fragments and thin (1-2 m) lignite beds. Sulphides (pyrite) associated with carbonaceous matter	Flood plain and alluvial deposits, draining from rainforest
49.0-60.0			Basal gravel, sand and silt, with silty lignite beds. Sub-angular to sub-rounded quartz gravel and sand; sulphides (pyrite) associated with carbonaceous matter	Fluvial channel draining from rainforest
>60.0			Clay-rich saprolite, after dolerite	

The stratigraphy of the Mitchell and Challenge-Swordsman channels have not been studied in detail in the project, but a summary of the stratigraphy appears in Table 2.2. Gold mineralization is present in the basal sandy horizons of the channel sediments and in the underlying saprolite, but the nature of the Au occurrence, its distribution and relationship to the weathering history have not been studied. Again, however, the presence of lignite and reducing sediments at the base of the channel appears to have precluded post-depositional Au mobility and, therefore, direct surface expression of the deposits.

Table 2.2: Stratigraphy of the Challenge-Swordsman palaeochannel (after data supplied by Resolute-Samantha Ltd., Lintern *et al.*, 1996). Formation names, dates and depositional environments interpreted from Clarke (1994).

Depth (m)	Formation	Age	Description	Environment
0.0-2.0 2.0-4.0		Quaternary	Calcareous red-brown sandy clays, with carbonate nodules Non-calcareous red-brown clays	
4.0-10.0 10.0-16.0	?Revenge	Oligocene-Miocene	Strongly mottled clays; some ferruginous/siliceous cementation Puggy clays, red-yellow mottling, some sandy lenses	Shallow lake sediments Fluvio-lacustrine
16.0-35.0 35.0-40.0	?Werrilup	Early to late Eocene	Pale to dark grey plastic clays; carbonaceous fragments locally abundant; some thin lignite beds. Basal gravel, sand and silt, with silty lignite beds. Sub-angular quartz gravels and sand.	Flood plain and alluvial to estuarine or shallow marine deposits, draining from rainforest Fluvial and estuarine draining from rainforest
>40.0			Saprolite	

Roe palaeodrainage

The Steinway, Wollubar, Kurnalpi, Kanowna and Lady Bountiful Extended sites studied during this project, as well as Mulgarrie and Zuleika investigated during Project 241A, are all situated in the east-draining Roe palaeodrainage. The sediments in this system are non-marine, except where the drainage originally entered the Eucla basin, over 150 km east of Kalgoorlie. The stratigraphic and sedimentological features of Lady Bountiful Extended and the Kanowna QED deposits by Dusci (1994), Dell (1992) and Ladhams (1994) typify those of the other sites.

The palaeochannels at Lady Bountiful Extended were incised into weathered Archaean granitic rocks. They form a dendritic system of third to fourth order channels that vary from 90 to 400 m wide, a depth up to 40 m and a gradient of about 30 m in 1500 m (Devlin and Crimeen, 1990; Dusci, 1994). A generalized stratigraphy is given in Table 2.3 and illustrated in Figure 2.5. The sediments are unusually sandy compared to most palaeochannels that have been studied, because of the granitic bedrock, and thus many more sedimentary features have survived post-depositional weathering. The Kanowna channels were incised into weathered Archaean volcaniclastic and ultramafic rocks. They form a dendritic system of third order channels about 30 m deep (Ladhams, 1994). They are more clay-rich than Lady Bountiful, largely due to the provenance of the sediments, and their stratigraphy (Table 2.4) is similar to the majority of channels associated with Au mineralization in the Kalgoorlie region. Post-depositional weathering, particularly the strong mottling in the clays, has destroyed most sedimentary features. However, there is some evidence that the lower units contain detrital ferruginous material derived from the erosion of pre-existing lateritic regoliths. Some may have been partly destroyed (dissolved) in an originally reducing environment. Subsequently, however, pisoliths have developed *in situ*, within the clays.

Table 2.3: Generalized regolith stratigraphy of the Lady Bountiful Extended palaeochannels (after Dusci, 1994). Formation names and dates interpreted from Kern and Commander, 1993; Clarke, 1994.

Depth (m)	Formation	Age	Description	Environment
0.0-2.4		Quaternary	Sandy clay loam (0.3 m) over calcareous sandy loam. Abundant hematite and maghemite nodules	Semi-arid
2.4-3.2		?Pliocene	Polymictic gravels; ferruginous nodules, pisoliths and granules; quartz and lithic fragments	Sheetwash and ephemeral drainage; semi-arid
3.2-7.4	? Revenge	Miocene-Oligocene	Mottled sandy clays with trough-bedded lenses of polymictic gravels consisting of ferruginous nodules, pisoliths and granules, quartz and lithic fragments	Lacustrine to fluvial; semi-arid flood
7.4-21.0	Perkolilli Shale	Late Eocene (??Tuketja Transgression)	Mottled and mega-mottled clays, merging gradationally downwards to grey kaolinitic silty clays, with some smectite; scattered pisoliths at base	Lacustrine to swampy
21.0-27.0			Massive, white kaolinitic clay, in sharp contact with underlying sand. Some interbeds of sandy clay	Lacustrine
27.0-30.0	Wollubar Sandstone	Middle to Late Eocene.	Poorly sorted quartz sand, with 5% clay. Some cross-bedding.	High energy fluvial
30.0-33.0		(??late phase of Tortachilla Transgression)	Matrix (clay) supported sand and up to 20 cm basal lag/conglomerate. 30-60% kaolinite with angular to sub-rounded quartz. Cyclic, fining upward units, about 0.5 m thick. Some rounded reworked gravels.	Low energy fluvial; probably proximal to source
>30 m	Liberty granodiorite		Granite saprolite	

The sandy and clay-rich units in the channels are equated with the Wollubar Sandstone and Perkolilli Shale, respectively. These have been dated from palynological evidence in the type areas as Middle to Late Eocene (Kern and Commander, 1993), but the sediments at these sites, and all others investigated in this area, are oxidized and all organic matter has been destroyed. However, the common occurrence of ferruginized plant matter as nuclei to the *in situ* pisoliths suggest that they were originally organic rich, possibly locally lignitic, and strongly reducing.

Gold mineralization associated with channels in the Roe palaeodrainage occurs as sub-horizontal, concentrations of supergene Au in the clays (*e.g.*, Kanowna) and basal sands (*e.g.*, Kanowna, Lady Bountiful, Zuleika,) of the sediments, or in the underlying saprolite (*e.g.*, Lady Bountiful, Baseline, Steinway (see Figure 2.6), Greenback). The last are commonly directly associated with a primary source, although this may be minor and uneconomic. Because of the evident secondary mobility of Au, including the presence of dissolved Au in groundwater in some channels, geochemical expression of buried mineralization is possible in the sediments or the soils. This was investigated closely at several sites, but at none has it been shown that there is a direct relationship between Au abundances in soil or shallow sediments and underlying mineralization. Where a surface anomaly does appear to be present (*e.g.,* Steinway) this is thought to be coincidental, due to deposition of Au-enriched gravels from an outcropping deposit upslope (Section 3.13).

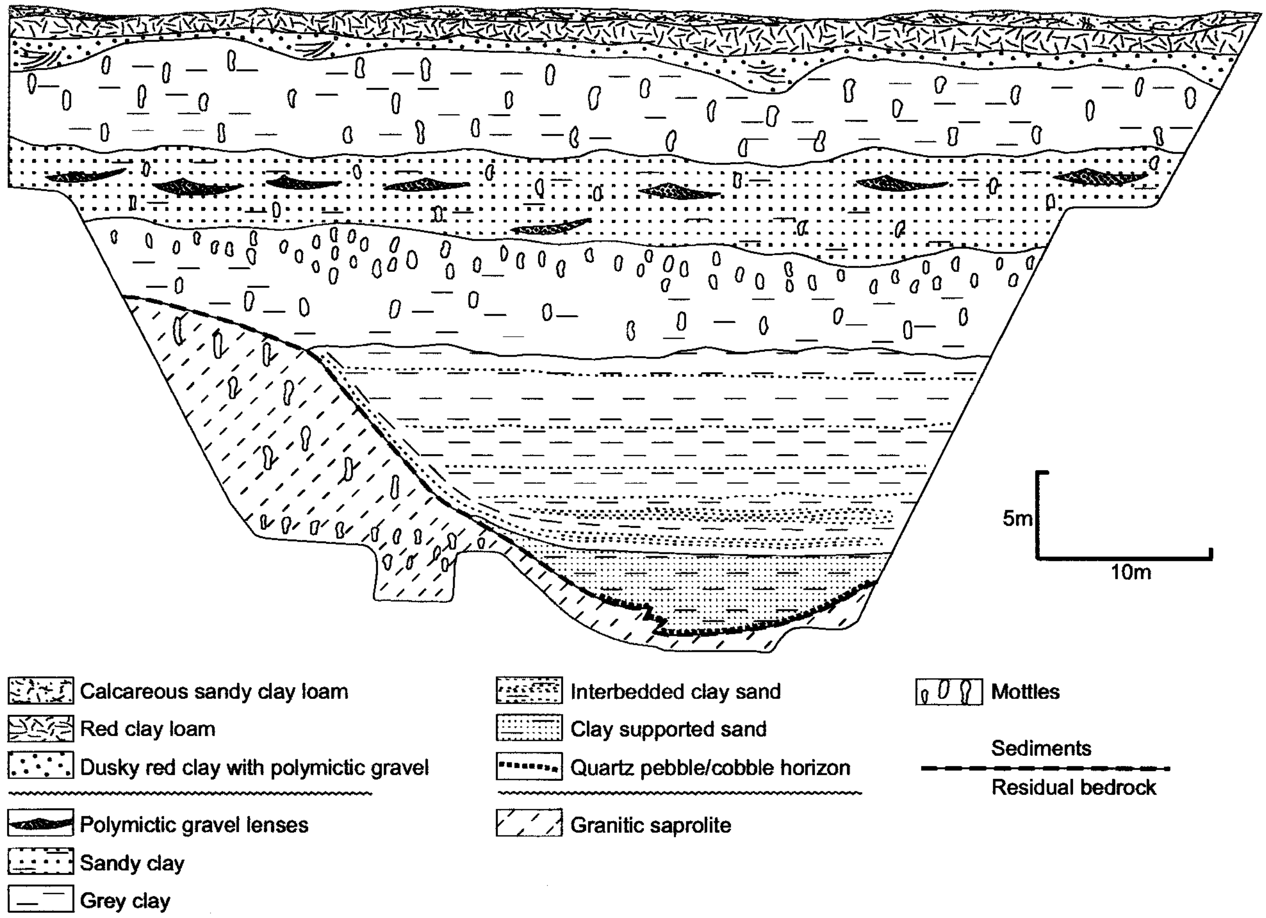
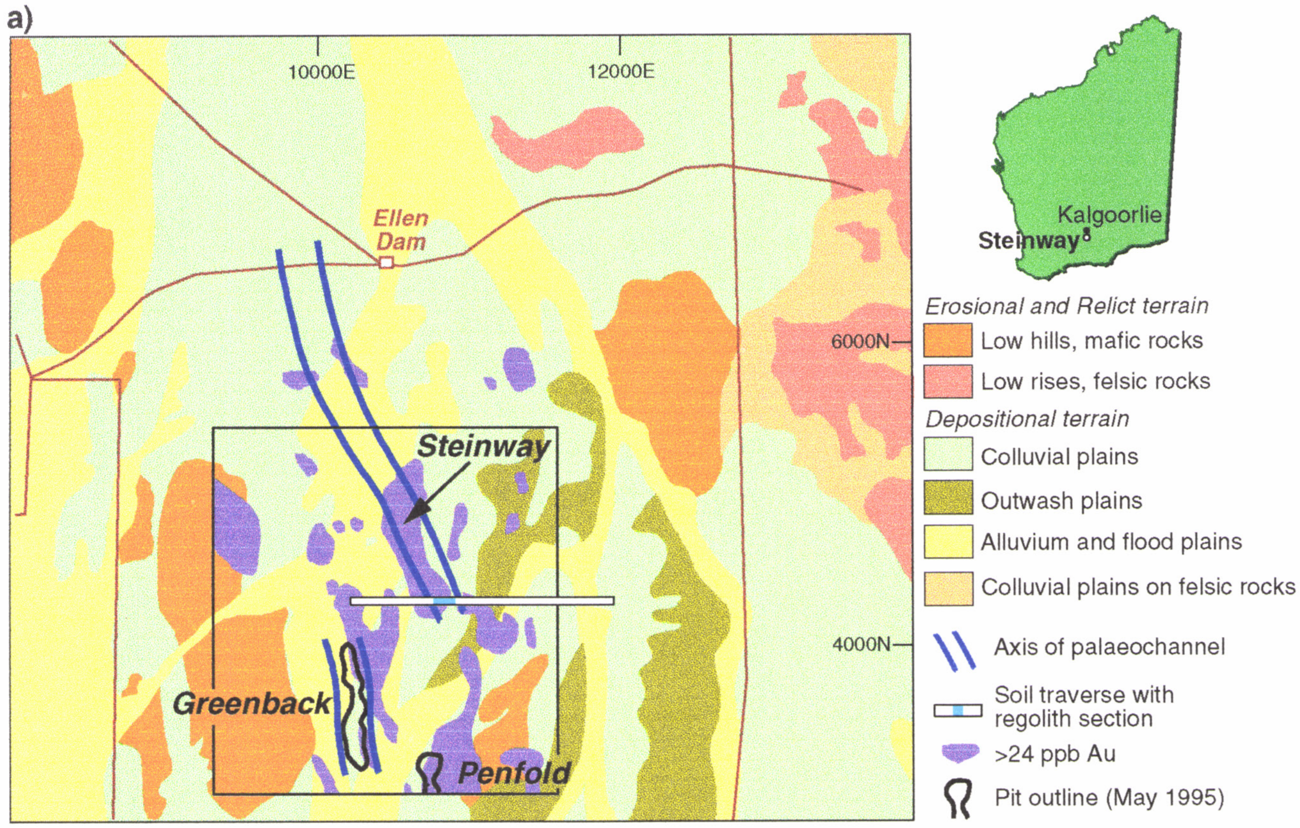


Figure 2.5: Section across the west face of South Palm pit, Lady Bountiful Extended (after Dusci, 1994).

Table 2.4: Generalized regolith stratigraphy of the Kanowna QED palaeochannels (after Ladhams, 1994). Formation names and dates interpreted from Kern and Commander, 1993.

Depth (m)	Formation	Age	Description	Environment
0.0-2.0		Quaternary	Calcareous red clay soil in silty clay with ferruginous granules, quartz.	Sheetwash; semi-arid
2,0-4.0			Non-calcareous red clays and polymictic gravels - ferruginous granules, quartz and lithic fragments	Sheetwash and ephemeral drainage; semi-arid
4.0-22.0	Perkolilli Shale	?Miocene to Late Eocene (??Tuketja Transgression	Mottled and mega-mottled massive white to grey clay. Sedimentary features mainly destroyed.	Lacustrine
22.0-23.0	Wollubar Sandstone	Middle to Late Eocene (??late phase of Tortachilla Transgression)	Pisolitic, nodular and quartz gravels in grey to red clay. Ferruginous materials appear to be detrital. Unconformable upper and lower contacts.	Moderate/high energy fluvial
23.0-26.0			Light grey matrix (clay) supported, medium grained, sub-angular to sub-rounded sands; some sub-rounded quartz gravel.	Moderate/light energy fluvial to lacustrine
26.0-26.5			Clay-rich conglomerate, quartz sand and pebbles.	Moderate energy fluvial
>26.5			Saprolite	



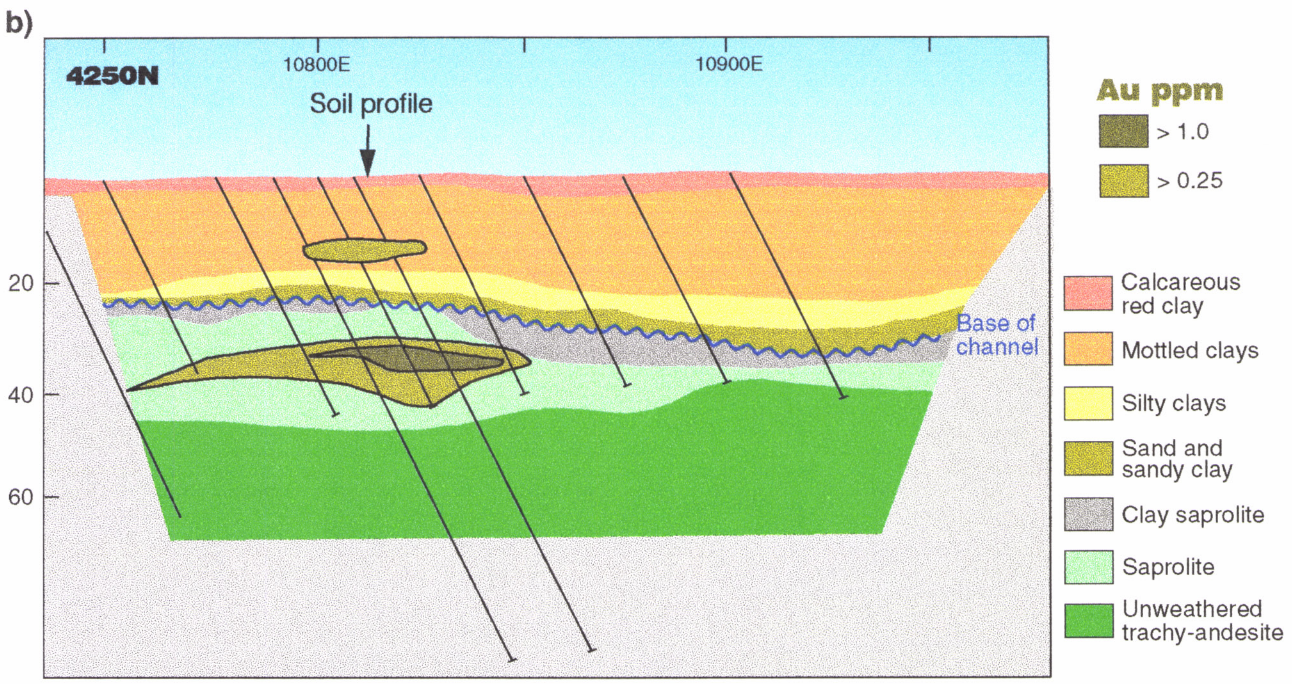


Figure 2.6: Regolith map (a) and stratigraphy (b) of the Steinway area showing the location of the soil anomalies, palaeochannels and mineralization (after Gardiner, 1993 and company data).

Palaeodrainages of northern Yilgarn

The channels of the northern Yilgarn have been less well studied. Although there are palaeochannels over or adjacent to several of the deposits studied in this project, none appear to have played a significant role in the secondary accumulation of Au. There may have been some dispersion of W into channel sediments at Harmony, possibly at the time of sedimentation but there is no significant Au concentration within or beneath the channels. The stratigraphy and post-depositional weathering is broadly similar to that in the Roe palaeodrainage, namely a lower basal sand and gravel unit in the axis of the channel, overlain by a thick sequence of clay-rich sediments, strongly over-printed by ferruginous mottling. The stratigraphy of the channel adjacent to the Harmony deposit appears to be typical (Table 2.5; Figure 2.7). This is one of two channels, both steeply incised into Proterozoic bedrock. They are fairly shallow (10 and 30 m) and are close to the divide between the present Gascoyne and Murchison systems. The thick, now mottled, clays appear similar to the Perkolilli Shale of the Roe system, but it is uncertain whether they were originally carbonaceous - the ferruginous nodules containing wood fossils may themselves be detrital. Although not specifically investigated, the Mt. Magnet and Bronzewing channels probably have similar features. Dolomitic lenses, 5-6 m thick, equivalent to the strong dolomitic mottling at the base of the clay unit at Harmony are present at Bronzewing, but not seen at Mt. Magnet, were not seen elsewhere. This mottling is unlikely to be equivalent to the sedimentary dolomite in the main Roe palaeodrainage, since it would not have survived post-depositional weathering. The time of dolomite emplacement is unknown, but is a feature of later arid phases. The dolomites differ from valley calcretes of the region, which are surficial deposits in major drainages, precipitated at shallow water-tables in unconfined aquifers.

Table 2.5: The stratigraphy of the channel adjacent to the Harmony deposit, Baxter (after Robertson *et al.*, 1996a).

Depth (m)	Description	Environment
0.0-2.0	Gritty colluvium: round to angular nodules, ferruginous lithorelics, quartz	Sheetwash and ephemeral drainage; semi-arid
2.0-4.0	Silty colluvium: nodules, ferruginous lithorelics in silty matrix; Mn oxides on partings	Sheetwash and ephemeral drainage; semi-arid
4.0-8.0	Silty-sandy colluvium: nodules, ferruginous lithorelics, quartz, in silty matrix	
8.0-13.0	Mottled plastic clay: kaolinite and minor smectite; abundant hematitic pisoliths and lateritic clasts.	Lacustrine to swampy
13.0-15.0	Mottled clay: kaolinite, minor smectite; irregular goethitic mottles	
15.0-19.0	Clay: kaolinite, minor smectite; some grit layers	
19.0-21.5	Ferruginous clay: kaolinite, minor smectite. More Fe-rich with depth; some Mn oxides	
21.5-26.0	Dolomite-mottled smectite clay; minor goethite and muscovite.	
26.0-30.5	Ferruginous grey clay: smectite>kaolinite; large compound dolomite-goethite-hematite mottles.	
30.5-32.0	Dolomite-mottled smectite clay	
32.0-34.5	Clay: brown, with kaolinite and smectite. Some dolomite, Mn oxides	
34.5-36.0	Fine to medium grey sand; some clast quartz, quartzite	Moderate energy fluvial
>36.0	Saprolite after metavolcanic rocks	

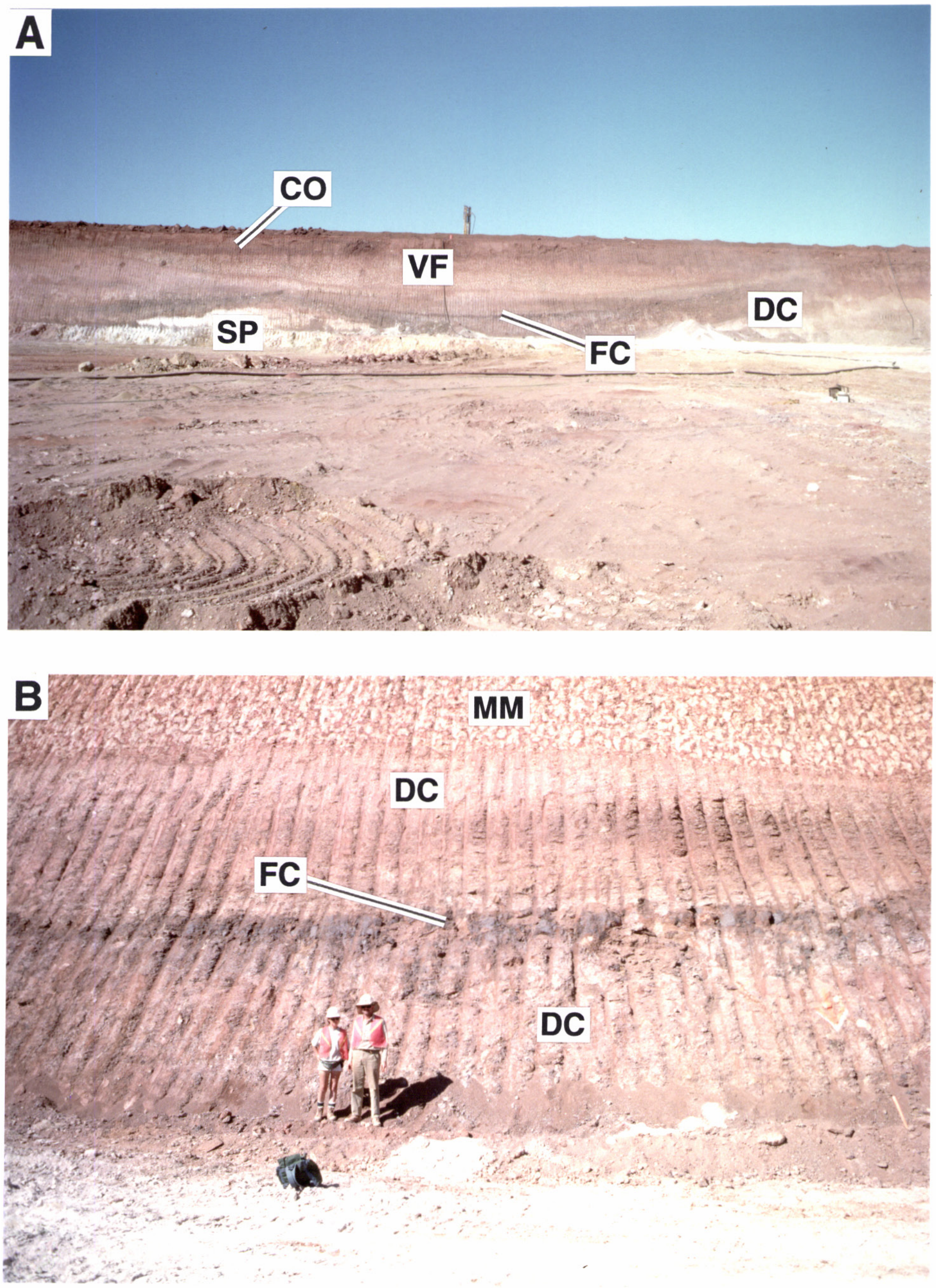


Figure 2.7: (a) A section across the Harmony valley-fill sediments (VF) as they appear in the northeast wall of the Harmony pit. This is underlain by duricrust (DC), ferricrete (FC) and saprolite (SP) and overlain by colluvium (CO).

(b) Detail of the 'mega-mottled' smectitic clays (MM) filling the Harmony palaeovalley and the thin ferricrete layer (FC) in the duricrust (DC) beneath the valley-fill clays.

2.5 Sediments deposited during arid periods

2.5.1 Erosion and deposition

A wide range of sediments is present overlying older transported and residual regolith on the Yilgarn Craton. The sediments have been derived from increased erosion following the change to more arid climates, in part a result of instability caused by a reduction in the vegetative cover. Although certain regolith units have been indurated by irreversible dehydration (*e.g.,* lateritic duricrust) or by introduced cements such as silica and Fe oxides (*e.g.*, silcrete and ferricrete), much of the regolith is soft and unconsolidated and hence susceptible to severe erosion by water (and wind), even in areas of low relief. Because of the reduced rainfall, much of the drainage is incompetent and sediments remain in the landscape, further reducing the relief. This particularly applies to inland areas where erosion is to the base level of the playas. Near the coast in the south, but extending far upstream in the west, rivers have more competent drainage, erosion is to the base level of the ocean and there is some loss of sediment. This influence extends to a nick-point (the "Meckering Line": Figure 1.1).

Much of the rainfall in the semi-arid interior is spasmodic but heavy, and excess water runs off as a fairly continuous film or sheet, washing across the surface. Sheetwash is a dominant process of erosion on surfaces of low relief in all but thickly vegetated regions. When the uppermost horizons are saturated and soft, run-off increases and becomes erosive. The process is able to transport clays, silt and fine sand even in rainforests, but in arid areas, during heavy rainstorms, gravel and small pebbles may be moved across slopes of less than 1°. Fine particles are carried in suspension and coarser fractions as a traction load. Water flow is discontinuous, changing with surface irregularities and rainfall intensity. Networks of braided rills and wash channels can develop and, depending upon the local topography, may converge into larger washes or diverge across flatter depositional areas. Such networks are only temporary and, from season to season, the whole surface is affected. The resultant sedimentary sequence consists of a series of discontinuous, mostly poorly-sorted, beds, commonly cross-cut by infilled scours and channels. These sediments are commonly referred to as *colluvium* (or colluvium-alluvium), and are seemingly the most widespread and abundant type of transported overburden on the Yilgarn. Better sorted and mostly finer grained sediments (silty clay and clay), generally associated with more defined drainages and in valley axes and flood plains, are referred to as *alluvium.* Around playas, these merge with mostly clay-rich lacustrine sediments, which have a strong evaporitic component at the surface, dominantly gypsum and halite. Groundwater or valley *calcretes* are present as narrow lenticular units, 5-30 m thick, in drainage axes north of the Menzies Line. There is a significant *aeolian* component in many soils, commonly in the finer (<250 μm) fractions. Fully aeolian deposits are confined to the margins of the playas, where sand and gypsum (kopi) dunes are present, particularly on the eastern sides; some sand dunes are present on the more extensive sand plains on granitic rocks.

The research sites in this project are all in areas dominated by colluvium and/or alluvium. There were no sites within playas, nor any with a significant cover of aeolian material, except for a thin sand cover at Argo and Apollo. However, although the colluvial and alluvial sediments are broadly similar throughout the semi-arid Yilgarn, there is an important difference in the soils and upper horizons across the Menzies Line. In the south, these horizons commonly comprise calcareous and non-calcareous red clays whereas, to the north, they are lithosols and red-brown hardpan.

2.5.2 Southern Yilgarn

Sites south of the Menzies Line, investigated in this and previous projects, generally have colluvial sediments less than 10 m thick, overlying saprolite or, more commonly, the mottled clays of the palaeochannels. At Kanowna Belle and Wombola (Anand *et al.*, 1993), the colluvium consists of multiple units of poorly sorted clays, silts and polymictic gravels, overlying saprolite and mottled zone. At Steinway, Kanowna QED, Lady Bountiful Extended, Kurnalpi, Wollubar and Challenge-Swordsman, similar material overlies palaeochannel sediments, with the coarser units commonly infilling scours and channels that have cut into underlying colluvium or channel clays. The colluvium is derived from the erosion of lateritic regoliths and the gravels consist dominantly of fragments of pisoliths, nodules and ferruginous lithorelics. The matrix generally comprises silty kaolinitic clays, but at Lady Bountiful Extended and Mt. Celia, where the source rocks are mainly granitic, it tends to be more sand-rich. At Mt. Celia, the source of the sediments appears to have been less lateritic and there are few ferruginous clasts.

Pedogenic carbonates are important sample media in the region, but it has become increasingly evident in this project that the provenance of the soil parent material is significant in determining their Au content. Where derived from regoliths developed on mineralized rocks, the coarse, ferruginous, component of the soils may be enriched in Au and other pathfinder elements, potentially giving rise to displaced or false anomalies. At Steinway, the Au anomaly in calcareous soils is probably reflecting the presence of Au-rich colluvial gravels derived from the nearby, outcropping Penfold deposit, rather than the underlying mineralization (Section 3.13). Such a result gives misleading support for the use of soil (carbonate) sampling in such depositional environments.

Alluvial clays and sandy clays, possibly lacustrine in part, are abundant in broad valleys and plains surrounding playas. At Apollo and Argo, sands and sandy clays form a uniform cover about 5.0 m thick over saprolite and palaeochannel sediments. These appear to be fluvial and fan sediments on the lake margin (Woolrich, 1994), and may be time-equivalents of the Pliocene-Holocene Roysalt Formation (Clarke, 1993), which are interpreted as having been precipitated in semi-arid conditions similar to those prevailing at present

Soils in greenstone terrains in the Kalgoorlie region, and the southern Yilgarn generally, commonly consist of up to 5 m of structureless acid red clays that become alkaline and strongly calcareous in the upper 2 m. Small, ferruginous granules occur throughout and the clays are smectitic towards the base. These soils are developed over residual, semi-residual and transported substrates, but their origin is uncertain. Despite the inferred long period of aridity, however, pedogenic carbonates are rarely found below 2 m, even in depositional areas, suggesting that any older carbonates have been dissolved. Precipitating carbonates may both displace and replace the host matrix, including saprolite and ferruginous lateritic materials, whether *in situ* or transported. It is possible, therefore, that some red clays are a product of the chemical and physical effects of the precipitation and later dissolution of pedogenic carbonates in these materials. The presence of smectites might also permit churning and homogenization of the clays.

2.5.3 Northern Yilgarn

Sites north of the Menzies Line investigated in this and previous projects generally have colluvial and alluvial sediments up to 20 m thick, overlying lateritic residuum, saprolite or the mottled clays of the palaeochannels. Typical sedimentary relationships are illustrated in Figure 2.8. Colluvium and alluvium are derived from the erosion of lateritic regoliths and generally consists of polymictic gravels, dominantly quartz and fragments of pisoliths, nodules and ferruginous lithorelics, in a silty clay matrix. In places, the sediments may become finer grained, locally with clay-rich horizons, and elsewhere, there may be coarse, mostly poorly-sorted gravelly lenses and channels, consisting of rounded pebbles of quartz and lateritic debris, indicating alluvial environments. In many instances , the lower horizons consist dominantly of detrital pisoliths and nodules, which may overlie either lateritic residuum (*e.g.,* Bronzewing, Stellar, Harmony) or mottled clays and saprolite (*e.g.,* Golden Delicious). Identification of the exotic origin of this material is essential, because transported gravels may only be useful sample media if present in low energy sediments, indicating a proximal source. Commonly, the proportion of ferruginous lateritic debris decrease upwards, which is interpreted as a consequence of general erosion of lateritic regoliths, essentially inverting the stratigraphy of the regolith.

The composition of the sediments broadly reflects that of the catchment. Thus, at Fender, the colluvium-alluvium is quartz-kaolinite rich and contains abundant feldspars, and is derived from deeply eroded granitic rocks about 1 km to the west. The abundances of elements commonly associated with Au mineralization are low. Ferruginous materials are a small component of the sediments, but those in the lower two or three metres, in a low-energy silty clay unit, are locally derived and indicate the proximity of mineralization. Where sediments are derived dominantly from greenstone rocks, they may contain exotic Au-bearing components, usually ferruginous clasts. This may give rise to sporadic anomalous samples, such as at Bronzewing, an irregularly distributed background, *e.g.*, <5-12 ppb, at Golden Delicious, indicating derivation from a Au-bearing province, or a more pervasive background enrichment (*e.g.*, about 50 ppb Au, with local maxima to 150 ppb at Quasar), sourced from a specific well-mineralized district.

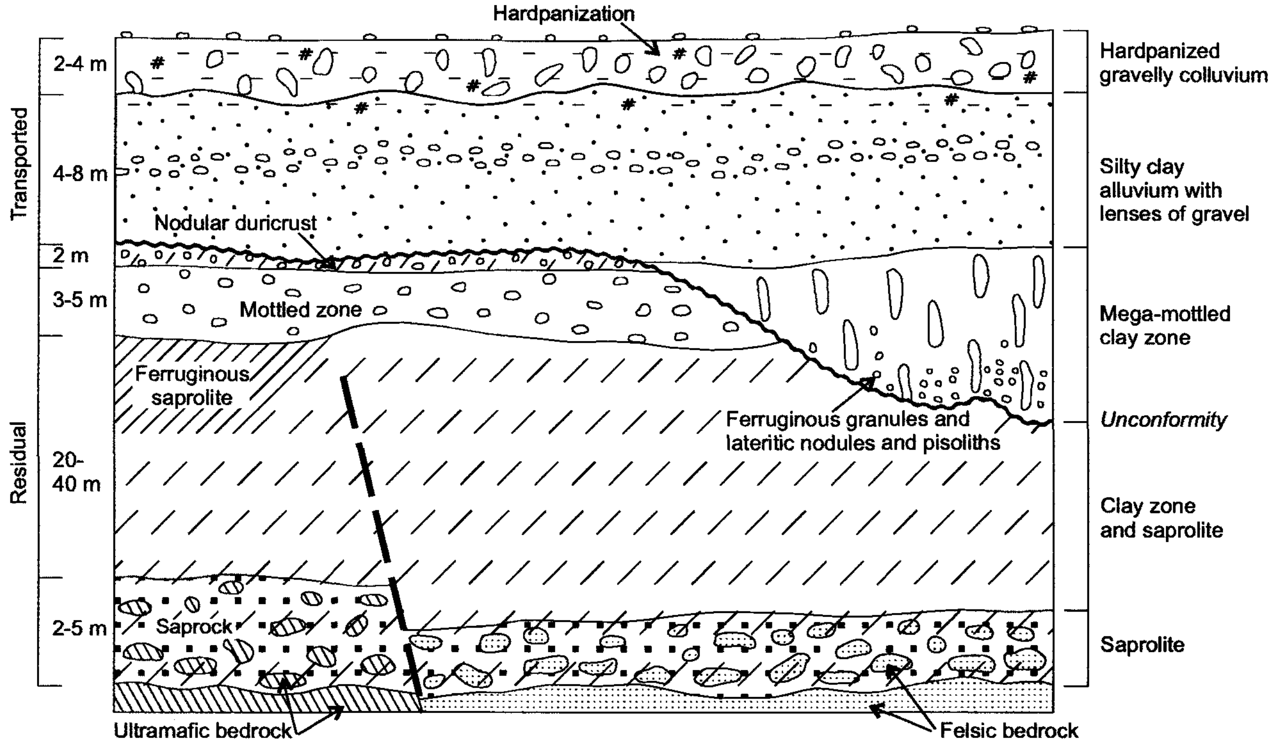


Figure 2.8: Regolith stratigraphy, Stellar Pit (after Robertson *et al.*, 1994).

2.6 Sources of sediments

The sedimentary record in the palaeochannels and colluvial-alluvial plains bears ample evidence that weathering products have repeatedly contributed to the formation of sediments since the Eocene. The composition of sediments depends on the nature of the regolith in the source area that is supplying detrital material. The stratigraphy and composition of the sediments suggest that, prior to the pre-Eocene, the regoliths mantling the landscape of the Yilgarn Craton not only included profiles with lateritic residuum but others having thick, uniformly Fe oxide-stained, red clay soils. These profiles developed in different sites in response to differing geological and topographic conditions. Duricrusts were developed principally on mafic and ultramafic lithologies, mainly in areas of low relief, whereas the red soils were probably largely restricted to felsic lithologies on well drained upslopes. These red soils, also known as latosols, ferrallitic soils or ferrisols have been reported from the other parts of world, developed under humid tropical or equatorial climates in regions covered by rain forest, particularly on well drained upper slopes (Chauvel, 1977). These soils do not harden upon exposure to air; Fe distribution is very homogenous and concretions are absent or nearly so.

The occurrence of transported kaolinitic clays in palaeochannels, valleys or alluvial plains, commonly overlain by later gravelly colluvium, suggests that such red clays were the principal source of sediments during the Eocene. This conclusion is supported by the absence or generally low abundance of lateritic gravels in the lower units in palaeochannels. This is not surprising because red soil profiles would be more susceptible to erosion than the duricrust capped profiles (although it could be argued that the gravels might dissolve in the reducing environment produced by the organic, clay-rich sediments). Thus, much of the filling of the palaeochannels and valleys is probably derived from the erosion of kaolinitic red soil profiles, with a few lenses of ferruginous gravel derived from duricrust. Smectite-rich grey clays in the palaeochannels may have been derived from the lower parts of the eroded weathering profile; alternatively, they may indicate that these profiles developed under less humid conditions than implied above or that the smectites are authigenic, forming under semi-arid conditions since sedimentation.

The red clays appears to have been the source of Fe forming the mega-mottles. The bulk Fe_2O_3 contents of red clay soils in the Kalgoorlie region and the mega-mottled sediments are very similar (10-12%). This suggests that the mega-mottles have formed through the mobilization and segregation of Fe by root action and/or reducing groundwaters. The cylindrical, locally branching form of the mottles, and the presence of fossil wood in authigenic pisoliths attest to the influence of organic matter.

The gravel-rich, colluvial sediments in the upper parts of the channel sequence indicate derivation from duricrust-capped profiles, including some that may have developed during and after the channel clays were deposited. This phase of erosion was probably triggered by the combined effects of minor tectonism and the trend to a generally drier climate since the Late-Miocene. Despite the protection provided by duricrusts, decreased vegetation and channelling of surface drainage have led to slope instability and erosion of the duricrust-capped profiles in most areas of the Yilgarn Craton. The resultant detritus may overlie pre-existing erosional areas of fresh and weathered basement rocks, as well as depositional environments, including the mega-mottled, clay-rich sediments in the palaeochannels. In many instances, a stratigraphy is developed in the sediments which is inverted in relation to the residual regolith profile, so that materials derived from the upper, ferruginous parts of the residuum occur at the base of the colluvial-alluvial cover.

Very generally, soils in the northern Yilgarn and environs have poor-horizon differentiation and have compositions that closely reflect those of their immediate parent material, whether this is residual or transported. In depositional regimes, the surface is commonly strewn with a polymictic lag and has a thin (10-30 cm, rarely greater than 50 cm) friable soil over red-brown hardpan. The soil may have a relatively higher content of silty clays, particularly in flatter areas in outwash plains, and a minor organic component to the top 10 cm. Hardpan development is ubiquitous, characterized by the partial replacement and cementation of the matrix and some clasts of the sediment by hyalite (opaline silica), a broadly, sub-horizontal, laminar structure and Mn oxide precipitation on partings. Such "hardpanization" may vary from less than 1 thick (Fender) to over 8 m (Bronzewing), and affect both sedimentary and residual units. Thus, hardpan may form in transported and residual lateritic gravels, in colluvium and in saprolite, and must be regarded as a modification of a pre-existing regolith unit, rather than as a specific horizon.

2.7 Post-depositional modification

Sediments have been modified by each of the principal weathering episodes that has occurred since their deposition, assuming that their thickness is less than the depth to the weathering front. Thus, the deepest units of the Permian glacigene sediments and the Tertiary channel sediments seem to have been unaffected by post-depositional weathering, whereas shallower units have been strongly oxidized.

The principal modifications and the units affected are as follows:

Period	*Climate*	*Weathering*	*Youngest units affected*
Quaternary	Semi-arid to arid; cool during glacial maxima, temperate to warm during interglacials	*South*: pedogenic carbonate precipitation *North*: silicification and hardpan formation; groundwater calcrete precipitation	All recent sediments, especially colluvium derived from truncation of lateritic regoliths;
Pliocene to Mid-Miocene	Warm to sub-tropical; aridity increasing.	Mottling; leaching associated with salinity, lower water-tables	Colluvium, alluvium and lacustrine sediments
Mid-Miocene to Late Eocene	Warm to sub-tropical; seasonally humid	Lateritic weathering; intense mottling and leaching	Palaeochannel sediments
Early to Late Eocene	Warm to sub-tropical; seasonally humid	Lateritic weathering; erosional and depositional events associated with marine incursions	Colluvium/alluvium deposited contemporaneously with weathering
Mesozoic	Temperate to warm; humid	Lateritic weathering	Permian glacial sediments; Archaean and Proterozoic basement

2.8 Identification of residual and transported components

The following characteristics may be used to distinguish sedimentary units and sequences from residual regolith materials:

Sediments:
Polymictic gravels
Fractured ferruginous fragments
Maghemite at depth - indicates material once at the land surface
No cutans on pisoliths - unless pisoliths developed *in situ* in sediment
Change in resistate mineralogy - *e.g.* mica, talc
Presence of weatherable minerals in near-surface
Absence of lithic fabrics - care with Permian glacials, detrital lithic fragments
Lignite and organic matter
Rounded quartz- especially in basal gravels

Sequences
Channels: commonly have massive structureless clay, mottled in upper part, overlying a quartz-rich gravel and sand unit; the latter will be approximately horizontal (distinguishing it from veining), have some rounded quartz, attenuate laterally (across channel) and be below the deepest section of the clays. Carbonaceous material may be present in reducing environments and marine sediments, such as spongolites, occur in the south east (Table 2.6).

An 'inverted' regolith stratigraphy, with fine, clay-rich materials overlying ferruginous gravels, may indicate colluvium-alluvium derived from the erosion of a lateritic landscape.

The presence of hardpan (red-brown silica cementation, Mn oxide precipitates on partings) is not an indication of transportation, since this is a modification of pre-existing materials and can thus affect both residual and transported components of the regolith.

Table 2.6: Comparative stratigraphy of palaeochannels on the Yilgarn Craton.

		COWAN/LEFROY		ROE		N YILGARN	ENVIRONMENT	CLIMATE
PLIOCENE-RECENT		Colluvium-alluvium	Transgressions	Colluvium-alluvium		Colluvium-alluvium	Floodplain	Semi-arid
OLIGOCENE-MIOCENE	REVENGE	Mottled sandy clays and gravels Red-yellow mottled clays	Aldinga	Mottled clays		?	Floodplain, fluvial fan Shallow lake	Semi-arid Humid, becoming arid
LATE EOCENE	PRS	Spongolite and silty clay	Tuketja	Massive grey clay; mega-mottled at top	PERKOLILLI	Massive grey clay; mega-mottled at top	Tidal channel or estuary; floodplain, alluvial or lacustrine	Humid; rainforest
EOCENE	WERRILUP/ PIDINGA	Grey clay; carbonaceous; some lignite Gravel, sand and silt; silty lignite	Tortachilla	Quartz sands and pebbles, some pisoliths, clay	WOLLUBAR	Quartz sands and pebbles	Floodplain, alluvial and lacustrine; fluvial channels	Humid; rainforest

3. SUMMARIZED CASE HISTORIES

3.1 Apollo Deposit, Eastern Goldfields

Location
Apollo is located about 25 km SE of Kambalda, about 500 m NE of the Argo deposit, and 2 km E of Lake Lefroy. AMG: Zone 51 384100E 6526000N.

Climate, vegetation and landform
The climate is semi-arid with unreliable average annual rainfall of 280 mm. Vegetation is sparse and composed of open woodland of *Eucalyptus* ssp., the occasional *Casuarina* (she-oak), and small shrubs including *Eremophila* (poverty bush) and bluebush (possibly *Maireana* spp). The landscape is typical of the floodplains bordering the salt lake regimes of the region. A broad colluvial plain with occasional clay pans drains the study area to the SW towards Lake Lefroy, where dunes cover large areas.

Geology and mineralization
Apollo is located in the western limb of the St Ives Antiform, part of the Archaean Norseman-Wiluna belt of the Yilgarn Craton. The local bedrock consists of the Paringa Basalt, the Black Flag Group and the Condenser Dolerite, all of which strike NE, dip 70-80° SW and are metamorphosed to low grade. The deposit is hosted within the Condenser Dolerite, a sill up to 400m thick, which fractionated *in situ* to four zones. Gold mineralization tends to have an affinity with the highly siliceous and Fe-rich zone 4. Mineralization is encountered at about 15 m depth and dips to 760 m or more to the W. It is confined to bedrock and saprolite, and is associated with albite alteration products within two NNE trending mylonitic shear zones.

Regolith
A palaeochannel has been incised into the residual regolith 250 m to the S of the Apollo deposit and cuts across the nearby Argo deposit in an approximate E-W orientation. The U-shaped palaeochannel has a maximum depth of 60 m and average width of 400 m, and has been infilled by sediments. The residual regolith profile consists of variably coloured, dark, clay-rich saprolite. The saprolite is generally between 20-30 m thick, but is thinner beneath the palaeochannel.

Three transported sedimentary units cover the residual regolith and palaeochannel sediments in the Apollo area. The saprolite is covered by a unit of hard red and grey clays with variable ferruginous mottling. This unit contains zones of indurated ferruginous and siliceous material, forming a pan of variable thickness, generally between 2-7 m depth. It is covered by a calcareous clay-rich red soil. This soil occurs from about 0.2-2.0 m depth, and contains a dark manganiferous horizon at 1.5 m depth. The soil is characterized by locally abundant calcrete nodules 1-2 cm in width. Carbonate coats the clays and lithorelics in the soil, and forms cutans on the nodules. A sandy aeolian topsoil covers the calcareous soil. It is about 0.2 m thick, but is up to 2 m thick in places.

Geochemical dispersion in the regolith
The mean Au content in composite samples from 0-1 m (CSIRO) and 1.3-1.8 m (WMC) over mineralized areas is 9 ppb compared to a background of 11 ppb. However the soil profile over mineralization has higher Au content than the soil profile over background. Both soil profiles have highest Au concentrations between 0.5-0.8 m and below detection from 0.0-0.1 m.

Two drill holes indicated that beneath the top 2 m of the soil there is very little Au present (less than 10 ppb) in the sediments and upper (ferruginous) saprolite. However Au contents of deeper saprolite exceeded 500 ppb.

The distribution of Au and alkaline earths appear to be related in 0-1 m composite samples. Gold is weakly associated with Ca and Mg carbonates in the top soils (0.05-0.15 m) and has a general association within the soil profiles. As at Argo, the highest concentrations of Au appear in the calcareous horizon.

Ferruginous materials, including sediments and lithorelics, taken from the transported overburden have Au concentrations close to, or below, the detection limit of 5 ppb. However, Au concentrations are slightly higher (7 and 10 ppb) in the south, where depth to mineralization is less. Gold concentrations are not related to Fe content, which varies from 18 to 31%.

Arsenic is not significantly associated with mineralization. The highest concentrations of As were found in ferruginous material (180 and 200 ppb), but generally As concentrations are low. In contrast, Zn concentrations are strikingly elevated in soils over mineralization (maximum 540 ppm); but, Fe and Mn, well-known scavengers of base metals, are not. Absolute Zn concentrations are lower in saprolite and bedrock than in soil, and there is no Zn anomaly at nearby Argo.

Partial extraction techniques using water, iodide and cyanide do not directly assist in the location of buried mineralization at Apollo. The same conclusion has been reached with the partial extraction methods: enzyme leach, MMI, 4M and 10M HCl and pH5 acetate. Compared with other sites, Apollo has the most water and iodide-soluble Au. This suggests that the Au is in a potentially more mobile form than that of other sites, including Argo.

Biogeochemistry
Gold concentrations up to 21 ppb are contained in dried bluebush. However, Au concentrations in *Eucalyptus* leaves are at, or below, detection (0.5 ppb). Gold concentrations in bluebush appear to be higher over mineralization than over background, and are strongly related to those of Fe and As, Ce, Co, Cr, Hf, La, Sc, Sm, Th and Yb. It is uncertain if the bluebush anomaly is genuine. The Au concentrations in the soil are too low to cause the anomaly, so that the source must be mineralized saprolite. However, the hairiness of the plant gives it the ability to trap dust from the pit, posing the real possibility of contamination. However, it may be an authentic anomaly, and in this case Au concentrations might be used to locate mineralization. More follow up work is needed. The occurrence of the other elements is controlled by Fe, but why this is elevated over the mineralization is unclear.

3.2 Argo Deposit, Eastern Goldfields

Location
Argo is located about 28 km SE of Kambalda, and 3 km E of Lake Lefroy. AMG: Zone 51 383600E 6525600N.

Climate, vegetation and landform
Climate is semi-arid with unreliable average annual rainfall of 280 mm. Vegetation is sparse and composed of open woodland of *Eucalyptus* ssp., the occasional *Casuarina* (she-oak), *Eremophila* (poverty bush), bluebush and other small shrubs. A broad colluvial plain with occasional clay pans drains the study area to the SW towards Lake Lefroy, where dunes cover large areas. The landscape is typical of the floodplains bordering the salt lake regimes of the region.

Geology and mineralization
Argo is located in the western limb of the St Ives Antiform, part of the Archaean Norseman-Wiluna belt of the Yilgarn Craton. The local bedrock consists of the Paringa Basalt, the Black Flag Group and the Condenser Dolerite, all of which are metamorphosed to low grade, strike NE and dip 70-80° SW. The deposit is hosted within the Condenser Dolerite, a sill up to 400m thick which fractionated *in situ* to four zones. There is an increase in Fe and silica content from Zone 1 to 4, and the Au mineralization tends to have an affinity with the highly siliceous and Fe-rich zone 4. Mineralization is associated with albite alteration products within two NNE trending mylonitic shear zones of variable dip to the W.

The Archaean stratigraphy has been blanketed by transported material. Primary and secondary mineralization is confined to bedrock, saprolite and the unconformity with the transported material, where it appears to follow the palaeotopography downslope.

Regolith

The Argo deposit is situated on the side of an E-W trending palaeochannel which has a maximum depth of 60 m and average width of 400 m. The channel has been incised into a residual regolith profile of variably coloured, clay-rich saprolite. The saprolite is generally between 20-30 m thick, but is thinner beneath the palaeochannel.

Seven sedimentary units infill the channel, the upper three of which appear to blanket the entire region (Figure 2.4; Table 2.1). The four units confined to the palaeochannel consist of a basal unit of fluvial gravels, sand and lignitic silts, up to 16m thick, over which are about 30 m of grey clays containing carbonaceous woody fragments and lignite. This is overlain by approximately 15 m of spongolite, consisting of pale silts with about 50-60% siliceous sponge spicules, and mottled lacustrine clay about 10 m thick. These clays consist of kaolinite and quartz, with secondary accumulations of goethite and hematite.

Over the mottled clay zone, and the entire Argo region, is a unit of variably mottled hard red and grey clays. These contain zones of indurated ferruginous and siliceous material, forming a pan of variable thickness, generally between 2-7 m depth. Calcareous clay-rich red soil, 0.2-2.0 m thick overlie the hard clay unit. The red clay soils are characterized by locally abundant calcrete nodules, 1-2 cm in diameter. Carbonates coat the clay peds and lithorelics in the soil, and forms cutans on the nodules. A dark, manganiferous horizon occurs at 1.5 m depth. The uppermost unit consists of sandy aeolian topsoil, about 0.2 m thick, but reaching to 2 m in places.

Geochemical dispersion in the regolith

The distribution of Au in the soil at Argo does not appear to be related to underlying mineralization. There are no significant differences in the distribution characteristics, or total Au content, between mineralized and background areas. The Au concentrations in the soil are generally less than 10 ppb, with maxima occurring between 0.3-0.5 m (max 23 ppb) in the carbonates, and 1.2-1.8 m depth (max 24 ppb). The latter corresponds to the Mn-rich horizon, which has also scavenged As, Co, Mo, Sb, W and REE.

The Au in the top 2 m of the soil at Argo is generally associated with Ca-Mg carbonates, although the relationship is not as strong as at sites such as Panglo, Bounty and Zuleika (Lintern, 1989; Lintern and Scott, 1990; Lintern and Butt, 1992). However augering the top 1-2 m remains the most effective sampling technique.

In the palaeochannel, variable concentrations of Au (up to hundreds of ppm) occur mainly within the basal sands and gravels, and the underlying saprolite. Minor concentrations of Au (up to tens of ppb) found in the grey clay are associated with lignitic, carbonaceous and sulphide zones laterally adjacent to, but not above, the mineralization. Carbonaceous samples from reducing environments had the highest Au content (over 200 ppb), and enrichments in Na, Br, Hf, La, Pb, Sm, Ta, U, Zn and Zr. Concentrations of W in the transported material were generally below detection (3 ppm). In contrast W concentrations in the saprolite and bedrock were enriched (*e.g.* 27 ppm), especially where Au concentrations exceed 5 ppm.

Hydrogeochemistry

The watertable at Argo is commonly at 8-12 m depth. The groundwaters are acid and highly saline, salinity and pH both increase with depth (about 5-8% TDS, pH 3.5-4.0 for shallow samples, and 19-26% TDS, pH 4.5-5.5 for deep samples). Major element abundances suggest the waters have been evaporated within a salt lake environment. They are saturated in gypsum and the most saline waters approach halite saturation. They are depleted in K, but enriched in Mg and SO_4, which remain in solution when other salts precipitate.

Trace element compositions are similar to other sites in the Kalgoorlie region, being enriched in Al, Si, Mn, Fe, Co, Ni, Cu, Zn, Pb, Y, REE, and weakly in U. These enrichments commonly occur where acid groundwaters contact mafic rocks. Iodine also has high concentrations in Argo groundwaters, as observed in other mineralized sites in the Yilgarn. In comparison, abundances of chalcophile elements, Ga, Mo, W, Ag, Sb, and Tl, are low; these elements are commonly enriched in neutral groundwaters in contact with sulphides. The only element enrichments that appear associated with mineralization are Mo, which has relatively high concentration for an acid groundwater, and Co, Ni, and Au.

Halides (chloride and/or iodide), are expected to be an important mechanism for the dissolution of Au in acid saline groundwaters, such as those at Argo. However, despite high redox potentials (Eh) most shallow groundwaters at Argo have moderate Au concentrations. The Au in the regolith is probably not very accessible to the groundwater, possibly due to mineralogy (*e.g.* larger Ag-poor Au grains), or obstructions to flow (*e.g.* compact clay horizons), leading to preferential flow in fractures avoiding most of the Au.

Biogeochemistry
Analyses of *Eucalyptus* leaves, and *Eremophila* whole plant and mull, do not indicate the presence of mineralization. Gold concentrations in the *Eucalyptus* leaves and *Eremophila* plants over the mineralization were equivalent to background (0.5 ppb or less). The *Eremophila* mull had a maximum concentration of 4.9 ppb Au, compared to a maximum background concentration of 3.4 ppb Au. These concentrations are lower than those found at comparable sites such as Bounty, Zuleika and Panglo (Lintern, 1989; Lintern and Scott, 1990; Lintern and Butt, 1992).

3.3 Bronzewing Deposit, Northeastern Goldfields

Location
The Bronzewing deposit is located about 400 km north of Kalgoorlie, AMG: Zone 51 303000E 6970000N.

Climate, vegetation and landform
The climate is semi-arid, with hot summers and mild winters. The mean annual rainfall of 205 mm falls mainly in the summer months during erratic local thunderstorms. The area is subject to both drought and short-term floods.

Vegetation corresponds to the four principal physiographic units in the area. The sandplains are characterized by a sparse to moderate cover of *Triodia* (spinifex) and *Eucalyptus* ssp. Halophytes such as *Atriplex* ssp. (saltbush) grow on the salt lake margins. Areas of rock outcrop are dominated by *Casuarina* (she-oak) and *Brachychiton* (kurrajong) ssp. The broad plains of transported overburden are dominated by *Acacia* ssp. and a range of small shrubs, with *Santalum* (sandalwood) and *Eucalyptus* ssp. in the creeks.

Bronzewing is on an alluvial plain sloping very gently NE, within a broad undulating terrain of low relief. The few hills are secondarily silicified or relatively fresh Archaean greenstone sequences. Locally, greater relief is provided by breakaways.

Geology and mineralization
The Bronzewing deposit is in the Archaean Yandal Greenstone Belt. Gold mineralization occurs within a sequence of mafic volcanics (basalts, dolerites) and minor sediments, which are intruded by felsic porphyries. The mineralization is associated with a dense stockwork of quartz veining, and

alteration of the host sequence, and is accompanied by pyrite, pyrrhotite and minor chalcopyrite and scheelite. The predominant foliation of the host rocks is N-S and primary mineralization generally follows this structural orientation.

The use of lateritic residuum and ferruginous saprolite sampling methods were an important factor in drawing initial attention to the area, eventually leading to the discovery of the Bronzewing Au deposit in 1992 by Great Central Mines N.L. Drilling for buried geochemical halos in laterite included initial intersections of 4.65 g/t Au. Pre-mining reserves at Bronzewing were calculated to be 9.137Mt @ 4.6 g/t cut or 9.137Mt @ 5.7 g/t uncut. Four mineralized zones have been found: the Western Zone; Central Zone; Laterite Zone; and Discovery Zone. The latter three are now pits.

Regolith

Colluvial and alluvial sediments cover much of the weathered Archaean sequence. They are 20-30 m thick in the Discovery Zone and directly overlie saprolite. In the SW of the Central Zone, the sediments are 15-20 m thick and overlie lateritic residuum in places. The sediments thin towards the NE to less than 5 m thick in the Laterite Zone. Alluvium is most likely derived from the S, and the colluvium from the E where there is a subdued breakaway. The thickness of the transported overburden reflects the palaeotopography. There are three principal units:

1. Red-brown sandy-silty-clay soils, 1 m thick, developed on the colluvium and alluvium.

2. Alluvial channel deposits, colluvial talus and sheetwash. The unit fines towards the top and can be subdivided into an upper silty and a lower gravelly component. Hardpanization is generally restricted to the upper silty component.

3. Fine silty lacustrine clays that appear to occupy a palaeochannel and have been subjected to intense post-depositional mottling.

Where fully preserved, the residual profile beneath the colluvium and alluvium has a 2-5 m thick lateritic horizon consisting of ferruginous gravels, mainly pisoliths and lithic nodules, set in a silty clay matrix. The nodules were formed by the fragmentation and collapse of the underlying ferruginous saprolite. The ferruginous saprolite, a few metres thick, grades downwards into saprolite. Fresh rock is encountered at 80 to 120 m depth.

Geochemical dispersion in the regolith

Smooth, almost equi-dimensional to tabular hematite-rich fragments, from the ferruginous saprolite were analysed. They contain slightly anomalous concentrations of Cu (252 ppm) and Au (16.4 ppb). Primary fabrics are commonly preserved with some pseudomorphic replacement by Fe oxides. Hematite and goethite are the dominant minerals, with some minor kaolinite, anatase, quartz and trace mica also present in some samples.

The lateritic duricrust and gravels of the Laterite and Central Zones, where developed over primary mineralization, contain significant amounts of Au. The mean concentration of sampled lateritic residuum is 560 ppb Au, with a maximum concentration of 9060 ppb developed over subeconomic bedrock of the Laterite Zone. Elements associated with the Au mineralization in the lateritic residuum of the Laterite Zone are Ag, Ga, Ba, Ce, W, Mo, As, Sb and Cu. The Au anomalies are not as consistent in the Discovery Zone, and the lateritic residuum of both the Central and Discovery Zones are enriched in Cu and W close to the primary mineralization.

Nodules and pisoliths (3-10 mm diameter) from the lateritic residuum typically have a hematite-rich core and a goethite-rich cutan. Many of the cutans are slightly worn suggesting local transport. Such materials are considered relict if close to their probable source, or if in stratigraphic continuity with clearly *in situ* lateritic residuum. Hematite, goethite and kaolinite are the dominant minerals; minor maghemite, gibbsite, anatase and trace quartz are also present.

The buried lateritic residuum contains Au to ore grade, which sometimes extends into the colluvium. This relationship is particularly apparent in the Central Pit area where extensive Au anomalies occur across the unconformity, and are comparable to those found at or close to the surface elsewhere in the Yilgarn Craton, *e.g.* Golden Grove (Smith and Anand, 1992).

Size fractionation of the gravelly colluvium that occurs within a metre of the residuum/colluvium interface, indicates that Au is concentrated in the plus 2 mm fraction and depleted in the minus 75 µm fraction, relative to the bulk sample. It is inferred that the enrichment in the coarse fraction represents clastic dispersion of lateritic detritus. The palaeosurface represented by the unconformity has sufficient slope for the colluvium to have come from mineralized lateritic nodules upslope. Hydromorphic dispersion might be expected to lead to an enrichment of the fine fraction. However, there is no evidence to show that hydromorphic dispersion is currently accumulating Au in the fine fraction. The present fresh groundwaters are unlikely to be able to dissolve or disperse Au as a halide complex and other ligands, such as organic and thiosulphate ions, are similarly absent or at very low concentrations.

Mottles extracted from the lacustrine clay contain no significant enrichment of pathfinder elements, and Au contents are below detection (5 ppb). The mottles consist of hematite, quartz and kaolinite, and minor amounts of goethite.

No significant concentrations of Au or pathfinder elements are present in bulk soils collected from 0.3-0.5 m depth; the Au content barely exceeded the detection limit of 5 ppb. The minus 250 µm fraction consists mainly of aeolian silt-sized quartz, kaolinite and hematite. The hematite is present as fine sand to clay-sized particles, as fine coatings on quartz grains and presumably within the clay matrix.

3.4 Curara Well, Murchison district

Location

Curara is located about 70 km SSW of Mt. Magnet. AMG: Zone 50 576075E 6825375N.

Climate, vegetation and landform

The climate is semi-arid with a highly variable mean annual rainfall of approximately 230 mm. Vegetation is dominated by *Acacia* spp,. and various types of *Eremophila* ssp (poverty bush). Curara is situated on a flat depositional plain, with extremely poor outcrop.

Geology and mineralization

The Curara Well Au prospect is located in the Wydgee Fold Belt, immediately S of the Mt. Magnet greenstone belt. A lateritic resource is situated over a tonalitic porphyry stock, bound to the E by mafic amphibolite schists. Aeromagnetics show that the stock is cut by a number of NW-NNW-trending fault splays off a regional shear to the E of the prospect. The laterite straddles one of these splays, and the strongest mineralization has developed where a wedge of porphyry has been faulted out of the main body.

Primary mineralization is present both within the porphyry wedge, and the hanging wall mafic schists on the eastern side. It is associated with thin (less than 1 cm) sulphide-poor (less than 3%) quartz-actinolite veins. Supergene mineralization consists of a lateritic component hosted by the nodular mottled zone with deeper zone of Au enrichment in the saprolite. To date, the lateritic resource is estimated at 100,000 oz.

Regolith

Up to 10 m of hardpanized alluvium-colluvium overlies a 30-60 m thick lateritic profile at Curara, and lateritic residuum outcrops in the SW of the anomalous areas. A palaeochannel to the E contains 50 m of sediments beneath the alluvium-colluvium. The residual profile is truncated to lower laterite, nodular mottled zone or upper saprolite. Gold enrichment in these upper ferruginous zones delineates the primary mineralization.

3.5 Fender Deposit, Murchison District

Location

The Fender deposit is located approximately 28 km WNW of Cue. AMG: Zone 50 562600E 6975353N; RL 437.5.

Climate, vegetation and landform

The climate at Fender is semi-arid, and has a mean annual rainfall of 224 mm with a weakly bimodal distribution (January-February and May-June). Vegetation consists of scattered shrublands dominated by *Acacia* and *Eremophila* ssp, with ephemeral herbaceous plants. The site is on the margin of a colluvial-alluvial plain that slopes gently to the N and E. The deposit is overlain by thin transported cover and there is no outcrop in the immediate vicinity, though residual regolith, including lateritic residuum, is exposed 150 m to the W.

Geology and mineralization

Fender is located in the Murchison Province of the Archaean Yilgarn Craton. The deposit is hosted by a regional volcanic and sedimentary sequence in a steeply-dipping, strongly attenuated and overturned greenstone belt about 830 m wide. It is confined to the E and W by granitic rocks, and the regional metamorphic grade is low to middle greenschist.

Primary mineralization is hosted by quartz-muscovite-potassium feldspar schists. The primary mineralization is enriched in a range of pathfinder elements. Samples with Au concentration greater than 1000 ppb also had high mean concentrations of Ag (1.4 ppm), As (145 ppm), Sb (450 ppm), W (130 ppm), Mo (37 ppm), Tl (7 ppm), Zn (475 ppm) and, surprisingly, Hg (100 ppm), a similar suite to the Big Bell deposit 2 km to the N. Exploitable mineralization, however, appears to be confined to a small lateritic resource in the S, and as weathered primary mineralization in saprock and saprolite. The resource was discovered by drilling along strike from Big Bell, and is estimated at 248000t @ 2.4 g/t Au.

Regolith

The residual regolith consists of an apparently complete lateritic profile in the southern part of the deposit, and a truncated profile in the northern part. The complete profile consists of lateritic residuum (pisolitic and nodular ferruginous clays) and ferruginous saprolite, that form a small lateritic Au resource, 2-5 m thick, overlying 40 m of saprolite. The truncated profile consists of saprolite, locally leached and depleted of Au, but elsewhere, with Au concentrations at ore-grade immediately beneath the overburden. Residual regolith, consisting of saprolite, and of nodular lateritic residuum continuous with buried nodular ferruginous clay, outcrops about 150 m to the W. Fresh rock is generally encountered between 40-60 m depth.

The deposit and lateritic residuum occur on the upper parts of a palaeoslope which had greater relief than the present topography. The transported overburden is about 2-4 m thick over the deposit. Over the lower parts of the palaeoslope where the lateritic residuum is absent, about 200 m to the E, it is about 13 m thick. The top 2-5 m of the sediments consist of fine- to coarse-grained sandy clay, sand and gravel, of which the top metre is hardpanized. Silty clays, 1-8 m thick occur beneath the sandy unit, and both units contain detrital gravels and feldspar which indicates that they are probably derived from granites to the W. Some of the deeper sediments have been mottled, and there is no pedogenic carbonate.

Geochemical dispersion in the regolith

Exploration drilling has indicated that a pronounced depletion zone exists in the saprolite beneath the ferruginous nodular clays; where these are absent the depletion zone may extend to the unconformity with the transported overburden. Elsewhere, the ore-grade mineralization subcrops at the unconformity. In both situations, As (180-250 ppm), Sb (250-500 ppm) and W (30 to over 100 ppm) concentrations are high.

The ferruginous nodular clays and ferruginous saprolite are enriched in Au, As, Sb and in part W. The most widespread anomaly in this material is provided by As (100 to over 300 ppm) and Sb (30 to over 130 ppm), and this extends to the surface 150 m W of the deposit. Gold enrichment (100 to over 6000 ppb) is also quite extensive but with no surface exposure. Tungsten (10-16 ppm) is confined centrally within ferruginous nodular clays, possibly indicating the position of the primary source.

Silty clays directly overlie the saprolite but appear to be absent where lateritic residuum is preserved. Generally, Au concentrations are less than 5 ppb, although there are spot concentrations of 80-245 ppb immediately over subcropping saprolite mineralization, and an associated weak enrichment (5-16 ppb) extends 50 m downslope. The silty clays E of the deposit are significantly anomalous in Au (60 ppb) for over 100 m E of the subcropping lateritic residuum, probably representing mechanical dispersion of this Au-rich unit.

Arsenic (40-120 ppm), Sb (12-50 ppm), and in the N, W (5-17 ppm), are also enriched in the silty clays, and an anomaly extends at least 200 m downslope to the E. The enrichment of As, like Au, is strongest in the ferruginous silty clays, closest to the lateritic residuum. Essentially all of the As and Sb in the silty clays is hosted by mechanically transported ferruginous nodules (300-450 ppm As, 80->100 ppm Sb). In contrast, W concentrations are below detection in the silty clays proximal to the lateritic residuum, but increase to the N. Neither W nor Au are concentrated in the ferruginous nodules in the silty clays.

The medium-coarse sand is slightly enriched in Au (20-80 ppb), where it directly overlies lateritic residuum and there is a greater concentration of Fe-rich nodules and clay. Elsewhere, Au abundances are less than 5 ppb. Arsenic, Sb and W contents are at background concentrations in this unit.

Soil and hardpan over Fender have developed in the top metre of the sandy sediments. Over the lateritic resource these sands are only 2-4 m thick and the overlying soil and hardpan is weakly anomalous in Au (10-27 ppb) compared to a background of less than 5 ppb Au. The As, Sb and W contents of the soils are at background abundances over mineralization, but As and Sb contents increase to the W, reflecting the contribution of shallowly buried and outcropping lateritic residuum to the soil. To the N, where the sands and silty clays overlie saprolite, Au, As, Sb and W are at background abundances, although once again, As and Sb contents increase to the W.

3.6 Golden Delicious Deposit, Lake Carey

Location

The Golden Delicious Deposit is located 50 km S of Laverton. AMG: Zone 51 447250mE 6790200mN .

Climate, vegetation and landform

The climate is semi-arid with a highly variable annual rainfall averaging 200-250 mm. Vegetation in the area consists of sparse to dense woodland of *Acacia* spp., with an understorey of smaller shrubs of *Acacia*, *Cassia* and *Eremophila* (poverty bush) spp. Golden Delicious is situated on a broad colluvial plain, and the present land surface slopes very gently towards the NW.

Three regional surface regolith units can be delineated by Landsat TM imagery. These consist of dominantly post Archaean sediments covering over 85% of the region, residual Archaean units, and ferruginous materials developed in both the Archaean units and the post Archaean sediments.

Geology and mineralization

The Golden Delicious Deposit is in the Archaean Norseman-Wiluna belt, in the southern part of the Laverton Tectonic Zone. The region is comprised of variously faulted, folded and metamorphosed Archaean greenstone sequences surrounded by granites.

Gold mineralization is hosted in the western margin of a suite of granitoids that intrude intermediate to mafic volcanics and volcaniclastic "greenschist" host rocks. The resource is estimated at 6.1Mt @ 1.3g/t Au.

The granitoids can be divided into two suites:

1. A co-magmatic monzonite-syenite suite that formed as a result of the same intrusive event, and shows extensive propylictic alteration.

2. A granite that is the product of a different intrusive event to the monzonite-syenite, though the relationships are not understood. Most contacts between monzonite-syenite and the granite are strongly sheared and the two suites lie on different fractionation trends.

Regolith

The weathered Archaean bedrock consists of a mottled zone, characterized by large (up to 200 mm diameter) hematite-rich mottles overprinting clay-rich saprolite. The clay-rich saprolite merges into saprolite between 30-50 m depth, and fresh rock is usually encountered at about 70m depth.

Transported overburden ranging from 9-16 m thick, lies directly over the mottled zone and, in places, over saprolite. The sediments are poorly-sorted polymictic colluvium-alluvium consisting of clay, silt and gravels that generally become coarser with depth. The colluvium-alluvium can be divided into three units:

1. Calcareous, hardpanized silty clays, 3-5 m thick, that are strongly indurated with silica, carbonates and Fe oxides. Secondary carbonate occurs extensively as thin subhorizontal laminar precipitations and manganese oxides are present as dendritic coatings.

2. A variable unit, 3-6 m thick, dominated by fine sediments. Ferruginous gravels are more common than in the upper unit, and it is less strongly indurated by silica and Fe oxides. Carbonate is present, mostly as irregular masses up to 40 mm in diameter.

3. The lowermost unit, up to 10 m thick, is below the watertable. It contains 25% coarse material consisting of: abundant ferruginous gravels; pisoliths and nodules which are mostly broken and abraded; and minor quartz and lithorelics, some of the later being almost fresh. Maghemite is common in the pisoliths and the upper few metres of this unit, particularly in the NE, have minor amounts of concretionary goethite, seemingly formed *in situ*.

The palaeotopography at the Golden Delicious Deposit, like the modern day topography, slopes to the NW but at a much steeper and more variable gradient. Much of the transported overburden is believed to be derived from the greenstone uplands 5-10 km ESE. It is possible that widespread lateritic profiles once existed there, as the sediments at Golden Delicious mimic, in reverse order , the materials of such profiles.

Geochemical dispersion in the regolith

The basal ferruginous gravels of the lowermost sedimentary unit provide the greatest target enlargement of any sample media at the Golden Delicious Deposit. Gold concentrations up to 107 ppb are distributed for 400 m across strike and offset slightly downslope. Shallower sediments have much lower Au contents (less than 5-12 ppb).

Gold concentrations of 12-81 ppm in the upper few metres of residual regolith are distributed 300 m across strike and are not offset. The Au content of the weathered Archaean increases with depth, due to either depletion from the upper part of the zone, or to the original primary distribution. The solubility of Au in the prevailing hydrogeochemical environments, and the presence of dissolved Au in the groundwater, suggests depletion may have occurred.

Tungsten concentrations are high in the primary mineralization (up to 125 ppm) and sharply decrease over a few metres within the mottled zone, to less than 2 ppm W. There is no detectable W in the overlying sedimentary units. The sharp decrease in W concentrations through the mottled zone may also suggest depletion. However, laboratory experiments show that W in the saprolite is very insoluble, indicating that the present W distribution reflects its original distribution prior to weathering.

Antimony contents increase with depth, although the concentration of Sb in the primary mineralization is low (maximum 8 ppm) and would not normally be considered anomalous. Similarly, there is no As enrichment in the primary mineralization, but As is weakly anomalous in the upper mottled zone (maximum 41 ppm). The concentration of Fe controls the distribution of Sb, and As has a similar distribution to Sb. Normalization of Sb with Fe indicates a broad Sb anomaly in the upper mottled zone over the mineralization, however, normalising As with Fe gives no indication of mineralization, and the spatial distribution is random. The basal gravels also contain statistically discernible accumulations of As and Sb, which are proportional to Fe, but there is no spatial variation of the Sb/Fe or As/Fe ratios in these materials.

The distribution of ferruginous gravel dictates the distribution of Fe in the transported materials. The concentrations of Fe in the mottled zone are highly variable, but tend to increase upwards, probably due to collapse and compaction of mottles or more pervasive ferruginization. Elevated Hf concentrations in the upper few metres also seem to reflect this process.

There is no apparent association of Au with the carbonates present in any of the regolith units. Carbonate morphology is possibly significant, as the carbonate does not exist in the powdery, pedogenic form in which the Au-Ca association is commonly found (Lintern and Butt, 1993).

In summary, W, Sb, and also K and the REE are associated with Au mineralization at Golden Delicious, though none displayed a very direct correlation. Only Au showed evidence of significant remobilization, the other elements approximating their distribution prior to weathering.

Hydrogeochemistry

The watertable occurs at 8-11 m depth, several tens of metres above the weathering front. Groundwaters are weakly alkaline and saline, to hypersaline at depth. The halide complex is the most likely mechanism for the dissolution of Au. Gold concentration is low to moderate (maximum 0.2 ppb Au), similar to other groundwaters from the central Yilgarn. It contrasts with the typically lower concentrations (0.04 ppb) of the N, and the usually higher concentrations of the Kalgoorlie region (up to 4 ppb). Gold in the primary mineralization is somewhat soluble and accessible, and its concentration and distribution in the groundwater reflects mineralization; groundwaters at Golden Delicious are anomalous in Au for 200 m across the mineralization. The shallow groundwaters provide a medium for the dispersion of Au into the cover sequence, and the appreciable mobility of the Au indicates hydrogeochemistry could be a suitable exploration tool. Other dissolved elements that appear to correlate with the mineralization are I, and possibly Mo, Tl, Pb, Bi and U. This suite of elements is similar to multi-element responses observed in other neutral, groundwaters in contact with Au-rich rocks and regolith materials.

3.7 Harmony Deposit, Baxter

Location
The Harmony Deposit is approximately 10 km W of Peak Hill. AMG: Zone 50 663400E 7163250N.

Climate, vegetation and landform
The climate is semi-arid and has irregular average rainfall of 200 mm pa. Vegetation cover is thin, mainly consisting of *Acacia* ssp. and other drought resistant shrubs and grasses. The deposit is located on a depositional plain surrounded by low hills and rises.

Geology and mineralization
Harmony is located within the Proterozoic Glengarry Basin, on the contact between the folded mafic and ultramafic Narracoota Volcanics and the thick turbidite sequence of fine-grained, lithic, feldspathic and mafic wacke of the Ravelstone Formation. Both sequences were metamorphosed to lower or middle greenschist facies.

Primary stratabound Au mineralization is hosted within dolerite and basalt at the top of the metavolcanic sequence, and is associated with sulphide-poor quartz veining. A sub-horizontal, near-surface, supergene deposit occurs mainly within the saprolite, and there is a significant lateritic resource that extends into the overlying colluvium. The depth of oxidation averages about 80 m; the watertable is at 30 m. The deposit was discovered by sampling soil gravels and buried lateritic residuum, and has a reserve of 2.148Mt @ 3.6g/t Au.

Regolith
To the S of the Harmony deposit lies a bevelled breakaway. Further S, an erosional plain, with a surface of coarse, polymictic lag overlying ferruginous saprolite, has developed on the Ravelstone metasediments. In the E and SE, low rises characterise the landscape where ferruginous duricrust, gravels and saprolite have developed on the Narracoota Volcanics. To the NE, are the low hills of the Horseshoe Range containing areas of manganiferous lateritic duricrusts.

Harmony is on a NW-SE trending palaeohigh of ferruginous saprolite, now completley blanketed by colluvium. Preserved on the flanks of the palaeohigh is nodular, pisolitic lateritic duricrust (Figure 2.7). The nodules are dark red and have distinctive yellow-brown cutans. The lateritic duricrust is about 8 m thick, but can reach 19 m in places, where a transported component is likely.

A deep palaeochannel parallels the palaeohigh to the S of the deposit. It drains to the W, from the Narracoota Volcanics to the Ravelstone Formation. A smaller, shallower, palaeochannel subparallels the palaeohigh on the N side. Both palaeovalley floors are particularly deeply weathered, and have been eroded to mottled zones and clay-rich saprolite. They have been partly filled with mottled, soft, puggy, clay-rich sediments. They are patchy in the northern palaeovalley but extensive in the southern palaeovalley. Generally, they are about 10 m thick, but locally are up to 24 m thick (Table 2.5).

Colluvium, 7-12 m thick, overlies the clays in the palaeovalleys. On the palaeohigh, however, colluvium lies directly over the residual profile, and is only 0.5-3.0 m thick. The uppermost colluvium consists of sandy grit that has been silicified to red-brown hardpan. It contains matrix-supported, goethitic and ferruginous clay fragments in a vesicular, brown, clay-rich silt. The lower colluvium has a similar composition but is finer grained, with a smaller proportion of coarse, clastic material. Ferruginous nodules and fragments in the upper colluvium have no cutans, but towards the base, some granules have thin, partly worn cutans.

Geochemical dispersion in the regolith

Ferruginous residual regolith (lateritic residuum, mottles and ferruginous saprolite) has anomalous concentrations of Au (over 100 ppb) and W (over 6 ppm) close to the deposit; background concentrations are 10 ppb and 2 ppm respectively. Gold is concentrated in the upper part of the lateritic duricrust (825 ppb) compared to the lower duricrust (50 ppb). The lower duricrust is enriched in As (710 ppm) and Sb (8 ppm) close to the mineralization. However, ferruginous saprolite developed on metasediments has low concentrations of As (less than 40 ppm) and Sb (less than 1 ppm Sb). Ferruginous saprolite developed on ultramafic rocks have As contents in excess of 50 ppm. The ferruginous saprolite was not particularly enriched in Au (maximum 72 ppb), although one sample immediately to the SW of the mineralization had a concentration of 975 ppb Au, suggesting limited dispersion in this material. Saprolite in the pit has a mean Au content of 33 ppb.

Concentrations of Ni (over 300 ppm) and Cr (over 2000 ppm) in the upper regolith indicate that the weathering profile has formed on ultramafic bedrock. Concentrations of Pb and Rb above 20 ppm indicate derivation from the Ravelstone Formation metasediments.

Prior to deposition of the colluvium, the residual profile was eroded so the lateritic residuum is only partly preserved. Dispersion along the lateritic residuum-colluvium interface produces larger and more consistent anomalies than the stripped basement. Interface sampling revealed that Au is anomalous over the deposit on the palaeohigh (over 200 ppb), and there are dispersion trains down the palaeoslopes. Weak dispersion trains are shown by W (over 6 ppm).

Geochemical dispersion in the palaeochannel sediments is complicated by indurated layers, vertical leaching and, in the upper layers, by mixing with colluvium. The palaeochannel clays have low Au abundances, even in the vicinity of the deposit, averaging 25 ppb in the southern palaeovalley and 10 ppb in the northern palaeovalley. The Au is, however, enriched in the upper pisolitic sediment and in basal sands (maxima 225 ppb and 125 ppb respectively). Tungsten has a mean concentration of 2 ppm in the sediments, and it too has higher concentration in the basal sands (13 ppm). Mean W concentration in the palaeochannel sediments is 18 ppm close to the deposit. Arsenic (19 ppm) and Sb (2.3 ppm) are at background in the palaeovalley clays.

The soil has weak enrichments of Au (15 ppb) and W (4 ppm) in the less than 75 μm fraction, compared to backgrounds of 3 ppb and 1 ppm respectively. These occur only where the colluvium is thin (less than 1 m), and fragments of lateritic residuum have been brought to the surface. Indeed, the variance of all pathfinder elements in the soil at Harmony is random, rather than related to mineralization, except where the colluvial cover is thin.

In summary, there is a geochemical halo in laterite and inthe base of the colluvium around the Harmony deposit, and the most effective pathfinder elements are Au and W. However, in palaeochannel clays, Au contents are low and W seems to be a more effective indicator of mineralization. Tungsten tends to be independent of Au, has limited dispersion in the regolith, and may occur where Au has been leached.

Hydrogeochemistry

The groundwaters at the Harmony deposit are neutral (pH 6-8) and have very low salinity (mean 0.04% TDS), and as such they are distinct from the saline acid groundwaters of the southern Yilgarn. They have a similar Eh range to neutral groundwaters of the central Yilgarn.

Relative to seawater, the proportions of Na and Cl are low compared to Mg, Ca, K and SO4. This contrasts with the highly saline groundwaters of the southern Yilgarn, in which the ion proportions are very similar to sea water. The major ion abundances at Harmony are controlled by lithological and hydrological factors. The low salinity at Harmony means that the dominant mechanism for mobilization of Au in the southern Yilgarn, mainly through the formation of halide complexes, is not expected to be significant. Other important mechanisms for Au mobilization, *i.e.* formation of complexes with organic ligands or thiosulphate, are also unimportant because groundwaters are organic-poor and conditions are not condusive to the weathering of sulphides and the formation of thiosulphate.

Consequently groundwaters at Harmony have extremely low Au concentrations and accordingly, Au will not be a useful pathfinder element. Gold is not dispensed chemically into the regolith to any great extent under present-day conditions, and therefore is unlikely to be mobilized into soil or transported overburden. However, Sc, Mo, W and possibly Rb have greater groundwater concentrations in areas of Au mineralization, and may be useful pathfinders for exploration. Dissolved Cr concentrations correlate closely with the presence of ultramafic lithologies at the Harmony deposit and elsewhere in the Yilgarn.

3.8 Higginsville, Eastern Goldfields

Location

The Higginsville study sites are 120 km S of Kalgoorlie. AMG: Zone 51 378200-82200E 6480980-5560N.

Climate, vegetation and landform

The climate is semi-arid with an average annual rainfall of 270 mm. The vegetation at Higginsville consists of open woodland dominated by *Eucalyptus* and *Melaleuca* ssp. Small shrubs including bluebush, *Cratystylis* (false bluebush), *Atriplex* (saltbush) and *Eremophila* (poverty bush) comprise the understorey. The study area situated within mostly depositional terrain, and outcrop is generally poor.

Geology and mineralization

The study area is located within the Archaean Norseman-Wiluna greenstone belt. The Zuleika Shear runs through the area, and mineralization is associated with second order splays. Two of these structures, the Posieden South Fault and the Mission Fault, bound a steeply dipping, N-NW trending, sediments of the Black Flag Group. To the E and W of the sedimentary units, high-Mg basalts and ultramafics with minor sediments, intruded by gabbros, dolerites and acid porphyries, represent the limbs of a regional syncline.

The Higginsville area contains the Mitchell and Challenge-Swordsman palaeochannels. These were buried by estuarine and lake sediments during marine incursions in the Eocene. Gold mineralization is present in basal sands, grits and conglomerates. The palaeochannels overlie major shears and significant alteration of the Archaean lithology, and intersections of patchy primary mineralization, indicate that the Au deposits are probably a chemical supergene deposit remobilized from a proximal Archaean source. However, it is possible that the Au was washed into the river from an unknown source, or that Au-bearing fluids were injected up underlying basement faults into the sandy sediments.

Regolith

Extensive ferruginization, calcareous soils, aeolian sands, and large areas of partly weathered, remnant, Tertiary lacustrine and fluvial sediments overlie deeply weathered Archaean basement (Table 2.2). The resulting regolith is complex, with fresh rock occuring below 80 m. A typical section over the palaeochannel mineralization consists of:

0-2 m	Dense red calcareous clays with abundant ferruginous gravels.
2-6 m	Red, non-calcareous clays with some grey mottling.
6-10 m	Multi-coloured clays with abundant ferruginous nodules and some pisoliths.
10-18 m	Red and khaki puggy clays with some Fe-rich nodules, becoming paler with depth.
18-34 m	Cream to white silty sandy clays.
34-40 m	Sandy clays with carbonaceous (including fossil wood) and sulphidic material.
40-80 m	Clay saprolite consisting of variably coloured clays, quartz and rock fragments.

Geochemical dispersion in the regolith

Soil samples (0-1 m) were collected on auger traverses across the Pluto deposit, in the Challenge-Swordsman palaeochannel, and the Mitchell-4 deposit, in the Mitchell palaeochannel. A third traverse ran from the Vine deposit to the Graveyard-Aphrodites deposits, also located in the Mitchell palaeochannel. In addition, eleven soil profiles were examined, and sampled in more detail, and ferruginous granules were collected from selected soils and drill cuttings of transported overburden.

There is a general association between Au and pedogenic carbonate in the soils. There are strong associations in residual soils over mineralization at the Vine deposit, and in soils and soil profiles within the palaeochannels. Partial extractions suggest that soils close to sub-cropping mineralization (Vine-Graveyard) have higher Au/Ca ratios than those over buried mineralization in the Pluto and Mitchell palaeochannels. Iron concentrations are inversely related to Ca, consistent with the observation that carbonate is a late stage diluent of Fe oxides, and associated elements, in soils at Higginsville.

The Au content of the soils at Mitchell and Pluto are not directly related to underlying mineralization. No Au was detected in any samples directly overlying the mineralization at Mitchell and Pluto (detection limit 5 ppb). A relationship between Au in the soil and underlying mineralization Vine and North Graveyard is possible, although the latter is possibly related to higher Ca contents. The highest Au concentration (425 ppb) is within a soil profile located immediately to the E of the Aphrodites pit.

Soils at the Mitchell palaeochannel from 0.0-0.1 m depth have lower Au concentrations (<5-11 ppb) than the 0-1 m composite soils (<5-20 ppb), but neither reflect the occurrence of buried mineralization. However, the Au concentrations for 0.0-0.1 m and 0-1 m composite samples are associated, indicating that samples taken carefully from the surface may be representative of deeper composite samples. This relationship is not always dependable as, for example, individual soil samples from the Pluto traverse are highly variable.

Gold concentrations over the Mitchell traverse are significantly higher in the 0-1 m soil samples (7 ppb) than in the 0.0-0.1 m samples (5 ppb). Partial extractions indicate that this Au is more extractable in water (26% compared to 12%) but less totally extractable (22% compared to 28%). The highest percentage of water-extractable Au (46%) in 0-1 m soil samples occurs over mineralization, but this is not the case with the 0.0-0.1 m samples. At Pluto, the soil with the highest total extractable Au concentrations (maximum 12 ppb) is in the western portion of the traverse, whereas the soils with the highest proportion of water-extractable Au are in the central and eastern parts of the traverse. The sample with the highest proportion of water-extractable Au (81%) occurs adjacent to mineralization.

Mobile Metal Ion (MMI) extractions were preformed on 0.0-0.1 m samples from Mitchell. There is a strong correlation between MMI-extractable and iodide-extractable Au, suggesting that the two extraction procedures are dissolving the same type of Au. MMI extraction data for Ag, Co, Ni and Pd do not help locate mineralization. Silver concentrations are higher in the eastern part of the traverse coinciding with the highest Au concentrations.

Fifty individual ferruginous granules were randomly selected from a profile at Graveyard-Apphrodites. The ferruginous granules have highly variable Au contents. One granule contained 51000 ppb, compared to the total soil Au content (400 ppb), but many other granules have Au contents below detection (100 ppb). Petrological investigations of Au-rich (over 250 ppb) ferruginous granules show the samples are pervasively ferruginized, with some having partly-preserved primary lithic fabrics. Some contain Au grains up to 10 µm in size, although no Ag was detected within them. It is probable that Au released from the ferruginous granules is the immediate source of much of the Au associated with carbonates in overlying soils.

Iron concentrations strongly control the distribution of Sb, Cr, As and Sc, and the data suggests two catchment-related populations, presumably reflecting provenance. The highest As/Fe ratios are related to sub-cropping mineralization at Vine. Another association occurs between Na and Br, consistent with deflation of Na-rich salts from the nearby playa. REE data indicate that the two catchments (Mitchell and Challenge-Swordsman) have different Y and Sm ratios, but there is little difference in their Ce/Sm ratios.

Biogeochemistry
Bluebush leaves and branches were sampled on a traverse at Pluto. A single representative species was absent, and two different species were used. Gold concentrations in the vegetation have similar trends to those in the soil. They are greatest in the W of the traverse (maximum 2.7 ppb), whereas over mineralization and in the E of the traverse, they are below detection (<0.2 ppb). However, these low Au concentrations coincide with the occurrence of the first bluebush species, and the relatively high western concentrations coincide the second bluebush species. The data are thus inconclusive.

3.9 Kurnalpi Prospect, Eastern Goldfields

Location
The Kurnalpi Prospect is located about 70 km NE of Kalgoorlie. AMG: Zone 51 423500E 6619450N.

Climate, vegetation and landform
The climate is semi-arid with an annual rainfall of about 280 mm. Vegetation is dominated by *Acacia* ssp., some *Casuarina* ssp., and on higher ground, stunted *Eucalyptus* ssp. grow. Small shrubs are scarce due to the impact of grazing sheep. Kurnalpi is located on the edge of a broad flat floodplain. There is a range of hills to the E and NE, and Mt. Parkin rises 100m above the floodplain 2.5 km to the SE. Present day ephemeral streams, some choked with ferruginous lag, generally flow in a SW direction, draining to a side branch of Lake Yindarlgooda about 4 km S. The landscape is typical of floodplains E of Kalgoorlie.

Geology and mineralization
The Kurnalpi deposit is situated in the Kurnalpi Terrane, part of the Archaean Norseman-Wiluna greenstone belt. The widespread Mulgabbie Formation forms the bedrock, and at the study site predominantly consists of komatiite and variolitic basalts, mafic schists and (minor?) intrusions of gabbro, dolerite and felsic porphyry. The rocks have been extensively deformed and subjected to low-grade regional metamorphism. Two main shears cross the study area; one approximately trending NW-SE and the other NE-SW. Mineralization is associated with quartz veining hosted by weathered and altered basalts.

Regolith
The Kurnalpi deposit is situated alongside a palaeochannel which appears to be influenced by the two shears that cross the study area. The northern part of the palaeochannel follows the NE-SW trending shear, but where the shears cross, the southern section follows the NW-SE trending shear. Four sedimentary units infill the palaeochannel:

0-5 m	Clay-rich red soil containing abundant ferruginous granules, with pedogenic carbonate, principally as calcite in the top 2 m.
5-20 m	Mottled pale and pink clays, with abundant ferruginous granules.
20-30 m	Variably coloured puggy clays with occasional pisoliths, which are most abundant in the grey reducing zones of the puggy clay.
30-60 m	Clayey sand, with some coarser gravels.

Beneath the transported cover, the thickness of the saprolite is variable. Fresh rock is generally present by 80 m depth, although the depth to fresh rock is shallower on the margins of the palaeochannel. Buried lateritic residuum is locally present, again on the channel margins.

Geochemical dispersion in the regolith

A limited geochemical study was undertaken at Kurnalpi, targeting soil, ferruginous components in the transported cover, and material from saprolite and bedrock. Soil was sampled by augering to a depth of 2 m over three traverses, one downstream of mineralization, one over mineralization, and one upstream of mineralization. Sediment, saprolite and bedrock samples were collected from RC drill cuttings.

In soils downstream of mineralization, there is no observed correlation between Au distribution and the position of either the palaeochannel or mineralization. The mean Au concentration is 10 ppb for the 0-1 m depth material, with Ca concentrations (6-12%) relatively constant across the traverse. Normalising Au with respect to Ca results in two distinct one-sample maxima over the palaeochannel. Soils in the traverse directly overlying the mineralization have marginally higher Au concentrations (mean 19 ppb) than those downstream. Normalising Au concentration with respect to Ca broadens the anomaly to 500 m. Cerium, K, La, Sm, Sr, Zn, and possibly Eu and Yb, appear to be more concentrated over the palaeochannel, and adjacent to mineralization, and may be associated with Mn oxides. Soils upstream of the mineralization are considered as representing background. Gold concentrations (mean 16 ppb) in these soils were comparable with those over mineralization, though some Ca concentrations were very low.

Partial extraction of Au, by water, iodide and cyanide, from soil sampled over mineralization does not produce any significant enhancement of the data with respect to mineralization. However, the concentrations of water- and iodide-soluble Au are related, suggesting they may be in the same proportions throughout the study area. Mean water-soluble concentration (27%), and mean iodide-soluble concentration (64%), are similar to levels observed in other carbonate-rich soils of the southern Yilgarn. Gold in the soil at Kurnalpi is largely confined to the calcareous horizon which generally occurs within 2 m of the surface. Overall, the distribution of Au in the soils is fairly constant across the study area, and does not appear to be related to the underlying mineralization.

Ferruginous material separated from the transported overburden generally has Au concentrations below detection (5 ppb) regardless of proximity to mineralization. There is a trend towards higher concentrations of Ce, Co, Cu, La, Lu, Ni, Pb, Sm and Yb towards the base of the transported overburden, and Cu, Lu, Ni, Sm and Yb contents tend to increase closer to mineralization. Gold is present in significant concentrations (1.2 ppm) at the interface between the transported overburden and the residual regolith at the base of the channel.

Samples of lateritic residuum from 25 m depth were analysed, one 250 m distant from mineralization, and the other a further 50 m away. The first sample has an Au concentration of 50 ppb whereas the other is below detection for Au. Both samples are enriched in Mn (mean 1200 ppm), As (mean 90 ppm), Co (mean 280 ppm), Ni (mean 600), Rb (mean 40 ppm) and Zn (mean 335 ppm) with respect to ferruginous material from the transported overburden.

Saprolite samples high in Au (greater than 1 ppm) are also weakly enriched in As (46 ppm). These samples also tend to be enriched in Cr (2455 ppm). Fresh rock with moderate Au concentration (0.1-1 ppm) has a relatively high W content (18 ppm), but no other samples contain more than 5 ppm W. Silver (5 ppm), Bi (1 ppm), Ir (20 ppb), Se (5 ppm) and U (2 ppm) were below detection (in brackets) in all sample media.

The Kurnalpi deposit has no surface geochemical expression in total or partial extractable Au, or in other elements. Any Au derived by active processes and recently introduced or mobilized in the soil, would be expected to be the most soluble. However, neither water-soluble nor iodide-soluble Au concentrations are greater over mineralization, suggesting that any such introduced component is minimal in comparison with Au mobilized by normal pedogenic processes. It is possible that such processes have led to widespread homogenization of Au, possibly creating a broad low order soil anomaly. Such an anomaly would only be apparent on the district scale, rather than the local traverses of this study.

3.10 Quasar Deposit, Mt. Magnet

Location
The Quasar Au deposit is about 5 km W of Mt. Magnet. AMG: Zone 50 578050E 6892100N.

Climate, vegetation and landform
The climate is semi-arid with an average annual rainfall of 234 mm. Vegetation is dominated by various *Acacia* ssp and *Eremophila* ssp. (poverty bush and turpentine), with isolated *Brachychiton* ssp. (kurrajong). Prior to mining, the surface at Quasar was nearly flat to the west, with a very low, approximately north trending ridge in the centre and E.

Geology and mineralization
The Archaean greenstone belt at Mt. Magnet is comprised of ultramafic, mafic and felsic volcanic rocks with subordinate sediments, BIF and chert. The greenstone sequence has been deformed into a domal structure with a steeply plunging synformal configuration - the Boogardie Synform. The Boogardie Synform at Stellar consists of two major bedrock units:

1. The Boogardie Formation, composed of talc-carbonate altered ultramafic flows and other Mg-rich mafic rocks. The sequence is cut by fine medium-grained felsic intrusives.

2. The Sirdar formation, composed of BIFs and mafic flows, overlain by ultramafic flows, felsics flows and tuffs. It hosts the majority of exposed mineralization in the nearby Hill 50 Mine area.

Gold mineralization at the Quasar deposit is associated with ductile shearing in high-Mg mafic-ultramafic rocks that have been altered to talc-chlorite-sericite schists, at the contact with a felsic porphyry stock. Mineralization is sulphide-poor (quartz-chlorite-pyrite ± carbonate) and has little quartz veining. Weakly mineralized quartz-tourmaline veining is restricted to the felsic porphyry, occurring marginal to the contact. Quasar was discovered by bedrock reconnaissance drilling by Metana Minerals, and together with the nearby Stellar deposit, were the first blind orebodies to be mined by Hill 50 Gold Mines within the Synform.

Regolith
Regionally, the Boogardie Formation is mostly obscured by a cover of colluvium-alluvium, which is partly underlain by palaeochannel sediments. The thickness of the colluvium-alluvium generally increases away from the enclosing BIF ridges. Erosional regimes comprise about 25% of the local area, and are largely restricted to outcropping semi-continuous BIF ridges, flanking upland slopes and, in the NE, breakaways on the northern margin of the BIF ridges. Scattered patches of lateritic duricrust are preserved. Depositional regimes occupy the remaining 75% of the local area. They

cover the lower slopes and the colluvial-alluvial plains. The colluvium-alluvium has local to distal provenances and reach up to 20 m thick, overlying both complete and variably truncated lateritic profiles.

The hardpanized colluvial-alluvial cover at Quasar has a fairly uniform thickness of between 4-8 m. It is largely composed of lateritic nodules and pisoliths (with and without cutans), and fragments of quartz and ferruginous saprolite, in a silty-clay matrix. The upper part of the transported cover consists of poorly sorted gravels with coarse, angular fragments of quartz and lithic material, typical of colluvium. At lower levels lateritic debris is dominant, and the transported cover becomes matrix dominated with associated manganese staining. Towards its base, the colluvium-alluvium contains coarse, poorly sorted gravelly lenses, consisting of rounded quartz pebbles and lateritic debris, indicating an alluvial environment.

Locally, the colluvium-alluvium overlies a truncated regolith profile and, in the SW, sediments in a shallow arcuate palaeochannel. Drilling has indicated that the palaeotopography beneath the colluvium at Quasar sloped gently to the S, towards the palaeochannel. The northern gradient was steep and the flow direction was possibly to the SW. Sediments were deposited in the palaeochannel and are generally 3 m thick (but up to 6 m thick) and consist of white, kaolinitic clays with distinct layers of lateritic gravels with cutans.

The residual profile consists of weakly mottled, clay-rich, ultramafic saprolite; kaolinitic saprolite; and silicified, clay-rich, felsic porphyry. Some weak mottling also occurs in the porphyry, where the base of oxidation steepens towards the structural contact. The weathering front on the ultramafic rocks is around 35 m depth, and on the felsic rocks it ranges from a few metres, to over 40 m near the shear zone.

Geochemical dispersion in the regolith
The weathered Archaean was eroded prior to deposition of the colluvium-alluvium. Accordingly, there is little preservation of lateritic residuum, so anomalies in this stripped environment present small targets. Gold in the residual profile is not significantly anomalous, although one intersection immediately south of the pit, on the sheared contact, contained 1460 ppb Au. The As and Sb contents of the saprolite at the top of the residual profile are generally low (less than 5 ppm and 3 ppm respectively) and As and Sb are not effective in detecting mineralization at Quasar. Bismuth has a background concentration generally less than 1 ppm and is weakly enriched (2 ppm) at the top of the residual regolith. There is a single point Pb anomaly of 200 ppm from the residual profile, compared with a background of 10 ppm. This coincides with the Bi anomaly on the western side of the pit.

The interface between the residual profile and the colluvium-alluvium shows a broader, but lower order, Au anomaly than the residual profile on its own. Average Au concentration is 100 ppb, reaching 250 ppb, in much of the southern part of the pit. The interface also contains similar, but wider, Bi anomalies to the residual profile in the western part of the pit. A broad Pb anomaly of 35-40 ppm is present in the interface over much of the northern part of the pit. Homogenous dispersion patterns of Cr, Ni, Cu, V and Zn at the interface between the residual profile and the palaeochannel sediments reflect the underlying lithology.

The palaeochannel sediments, particularly the ferruginous materials within them, may be a useful prospecting tool. Arsenic is strongly correlated with Fe, Sb and Cr, and is probably adsorbed by Fe oxides.

The colluvium-alluvium is derived from the auriferous Boogardie Synform, and has an average background of 50 ppb Au. This makes it difficult to detect possible subtle responses in the cover that may be related to buried mineralization. The auriferous nature of the sediments tends to mask geochemical signatures from underlying rocks, hence the total element composition of surficial sediments is probably unreliable, even at a district scale. The geochemical halo at Quasar, however, has a multi-element nature; a combination of pathfinder elements improves target size and accurately defines the mineralization in the pit area.

Element distribution in surface lag and the upper horizons of the colluvial sediments have no spatial correspondence with those in the basement. Any weak statistical correlations between the 1-2 m and 3-4 m intervals of the transported cover for Au, Ba, Cu, Pb, Th and V are most likely to be random. Those that exceeded the 95% confidence limit, Co, Cr, Fe, Ga, Nb, Ni, are either related to provenance, or in the case of Mn, to hardpanization. Arsenic and Sb were the only pathfinder elements that had any significant interlayer correlation, and this is believed to reflect a mafic-ultramafic source to the SE.

Overall, the most promising sample media was regarded as the upper metre of the residual profile and the interface sample that includes the unconformity between weathered rock and transported cover.

3.11 Runway Prospect, Eastern Goldfields

Location
The Runway prospect is located about 10 km N of Kalgoorlie. AMG: Not available (Zone 51).

Climate, vegetation and landform
Climate is semi-arid with average annual rainfall of 280 mm. Runway is situated on a flat plain with areas of subcropping saprolite. Vegetation consists of open woodland of *Eucalyptus* ssp. over residual terrain, and depositional areas are dominated by small shrubs including bluebush.

Geology and mineralization
The Runway prospect is located in the Kalgoorlie Terrane of the Archaean Wiluna-Norseman greenstone belt. The deposit is hosted by sediments of the Black Flag Group that dip steeply to the W, and trend N-S. The lithology is comprised of four main units which are, from W to E: volcanic sandstone, interbedded conglomerate-sandstone, black shales and siltstones, and massive sandstone.

Mineralization at Runway occurs as a thin, sub-horizontal zone of supergene Au enrichment close to the weathering front, beneath 50 m of leached or barren saprolite. Primary mineralization occurs as sporadic, narrow quartz veins. Minor sulphides, including pyrite, arsenopyrite, sphalerite and galena, are present and have resulted in significant concentrations of As, Ag, Cu, Pb and Zn associated with Au mineralization. The veins appear to be generally restricted to the interbedded conglomerate-sandstone unit, which exhibits pervasive carbonate-sericite alteration and disseminated pyrite and arsenopyrite.

Regolith
The saprolite at Runway is thinly covered by semi-residual, calcareous, red, sandy clay soils. The soil is less than 1 m deep in places and grades into the saprolite. Reddish brown sandy clay extends from the surface to about 25 cm depth, and contains small (to 10 mm) carbonate nodules. Orange silty sandy clays are present between 0.25-1.00 m.. They contain carbonate nodules, of varying size; nodules up to several centimeters in diameter occur between 25-50 cm, whereas those from 50-100 cm are mostly less than 1 cm. Calcareous, orange and yellow, clayey silt, at 1-2 m depth has friable lithic nodules.

Geochemical dispersion in the regolith
A limited geochemical study targeting the soil was undertaken at the Runway prospect. Soil was sampled by augering on an E-W traverse over the thinly covered mineralized basement, and the 0-1 m depth interval was analysed. A soil profile directly over mineralization was also analysed to a depth of 2 m.

Gold in the soil appears to be associated with underlying mineralization, with a maximum concentration of 270 ppb. Arsenic (maximum 405 ppm), Sb (8 ppm) and, possibly, W (11 ppm) are also anomalous compared to backgrounds of <20, <1 and <2 ppm respectively. Soils below 0.5 m have moderately higher concentrations of Au over the mineralization, and of As, Sb and W in the general area. Samples are more calcareous (Ca- and Mg-rich) over mineralization and there is a weak association between Au, Ca nd Mg in the top 1.3 m. However most of the Au (80 ppb) and the least Ca and Mg are found below 1.5 m. Highly anomalous concentrations of As (2700 ppm), Sb (42 ppm) and W (45 ppm) are present between 1.75-2.00m.

Partial extraction analysis of Au in soil are dominated by a high proportion of iodide-extractable Au (mean 87%). Relatively low proportions of water-extractable Au are present (10%), especially over mineralization (4%). It is possible that the low extractability of Au in water reflects its coarser nature closer to the deposit. Compared to cyanide-extractable Au, ther is within the soil profile an increasing proportion of water-soluble Au, and in particular iodide-soluble Au, with depth. This is possibly due to the presence of coarser Au grains in the top metre.

The coarse fraction from three samples taken from over mineralization was sub-divided into 5 components; calcareous nodules, green lithic fragments, assorted saprolite/mottled zone fragments, ferruginous saprolite, and magnetic ferruginous granules. Gold occurs in each, with the highest concentrations in the calcareous fraction (over 500 ppb) and in the ferruginous granules (295 ppb). Consequently, specific selection of these components may enhance concentrations compared to those in the bulk samples. Antimony, Ba, Br, Ce, Th and Co are associated with Fe, and are most enriched in the saprolite and ferruginous granules. Chromium, Cs, K, Na and Rb concentrations are highest in the green lithic fragments which are probably fuchsitic. Tungsten and As are mostly associated with either ferruginous granules or saprolite; W was not detected in calcareous material.

Biogeochemistry

Gold is present in one of the bluebush samples overlying mineralization, but the concentration (1.9 ppb) is close to detection. Two samples, one above mineralization and the other from background, have detectable As at 0.5 ppm and 0.57 ppm respectively.

3.12 Safari Prospect - Mt. Celia, Lake Carey

Location

The Safari Prospect is located 200 km NNE of Kalgoorlie and 9 km NE of the margin of Lake Raeside. AMG: Zone 51 450800mE 6732300mN

Climate, vegetation and landform

The climate is semi-arid with mean annual rainfall of 200-250 mm. Rain falls variably throughout the year, resulting from frontal systems in winter, or convectional storms and cyclone-related depressions in summer. The vegetation is medium to dense woodland of *Acacia* ssp. with minor *Eucalyptus* ssp. Safari is situated on a broad, sandy, colluvial valley that slopes gently to the SW.

Three regional surface regolith units can be delineated by Landsat TM imagery. These consist of dominantly post Archaean sediments covering over 85% of the region, residual Archaean units, and ferruginous materials developed in both the Archaean units and the post Archaean sediments.

Geology and mineralization

The Safari Prospect lies within the southern extension of the Laverton Tectonic Zone, part of the Archaean Wiluna-Norseman belt. The bedrock geology consists of a greenstone assemblage composed of a wide variety of volcanic and volcaniclastic rocks. These rocks are heterogeneously deformed and generally strike NNW. They have nearly vertical to WSW dipping tectonic foliation, and sub-horizontal to down dip mineral lineation. Regionally, the greenstone sequence has been metamorphosed to lower greenschist facies, but alongside large plutons of intrusive porphyritic syenite, coarse granodiorite and ademellite, the greenstone sequence has been metamorphosed to amphibolite facies.

Drilling to date indicates a resource of 1.08Mt @ 3.3g/t Au. The mineralization is hosted by andesite to dacite metavolcanic rocks, now largely represented by quartz-chlorite-sericite ± carbonate schists. They are bound to the W and E by serpentinized komatiite and talcose schists. Gold is primarily associated with quartz veins within an anastomosing shear.

Regolith

The palaeosurface is much steeper and more variable than the present land surface at Safari. The most prominent features of the palaeosurface are a palaeohigh that meets the present land surface, and a valley draining W in the northern part of the area.

The study area is completely blanketed by transported overburden, except in the small area coinciding with the palaeohigh where Archaean rocks outcrop. There is a uniform distribution of sheetwash and aeolian sand up to 1 m thick at the surface. The composition and thickness of the sediments, including the sheetwash, varies. Generally the sediments are 5-10 m thick, reaching 20 m in the northern palaeovalley.

The sediments below the sheetwash are a polymictic assemblage containing 2-10% coarse material in a matrix of sand, silt, and in places, clay. The coarse fraction commonly occurs towards the base and is comprised of angular, weakly weathered rock fragments over most of the area, including near the mineralization. However, in the northern palaeovalley there is a mixture of ferruginous pisoliths, nodules and lithorelics. In places, drilling has intersected narrow lenses of coarse alluvial sand and gravel.

Post-depositional modification of the sediments is widespread; most significant is the widespread calcification from about 0.5-5.0 m below the surface. Mottles of carbonate a few tens of millimetres in diameter occur only 20 cm below the surface, but the carbonate morphology below 1 m depth is uncertain because the only samples are drill cuttings. Beneath the zone of intense calcification, the sediments are commonly indurated, moderately to strongly, by silica and Fe oxides.

Most of the residual regolith consists of saprolite with a variable clay content, although in isolated areas in the north of the prospect, there are deep profiles with highly ferruginous upper horizons. Incipient mottling is present throughout the saprolite and the upper few metres are commonly indurated by silica and/or carbonate. Fresh rock is generally encountered 10-20 m below the unconformity. The bedrock is reasonably fresh where it subcrops, but it is subject to the same calcification as that of the upper few metres of the sediments. Calcium carbonate causes the brecciation of the subcrop and the upper few metres contain large (to tens of cm) nodular structures.

Geochemical dispersion in the regolith

High concentrations of Au (maximum 31 ppm) are usually accompanied by Pb enrichments (maximum 1100 ppm), although correlation with grade is generally not particularly good. Also not specifically related to Au grade are the general enrichments of As (maximum 1000 ppm), S (maximum 1.1%) and W (maximum 79 ppm). The enrichment of Zn (maximum 1300 ppm) at one of the intersections suggests that there may have been more than one mineralising event.

Anomalous Au occurs in the saprolite just below the unconformity, especially where it directly overlies primary mineralization (*e.g.* 1200 ppb in a quartz vein from the top two metres of the saprolite). The mean Au contents of the top 1 m gives a very strong anomaly peaking over mineralization (1000 ppb), compared to an elevated and noisy background of 10-50 ppb Au.

Anomalous Au (22-60 ppb) is also present in the carbonate horizon, with enrichment strongest from 0.5-2.5 m depth directly over mineralization. Concentrations of Au (over 7 ppb) above background occur in the calcareous horizon for 800 m across strike of the mineralization. Using a cyanide leach with low detection limits (0.04 ppb), an anomaly in the top half metre, with excellent contrast, peaks directly over the primary mineralization with concentrations exceeding 5 ppb for over 600 m across strike. Despite having higher absolute Au contents, preferentially sampled highly calcareous fragments do not increase anomaly contrast, and the Au/Ca ratio in these is consistently lower than a bulk sample from the same interval.

The Au anomaly associated with carbonate at Safari accurately reflects mineralization, with optimum sampling between 0.5 and 2.5 m depth. In contrast, Au and Ca concentrations at Bounty and Argo in the southern Yilgarn are concentrated in the top metre of the profile. Safari and Argo have poorer correlation between Au and Ca than Bounty (which has no transported overburden).

Gold solubility in the saprolite varies from less than 10% in the mineralization, to over 80% further away. This implies secondary lateral dispersion in the saprolite, probably prior to sedimentation. Later the Au has been mobilized upwards into the overburden, where it has associated with evaporative precipitation of carbonate, 0.5-4.0 m from the surface. Gold solubility is uniformly high (over 70% iodide soluble) throughout this calcareous horizon.

Biogeochemistry
Plant material was found to be ineffective in detecting mineralization. Bromine was anomalously high (up to 160 ppm) in Acacia growing over mineralization against a background of around 20 ppm. All other elements were present in very low concentrations, and only one sample (mull) over mineralization had elevated concentrations of Au, As, Ce, Co, Fe, La, Na, Sc, Sm, W and Yb. It is suspected that these elevations, and the inhomogeniety of Au distribution in the samples and sub-samples, is due to contamination from drill dust.

3.13 Steinway Prospect, Northeastern Goldfields

Location
Steinway is located about 27 km SSW of Kalgoorlie. AMG: Zone 51 355200E 6573100N.

Climate, vegetation and landforms
Climate is semi-arid with unreliable mean annual rainfall of 280 mm. Vegetation consists of open woodland of *Eucalyptus* ssp. and a sparse understorey that includes *Maireana* (bluebush). Steinway is located on a flat depositional plain, with higher areas rarely rising 5 m above it. To the S, an erosional area composed of mafic saprolite hosts the nearby Penfold Au mine, and to the SE a palaeochannel hosts the Greenback Au deposit (Figure 2.6). Present day ephemeral channels cross the depositional plain, generally flowing N to White Lake, a playa about 10 km distant. The ephemeral channels separate the Steinway and Penfold soil anomalies.

Geology and mineralization
The Steinway prospect is located adjacent to the regional contact between mafic-ultramafic rocks of the Saddle Hills Greenstone Belt, and the overlying intermediate to felsic volcanics and sedimentary rocks of the Black Flag Group. Mineralization at Steinway is twofold: primary mineralization is associated with quartz stockwork veining within mafic andesites/amphibolites; and supergene mineralization is located below a palaeochannel.

Regolith
Fresh rock is encountered at about 50 m depth, and the residual regolith profile at Steinway consists of saprolite, becoming more clay-rich towards the top. It is about 20 m thick and is overlain by four sedimentary units. These consist of a basal sand and silty clay unit, between 25-30 m depth, overlain by massive clays between 5-25 m depth that contain strongly mottled zones of Fe-rich material. A

non-calcareous clay containing large amounts of ferruginous granules occurs between 2-5 m depth, and the uppermost unit consists of calcareous, clay-rich red soil with abundant ferruginous granules.

Geochemical dispersion in the regolith
Primary Au mineralization in the saprolite and bedrock at Steinway is associated with relatively high concentrations of Lu (0.5 ppm maximum, background of <0.2) and Yb (0.4 ppb maximum, background of <0.2) in areas of medium Au concentration (0.1-1 ppm) and high Au concentration (over 1 ppm). The saprolite and basement are depleted in Al, Br, Cr, Hf, Th and Zr compared to the palaeochannel sediments.

Ferruginous material collected from the palaeochannel sediments between 6-20 m depth have a maximum Au concentration of 17 ppb. This sample also has the highest concentrations of Fe, Ba, Ce, Cr, Eu, La, Lu, Mn, Ni, Pb, Sb, Sc, Sm, Th, U and Yb. These elements are probably concentrated within Fe and/or Mn oxides, rather than being specifically related to Au. The sediments from 6-20 m depth have lower Au concentrations than surficial samples. Multi-element analyses suggest there is a surface enrichment (0-5 m) in Au, Ca, K, Mg, Mn, S, Cl, Cs, Cu, Pb, Rb, Sr, Zn and REE, compared with the subsurface (5-10 m). The Fe content appears to influence the distribution of several elements, including As, Ni, Sb, Sc and V. Ratios of As/Fe and Cr/Fe indicate that there may be two distinct types of sediments in the transported overburden. The boundary between the two occurs at about 15 m depth and may represent different depositional events, or later weathering effects. A patchy S-rich horizon at this depth has elevated Au concentrations (up to 85 ppb) relative to the adjacent sediments, which generally contain less than 20 ppb Au.

Analysis of a soil profile located above mineralization show that Au concentration gradually increases with depth, whereas Ca and Mg concentrations sharply increase and then decrease. Gold and Ca are probably associated in the upper horizons, but the relationship is not as clear as that at sites such as Panglo, Bounty and Zuleika (Butt *et al.*, 1991, 1993). Iron concentrations gradually increase with depth and, below 0.5 m, Au and Fe appear correlated. Gold concentrations are higher in the second metre of the profile but, as the concentration in the top metre averages 200 ppb, augering is considered an effective sampling technique at Steinway.

Sequential extraction (water, iodide, cyanide) of Steinway soils indicates that the proportion of total Au increases with depth, but water soluble Au in the profile decreases with depth. The most water soluble Au (20% of total) is in the topsoil, where the highest concentration occurs over the mineralization at 106 ppb Au, which is significantly higher than background (approximately 20 ppb Au). The mean proportion of iodide soluble Au is approximately 80% of total Au, and cyanide removes remaining Au. The concentration of water soluble Au in the soil profile appears to be strongly related to organic C content.

Ferruginous granules from 1.6 m depth in the soil profile were wet sieved into four size fractions: plus 710 μm, 710-250 μm, 250-53 μm and minus 53 μm. The coarse fraction (plus 710 μm) representing 10.6% of the total weight of the sample, has the highest Au concentration at 450 ppb, 17% of the total mass of Au. It is also enriched in As, Cr, Eu, Fe, La, Sb, Sc, Sm, Th and W. Most of the Au (80%) is found in the fine fraction (minus 53 μm). Further detailed sampling and analysis indicated that some individual Fe granules had Au concentrations in excess of 15000 ppb. Granules containing over 250 ppb Au have visible Au, in some granules, primary lithic fabrics were present. This evidence strongly supports the hypothesis that the granules and Au are transported and that the anomaly is displaced, lying coincidentally over the underlying mineralization. However, some post-depositional modification, including the addition of Au, is not excluded.

The Au anomaly (>24 ppb) in the 0-1 m composite samples from Steinway reaches 150 ppb against a background of less than 20 ppb. The anomaly is over 150 m wide in an E-W direction and stretches over 1 km to the NW, following the direction of the palaeochannel. There are also high concentrations of Au (maximum 107 ppb) in the coarse, ferruginous fractions of the soil in the same area. Chromium, As, Sc and Sb appear to be associated with Fe.

The distribution of Au in 0-1 m composite soil samples at first appears to be related to underlying mineralization. However, broken pisoliths and other transported fragments, the probable source of lithorelics from upslope, and the random concentration of Au in the ferruginous granules, all indicate that the apparent association is coincidental.

Hydrogeochemistry
Groundwaters at Steinway vary from moderately acidic (pH 5.8) to highly acidic (pH 3.4). They are enriched in Al, Si, Mn, Fe, Co, Ni, Cu, Zn, Yb, Pb, and REE. The most acid groundwaters are also enriched in U. These enrichments commonly occur where acid groundwaters contact mafic rocks. Iodine also has high concentrations in Steinway groundwaters, as observed in other mineralized sites in the Yilgarn. Chalcophile elements, Ga, Mo, W, Ag, Sb and Tl have low concentrations, as these elements are commonly enriched in neutral groundwaters in contact with sulphides.

The acid groundwaters at Steinway are appreciably saline (up to 9% TDS). Halides (chloride and/or iodide) are an important mechanism for Au dissolution in such groundwaters, but Steinway groundwaters are insufficiently oxidising, so Au contents are low (less than 0.03 ppb). Groundwater Eh is very sensitive to concentrations of dissolved Fe and Mn, and the degree of equilibrium with atmospheric oxygen. These conditions could vary over time, so favourable conditions for dissolving Au in the Steinway area are quite possible.

Biogeochemistry
Analysis of *Eucalyptus* (leaves, bark, twig and mull) and bluebush do not indicate the presence of mineralization. Gold concentrations in both *Eucalyptus* and bluebush over the mineralization are similar to background. The *Eucalyptus* mull has a maximum concentration of 4.4 ppb over mineralization compared to a maximum background of 4.1 ppb, and the bluebush has a maximum concentration of 1.7 ppb over mineralization compared to maximum background concentration of 1.8 ppb Au. These concentrations are lower than those found at comparable sites such as Bounty, Zuleika and Panglo (Lintern, 1989; Lintern and Scott, 1990; Lintern and Butt, 1992).

3.14 Stellar Deposit, Mt. Magnet

Location
The Stellar Au deposit lies some 5 km W of Mt. Magnet. AMG: Zone 50 576569E 6897137N.

Climate, vegetation and landform
The climate is semi-arid with an average annual rainfall of 234 mm. Vegetation is dominated by various *Acacia* ssp and *Eremophila* ssp. (poverty bush and turpentine), with isolated *Brachychiton* ssp. (kurrajong). Prior to mining, the surface at Stellar sloped gently to the S.

Geology and mineralization
The Archaean greenstone belt at Mt. Magnet is comprised of ultramafic, mafic and felsic volcanic rocks with subordinate sediments, BIF and chert. The greenstone sequence has been deformed into a domal structure with steeply plunging synformal configuration - the Boogardie Synform. The Boogardie Synform at Stellar consists of two major bedrock units:

1. The Boogardie Formation, composed of talc-carbonate altered ultramafic flows and other Mg-rich mafic rocks. The sequence is cut by fine-medium grained felsic intrusives.

2. The Sirdar formation, composed of BIFs and mafic flows, overlain by ultramafic flows, felsics flows and tuffs. It hosts the majority of exposed mineralization in the nearby Hill 50 mine area.

Gold mineralization at Stellar is associated with quartz-tourmaline veining in a brittle dilational zone and is sulphide-poor. It is hosted by dacitic quartz porphyry, near its structural contact with an ultramafic rock. Stellar was discovered by systematic RAB drilling targeting buried laterites and mottled zones. Together with the nearby Quasar deposit, it was the first blind orebody to be mined by Hill 50 Gold mines within the Synform.

Regolith

Regionally, the Boogardie Formation is mostly obscured by a cover of colluvium-alluvium, which is partly underlain by palaeochannels. The thickness of the colluvium-alluvium generally increases away from the enclosing BIF ridges. Erosional regimes comprise about 25% of the local area, and are largely restricted to outcropping semi-continuous BIF ridges, flanking upland slopes and, in the NE, breakaways on the northern margin of the BIF ridges. Scattered patches of lateritic duricrust are preserved. Depositional regimes occupy the remaining 75% of the local area. They cover the lower slopes and the colluvial-alluvial plains. The colluvium-alluvium has local to distal provenances and reach up to 20 m thick, overlying both complete and variably truncated lateritic profiles.

The colluvium-alluvium blanketing the Stellar area can be divided into two units(Figure 2.8). An upper polymictic gravelly unit about 3 m thick, contains fine- to medium-sized lateritic nodules and pisoliths (4-15 mm). It overlies a4-8 m thick silty-clay unit that is subdivided into three facies. From top to bottom these are: red-brown silty-clay, up to 3 m thick; lenses of well rounded lateritic gravels, between 1 and 2 m thick; and sand to sandy clay, up to 1 m thick. The clays appear to derive from eroded saprolite, and the gravels from laterite. Both units have been hardpanized and are typically characterized by Mn oxides on fracture surfaces.

The colluvium-alluvium overlies lateritic residuum and, in part, sediments in a palaeochannel cut into the lateritic regolith. To the N and W a palaeohigh existed, and to the E and SE sediments were deposited into a palaeochannel was eroded into the basement. Later surface expression was almost a complete reversal. Prior to deposition of the colluvium-alluvium, there was a palaeohigh to the E and the SE of Stellar. The surface sloped steeply to the pit, had a gentler gradient in the pit area, then once again sloped steeply to the NW, where the thickest sediments are. Possibly, the palaeochannel sediments were once widespread, and were eroded prior to deposition of the colluvium-alluvium.

The palaeochannel sediments consist of grey, plastic clay and minor sandy clay (smectite and kaolinite). Vertically elongate hematitic mottles up to 400 mm occur in a mega-mottled horizon. Lateritic nodules and pisoliths (4-10 mm) are contained in the mottles, and are also scattered throughout the basal clays of the palaeochannel. Small, black, angular to well-rounded granules (2-5 mm) are also abundant in the mottles. Their cores have metallic lustre, some have thin cutans and some are magnetic. The origin of the nodules, pisoliths and granules is unclear; some appear to be transported, yet others have developed *in situ*.

The laterite forms a semi-continuous horizon from 1.5 to 2.0 m thick. It is nodular to pisolitic, and is either weakly indurated or more strongly cemented, as duricrust. The nodules are irregular to subrounded, 5-10 mm in size and have cutans up to 0.5 mm thick.

Within the basement, quartz-tourmaline veins have weathered *in situ* to coarse, rounded cobbles. These trace the original projection of the veins into the laterite horizon, and are widely dispersed in the upper parts of this horizon. Minor lateral transport, possibly by mass flow is suggested, and this might also account for the now mined "boulder bed" that hosted supergene mineralization at Stellar.

The residual profile consists of an upper ferruginous horizon, a mottled zone, clay saprolite and saprolite which, in turn, passes into felsic or ultramafic bedrock. A zone of ferruginous saprolite is preferentially developed on ultramafic lithology. The base of oxidation varies but tends to be around 60 m.

Geochemical dispersion in the regolith
The colluvium-alluvium is derived from the auriferous Boogardie Synform, and has an average background of 50 ppb Au. This makes it difficult to detect possible subtle responses related to buried mineralization. Compared to other regolith units, the colluvium-alluvium also tends to be enriched in Cu, Zn, Nb, Y, V and, in the upper parts, Pb and Ba. In contrast, the palaeochannel sediments are particularly poor in Au, and also Ni and Ba.

There are significant concentrations of Au (mean 1000 ppb) in the lateritic duricrust, ferruginous saprolite and mottled zone. These units are also enriched in Cr, U and weakly Ba. Arsenic (15-35 ppm) and Sb (2-8 ppm) are also concentrated in the lateritic duricrust, although As and Sb appear to be related more to the abundance of Fe than to mineralization. Nickel is depleted relative to saprolite and bedrock below.

The nodular duricrust is dominated by goethite and kaolinite, with variable amounts of quartz, hematite, smectite and maghemite. The lateritic pisoliths and nodules, and the small black granules, in the palaeochannel sediments consist of hematite and maghemite, with small amounts of goethite, kaolinite and quartz. The granules contain Cr and Ni up to 19832 ppm and 405 ppm respectively, compared to mean bedrock contents of 10945 ppm and 417 ppm respectively. The granules have low concentrations of Au (26 ppb maximum) and As (53 ppm maximum) which contrasts with the lateritic duricrust.

Free Au occurs in the lateritic nodules as subhedral to anhedral crystals, and as delicate wire forms on the surfaces of goethite and hematite. The Au crystals show dissolution and surface pitting, and their morphology and close association with Fe indicates that the Au is dominantly secondary.

The clay saprolite and saprolite have Au concentrations of 20-20000 ppb within the mineralization compared to background concentrations of 10-50 ppb. Arsenic and Sb abundances are generally low and this is thought to be related to felsic lithology as concentrations are slightly greater in mafic saprolites. Elevated Fe, Cr, Ni and Co in the saprolite are also indicative of mafic lithology.

The geochemical differences between the ultramafic and felsic parent rocks diminish up profile. The distinction remains evident in the saprolite and mottled zones but in the lateritic duricrust the Al, Si, Fe, Mg, Zr, Cr and Ni contents are similar over both felsic and mafic rocks. This suggests that the laterite has developed in transported material.

3.15 Wollubar-Enigma Prospect, Eastern Goldfields

Location
Wollubar-Enigma is located about 35 km SSE of Kalgoorlie. AMG: Zone 51 363000E 6564700N.

Climate, vegetation and landform
The climate is semi-arid with an average annual rainfall of about 280 mm. Vegetation is sparse and consists of open woodland of *Eucalyptus* ssp. with *Eremophila* (poverty bush), bluebush and other small shrubs. The area has been extensively logged in the past, and there is a considerable groundcover of grasses. The site is on a flat, depositional plain with some development of ephemeral drainage in the W of the study area.

Geology and mineralization
The deposit is located within the Kambalda Domain of the Kalgoorlie Terrane, part of the Archaean Wiluna-Norseman Greenstone Belt. Bedrock consists of high-Mg basalts, some with pillows and variolitic textures, and sediments, felsic volcanics and volcaniclastics of the Black Flag Group. Bedrock has been regionally metamorphosed to upper greenschist - lower amphibolite facies. The N-S trending Mt. Hunt fault runs though the prospect, and the Au bearing Boulder-Lefroy Shear occurs 4 km to the W. Primary Au mineralization at the Wollubar-Enigma prospect is associated with

sericitic schist. Supergene mineralization is present in sub-horizontal enrichment in sands at the unconformity between the transported overburden and residual materials.

Regolith

The study area is adjacent to a large palaeochannel, which is infilled by clays and sands. Within the channel, the partly stripped residual weathering profile is covered by some 55 m of sediment. The saprolite is clay-rich beneath the unconformity, and is increasingly indurated with depth, so that saprock is reached at about 90 m depth. Pale (cream, yellow and pink) clays occur from 15 m depth to the base of the palaeochannel, and directly over the palaeochannel, grey reducing clays are present from 35 m depth. Rounded to subrounded sand grains can be sieved from the clays from 20-55 m depth. Clay-rich red soils occur between 0-15 m depth. The subsoil contains Fe-rich granules and pisoliths, and the clays are often puggy. It is overlain by a thin sand-rich topsoil, about 10 cm thick, containing considerable quantities of ferruginous granules. Carbonate infuses the top 1-2 m of the red clays.

Geochemical dispersion in the regolith

A limited geochemical study was undertaken at Wollubar-Enigma, targeting soil, ferruginous components in the transported cover, and material from saprolite and saprock. Soil was sampled by augering to a depth of 1 m on an E-W traverse over mineralization. Sediment, saprolite and saprock samples were collected from RC drill cuttings.

The distribution of Au in the soils at Wollubar-Enigma does not appear to be related to underlying mineralization. In general, Au concentrations are low, averaging about 12 ppb. The maximum Au concentration is 25 ppb and several samples, some directly over mineralization, are below detection (less than 5 ppb). Calcium and Mg are evenly distributed over most of the traverse, with the highest concentrations of Ca towards the W. Normalising Au with respect to Mg or Ca does not produce any significant trends.

The partial extraction of Au by water, iodide and cyanide from the soil samples does not produce any significant enhancements of the data. The concentration of water- and iodide-extractable Au are proportional to total Au, and slightly greater Au proportions of all three extractions occur where no Au mineralization has been recorded in the eastern section of the traverse. Normalising water-extractable Au with total Au, or with iodide-extractable Au, does not produce any significant trends, nor does normalising iodide-extractable Au with total Au.

The Wollubar-Enigma deposit has no surface geochemical expression in total, or in partially extractable Au, or in other elements. Water would be expected to dissolve the most active Au and thus emphasis the contribution of the most recently mobilized or introduced component, including any derived from mineralization. The absence of such a response suggests that any such introduced component is minimal in comparison with Au mobilized by normal pedogenic processes. It is possible that such processes could have led to widespread homogenization of Au, possibly creating a broad low order soil anomaly. Such an anomaly would only be apparent on a regional scale, rather than on the local traverse of this study.

Gold concentrations in ferruginous samples separated from the transported overburden are below the detection limit (5 ppb), except for the sample taken closest to mineralization which has a concentration of 8 ppb Au. Other samples close to the mineralization have higher concentrations of As, Co, Cu, Eu, Lu, Mo, Pb, Sb, Sm and W relative to background.

Saprolite samples with high concentrations of Au (greater than 2 ppm) are enriched in K, Ti, Co, Cr, Mo, Ni, Sb, Sb, Sc and W. Some are also enriched in Cu, Pb and Zn. Concentrations of Ag (5 ppm), Bi (1 ppm), Ir (20 ppb), Se (5 ppm), Ta (1 ppm) and U (2 ppm) are below detection limits (in brackets) in all sample media.

Hydrogeochemistry

Groundwaters from the Wollubar-Enigma area are acid, with pH ranging from 3 to 6. Those closest to the deposit have pH between 3.2 and 3.6, low dissolved Au concentrations (less than 0.01 ppb), and no significant concentrations of other elements. The groundwaters are Fe-rich, and tend to have lower Eh values than other sites with acid groundwaters. With the exception of Au, the minor elements are undersaturated with respect to their least soluble phase, indicating that dissolution is occurring only slowly and/or that concentrations are being limited by other mechanisms such as sorption, or co-precipitation with Fe oxides. Base metals and most other metals, except Al, Sc, Cr and U, show no clear relationship with pH, possibly because their abundance is affected by other hydrological or lithological factors. In contrast, the concentrations of the rare earth elements in the Wollubar-Enigma area are at least 5 times greater than any other documented groundwater in the world.

Biogeochemistry

There are no significant differences between the Au content of vegetation (*Eucalyptus* leaves, *Eremophila*, bluebush and mull) overlying mineralization at Wollubar-Enigma compared with background. A maximum of 3.1 ppb Au is found in bluebush.

4. DISPERSION FROM BURIED DEPOSITS

4.1 Geochemical dispersion models

The characteristics of geochemical dispersion in the various sites investigated in this project can be summarized by appropriate modifications of established models (Butt and Zeegers, 1992). The purpose of the models is to summarize geochemical dispersion in terms of regolith, landform, bedrock and environmental relationships. The intent is that the geochemical dispersion models which result (a) will allow ease of reference to generalised patterns of dispersion and (b) can be used predictively in comparable terrains. The criteria upon which these models are based are as follows (see also Table 4.1).

Degree of preservation of the pre-existing lateritic regolith profile
This largely determines the significance of geochemical and mineralogical characteristics inherited from previous weathering episodes, for example, enrichments of Al, Fe, Ni and Au, and depletions of Na, K, Ca, Mg, Cu and Zn. It also determines the nature of the uppermost residual horizon, whether modified as soil or buried beneath transported overburden:

"A" type models are those in which the profiles are fully preserved. The uppermost residual horizon is commonly the lateritic ferruginous horizon.
"B" type models are those in which profiles are partially truncated by erosion. Saprolite, with quite different geochemical characteristics to lateritic residuum, forms the uppermost residual horizon.
"C" type models are those in which the earlier regolith has been entirely eroded.
This project has investigated sites in which these regoliths, whether preserved or truncated, are buried by transported overburden.

Recent alteration
Marked chemical alteration of the regolith may have occurred under the present climate or during an intermediate period since earlier deep weathering, induced by changes in weathering conditions due to tectonic activity and/or climatic change. The result is commonly either increased leaching or the neoformation or accumulation of secondary minerals. The degree of alteration is only subjectively estimated as 'minor', 'low', 'moderate' or 'strong'; in arid areas, such alteration is marked dominantly by replacement, *e.g.* by carbonates or silica.

Neoformation or accumulation of minerals
These are consequences of changes in the degree of leaching. As a result of increased aridity, smectites may form instead of kaolinite, and silica and alkaline earths may be retained in the soil sequence, commonly as cements (*e.g.* as silcrete and calcrete).

The presence and nature of overburden
The materials that form the surface layer are commonly critical in determining the most appropriate exploration sample media. In relict and erosional terrain, lateritic residuum, saprolite or fresh bedrock, or soils derived from them, occur at surface. In the depositional terrains studied in this project, various types of transported overburden conceal the residual regoliths.

A simple classification based on these criteria is given in Table 4.1 and can be used to summarize the characteristics of each site or prospect as a code (*e.g.*, a prospect in an arid area of low relief, model code B 1 Ca [3], has a truncated profile with transported overburden slightly modified by the development of calcrete). In most of the locations studied in this project, a range of different models may apply, depending on local changes in characteristics. Thus, there may be areas of relict/erosional terrain, in which preserved or truncated residual regolith are exposed at the surface, and adjacent areas of depositional terrain in which they are buried. The depositional terrains are rather more complex than expressed by this classification, and modification might be necessary to account for different types and depths of overburden. More importantly, the classification essentially assumes a single deep weathering event. In effect, this assumption seems acceptable in many relict and erosional terrains on the Yilgarn, but relationships can be more complicated where there are palaeochannels, since some of these appear to be incised into or, in part, to overlie, older regoliths and are themselves deeply weathered. With these provisos, the following situations prevail in depositional environments:

Pre-existing profile preserved, buried
Pre-existing profile truncated, buried
Pre-existing profile partly developed in cover sequences.

The models that apply in depositional areas can only be determined when regolith-landform mapping is supplemented by drilling to determine stratigraphy. Ground geophysical survey methods (such as electromagnetics, and seismic reflection or refraction) can be important adjuncts in delineating regolith stratigraphy. The relationship between regolith-landform regimes and geochemical dispersion models is illustrated in Figure 4.1.

Table 4.1: Classification of geochemical dispersion models for tropically weathered terrains (after Butt and Zeegers, 1992).

Modifications to pre-existing regolith

Pre-existing regolith	**Recent alteration**	**Recent accumulation, cementation or neoformation**	**Overburden**
A: Mostly preserved B: Partly truncated C: Fully truncated	0: Minor 1: Low 2: Moderate 3: Strong	0: None Al: Al oxides AS: Al silicates Ca: Ca and Mg carbonates Gy: Gypsum Fe: Iron oxides Si: Silica Sm: Smectites	0: None 1: Residual soil 2: Semi-residual 3: Transported

Example:
B 1 Ca [3]: truncated profile, some recent alteration with pedogenic calcrete and transported overburden.

NB. An asterisk * can be used for generalized models for which a characteristic is not diagnostic:
e.g., B * * [3]: buried truncated profile, with any type of recent alteration, neoformation or cementation.

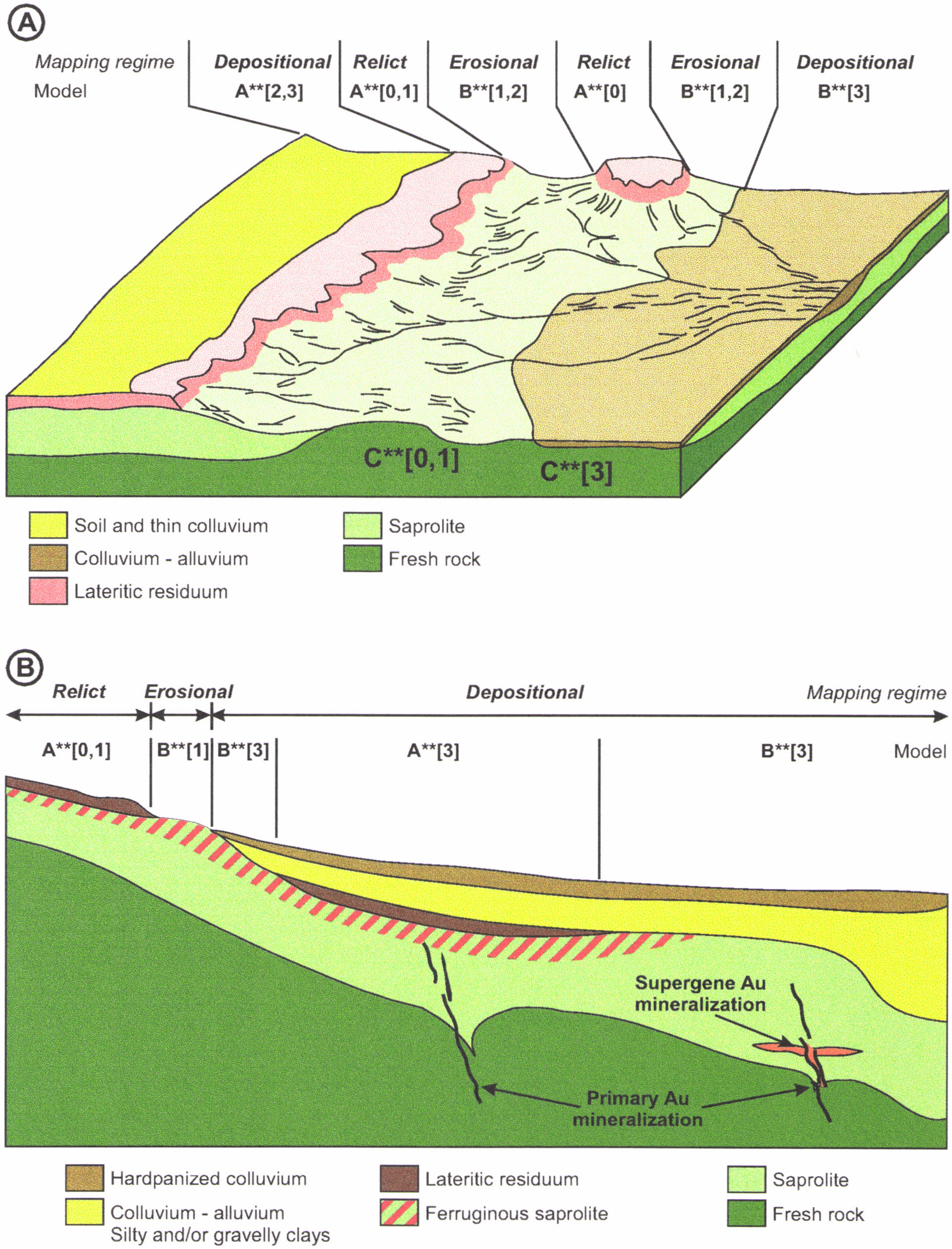


Figure 4.1: Relationship between regolith-mapping units, regolith stratigraphy and geochemical models.

4.2 Pre-existing profile preserved, buried (A-type models)

Sites representing A-type models studied in this project occur over all or part of the Bronzewing, Harmony, Curara, Stellar and Fender deposits, which are north of the Menzies Line. At each of these, the results confirm that strong, widespread, multi-element anomalies are present in the lateritic residuum. Accordingly, this is the preferred exploration sample medium. Wide-spaced drilling to sample this specific horizon is an effective regional approach that can be followed-up by similar, closer-spaced drilling and sampling (Figure 4.2). At each of these sites, which are typical of the region, the degree of preservation of the lateritic residuum is variable, and the thickness may vary over very short distances. At Bronzewing, for example, the lateritic residuum consists of pisoliths and nodules merging to collapsed ferruginous saprolite with depth. The unit is over 5 m thick at the Laterite Zone, beneath about 5 m of colluvium, 1-5 m thick beneath 15-20 m of colluvium 1 km further south at the Central Zone and absent in the Discovery Zone, where the cover is over 30 m deep. Within the Central Zone, erosion has locally reduced the total thickness to about one metre, yet adjacent solution-collapse structures in the saprolite may be filled with ferruginous material, hence the "thickness" of the lateritic horizon may vary by 2 or 3 m over a horizontal distance of 5 m.

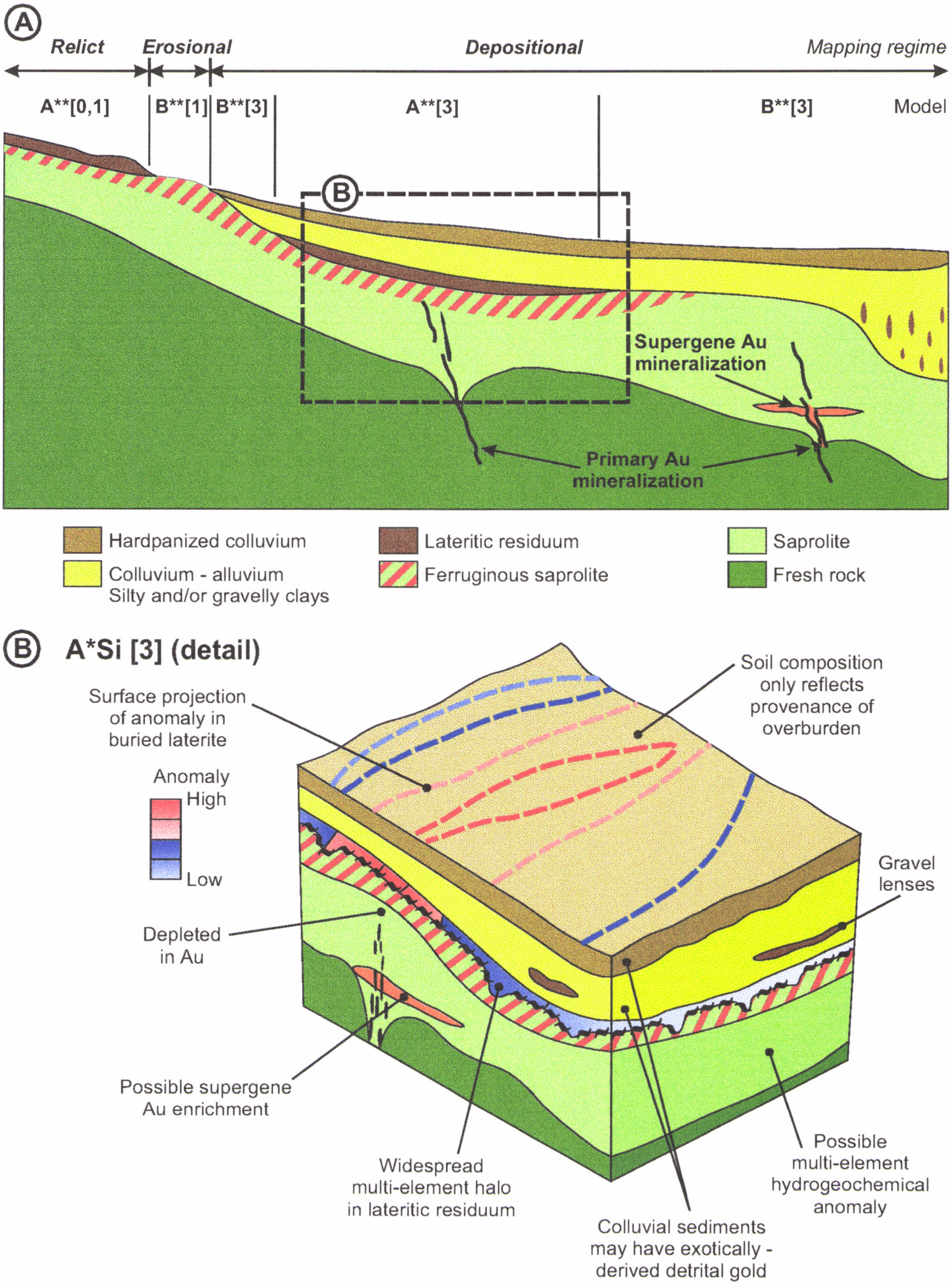


Figure 4.2: Model illustrating the dispersion associated with buried lateritic residuum.

The wide geochemical haloes in the lateritic residuum are largely a product of residual accumulation and physical and chemical dispersion occurring during deep weathering (Section 2.4.2). The lateritic horizon is partly colluvial in origin and has developed by both by collapse, which entails both vertical and lateral movement, following chemical wasting, and mass flow (soil creep), resulting in downslope movement. The geochemical anomalies include a residual component comprising elements hosted by stable primary and secondary minerals. At most sites investigated, the lateritic residuum is overlain by similar, colluvial or alluvial gravels. The lower units of these gravels may also be anomalous, but it is important to be able to distinguish between the residual and transported components, since the latter may be of distal origin, especially if deposited in high energy environments or high in the sedimentary sequence. A polymictic composition, rounding of quartz or lithic clasts, fractured ferruginous materials and an absence of cutans on pisoliths and nodules are important criteria.

No evidence has been found at any of the sites investigated for significant hydromorphic dispersion of Au or pathfinder elements into the cover sequence in areas where the pre-existing profile is presented. Anomalous concentrations of these elements within 2 or 3 m of the unconformity appear to be physical in origin. At Bronzewing, for example, the lowest transported units are also anomalous in Au and pathfinder elements, either because they are very locally derived, or due to mixing during or after sedimentation. At Harmony and Fender, where the cover is very thin (<3 m), such mixing (*e.g.*, by bioturbation) gives a surface or near-surface (top metre) expression to the mineralization. Conversely, at Curara, where the colluvium is over 10 m thick, there is a seemingly hydromorphic, multi-element surface anomaly (without Au), evident in both total and partial extraction analyses, directly overlying mineralization. However, this is attributed to co-precipitation with secondary Mn oxides in a modern drainage that overlies the deposit (see Section 8.5.4). These elements would appear to be derived laterally from ongoing, near-surface weathering within the drainage catchment, rather than vertically from the underlying deposit. At Harmony, precipitation of Mn oxides gives a similar anomaly adjacent to the mineralization. There is no evidence from any site that partial extraction analyses reveal any surface expression of otherwise blind mineralization. Hydrogeochemical surveys, however, do offer promise in some environments (Chapter 6), including Harmony.

4.3 Pre-existing profile truncated, buried (B-type models)

4.3.1 Residual regolith

Sites represented by buried B-type models occur at all areas studied in this project, except those wholly confined to palaeochannels as discussed in section 4.4. In all such sites, lateritic residuum is absent (presumably eroded although, in places possibly never formed) and hence so also absent are the broad anomalies associated with this horizon. Accordingly, different and, in many respects, more intensive (and thus more expensive), sampling options are required. Anomalies in the upper residual regolith (*e.g.*, saprolite or mottled clay zone) are likely to be smaller in area than those where lateritic residuum is present and, for Au, if corresponding to the depletion zone, of low contrast. This is evident in the buried uppermost saprolite at Fender, in which Au and W haloes are very restricted, whereas those of As and Sb are more extensive, although it is uncertain whether the latter reflect secondary dispersion or are partly related to primary alteration. At Golden Delicious, a lithological change appears to coincide with the uppermost residual horizon (mottled zone). The abundance of W, the most promising pathfinder element, is low in this zone, but this may be a primary geochemical feature, rather than due to depletion during weathering. Wider dispersion is possible for some mobile pathfinder elements (*e.g.*, As) or contrast may be greater for less mobile elements (*e.g.*, Sb, W). Reduced dispersion, giving restricted anomalies, commonly with high contrasts, occur where truncation is deeper, *e.g.*, to lower saprolite, saprock or fresh rock, a feature at both Quasar and Safari. In environments where supergene Au enrichments may be expected in saprolite - such as in highly saline sites close to playas, these may be targeted by drilling to saprock.

4.3.2 Transported overburden: north of the Menzies Line

There is some evidence for secondary dispersion haloes in the transported overburden at sites where it overlies truncated regoliths. This dispersion may be chemical or physical or both, and generally occurs at or just above the unconformity (Figure 4.3).

At Fender and Harmony, the dispersion is probably almost entirely physical, due to the erosion and transport of detrital fragments derived from anomalous lateritic residuum. The anomaly at Harmony is present in the basal horizon of the colluvium, particularly where this consists of a complex, metre-thick mixture of residual (saprolite, lateritic residuum) and detrital materials that probably represents a buried palaeosol, rather than a sharp, erosive unconformity. Interface sampling on a 150 m triangular grid yielded anomalies of Au (200->1500 ppb) and W 5-70 ppm) over much of the southern part of the Harmony deposit and down the palaeoslopes on the periphery.

At Fender, significant dispersion haloes are evident in the lower, silty clay unit of the transported overburden, which directly overlies saprolite. Arsenic, Sb and, to some extent W, but not Au, remain anomalous as far as 200 m away to the east of the subcrop of mineralization. The As and Sb are almost entirely hosted by detrital ferruginous nodules, which generally form less than 20% (by weight) of the sediment. The mixture of size fractions, *i.e.*, matrix-supported nodules, up to 6 mm diameter, in fine silty clays, implies a low energy sedimentary environment and probable proximal origin of the coarse material. The optimum sampling procedure is to separate and analyse the nodules, possibly from composite samples of the basal 2 to 4 m of the silty sediments, rather than to analyse single or composite samples of the bulk material. Normalizing the data with respect to Fe is recommended for As and Sb, in particular. This yields higher concentrations, higher contrasts and a broader anomaly, and will be most beneficial where the mineralization has lower primary abundances of these elements which, at Fender, are rather high (mean 145 ppm As, 450 ppm Sb, 130 ppm W). The anomalous nodules at Fender are derived from erosion of lateritic residuum, not from the sub-crop of mineralization at the saprolite-colluvium unconformity, hence similar dispersion patterns may not be found where truncation is deeper and there are no residual lateritic remnants.

The overburden at Quasar and Golden Delicious represents a higher energy depositional environment and more distal provenance than Fender or Harmony. Middle to upper units of the sediments have sporadic Au anomalies, reflecting district or regional scale features. For example, the background Au abundance in alluvium and colluvium at Quasar is over 50 ppb, in response to the widespread mineralization in the catchment, but isolated higher values are unrelated to specific underlying sources. Colluvium at Golden Delicious is similar, although background is lower (<10 ppb), with local maxima unrelated to underlying mineralization. The material at Golden Delicious is also strongly calcareous, but there gives no geochemical response to mineralization. At both sites, however, sampling across the interface gives significant, coherent anomalies that are broader than those evident in the upper residuum (saprolite or mottled clay zone) that extend, for Au, about 150 m and 300 m downslope at Quasar and Golden Delicious, respectively. Neither deposit has a strong pathfinder suite, but similar broadening of the multi-element response is evident at this interval. At Quasar, Cu and, to a lesser extent, Zn, also give broad anomalies at the unconformity, whereas those of Bi and Pb are restricted, though still greater than in saprolite. It is possible there has been hydromorphic dispersion of Au, Cu and Zn, but only clastic dispersion of Bi and Pb.

The basal units of the sediment may contain locally-derived detrital fragments or material introduced by post-depositional churning, but the anomalies also appear to include a chemical component. This is suggested by partial extraction analyses of basal gravels (whole sample) in the colluvium at Golden Delicious. A high proportion (over 80%) of the Au is iodide-soluble, even in unpulverized samples, implying a chemical origin; the proportion is much lower in the underlying saprolite.

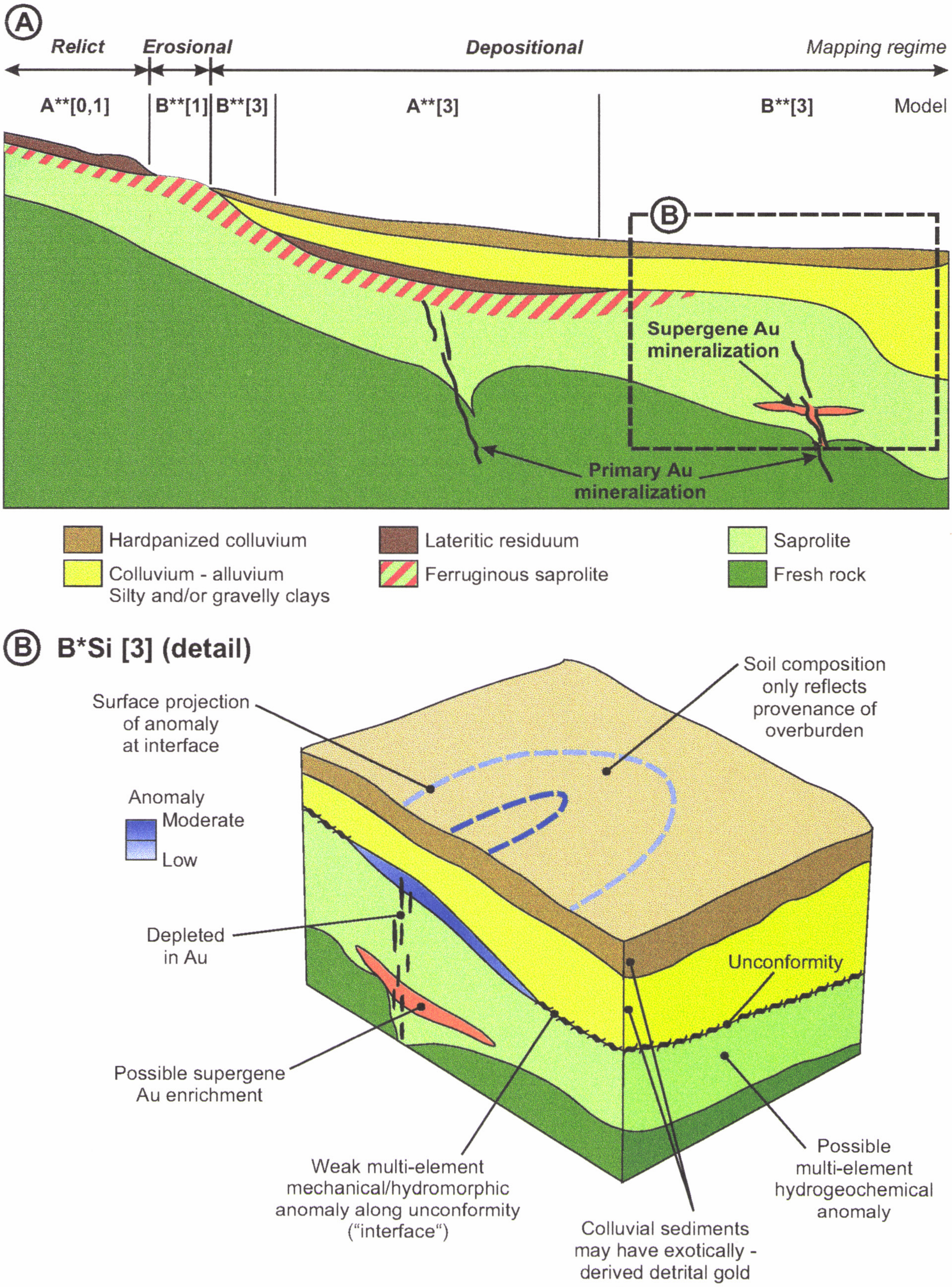


Figure 4.3: Model illustrating the dispersion of Au and pathfinder elements at the unconformity between transported overburden and saprolite.

In summary, sampling of transported overburden has little value except where it is thin (probably less than about 2 m) and bioturbation can occur, or where the basal unit is sampled, either alone or as part of a sample across the interface. When sampling a basal unit, specific selection of ferruginous materials is recommended, particularly where they are a minor component of the sample, and these could be composited over 2 or 3 metres. In general, for bulk samples, analysis of individual 1 m intervals is preferred, although composite sampling may be useful across the interface.

4.3.3 Transported overburden: south of the Menzies Line

In the southern Yilgarn, the surface expression of Au mineralization in transported overburden, other than sediments in palaeochannels, was investigated at two sites, Safari and Argo. This supplemented earlier investigations at Kanowna Belle, Wombola and Matt Dam, studied as part of Project 240A (Anand *et al.,* 1993). In addition, minor investigations were conducted at Panglo and Runway, where very thin (generally less than 1 m) transported or semi-residual cover overlies leached saprolite, with supergene mineralization at 30-50 m depth. Each of these sites is characterized by the presence of pedogenic carbonate, which commonly occurs in the top 1.5 to 2.0 m. At Safari, however, the most northerly site, much of the carbonate is deeper (1.0-4.0 m), possibly because of the sandy matrix of the overburden. As in relict and erosional areas, there is generally a close association between Au and Ca, related to the occurrence of pedogenic carbonate. Results are summarized in Table 4.2.

The sediments are rarely more than 0.5 m thick at Panglo and Runway, and there are strong soil anomalies in the calcareous soils and upper saprolite, directly overlying mineralization, despite the depletion. At both sites, particulate gold is present in some of the ferruginous lithic fragments that comprise the coarse fractions of the residual sub-soil. These are probably relict grains that either were retained in less leached horizons, or were protected from the processes that led to depletion. Such grains, rather than the supergene mineralization, may be the immediate source of the Au now associated with the carbonates.

At Wombola and Kanowna Belle, calcareous and non-calcareous clay soils are developed in colluvium that overlies leached saprolite. Gold anomalies are present in the calcareous soils directly overlying mineralization at both sites. Gold-rich silcrete in the upper saprolite is possibly the immediate source of gold at Kanowna, but no equivalent shallow source is known at Wombola. Broader, multi-element (As, Sb, W) anomalies are shown by selective sampling of ferruginous granules, although maximum Au abundances are much lower than in calcareous soil, and it is probable that these anomalies do not indicate directly underlying mineralization. A pronounced Au anomaly is also present in the calcareous soils at Safari. This directly overlies mineralization, which subcrops at the unconformity at about 8 m depth.

Apollo and Matt Dam have a deeper (up to 10 m or more) cover of dominantly clay-rich alluvial or lacustrine sediments; Matt Dam is marginal to a palaeochannel. High Au contents (to 450 ppb) are present in the fine (minus 75 μm) calcareous fraction of the soils at Matt Dam, but this is considered to reflect the presence of Au-rich ferruginous nodules derived from the adjacent erosional area, rather than underlying mineralization. In contrast, at Apollo, Au abundances in calcareous soils and transported units are very low (with the maximum, 17 ppb, in a background area) and show no distribution patterns related to the occurrence of mineralization, despite its relatively shallow depth (15 m). At best, these abundance levels of Au may represent a weak regional- or district-scale enrichment indicating the presence of prospective sequences. An unusual feature at Apollo is an apparent biogeochemical anomaly (maximum 21 ppb Au, plus elevated Fe and other elements, Section 7.2) in bluebush. It is uncertain whether this anomaly is genuine, presumably derived from saprolite, or whether it is due to mine dust trapped by hairs on the leaves.

Table 4.2: Geochemical response in calcareous soils to concealed Au mineralization, southern Yilgarn Craton.

Sediment thickness	Characteristics of upper regolith	Depth to mineralization	Soil Au content ppb	Possible Au source	Reference
Runway					
Up to 0.5 m; sheetwash	Calcareous soils on saprolite	Supergene mineralization at 50 m depth.	20-270 ppb Au in surface soil (0-1.0 m); background <20 ppb.	Particulate Au in Fe saprolite and nodules	Lintern, 1996a
Panglo					
Up to 0.5 m sheetwash	Thin calcareous soils on saprolite	Supergene mineralization at 30-40 m	25-115 ppb Au in top 10 cm; back-ground <20 ppb.	Particulate Au in Fe saprolite and nodules	Lintern and Scott, 1990; Lintern, 1996b
Wombola					
2-5 m colluvium	Calcareous and non-calcareous red clays, abundant Fe oxide granules and pisoliths; on mottled clay	Weathered mineralization at 40 m.	60-440 ppb Au in calcareous soil (0-1 m)	Not known.	Anand *et al.*, 1993
Kanowna Belle					
2-6 m colluvium	Calcareous and non-calcareous red clays with Fe oxide granules, on saprolite	Supergene mineralization at 30-50 m	40-225 ppb Au in calcareous soil (0-1 m); background 20 ppb	Au-rich silcrete	Anand *et al.*, 1993
Safari					
2-10 m; sheetwash, sandplain	Sandy sediments, on saprolite and saprock; calcareous between 0.5-4.0 m.	Weathered mineralization at unconformity	7-85 ppb Au in calcareous zone (0.5-3.0 m); 7-25 ppb over 350 m in top 0.5 m. Mean back-ground 4 ppb.	Sub-cropping mineralization	Bristow *et al.*, 1996b
Apollo					
5-10 m alluvium, lacustrine clay	Sandy soil (0-0.2 m), calcareous and non-calcareous red clays, over mottled grey clay and saprolite	Weathered and ?supergene mineralization at 15-70 m	10-15 ppb Au in calcareous soil at 0-1.0 m (background 6-17 ppb).	Regional	Lintern *et al.*, 1997.
Matt Dam					
8-10 m colluvium-alluvium	Calcareous and non-calcareous red clays with Fe oxide granules, on channel clay and saprolite	Supergene mineralization at 20-40 m	50-450 ppb Au in calcareous soil at 15-20 cm. (minus 75 µm fraction)	Possibly Au in gravels washed from erosional area. Some Au in ferruginous saprolite.	Anand *et al.*, 1993

It is concluded that the calcareous horizon is the optimum sample medium for soil sampling in erosional and depositional regimes for directly targeting concealed mineralization, with the proviso that the sediments in the depositional regime are shallow *i.e.*, no more than 5 to 8 m over most of the prospect. It is probable that the Au is only directly derived from mineralization if that is present at the unconformity; at sites where there has been considerable leaching and depletion, there is probably a secondary source, such as relict Au grains in saprolite (Figure 4.4B). Where the sediments are thicker, it appears that no direct response from concealed mineralization may be expected and that any anomalies may reflect the presence of Au-rich materials within the sediments of distal origin. A similar finding is apparent in palaeochannel environments, as discussed in the following section.

4.4 Pre-existing profile partly developed in cover sequences

4.4.1 Model classification

This situation refers largely to the weathering profiles of sediments within palaeochannels. The stratigraphy of the channels is described in Section 2.4.3. Such environments are present throughout the Yilgarn Craton and adjacent areas, although the majority of study sites are in the Kalgoorlie-Norseman region. Their occurrence is a not readily defined in terms of the simple classification of geochemical models given in Table 4.1. If the weathering of the sediments is regarded as equivalent to the lateritic regolith on the basement, then they may be considered as A (or, where eroded, B) models, with a thin, late-stage cover of transported overburden and minor to moderate recent alteration *i.e.*, model A(or B)1*[3]. Alternatively, they represent situations having a truncated original (pre-depositional) deep weathering profile, overlain by transported overburden and considerable 'recent' (post-depositional) alteration - *i.e.*, model B3*[3].

4.4.2 Palaeochannels in the northern Yilgarn Craton

Palaeochannels are present over parts of the Harmony, Stellar and Bronzewing (Central Zone) deposits, and to the south of Quasar. Supergene enrichment of gold was mined at Stellar prior to the commencement of the research, but no material remained for examination. The relationship with the channel is uncertain, but appears to have been associated with colluvial quartz cobbles on its margin. No supergene enrichment of gold is known in either the sediments or the underlying saprolite at Quasar and Harmony, and it is only minor at Bronzewing. The palaeochannel sediments at Stellar and, particularly, Bronzewing were not studied in detail, but neither have any geochemical indications of proximity to mineralization. At Harmony, however, there are two channels draining away from the deposit. The *Waste Dump* channel drains south west from the mine and samples from a hole 500 m from it are weakly to moderately (and very variably) enriched in gold (lower colluvium has a maximum 125 ppm Au), upper pisolitic horizon of the channel sediments (maximum 224 ppb Au); lower channel sediments (mean 24 ppb Au, maximum 74 ppb Au). There are other bedrock anomalies between this site and the mine and a saprolite sample from beneath the channel here contains 33 ppb Au. The As, Sb and W contents of the sediments are generally low, although there is minor W (mean 10 ppm) in the basal sands. The *Harmony* channel drains NNE from the deposit and is exposed in the NE pit wall. About 120 m from the pit, anomalous concentrations of Au (305 ppb), As (490 ppm) and Sb (7 ppm) in the lateritic duricrust residual form part of the geochemical halo around the deposit, but the overlying clays have low concentrations of these elements (means 10 ppb, 9 ppm and 2 ppm respectively). In comparison, W is anomalous in both the duricrust (mean 38 ppm) and the clays (mean 18 ppm). Both channels originate close to the deposit, hence much of the sediment is locally derived. The data suggest that the sediment compositions may be reflecting either the general occurrence of mineralization in the district (Waste Dump channel), or Harmony deposit itself (Harmony channel).

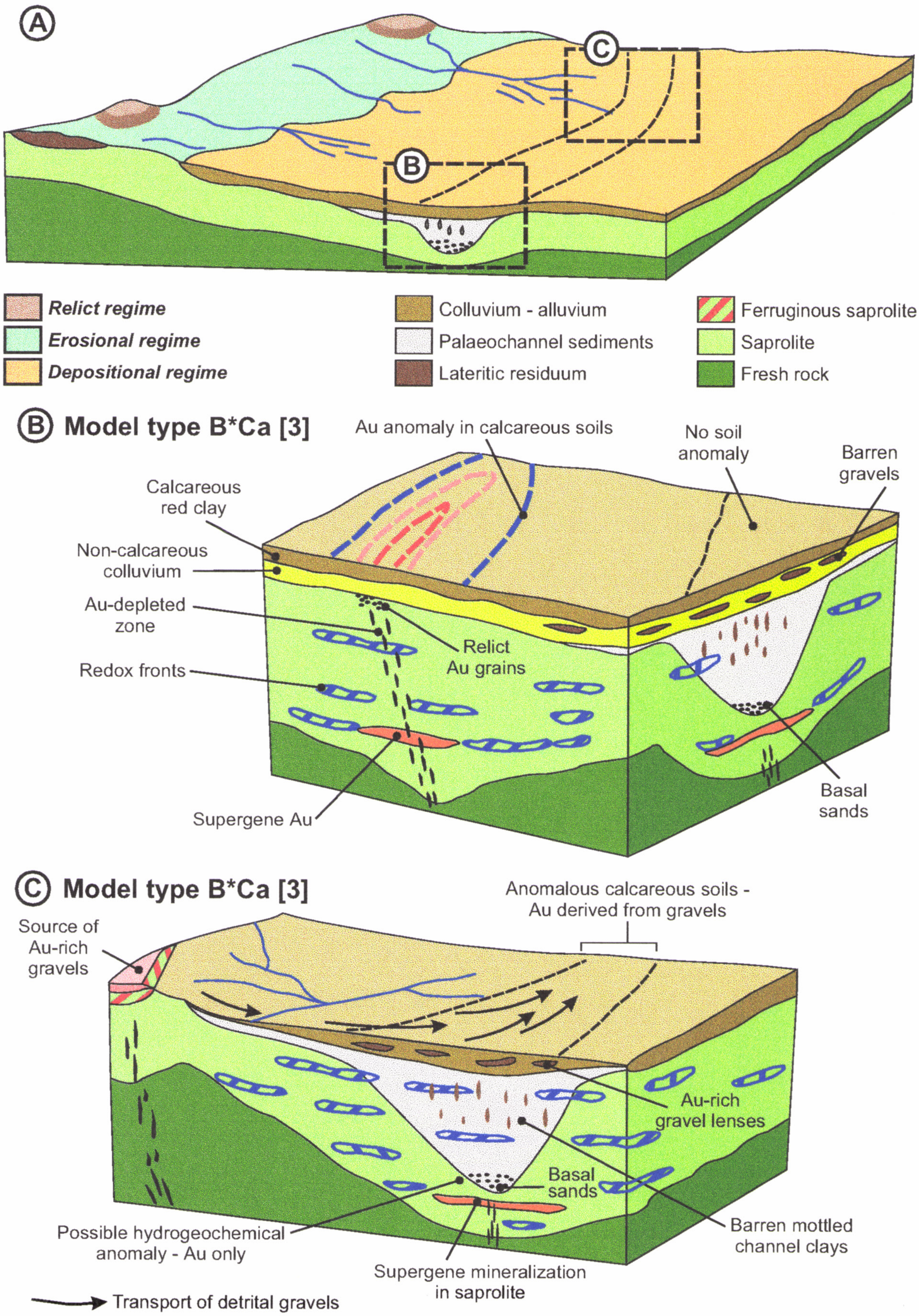


Figure 4.4: Model illustrating the dispersion of gold and pathfinder elements in depositional areas with buried palaeochannels. (A) Generalized landscape; (B) Development of Au anomaly in pedogenic carbonate from relict Au grains in area of shallow (<10 m) overburden. No anomaly over palaeochannel; (C) Spurious anomaly over palaeochannel mineralization, developed from Au grains in detrital gravels.

4.4.3 Palaeochannels in the southern Yilgarn Craton

Supergene gold mineralization is associated with many tributary channels of the Roe, Lefroy and Cowan palaeodrainages, and occurs within and/or, beneath the channel sediments. Known deposits in the Roe channel are all in currently oxidizing environments, although in the past some sediments were probably reducing, whereas those in the Lefroy and Cowan palaeodrainages remain dominantly reduced (see Chapter 2). The principal objective of studies in these environments has been to determine whether the presence of mineralization is expressed in the soils, upper sediments and/or plants, concentrating particularly on calcareous and ferruginous materials as probable hosts of Au and associated pathfinder elements.

Investigations of deposits in the Roe palaeodrainage concentrated at Steinway, Wollubar, Kurnalpi, Kanowna QED and Lady Bountiful Extended, supplementing previous research at Zuleika and Mulgarrie. Exploration data had suggested that the Baseline deposit, east of Panglo, was delineated by calcareous soils containing over 50 ppb Au (background 20 ppb Au; maxima >150 ppb Au), although the mineralization occurred at about 20-25 m depth, beneath about 18 m of barren sediments (R. Howard, Pancontinental Mining Ltd., personal communication, 1992). Baseline was mined before further studies could be undertaken, and results from Zuleika and Mulgarrie were inconclusive, due to the probability of natural contamination from adjacent outcropping mineralization, although in neither case were there pronounced anomalies. Accordingly, other sites were investigated to determine whether this observation was a common feature over these deposits. Of these, only Steinway has a soil anomaly overlying mineralization, which is delineated by the Au contents >24 ppb (maximum 150 ppb). However, soils over the adjacent Greenback deposit, which has now been mined, were not anomalous. A detailed investigation at Steinway has indicated that detrital pisoliths and ferruginous lithic nodules in the soil and immediately underlying units are randomly enriched in Au, and that some contain Au grains. It is concluded that the occurrence of the soil anomaly immediately overlying mineralization at Steinway is probably coincidental, and that the Au is derived from another source, such as the outcropping Penfold deposit, 1 km south. The origin of the Baseline anomaly is uncertain, but similar, adjacent mineralization has no surface expression. This situation is represented by the model depicted in Figure 4.4C.

Broadly similar conclusions have been reached from investigations of the deposits in and beneath reducing sediments at Argo (Lefroy palaeodrainage) and in the Challenge-Swordsman and Mitchell channels (Cowan palaeodrainage). The distribution of Au in soil at Argo does not appear to be related to the underlying mineralization and there are no significant differences in the distribution, total or partial Au contents between mineralized and background areas. In addition, there is no biogeochemical response, unlike that apparently present over the adjacent Apollo deposit. The Au contents of calcareous soils over the Pluto (Challenge-Swordsman channel) and Mitchell-4 (Mitchell channel) deposits are not directly related to mineralization. Indeed, no Au was detected (detection limit 5 ppb) in samples overlying either deposit, although there is a general association between Au and pedogenic carbonate in the soils of the region. Neither conventional nor proprietary (MMI, enzyme leach) partial extraction techniques delineate mineralization. In contrast, soils over outcropping mineralization at the Vine deposit gives a strong anomaly in calcareous soils. This anomaly extends downslope to the Graveyard-Aphrodites deposits in the Mitchell channel, but as at Steinway, the immediate sources of Au in the soils are probably detrital ferruginous granules. The granules have highly variable Au contents (<100-5100 ppb), with Au present, at least in part, as discrete grains, and are probably derived from exposed mineralization (*e.g.*, Vine). Gold derived hydromorphically from buried mineralization would be expected to be evenly distributed. Accordingly, the occurrence of the soil anomaly at Aphrodites also appears to be coincidental. These contrasting resonses are illustrated in Figures 4.4B and 4.4C.

4.5 Conclusion: dispersion into transported overburden

The evidence from the various investigations conducted during this and previous AMIRA projects in the Yilgarn Craton suggests that there has been little significant geochemical dispersion into or through transported overburden. Accordingly, it should not be expected that there will be a near-surface expression of concealed mineralization, particularly where the overburden is over 10 m thick. An exception is the presence of zones of supergene Au enrichment in the sediments of some palaeochannels, including basal sands (Lady Bountiful Extended, Zuleika), lignite (Argo, Challenge-Swordsman) and clay (Kanowna QED). However, none of these is further expressed in the overlying colluvial sediments or soils.

A geochemical response is commonly present in the sediments in the two or three metres immediately above the unconformity with the weathered bedrock. In the northern Yilgarn, these appear to be due largely to physical processes during or after deposition. For example, the low grade anomalies in the top metre of shallow (1-3 m) sediments over lateritic residuum at Harmony and Fender are probably due to bioturbation. In comparison, mixing during erosion and colluvial sedimentation has lead to the broadening of anomalies at the base of the deeper overburden, both where lateritic residuum is partly preserved (Bronzewing, Harmony) and where it has been eroded and saprolite underlies the unconformity (Quasar, Golden Delicious, Harmony). At Golden Delicious, chemical dispersion along the unconformity may also have contributed to the anomaly. Wide physical dispersion is a feature at Fender, where ore-associated elements, principally As and Sb, are hosted by detrital ferruginous nodules scattered through low energy silty clays. The nodules are derived from the erosion of lateritic residuum.

Chemical dispersion, both in groundwater (see Chapter 6) and the regolith, is more prominent in the southern Yilgarn. Active chemical mobilization of a wide range of other elements under present conditions is well established (Mann, 1984; Butt *et al.*, 1991, 1993). For Au, this is demonstrated by high concentrations dissolved in acid, saline groundwaters, and by enrichment as highly soluble forms in pedogenic carbonates. However, this mobility does not appear to give rise to detectable dispersion haloes in transported overburden, except where this is thin. Thus, there are anomalies in calcareous soils at Safari, Kanowna Belle and, perhaps, Wombola, where the cover over residual regolith is generally 5-8 m thick, but not at Apollo or any of the palaeochannel sites where thickness are 10->50 m. There is no response in any other element.

At Panglo and Runway, sub-horizontal zones of supergene Au mineralization occur beneath 40-50 m of leached saprolite, yet still have a surface expression in the soils. These were considered to be possible analogues of channel deposits overlain by barren sediments and were examined further, to determine the cause of the response. Sub-soils at both sites have fragments of ferruginous saprolite containing Au particles. They thus resemble the Steinway and Aphrodites channel deposits, the only sites having a surface response to mineralization, at which ferruginous granules in sub-soil also have Au particles. At Panglo and Fender, the particles and their hosts are probably relict whereas, at Steinway and Aphrodites, they are detrital; however, in each case, they are the immediate source of Au in the carbonates. It is concluded that the soil anomalies at Steinway and Aphrodites are coincidental and cannot be regarded as successful exploration case histories. There are numerous reports of anomalies without underlying sources and of mineralization with no surface expression; these sites represent sites where these situations coincide.

No additional response is gained by the use of partial extraction analyses of any type. However, such extractions appear to highlight another coincident anomaly, at Curara.

5. MOBILITY AND COLUMN EXPERIMENTS ON THE CHEMISTRY OF GOLD IN THE YILGARN CRATON

5.1 Introduction

A important aspect of the Project has been to examine the chemical processes whereby Au can potentially be redistributed within *in situ* or transported regolith. The chemistry and mobility of Au in soils is generally poorly understood. Soils contain organic matter, amorphous Fe oxides and fine clays that are difficult to analyze and have very complex interactions with metals. As part of previous AMIRA projects, specific partial extraction techniques have been developed to investigate the chemistry of Au in soils (Gray *et al.*, 1990, Gray and Lintern, 1993). These techniques are used to provide information on the nature of Au in regolith material. If Au is extractable using weak reagents, this suggests that it may be easily mobilized in its natural location and may be present as fine particles or as a compound. Where this high extractability is observed even in uncrushed material, then Au is presumably easily accessible to mobilizing fluids. Gold that does not readily extract may be encapsulated within resistant material, be firmly adsorbed on surfaces (such as carbon) and/or be coarse grained.

Gray and Lintern (1993) summarized development of the iodide and water methods for soil and regolith samples taken from the southern Yilgarn Craton (Bounty deposit, Mt. Hope, Panglo, Mt. Percy, Mulline, Lights of Israel, Zuleika and Mulgarrie), with two sites (Granny Smith and Beasley Creek) north of the Menzies line. These investigations have been extended as part of this project: from sites south of the Menzies Line in the Kalgoorlie-Norseman area, namely Steinway, Argo, Kurnalpi, Enigma, Runway, Panglo, Apollo, Higginsville (Lintern and Gray, 1995a,b,c,d; Lintern, 1996a,b; Lintern *et al.*, 1997, 1996); from sites within and just north of the Menzies line, namely Golden Delicious and Safari(Bristow *et al.*, 1996a,b); some minor investigations in some more northern sites (Fender, Baxter, Curara and Bronzewing); an additional small study of a reduced palaeochannel in the Gindalbie region. These sites all contain extensive transported overburden, of varying depths. The objectives of the investigations in this project were:

(i) further study of the chemistry of Au in soils;
(ii) to develop partial extraction methods as exploration techniques in areas of transported overburden;
(iii) to investigate the chemistry of Au in deeper regolith, with a view to understanding Au dispersion processes in residual and transported regolith;
(iv) to simulate some of the hypothesized processes of supergene Au mobilization.

Objective (i) has been substantially completed, and has, to a large extent been discussed in Gray and Lintern (1993), though a brief summary is given in Sections 5.3 and 5.4. The second objective (Sections 5.5 and 5.6) has, with a few minor exceptions, been unsuccessful. As discussed in Chapter 8, this also has consequences for the usefulness of other, similar, methods. The third objective is still under investigation, and results to date are reported in Section 5.7, and objective (iv), using column simulation, is still in the early stage of research, although results to date are presented in Section 5.8.

5.2 Methods

Soil and regolith samples were carefully collected from shallow pits and drill core, or using RAB, vacuum or auger drilling methods, along traverses across mineralization and into background areas. Three partial extraction solutions were used to test the solubility of Au (Gray and Lintern, 1993). In all cases, a 25 g portion of unpulverized (denoted as COARSE) or pulverized (to nominal <75 μm; denoted as FINE) sample material was mixed with 50 mL of extractant in a screw-cap polyethylene plastic bottle, and then gently agitated for one week, after which the total Au extracted was measured. In early tests, total Au was measured by analyzing the solution (denoted as a NET extraction). Later analyses were done by adding a 1 g carbon sachet with the sample and analyzing the carbon using INAA (denoted as a GROSS extraction): the carbon sachet procedure reduces re-adsorption of the dissolved Au on components within the sample. The three solutions were:

(i) deionized water: dissolves the most soluble Au;

(ii) iodide: a 0.1M KI solution is adjusted to pH 7.4 with HCl whilst CO_2 is bubbled through. This extraction dissolves more Au than water alone. Another form of this test did not involve pH adjustment; there is little difference in Au recovery for carbonate-rich soils;

(iii) cyanide: 0.2% KCN in alkaline solution.

The partial extraction tests were performed either on separate portions or as a sequential extraction using 3 different carbon sachets commencing with deionized water and finishing with cyanide.

5.3 Kinetic tests

These tests were described in detail in Gray and Lintern (1993), and briefly summarized below. In the absence of carbon (net results in Figure 5.1), significant re-adsorption of dissolved Au occurred, particularly for fine (*i.e.*, pulverized) samples. When carbon was used in the extraction to absorb all dissolved Au (*i.e.*, gross extraction), significantly more Au was extracted.

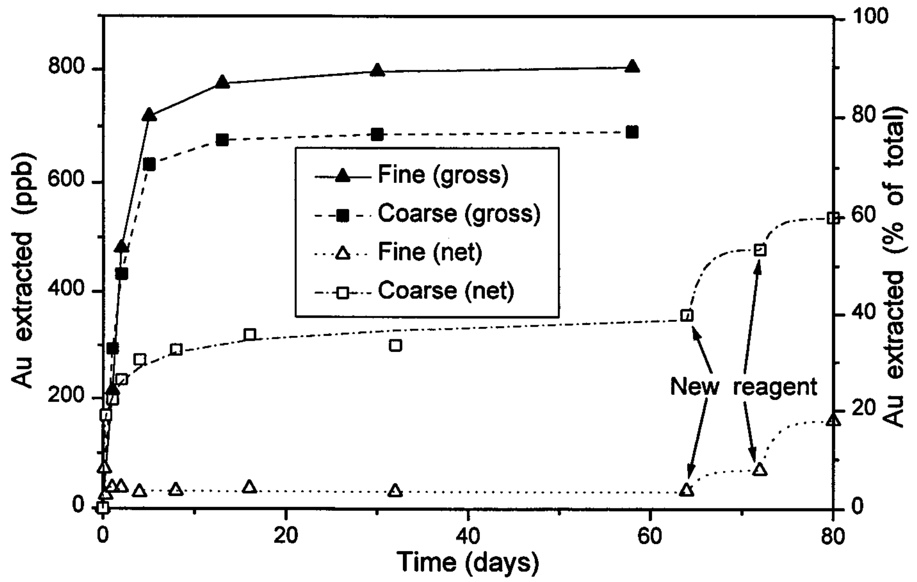


Figure 5.1: Iodide extraction of Au from carbonate-rich sample from Bounty (Gray and Lintern, 1993).

5.4 Soil profile studies

Previous work (Gray and Lintern, 1993 and references given therein) has demonstrated the close correlation of total Au and Ca in a number of carbonate soils throughout the southern Yilgarn Craton (*e.g.*, Figure 5.2). Additionally, this Au is highly soluble (Figure 5.3): for carbonate, and other biologically active soils such as those in drainage areas, 50-90% of the Au is gross iodide soluble for coarse material (indicating that most of the Au is highly soluble and accessible to the solution), increasing to greater than 90% for fine material. Other, less biologically active material, such as lateritic gravels (Figure 5.4), calcrete or silcrete (Figure 5.11), have gross iodide solubilities less than 50%, even for fine material, suggesting that biological factors are important in increasing solubility of Au.

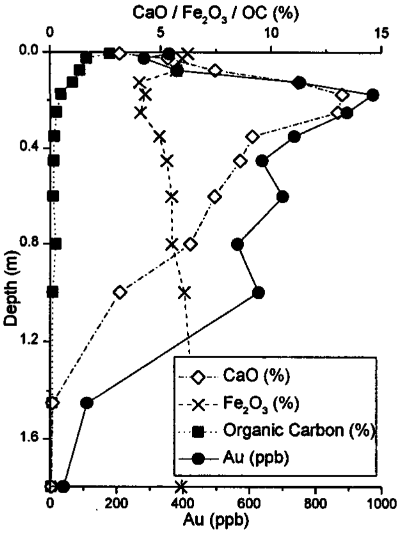


Figure 5.2: Composition vs. depth for carbonate-rich profile, Bounty.

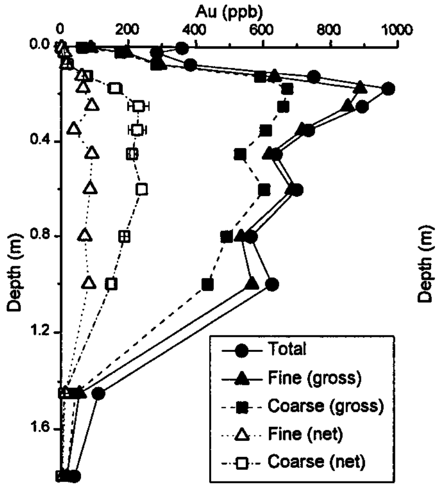


Figure 5.3: Iodide extraction from carbonate-rich profile, Bounty.

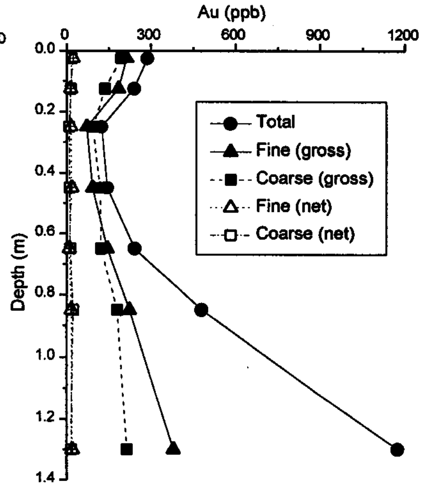


Figure 5.4: Iodide extraction from lateritic gravels, Bounty.

The repeatability of water and iodide extractions of Au is good. For example, duplicates of Au dissolved from fine (pulverized) material by both water and iodide with carbon added at Safari generally show less than 5% variability (Figure 5.5). A notable exception was one sample where the total cyanide extractable component varied by more than 150%, presumably due to nugget effects. Indeed, iodide extraction (even of coarse material) commonly gives better repeatability than cyanide, consistent with the more soluble Au been uniformly dispersed within the soil. As suggested by these comparisons and the results given above, gross (*i.e.*, carbon added) iodide extraction of coarse material produced the "best" results, in terms of least sample treatment, good analytical sensitivity and experimental robustness. However, care must be exercised to avoid contamination of the carbon by coarse, Au-rich particles when analyzing unpulverized samples, particularly when samples contain high concentrations of Au.

Unless otherwise noted, all subsequent results are for gross iodide extractions of coarse material. It was also found that, for carbonate-rich soils, the iodide reagent need not be pH buffered, enabling easier development of sequential extraction methods. However, for deeper or carbonate-poor materials, buffering makes a major difference to the amount of Au extracted, so that pH buffering should be continued for these samples.

The usefulness of Au extraction for exploration has been tested for various soils, particularly in the Kalgoorlie region. A soil located above mineralization might be expected to have a higher Au solubility than soils distant from mineralization. This was tested on separate aliquots of soils from Argo. The results indicate that soil samples taken at 0.1 to 0.2 m intervals above mineralization were not significantly different with regards to extractable Au from soils in background areas. The amount of iodide-extractable Au appears to be strongly associated with total Au, whereas water-extractable Au demonstrated a weaker association. Most Au in the near surface horizon is found associated with carbonate.

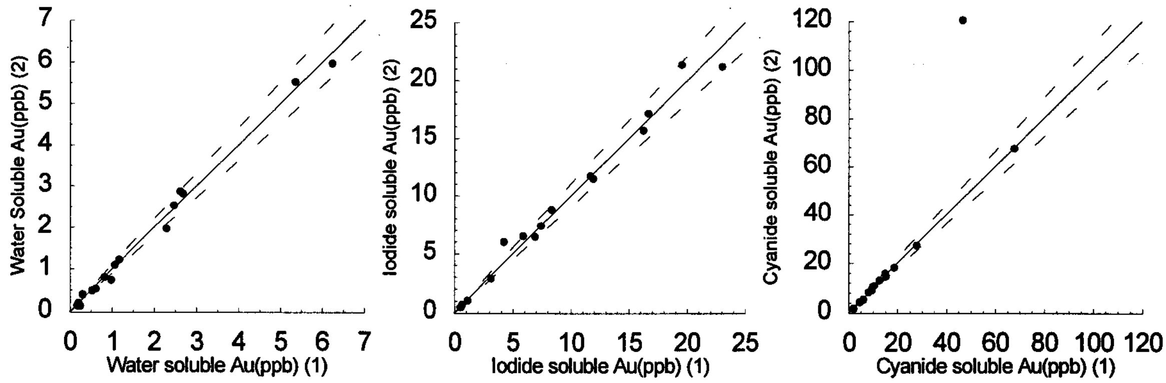


Figure 5.5: Comparison of duplicate sequential extraction data for soil samples from Safari. The 0% and ±5% deviation lines are shown.

Partial extraction tests may also indicate the nature of Au anomalies occurring in the soil. Soil located above mineralization at Steinway is highly calcareous in the top metre, but becomes Fe rich and less calcareous with depth. The maximum Au concentration is 320 ppb. Partial extraction tests were performed using a sequential extraction procedure. Iodide-soluble Au is strongly related to total Au, whereas the water-soluble fraction decreases with increasing depth. Subsequent detailed analysis of material within the lower part of the profile indicated that some of the Au is present in ferruginous granules; thus, while this Au is accessible to iodide, it is not particularly water soluble. The Au content of individual Fe granules indicated that some were extremely rich in Au (up to 15 ppm) and Au particles were visible under the optical microscope.

The differing solubility at Steinway is due to the form of occurrence of Au in soil. The higher solubility in the upper part of the profile is due to the weathering of Au from the particles of Au in Fe granules and its migration to the surface by a variety of mechanisms, including capillarity, bioturbation and in vegetation.

Table 5.1: Site characteristics for partial extraction study sites in the Kalgoorlie area.

Study area	Thickness of transported overburden (m)	Depth to mineral-ization (m)	Other comments	Reference
Steinway	25	30-35	palaeochannel	Lintern and Gray (1995a)
Wollubar-Enigma	50-60	50-60	palaeochannel	Lintern and Gray (1995d)
Argo	10-70	30-70	close to salt lake	Lintern and Gray (1995b)
Apollo	5-10	15-30+	adjacent to Argo	Lintern *et al.* (1997)
Mitchell	50	50	palaeochannel	Lintern *et al.* (1996)
Challenge-Samantha	50	50	palaeochannel	Lintern *et al.* (1996)
Kurnalpi	55	55-60	palaeochannel	Lintern and Gray (1995c)
Runway	<1	55	erosional site	Lintern (1996a)
Zuleika	20	20	palaeochannel	Lintern and Butt (1992)

5.5 Surface investigations of palaeochannel sites in the Kalgoorlie area

Partial Au extractions were performed on samples across nine Au deposits in the Kalgoorlie area: Steinway, Wollubar-Enigma, Argo, Apollo, Mitchell, Challenge-Samantha, Kurnalpi, Runway and Zuleika (further details of some of the study sites in Chapter 2). Most sites selected were typical of deeply buried deposits in the Kalgoorlie area (Table 5.1); the Runway deposit differs in that it is covered by 50 m of leached saprolite. At all sites but two (Steinway and Runway), Au concentrations above mineralization showed no clear differences from adjacent unmineralized areas (Figure 5.6).

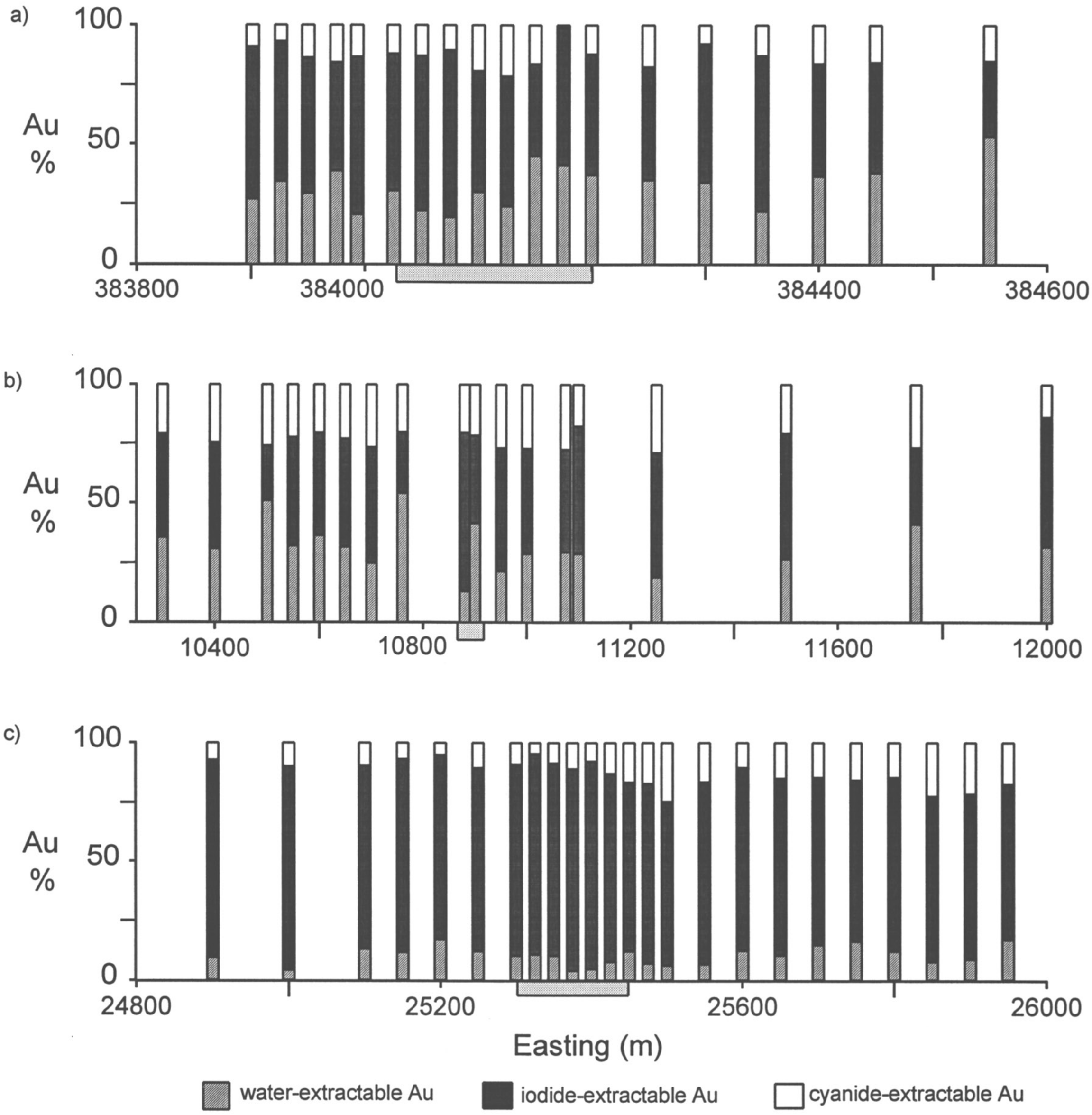


Figure 5.6: Stacked Au concentrations for partial extractions at a) Apollo, b) Steinway and c) Runway. Grey bar at base locates mineralization.

At Runway and Steinway, significant total and extractable Au concentrations were observed in the soil overlying mineralization. At Runway, the depth of transported material is less than 1 m above mineralization, and it is considered that the high concentrations of Au are related to its association with sub-cropping saprolitic material; this is consistent with the low concentrations of water-soluble Au, which suggest that some of the Au is coarse grained. At Steinway, a similar situation occurs, except that some Au appears to be present in transported, ferruginous granules (Section 5.4); some of the Au is coarse grained and relatively water-insoluble, suggesting a clastic origin to the Au not directly related to the underlying mineralization. In earlier studies at Zuleika (Lintern and Butt, 1992), the presence of unusual high concentrations of Au (with Ag) was also noted in soils in the depositional sheetwash area above the palaeochannel, similarly suggesting a detrital origin.

At other sites, there was no correlation in total or extractable Au (either absolute or as a proportion of the total Au; Figure 5.6) with buried mineralization. There were specific site differences in the proportions of extractable Au (Figure 5.7); these may be due to a variety of reasons, including the provenance of the Au, proximity to up slope mineralization, size of the Au particles present and the maturity of soil processes with respect to dissolution/adsorption of Au.

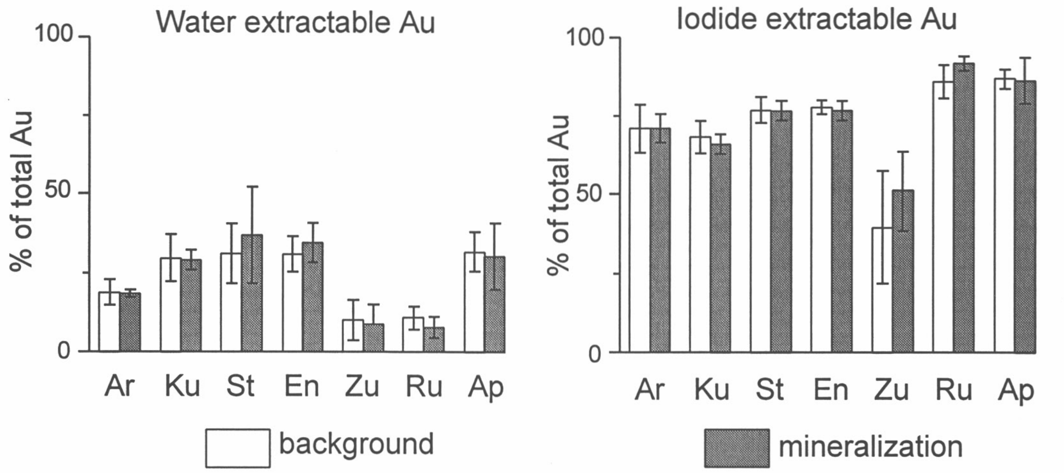


Figure 5.7: Comparison data for partial extraction studies for the Kalgoorlie area. Mean (histograms) and standard deviation (bars) are shown. Ar-Argo, Ku-Kurnalpi, St-Steinway, Em-Wollubar-Enigma, Zu-Zuleika, Ru-Runway and Ap-Apollo.

In summary, partial extractions using water, iodide or cyanide or total Au do not assist in the location of buried mineralization at the sites studied; where high concentrations of Au appear to assist in the location of mineralization (Steinway), the body of evidence suggests it is either fortuitous (in the case of Steinway) or is due to relative enrichment during weathering (in the case of Runway).

5.6 Soil traverses for areas of transported overburden at and north of the Menzies Line

At Safari (Figure 5.8), Fender (for 0-1 m samples) and, to a lesser degree, Baxter, the soil Au concentration (total and extractable) is closely correlated with underlying mineralization, probably because of the low to moderate amount of transported cover. In areas of deeper cover (*e.g.*, Bronzewing, Curara, Golden Delicious), there is no correlation with buried mineralization, either for total Au, or using iodide or water extractions (or indeed other extraction techniques; Chapter 8), suggesting no enhanced exploration utility of these methods.

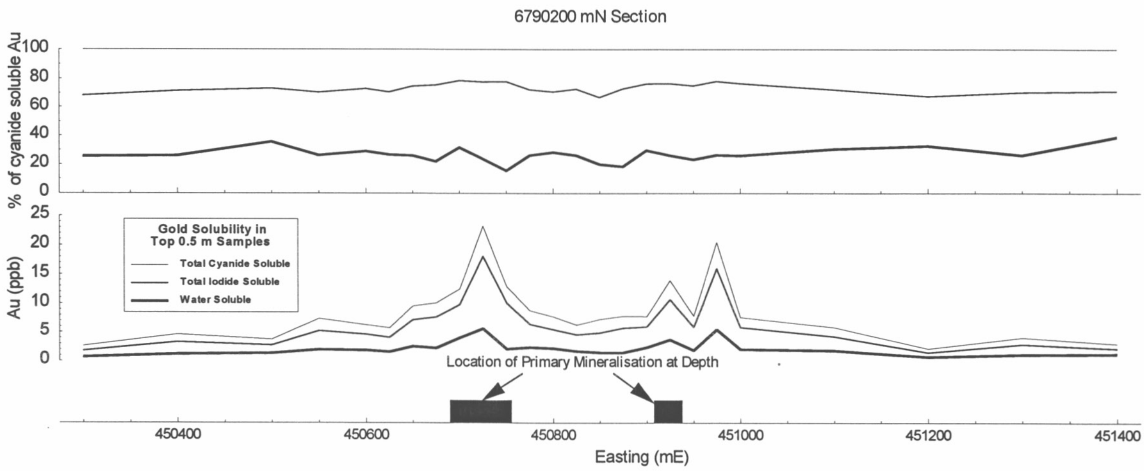


Figure 5.8: Absolute and relative Au solubility in top 0.5 m of regolith at Safari.

5.7 Use of iodide extractions for deeper regolith

Regolith underneath the soil cover (roughly the top 1-2 m) has been less extensively investigated using extraction techniques than soils. However, the minor studies so far conducted, briefly discussed below, indicate a usefulness in understanding some of the processes of Au dispersion. This is also being supported by column simulations of supergene processes (Section 5.8).

5.7.1 Safari

Although sub-cropping mineralization is overlain by 5-10 m of transported material, significant Au, correlated within the buried mineralization, is spatially associated with secondary carbonate (Figure 5.8). As at other sites, this Au is highly soluble, with proportions of iodide-soluble Au in samples commonly up to 80%. Deeper in the regolith, solubility appears to depend on proximity to primary mineralization, with auriferous samples further from mineralization tending to contain proportionally more soluble Au. There is a close, though imperfect, association between Au and Ca with depth (Figure 5.9). Maxima in water- and iodide- soluble Au just below the unconformity correspond to a maximum in Ca, whereas the total cyanide-soluble Au peaks higher, at the unconformity. Most importantly, a significant proportion of Au in saprolite is soluble, indicating the Au is available for migration to the surface.

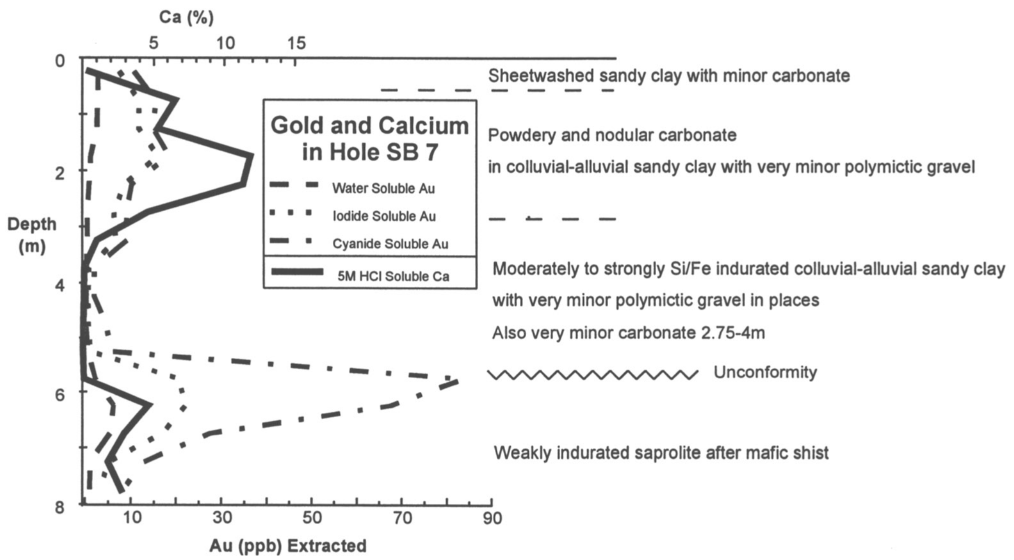


Figure 5.9: Comparison of Au (sequential extraction components) with Ca in hole SB7, Safari.

5.7.2 Granny Smith

Colluvial sediments at Granny Smith are characterized by the development of hardpan in the top 2 m. In Profile 1 (Figure 5.10), the fine and coarse net iodide solubilities are very similar. However, in Profile 6, Au solubility in coarse material is very low (Figure 5.11), suggesting that the secondary silica cement is acting to occlude the Au. Even when the material is finely pulverized, the iodide solubility is still lower than that observed for other soils (*e.g.*, Figure 5.3), suggesting weaker biological influences in this silica-impregnated material. As at Safari, Au in the saprolite is moderately soluble, with even water dissolving up to 40% (gross). Therefore, Au in the saprolite could potentially migrate to other parts of the regolith.

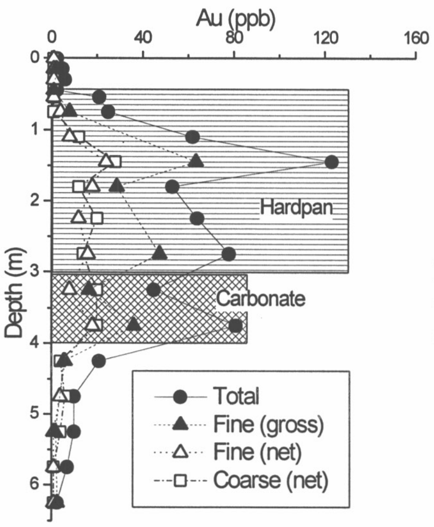


Figure 5.10: Iodide-soluble Au for Granny Smith Profile 1

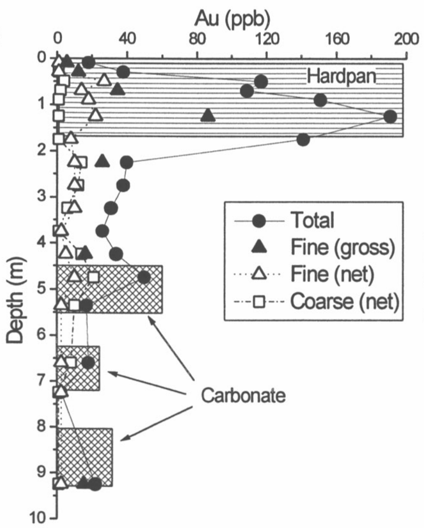


Figure 5.11: Iodide-soluble Au for Granny Smith Profile 6

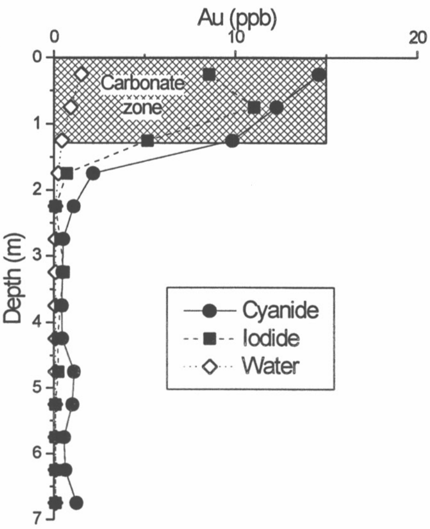


Figure 5.12: Partial extraction data for Argo Profile J.

5.7.3 Argo

Partial extractions were performed on material sampled from the Argo pit wall, 40 m above mineralization (Figure 5.12). The highest Au concentrations were found in the calcareous zone of the soil; this Au has a high iodide-solubility, as in other calcareous soils. Water-extractable Au was generally low, and close to or below detection beneath the carbonate horizon. In comparison with Safari and Granny Smith, the Au at depth was highly insoluble to iodide and water, indicating a very poor mobility. This may be due to highly saline and acid groundwater precipitating Au as pure Au metal, which will be very insoluble in these reagents.

5.7.4 Gindalbi

A drill hole in the Gindalbie area intersected sulphides lying directly below the sandy base of a palaeochannel. The basal sediments contain 400 ppb Au (Figure 5.13) along with secondary sulphides. The Au has a moderate iodide solubility (about 30% of the total Au), compared with <10% in the residual material below the unconformity. Thus, it appears that the secondary Au has precipitated in a moderately soluble form and, in favourable circumstances, could be remobilized.

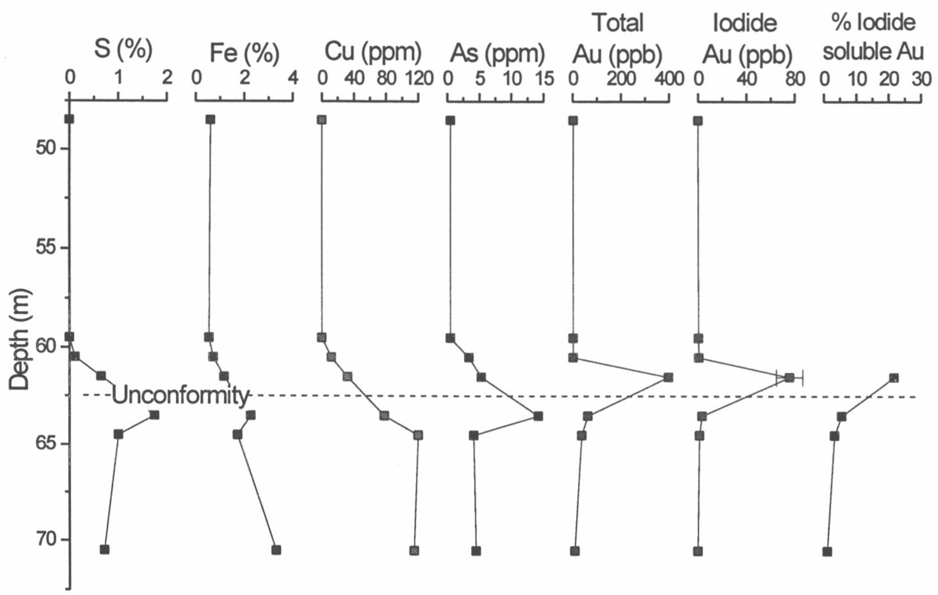


Figure 5.13: Elemental and Au extraction data vs. depth for Gindalbie Drill hole KSC 2181

5.8 Column investigations

These studies have been initiated to model some of the hypothesized processes for the formation of supergene deposits, whereby sub-horizontal Au enrichments occur in saline environments. Regolith material is placed in an enclosed column, saturated with water and Au halide solution diffused from the top of the column. In order to precipitate Au, a reduced Fe solution is diffused from the base of the column (Figure 5.14), though other methods, such as layers of reducing materials such as lignite or sulphide, could also be used in future studies.

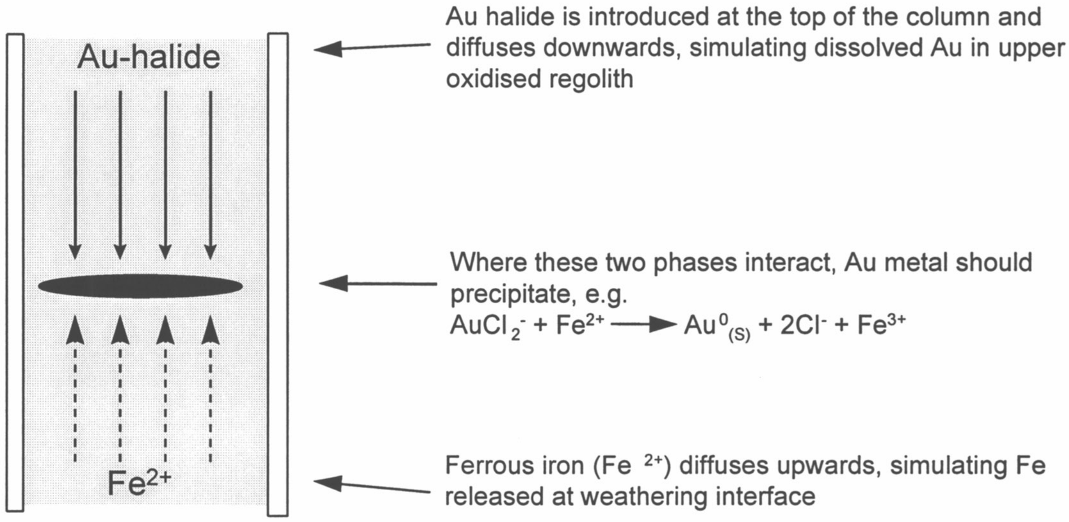


Figure 5.14: Diagrammatic representation of column investigation.

The column has an internal diameter of approximately 9 cm and is up to 35 cm in height. Following diffusion tests, fine quartz (50-100 µm) was selected as giving even diffusion, though at slow velocities, requiring experiment periods of 3-6 months. Coarser quartz has been tested as an alternative but, although diffusion is much faster, it is very uneven and therefore gives unsatisfactory results. The sand is pre-conditioned to pH 4, 5.5% TDS. At completion, the column is flushed with several bed volumes of water (analysed for Au), the column dismantled and sections analysed. Initial results suggest that:

(i) Where Au is introduced as the chloride complex, with initial dissolved concentrations of 20 to 2000 ppb, Au is always precipitated at the top of the column. The precipitated Au is about 10% water soluble and 95% iodide soluble, a similar range to Au in carbonate soils (Section 5.4), but much higher than that for colloidal Au (3% water, 16% iodide soluble). This suggests AuCl is sorbed rather than reduced.

(ii) When Au was introduced to the top of the column as the iodide complex, over 60% remained in solution after 2 months. About 15% precipitated on the top 7 cm, and 7% on the next 7 cm of the 35 cm column. Sorption experiments (Gray, 1990b; Gray, unpublished data) demonstrate Au chloride is much more strongly sorbed than Au iodide for all regolith materials tested. Additionally, groundwater studies (Chapter 6) suggest importance of iodide to Au supergene mobility. Further column experiments will use Au iodide.

6. HYDROGEOCHEMISTRY IN THE YILGARN CRATON

6.1 Introduction

Hydrogeochemistry has been extensively investigated in this and earlier projects, at 14 different sites across the Yilgarn Craton and its margins. Hydrogeochemistry may be useful for exploration for Au and other metals, and may also provide information on how various materials are weathering. This enhances understanding of active dispersion processes and assists in the development of weathering and geochemical models, which are essential for effective exploration in regolith-dominated terrain. Particular emphasis has been placed on Au, both in terms of site selection and on laboratory investigations that assist in interpretation of the data. Enhanced understanding of the hydrogeochemistry of Au may be valuable in predicting the form and degree of supergene mobilization of Au in the regolith.

The aims of the hydrogeochemical studies were, therefore:

(i) to provide information on whether groundwater can be used successfully as an exploration medium in the Yilgarn Craton adjoining belts;
(ii) to yield data on geochemical dispersion processes;
(iii) to create a groundwater database on the characteristics of groundwaters at various sites;
(iv) to enhance our understanding of groundwater processes in mineralized zones;
(v) to develop techniques for interpretation of groundwater data from mineralized areas.

Important observations from these investigations, as well as a regional model of groundwater characteristics, are discussed below.

6.2 Study sites

The sites investigated in these projects (Figure 6.1) can be grouped as follows:

(i) *Northern groundwaters* (N Yilgarn and margins) -
Baxter (Gray, 1995) and Lawlers (Gray, 1994).
Groundwaters in these areas are fresh and neutral, trending more saline in the valley floors.

(ii) *Central groundwaters* (close to and north of the Menzies line) -
Granny Smith (Gray 1993a), Golden Delicious (Bristow *et al.*, 1996a), Mt. Gibson (Gray, 1991) and Boags (Gray, 1992a)
Groundwaters are neutral and brackish (commonly <1% TDS) to saline (about 3% TDS), trending to hypersaline (10-30% TDS) at the salt lakes, with common increases in salinity with depth.

(iii) *Kalgoorlie groundwaters* -
Golden Hope mine, (Gray, 1993b), Wollubar palaeochannel (Gray, 1993b), Panglo deposit (Gray, 1990a), Baseline mine, Mulgarrie palaeochannel (Gray, 1992b), Steinway palaeochannel (Lintern and Gray, 1995a) and Argo palaeochannel (Lintern and Gray, 1995b). These groundwaters are commonly acid (pH 3-5), except where buffered by extremely alkaline materials (*e.g.*, ultramafic rocks), and saline within the top part of the groundwater mass, trending to more neutral (pH 5-7) and hypersaline at depth and when within a few km of various salt lakes in the region.

(iv) *Officer Basin* -
Mulga Rock palaeodrainage system (Douglas *et al.*, 1993).
Groundwaters are saline to hypersaline and neutral to acid. The major ion chemistry is similar to that of the Kalgoorlie region, but the dissolved concentration of many other ions is low, due to the presence of lignites in the channel sediments

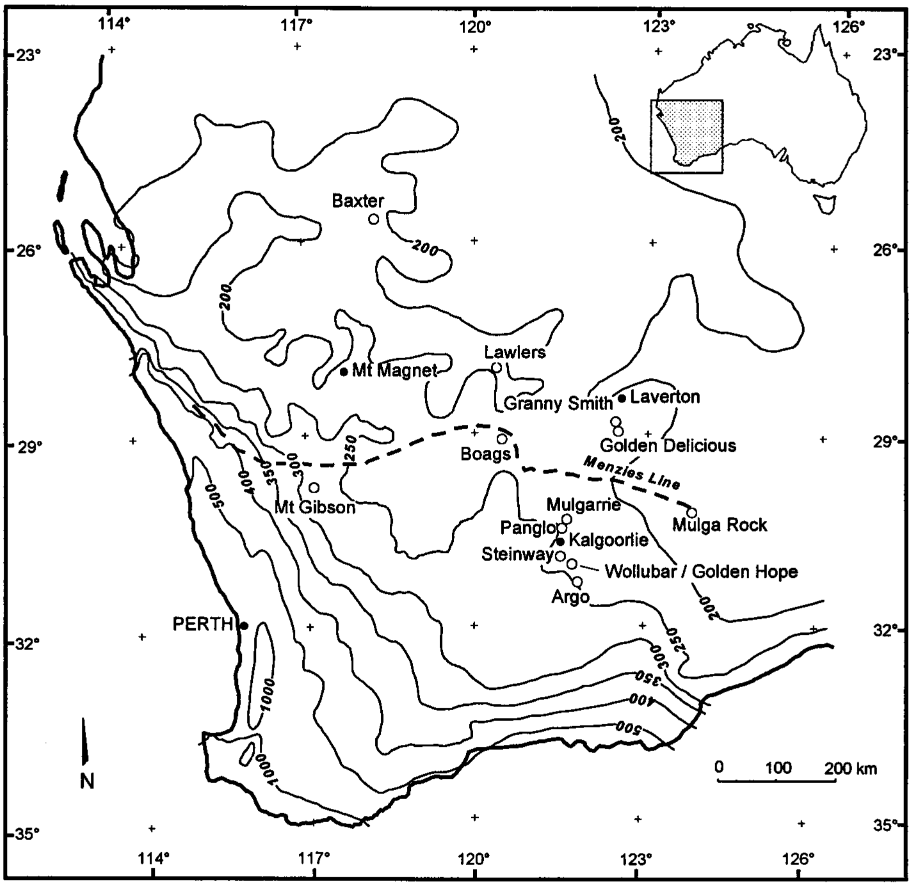


Figure 6.1: Location map of groundwater investigation sites.

Discussion and summary of this research are given in site-specific reports and Gray (1996).

6.3 Sampling and analytical methods

Groundwaters are commonly collected using direct collection within drill holes, preferably 5 m or more below the water-table. Waters are analysed for pH, temperature, conductivity and oxidation potential (Eh) at the time of sampling, and a sample collected, with overfilling to remove all air, for later HCO_3^- analysis by alkalinity titration in the laboratory. About 1.5 L of water is filtered (0.2 μm) in the field: 100 mL of the filtered solution is acidified and analysed for Ag, Al, As, B, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Hg, Ho, I, K, La, Li, Mg, Mn, Mo, Na, Nd, Ni, P, Pb, Pr, Rb, Sb, Sc, Sm, Sn, SO_4, Si, Sr, Tb, Th, Ti, Tl, Tm, U, V, Y, Yb, Zr and Zn in the laboratory; 50 mL of filtered water is separately analysed for Cl and Br; and a one litre sub-sample of the filtered water is shaken with one gram sachet of activated carbon in a saline/acid medium and the carbon analysed for Au (quantitative to <0.005 μg/L) and other elements (qualitative for As, Mo, W, U, La, Ce and Sm).

Additional understanding of groundwater processes is obtained by computing the solution species of many of the major and trace elements and degree of mineral saturation from solution compositions, using the program PHREEQE (Parkhurst *et al.*, 1980; described in detail in Gray, 1990a and Gray, 1991). To obtain highly accurate speciation data on a limited suite of the major elements (Na, K, Mg, Ca, Cl, HCO_3, SO_4, Sr and Ba) for highly saline solutions, the specific ion interaction model known as the Pitzer equations is applied, using the program PHRQPITZ (courtesy USGS).

6.4 Effect of sample depth on salinity, Eh and pH

Deep groundwaters in contact with mineralization commonly have high concentrations of dissolved Fe and other chalcophile elements, probably derived from the first stage of the oxidation of pyrite and other sulphides:

Equation 1 $$2FeS_2 + 7O_2 + 2H_2O \rightleftharpoons 2Fe^{2+} + 4SO_4^{2-} + 4H^+$$
(pyrite)

At depth, such acid production is buffered by minerals such as carbonates or feldspar. These groundwaters contain significant dissolved Fe (>0.1 mg/L) and are neutral and reduced [solid symbols in the neutral region (6< Ph <8) in Figure 6.2], commonly having Eh values of 200 mV or less.

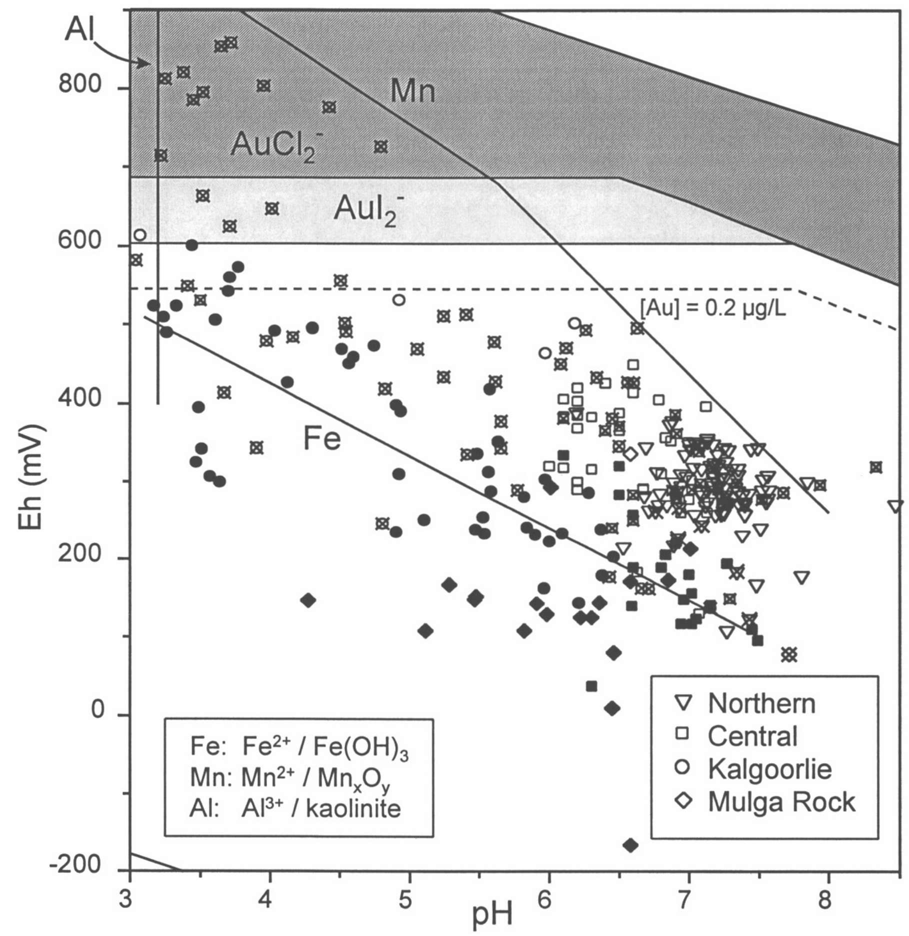


Figure 6.2: Eh vs. pH in groundwaters from WA research sites: solid symbols indicate samples with [Fe] >0.1 mg/L (ppm); grey-filled symbols have [Fe] <0.1 mg/L and [Mn] >0.1 mg/L; open symbols have [Fe] and [Mn] <0.1 mg/L. The Mn line is derived using data from Moussard et al. (1974), assuming [Mn] = 10-4 M (5.5 mg/L). Dark grey area is zone where [Au] >2 µg/L (ppb) in 1 M (5.7%) NaCl solution, with light grey area showing the increased Eh field in which 2 µg/L Au will dissolve in the presence of 10-5 M (1.3 ppm) I-. Dashed line is lower Eh limit for [Au] = 0.2 µg/L in 10-5 M I- / 1 M NaCl solution.

Closer to the surface, conditions are more oxidizing, and soluble Fe^{2+} will oxidize to Fe^{3+}, which then precipitates as an oxide/hydroxide, generating acidity (Equation 2). As this occurs higher in the profile, and (unlike the initial phase of sulphide weathering; Equation 1) buffering minerals are commonly absent, highly acid conditions can ensue. This critical groundwater Eh/pH control is known as the "ferrolysis" reaction (Brinkman, 1977).

Equation 2 $$2Fe^{2+} + \frac{1}{2}O_2 + 5H_2O \rightleftharpoons 2Fe(OH)_{3(S)} + 4H^+$$

Because the reaction is governed by both Eh and pH, the ferrolysis control is an angled line on an Eh/pH diagram (denoted by the Fe line in Figure 6.2). All groundwaters with significant Fe concentrations (>0.1 mg/L; solid symbols in Figure 6.2) congregate around this line.

Under most weathering conditions, there is a absolute groundwater pH limit of 3, because such acid conditions cause alumino-silicates such as kaolinite to dissolve and buffer acidity:

Equation 3 $$\underset{\text{(kaolinite)}}{Al_2Si_2O_5(OH)_4} + 6H^+ \rightleftharpoons 2Al^{3+} + 2Si(OH)_4^0 + H_2O$$

This maintains the solution pH at about 3.2. The control is Eh independent (the Al line in Figure 6.2). In the more acid groundwaters, dissolved Si concentrations are high, and reach saturation with amorphous silica. Thus, Al and Si dissolved from kaolinite appear to equilibrating with phases that have fast precipitation/dissolution reactions, such as jurbanite ($AlOHSO_4$) and amorphous silica.

Many acidic groundwaters contain significant Mn, which can stabilize them at very high Eh values (up to 850 mV; shown as the Mn line in Figure 6.2) in the Mn analog to ferrolysis. As will be discussed later (Section 6.7.2), this control is critical to the mobility of Au in the Kalgoorlie and, possibly, Central regions.

The final type of groundwater observed in the study areas is that containing neither significant Fe nor Mn (open symbols in Figure 6.2). These waters almost exclusively have neutral pH (6-8.5), include virtually all of the Northern, some Central and few Kalgoorlie groundwaters, and are denoted as the HO group. Although there are redox couples within the range measured for these waters (the most probable being H_2O_2/O_2; Sato, 1960), they have slow kinetics and the solution Eh will be weakly controlled. This group is the least chemically active of the waters, being neither strongly reducing (neutral group Fe waters), strongly acid (group Al) nor strongly oxidizing (group Mn).

These four Eh/pH groups appear adequate to model the Eh/pH data from all Yilgarn sites investigated to date. The Eh/pH characteristics vary from neutral to moderately acid and reducing at Mulga Rock (which has extensive lignite), neutral to highly acid and oxidizing in Kalgoorlie, and neutral in the Central and Northern Regions.

6.5 Major element hydrogeochemistry

The major elements and/or species are classified as those primarily controlled by salinity effects (*i.e.*, Na, K, Mg, Ca, Cl, SO_4, Br) as well as HCO_3^-, Si, Al and Fe. There are major salinity differences between the four groundwater regions, as demonstrated in a plot of pH vs. TDS (Figure 6.3): Northern groundwaters are neutral and fresh; Central groundwaters are neutral and fresh close to groundwater divides but highly saline adjacent to salt lakes; Kalgoorlie groundwaters vary from saline and acid close to the surface to hyper-saline and neutral at depth and close to salt lakes. The few Kalgoorlie groundwaters that are neutral and saline (rather than hyper-saline) are shallow groundwaters in contact with weathered ultramafic rocks. In all but the Northern region, salinities show major increases with depth, probably due to back-flow from salt lakes (Figure 6.4). These differences between sites for which the Northern, Central and Kalgoorlie groundwaters plot in distinct domains:

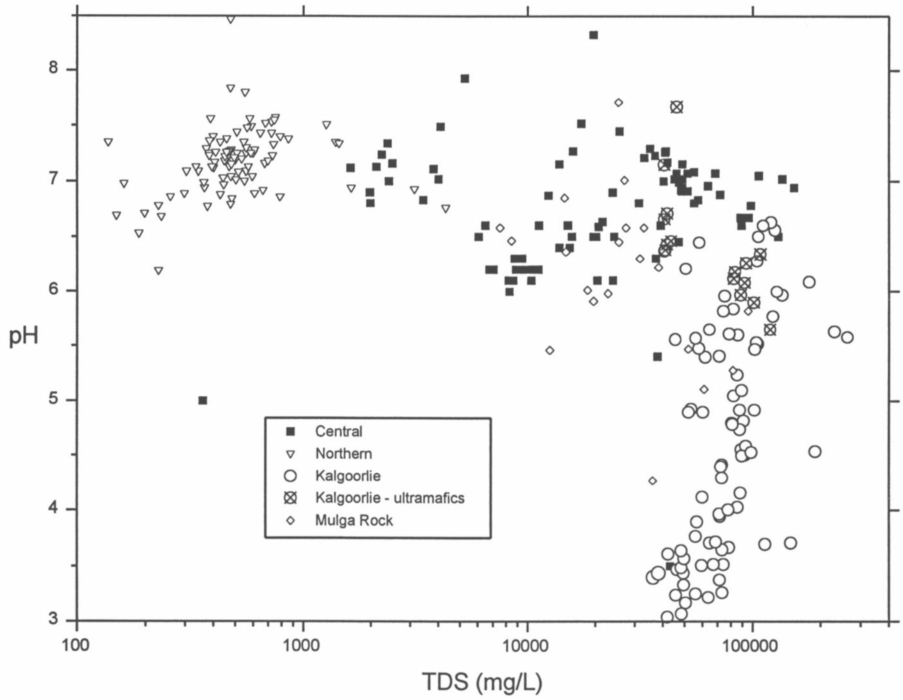


Figure 6.3: pH vs. TDS for groundwaters in Western Australian study areas.

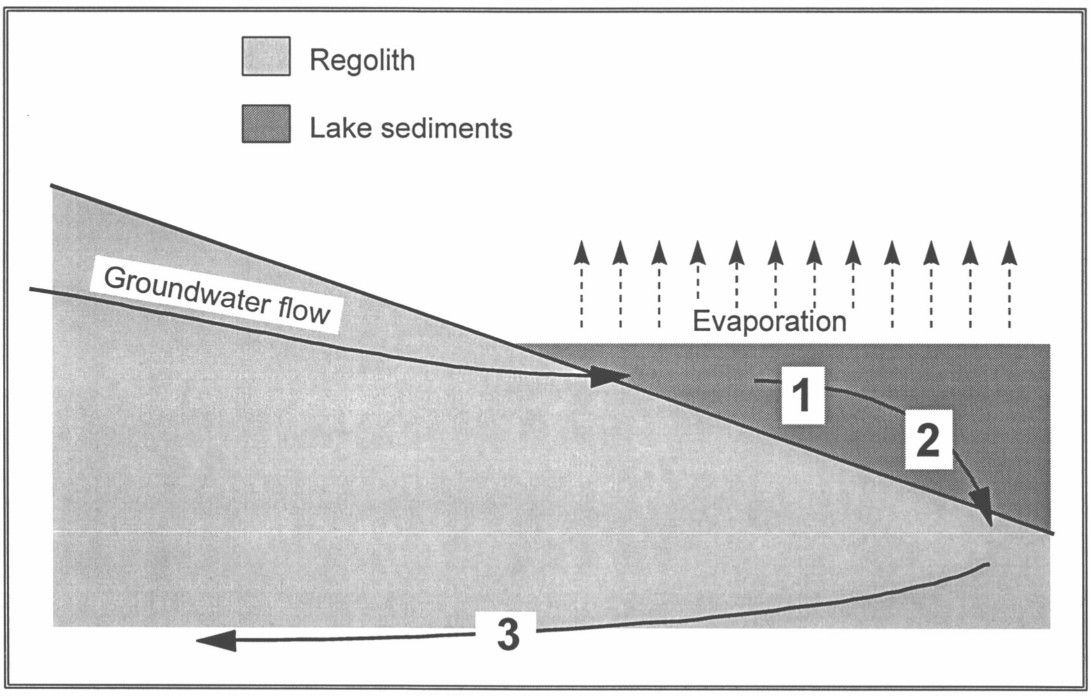


Figure 6.4: Diagrammatic representation of groundwater evaporation and flow at salt lakes: 1. Evaporation, leading to saline and dense groundwater; 2. Downward flow of dense groundwater; 3. Back-flow of saline waters, leading to higher salinity at depth.

Ion ratios for the Central, Kalgoorlie and Mulga Rock sites suggest a sea water norm, possibly due to a marine incursion or deposition of sea water as an aerosol. The most critical modifications are:

(i) moderate and severe reductions in SO_4 and K, respectively, in the Kalgoorlie region, reflecting pervasive precipitation of alunite [$KAl_3(SO_4)_2OH_6$], as a by-product of the dissolution of kaolinite and other alumino-silicates in these acid systems (Equation 3);

(ii) the significant depletion of Br in the Kalgoorlie and some of the Central region, probably due to oxidation of Br^- to Br_2. This would be expected to be slow, even for the oxidized Kalgoorlie groundwaters, and would suggest them to be very old. Volatilization would be likely to be even more significant for I (which oxidizes more readily than Br), with important consequences for Au hydrogeochemistry (Section 6.7.2)

In contrast, the Northern groundwaters are distinctly different from sea water, although both sites have very similar ion ratios. This may reflect a general groundwater characteristic for dissolution of a suite of mafic/ultramafic and granitic rocks.

In some circumstances the concentrations of most of the major elements in groundwater are controlled by mineral equilibria, with the important phases being halite and gypsum in saline environments, calcite, magnesite and sepiolite [$Mg_2Si_3O_{7.5}(OH).3H_2O$] in neutral/saline conditions, and alunite (possibly coated with more amorphous phases) and amorphous silica in acidic environments.

Where ion/TDS ratios differ from the regional trend, this may relate to mineralization or other sources that contrast with the surrounding country rock. In particular, localized enrichments in SO_4, as observed for the Golden Hope (Kalgoorlie; SO_4/TDS = 0.13) and Boags (Central; SO_4/TDS = 0.17) pit areas, and in groundwaters in overburden above Four Corners mineralization at Lawlers (North; Figure 6.5), may indicate oxidation of major sulphide bodies.

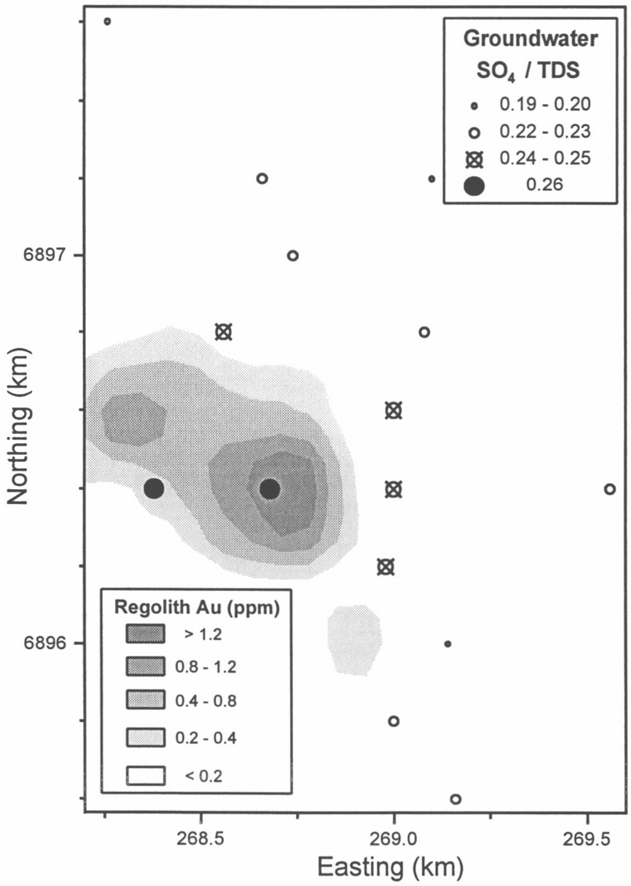


Figure 6.5: SO_4/TDS distribution in groundwaters at Four Corners, Lawlers study area, Western Australia.

6.6 Minor element hydrogeochemistry

Relevant median concentrations in Yilgarn groundwaters are listed in Table 6.1. The last column gives the postulated control on groundwater concentration. Thus, for example, REE concentration is primarily controlled by pH, whereas Co concentration is high in waters in contact with mafic or ultramafic rocks, with further enhancement in acid groundwaters. Elements whose concentration is controlled by equilibrium with specific secondary minerals are generally not very useful for exploration, whereas other elements may give useful information as to lithology and/or presence of sulphides.

Table 6.1: Median minor element compositions of groundwaters.

	Seawater	Northern	Central	Kalgoorlie	Mulga Rock	Controls
Iodide	nd	nd	0.1 ± 0.8	0.3 ± 0.6	0.52 ± 0.25	
I	0.06	0.2 ± 0.3	5 ± 4	5.8 ± 1.9	0.32 ± 0.22	S/Sal ?
Li	0.18	<0.005	<0.005	0.9 ± 0.6	nd	Ac ?
Rb	0.12	0.013 ± 0.006	0.051 ± 0.013	0.032 ± 0.028	nd	Min ?
Ba	0.013	0.04 ± 0.03	0.02 ± 0.04	0.04 ± 0.04	0.03 ± 0.04	Eq/Min
Sc	0.0000006	0.009 ± 0.008	0.017 ± 0.004	0.019 ± 0.017	nd	Ac/Min
Cr	0.0003	0.01 ± 0.05	<0.005	0.003 ± 0.07	0.002 ± 0.017	Um
Mn	0.0002	0.01 ± 0.09	0.1 ± 2.3	2 ± 7	0.3 ± 0.8	Mf/Um/Ac
Fe	0.002	0.003 ± 0.010	0.05 ± 7	0.1 ± 21	1 ± 18	S
Co	0.00002	<0.0005	0.002 ± 0.030	0.16 ± 0.23	<0.002	Um/Mf/Ac
Ni	0.00056	0.002 ± 0.008	0.001 ± 0.04	0.26 ± 0.30	0.020 ± 0.023	Ac/Mf/Um
Cu	0.00025	0.003 ± 0.002	0.003 ± 0.033	0.05 ± 0.09	0.00 ± 0.09	Ac/Mf
Zn	0.0049	0.006 ± 0.008	0.01 ± 0.10	0.05 ± 0.6	0.04 ± 0.08	Ac/Mf
Ga	0.00003	0.002 ± 0.002	<0.005	0.006 ± 0.017	nd	S
As	0.0037	<0.0002	0.09 ± 0.09	<0.02	<0.02	S
Mo	0.01	0.001 ± 0.002	0.009 ± 0.020	<0.01	nd	S
Ag	0.00004	<0.001	0.0005 ± 0.0008	0.001 ± 0.002	nd	?
Cd	0.00011	<0.002	0.001 ± 0.002	<0.002	<0.001	?
Sb	0.00024	<0.0003	0.001 ± 0.050	<0.001	<0.0004	S
REE	0.000013	<0.002	<0.008	0.8 ± 1.9	0.013 ± 0.005	Ac
W	0.0001	<0.0002	0.001 ± 0.003	0.001 ± 0.027	nd	S
Au	0.004	0.004 ± 5.9	0.03 ± 0.19	0.05 ± 0.46	0.001 ± 0.006	Min
Hg	0.00003	<0.0002	<0.001	0.002 ± 0.013	<0.001	S
Tl	0.000019	<0.0002	0.001 ± 0.008	<0.002	0.0005 ± 0.0002	S
Pb	0.00003	<0.001	0.001 ± 0.17	0.06 ± 0.32	0.012 ± 0.014	Ac/Min
Bi	0.00002	<0.0002	0.001 ± 0.006	<0.001	<0.002	S ?
Th	0.000001	<0.0002	<0.001	<0.002	<0.001	?
U	0.0032	0.0003 ± 0.0017	0.002 ± 0.017	0.004 ± 0.06	<0.002	Ac

All concentrations in mg/L (ppm), except Au in µg/L (ppb)　　nd: not determined

Eq mineral equilibrium
Ac enriched in acid groundwaters
Um enriched in waters contacting ultramafic rocks
Mf enriched in waters contacting mafic rocks
Min enriched in waters contacting Au mineralization
S enriched in waters contacting weathering sulphides
Sal enriched in saline groundwaters
? not clearly defined

As will be discussed in later Sections, a number of the minor elements may have value for lithological discrimination, pathfinders for mineralization or as indicators of the degree of weathering. However, the usefulness of these elements depends on regional groundwater effects, as detailed below.

Many elements, including Al, F, Li, Ge, Y and the REE, and U, have higher concentrations in acid groundwaters, such as those in the Kalgoorlie region. Although extensively redistributed in the regolith, they are not expected to be useful for Au exploration in the Kalgoorlie region, because of the dominance of the pH control. The REE have particularly high concentrations in the Kalgoorlie region, with light REE concentrations (*e.g.*, La and Ce) greater than those for most of the base metals and only exceeded by the major elements, B, F and Sr. A compendium of recent published data on dissolved REE concentrations (Gray, 1996b) shows the average REE content of the Wollubar groundwaters to be about 5 times that of the highest recorded REE concentrations outside the Yilgarn Craton (Carnmenellis metasediment, England), and the highest individual sample is about 20 times greater. It is calculated (Gray, 1996b) that approximately 4000 kg per annum of total REE are abstracted from the Wollubar palaeochannel bore field. The high REE concentrations are primarily related to hydrogeochemical rather than lithological effects, presumably due to the interaction of the solids with highly acid and saline groundwaters.

Dissolved concentrations of the base metals (Mn, Co, Ni, Cu and Zn) and Ga are less closely correlated with acidity than the REE. These elements do show scope for lithological discrimination (Section 6.8.1), but there is no apparent relationship with Au mineralization. Chromium shows a surprising (on the basis of its normal aqueous chemistry) lack of correlation with acidity: dissolved Cr concentrations can be very high, with no pH relationship, and show an absolute correlation with ultramafic rocks (Section 6.8.1). Moreover, these concentrations of Cr appear to be strongly over-saturated with respect to secondary Cr oxides above pH 6. It may be that the weathering reactions releasing Cr cause oxidation to CrO_4^{2-}, which has a much higher mobility than Cr^{3+}. A high oxidation state of Cr is also suggested by its highly anti-pathetic relationship with Fe (Gray, 1996b), possibly due to the capacity of dissolved Fe^{2+} to reduce CrO_4^{2-} to the less soluble Cr^{3+} ion.

In contrast, a number of elements, including As, Sb Mo, W, Bi and, possibly, Zr and Tl, have low concentrations in acid groundwaters, but have higher concentrations above pH 6.5, particularly for the Central groundwaters. These elements commonly occur as oxy-anions (*e.g.*, $H_2AsO_4^-$), which are better adsorbed by Fe oxide (or other) surfaces at low pH, due to protonation resulting in positive charge on surfaces when the pH is below the point of zero charge (PZC). This implies that the acid (particularly Kalgoorlie) groundwaters will be poor media for the use of these elements as exploration pathfinders. Molybdenum differs from the other elements in this group in having significant, though lower, concentrations at low pH - the reason for this difference is not known, but this observation is consistent with the potential of Mo as a pathfinder element in groundwater.

The concentration and speciation of dissolved iodine may be important for the solubility of Au. Iodine may be present in a number of forms with contrasting oxidation states, including I^- (as free, weakly or strongly bound iodide), I_2, IO^- and IO_3^-. The iodide ion may well be a important ligand for Au (Section 6.7.2), whereas the other, oxidized, forms could well be important in maintaining oxidizing conditions for Au dissolution. Results to date indicate high groundwater iodine contents, much greater than for sea water. Iodine (Gray, 1996b, and references given therein) may behave as a chalcophile element, with major enrichments associated with sulphides.

In contrast with other regions, the Northern groundwaters have low concentrations of most elements, with a few exceptions:

(i) P and V concentrations are higher than for other groundwaters, probably due to the low concentration of metals that cause precipitation of these elements, particularly Ca (which precipitates P as apatite), Fe (P as strengite, V as Fe vanadate) and Pb (V as chervitite);

(ii) Si concentrations match those at the other regions;
(iii) Sc concentrations are only slightly lower on average than the other regions;
(iv) Cr concentrations can be high in the Northern region, with a similar amount of enhancement in ultramafic groundwaters to elsewhere in the Yilgarn;
(v) though dissolved concentrations of the oxy-anions are lower in the Northern region than in the Central area, several, namely As, Mo, Sb and W, still have significant concentrations in the Northern groundwaters;
(vi) Rb concentrations are much higher than expected, on the basis of the normal sea water Rb/TDS and/or Rb/K ratios. This is consistent with the observed potential of Rb as a pathfinder element for Au in non-saline environments (Section 6.8.3), and may indicate muscovite in alteration haloes.

6.7 Gold hydrogeochemistry

6.7.1 Thiosulphate dissolution

During initial sulphide weathering (Section 6.3) in neutral to alkaline conditions, significant concentrations of the intermediate sulfur compounds thiosulphate ($S_2O_3^{2-}$) and sulfite (SO_3^{2-}) are commonly produced (Granger and Warren, 1969; Goldhaber, 1983; Mann and Webster, 1990):

Equation 4 $$FeS_2 + 3O_2 \rightleftharpoons Fe^{2+} + S_2O_3^{2-}$$

In such conditions, Au will dissolve as the thiosulphate complex [$Au(S_2O_3)_2^{3-}$]. Given the conditions required for thiosulphate generation, and its instability in acid, oxidizing environments, it is expected that Au thiosulphate will only be important for the groundwater mobility of Au at the weathering front. A few groundwaters sampled from rock or saprock within mineralized zones have anomalous Au (1-41 µg/L). However, this has only been observed in drill holes from within pits, indicating that the hole has to intersect mineralization in order to give high dissolved Au concentrations. Indeed, it is possible that these high dissolved Au concentrations may be partially or wholly an artifact, due to destabilization of the rock by exposure to air after excavation of the pit, with release of unnaturally high concentrations of thiosulphate. Whatever the cause for the high dissolved Au concentrations in these conditions, sampling of groundwaters near to anomalous areas of this type, at Mt. Gibson and Lawlers (Gray, 1991, 1994), indicate little dispersion of Au in groundwater, suggesting that sampling deep groundwaters for Au will be a ineffective exploration method.

6.7.2 Halide (iodide and chloride) dissolution

In shallow groundwaters, particularly in the Kalgoorlie region, the high acidity will destabilize thiosulphate. However, saline/acidic/oxidizing (Figure 6.2) groundwaters may be highly effective in dissolving Au as the chloride or iodide complex. The dark grey area in Figure 6.2 is the zone for which up to 2 µg/L (ppb) Au will be dissolved as $AuCl_2^-$ in a 1 M Cl solution (about twice sea water). This is approximately the mean salinity for Kalgoorlie groundwaters and the upper range for Central groundwaters. A significant proportion of the Kalgoorlie groundwaters are within the Eh range required. However, thermodynamic calculations suggest that $AuCl_2^-$ may not be the most significant complex, even in these highly saline conditions. Based on free iodide and total iodine determinations of (Table 6.1; Section 6.6), available iodide (free plus loosely complexed iodide) could be reasonably expected to commonly be greater than 10^{-5} M (1.3 ppm). Because Au complexes strongly with iodide, this concentration of available iodide considerably extends the theoretical Eh range for the dissolution of at least 2 µg/L Au from 690 to 600 mV (Figure 6.2). If a lower dissolved Au concentration of 0.2 µg/L is used, the required Eh for Au dissolution is lowered further to about 550 mV, which includes many of the Kalgoorlie groundwaters.

The possibility of Au iodide dissolution is also important because sorption studies (Gray, 1990b and unpublished data) indicate that Au iodide is absorbed much less by most regolith and soil materials, even in neutral conditions. This implies a high mobility, including the possibility of Au diffusing upwards into the overlying soil, and therefore forming soil anomalies correlating with mineralization.

As expected, there is a weak correlation between dissolved Au concentrations and Eh (Figure 6.6). However, it is clear that virtually none of the Central groundwaters have Eh values high enough to explain the observed concentrations of dissolved Au. One possibility is that surface- or micro-processes generate transient highly oxidizing conditions that can dissolve Au. Once dissolved, the Au-halide complex is meta-stable, and may be only slowly removed from solution, except in Fe-rich solutions:

Equation 5 $$AuCl_2^- + Fe^{2+} + 3H_2O \Rightarrow Au_{(S)} + Fe(OH)_{3(S)} + 2Cl^- + 3H^+$$

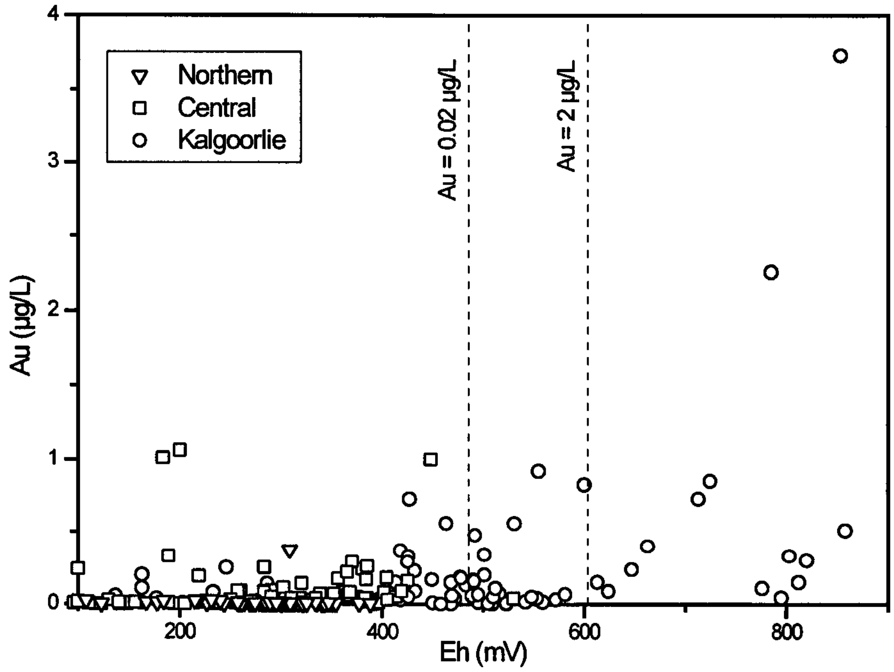


Figure 6.6: Dissolved Au vs. Eh for the Western Australian sites.

Acid groundwaters (Butt *et al.*, 1993) show a strong antipathetic relationship between dissolved Au and Fe, supporting the hypothesis that dissolved Fe is important in precipitating Au from halide complexes (Equation 5). Such a mechanism will have major implications for the control of supergene depletion and enrichment zones, and for the interpretation of drilling data.

6.7.3 Regional differences in Au hydrogeochemistry and implications for supergene mobilization

The importance of halides for the dissolution of Au is illustrated by the low dissolved Au concentrations in the Northern region (Figure 6.7), which have groundwaters with low Cl, I and Eh. Over 80% of the Northern groundwaters have dissolved Au concentrations ≤ 0.01 µg/L, which is well within background for the other regions. The few Au-bearing groundwaters in the Northern region are from within pits and appear to represent localized thiosulphate dissolution (Section 6.7.1). The Kalgoorlie region has the highest mean dissolved Au content, consistent with the observed optimal conditions for dissolution (Section 6.7.2), with the Central region having moderate levels of dissolved Au. This has major implications for the interpretation of dissolved Au data for exploration, as discussed further in Section 6.8.3.

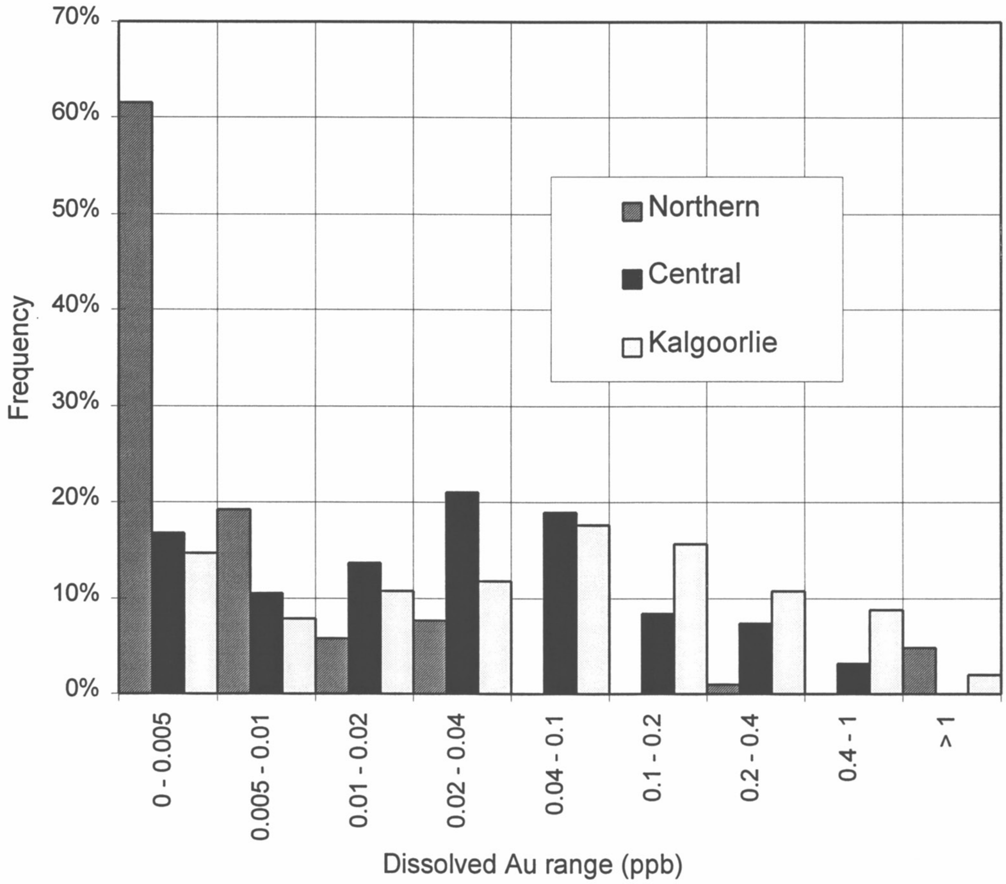


Figure 6.7: Distribution of dissolved Au concentrations for the Northern, Central and Kalgoorlie groundwater regions.

Extensive supergene mobilization of Au is expected to have occurred, and be occurring, in the Central and Kalgoorlie regions. Oxidizing conditions in the upper parts of the groundwater will lead to extensive dissolution of Au, which will diffuse though the water mass. Where dissolved Au-halide contacts dissolved Fe, possibly derived from continuing weathering of saprolite and saprock, Au will be reduced (Equation 5) in a redox front reaction, resulting in characteristic horizontal and sub-horizontal supergene anomalies. The lower dissolved Au contents of Central groundwaters, which are postulated to be due to the less acidic groundwater conditions, suggests this process may take longer for this area, though extensive redistribution would still be expected over the long period of surface weathering. In addition, the observation of Br depletion in some Central groundwaters suggests that past conditions may have been more oxidizing (Section 6.5) and Au solubility even higher.

6.8 Implications for exploration

6.8.1 Lithological discrimination and influence of fault zones

One example of the potential use of hydrogeochemistry in lithological discrimination is illustrated in Figure 6.8. By comparing the sample location with the known geology, groundwaters at Panglo (Gray, 1990a) have been characterized into those in contact with shales, mafic and ultramafic lithologies. These different groundwater groups are clearly delineated by plotting each water, using an ultramafic (Ni+2Cr) vs. a mafic (Mn+13Co+9Zn+36Cu) index. This discrimination is effective even for waters in contact with highly weathered rocks. Hydrogeochemistry may also indicate shear zones; two samples at the top right of the plot appear to be from shear zones which, at Panglo and elsewhere, are rich in dissolved base metals.

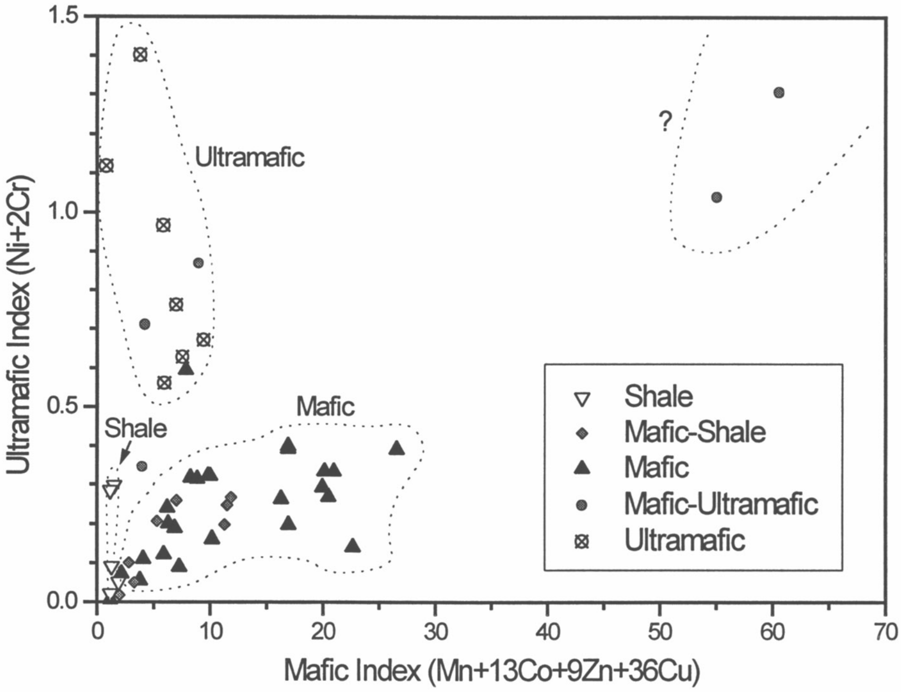


Figure 6.8: Mafic vs. ultramafic indices for groundwaters at Panglo.

This procedure will presumably be most effective for a consistent sample medium (in terms of acidity and, possibly, salinity), so that different sites may well have to be treated separately. The concentrations of base metals in acidic, shallow Kalgoorlie groundwaters will be significantly higher than those in Central, Northern or deeper Kalgoorlie groundwaters. However, dissolved Cr contents can be used to recognise ultramafic rocks across all regions. Groundwaters in contact with freash and weathered ultramafic rocks contain consistently high (0.01-0.43 mg/L) dissolved Cr concentrations, whereas waters in contact with other lithologies have Cr concentrations below detection. This effect is highly robust and offers a straight-forward method for recognizing the presence of ultramafic rocks.

Fault zones might well be expected to influence groundwater characteristics. Weathering is generally deeper along faults and shears, which may have distinct chemistries and are commonly zones of enhanced water flow. At the Wollubar channel (Gray, 1993b), groundwater close to Boulder-Lefroy shear has a much higher Al concentration than expected at that particular pH, and also has raised concentrations of Si, Fe and Sc, Y, REE, Pb and U. This may well reflect the influence of highly active weathering in the shear zone on the chemistry of the groundwater in the palaeochannel. Similarly, at Panglo, strong base metal enrichment of groundwaters (Figure 6.8) may reflect the proximity of a fault zone.

6.8.2 Presence of sulphides

Groundwaters in contact with sulphide-rich rocks buffered by alkaline minerals (*e.g.*, carbonates) may be neutral to alkaline at depth, and acid as they become oxidizing closer to the water-table, particularly in the Kalgoorlie region. The deep, neutral waters close to sulphides are characterized by:

1. near neutral pH and relatively low Eh;

2. enrichments in Fe, SO_4 (possibly from sulphides), HCO_3, Mg and, to a lesser extent, Ca and Sr (possibly from carbonates). This element association probably reflects oxidation of sulphides at depth, with neutral pH conditions being maintained by carbonate buffering;

3. enrichment in several anionic chalcophile pathfinder elements, including As, Mo, Ag, Sb, I, Hg and Tl.

Acid-oxidized waters may well lose most of these signatures, because most of the anionic chalcophile elements are precipitated in acid conditions (with the possible exception of Mo, Section 6.6), Fe is precipitated, HCO_3 removed, and SO_4, Mg, Ca and Sr enrichments may be obscured in saline groundwaters. Thus, with the major exception of dissolved Au itself, few elements give useful Au exploration data in acid groundwaters.

6.8.3 Presence of Au mineralization

The clearest indication of Au mineralization in Kalgoorlie and Central groundwaters is given by dissolved Au. It is not clear whether other elements, such as As or Sb, specifically indicate Au mineralization or merely the presence of sulphides. Interpretation of dissolved Au concentrations is complicated by there being two mechanisms for transport of Au in groundwater (thiosulphate and halide complexing, Section 6.7), with a third mechanism (organic complexation) specific to soils (and possibly lignitic horizons). Where Au appears to be dissolving as a thiosulphate complex, as at Boags and the Hornet pit at Mt. Gibson, the distribution of dissolved Au closely matches that of mineralization, but this effect is highly localized and would probably be missed in an exploration sampling program.

In oxidizing environments, Au dissolves to form chloride or iodide complexes (Section 6.7.2) and, where this mechanism is expected to be active, high concentrations of dissolved Au are observed. However, Au concentration is strongly affected by factors not directly related to mineralization (Eh and dissolved Fe; Section 6.7.2), and the distribution of dissolved Au only approximately matches that of primary mineralization. However, this technique would still provide useful extra exploration information. A few other elements, such as As, Sb, Mo, I and various base metals may also have value as pathfinders, although they commonly have reduced concentrations in acid conditions (Section 6.6) and analyses for them in saline groundwaters may be difficult, expensive or of poor sensitivity. For the Kalgoorlie region, a limited suite of parameters, namely salinity, pH, Eh, dissolved Au, Fe, Cr and, possibly, other base metals, could be analysed cheaply (using standard probes, sorption onto carbon for Au, and ICP-AES and/or colorimetric analyses for Fe and Cr) but extending this to the other elements of interest will add considerably to cost, with little added exploration benefit. A threshold dissolved Au concentration of approximately 0.05 µg/L would appear to locate most mineralized areas. For the Central areas, a slightly lower dissolved Au threshold (0.02 µg/L) appears appropriate (Figure 6.9), and a number of chalcophile elements (*e.g.*, As, Sb, Mo, W, Tl, Bi) may also give valuable exploration data. However, further work is required to study the relative degrees of groundwater dispersion of these elements.

In the Northern region, dissolved Au contents are much lower, although higher values may still correlate with mineralization. However, even though Au and indicator elements will occur at low concentrations, the low salinity means that multi-element ICP-MS analyses are both cheap and highly sensitive. At Baxter (Gray, 1995), a number of indicator elements either correlate closely with the position of buried mineralization (Rb, Sc, Mo, W) or have use for lithological discrimination (Cr, Ni, As). In addition, the low variation in salinity, Eh and pH with depth indicates that sample depth is less critical than at other sites.

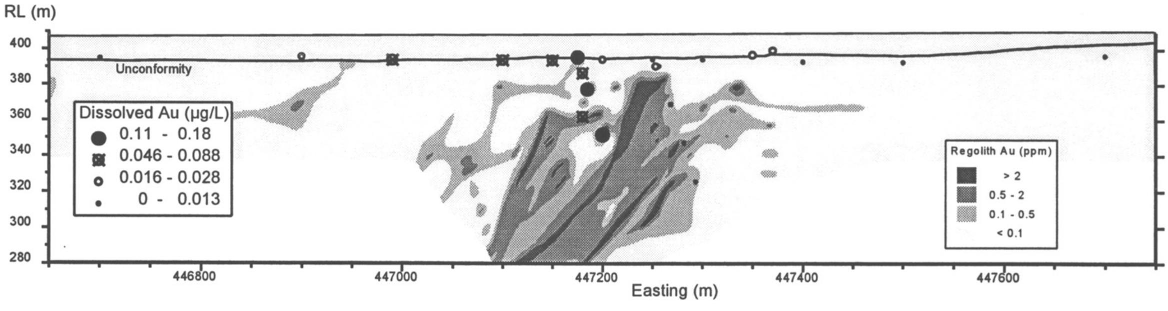


Figure 6.9: Dissolved Au distribution at Golden Delicious, superimposed on regolith Au contours (from Bristow *et al.*, 1996a).

Groundwaters seem to have a limited ability to "see through" barren transported overburden, as opposed to its success when sampling groundwater even from supposedly depleted *in situ* material (*e.g.*, Panglo; Gray, 1990a). This appears to be most useful in the highly active Kalgoorlie groundwaters, with those sampled from the Wollubar palaeochannel appearing to show significant influences from underlying rocks (Gray, 1993b), and poor for the least active groundwaters in the Northern region (*e.g.*, Lawlers (Gray, 1994). However, the degree of interference from the overburden will depend on the element used, with chemically conservative species, such as SO_4, appearing to give good signals even in overburden (*e.g.*, Figure 6.5), and more active elements, such as Mo or Au, giving poor signals in groundwaters from barren overburden. It is recommended that, if possible, groundwaters be sampled below the transported overburden for optimum results.

Therefore, it is recommended that use of groundwater for exploration is best restricted to shallow samples in Kalgoorlie and Central regions, with depth being less critical in the Northern region. Waters should be contacting, or within a few metres of, *in situ* material. Particularly in the Kalgoorlie region, it may well be more cost-effective to restrict analyses of the saline waters to a select group of parameters, which should at least include salinity, pH, Eh, Au, Fe and Cr. A more expanded analytical suite, including As, Sb, Mo, W, Bi and Tl, may well be useful, though at significant cost, for Central groundwaters. In comparison, for the Northern groundwaters, multi-element analyses are cheaper and have been shown to have potential.

7. BIOGEOCHEMICAL EXPLORATION FOR GOLD

7.1 Introduction

The major perceived advantage that biogeochemistry has over soil sampling is that plants, particularly trees, have the potential to sample material from greater depths and wider areas. The composition of vegetation reflects, to a great extent, (a) the availability of an element in the vicinity of the root system and, (b) the ability of the plant to absorb, transport and accumulate the element. Many plant organs have been used for exploration purposes in order to maximize the biogeochemical response and include leaves, branches, roots and bark. Mull, or decaying plant litter, may contain concentrations of elements in excess of the original plant material due to (i) nutrient withdrawal during the senescence process prior to leaf fall or (ii) preferential leaching of more mobile constituents such as Ca, Cl, Mg and Na. However, the presence of adhering soil particles makes it difficult to clean and use as a sample medium.

Biogeochemistry has been used extensively as an exploration technique for Au in North America and the states of the former USSR, but its application has been limited in Western Australia for two main reasons. *Firstly,* sampling of soils and other surficial materials has been reasonably effective in locating concealed deposits, so that biogeochemistry has been used merely to supplement data from soil geochemical surveys; no economic deposit of Au, or any other commodity, has been found specifically by biogeochemistry in Australia. *Secondly,* interpretation of the data requires a consistent and regionally typical sample type. This is feasible in regions where a few plant species are widely distributed, such as over much of Canada but, in Australia, species can vary considerably even within a few tens of metres and many are not readily identifiable.

Biogeochemical sampling must ensure a consistent plant organ is sampled *e.g.*, leaves, bark, roots or branches, and take into account the age and health of the plant, genetic variation and, except for bark because it is dead tissue, the time of year sampled. Furthermore, comparisons between the chemical composition of soils and vegetation should be treated with caution, since the soil horizon sampled may not necessarily reflect the zone utilized by the plant species for nutrients and water. The location of the root system of plants in semi-arid areas predominantly reflects the availability of water, *i.e.* soil moisture and soil structure. Many plant species, *e.g.*, Chenopodiaceae (saltbush, bluebush and samphire), have adapted to dry and saline conditions by having some of their roots very close to the surface so they can readily absorb water from minor rainfall events before it evaporates. Other plants, *e.g.*, *Eremophila* (poverty bush), have root systems that occur extensively within the top metre (rather than at the surface). *Eucalyptus* may have, in addition to the near-surface root system, a long tap root (sometimes tens of metres in length) capable of absorbing nutrients and water from very deep in the profile. Nutrients and water absorbed by *Eucalyptus*, therefore, might represent a composite of that obtained by roots from two or more depths within the profile.

Biogeochemical studies have been undertaken at several deposits in conjunction with other studies of the regolith as part of previous CSIRO-AMIRA Projects 241 and 241A and include Bounty (Lintern, 1989), Panglo (Lintern and Scott, 1990) and Zuleika (Lintern and Butt, 1992). Further studies during this project have been undertaken at Apollo-Argo (Lintern and Gray, 1995b; Lintern *et al.*, 1997), Higginsville (Lintern *et al.*, 1996), Steinway (Gardiner, 1993), Wollubar-Enigma (Lintern and Gray 1995d), Safari Bore (Bristow *et al.*, 1996b) and Runway (Lintern, 1996a). Summaries and conclusions from these studies are presented below.

7.2 Apollo and Argo

Two biogeochemical surveys were undertaken in the Apollo and Argo areas (Lintern and Gray, 1995b; Lintern *et al.*, 1997). Six sites from Argo (3 each from mineralized and background areas) were chosen close to soil profile sampling sites. The results indicated that *Eucalyptus*, *Eremophila* and mull were not effective in delineating mineralization (Table 7.1). Previously, *Eremophila* has been shown to indicate the location of buried mineralization at Panglo but, unlike Argo, soils at Panglo were highly anomalous in Au; *Eremophila* is shallow-rooted and its Au content is probably related more to that of soils, rather than mineralization itself. *Eucalyptus* has been tested at several other sites, including Steinway, Bounty, Panglo and Zuleika; results indicate that Au is usually close to detection and reflect the abundance in soil.

Table 7.1: Gold concentrations (in ppb) of dried vegetation at Argo (Lintern and Gray, 1995b).

Sample Type	Over mineralization	Over background
Eucalyptus leaves	<0.5, <0.5, <0.5	<0.5, <0.5, <0.5
Eremophila	<0.5, <0.5, 0.5	<0.5, <0.5, 0.5
Mull	1.9, 2.3, 4.9	1.6, 2.2, 3.4

At Apollo (Lintern *et al.*, 1997), a more extensive biogeochemical survey was undertaken using bluebush (Figure 7.1); results indicate:

(i) there is a strong association between Au and Fe;
(ii) gold concentrations near and over mineralization are about ten times greater than background and are comparable to the Au content in soil;
(iii) gold concentrations are some of the highest recorded for vegetation in CSIRO-AMIRA studies;
(iv) gold concentrations in soil (0-0.1 m) are anomalous over mineralization located at 20 m depth.

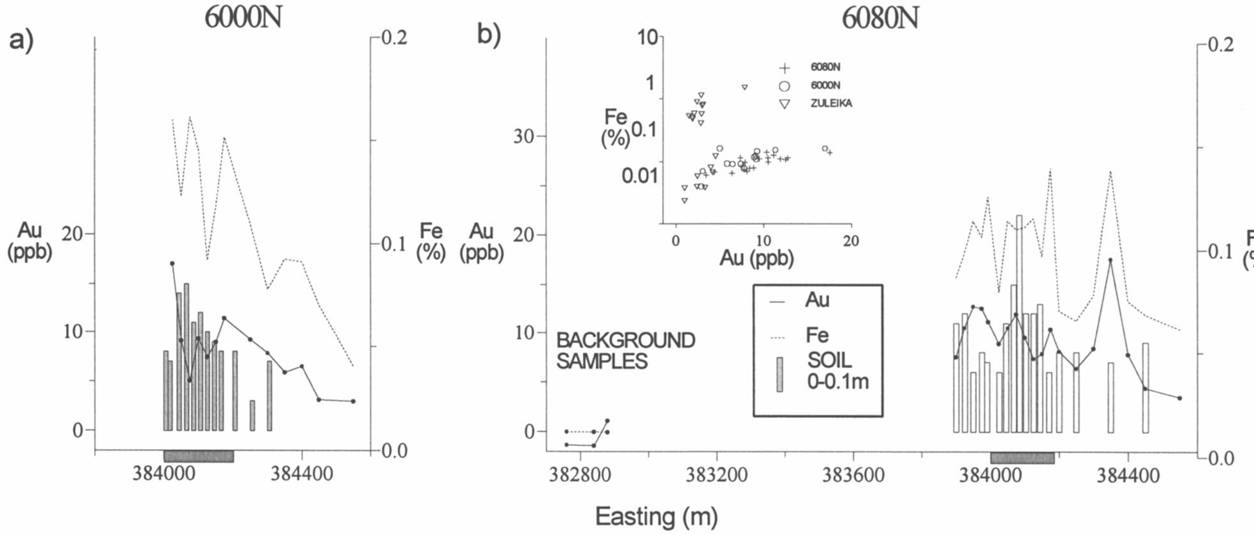


Figure 7.1: Gold and Fe concentrations for a) 526000N (soil and bluebush) and b) 526080 N, Apollo (Lintern *et al.*, 1997). Inset scatter plot in b) shows relationship between Au and Fe for bluebush at Apollo, Higginsville (Lintern *et al.*, 1997, 1996) and Zuleika (Lintern and Butt, 1992) (see below). Stippled area beneath axis is location of mineralization at 20-30 m.

The strong relationship with Fe (and with other elements such as Cr, As, Co, Hf and REE) has also been noted with some samples from the Zuleika Sands Au deposit (Lintern and Butt, 1992) and may suggest contamination either from drilling or ore haulage. The leaves of the bluebush sampled are covered in woolly hairs, and the bark is rough; both may trap dust particles and may be difficult to remove, even after washing. An alternative explanation is that Fe is controlling the uptake of other elements, but why it appears in higher concentrations in mineralized areas is not clear.

7.3 Higginsville

At Higginsville, the problem of obtaining a consistent biogeochemical sample was experienced. Gold concentrations in bluebush appear to be related to concentrations of Au in soil rather than the underlying mineralization (Figure 7.2), which is buried by 40 m of transported overburden (Lintern *et al.*, 1996). However, two species of bluebush were used and may explain the differences observed, due to contrasting abilities to uptake certain elements; Au, Fe and several other element contents are higher in the western portion of the traverse.

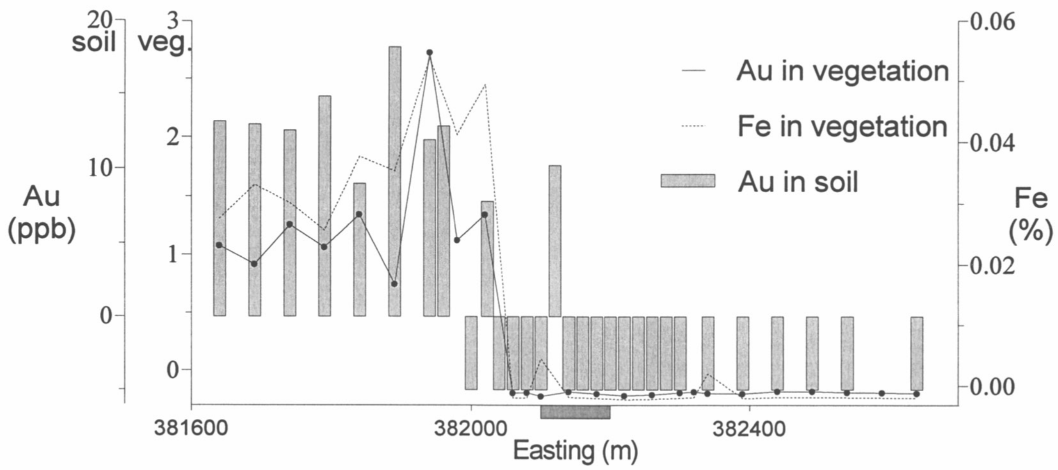


Figure 7.2: Gold and Fe contents for bluebush, and Au contents in soil (0-1 m) for 6481000N at Higginsville. Stippled area beneath axis is location of mineralization at 40 m (Lintern *et al.*, 1996).

7.4 Runway

Of the six bluebush samples taken at Runway, most samples are below detection for many of the elements determined, including Au (detection limit 1.7 ppb) (Lintern, 1996a). One sample (above mineralization) had detectable Au (1.9 ppb). No Fe was detected in the samples (<0.03%). There is a strong Au anomaly in soil over mineralization, which is concealed by 55 m of leached saprolite.

7.5 Steinway

At Steinway, Au concentrations in vegetation (*Eucalyptus*, bluebush and mull) are close to detection and/or there are no significant differences between mineralized and background areas; these sample media, therefore, cannot be used to detect the underlying mineralization at about 30 m depth buried beneath 25 m of transported overburden and 5 m of saprolite (Table 7.2).

Table 7.2: Gold contents (in ppb) of dried plant material at Steinway (from Gardiner, 1993).

Sample Type	Over mineralization	Over background
Eucalyptus leaves	0.8, <0.5	<0.5, <0.5
Eucalyptus bark	<0.5, <0.5	<0.5, <0.5
Eucalyptus twigs	1.1, 1.1	1.2, 0.5
Mull	3.8, 4.4	4.1, <0.5
Bluebush	0.9, 1.7	1.8, 1.7

7.6 Wollubar - Enigma

A variety of biogeochemical media were sampled at the Wollubar-Enigma Au deposit. As with the Steinway and Runway deposits, Au concentrations in vegetation are close to detection and/or there are no significant differences between mineralized and background areas (Table 7.3); these materials, therefore, could not be used to detect the mineralization concealed by 55 m of transported overburden.

Table 7.3: Gold contents (in ppb) of dried plant material from Wollubar-Enigma.

Sample Type	Over mineralization	Adjacent to mineralization	Over background
Eucalyptus leaves	<0.5	<0.5	<0.5
Eremophila	<0.5	0.6	1.6
Bluebush	4.3	2.2	3.1
Mull	2.1	2.8	3.0

7.7 Safari

At the Safari Prospect (Mt. Celia), Au concentrations in mull and *Acacia murrayana* were determined over mineralized and background areas (Bristow *et al.*, 1996b). All analyses were below detection for *A. murrayana*. No significant differences were detected between the two groups of analyses; these plant materials, therefore, could not be used to detect the mineralization concealed by 5 m of transported overburden.

Table 7.4: Gold contents (in ppb) of dried plant material from Safari.

Sample Type	Over mineralization	Over background
Acacia murrayana leaves	<0.5, <0.5, <1, <1	<0.5, <1
Mull	<0.5, 1.4, <0.5, <0.5	3.4, <0.5

7.8 Zuleika

Additional data have become available for bluebush from traverse 4490N at Zuleika Sands deposit and are presented, with other data, for comparative purposes (Figure 7.3). Mineralization at Zuleika Sands is located at the base of a palaeochannel at about 20 m. For both traverses, Au anomalies occur in vegetation in the erosional and depositional areas (Figure 7.3); the highest Au contents in mull, bluebush, *Eucalyptus* are 19.2, 7.9 and 1.2 ppb, respectively. Significantly, bluebush has anomalies above palaeochannel mineralization; on traverse 4705N, there is a single point anomaly and for 4490N there is a broader anomaly extending into the erosional areas. Lower concentrations of Au are present in *Eucalyptus* in the depositional areas, and over the palaeochannel mineralization but, although this essentially duplicates the distribution shown by soil sampling, the contrast is very much lower for vegetation. The results suggest that bluebush could be used to detect underlying Au mineralization located beneath 20 m of transported overburden, although this should be confirmed by further sampling on sections that are located away from erosional areas and at sites where lateral enrichment of surficial sediments from another source is not possible.

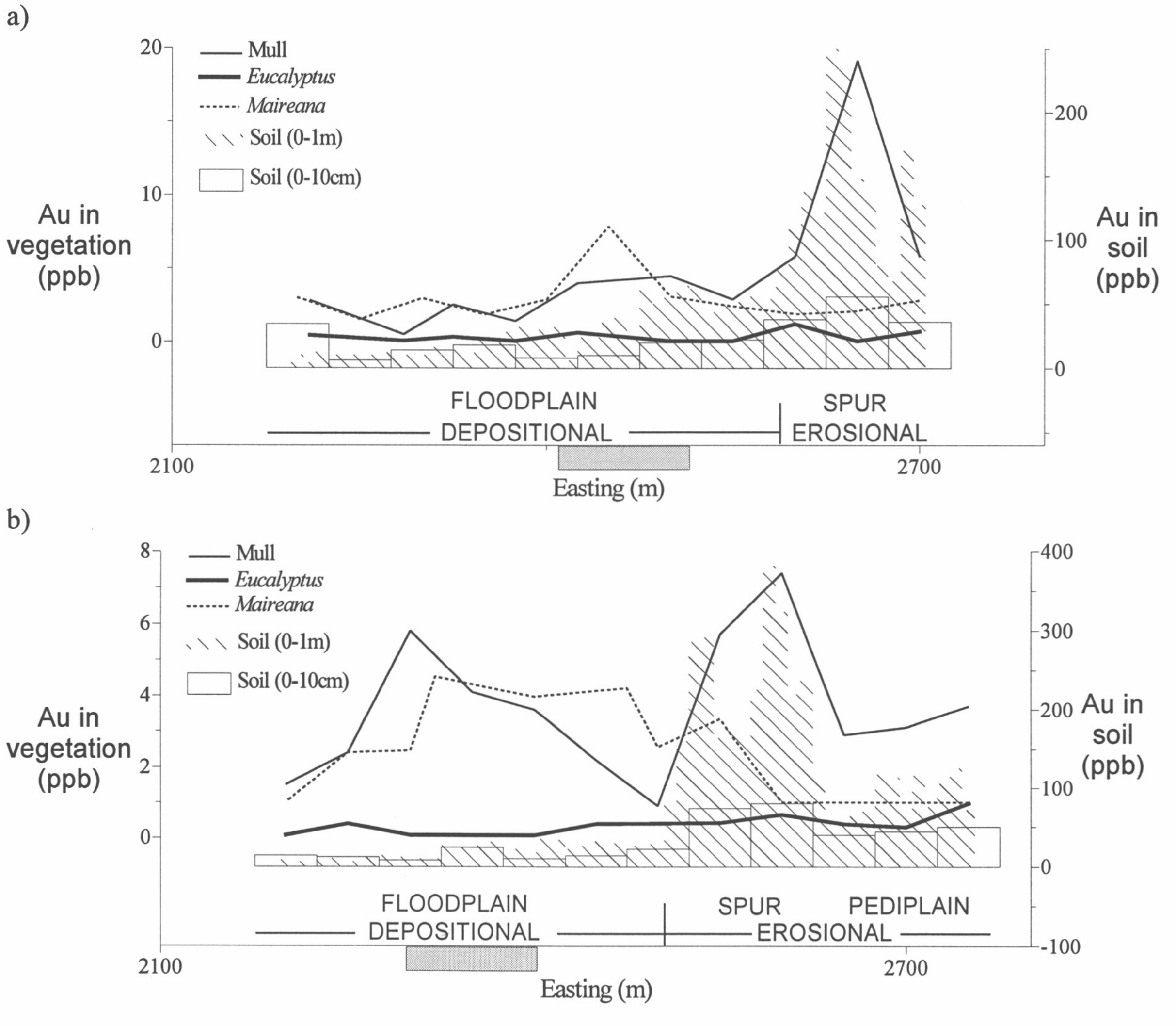


Figure 7.3: Vegetation and soil Au concentrations for a) 4705N and b) 4490N at Zuleika. Stippled area beneath axis is location of mineralization at 20 m.

7.9 Discussion and conclusion

Previous CSIRO-AMIRA projects (Weathering Processes 241, 241A) have investigated the use of vegetation for Au exploration, mainly in erosional terrains. Those results indicated that high concentrations of Au in vegetation reflect the presence of Au in soil which, in turn, is related to mineralization. In addition, some studies were undertaken in areas of transported overburden at Zuleika and Panglo, which suggested that *Eremophila* and bluebush could be useful sample media for detecting buried mineralization. However, the proximity of the sample sites to erosional areas having outcropping mineralization reduce their usefulness as ideal study sites, since the possibility of local "natural" contamination cannot be entirely discounted. Study areas and sampling points in the present project were specifically selected to minimize this possible effect.

The results of these further studies have suggested that bluebush should be investigated further as a possible exploration sample medium for Au exploration in areas of transported overburden. Encouraging results were obtained at Zuleika and Apollo, where the depth of transported overburden is 20 m or less; at Apollo, Au in topsoil was anomalous over mineralization. However, results from Wollubar-Enigma, Higginsville, Runway and Steinway suggest that, where the thickness of overburden is in excess of 30 m, bluebush is totally ineffective as a sample medium; at Runway, the overburden is almost entirely leached saprolite. The principal concern with the results is the possibility of contamination from anthropogenic sources. More samples from less disturbed areas and close examination of the leaves and bark for dust would assist the evaluation of bluebush as a sample medium. The concentrations of Au in bluebush at Apollo are similar to those found in the soil, so that if samples have been contaminated, then the dust must be derived from elsewhere such as drilling activity or ore haulage. There is also concern over the disparity in some of the Au concentrations between sites. Concentrations in bluebush are relatively high at Wollubar-Enigma compared with Steinway and Runway, even though concentrations in soil at the latter sites are about an order of magnitude higher; the reasons for this are unclear, but may be due to species differences. Future sampling must ensure that different bluebush genus/species are identified.

As a biogeochemical sample medium, *Maireana sedifolia* (a bluebush) has several positive attributes. It is widely distributed, reputedly long lived (300 years according to anecdotal evidence in Mitchell and Wilcox, 1988), easily identified, readily sampled and tends to occur in depositional areas, which appear to present the most intransigent problems for more traditional exploration techniques. Its disadvantages are that it is not easily cleaned, has high salt contents which increase detection limits for Au using INAA analysis, and will decline under heavy grazing by sheep and rabbits.

8. SELECTIVE AND PARTIAL EXTRACTION ANALYSES OF TRANSPORTED OVERBURDEN FOR EXPLORATION

8.1 Introduction

Selective extraction is a technique whereby particular soil phases are dissolved in a controlled manner, so as to investigate how trace elements are distributed. These extractions have been used in the past for geochemical exploration, because it has been perceived that elements associated with mineralization (especially those hosted by sulphides) are more readily released during weathering than those in barren rocks (hosted by silicates), more widely dispersed, more probably held by secondary minerals and hence likely to be preferentially released by extraction solutions. In contrast, many of the new extraction techniques currently been introduced for geochemical exploration are partial rather than selective digests: *i.e.*, they extract part of a phase or phases, rather than a selected mineral. These new methods are being claimed to have a high efficacy in the location of buried or otherwise hidden orebodies, and there has been a high degree of interest in their application because, if effective, they would offer an inexpensive and easy method for exploration in areas of transported overburden. This study, using selective extractions for carbonates, Mn oxides and amorphous Fe, varying HCl treatments, the CSIRO iodide extraction for Au, mobile metal ions (MMI) and Enzyme leach, and reported in detail in Gray *et al.* (1996), has been designed to examine the chemistry of partial and selective extractions and the mineralogical implications more fully. Particular questions are: whether soil extraction anomalies exist over buried mineralization; can these anomalies be observed using different techniques; what is the primary cause of the anomalies ?

8.2 Study sites

Seven different sites (with locations and site descriptions given in Chapter 2) have been used for selective/ partial extractions. They are grouped as follows:

(i) *Northern* (N Yilgarn and margins) -

Baxter: 90 km N of Meekatharra, in early Proterozoic basin on the northern margins of the Yilgarn Craton, primarily mafic and ultramafic volcanics;

Fender: 28 km WNW of Cue, hosted by a regional volcanic and sedimentary sequence in an attenuated greenstone belt about 830 m wide;

Bronzewing: about 400 km N of Kalgoorlie, within a sequence of mafic volcanics and minor sediments, which are intruded by felsic porphyries.

(ii) *Central* (close to and north of the Menzies line) -

Curara: 70 km SSW of Mt. Magnet, in a tonalitic porphyry stock, bound to the E by mafic amphibolite schists;

Safari: 200 km NNE of Kalgoorlie, in a greenstone assemblage containing a wide variety of volcanic and volcaniclastic rocks.

(iii) *Kalgoorlie region* -

Steinway: a minor palaeochannel system over mafic andesites with trachytes, porphyritic tuff and black shales, 15 km W of New Celebration;

Apollo: reduced palaeochannel over high-Mg basalts and dolerite, 25 km S of Kambalda.

8.3 Methods

8.3.1 Sample collection and preparation

Samples from each site were taken on traverses across buried Au mineralization. Samples from Safari, Apollo and Curara were collected into calico bags and air dried then stored in plastic. Samples from Fender, Bronzewing, Baxter and Steinway were collected into plastic bags and air dried. Samples were sieved to < 2 mm, and then riffle split into four aliquots for extraction studies.

8.3.2 Sequential selective extractions

These three methods are highly selective for particular mineral phases in soils (Chao, 1984):

(i) pH 5 acetate (carbonates and surface adsorbed metals);
(ii) 0.1M hydroxylamine (Mn oxides);
(iii) 0.25M hydroxylamine (amorphous Fe oxides).

8.3.3 HCl extractions

Two separate HCl extractions were performed by Ultra Trace Pty Ltd:

(i) cold 4 M HCl;
(ii) concentrated (10 M) HCl.

Extractions were also performed with an added oxidizing agent, giving an "enhanced" Au digest.

8.3.4 Mobile metal ion analysis

The Mobile Metal Ion (MMI; ® Wamtech Pty Ltd.) process uses two leachant solutions to dissolve target metals (Mann *et al.*, 1995). The technique involves acid solution analysis by ICPMS for Cd, Cu, Pb, Zn and alkaline solution analysis by ICPMS for Ag, Au, Co, Ni, Pd.

8.3.5 Enzyme leach analysis

Enzyme leach utilizes a reaction between glucose oxidase and dextrose to produce low concentrations of hydrogen peroxide to partially leach amorphous Mn oxides (Clark, 1993) from soils.

8.4 Comparisons between methods

8.4.1 Sequential selective extractions

The selective extractions are generally successful at specifically dissolving certain minerals or phases. The pH 5 reagent extracts ALL of the Ca from the carbonate-rich Kalgoorlie sites (*i.e.*, Steinway and Apollo) and the low soil carbonate Safari and Curara sites, though less Ca is extracted in the Northern sites, where some to all of the Ca is as non-carbonate minerals. Other elements partially (bracketed) or mostly to wholly extracted by this reagent are As (Kalgoorlie sites) Ba, (Be), Cd (Kalgoorlie), (REE), (Cr), (Cu) (Kalgoorlie), (Li) (Kalgoorlie), (Mn), (Ni) (Apollo), (Pb), Th, U and Zn (Apollo). For a number of these elements, particularly As, REE, Th and U, only a small proportion were extractable by any reagent, so this comment relates to that proportion of the extractable component dissolved by pH 5 acetate. Manganese dissolved by pH 5 acetate reagent may represent Mn within carbonates, separate-phase $MnCO_3$, or very soluble Mn oxides (as represented in Figure 8.1).

The second extraction, 0.1 M hydroxylamine, dissolves separate phase Mn oxides. Other elements partially (bracketed) or mostly to wholly extracted are (Au) (Steinway), (Ba), Co, (Ni), (Pb) (Bronzewing and Baxter) and (Tl) (Bronzewing). The low number of elements substantially dissolved by this reagent is surprising, given the accepted capacity of separate phase Mn oxides to be major sinks for metals. The extractable Mn broadly correlates with total extractable Fe (Figure 8.2), even though these two elements are dissolved by different reagents, suggesting an secondary cause for these two phases, such as presence of a drainage channel, or particular biological effects. Thus, a number of extractable metals can correlate with total and extractable Mn, even though most of these elements are hosted by amorphous Fe oxides, but show no correlation with TOTAL Fe.

The 0.25 M hydroxylamine reagent dissolves 'amorphous' Fe oxides. Although only a very minor proportion of the total Fe is dissolved, there is good agreement between Fe dissolved by the selective extractions and 4 M HCl, suggesting dissolution of specific Fe-rich components, be they separate phase minerals or disordered surfaces. Other elements partially (bracketed) or mostly to wholly extracted with amorphous Fe oxides are Ag, (Ba), Be, (Cd), (Co), Cr (Safari and Kalgoorlie), Cu, Li (Kalgoorlie), (Mn), Ni, Pb, REE, (U) and (Zn).

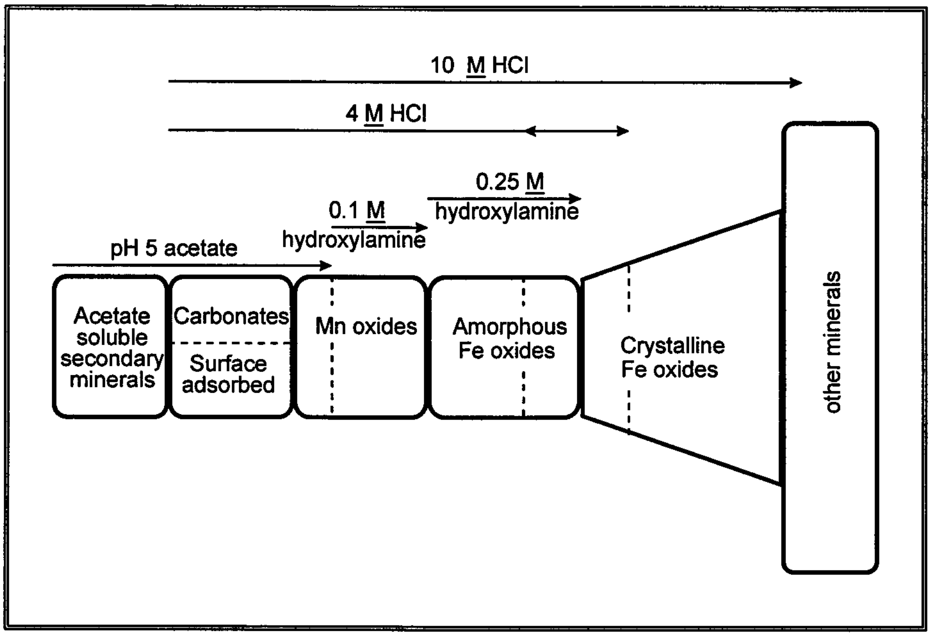


Figure 8.1: Diagrammatic representation of the phases dissolved by selective and acid extractions. Arrowed lines indicate effectiveness of reagents in dissolving different phases (see text).

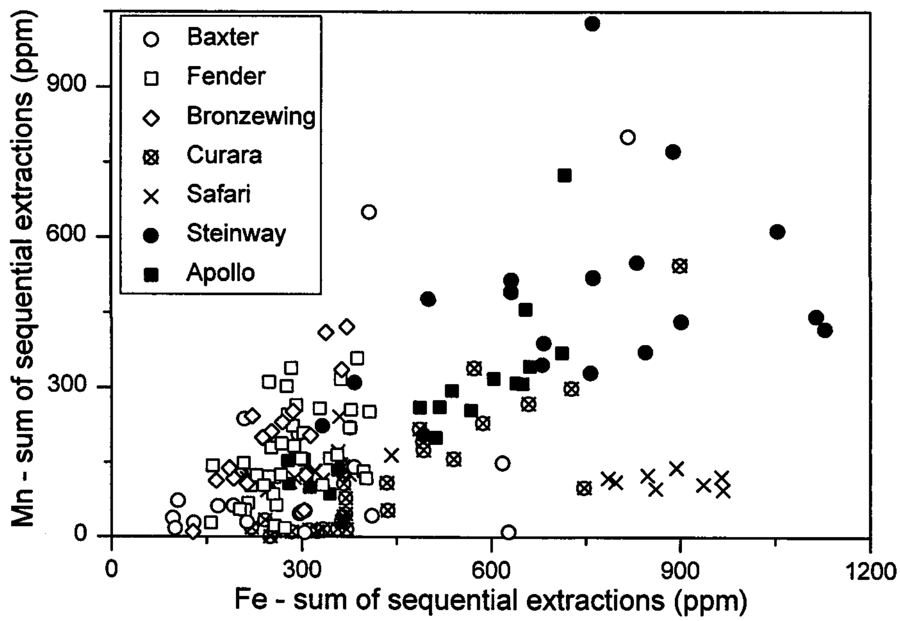


Figure 8.2: Correlation between Mn and Fe extracted by the three sequential extractions.

8.4.2 HCl extractions

There are two separate (not sequential) reagents. The first, 4 M HCl, dissolves similar elemental concentrations to that of the sum of the sequential extractions. Minor exceptions were observed for Co, Ce, Ba, and, to a lesser extent, Fe for Fender and Safari, possibly due to granite-derived material at surface. In Figure 8.1, the variation in Fe dissolved by 4 M HCl (relative to the sequential extractions) is represented by the double-headed arrow: *i.e.*, incomplete dissolution of the amorphous Fe by 4 M HCl in some cases, and partial dissolution of crystalline Fe for other samples.

The 10 M HCl reagent extracts 10-50 times more Fe than 4 M HCl and commonly dissolves 5-30% of the total Fe. Other elements for which moderately (bracketed) or significantly more was extracted by 10 M HCl than for 4 M HCl are (Ag) (Fender and Apollo), As, (Ba) (Baxter and Bronzewing), (Ca) (Safari), (Cd), (Co) (Fender only), (Cu) (Northern and Central), Hf (≤ 0.1% of total), Mn (Northern), Mo, Nb, (Ni) (Central and Northern), Pb, (REE), Sb, Se (Baxter, Fender, Bronzewing and Safari), Sn, Th, Tl, (U) (Northern and Central), W and Zn (all except Apollo).

8.4.3 Mobile metal ions

MMI is two separate techniques. The first, an acid extraction for Cd, Cu, Pb, Zn, gives results that are similar, in terms of comparison between samples at each site, to HCl and selective extraction. The carbonate-rich Kalgoorlie sites give much lower MMI responses, relative to other reagents; possibly due to the carbonate to neutralizing the acid MMI reagent and reducing the metal solubility.

The second method is an alkaline extraction for Ag, Au, Co, Ni and Pd, which gives virtually identical Au results to the CSIRO iodide (Section 5.2) and enhanced HCl extractions. In soils containing significant carbonate (Safari, Steinway and Apollo), these extractants dissolve 70-80% of the total Au (Figure 8.3), whereas the proportion of Au extracted in the northern sites is significantly lower, probably because of occlusion of Au. In addition, MMI is also very effective at dissolving Ag, as expected for a method optimized for Au. Therefore, the MMI extraction does not appear to be giving any additional information for Au or Ag than can not be obtained using total or standard (*e.g.*, cyanide or *aqua regia*) analyses. Probably as a consequence of this MMI method being done under alkaline conditions, the Co (though not Ni, for which MMI and 4 M HCl results show a good proportional match) data are unlike those observed for other techniques. For all elements except Co and Ni, MMI gives much greater (generally by at least 5 times) extraction than enzyme leach .

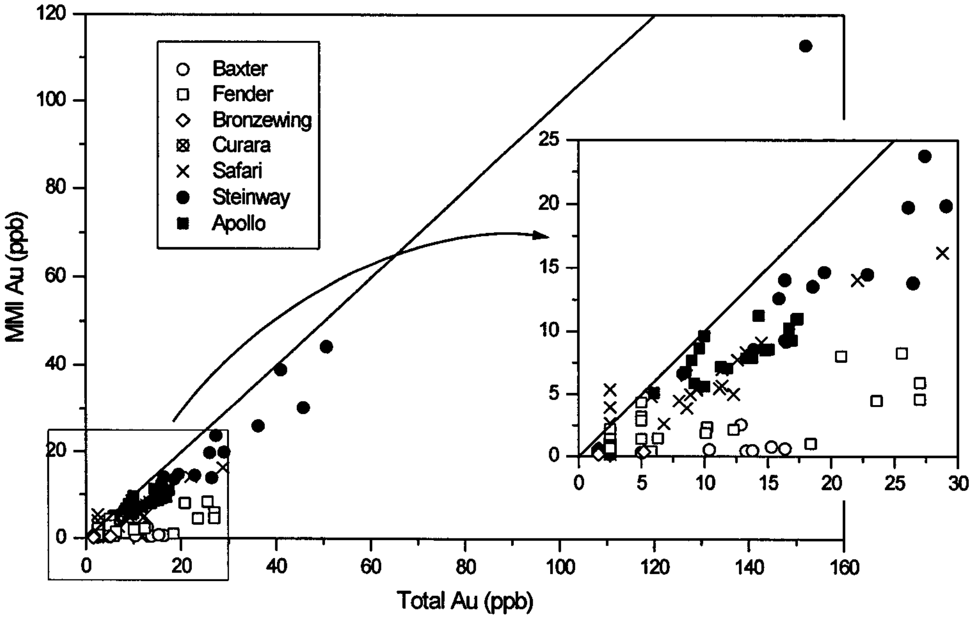


Figure 8.3: MMI Au vs. total Au for all sites. Inset shows enlargement close to origin.

8.4.4 Enzyme leach

The enzyme leach reagent is targeted at an 'amorphous' Mn phase, although the proportion of enzyme leach Mn varies dramatically between sites (Figure 8.4) from about 20% at Bronzewing to <0.5% at Steinway. Except for enzyme leach Co, no other element shows any clear correlation with Mn. In general, enzyme leach element results are not correlated with other methods, and a much larger range of elements is determined than for MMI. However, a number of enzyme leach elements, namely Cs, Fe, Ga, Hf, La, Nb, Pb, REE, Sc, Sn, Th, Ti and Zr, show very close linear correlations with each other. Most, but not all, of these elements tend to be high-charge, with only low concentrations (except for Fe). This suggests either a highly specific interaction between these elements and Fe within those soil phase(s) dissolved by enzyme leach or an analytical interference from Fe. This effect should be understood before these elements are routinely used.

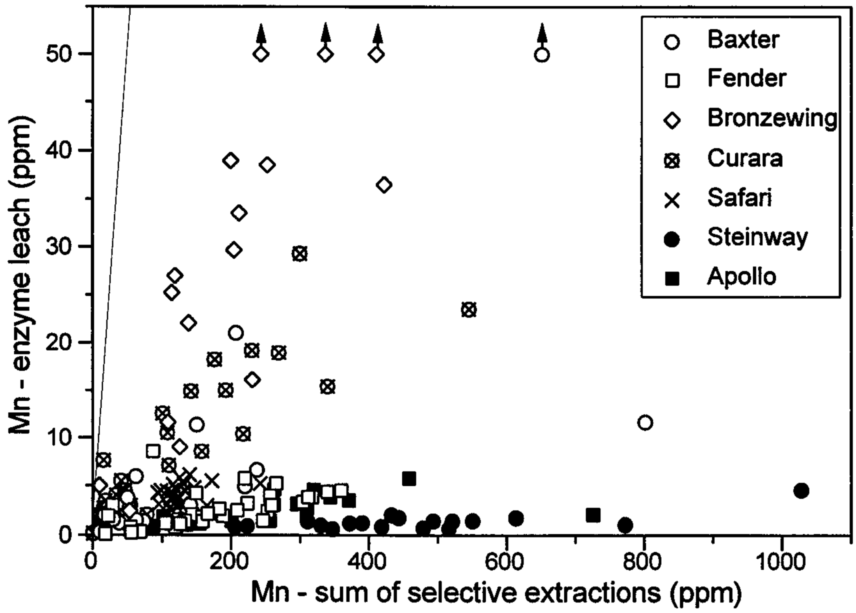


Figure 8.4: Enzyme leach vs. selective extractions for Mn.

8.5 Comparison of sites

8.5.1 Baxter

Two traverses were used at this site. With the exception of Au, no elements appear to give useful exploration data. The Harmony deposit has 0.5-3 m colluvium over mineralized ferruginous saprolite, and there has been sufficient mechanical or biological mixing to bring some Au to the surface. There are up to 15 ppb Au in soils over mineralization, and MMI and HCl digests both give useful results. However, these reagents dissolve most of the accessible Au, and it is expected that either total Au, *aqua regia* or CN digests, including BLEG, would give equivalent results.

There is a higher concentration of Mn oxides for the most easterly sample on both traverses, although the multi-element response differs dramatically: one of these anomalous samples is enriched in a number of elements using the various extractants, namely Ag, Cd, Ce, Co, Cu, Fe, Mn, Ni and Zn; whereas the other sample is anomalous in Ce, Cu and Mn only. The reason for the differences between the two samples is not known, but the critical observation is that they appear to represent FALSE positives: *i.e.*, there is a positive soil response that appears to be unrelated to any mineralization. Enzyme leach I and Cu weakly correlate with mineralization on one of the two traverses, and MMI Ni on the other. However, the poor repeatability, the lack of any clear reason for I, Cu and Ni correlating with mineralization, and the strong false positives, suggest these correlations are accidental.

8.5.2 Fender

This site has 2-8 m sand and silty clay over mineralization (in saprolite or lateritic residuum). Primary mineralization contains Au, Ag, As, Sb, Cu, W, Hg and Mo. Three traverses were used, in one of which the saprolite is depleted in Au. The total and extractable (not enzyme) Au in the soils peak over mineralization on one Au-rich traverse, which (as at Baxter) is probably due to the thin cover. No other elements (total or extractable) are correlated with mineralization. Concentrations are comparable for all 3 traverses, despite the major variation in the magnitude of mineralization at the unconformity for the three traverses. This poor success includes extractions possibly successful at other sites (*e.g.*, enzyme leach Cu and I, MMI Ni).

A strong soil anomaly is observed for the eastern-most sample of the Au-poor traverse, which shows high concentrations of Ag (480 ppb), Cd (180 ppb), Cu (12 ppm), Pb (45 ppm), Zn (7 ppm) and, to a lesser extent W (5 ppm), generally observed for all of the extraction methods. For this sample the MMI reagent is dissolving a highly significant proportion of the base metals: MMI to 10 M HCl (the most extreme extractant used) ratios are Ag (38%), Cd (42%), Cu (16%), Pb (5%) and Zn (55%). This sample appears to be a FALSE positive anomaly.

8.5.3 Bronzewing

Mineralization at Bronzewing is covered by 5-25 m of colluvium and alluvium derived from distal sources, with no significant Au anomaly at surface. Enzyme leach Cu correlates (weakly) with mineralization, though this could be coincidental. Enzyme leach Co and Mn are higher than elsewhere, and Co is correlated with Mn for most of the extraction methods. At this site, there is an active major drainage that is not coincident with the mineralization (compare with Curara; Section 8.5.4), and the geochemical signal is stronger in the channel than over mineralization (*i.e.*, a FALSE positive), possibly related to Mn in the hardpan precipitated by ephemeral drainage in the channel.

8.5.4 Curara

At Curara an active drainage system overlies the buried mineralization. Soils in the drainage have high concentrations of separate phase Mn oxides (up to 500 ppm Mn; Figure 8.5) and amorphous Fe (up to 600 ppm Fe). All methods, including total analysis, give anomalous responses directly overlying mineralization (Figure 8.5). No method shows particular superiority in terms of signal to noise: the worst methods being pH 5 acetate (high detection limits), 10 M HCl (high backgrounds) and totals. Other elements that are high over mineralization, for various extractions, are As, Ba, Be, Cd, Ce, Co, Cs, Cu, Ga, Hg, Mo, Nb, Ni, Pb, Pd, Pt, REE, Sb, Sn, Te, Th, Tl, U, W, Zn and Zr. Very few of these elements are correlated with primary mineralization, and there is no reason why there presence at surface should be considered significant.

It is postulated that accumulation of amorphous Fe oxides and Mn oxides is the main control over metal solubilities, and the good correlation of element concentration with buried mineralization is coincidental. This is discussed in further detail in Gray (1996a). These results can be compared with those for Baxter (Section 8.5.1) and Bronzewing (Section 8.5.3), for which the Mn drainage anomaly is not over mineralization.

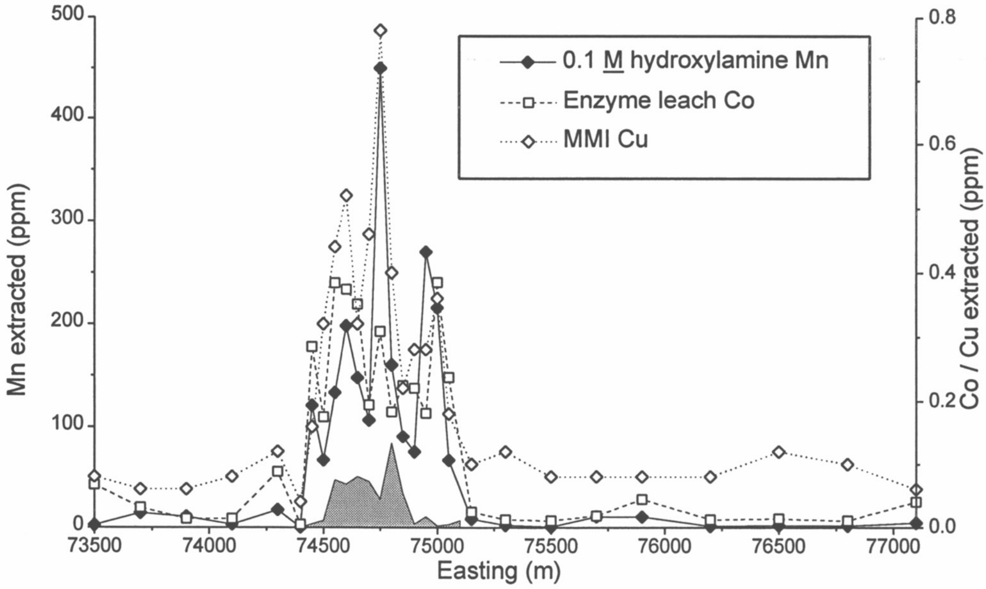


Figure 8.5: Selected extraction results across the Curara traverse. (Shaded area represents Au in buried laterite).

8.5.5 Safari

The Safari traverse has 4-6 m sandy calcareous cover over Au-rich saprolite. Total and extractable Au in the soils (by most methods) peak over mineralization, probably as a function of the thin cover. Tungsten (4 M HCl and enzyme leach) also appeared correlated with mineralization, though not as closely as Au. No other elements correlate with the position of mineralization. Distributions of Ce, Co, Cu, Ni, Pb and Zn appear to be weakly correlated with that of extractable Mn or Fe, for some extractions.

8.5.6 Steinway

Mineralization at Steinway is overlain by 5 m of leached saprolite and 25 m of palaeochannel sediments. Despite this, total Au peaks at 155 ppb, approximately 100 m E of mineralization, and other extraction methods confirm this result. MMI, iodide and the enhanced HCl reagents extracted similar proportions of the Au from all samples, except the one with the highest Au content. This sample shows relative solubility differences in the order MMI > Iodide > Conc. HCl (enhanced) > 4 M HCl (enhanced). Thus, for example, the 4 M HCl (enhanced) reagent dissolved only 11% of the total Au in this soil sample, but 73±18% of the total Au for other samples in the traverse. This indicates that Au in this sample is less soluble, and therefore suggests that it to be primary and physically transported. Total and extractable Ag also show a well-defined peak over mineralization, though 80 m to the W of the main Au peak. Total and HCl extractable (but not enzyme leach) W also overlie mineralization. Other elements that appear to correlate with the position of buried mineralization are Co (selective extractions only) and Zn (HCl and selective extractions). In contrast, Ni and Pb correlate with the Mn high 200 m E of the position of buried mineralization and do not appear to define mineralization. Cobalt and, possibly, Cd appear to have two peaks: one above mineralization and the other associated with the Mn high.

Several aspects of the Steinway soil anomaly, namely:

(i) the very high Au concentration;
(ii) the poor solubility of the Au-rich sample
(iii) the single point Ag anomaly, 80 m west of the Au anomaly;
(iv) a total W (which is generally highly insoluble) anomaly;

suggests that the signal is probably due to physical transport of Au-bearing detritus, possibly from outcropping mineralization approximately 1 km south of Steinway (Lintern and Gray, 1995a). Transported lateritic gravels containing Au grains occur at 2-5 m depth, beneath the calcareous topsoils.

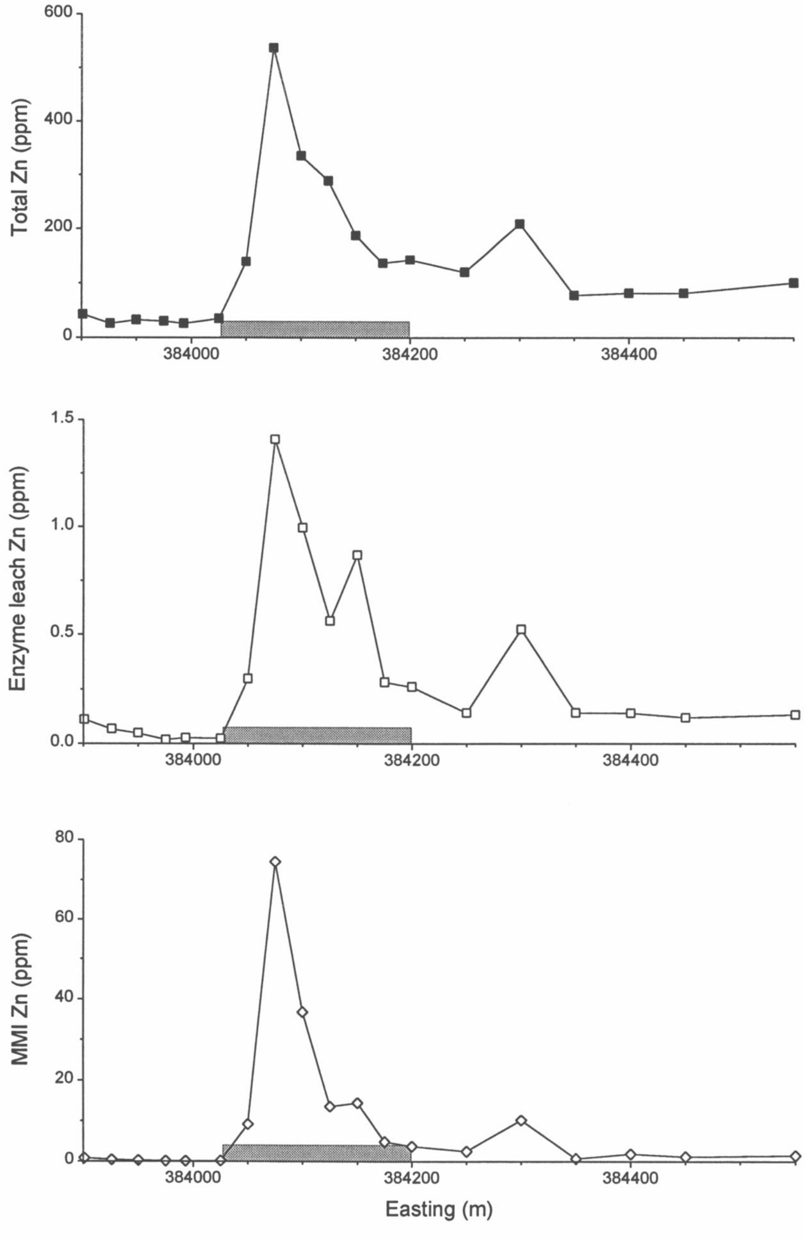


Figure 8.6: Total, enzyme leach and MMI Zn from Apollo traverse. (Shaded area represents Au mineralization in Archaean)

8.5.7 Apollo

This site has 5-10 m transported cover over 10-30 m variably leached saprolite and saprock. Gold concentrations show no correlation with buried mineralization. In contrast, there is a major Zn anomaly (550 ppm; Figure 8.6) directly overlying mineralization. Approximately 85% of the Zn is extracted by pH 5 acetate, suggesting an association with carbonates. Both enzyme leach and MMI gave good Zn responses, as did the other methods. Thus, this is not a subtle anomaly only observed by the partial extractions, but a zone with a major enrichment of Zn. MMI Co and (weakly) pH 5 acetate Co and Mn appear to correlate with this anomaly. The coincidental nature of this anomaly is also indicated by the absence of Zn enrichment in the primary mineralization.

A second multi-element anomaly was observed for the western-most soil, which was anomalous in Ag (450 ppb), Cd (170 ppb), Cu (15 ppm), pH 5 acetate Fe (27 ppm) and 4 M HCl W (26 ppb). The Ag was dissolved by 0.25 M hydroxylamine, suggesting incorporation in amorphous Fe oxides, whereas the Cd and Cu are pH 5 acetate soluble. It is possible that this anomaly could increase to the west. Thus soils at this site showed two separate anomalies, each with distinct multi-element signatures, in which the anomalous elements were highly extractable, even by the weak reagents. Further work would probably define the source(s) of these anomalies, but they could be explained by elemental dispersion from weathering sulphides north of the traverse, precipitating in the soils either as separate phase carbonates, or within the pervasive soil calcite.

Cerium, Co, Cu, Ni and Pb have distributions and solubilities indicating association with Mn oxides and/or amorphous Fe, which have greatest concentrations to the east of the traverse. Thus, this site shows a number of soil anomalies that appear unrelated to buried mineralization.

8.6 DISCUSSION AND CONCLUSIONS

The results discussed here are highly site-specific. This may be due to effects of the soil matrix, such as the presence or absence of carbonates, Mn oxides and/or less crystalline Fe oxides. There may also be a significant effect from landscape position, and presence of present-day drainage channels. The groundwater conditions vary considerably from fresh and neutral to the north, to highly saline and acid in the Kalgoorlie area, which has major consequences for the transport of a number of elements (see Chapter 6). Another factor that can vary significantly in arid environments is the amount of organic material, which will be affected by the ephemeral nature and/or scattered distribution of the vegetation.

The depth of transported cover appears to be significant. With the possible exception of Steinway, for which the anomaly appears to be due to physical transport from up-gradient (Section 8.5.6), sites with greater than 10 m transported material do not appear to show any anomaly at surface.

The partial extraction methods have particular characteristics that are important for interpretation. The MMI analysis is two separate techniques. The first, an acid extraction for Cd, Cu, Pb, Zn, plus Ni dissolved using the second alkaline extraction, give results that are similar, in terms of comparison between samples, to HCl and the selective extraction reagents. However, the absence of Fe and Mn data for this extraction, make inference on the effects of surface conditions difficult. As these are the primary metal scavengers, inclusion of analyses for these elements is judged to be an important requirement for the correct interpretation of the data obtained by this method.

The second MMI method is an alkaline extraction for Ag, Au, Co, Ni and Pd, which appears to be optimized for Au and Ag. In soils containing significant carbonate, 70-80% of the total Au is dissolved, whereas the proportion of Au extracted is significantly lower in the northern sites. These results closely match the CSIRO iodide method and the enhanced HCl digests. None of these extractants appear to be giving any additional exploration information for Au or Ag than cannot be obtained using standard analyses. In comparison, probably because the extraction is alkaline, Co data are unlike those observed for other techniques. In only one case (MMI Ni for one of two traverses at Baxter) do MMI results appear to show any correlation (albeit weak) with buried mineralization, that could not be observed using other methods.

The enzyme leach method also appears to give unique results, quite dissimilar to those from other methods, although the strong correlation between Fe and Cs, Ga, Hf, La, Nb, Pb, REE, Sc, Sn, Th, Ti and Zr is a significant issue for interpretation. With a few minor exceptions (I and Cu for one of two traverses at Baxter, and a weak Cu correlation at Bronzewing), enzyme leach does not appear to give data that correspond to the location of buried mineralization.

Some apparent (weak) association between mineralization and one or two elements at surface using partial extractions are noted above. However, there is commonly no obvious relationship between such observations, nor any reason why there should be any correlation. Given the many elements analysed and the number of sites investigated, such apparent 'correlations' would be expected. However, they commonly involve metals unrelated to primary mineralization and the correlation should be discounted. The presence of such metals in a multi-element anomaly may provide a means for identifying it as false.

Use of partial extractions, as summarized here, showed *either* strong false positives (or in the case of Curara, possibly a 'false positive' coincidentally over mineralization), *or* very poor ability for the extraction methods to indicate buried mineralization, except where totals would work anyway. At several sites (*e.g.*, Baxter, Fender and Safari), Au (by several methods) successfully delineates mineralization, but partial extractions of pathfinder elements are unsuccessful. It is concluded that, at the sites investigated, partial extractions only successfully locate buried mineralization where this can also be done using conventional methods. Although the partial extraction methods may still have value in giving better signal-to-noise ratios, or making subtle anomalies more obvious, they do not appear to offer any advantages for Au exploration in areas of transported overburden in the Yilgarn.

9. APPLICATIONS OF GROUND GEOPHYSICS IN EXPLORATION THROUGH TRANSPORTED OVERBURDEN - CASE STUDIES FROM THE YILGARN CRATON

9.1 Introduction

9.1.1 Background

Mineral exploration through transported cover in regolith-dominated terrains requires the application of interdisciplinary approaches, in which regolith geology, geomorphology and geochemistry are combined with geophysical methods. The use of geophysics in such environments presents significant challenges, particularly as regolith materials exhibit physical properties that have a profound effect on geophysical response (see, for example, the reviews by Doyle *et al.*, 1981; Butt, 1981; Palacky, 1987; Doyle and Lindeman, 1985; Smith and Pridmore, 1989; Dentith *et al.*, 1994). Whereas deeply weathered materials and an alluvial-colluvial cover have a very varied influence on geophysical response from bedrock, causing problems in analysis and interpretation, these characteristics may also be used to advantage when exploring through the regolith. Features that both hinder and enhance the application of geophysics in environments such as the Yilgarn are summarized in Table 9.1.

Table 9.1: Features that enhance and hinder the application of conventional geophysical methods in regolith dominated terrains (adapted from Smith and Pridmore, 1989).

Negative Features	Positive Features
1. Thick and variable oxidized cover - complex geophysical responses	1. Relatively gentle topography - aids the acquisition of high resolution airborne data.
2. High conductivities, masking deeper responses.	2. Arid climate - sparse vegetation cover permits easy access.
3. Saline groundwater - very conductive, making application of electrical methods difficult.	3. Differential weathering - promotes contrasting physical properties.
4. Development of maghemite - source of noise in high resolution magnetics.	4. Development of maghemite - concentrates in palaeochannels.

9.1.2 Effects on geophysical response

Density, magnetization and conductivity contrasts within the regolith, between transported cover and underlying materials, and at the weathering front combine to produce a range of geophysical responses that can be difficult to interpret. Some of these properties and their effects are summarized below:

Magnetic effects

Resistant primary magnetite and secondary maghemite may be concentrated by weathering and landscape development. Weathering of magnetite can produce non-magnetic species of Fe oxide in the regolith (Dentith *et al.*, 1992). However, this can vary and, in some cases, the magnetic character may be preserved. When maghemite is developed, it can display variable remanence, susceptibility and super-paramagnetic behaviour (Clark and Emerson 1991). Maghemite gravels may be concentrated through geomorphic processes accumulating, for example, in palaeochannels. Ground magnetics are dominated by short-wavelength anomalies with very high amplitudes, commonly attributable to the presence of maghemite.

Gravity
Low densities and marked density contrasts in regolith materials, combined with variations in thickness, hinder the application of gravity surveys by introducing high background or noise levels in gravity data. The common high irregularity of the weathering front, coupled with variations in the density structure, generate anomalies of the same order as those relating to bedrock.

Seismology
The complex zonation of the regolith, allied with transitional boundaries and irregular interfaces, hinder the application of seismic methods. However, the marked velocity contrasts between the regolith and bedrock may aid the application of shallow seismic techniques in resolving the nature and geometry of the saprolite-saprock/bedrock boundary. Similar velocity contrasts may be usefully resolved higher in the regolith.

Electrical methods
Marked conductivity contrasts within the regolith affect electrical and electromagnetic data. Regolith materials are commonly porous and contain water with dissolved salts. The presence of conductive clays and saline groundwaters yield conductivities in the range 0-100 Siemens (resistivities of 0.1-100Ω m). Polarisable clays in the regolith can cause IP effects in EM data. In areas of high conductivity, electromagnetic coupling can result, superimposing signal (noise) on deeper sources. At the base of the weathering profile, the transition between saprolite and essentially unweathered rock is reflected in a marked changes in conductivity. The weathering front is very irregular and a deep, conductive, regolith can abut unweathered resistive rocks that may be close to the surface. Rocks that may be resistive to weathering can remain unaltered high in the weathering profile. Where they exhibit physical properties that cause them to be either resistive or conductive, then application of electrical methods and the interpretation of derived data can become very difficult (Butt, 1981).

Radiometric methods
The radiometric response from weathered materials can vary significantly. Transported overburden will effectively mask the response from underlying bedrock. These materials are commonly characterized by a relatively high response in Th and U that can be related to the concentration of resistant secondary minerals (*e.g.*, zircon, ilmenite and monazite). Geomorphological processes control the distribution and relative concentration of radioelements. Gamma-ray surveys may be used to help elucidate the nature and distribution of regolith materials in the landscape and contribute to an understanding of its development.

9.2 Ground geophysics in areas of transported overburden

Joint field and laboratory studies within this project have involved the Department of Exploration Geophysics, Curtin University, and the Cooperative Research Centres for Australian Mineral Exploration Technology (CRC AMET) and Landscape Evolution and Mineral Exploration (CRC LEME). This collaboration has progressed research on the application of ground geophysical methods to regolith characterization in areas of transported cover, critical to developing improved geophysical processing and interpretation methods, particularly for airborne techniques.

Results from four study areas are reviewed here. These are the Harmony Au deposit (Baxter), in the Peak Hill District of the Glengarry Basin (Fowler, 1994 and Wilkes, 1995); Bronzewing, in the vicinity of the Discovery, Central and Laterite Pits (Lowe, 1994 and Roberts, 1994); background studies over the Agnew Greenstone Belt in the Lawlers District (Anning, 1993 and Rive, 1993) and studies over the Roe palaeochannel in the Kalgoorlie area (Cooper, 1995). A variety of ground geophysical tools were used (see Table 9.2). The survey parameters are also summarized in that table. Although the research was by no means comprehensive, they form the basis for linking airborne geophysical methods with surface and sub-surface regolith relationships. They also provide further insights on how geophysical methods may be used to aid regolith characterization through transported overburden. This research formed the basis for B.Sc. Honours projects in the Department of Exploration Geophysics at Curtin University of Technology, and full details are given in the theses referred to above.

9.3 Study areas, objectives and outcomes

9.3.1 Baxter

The Harmony Au Deposit located some 750 km north of Perth, in the Peak Hill area of the Glengarry Basin (Figure 1.1), was the focus for two separate studies on the application of ground geophysical methods for regolith characterization beneath cover. The Harmony deposit was completely covered by a blanket of soil and colluvium at the time of these studies. Drilling had identified a complex regolith of weathered, partially lateritized Proterozoic basement, clay rich valley sediments and colluvium (see Chapter 2). The bedrock consists of mafic and ultramafic metavolcanics and fine grained metasediments.

The research at Harmony had the following objectives:

(i) to examine geophysical methods for elucidating regolith structure and stratigraphy under cover;
(ii) to locate the contact between the metasediments and metavolcanics.

Several geophysical data sets and techniques were examined. These included gravity, ground magnetics, and time domain EM.

Gravity data were useful for defining the contact between the Ravelstone metasediments and the metavolcanics (Figure 9.1), due to the high density contrast between the two units. The modelled gravity response supported the general structural interpretation of the area.

Ground magnetic data were dominated by noise, which was attributed to the widespread distribution of maghemite gravels in the colluvium (Figure 9.2). A low sensor height of 0.75 m made the interpretation difficult. General trends, such as the higher response over the metavolcanics, are noted. The elevated response of the magnetics to the north and west of Harmony relates to the volcanics which plunge in a NNW direction under a thin cover of metasediments. Several confined highly anomalous areas are also apparent. These may relate to the accumulation of maghemite gravels and/or the presence of lateritic residuum. On the eastern side of the Harmony Pit, an increase in the magnetic response coincides with the location of a small palaeovalley, which is exposed in the pit wall (see Chapter 2). Drilling and exposures indicate an accumulation of gravels on the flanks of this valley. A similar interpretation can be invoked to explain the anomalous magnetic highs noted to the south and south-west of the pit. In this instance the maghemite gravels may be accumulating on the flanks of the larger palaeovalley which runs to the west of the pit (see Chapter 2). A subsequent ground magnetics survey indicated that better results would have been obtained from the sensor being positioned at 2 m height.

Time domain EM studies were conducted using SIROTEM MkII and PROTEM EM-47 instruments. A grid was generated using SIROTEM data over the Harmony deposit. Various regolith units were resolved using these data. Gridded early time TEM (Ch6, 0.319 msecs) data from SIROTEM showed a good correspondence with the valley-fill sediments that underlie the colluvial cover in the area (Figure 9.3). These sediments comprise smectite-kaolinite clays and were conductive in the TEM data. Standard time TEM channels also showed the thick sequences of transported materials that straddled the palaeohigh in the area. Several lines of PROTEM data across the Harmony deposit confirmed the results obtained from SIROTEM, in that the valley-fill sediments were associated with elevated conductivities. However, some problems were encountered in trying to resolve the base of the transported overburden.

Table 9.2: Summary of ground geophysical methods, survey parameters and results in areas of transported overburden

Ground Geophysics Study Area	Method	Instrument	Survey Parameters	Results
Baxter	Electromagnetics (TEM)	SIROTEM MkII PROTEM EM-47	Coincident longs 100 m x 100 m, 50 m spacing. Standard and early time 5 lines (>200 m apart) 40 x 40 m loop, 20 m offset soundings.	Palaeovalley sediments defined using early time data. Areas of thicker transported cover also resolved.
	Gravity	LaCoste & Romberg Gravity Meter	Stations 40 m apart.	Located the contact between Ravelstone metasediments and Narrocoota Volcanics under cover.
	Magnetics	(i) GT-TMG caesium vapour magnetometer with base station. (ii) Proton precession magnetometer	Stations over 0.5 m 10 m apart, sensor height 0.75 m 1 m station spacing, sensor height 2.0 m.	Very noisy due to effects of maghemite. Maghemite distribution exerts major control on observed response.
Bronzewing	Electromagnetics	SIROTEM MkII PROTEM EM-47	Coincident loops 50 & 100 m spacing. 20 m loops, 40 m sampling. 20 m offset soundings.	Lateral distribution and vertical extent of a resistive (laterite) was mapped under a colluvial cover.
	Magnetics	Geonics 856 Magnetometer	2 m sensor height, 6 lines (1.5 km).	Random, sharp, high frequency and amplitude variations observed. They may be related to buried duricrust or maghemite gravels.
	Gravity	Worden Gravimeter	20 m sampling 3 lines (1 km).	General, bedrock-related contrasts observed.
Lawlers	Electromagnetics	PROTEM EM-47	20 x 20 m loop, 40 m sampling. 20 m offset soundings.	Resistive units within saprolite resolved (*e.g.* silicified saprolite, duricrust); base of weathered zone delimited. Variations in weathering related to structure and lithology recognised.
	Magnetics	Proton precession magnetometer	2 m survey height, 10 m spacing.	Transported maghemite gravels dominate response, although deeper sources (bedrock?) also recognised.
Kalgoorlie Line 10 (~1800 m long) (Wollubar Channel) Line 18 (1 km long) Yindarlgooda North Channel	Magnetics	Proton precession magnetometer	2 m sensor height, 1 m spacing.	Low frequency variations (bedrock related) for line 18; high frequency variations - maghemite related for line 10.
	Shallow seismic reflection	OYO DAS-1 Seismic Data Acquisition System	Line 18 - split spread, 3 m shot spacing. Line 10 - off end, 6 m shot spacing. Geophone spacing 1.5 m.	Defined details relative to regolith stratigraphy in palaeochannel and its base over saprolite.
	Gravity	Worden Gravimeter	25 m spacings.	Highlighted palaeochannel shape, position and general outline.
	Electromagnetics (TEM)	SIROTEM MkII PROTEM EM-47	Coincident loop - 100 x 100 m, 50 m spacing. Loop 40 x 40 m (line 10), 50 x 50 m (line 18); 50 m stations.	Defined palaeochannel extent and geometry - did not resolve base of channel.

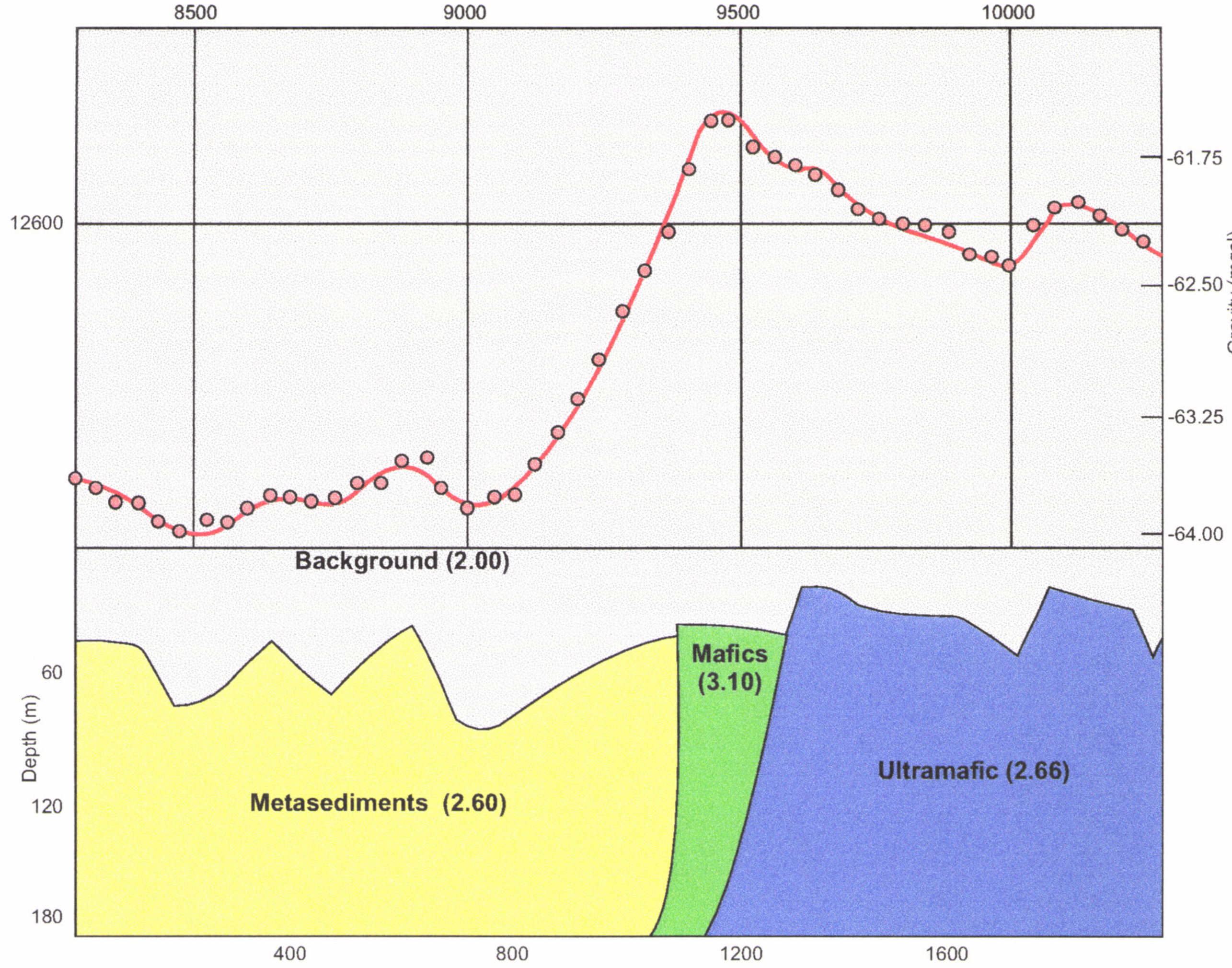


Figure 9.1: Final model of gravity for line 12400N, which traverses the Harmony Au deposit.

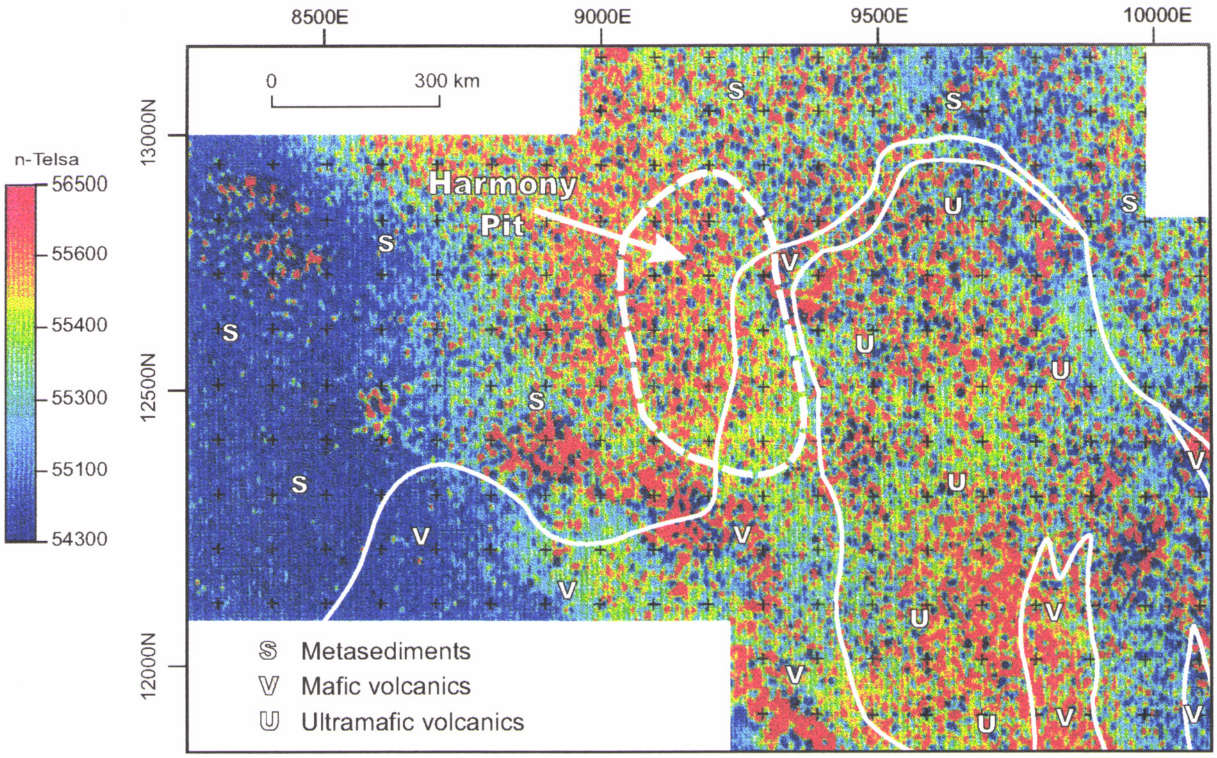


Figure 9.2: Grid of ground magnetics data over the Harmony Au deposit. The Harmony Pit outline and interpreted bedrock boundaries are overlain.

9.3.2 Bronzewing

Located in the Yandal Greenstone Belt some 400 km north of Kalgoorlie (Figure 1.1), the Bronzewing Au deposits, hosted by a sequence of mafic volcanics and minor sediments, were totally obscured by a deep transported cover (30 m) and an intensly weathered, residual, regolith. Bedrock is encountered some 80-120 m below the surface. The principal objective of the geophysical studies conducted in the vicinity of the Discovery, Central and Laterite Zones was:

(i) to determine the effectiveness of ground geophysical methods, specifically magnetics, time domain electromagnetics and gravity for mapping features, notably lateritic residuum, within the regolith under thick transported cover.

The magnetics data were collected as a grid across the Central and Discovery Zones, and are presented as stacked profiles in Figure 9.4a. These data exhibited random, sharp, high frequency, high amplitude anomalies. They were filtered using non-linear methods to remove the effects of deeper sources and those which could lie very close to the surface. Filters with a halfwidth of 3 and 35 m were used. The results are presented in Figure 9.4b. The extent of buried residuum identified from drill core is also shown. Anomalies associated with the buried laterites are apparent, but similar anomalies were also noted elsewhere. These may be attributed to accumulations of maghemite in the transported cover.

PROTEM EM-47 and SIROTEM data were acquired along several traverses in the same area. A resistivity-depth section from inverted PROTEM data for line 9800N is shown in Figure 9.5. A reasonably good correlation is observed between the conductivity contrasts observed in the PROTEM data and the regolith defined from drill cuttings. The PROTEM and SIROTEM resolved the interface between the fresh bedrock and the saprolite-saprock. The lateral extent of buried lateritic residuum resolved using magnetics and early time EM data suggested that the best results would be obtained from the combined use of these techniques. Vertical electrical soundings were also recommended to aid the modelling of TEM data in areas of cover.

Bouguer gravity stacked profiles indicated that bedrock density contrasts were dominant in determining the response, and that the influence of the regolith *per se* was small. There was some suggestion that large scale palaoedrainage trends could also be observed. However, these may be structurally or bedrock related.

9.3.3 Lawlers

The Lawlers district, located some 300km north of Kalgoorlie (Figure 1.1), is characterized by a varied regolith, with transported cover accounting for some 40% of the area. These depositional units commonly conceal extensive, essentially "complete" lateritic weathering profiles (Anand *et al*., 1992). Geophysical methods have the potential to provide a more complete picture of the regolith, including the stratigraphic relationships that are necessary to define rational geochemical sampling, analysis and interpretation strategies for the area.

Several studies on the application of ground geophysics for regolith characterization have now been completed in the Lawlers district. These include the work of Mayes (1992) who described that it was possible to resolve the presence of a resistive duricrust, the depth to bedrock and other resistivity contrasts beneath transported colluvium and alluvium in an ground-based early-time TEM (PROTEM EM-47) survey. This study was located between the North and Turret Pits. In follow-up studies conducted in under the auspices of this project, Anning (1993) and Rive (1993), reported similar findings.

Their studies had the following objectives:

(i) to map regolith stratigraphy through transported cover;

(ii) to map variations in the bedrock geology and structure beneath the regolith.

Several techniques were tested, including magnetics and time domain EM.

A ground magnetics survey with a sampling interval of 10 m introduced severe aliasing in the data over areas of high frequency "noise". Non-linear filters were used to separate distinct high and low frequency anomalies, with the latter being attributed to bedrock sources.

Considerable success was reported for the EM data. A relatively resistive (averaging 20Ω m) upper layer, overlying a more conductive (averaging 3Ω m) second layer was modelled for the soundings taken over several traverses in transported cover. The second layer was commonly associated with saprolite. The inversion of the PROTEM data assumed a horizontal (I-D) layered earth. This assumption was considered representative for the areas studied. In areas characterized by rapid variations in layer thicknesses and vertical contacts, the modelled results would not be reliable.

Features that were resolved with the aid of drill hole data were the weathering front, which exhibits significant variations in geometry, and a resistive silicified saprolite zone over ultramafic rocks and the lateral extent of lateritic duricrusts beneath cover (Figure 9.6a,b). The thickness of alluvium-colluvium was not confidently resolved in the work reported by Anning (1993) unless drill hole data was available to help constrain the modelling. This was attributed to the effects of more conductive, near-surface, groundwaters saturating the interface region between the alluvium-colluvium and upper saprolite (Figure 9.6b).

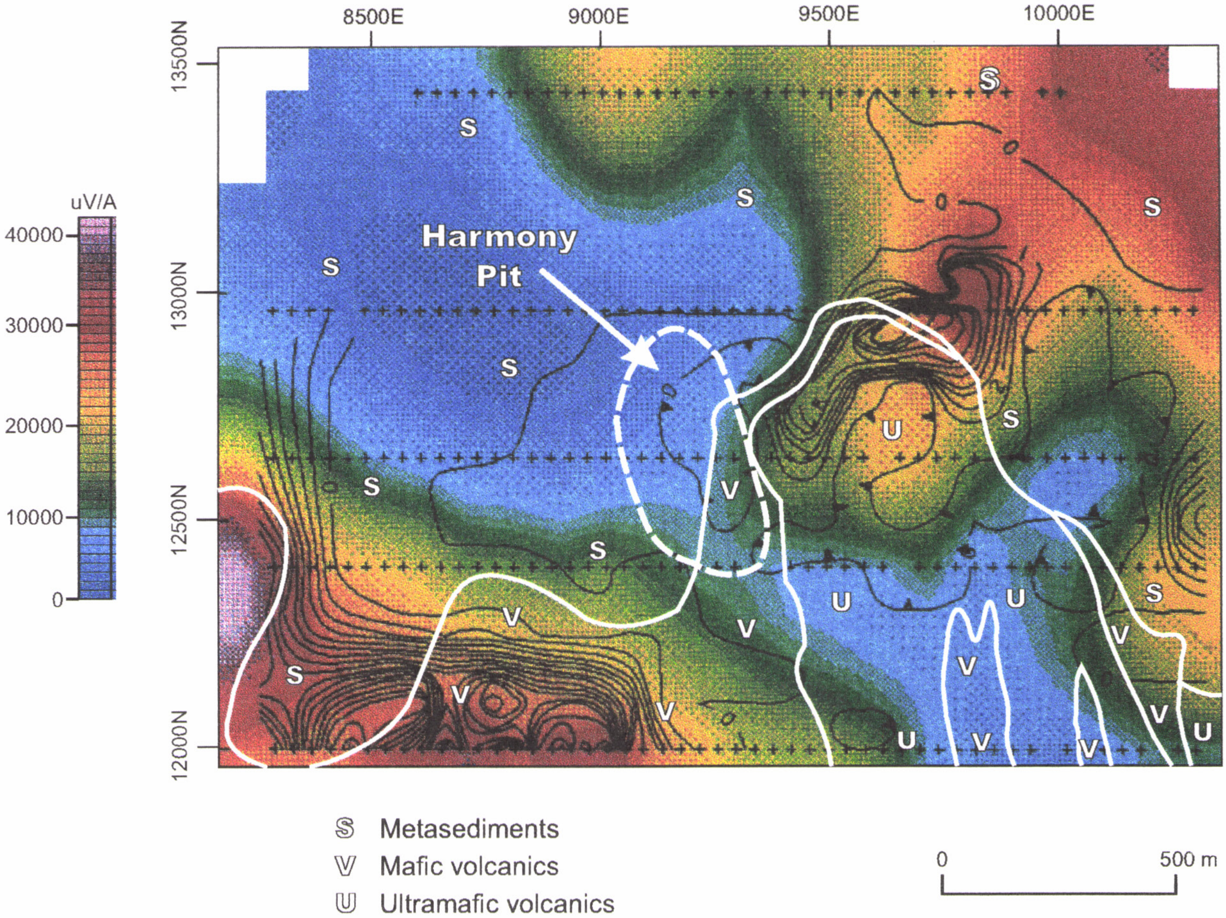


Figure 9.3: Gridded early time SIROTEM data (Ch6, 0.319 m secs) over the Harmony Au deposit. Isopachs of valley fill sediments are overlain in black. Thicker valley-fill sedimentary sequences are associated with elevated conductivities. The outline of Harmony Pit and bedrock contacts are overlain in white.

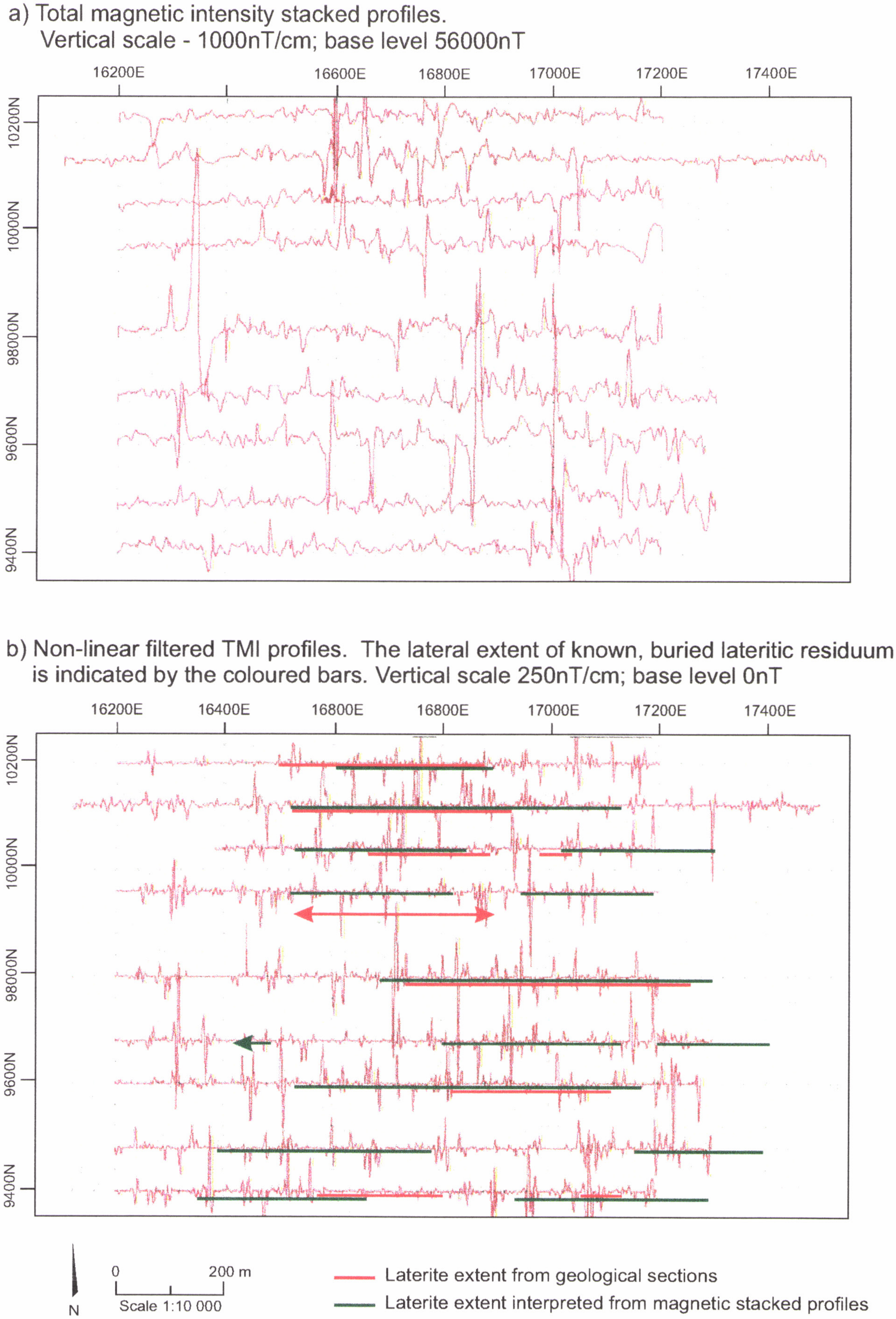


Figure 9.4: Total magnetic intensity profiles for the Central and Discovery Zones, Bronzewing.

Variations in bedrock lithology could be mapped indirectly with the early time EM data using variations in the thickness of the regolith or depth to the weathering front. Marked conductivity contrasts are characteristic of this interface. Conductive zones observed to continue down from that nominal interface, in the resistivity-depth sections, were attributed to water-filled fracture zones, or different rock-types that weather recessively. These results confirm observations made elsewhere, namely that the weathering front is highly irregular and exhibits a strong lithodependence.

9.3.4 Kalgoorlie

A relatively comprehensive case study on the relative merits of geophysical techniques for the study of transported overburden, specifically palaeochannels, was conducted in the vicinity of Kalgoorlie. The Roe palaeodrainage system (Section 2.4.3) was targeted for this as, it was the subject of previous studies against which the geophysical data could be compared. The work had several objectives:

(i) determine the application of geophysical methods, including shallow seismics, time domain EM, gravity and magnetics, for defining palaeochannel geometry and stratigraphy;
(ii) determine whether the saprolite-palaeochannel sediment boundary can be resolved;
(iii) construct a physical property model of palaeochannels in the Kalgoorlie area.

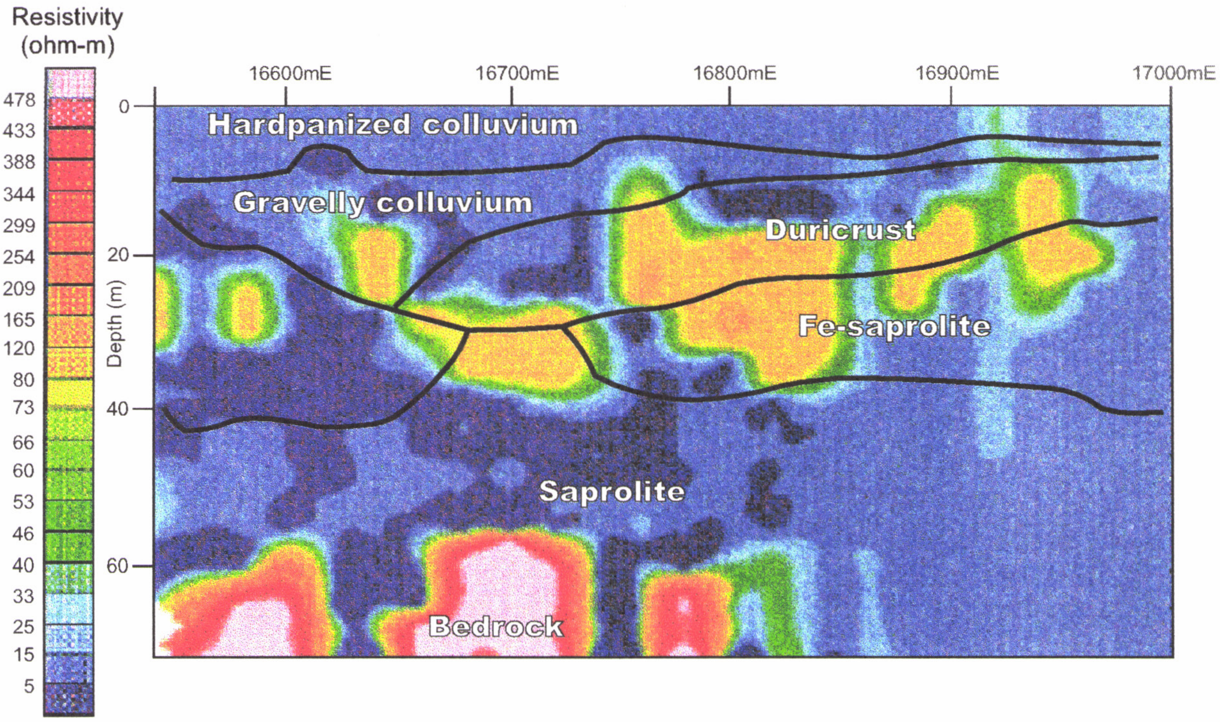


Figure 9.5: Resistivity-depth section from a ID inversion of PROTEM EM-47 data along line 9800N. The regolith stratigraphy overlain on this geoelectric section was interpreted from drill cuttings.

Two sites were chosen within the Roe Palaeochannel System (Figure 9.7), located in contrasting geological settings.

The choice of techniques was driven by a desire to map physical property variations within the palaeochannels themselves. Seismic reflection data detect changes in the acoustic impedance (velocity x density), whereas EM detects the presence of variably conductive saturated materials. Gravity should measure the density contrast between the palaeochannel sediments and the underlying bedrock, resulting in a gravity low over the channel. Ground magnetics, though not used as a direct method for the study of palaeochannels, may supply information on any controlling features (*e.g.* structure/lithology) that may be present.

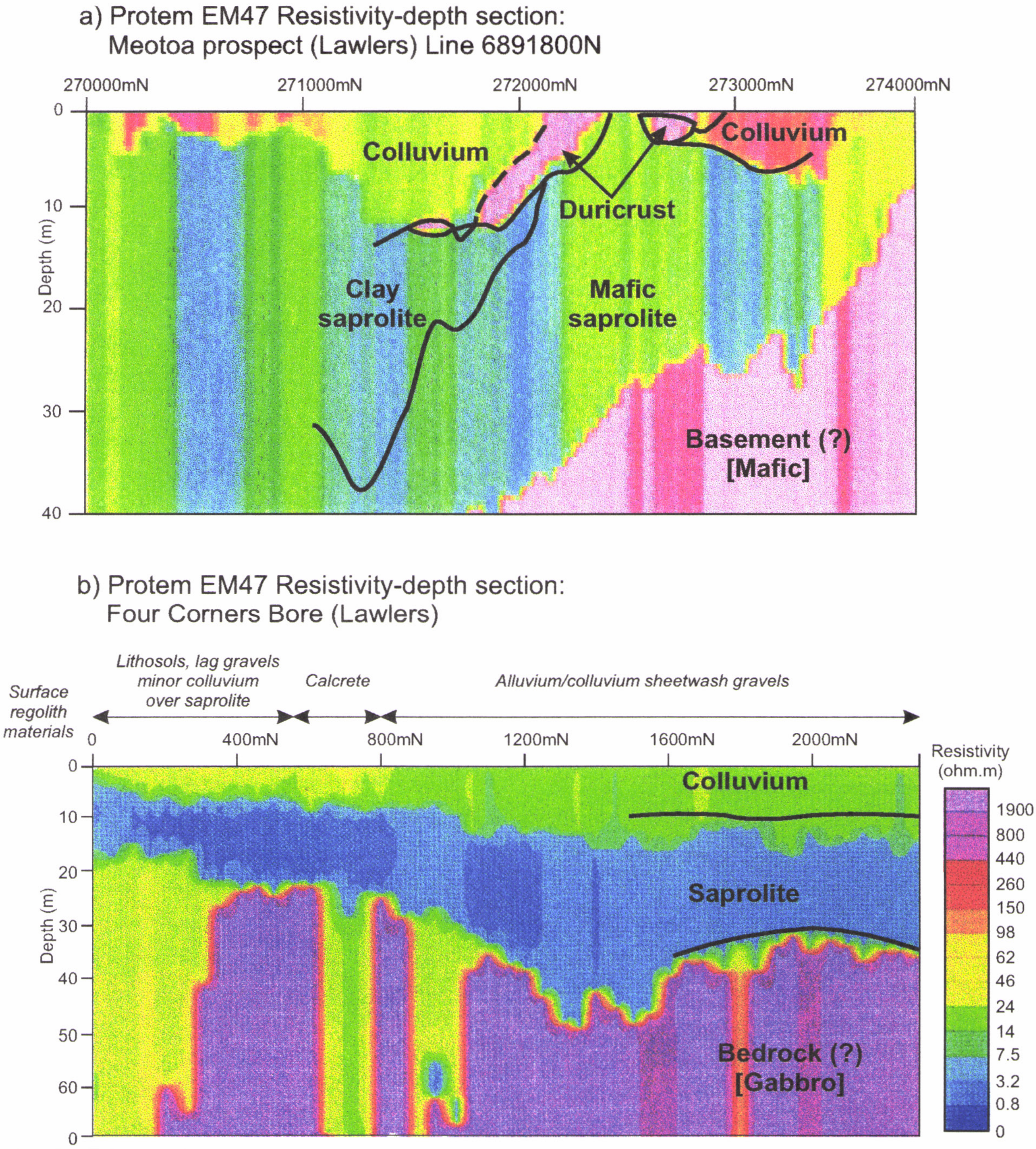


Figure 9.6: Resistivity-depth sections from a ID layered earth, inversion of PROTEM EM-47 data for two traverses over transported cover in the Lawlers area. The regolith stratigraphy overlain on these sections was determined from drill hole cuttings, and was used to constrain the inversions.

The seismic reflection method was successful, particularly for one of the lines (line 10) where an appropriate acquisition spread (see Table 9.2) enabled the geometry, stratigraphy and structure to be resolved within and beneath the channel. This was the only method that delimited the boundaries between the various sequences within the channel sediments. It also defined the boundary between the sediments and the underlying saprolite (Figure 9.8). Further studies were advocated to confirm these results.

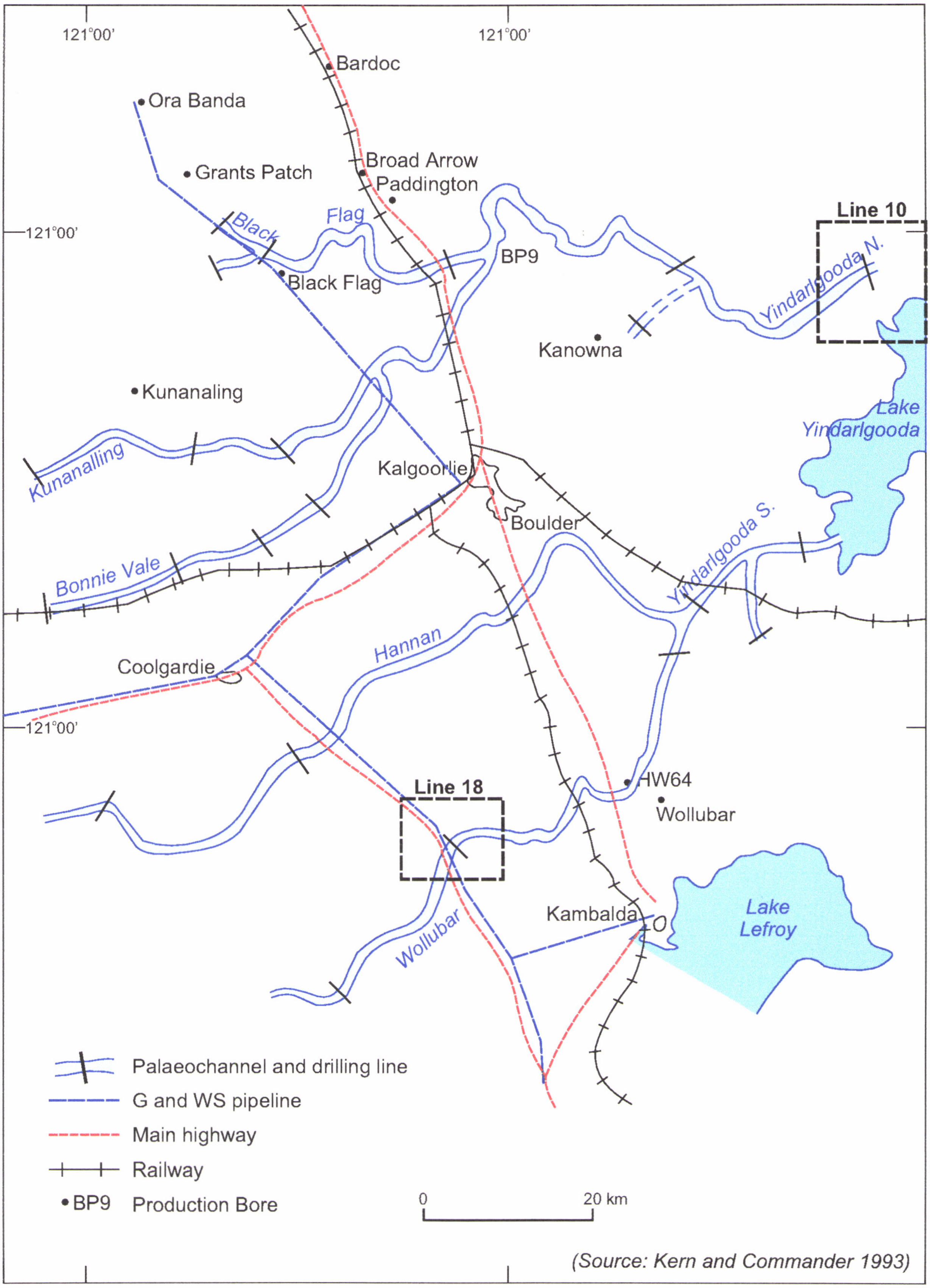


Figure 9.7: Location of study sites for the geophysical investigation of palaeochannels.

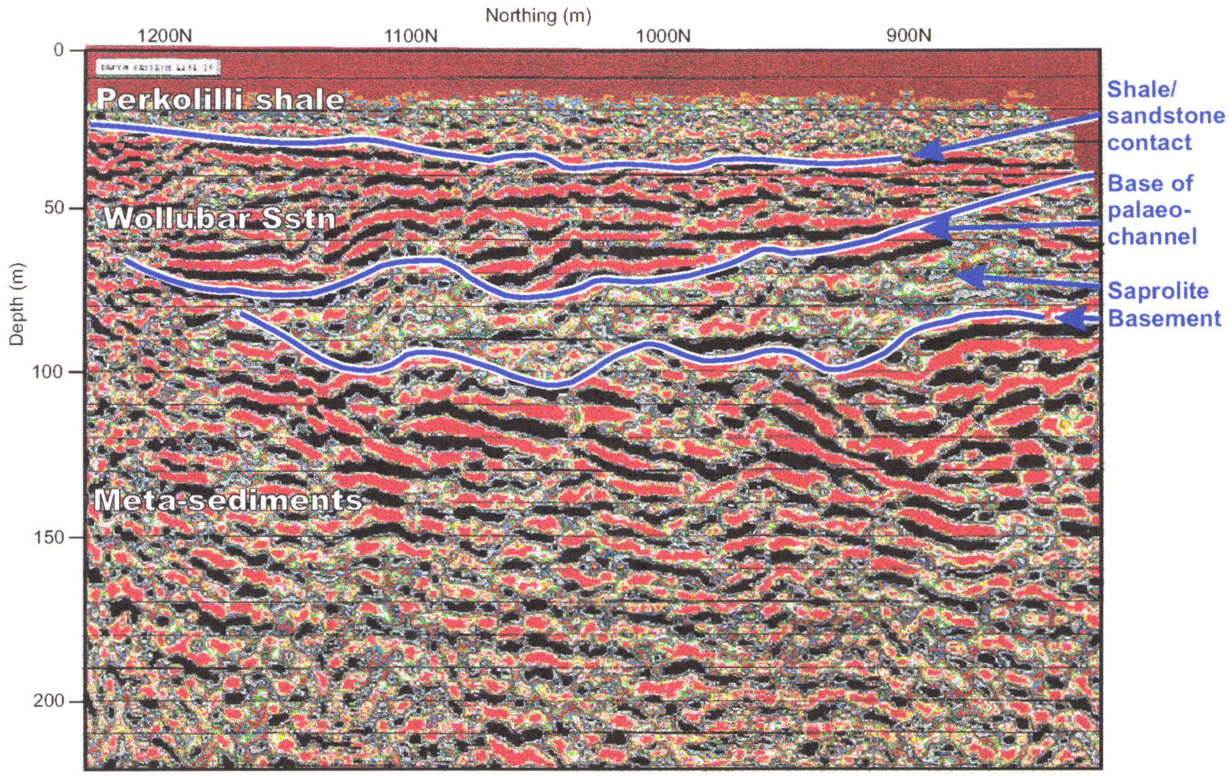


Figure 9.8 Seismic reflection section for line 10

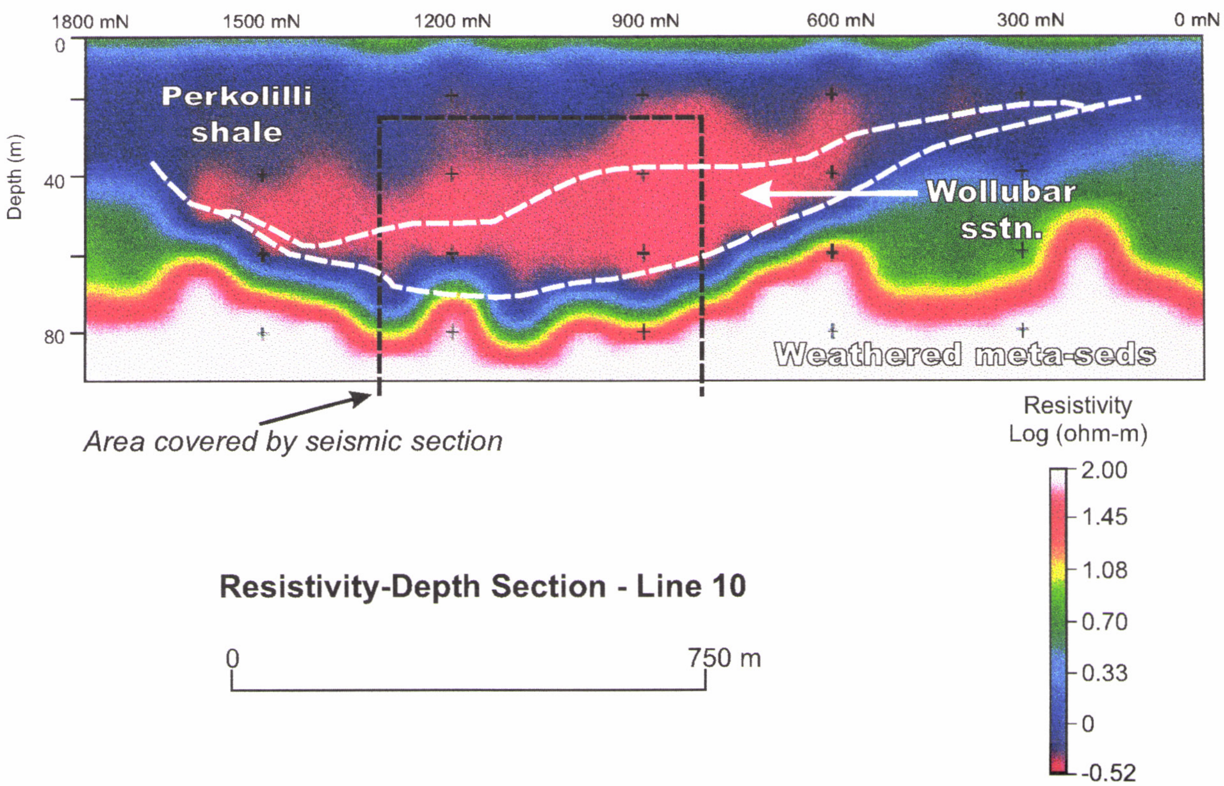


Figure 9.9: Resistivity-depth section from layered earth inversion of PROTEM EM-47 data for line 10.

Ground magnetics were severely affected by the presence of highly magnetic surface materials.

The electromagnetic and gravity techniques were able to outline the general shape of the palaeochannels, but were unable to resolve the stratigraphy, except in a general sense, nor the geometry of the channel (Figure 9.9 and Figure 9.10). Modelled electromagnetic data correlated well with the drilling data in places, defining the depth to fresh bedrock, probably reflecting a variance between the physical property contrast at the saprolite-bedrock boundary versus an interpreted depth based on the scrutiny of drill chips. The highly saline, conductive groundwater served to mask EM responses from greater depths. Gravity modelling over both survey lines correlated well with drilling information over the centre of the palaeochannels. However, the models were unable to resolve the base of the channel where saprolite depths increased. Similar results have been reported by Commander *et al.*, 1996.

In the exploration for palaeochannels, gravity and electromagnetic methods have considerable potential, particularly where saprolite thicknesses are not great. However, in areas of complex geology and deep weathering, seismic reflection methods may be the most effective for resolving regolith stratigraphy, geometry and extent.

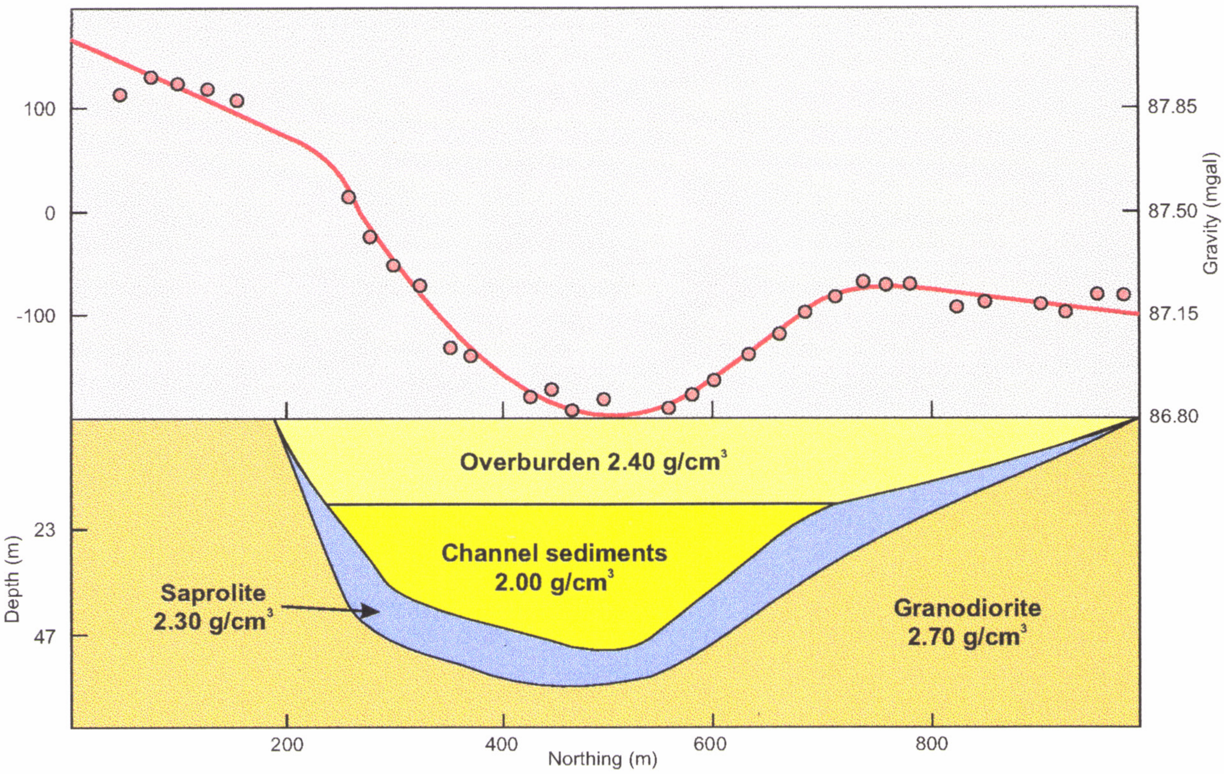


Figure 9.10: Final model of gravity for line 18 across the Wollubar palaeochannel near Kalgoorlie (see Figure 9.7).

9.4 Summary and implications for mineral exploration through transported cover

9.4.1 Magnetic methods

In areas of substantial transported cover:

(i) Ground magnetics are commonly dominated by short-wavelength, high amplitude responses that can be linked to the accumulation of maghemite relating to geomorphic processes.
(ii) Non-linear and low pass wavelength filters help suppress the effects from near-surface sources that have a high spatial variability.

Acquisition of ground magnetic data is rapid, but low level, high resolution airborne magnetics may be more cost-effective because noise introduced by near-surface materials will be suppressed.

9.4.2 Gravity

Gravity gradiometers can be used to advantage when working in areas of transported cover - because they can detect variations in the thickness of regolith and the density of regolith materials. In the case studies reported here:

(i) Gravity lows were observed over palaeochannels in the Kalgoorlie region. Forward modelling of gravity data allowed the position and their general geometry to be resolved in different geological settings. General stratigraphic subdivisions were possible and showed good correlation with available drill-hole data.
(ii) At Baxter, density contrasts between sediments and volcanics permitted the modelling of their contact under cover.
(iii) Spatial trends in the regolith may be difficult to discern where regional (bedrock) trends are significant.

Data acquisition is rapid and processing has been made considerably easier with the advent of GPS.

9.4.3 Shallow reflection seismology

Reflection seismology demonstrated that when studying transported materials associated with major palaeochannels:

(i) Regolith stratigraphy within the deepest part of major palaeochannels could be resolved, in contrast to electromagnetic and gravity methods. Depths to significant regolith units can be determined.
(ii) Variations in the geometry of the channel-saprolite interface were well defined.
(iii) Structure within the underlying basement is also observed.

Shallow seismic data are more costly and time consuming to conduct. However, they may have application for mining and mineral exploration where it is important to locate particular stratigraphic units and the basal unconformity of the channel.

9.4.4 Electromagnetic methods

Transient electromagnetics (TEM) have considerable potential as a tool for mapping regolith variations beneath transported cover. Early time EM responses:

(i) Mapped the lateral and vertical extent of resistive lateritic material beneath cover at Bronzewing.
(ii) Resolved the thickness and variation of regolith cover in contrasting bedrock settings at Lawlers, Bronzewing and in Kalgoorlie.
(iii) Resolved variations in the geometry of the weathering front beneath cover.
(iv) Defined the spatial extent and variation in transported cover, particularly that related to palaeovalley sedimentary fill at Baxter.

(v) Defined the general geometry and extent of palaeochannels.

TEM can be acquired relatively rapidly, providing information on the thickness of regolith under transported cover. However, resolving the interface between transported and residual regolith may be problematic in some cases.

9.4.5 Conclusion

Results from these and related studies suggest that ground geophysical techniques provide potentially useful information on the nature and variability of regolith materials beneath cover. When used as part of an integrated exploration strategy, they may assist in defining the thickness and spatial variability of regolith cover. This may be pertinent in the planning and conduct of drilling programs over areas of transported cover. In certain instances, they provide information on the regolith stratigraphy that has value in defining appropriate geochemical sampling strategies. Information on the geometry and variability of regolith cover including the weathering front may assist in explaining dispersion patterns and hydromorphic pathways. When used in conjunction with airborne data, ground geophysical techniques may help in defining appropriate processing and intepretation approaches.

10. EXPLORATION IN AREAS OF TRANSPORTED OVERBURDEN: RECOMMENDATIONS

10.1 Tenement assessment

District-scale appraisal of regolith-landform characteristics is an important prerequisite for efficient exploration of a regolith-dominated terrain. This will assist in deciding the most cost- and technically efficient exploration procedures for different areas of a tenement. The appraisal can be achieved by mapping, using satellite imagery and aerial photography, supported by field checking. In areas that have previously been explored and for which drill cuttings and core are available, outline regolith information should be recorded, where possible including total depth of weathering, lithology, principal horizons, depth and nature of transported overburden, soil type and nature of lag. Where this information is unavailable, drilling for regolith stratigraphy becomes necessary, particularly in depositional areas. Ground geophysics, particularly early-time transient electromagnetics, may assist in the delineation of depth to resistive bedrock and may resolve buried lateritic residuum. In some cases the thickness of transported cover may be defined, although care must be taken when working in areas characterized by more saline groundwaters. The regolith-landform map is a guide to the nature of dispersion patterns and models that apply across the tenement, *i.e.*, in relict areas, A-type models (see Section 4.1), in erosional areas, B- and C-type models, and in depositional areas, subject to regolith data being available, A, B or C**[3] models. This information will determine some or all of the optimum sample type, sample interval, sampling procedure, analytical method and suite of elements, and data interpretation procedures to apply.

It is evident from the results of this and previous projects that accurate mapping of depositional regimes and the correct identification of the nature of the sediments and the depth of the unconformity are essential, because

firstly, as little as one or two metres of cover will greatly diminish, or even mask, the presence of sub-cropping ore-grade mineralization, particularly in non-calcareous soils north of the Menzies Line, thereby greatly restricting the use of surface sampling techniques and,

secondly, geochemical responses in transported overburden are generally confined to within about two metres of the unconformity between the cover and weathered bedrock, in either or both the overburden and the residuum.

Recommendation. Regolith-landform mapping, close attention to regolith characteristics and stratigraphy and continued upgrading of the information as exploration proceeds are essential to ensure that the most appropriate sampling strategies are employed.

10.2 Regolith-landform environments

*10.2.1 Lateritic residuum preserved beneath overburden (Models: A**[3])*

Regoliths with full residual lateritic profiles preserved beneath transported overburden are most commonly found on the backslopes extending from breakaways to adjacent colluvial plains. This situation is more widespread in the northern Yilgarn. In semi-arid areas in the south, lateritic residuum seems to be less abundant and may either have been destroyed by erosion or, alternatively, may never have formed. Wherever lateritic residuum is preserved, it is the preferred sample medium and can be utilized in the same manner as for relict regimes, so that sampling may be continued laterally from outcrop to material buried beneath overburden. Sample intervals may vary from 500 m for regional surveys to as close as 50 m for delineation of drill targets and, ideally, analysed for a range of pathfinder elements in addition to Au. Samples may represent individual 1 m drill intervals to composites over 2 or more metres. However, where composites are used, it is desirable that they are from the same unit - *i.e.*, not be a mixture of lateritic gravels and ferruginous saprolite. It is also important to ensure that the materials are indeed residual. The sediments overlying lateritic residuum commonly consist of, or contain, lateritic debris and, accordingly, drill cuttings must be carefully logged. Criteria such as the presence of cutans on pisoliths and nodules, an absence of fracturing, no apparent sorting and a monomictic composition suggest that gravels may be residual and an appropriate sample medium. However, these may be misleading in palaeovalleys where sedimentation pre-dated and/or was contemporaneous with deep weathering. In such situations, upper horizons of the profile are developed from sediment and lower horizons from bedrock, so that the upper horizons have no direct genetic relationship with the underlying bedrock. This appears to be the situation at Lancefield, where Permian glacial sediments overlie the Archaean, and at the Mt. Keith Ni sulphide deposit (Brand and Butt, 1995). Similarly, pisoliths with well developed, multiple, cutans have developed during the weathering of palaeochannel sediments. These are residual, with respect to the sediments, but there is no evidence that their composition reflects the occurrence of mineralization within or beneath the sediments, possibly because they developed prior to the main phase(s) of Au mobility and supergene enrichment.

Recommendation. Where regolith mapping has identified lateritic residuum in depositional areas, this is the preferred sample medium for district- to prospect-scale surveys. Logging must be accurate in order to distinguish and reject transported lateritic debris; drilling need continue into the top of the saprolite, although it can be cost-effective to drill to fresh bedrock at the prospect scale; some deeper drilling is appropriate to assist regolith and geological mapping. In the event of mineralization being intersected in saprolite or bedrock, strong anomalies in lateritic residuum can assist in identifying a substantial system from minor mineralization. Multi-element analyses should be used to give better target delineation.

*10.2.2 Lateritic residuum intermittently preserved (Models A**[3] and B**[3])*

Spatially variable preservation of lateritic residuum is very common, due to differences in the intensity of erosion of the palaeosurface. This situation prevails at Harmony, Fender and Bronzewing - at the last, for example, there are several metres of lateritic residuum in the Laterite Zone, 1-3 m - but locally absent - in the Central Zone and little or none at the Discovery Zone. Accordingly, a constant sample medium cannot be selected across the whole area. Because lateritic debris may be a significant component of the sediment, identification of suitable sample media is critical. Where lateritic residuum is preserved, it remains the favoured sample medium; where it is absent or very thin, it is appropriate to sample either the ferruginous saprolite just beneath the unconformity or, more probably, two or more samples across the unconformity. As noted above, it is desirable not to have a composite that mixes two regolith units, although this is inevitable in the interval across the contact itself. Comparisons of element abundances in the two media can be obtained where both materials are present in order to determine whether the sample sets can be combined. Saprolite sampling will be expected to give narrower dispersion haloes and, where depletion has occurred, lower element abundances, particularly for Au.

Recommendation. As for 10.2.1. Where lateritic residuum is absent, sampling should target ferruginous saprolite and/or ferruginous materials in the basal sediment. The data should be coded accordingly in the database and generally considered separately from lateritic residuum.

*10.2.3 Lateritic profile partly or wholly truncated (Models B**[3] and C**[3]*

Irrespective of whether or not the pre-existing profile had a well developed ferruginous horizon, the residual regolith has commonly been truncated prior to colluvial or alluvial sedimentation. There is little or no lateritic residuum and sediments accordingly rest directly on saprolite, saprock or, more rarely, fresh rock. This situation prevails at Quasar, Golden Delicious and Safari, as well as applying to parts of the Fender, Harmony and Bronzewing areas. As noted above (Section 10.2.2), geochemical anomalies in saprolite, just below the unconformity, are expected to be restricted in size and, for Au, possibly of low abundance and contrast compared to those in lateritic residuum. There is, however, commonly some enrichment in Au and/or pathfinder elements associated with the unconformity, in either the sediments or the saprolite or both. This enrichment generally occurs within 2 m of the contact. In the sediments, it may be due to either clastic or hydromorphic dispersion and, in the residual regolith, to hydromorphic dispersion and some residual concentration at the palaeosurface. At Golden Delicious, for example, hydromorphic dispersion has resulted in a Au anomaly of 500 m across strike in the sediments and 300 m in the saprolite. By comparison, at Fender, clastic dispersion of ferruginous nodules has given an As-Sb anomaly extending over 200 m downslope. At both locations, the anomalies are associated with ferruginous materials. Accordingly, the most appropriate sampling procedure is to sample both above and below the unconformity. Given the restricted vertical extent of the dispersion, composite samples, especially those of intervals greater than 2 m, are not recommended. Where possible, composites should not mix regolith units, except for the sample that intersects the contact itself. Because of the association between dispersed ore-related elements and ferruginous materials, there can be some advantage in selective sampling, *e.g.*, nodules, ferruginous saprolite, mottles, especially where these form a small proportion of the total sample, as at Fender. It should be noted, however, that the anomalous nodules at Fender are derived from erosion of lateritic residuum, not from the sub-crop of mineralization at the saprolite-colluvium unconformity.

In contrast with Golden Delicious, Quasar has relatively non-saline groundwaters, a deeper water-table and greater truncation. Nevertheless, samples across the unconformity (interface) give a similar, low contrast Au anomaly, extending for over 300 m across strike. Copper and, to a lesser extent, Zn, also give broad anomalies at the unconformity, whereas those of Bi and Pb are restricted, though still greater than in saprolite.

Recommendation. Where the residual regolith is truncated to the saprolite, sampling should concentrate on the 2-3 m above and below the unconformity. Accurate logging is essential to identify this interval and, where possible, samples of the two units should be kept separate and not composited. Specific sampling of ferruginous materials (pisoliths, nodules, mottles, ferruginous saprolite) is appropriate, especially if their abundance is low. For prospect-scale exploration, drilling should be at intervals of 50 to 100 m cross-strike, depending on the degree of truncation, and should continue to the upper saprolite. Some deeper drilling is appropriate to assist regolith and geological mapping. Multi-element analyses should be used to give better target delineation.

10.2.4 Mineralization within or beneath palaeochannel sediments

Supergene mineralization may occur entirely within palaeochannel sediments, be associated with the basal unconformity or occur entirely within saprolite, 5-10 m beneath the unconformity. Controls on the location, formation mechanisms and timing of the mineralization are uncertain, but are probably related to specific redox conditions during the continuing arid periods. The locations of channels are in part structurally-controlled and follow major faults and shears, many of which, such as the Zuleika Shear, are intermittently mineralized. Supergene mineralization in saprolite is commonly directly associated with underlying primary mineralization, but sources of Au in the sediments are generally less certain, with the exception that in lignites at Argo and Challenge-Swordsman. There is no evidence for any geochemical expression of the supergene mineralization, whether this is in bedrock or channel sediments, in overlying units. Even authigenic pisoliths in sediments overlying mineralization have no Au enrichment, possibly because supergene mobilization has post-dated their formation. Similarly, there are no soil anomalies over most deposits. Anomalies at Steinway, Graveyard and Baseline are exceptions, and probably coincidental, for adjacent deposits are blind.

Recommendation. Exploration for palaeochannel-related deposits depends on recognition of the structural and geomorphological setting, followed by drilling to determine channel stratigraphy and to intersect the broad, sub-horizontal targets of supergene mineralization. Knowledge of channel stratigraphy (Chapter 3) and the ability to recognise the different units and identify the unconformity are essential, in order to ensure that drilling is deep enough to reach the saprolite. Ground geophysics, particularly shallow seismology can aid in this respect. The location and general geometry of palaeochannels can be resolved using TEM and gravity.

10.3 Specific sample media

10.3.1 Lag

Lag sampling has been employed for regional surveys, with samples collected from all landform regimes. It may have value where the overburden is generally thin (<2 m), such as at Harmony and Bottle Creek (Robertson and Wills, 1993; Robertson *et al.*, 1996a). However, although regionally anomalous concentrations of Au and associated elements may be obtained from depositional areas with thicker overburden, there is no evidence to suggest that they represent a surface expression of underlying mineralization. The anomalies relate to the source area of the lag fragments, which may be several kilometres distant, transported by sheetwash or ephemeral streams. Thus, in the colluvial-alluvial plains overlying the Boogardie Synform near Mt. Magnet, the sediments have a high background Au abundance (approximately 50 ppb) which reflects the widespread Au mineralization in the catchment, and there are scattered spot high concentrations exceeding 200 ppb in lag samples. There is a low order lag anomaly over Quasar, but there is no comparison with element distributions in the underlying colluvium. Elsewhere, lag anomalies are unrelated to mineralization and their occurrence is considered to be random.

Recommendation. Lag sampling is inappropriate for exploration of areas having extensive transported overburden, except where the overburden is very thin.

10.3.2 Soil

Southern Yilgarn. The surface response obtained by soil sampling in the southern Yilgarn is dominated by the preferential accumulation of Au in pedogenic carbonates. These are generally present in the top 2 m of the regolith, although they may not occur at the ground surface. Accordingly, shallow soil samples (<30 cm) are only effective if they include calcareous materials. The recommended procedure is to target the carbonate horizon by auger drilling, and collect a 1 m composite sample through it. In some areas, (*e.g.*, at Safari), it may be necessary to drill below 2 m to reach the carbonates.

Evidence from studies at Safari, Kanowna and Wombola suggest that pedogenic carbonates are an appropriate sample medium in depositional areas where the sediments are up to 5 or 10 m deep. Such areas should be identified and data from them considered separately from those of erosional areas and where the sediment cover is thicker. Shallow auger drilling should thus be supplemented by deeper drilling to determine regolith stratigraphy. Nevertheless, it is possible that, in some localities with thinner sediments, there may be no response. Conversely, false anomalies could be developed where the sediments include detrital Au-rich gravels, similar to those at Steinway and Graveyard-Aphrodites.

Where sediments are deeper than 10 m, as at Apollo and all palaeochannel sites, there is no evidence for a surface geochemical response, in any element, in the carbonates or any other soil component, whether Au mineralization is in the sediments or the underlying saprolite. In depositional areas characterized by deep (>10 m) sediments, therefore, carbonate sampling is not a direct exploration tool that can be used to delineate drilling targets. However, because Au tends to accumulate in carbonates, they may have use in regional surveys, to identify prospective catchments and source areas. Where anomalies are present over mineralization, however, such as those at Steinway, Graveyard and, possibly, that reported from Baseline, they appear to be false or coincidental, derived from detrital, Au-bearing ferruginous gravels sourced from outcropping mineralization.

Recommendation. Soil sampling which targets the carbonate horizon may be effective in delineating concealed mineralization in areas of shallow overburden in the southern Yilgarn, but appears to be inappropriate where it is >10 m thick. In all depositional areas, the possibility of 'natural' contamination by Au-enriched sediments must always be considered. Soil carbonate sampling in areas of deep overburden may have value in district-scale appraisal, but not for selecting drill targets.

Northern Yilgarn. Pedogenic carbonates are of restricted distribution north of the Menzies Line. In effect, the precipitation of secondary silica (as hyalite) to form red-brown hardpans is their equivalent, but there is no apparent association between Au and hardpan. Manganese oxides are generally present coating fractures and surfaces in hardpan. No responses in Au or other elements are observed that reflect underlying mineralization (Ward, 1993). Hydrogeochemical investigations indicate that Au is chemically less mobile in the region and, in the absence of pedogenic carbonate, there is no similar host for Au in soils. Secondary carbonates precipitated deeper in the overburden, as at Golden Delicious and Granny Smith, do not appear to concentrate Au in the same manner as pedogenic carbonates and neither they, nor the transported or residual materials in which they occur, reflect underlying mineralization.

As with lag, seemingly anomalous soil samples will represent the provenance of the sediments from which they are developed. The only exceptions are where the overburden is very thin and bioturbation or other mechanical processes have mixed residual material with the sediment. Thus, low order anomalies in Au and pathfinder elements are present in the top metre of sediments overlying lateritic residuum at Fender and Harmony. However, where sediments are slightly thicker, such anomalies will not be present, so that drilling to sample the lateritic horizon directly is preferred.

Recommendation. Neither shallow (<30 cm depth) nor deeper (0-1 m) soil sampling are effective in depositional areas and soils are not recommended as sample media where the cover is more than about 2 m.

10.3.3 Colluvial and alluvial sediments

The results obtained in the project suggest that dispersion into the sediments, whether clastic or hydromorphic, is generally restricted to within about 3 m of the unconformity and that sampling above this is ineffective. The composition of the sediments may broadly reflect those of the catchment, as in the Boogardie Synform but, in general, catchments are too large and the sediments too difficult to characterize, for the provenance to be determined. Hydromorphic dispersion has led to a significant Cu-Zn anomaly (>1000 ppm) in alluvial silty clays, probably derived from black shales, at Dalgaranga (Butt, 1992). No similar pattern has been observed around Au deposits, possibly because of the generally low abundances of these elements in Au mineralization in the Yilgarn. Thus, Cu is widely dispersed at the interface at Quasar, but concentrations are low (<90 ppm).

Recommendation. Alluvial and colluvial sediments are generally ineffective sample media for detecting mineralization beneath them, unless within 2-3 m of the unconformity with the host unit. These basal sediments should be collected as part of an interface sample.

10.3.4 Lateritic residuum and ferruginous materials

As discussed in Section 10.2.2, lateritic residuum is the most favoured sample medium and gives the widespread, multi-element anomalies. Accurate logging is essential to distinguish detrital lateritic debris from lateritic residuum. Where the latter is absent, ferruginous materials (pisoliths, nodules, mottles and ferruginous saprolite) in the basal sediments and the upper residuum are the best option, since these may contain both clastically and hydromorphically dispersed elements. Where possible, samples from either side of the unconformity should be collected, and treated separately. Specific sampling of ferruginous components may be necessary, and composited over 2-4 m.

Recommendation. As for 10.3.1 and 10.2.2.

10.3.5 "Interface" samples

Transported and residual materials, respectively above and below the unconformity, are sites for secondary enrichment of elements. Dispersion may occur during erosion, during the formation of a residual or partly transported palaeosol, and after sedimentation, when the unconformity itself may be a zone for preferential seepage or flow of groundwater. Accurate logging is essential in order to locate the unconformity and, if composite samples are used, they should, as far as possible, not mix the sedimentary and residual components. Sampling at 50 x 100 m intervals is adequate to detect dispersion haloes of the dimensions present at Quasar, Golden Delicious (this project), Bottle Creek and Mt. McClure (Anand *et al.,* 1993).

Recommendation. As for 10.3.3.

10.3.6 Saprolite

Saprolite sampling, other than at the interface, is generally expected to give very restricted anomalies, although contrasts may be high. Sample intervals of 100 x 50 m, or even 50 x 50 m may be barely adequate to detect mineralization in these circumstances. Where there is severe Au depletion, however, sampling in the upper saprolite may yield low contrast Au anomalies and it may be appropriate to rely on pathfinder elements such as As, Sb, Bi and W. Conversely, in areas where sub-horizontal supergene enrichment 'blankets' are anticipated, deeper drilling at intervals of 100 x 100 m or wider may be appropriate. In any case, some drilling to the base of saprolite is wise to determine regolith stratigraphy and to assist in geological mapping. Similar broad dispersion of Pb has been noted from base metal deposits (*e.g.*, Butt, 1995), but their use in exploration has not been evaluated.

Recommendation. The top of the saprolite is collected as part of an 'interface' sampling program. Saprolite sampling is costly because of generally narrow dispersion haloes, but can give a direct indication of mineralization. Drilling should be sufficiently deep to penetrate depletion zones and to intersect supergene enrichment. The complete hole should be analysed (preferably multi-element), either as individual samples or as composites.

10.3.7 Vegetation

Vegetation and, in places, mull was sampled at several sites in the southern Yilgarn, mainly in conjuction with investigations in the use of carbonate sampling. As with previous studies (Butt *et al.*, 1991, 1993), equivocal results have been obtained but, in each instance, where an anomaly is present in plants or mull, a similar or better response is present in the soil (carbonate horizon for Au). As for soils, abundances are greater in erosional areas and, for *Eucalyptus* and *Eremophila,* tend to be close to or below detection limit in areas of transported regolith. Increased analytical sensitivities are required to evaluate fully the use of these genera as sample media in transported regolith. Bluebush (possibly *Maireana* spp.) gave promising results at Apollo, but it is uncertain whether the response is genuine or due to contamination, so that further testing is needed. Limited data for mull suggests that it is unsuitable as an exploration medium in areas of transported overburden.

Recommendation. Vegetation sampling is not recommended as a sample medium in any of the environments studied, although further testing, particularly of bluebush, is warranted. In all vegetation sampling, care must be taken to (i) collect the same species of plant and, preferably, the same organ; (ii) ensure that vegetation is properly cleaned prior to analysis, especially hairy plants such as bluebush, and (iii) use sensitive analytical techniques.

10.3.8 Groundwater

Southern Yilgarn. Groundwaters sampled in the Kalgoorlie region are commonly acid (pH 3 - 5), except where buffered by extremely alkaline materials (*e.g.*, ultramafic rocks), and saline within the top part of the groundwater mass, trending to more neutral (pH 5 - 7) and hypersaline at depth within a few kilometres of salt lakes, or within the lakes themselves.

The saline-acid-oxidizing groundwaters close to the water-table are highly effective in dissolving Au as the chloride or iodide complex. Once dissolved, the Au-halide complex is meta-stable, except in Fe-rich solutions, which effectively reduce and precipitate the Au. There is little scope for multi-element hydrogeochemistry for the highly acid groundwater, because of very high backgrounds for base metals (*e.g.*, Cu, Pb, Zn), and precipitation of anionic chalcophile elements (*e.g.*, As, Sb, Bi, W, Mo). Dissolved Cr in this and other regions of the Yilgarn Craton specifically delineates the presence of ultramafic rocks.

***Recommendation*.** For the Kalgoorlie region, sampling should be restricted to shallow groundwaters. A limited suite of parameters, namely salinity, pH, Eh, dissolved Au, Fe and Cr could be analysed cheaply (using standard probes, sorption onto carbon for Au, and ICP-AES and/or colorimetric analyses for Fe and Cr) but extending this to the other elements of interest will add considerably to cost, with little added exploration benefit. A threshold dissolved Au concentration of approximately 0.05 ppb would appear to locate most mineralized areas. Analysis of Fe should be used to check for false negatives (*i.e.*, where dissolved Fe is > 0.1 ppm, then dissolved Au will commonly be below background), even in close proximity to a Au deposit.

***Central Yilgarn*.** A zone approximately 100 km wide, approximately parallel to the Menzies Line, is characterized by neutral groundwaters that are brackish (commonly < 1% TDS) to saline (about 3% TDS), trending to hypersaline (10 - 30% TDS) at the salt lakes, with common increases in salinity with depth.

These groundwaters are moderately effective in dissolving Au as the chloride or iodide complex, again with interference from dissolved Fe. There is considerably more scope for multi-element hydrogeochemistry using base metals (*e.g.*, Cu, Pb, Zn), and/or anionic chalcophile elements (*e.g.*, As, Sb, Bi, W, Mo), although the more saline samples are more expensive to analyze and have higher backgrounds. Dissolved Cr in this and other regions of the Yilgarn Craton specifically delineates the presence of ultramafic rocks.

***Recommendation*.** For the Central region, shallow groundwaters should be used, with a threshold dissolved Au concentration of approximately 0.02 ppb appearing to locate most mineralized areas. Analysis of Fe should be used to check for false negatives (*i.e.*, where dissolved Fe is > 0.1 ppm, then dissolved Au will commonly be below background). As well as those parameters analysed for Kalgoorlie groundwaters (salinity, pH, Eh, Au, Fe and Cr), a more expanded analytical suite, including As, Sb, Mo, W, Bi and Tl, may well be useful, though at extra cost. Orientation studies to test multi-element responses may be valuable.

***Northern Yilgarn and Proterozoic margin*.** Groundwaters in these areas are fresh (commonly << 1% TDS) and neutral, though trending more saline in the valley floors. These groundwaters have very low dissolved Au concentrations, though with the very low detection limits (0.002 ppb) dissolved Au may still have value for exploration. Multi-element hydrogeochemistry using base metals (*e.g.*, Cu, Pb, Zn), and/or anionic chalcophile elements (*e.g.*, As, Sb, Bi, W, Mo), and other indicator elements (*e.g.*, Rb and Sc) is successful, with low detection limits and costs for the fresher groundwaters.

***Recommendation*.** For the Northern region, the threshold dissolved Au concentration is much lower (approximately 0.002 ppb). Sampling depth is not as critical as in other regions. A comprehensive analytical suite, including base metals, other chalcophiles (As, Sb, Mo, W, Bi and Tl) as well as Rb and Sc, is expected to give additional exploration data, with high sensitivity and moderate cost.

10.3.9 Use of partial extraction analysis

A suite of extraction methods, including iodide extraction, selective extractions for carbonate, Mn oxides and amorphous Fe oxides, acid extractions, MMI and enzyme leach, were evaluated at seven sites with significant transported overburden. Total and/or extractable Au (using a variety of methods) gave the best exploration response, though only where there is <10 m of transported cover. MMI, iodide and "enhanced" acid extractions gave virtually identical Au responses. Results for other elements appeared to be strongly controlled by surface phenomena, even for methods such as MMI and enzyme leach that are alleged to be able to "see through" the transported cover. The few apparent positive indications of mineralization are commonly by elements not associated with primary mineralization, indicating the 'correlations' to be coincidental. The weak acid digest gave similar results to the sum of the selective extractions for most elements, though with better sensitivity. Most of the MMI elements also gave similar patterns to the acid extractions. The enzyme leach results were different from those of the other techniques, though the strong correlation between Fe and many other elements is of concern. There was no viable evidence for these techniques improving the ability to search in areas of transported cover.

Recommendation. In areas of thin cover, Au is the only consistent pathfinder for buried mineralization, with the sampling procedures summarized above. The various partial extraction techniques give little or no useful additional data but, conversely, may yield further positive false anomalies. If such techniques are to be tested (such as in areas of minor cover and/or active hydromorphic dispersion), the weak acid digest appears to be most useful, in terms of agreement with standard extraction methods, good sensitivity and low cost. Iron and Mn should be included in the element suite selected for analysis, to aid interpretation. Anomalies with a wide range of elements, especially if associated with Fe and/or Mn enrichment, should be regarded with caution.

10.4 Ground geophysics

Ground geophysics can provide valuable ancillary information on the nature and disposition of regolith beneath cover. The depth to resistive bedrock and the presence of buried, resistive, lateritic residuum has been mapped using early time transient electromagnetics. In some cases the unconformity between cover and weathered bedrock may be resolved. However, in the presence of saline groundwater, this can be problematic, particularly where the transported cover and weathered bedrock exhibit similar electrical characteristics.

The high frequency content of ground magnetics profiles correlate with the presence of lateritic residuum. However, accumulations of maghemite-rich gravels may confuse this interpretation. Moderate amplitude, moderate frequencies are associated with buried residuum. Quiet areas are indicative of saprolite and bedrock responses. Analysis is best achieved using stacked profiles. Zoning according to the frequency content of the data can help define subsurface contrasts. Reflection seismology, whilst slow and potentially costly, can be used to define palaeochannel stratigraphy and the unconformity between transported cover and weathered bedrock. However, further work is required to refine the technique. Gravity data may help delimit density contrasts associated with variations in transported cover, *e.g.* palaeochannels.

Recommendation. Broadly space ground geophysics traverses can provide valuable information on nature of regolith beneath cover. Best results are obtained when limited drill hole data are used to constrain modelling and inversions. Results can be used to develop and refine drilling and sampling strategies as exploration progresses.

11. CONCLUSIONS

11.1 Outcomes versus objectives

The principal findings of this project are outlined below, with the objectives stated in the Project Proposal and as amended at the first and at subsequent meetings of sponsors as the project evolved.

Principal Objective
To develop geochemical methods for mineral exploration in areas having substantial transported overburden in the Yilgarn Craton and its environs, through investigations of the processes of geochemical dispersion from concealed mineralization.

Broad outcomes
Regional regolith-landform maps were established over six locations, namely Mt. Magnet (Boogardie Synform), Baxter, Bronzewing, Kurnalpi, Wollubar, Steinway, Argo-Apollo and Higginsville. Each of these areas has substantial areas of transported overburden concealing prospective bedrock sequences. Reconnaissance appraisal was also undertaken at two other districts (Golden Delicious and Safari). Within each of these, detailed multi-disciplinary studies were undertaken at one or more sites, including the stratigraphy, petrography and chemical and mineralogical composition of transported and residual regolith, coupled with investigations of geochemical dispersion from buried mineralization in a range of potential sample media including, wherever possible, groundwater and, in places, vegetation.

At several sites in the northern Yilgarn and the Proterozoic margin, the overburden is characterized by the presence of lateritic debris, which may overlie lateritic residuum or rest directly on saprolite. In such areas, it is generally essential to be able to recognise the lateritic debris, and distinguish it from lateritic residuum. The lateritic basal debris may be of value only in a "near-miss" situation if of local origin. The lateritic nodules that occur in low energy, clay-rich sediment at Fender are of only local origin, and are of use as sample media, being derived from erosion of another part of the same deposit. Conversely, lateritic gravels that occur as lenses within the transported cover, well above its base, have little likelihood of being useful sample media. Even if anomalies, their source would be unknown.

There seems to be little or no dispersion of gold or associated pathfinder elements into the sedimentary cover in these northern areas. The dispersion that does occur appears to be limited to the lowermost two or three metres, probably due to a combination of mechanical and chemical mechanisms, during and after deposition, including churning induced by wetting and drying, bioturbation, the formation of a palaeosol on the residuum and hydromorphic dispersion along the unconformity. These process may give a surface geochemical signature where the overburden is less than three metres thick, but otherwise contributes to an anomaly at the interface between the sedimentary and residual units.

Surface units of the sediments are characterized by late-stage and probably on-going silicification and alteration associated with the formation of red-brown hardpans. These processes do not appear to give rise to any surface expression of concealed mineralization.

The focus of most of the districts and sites investigated in the southern Yilgarn was on palaeochannels and the mineralization concealed within and beneath them. Lateritic debris is less abundant than in the north. However, degraded nodules and pisoliths are present in the basal units of some channels, and ferruginous granules and nodules are a common component of the surface colluvium.

Dispersion into transported overburden appears to be slightly greater in the south, with geochemical responses seemingly present where the cover is up to 5 and, locally, to 10 m thick. The anomalous response is generally hosted by pedogenic carbonates, commonly within the top 2 m, but over 4 m deep in sandy overburden (*e.g.*, at Safari).

Some anomalies in pedogenic carbonate reflect the occurrence of Au-bearing ferruginous granules in the substrate. At Panglo and Runway, which are in erosional areas, these are residual in the upper saprolite and contain relict primary and secondary Au particles. In depositional sites, they may be exotically-derived and give rise to false anomalies, as at Steinway and Graveyard-Aphrodites (Higginsville). The latter conclusion is of considerable importance. Anomalies such as these, which directly overlie otherwise blind mineralization, are commonly taken to be proof that a particular technique is effective as an exploration procedure. However, it is evident at both sites that adjacent mineralization does **not** have a surface anomaly (*e.g.*, Greenback and Mitchell-4). Conversely, many explorationists report finding anomalies with no underlying source. A possible explanation is that the latter also reflect exotically derived Au-bearing material. At Steinway and Graveyard-Aphrodites, it appears that coincidence has caused a false result. It is only by detailed studies such as those conducted in this project that the true relationships can be established and recommendations for exploration developed. In this case, neither soil nor carbonate sampling give a true indication of the occurrence of mineralization, so that exploration should be guided by the geology of the channels and basement, targeting the expected broad supergene enrichment haloes.

Hydrogeochemical investigations have built on data obtained in previous projects. They have confirmed that groundwaters in the arid areas of the Yilgarn Craton fall into three broad groups, Northern, Central and Kalgoorlie, based on composition (salinity) and pH. Each of these represents a different weathering and dispersion environment and, as such, demand a different approach for sampling and analysis when used in exploration. Broader anomalies are present in areas of saline groundwater (Kalgoorlie, Central), where Au is mobilized as a halide complex, than in fresher groundwaters (Northern), in which Au is complexed by thiosulphate and has a highly localized distribution. The results suggest that groundwaters have a limited ability to "see" through barren, transported overburden. This appears most useful in the chemically more active Kalgoorlie waters and much poorer in the less active Northern waters, with the chemically conservative species, such as SO_4, giving better signatures of bedrock than more reactive elements such as Au and Mo. Accordingly, if possible, sampled waters should be in contact with, or close to, residual material for optimum results. In areas of saline groundwater, such as the Kalgoorlie region, it is probably most cost-effective to restrict analysis to a few parameters such as salinity, pH, Eh, Au, Fe and Cr. A more expanded analytical suite, including As, Sb, Mo, W, Bi and Tl, may be useful, though more costly, in Central groundwaters whereas, in the north multi-element analysis are less expensive and have potential.

Biogeochemical investigations have been restricted to the Southern Yilgarn. In general, there appears to be no advantages in plant sampling compared to soil sampling. Anomalous Au contents in bluebush were obtained at Apollo, although the possibility of contamination by dust cannot be eliminated. Lower detection limits are required for full evaluation of the technique, but it is evident that the requirements for correct species identification, use of a common plant organ (such as twigs, leaves, bark) and the necessity to ensure that samples are scrupulously cleaned prior to analysis restrict application.

Specific Objectives

1. *Determine the characteristics of the principal types of surficial sediments and sedimentary environments in the region and to develop a system for the identification and classification of sedimentary overburden.*

The principal types of sediments on the Yilgarn Craton can be classified into three categories:

(i) sediments that pre-date the deep weathering, as exemplified by Permian glacial sediments;

(ii) sediments that were deposited contemporaneously with deep weathering, including colluvium and palaeochannel sediments of Tertiary age;

(iii) sediments that have been deposited during the continuing arid periods, namely colluvial sheet-wash deposits, alluvium, aeolian sands and clays, and a variety of evaporites, including valley calcretes and saline deposits, such as gypsum and halite in playas. These sediments are the most widespread and most variable. They may overlie not only fresh and weathered basement, but also the sediments of the other groups.

The characteristics of examples of these sediments have been described and illustrated in an Atlas of Transported Overburden for this project (Robertson *et al.,* 1996b), as an aid to identifying materials in hand specimen, drill cuttings and thin or polished section. Criteria for distinguishing between transported and residual regolith materials have been refined as, from the results of this research, this remains critical to effective exploration, given that there appears to be limited dispersion into the cover sequences from buried mineralization, especially north of the Menzies Line. Dispersion is commonly greatest at the unconformity (or interface), hence recognition of this contact is of great importance. Nevertheless, uncertainties remain, especially where like materials are in contact, such as lateritic debris overlying lateritic residuum or where the sequence emulates a residual profile, *e.g.*, lateritic debris overlying ferruginous saprolite. In some situations, the unconformable contact is gradational, due to churning, or is obscured by the overprint of later weathering.

The stratigraphy of the sedimentary cover has been established in most detail in the palaeochannels of the southern Yilgarn. These studies have confirmed those of previous workers, revealing regionally consistent sequences in the Cowan-Lefroy and Roe palaeochannels. The Cowan-Lefroy drainages contain marine and non-marine sediments, including reduced lignitic units. In many cases, these have been dated, giving ages from Early Eocene to Pliocene, with major changes equated to marine transgressions during this period. The sediments in the Roe channel, however, are simpler and appear to be non-marine; they are deeply weathered and are dated largely by correlation with sediments in the adjacent Lefroy channel. The seeming consistency of the sedimentary sequence, with a basal sandy unit (Wollubar Sandstone) overlain by kaolinitic clay (Perkolilli Shale), is a useful guide to identifying regolith stratigraphy during exploration for supergene gold deposits within and beneath the channels. Broadly similar sequences are evident in palaeochannel in the northern Yilgarn, although these have been studied in much less detail.

2. *Determine the geochemical expression, in the regolith, of concealed gold and base metal deposits in selected geomorphological settings, such as playas and highly saline environments, and plains dominated by colluvial, alluvial and/or aeolian sediments. Investigations include determination of the mechanisms of dispersion and the potential for these deposits being revealed by labile ions in surficial materials.*

Sites from a variety of regolith-landform settings were studied, although none was situated beneath a playa and none had a significant aeolian component to the sediments. The characteristics of the sites studied are summarized in Table 11.1. Geochemical dispersion was studied at each site and the probable mechanisms established. The use of labile ions in exploration was evaluated by comparing seven selective and partial extraction analytical methods at seven well-characterized sites, plus a number of other site-specific investigations. No base metal deposits were offered for study in the project and the dispersion of elements other than Au was restricted largely to those, associated with Au mineralization, that might have value as pathfinder elements. It was concluded that although, in some cases, such selective and partial extraction analyses may enhance anomaly contrasts, they do not appear to offer any advantages for Au exploration in areas having transported overburden. In addition, they tend to produce an unacceptably high number of positive false anomalies.

Table 11.1: Geomorphological and regolith settings of principal geochemical study sites in Project 409.

Pre-existing profile preserved, buried (A-type models)

Site	Geomorphological Setting	Thickness m	Overburden
Bronzewing	Colluvial plain, mid-lower slope. Colluvium overlies lateritic residuum and channel clays	5.0-25.0	Silty and gravelly colluvium, with lateritic debris
Curara	Colluvial plain, mid-lower slope	8.0-10.0	Colluvium; polymictic gravels with lateritic debris
Fender	Colluvial-alluvial plain, mid-slope	2.0-5.0	Immature granitic sand and silty clay
Harmony	Upland colluvial plain. Colluvium over palaeohigh and adjacent palaeochannel	0.5-3.0, to 7.0-12.0	Lateritic debris in sandy clay matrix; clays in channel
Stellar	Colluvial plain, mid-slope. Colluvium overlies lateritic residuum and channel clays	3.0-8.0	Colluvium; polymictic gravels with lateritic debris; gravelly silty clay

Pre-existing profile truncated, buried (B-type models)

Site	Geomorphological Setting	Thickness m	Overburden
Fender	Colluvial-alluvial plain, mid-slope	2.0-5.0	Immature granitic sand and silty clay
Harmony	Upland colluvial plain. Colluvium over palaeohigh and adjacent palaeochannel	0.5-3.0, to 7.0-12.0	Lateritic debris in sandy clay matrix; clays in channel
Quasar	Colluvial-alluvial plain, mid-lower slope. Colluvium overlies saprolite	4.0-8.0	Colluvium with alluvial gravels; poorly-sorted quartz, lithic and lateritic clasts in silty clay matrix
Golden Delicious	Colluvial-alluvial plain; lower slope	9.0-16.0	Calcareous, hardpanized silty clays; non-calcareous at depth, coarser, with lateritic debris
Safari	Upper-mid slope margin of colluvial plain	5.0-10.0	Aeolian and colluvial sands, finer at depth, with angular, near fresh lithic gravels. Calcareous in upper 5.0 m
Apollo	Alluvial plain	3.0-9.0	Aeolian sands and calcareous soil above lacustrine clays and
Panglo	Flat alluvial-erosional plain	0.0-1.0	Semi-residual, calcareous, sandy clay soils
Runway	Flat colluvial-erosional plain	0.0-1.0	Semi-residual, calcareous, sandy clay soils

Pre-existing profile partly developed in cover sequence (palaeochannel sediments)
Bronzewing, Harmony, Stellar - see above

Site	Geomorphological Setting	Thickness m	Overburden
Kurnalpi	Alluvial plain over palaeochannel	60	Calcareous clays, gravelly colluvium, above lacustrine clays and sands
Wollubar	Alluvial plain over palaeochannel	50	Calcareous clays, gravelly colluvium, above lacustrine clays and sands
Steinway	Alluvial plain over palaeochannel	25	Calcareous clay soil and gravelly colluvium, above lacustrine clays and sands
Argo	Alluvial plain over palaeochannel	60	Calcareous clay soil and gravelly colluvium, lacustrine and marine sediments, including lignites
Challenge-Swordsman	Alluvial plain over palaeochannel	40	Calcareous clay soil and gravelly colluvium, lacustrine and marine sediments, including lignites

3. *Determine the genesis of sub-horizontal supergene gold deposits, particularly those apparently associated with palaeodrainage channels, and their relationship to primary sources.*

This topic was given a low priority by sponsors of the project. Investigations of the stratigraphy and sedimentology of three channel deposits, Lady Bountiful Extended, Kurnalpi and Argo, were undertaken as Honours Projects, partly in order to determine the nature of the substrate hosting the Au mineralization. Most of the Au in these deposits is now secondary even if, initially, some was accumulated detritally, as a placer. Late in the project, some laboratory experiments were commenced to model Au migration and precipitation. Initial results indicate that the Au chloride and Au iodide complexes are sorbed, rather than reduced, when first precipitated, with sorption of the chloride complexes being much stronger.

4. *Develop methods of sampling, analysis and data interpretation for mineral deposits concealed within and beneath transported overburden and establish appropriate geochemical exploration models.*

Research in the project has shown that the most appropriate sample medium varies according to the district and, in particular, the landform setting:

Pedogenic carbonate	Southern Yilgarn; overburden less that 5-10 m thick
Undifferentiated shallow soil	Northern Yilgarn, overburden less than 3 m thick
Ferruginous gravels and nodules	In shallow overburden, or within 3 m of the unconformity
Lateritic residuum	In all environments
Interface	Where lateritic residuum is absent
Ferruginous saprolite	Where lateritic residuum is absent

These differences form the basis of local variations in established general exploration models.

A comparison of the responses obtained from a range of partial and selective extraction procedures with total analysis was undertaken and showed that no advantage was gained by their use. Such analyses can provide information about dispersion processes, as shown by the use of potassium iodide extractions.

5. *Establish the relative timing and significance of dispersion events in terms of regolith and landscape evolution.*

Observations made during the project have confirmed and supplemented our knowledge of the Phanerozoic evolution of the Yilgarn Craton, and its possible influence on geochemical dispersion. The events can be summarized as follows.

Period	**Event**	**Dispersion**
Permian	Glaciation of Proterozoic planation surface	Glacial smearing. No recorded example.
Mesozoic-Early Tertiary	Deep weathering, humid conditions	Leaching of ore and host rocks; accumulation and dispersion of Au and immobile elements in lateritic residuum
Early Eocene	Uplift, humid climate; some erosion of 'uplands'; incision of palaeochannels, mainly in pre-existing valleys, probably rapid with coarse basal sediments.	Clastic dispersion during erosion; possible depositional of placer Au, heavy minerals in channel sediments.
Mid Eocene	Marine transgressions; warm humid climate; continued deep weathering, with slow erosion and deposition of fine sediments in channels.	Hydromorphic and mechanical dispersion, locally enriching channel sediments
Mid-Eocene - mid-Miocene	Deep chemical weathering under warm humid climates	Leaching basement rocks and channels sediments; accumulation and dispersion of Au and immobile elements in lateritic residuum, overprinting earlier patterns
Mid-Eocene-Quaternary	Semi-arid, possibly cooler climates; some uplift. Erosion, local topographic inversion. Deposition of colluvium, alluvium and evaporites	Clastic dispersion; eg. of lateritic debris. Chemical/clastic reworking in soils on exposed surfaces, prior to burial. Hydromorphic dispersion under saline conditions
Quaternary to present	Semi-arid, cool to warm; continued erosion, with deposition choking valleys.	As above; Au mobility in saline waters and in carbonate soils

6. *Transfer research findings and skills to the industry through seminars and field excursions, and by one-on-one discussions with individual sponsor companies.*

Sponsors Meetings	Field Excursions
18 June 1993	5-8 September 1995, Murchison District
24 February 1994	14-17 May 1996, Eastern Goldfields
19 October 1994	
12 April 1995	
4 July 1996 (Final Meeting)	

In lieu of a meeting in late 1995, sponsors of the Project were invited to participate in one-on-one discussions with members of the research group. These were held in the period October 1995-May 1996. In addition, the project has issued individual reports and Honours theses, as listed in the Appendix.

11.2 Recommendations for future research

The following topics are seen as important for future research in the Yilgarn Craton:

- Correlation of Tertiary to Pliocene stratigraphy across the major palaeodrainage systems; in particular, improving the correlations between established stratigraphy in the Cowan and Lefroy systems with the partly established stratigraphy in the Roe and Avon systems, and extending this to the poorly studied northern systems.
- Stratigraphic and sedimentological study of aeolian, colluvial and alluvial sediments
- Continued development of field-based procedures for distinguishing between residual and transported components of the regolith.
- Development of partial and selective extraction procedures for identifying weathering processes
- Continued testing of partial extraction procedures for enhancing anomalies, particularly for base metal deposits.
- Field and laboratory investigation of the processes of supergene enrichment and depletion of Au under different hydrological and hydrogeochemical regimes.
- Continued investigation of the source, mechanisms and implications of Au enrichment in pedogenic carbonates. In particular, whether enrichments over leached or barren overburden are dominantly sourced from residual or detrital gold particles, respectively.
- Procedures for identifying positive false anomalies in multi-element data, whether these be from partial or total analyses.
- Continued investigation of the petrophysical properties of regolith materials through ground geophysical studies in well-constrained settings. Particular effort should be directed to multi-parameter downhole geophysical logging and the linking of these data with ground and airborne geophysical techniques to improve their application in regolith-dominated terrains.

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APPENDIX

LIST OF PUBLICATIONS ISSUED BY THE PROJECT

Reports

EM/ EG No	CRC LEME No	Title	Author(s)
383		Investigation of the hydrogeochemical dispersion of gold and other elements from mineralized zones at the Granny Smith Gold Deposit, Western Australia - 2 volumes	D.J. Gray
26		Investigation of the hydrogeochemical dispersion of gold and other elements at Lawlers Western Australia - 2 volumes.	D.J. Gray
48		Regolith evolution and geochemistry of the Stellar and Quasar gold mines - Mt Magnet WA - 2 volumes.	I.D.M. Robertson, J.D. King, R.R. Anand and C.R.M. Butt
95		Progress statement for the Kalgoorlie study area - Steinway Prospect.	M.J. Lintern and D.J. Gray
96		Progress statement for the Kalgoorlie study area - Argo deposit, Western Australia.	M.J. Lintern and D.J. Gray
97		Progress statement for the Kalgoorlie study area - Kurnalpi Prospect.	M.J. Lintern and D.J. Gray
98		Progress statement for the Kalgoolie study area - Wollubar-Enigma Prospect.	M.J. Lintern and D.J. Gray
169	3	Hydrogeochemical dispersion of gold and other elements at Baxter, Western Australia	D.J. Gray
210	9	Selective extraction techniques for the recognition of buried mineralization, Curara Well, Western Australia.	D.J. Gray
250	26	Geochemical studies of the soil at the Runway gold prospect, Kalgoorlie, WA	M.J. Lintern
251	10	Further geochemical studies of the soil at the Panglo gold deposit, Kalgoorlie, Western Australia	M.J. Lintern
252	27	Further geochemical studies of the soil at the Steinway Gold prospect, Kalgoorlie, Western Australia	M.J. Lintern and M.A. Craig
274	30	Geochemical studies of the soil and vegetation at the Apollo Au deposit, Kambalda, WA	M. J. Lintern, M. A. Craig and R. N. Carver
275	28	The distribution of gold and other elements in surficial materials from the Higginsville palaeochannel gold deposits, Norseman, Western Australia	M.J. Lintern, M.A. Craig, D.M. Walsh and N.C. Sheridan
280	15	Geochemical and spatial characteristics of regolith and groundwater around the Golden Delicious Prospect, Western Australia.	A.P.J. Bristow, D.J. Gray and C.R.M. Butt.
281	13	Geochemical expression of concealed gold mineralization, Safari Prospect, Mt Celia, Western Australia.	A.P.J. Bristow, M.J. Lintern and C.R.M. Butt
296	14	Atlas of transported overburden	I.D.M. Robertson, A.E. Koning, C.R.M. Butt and R.R Anand
305	16	Selective and partial extraction analyses of transported overburden for exploration in the Yilgarn Craton and its margins, Volumes I and II	D.J. Gray, J.E. Wildman and Longman, G.D

EM/ EG No	CRC LEME No	Title	Author(s)
308	18	Regolith-landform evolution and geochemical dispersion at the Bronzewing deposit	Z.S. Varga, R.R. Anand and J.E. Wildman
312	21	Hydrogeochemistry in the Yilgarn Craton	D.J. Gray
313	22	Geochemical dispersion in transported overburden and residual regolith, Fender Au deposit, Cue	C.R.M. Butt
333	36	Geochemical exploration in areas of transported overburden, Yilgarn Craton and environs, Western Australia. Final Report.	C.R.M. Butt, D.J. Gray, I.D.M. Robertson, M.J. Lintern, R.R. Anand, A.F. Britt, A.P.J. Bristow, T.J. Munday, C. Phang, R.E. Smith and J.E. Wildman
339	33	Supplementary notes and regolith map for the Enigma prospect (Wollubar), Kalgoorlie, Western Australia	M.C. Craig, M.J. Lintern and D.J. Gray

Field guides

DEM/ DG No	CRC LEME No	Title	Author(s)
164		Geochemical exploration in areas of transported overburden, Yilgarn Craton and environs - Murchison Field Trip.	C.R.M. Butt, I.D.M. Robertson, R.R. Anand, J.D. King, T.J. Munday, C. Phang and R.E. Smith
253	4	Eastern Goldfields Field Excursion Field Guide	C.R.M. Butt, R.E. Smith, M. Dell, R.R. Anand, M.J. Lintern, D.J. Gray, J. Viner, A.P.J. Bristow, I.D.M. Robertson, H.M. Churchward, Z.S. Varga, J.E. Wildman

Honours thesis

Issued to sponsors	Title	Author(s)
	Regolith geology and geochemistry of the Steinway gold prospect, Kalgoorlie, Western Australia.	N. Gardiner
√	Regolith-landform evolution of the Black Flag area with emphasis on upper reaches of the Roe palaeodrainage system, Western Australia	M.E. Dusci
√	The stratigraphy and gold mineralization of the Argo Tertiary palaeochannel at Kambalda, Western Australia	N.K. Woolrich
√	The sediments and regolith of the Middle Reaches of the Roe palaeochannel near Kanowna, Eastern Goldfields, Western Australia	B.A. Ladhams