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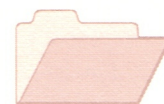
Cooperative Research Centre for
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GOLD AND ASSOCIATED ELEMENTS IN THE REGOLITH - DISPERSION PROCESSES AND IMPLICATIONS FOR EXPLORATION

P241A Final Report

*C.R.M. Butt, D.J. Gray, M.J. Lintern
and I.D.M. Robertson*

CRC LEME OPEN FILE REPORT 57

November 1998

(CSIRO Division of Exploration Geoscience Report 396R, June 1993.
Second impression 1998)

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

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

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

P241: Gold and associated elements in the regolith - dispersion processes and implications for exploration (1987-1991). Leader: Dr C.R.M. Butt.

The project investigated the distribution of ore and indicator elements in the regolith. It included studies of the mineralogical and geochemical characteristics of weathered ore deposits and wall rocks, and the chemical controls on element dispersion and concentration during regolith evolution. This was to increase the effectiveness of geochemical exploration in weathered terrain through improved understanding of weathering processes. It was supported by 26 companies.

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

P240A: Geochemical exploration in complex lateritic environments of the Yilgarn Craton, Western Australia (1991-1993). Leaders: Drs R.E. Smith and R.R. Anand.

The approach of viewing geochemical dispersion within a well-controlled and well-understood regolith-landform and bedrock framework at detailed and district scales continued. In this extension, focus was particularly on areas of transported cover and on more complex lateritic environments typified by the Kalgoorlie regional study. This was supported by 17 companies.

P241A: Gold and associated elements in the regolith - dispersion processes and implications for exploration. Leader: Dr C.R.M. Butt.

The significance of gold mobilisation under present-day conditions, particularly the important relationship with pedogenic carbonate, was investigated further. In addition, attention was focussed on the recognition of primary lithologies from their weathered equivalents. This project was supported by 14 companies.

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

This report (CRC LEME Open File Report 57) is a First revision (second printing) of CSIRO, Division of Exploration Geoscience Restricted Report 396R, first issued in 1993, which formed part of the CSIRO/AMIRA Project P241A.

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EXECUTIVE SUMMARY

This report summarizes the results of the two-year continuation of the CSIRO/AMIRA Project P241 *"Gold and associated elements in the regolith - dispersion processes and implications for exploration."* The continuation had the principal objective of extending the research into some important topics identified during the original project. The data complement and expand those obtained previously and the discussion of each topic draws on the results and conclusions of each phase of the Project. The principal fields of research and the outcomes are as follows:

1. Elemental dispersion in deep regoliths was investigated at Lights of Israel, Davyhurst and a background site at Mt. Percy, Kalgoorlie, with a minor study at Mulgarrie. The data confirm that, at local to sub-regional scales, Au is the best indicator of Au mineralization. However, sampling and interpretation must account for the distribution of Au in the regolith, in particular, its accumulation in ferruginous and calcareous surface horizons, its depletion for 5 to 20 m below them, and further sub-horizontal enrichment at depth. The most suitable pathfinders suite is As, Sb, W, +/- Bi, Mo, Pb; Ba, K and Rb give expression to some alteration zones. These elements provide confirmatory evidence for mineralization where Au has been depleted or where the distribution is patchy or has little focus.

2. The determination of bedrock lithology from its weathered counterpart is a major problem in regolith dominated terrain. The processes of rock weathering and procedures for geochemical, mineralogical and petrographic identification of different lithologies have been summarized in an *"Atlas of Weathered Rocks"* produced specifically for this Project. The Atlas illustrates the changes in fabric, mineralogy and composition that take place during weathering. It is far from an exhaustive catalogue of all lithologies, but demonstrates the amount of lithological information that can be obtained from chemical analysis and by careful observation, even at the hand lens scale.

3. The close relationship between the distributions of Au and pedogenic carbonate in areas south of the Menzies Line was further confirmed by detailed orientation studies at Lights of Israel and Zuleika (Ora Banda), with a minor study at Mulgarrie. Zuleika and Mulgarrie represent sites where soil Au anomalies directly overlie mineralization concealed beneath barren palaeochannel sediments. Unfortunately, due to natural contamination from nearby outcropping mineralization, no unequivocal evidence could be obtained to relate the anomalies and the concealed deposits, although such a relationship has been demonstrated during routine exploration programs elsewhere. Further soil investigations were conducted north of the Menzies Line, where Au tends to be associated dominantly with ferruginous materials in residual soils. However, in hardpan at Granny Smith, Au is associated with lithorelics and the siliceous cement. There is no obvious association with Mn oxides. Gold enrichment occurs towards the base of the hardpan, overlying leached and possibly depleted saprolite. Secondary carbonate is present in the lower hardpan and upper saprolite; this has much less Au than pedogenic carbonates, although much of it is highly soluble.

4. Laboratory investigations of the chemistry of Au in soil have led to an improved understanding of its associations with other constituents and the mechanisms of the formation of Au anomalies. Gold in carbonates is highly soluble and can be distinguished from that associated with Fe oxides by partial extraction. Gold and Ca are probably brought to the surface biochemically, being cycled via vegetation, but the Au-carbonate association in soil is probably largely physical in origin, arising from precipitation via evaporative processes. Gold in soil is highly labile and, at least in part, as water-soluble complexes, so that under wet conditions can readily be redistributed.

5. Hydrogeochemical data show that the clearest indication of Au mineralization is given by Au itself. Data interpretation depends upon knowledge of the dominant dispersion mechanism. Where Au is dissolved as a thiosulphate complex (Boags, Bottle Creek; Hornet, Mt. Gibson), Au distribution matches that of mineralization. Where dispersion is by halide complexation (Panglo, Wollubar and parts of Mt. Gibson), the distribution of dissolved Au is controlled by physico-chemical parameters unrelated to the presence of mineralization, in particular where a high Eh is maintained by Mn oxidation

in acid groundwaters. Additionally, there is a strong antipathetic relationship between dissolved Au and Fe, due to Fe^{2+} acting as a reductant. The presence of other elements, such as As and Sb, may indicate sulphides associated with Au mineralization. However, groundwaters in some drainages have very high concentrations of base metals and REE unrelated to the presence of such mineralization, probably having been leached from country rock and concentrated by evaporation.

6. The spectral characteristics of Fe oxides and clays in the 0.4 to 2.5 μm wavelengths may have use in distinguishing different minerals not always apparent by routine XRD analysis and, in field logging or remote sensing, for mapping regolith materials such as lateritic horizons, lag and exposed saprolite. Spectral identification and semi-quantitative estimation of micas has potential for identifying alteration zones and micaceous lithologies, but practical application is limited to materials having over 20% mica. Similarly, poor discrimination of soil carbonates means that the presence of this important sample medium cannot be recognized.

AMIRA PROJECT P241A

GOLD AND ASSOCIATED ELEMENTS IN THE REGOLITH - DISPERSION PROCESSES AND IMPLICATIONS FOR EXPLORATION.

FINAL REPORT, PROJECT P241A

FOREWORD

INTRODUCTION	x
SPONSORSHIP	x
OBJECTIVES	xi
PROJECT PERSONNEL	xii

SUMMARY	1
----------------	----------

1 GEOCHEMICAL DISPERSION AND REGOLITH EVOLUTION	5
--	----------

1.1 INTRODUCTION	5
------------------	---

1.2 LATERITIC WEATHERING UNDER HUMID WARM TO TROPICAL CONDITIONS	9
---	---

1.2.1 Principal characteristics	9
---------------------------------	---

1.2.2 Distribution of elements associated with gold mineralization.	11
---	----

1.3 WEATHERING UNDER SEMI-ARID AND ARID CLIMATES	12
--	----

1.3.1 Principal characteristics	12
---------------------------------	----

1.3.2 Secondary accumulation and cementation	12
--	----

1.3.3 Dispersion of minor and trace elements during arid weathering	12
---	----

1.3.4 Distribution of elements associated with gold mineralization.	13
---	----

1.4 ROCK TYPE DISCRIMINATION	14
------------------------------	----

1.4.1 Procedures for identifying parent lithology from weathered rock.	14
--	----

1.4.2 Geochemical database	14
----------------------------	----

1.4.3 Multi-element discriminant analysis	15
---	----

1.5 IMPLICATIONS FOR EXPLORATION	18
----------------------------------	----

2 SOIL AND LAG GEOCHEMISTRY	21
------------------------------------	-----------

2.1 SITES SELECTED FOR STUDY	21
------------------------------	----

2.2 RELATIONSHIP BETWEEN GOLD AND PEDOGENIC CARBONATE	21
---	----

2.2.1 Site studies	21
--------------------	----

2.2.2 Mechanism of gold carbonate association	23
---	----

2.2.3 Implications for exploration	24
------------------------------------	----

2.3 GOLD DISTRIBUTION IN HARDPAN	24
----------------------------------	----

2.3.1 Introduction	24
--------------------	----

2.3.2 Geochemistry and mineralogy of hardpan at Granny Smith.	24
---	----

2.3.3 Implications for exploration	25
------------------------------------	----

2.4	SOIL GEOCHEMISTRY NORTH AND SOUTH OF THE MENZIES LINE: COMPARISON OF BEASLEY CREEK AND LIGHTS OF ISRAEL	26
2.4.1	Regional setting	26
2.4.2	Size fractions and mineralogy of soils	27
2.4.3	Soil geochemistry	28
2.4.4	Implications for exploration	31
2.5	BIOGEOCHEMISTRY OF GOLD	32
2.5.1	Introduction.	32
2.5.2	Biogeochemistry of Au at Zuleika	33
2.5.3	Discussion and conclusion.	34
3	CHEMISTRY OF GOLD IN SOILS	36
3.1	INTRODUCTION	36
3.2	EXTRACTION METHODS	36
3.3	KINETIC STUDIES	36
3.4	REGIONAL INVESTIGATIONS	39
3.4.1	Unweathered rock and saprolite	39
3.4.2	Laterite and lateritic soils	39
3.4.3	Manganese-rich horizons	39
3.4.4	Calcrete and carbonate-rich soils	40
3.4.5	Organic-rich soils	42
3.4.6	Hardpan-dominated soils	42
3.5	DISCUSSION	42
4	HYDROGEOCHEMISTRY IN THE YILGARN BLOCK	44
4.1	INTRODUCTION	44
4.2	SITE CHARACTERISTICS	44
4.3	EFFECT OF SAMPLE DEPTH	45
4.4	ACIDITY AND OXIDATION POTENTIAL	46
4.5	MAJOR ELEMENT HYDROGEOCHEMISTRY	47
4.6	MINOR ELEMENT HYDROGEOCHEMISTRY	48
4.7	GOLD HYDROGEOCHEMISTRY	50

4.8	IMPLICATIONS FOR EXPLORATION	51
4.8.1	Possible applications	51
4.8.2	Lithological discrimination	52
4.8.3	Presence of sulphides	52
4.8.4	Presence of Au mineralization	52
5	SPECTRAL STUDIES OF REGOLITH MATERIALS	54
5.1	INTRODUCTION	54
5.2	TECHNIQUES	54
5.3	PANGLO	55
5.3.1	Introduction	55
5.3.2	Results and discussion	55
5.4	BEASLEY CREEK	56
5.4.1	Introduction	56
5.4.2	Results and discussion	56
5.5	BOUNTY	57
5.5.1	Introduction	57
5.5.2	Results and discussion	57
5.6	CONCLUSION	58
	APPENDIX 1. REPORTS ISSUED BY PROJECT P241	59
	APPENDIX 2. REPORTS ISSUED BY PROJECT P241A	62
	REFERENCES	63

LIST OF FIGURES

	Page No.
Figure F.1 Location of study areas for Projects P241 and P241A, indicating the approximate position of the Menzies Line (after Butt <i>et al.</i> , 1978).	xi
Figure 1.1 Regolith section, Lights of Israel mine; distributions of Au, CaO, As and Zr. The section is a composite between 940N and 1050N.	6
Figure 1.2 Section through a background area approximately 1 km north of the Mystery Zone, Mt. Percy. Geology and distributions of CaO, Cr and Zr. NB: there is a separation of 150 m between fresh rock and regolith sections.	7
Figure 1.2 (continued) Section through a background area approximately 1 km north of the Mystery Zone, Mt. Percy. Distributions of Au, As, Sb and W. NB: there is a separation of 150 m between fresh rock and regolith sections.	8
Figure 1.3 Plot of CV1 and CV2 for the whole data set, illustrating overlap between some groups.	16
Figure 1.4 CV1 - CV2 - CV3 plot rotated to achieve maximum separation of all groups.	17
Figure 1.5 Element contributions to discriminant analysis.	18
Figure 2.1 Possible pathways for surface enrichment of Au through leached and barren overburden by cycling via deep-rooted trees.	23
Figure 2.2 Gold distribution through hardpan, Granny Smith. Shading illustrates approximate position of hardpan.	25
Figure 2.3 Comparison of abundances of Au and potential pathfinder elements in saprolite from background sites and mineralization at Beasley Creek and Lights of Israel. Elements with similar abundances plot on the diagonal; those on lines parallel to diagonal represent x10 enrichment (right) or depletion (left).	27
Figure 2.4 Traverses across mineralization at Beasley Creek and Lights of Israel, illustrating the distribution of gold in different soil fractions and lag.	29
Figure 2.5 Comparison of abundances of Au and potential pathfinder elements in soil from background sites and mineralization at Beasley Creek and Lights of Israel. Elements with similar abundances plot on the diagonal; those on lines parallel to diagonal represent x10 enrichment (right) or depletion (left).	30
Figure 2.6 Binary plot illustrating differences in the Ti-Zr ratio in various soil fractions at Beasley Creek and Lights of Israel.	32
Figure 2.7 Gold in vegetation for 4705N and 4490N at Zuleika. Mull/soil ratios from the top metre of soil.	34
Figure 3.1 Iodide soluble Au in a carbonate-rich sample (04-1206).	37
Figure 3.2 Iodide soluble Au in an Fe oxide-rich sample (04-1251).	38
Figure 3.3 Water soluble Au in a carbonate-rich sample (04-1206).	38
Figure 3.4 Water-soluble Au in an Fe oxide-rich sample (04-1251).	39
Figure 3.5 Iodide soluble Au for a Mn-rich sample (04-4023).	40
Figure 3.6 Total Au and iodide-soluble Au in samples from Profile B, Mt. Hope, with the position of sample 04-1206 (Section 3.3) shown. (Errors determined by duplicate extractions from coarse materials).	41
Figure 3.7 Depth distributions for Profile 4169, Mulline: (a) Ca and total Au; (b) Ca and net iodide soluble Au.	41
Figure 4.1 Groundwater investigation sites for Projects AMIRA P240, P241 and P241A.	45

Figure 4.2	Eh and pH in groundwaters from research sites in the Yilgarn. Solid symbols indicate samples with Fe concentrations greater than 0.1 mg/L (ppm).	47
Figure 4.3	Gold vs. Fe for neutral ($\text{pH} \geq 6$) Yilgarn groundwaters.	50
Figure 4.4	Gold vs. Fe for acid ($\text{pH} < 6$) Yilgarn groundwaters.	50
Figure 4.5	Eh/pH data for Yilgarn groundwaters, superimposed on the stability field for dissolved Au chloride for Au concentration = 10^{-8} M (2 ppb) and Cl concentration = 1 M (3.5%).	51
Figure 4.6	Mafic vs. ultramafic indices for groundwaters at Panglo. Key: S - shale; M-S - at mafic-shale contact; M - mafic; M-U at mafic-ultramafic contact; U - ultramafic.	52
Figure 5.1	Reflectance spectrum of a typical soil showing the major absorbances with explanations.	54

LIST OF TABLES

	Page No.
Table F1 Sponsors of AMIRA Project P241A.	viii
Table 1.1 Element mobility during weathering.	10
Table 1.2 Geochemical database.	15
Table 1.3 Accuracy of the classification of the database.	17
Table 4.1 Mean major element compositions of groundwaters at research sites in the Yilgarn.	48
Table 4.2 Mean minor element compositions of groundwaters at research sites in the Yilgarn.	49

FOREWORD

INTRODUCTION

The CSIRO - AMIRA project "Exploration for Concealed Gold Deposits, Yilgarn Block, Western Australia" had the overall aim of developing improved geological, geochemical and geophysical methods for mineral exploration to facilitate the location of blind, concealed or deeply weathered gold deposits. The project had three partly-overlapping research modules, with each module funded separately, although with many sponsoring companies in common. The research undertaken in Module 2 of the project¹, AMIRA Project P241, aimed, in part, to take advantage of the unprecedented opportunities presented by the many open cut gold mines to document and study the deep regolith and the distribution of gold and other elements within it. In addition, detailed field and laboratory studies were conducted to investigate the processes of rock weathering and, specifically, the mechanisms by which gold has been dispersed during the evolution of the regolith on the Yilgarn Block.

The first phase of the research was carried out from 1987 to 1990, and the results were summarized in the Final Report entitled "Gold and associated elements in the regolith - dispersion processes and implications for exploration" (Exploration Geoscience Report 167R). The continuation of the Project, summarized in this report, had the objectives of following up some of the results from the first phase. Full details of the research are given in the Investigation Reports, which are listed in Appendix 2. The Investigation Reports contain all the data generated by the project, many with the data on computer disk.

SPONSORSHIP

The initial phase of the Project was sponsored by over 20 mining and exploration companies. Due to mergers and the recession, this was reduced to 14 sponsors for the continuation (Table F1).

Table F1. Sponsors of AMIRA Project P241A

Aberfoyle Resources Ltd.	Minsaco Resources Pty. Ltd.
Aztec Mining Company Ltd.	Newmont Australia Ltd.
BHP-UTAH Minerals International	Normandy-Poseidon Ltd.
Billiton Australia	Placer Pacific Pty. Ltd.
CRA Exploration Pty. Ltd.	Renison Goldfields Consolidated Ltd.
Dominion Mining Ltd.	RTZ Ltd.
Homestake Australia Ltd.	Western Mining Corporation Ltd.

¹ The other modules were:

Module 1. Laterite geochemistry for detecting concealed mineral deposits.

AMIRA Project P240. Project Leader: R.E Smith

continuation: Yilgarn lateritic environments.

AMIRA Project P240A. Project Leader: R.E Smith

Module 3. Remote sensing for gold exploration in Western Australia.

AMIRA Project P243. Project Leader: A.R. Gabell

OBJECTIVES

The overall objectives of Projects P241 and P241A were:

- i. To obtain a better understanding of the nature and genesis of lateritic and supergene gold deposits.
- ii. To determine characteristics useful for exploration, especially in areas of transported overburden, for:
 - a. further lateritic and supergene deposits, and
 - b. primary mineralization - including that having no significant overlying secondary mineralization.
- iii. To increase knowledge of the properties and genesis of the regolith.
- iv. To provide data applicable for exploration for other commodities in and beneath the regolith.

Specific aspects to be addressed in Project P241A included:

1. Commencement of preparation of an Atlas of Rock Weathering, depicting petrography at the hand lens and microscopic scale, mineralogy, geochemistry and other data.
2. Interpretation of soil and saprolite data from Lights of Israel and Mt. Percy
3. Investigation of the role of pedogenic carbonates in concentrating gold where there are significant thicknesses of gold depletion or barren transported overburden overlying gold mineralization.
4. Investigation of the fate of gold in the near-surface where there is extensive hardpan and no pedogenic carbonate present, *e.g.*, in the northern half of the Yilgarn Block, north of the "Menzies Line".
5. Investigation of the hydrogeochemistry of palaeodrainages close to known gold mineralization, if possible including those known to contain gold in the sediments.
6. Continuation of laboratory investigations on:
 - i. the high solubility of gold in some soils;
 - ii. the role of organic and halide ligands;
7. Investigation of the spectral characteristics of weathered materials at the Beasley Creek, Bounty and Panglo Au deposits to assist in the extraction of mineralogical information from remotely sensed data in collaboration with Project P243.

These investigations represent further studies in four of the five main fields addressed in the earlier Project, P241. The sites studied in this continuation Project, P241A, are highlighted:

1. *Mineralogy and geochemistry of rock weathering.* Mineralogical, petrographic and geochemical studies of the processes of rock weathering were aimed at establishing criteria for rock identification and the recognition of ore environments. Principal sites: Panglo, Mt. Magnet (Parkinson pit), Bottle Creek, *Reedy, Mt. Percy, Beasley Creek, Lights of Israel, Barr Smith Range.*
2. *Gold mineralization and profile development.* The dispersion of gold and associated elements during weathering was studied by determining the morphological, mineralogical and geochemical characteristics of lateritic and supergene gold deposits within the context of profile formation. Principal sites: Mt. Percy, Reedy, Panglo, Callion, Beasley Creek, Bottle Creek, Telfer, *Mulgarrie, Lights of Israel.*

3. *Gold distribution in the near surface.* The 'residence' and mineralogical association of gold in near-surface horizons of the regolith was determined with particular reference to the role of secondary minerals, organic matter and plants. Principal sites: Mt. Hope, Panglo, Mulline, Mt. Percy, Callion, Youanmi, Beasley Creek, *Lights of Israel*, *Zuleika*, *Granny Smith*.
4. *Solution chemistry of gold during weathering.* This involved field and laboratory studies of the conditions of gold mobilization and precipitation in the weathering environment. Field sites: Panglo, *Bottle Creek (Boags)*, *Mulgarrie*, *Wollubar-Golden Hope*. Laboratory studies: chemical interactions of gold with soils, soil minerals and organic matter.

The locations of the study sites are shown on Figure F.1.

No further investigations were conducted concerning the composition and morphology of gold. The study of geochemical dispersion in a humid savanna environment in Northern Australia was not carried out as originally proposed due to the reduced support for the Project and the lack of a suitable study site. Similarly, no investigations were made into the relationship between gold morphology and solution chemistry, or the electrochemistry of gold.

PROJECT PERSONNEL

Project Staff:

C.R.M. Butt (Project Leader)
I.D.M. Robertson
D.J. Gray
M.J. Lintern
D.L. Longman

Other contributors

H.M. Churchward
T.J. Cudahy
G.B. Douglas
M.F.J. Tenhaeff

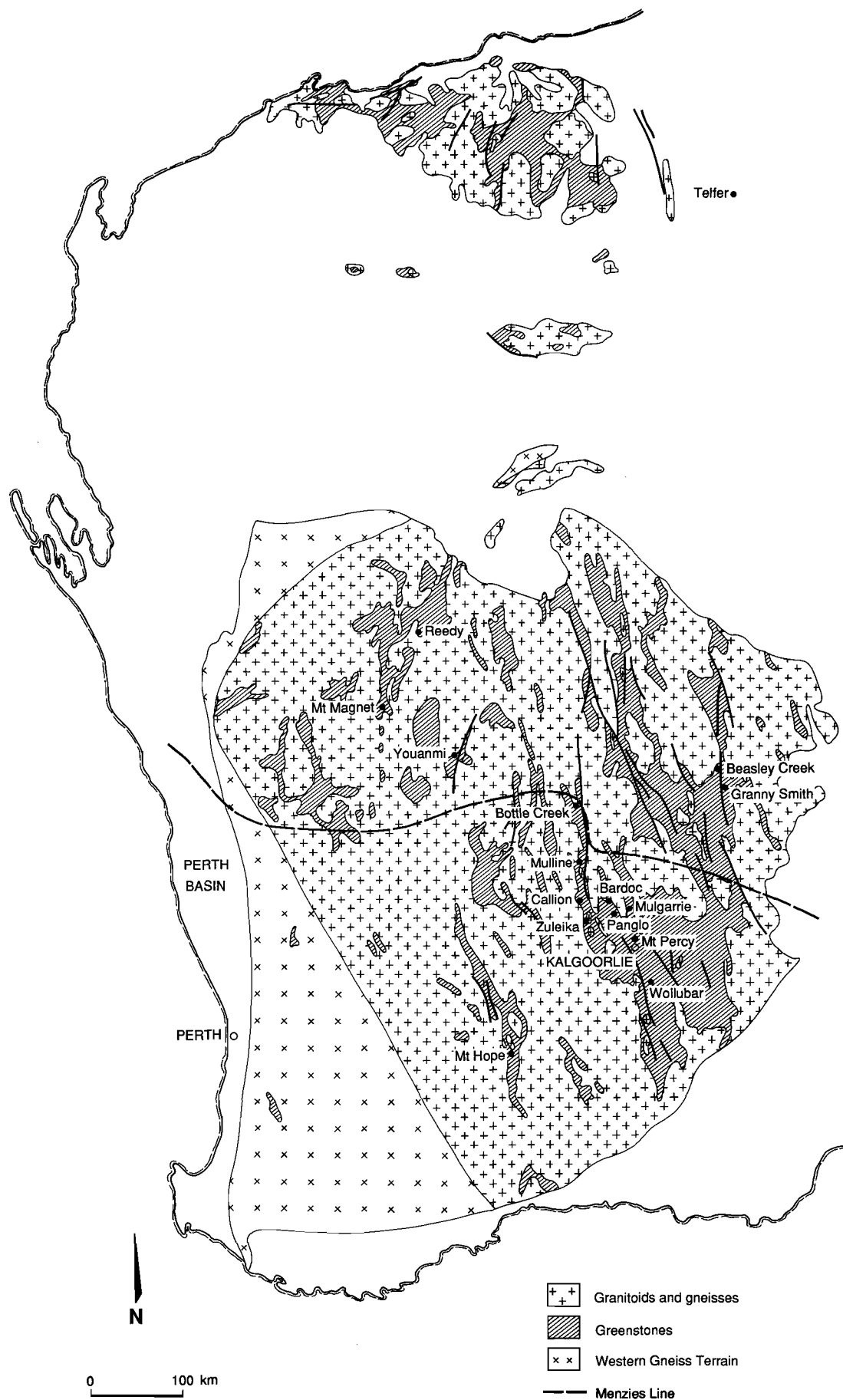


Figure F.1. Location of study areas for Projects 241 and 241A, indicating the approximate position of the Menzies Line (after Butt *et al.*, 1978).

AMIRA PROJECT P241A

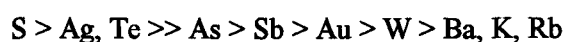
GOLD AND ASSOCIATED ELEMENTS IN THE REGOLITH - DISPERSION PROCESSES AND IMPLICATIONS FOR EXPLORATION. FINAL REPORT, PROJECT P241A

SUMMARY

This Project has undertaken further studies of multi-element dispersion patterns in the regolith and groundwaters. It has continued investigations of Au mobility and extraction from soils that have confirmed and extended the conclusions developed in the first phase of the Project. In summary, these are:

1. At local to sub-regional scales, Au itself is one of the best indicators of Au mineralization, despite (or perhaps because of) its chemical mobility during weathering.
2. Sampling must take account of the distribution of Au in the regolith. The accumulation of Au in calcareous and ferruginous surface horizons and its depletion for 5 to 20 m below them implies that sampling has to be carefully directed and that data interpretation will depend on the horizon sampled. Although Au may accumulate in some horizons of hardpan, this is not universally established and cannot be relied upon as a basis for sampling programmes.
3. Other elements commonly provide confirmatory evidence for the presence of mineralization and have particular value where Au either has been depleted or is patchily distributed, or where samples have been derived from the alteration zone rather than from the mineralization itself. The most suitable pathfinder suite is As, Sb, W, +/- Bi, Mo, Pb. Barium, K and Rb give a surface expression to some alteration zones, commonly wider targets than mineralization itself; K also offers potential for detection by radiometric surveys. However, these alkaline elements are not exclusively associated with mineralization and, in either event, the presence of K and Rb in the near-surface of intensely weathered regoliths is strongly dependent on the survival of the micas that host them.
4. Primary and supergene Au mineralization are indicated by broad Au anomalies in lateritic duricrusts and the lags and soils derived from them. These anomalies are comprised of (i) primary and (mostly) secondary Au associated with Fe oxides, presumably accumulated during lateritic weathering and (ii) principally in the south of the Yilgarn Block, secondary Au associated with pedogenic carbonates and accumulated during recent arid phases. Mineralization is also indicated by high concentrations of other ore-associated elements in these surface horizons, principally W, As and, less commonly, Sb, and alteration by K and Rb, but these do not appear to have wider or more consistent dispersion haloes than Au. These pathfinder elements tend to be associated with the ferruginous components and are not enriched in pedogenic carbonates - indeed, their concentrations tend to be diluted.
5. The mottled and plasmic clay zones and the upper saprolite are commonly depleted in Au. At sites where the regolith has been truncated and the ferruginous horizon is absent, the depleted zone commonly outcrops (Parkinson pit, Mt. Magnet), or subcrops beneath transported overburden (Granny Smith, Panglo). The depleted zone is not always well developed (Callion, Beasley Creek, Reedy, Lights of Israel) but its common occurrence demands that care must be taken to avoid sampling within it. The Au contents are generally <100 ppb, even where there are quartz veins, and give little or no indication of the underlying mineralization. Other ore- and alteration-associated elements Sb, W, K, Rb, Ba and, to a lesser extent, As remain throughout the depleted zone. They may be anomalous in residual soils developed from Au-depleted material in truncated regoliths even if Au contents are near to background values. If pedogenic carbonates are present, the depletion, or masking by transported overburden, may be offset by some surface enrichment, as at Panglo, Lights of Israel and Mt. Magnet.

6. Gold in the saprolite beneath the depletion zone is generally present at abundances similar to or greater than those in the fresh rock. Lateral dispersion and concentration commonly occur at one or more levels, thereby enhancing the weathered expression of the primary mineralization and becoming an exploitable resource in its own right; much of this Au is secondary. Recognition of the presence of an extensive, relatively thin (1-10 m) horizon of Au enrichment is important for data interpretation and in devising exploration strategies for further such deposits and for the primary mineralization from which they are derived. Sub-horizontal zones of supergene enrichment are best developed in highly saline environments (*e.g.*, Hannan South (see Gray *et al.*, 1992, Figure V.3-4), Panglo), but are also apparent in the background site at Mt. Percy, close to minor Au mineralization.
7. The abundances of the elements associated with Au mineralization are very variable, so that no universal 'threshold' values can be proposed. Compared to the primary mineralization, element distributions (including Au) in the saprolite are more homogeneous, due to dispersion and reprecipitation during weathering. In general, dispersion and increase in size and coherence of secondary anomalies over primary distributions are:



Arsenic, Sb and W may give wider expression to mineralization in those saprolite zones in which Au has not been dispersed, whereas Ba, K and Rb indicate the broader target of the alteration zone. Silver, Te and S are very mobile and are generally leached to background values, although at Beasley Creek, Ag appears to be retained throughout the saprolite, indicating that, although the mineralized unit is weathered to a considerable depth, it has not been very severely leached. Sulphur in the mid to upper saprolite (Mt. Percy, Beasley Creek, Lights of Israel), present as alunite, gypsum or other sulphates, is meteoric and appears unrelated to mineralization, although there may be some bedrock-derived S at Lights of Israel.

8. The enrichment of Au in pedogenic carbonates provides an important sample medium in the southern Yilgarn Block. Most Au in soils appears to be associated with carbonates, where present; in lateritic gravels and duricrusts invaded by carbonate, Au is also associated with Fe oxides. The Au-carbonate association gives surface expression to basement mineralization concealed by at least 20 m of leached and/or transported overburden. In soil surveys, it is essential that the carbonate horizon, where developed, is preferentially sampled. This is best achieved using a power auger, routinely sampling to a depth of about 1.5 m. However, the carbonate horizon may occur as deep as 5 m, hence the sampling programme must be carefully monitored. Plants are implicated in the dispersion of Au and Ca and their enrichment in the near surface.
9. Pedogenic carbonates are only sporadically developed in the northern Yilgarn Block. Samples containing carbonates must be treated separately, since they may have a background Au abundance an order-of-magnitude greater than non-calcareous soils and hardpans.
10. Gold in hardpan at Granny Smith is present in lithorelics and in the siliceous cement. Gold enrichment occurs towards the base of the hardpan, overlying leached and possibly depleted saprolite. Secondary carbonate occurs in the lower hardpan and saprolite, commonly between 4 and 10 m depth. This carbonate is not so enriched in Au as pedogenic carbonates, but much of the Au is highly soluble.
11. In many sites, bedrock lithology can be identified by petrography, mineralogy and geochemistry of regolith materials, either independently or in combination. Fabric and, to a lesser extent, mineralogy, are very useful discriminators in fresh rock, saprock and saprolite, but their value diminishes as the degree of weathering increases. Above the pedoplasation front, *fabrics* become altered by pedogenic processes, although relics, commonly pseudomorphed by goethite or hematite, may be recognizable in duricrust, nodules, pisoliths and lag even at the "hand lens" scale, and *mineralogy* becomes dominated by Fe oxides, clays and silica. These effects of intense weathering, and the pulverization of weathered material during drilling, commonly make geochemical procedures necessary. Simple bivariate and trivariate analyses based on Ti, Zr (or Hf) and Cr are effective in subdividing the principal groups of igneous rocks, but they are insufficient to classify

more complex lithologies, such as the fuchsite-altered ultramafic rocks and xenolith-contaminated porphyries from Mt. Percy, and quartz-rich mafic and ultramafic rocks from Reedy. Multi-variate discriminant analysis is effective in the classification of this “difficult” suite of rocks, but requires at least seven elements to accomplish an imperfect result. The elements that contribute most to the classification are, in nearly equal proportions, Ni>Cr>Co>Rb>Zr>Ti>Ba, with a slightly lesser contribution from Y>Al>Mn>V>Ce>Fe>Si. This compares to the earlier analysis of data from Reedy alone, which achieved 91% correct classification using seven elements (Cr, Nb, Co, Sc, Lu, Hf, Ba) and 85% with only four elements (Cr, Sc, Co, K). More effective geochemical discrimination can be achieved with a limited suite of rocks and/or by restricting the number of regolith horizons.

12. Soil extraction procedures have been successful at distinguishing differing chemical associations of Au with regolith materials in the Yilgarn Block:
 - a. unweathered rock and saprolite: - low Au solubility;
 - b. laterite and other Fe oxide-dominated regolith: - Moderate Au solubility;
 - c. Mn oxide-dominated regolith: - high Au solubility when pulverized;
 - d. carbonate: - high Au solubility even without pulverising;
 - e. organic-rich: - low Au solubility, possibly due to readsorption of dissolved Au.

These observations have significant consequences for an understanding of Au mobility during regolith development. The most critical feature is that, closer to the regolith surface, and particularly for soils with present-day pedogenic activity such as carbonate formation and/or movement of organic colloids, Au solubility increases. This is possibly due to two factors. Firstly, Au mobility can be enhanced by biologically-derived molecules, particularly those that contain S, which can readily dissolve Au. This is suggested by incubation experiments that demonstrate the ability of deionized water to dissolve Au from organic soils. Secondly, closer to the surface, and particularly in carbonated-dominated horizons, Au is in highly soluble forms, as indicated by extraction by iodide and deionized water. It is suspected that these two factors are related. Biologically-derived ligands bond with Au and impart a high solubility. This Au may have high mobility, depending on mineral charge characteristics, pore size and other soil properties. Like other mobile elements such as Ca, Au may percolate down the soil profile until stopped by the evaporative processes. However, once precipitated, the Au may remain bound to the organic ligands and therefore still have a potentially high mobility if the soil becomes wet. This suggests that Au is in a highly dynamic state in soil and, in unusually wet conditions, could be redistributed. This is supported by the detection of Au in seepage and run-off waters in areas of calcareous soil.

13. Hydrogeochemical data indicate that the clearest indication of Au mineralization in groundwater is given by dissolved Au itself. However, it is not clear whether concentrations of elements such as As or Sb specifically indicate Au mineralization or merely the presence of sulphides. Some groundwaters have high concentrations of base metals and REE, apparently unrelated to the presence of mineralization.
14. Interpretation of dissolved Au concentrations is complicated by there being two mechanisms for Au transport in groundwater, namely thiosulphate and halide complexation, with a third mechanism (organic complexation) in soils. Where Au appears to be dissolving as a thiosulphate, as at Boags, Bottle Creek, and Horner, Mt. Gibson, the distribution of dissolved Au closely matches that of mineralization, possibly because the conditions required for thiosulphate formation (*i.e.*, weathering sulphides in neutral-alkaline, carbonate-buffered environments) corresponds to carbonate-rich alteration around the mineralization. Although this is encouraging for the application of hydrogeochemistry in exploration for such deposits, it should be noted that at Golden Hope and one other site, where the thiosulphate mechanism should be active, concentrations of dissolved Au are much lower than expected. If the hydrogeochemistry is to have application, the reason for this discrepancy should be determined.

15. In acid oxidizing environments, Au dissolves to form chloride or iodide complexes, and at sites where this mechanism is expected to be active (Panglo, Wollubar and some areas of Mt. Gibson), high concentrations of dissolved Au are observed in groundwater. However, Au concentration is strongly affected by factors not directly related to mineralization (*e.g.*, Eh and/or dissolved Fe), and the distribution of dissolved Au does not match that of Au mineralization as closely as where Au is considered to be dissolving as the thiosulphate complex. The only groundwaters with Eh values sufficiently high to dissolve Au as halide complexes are those postulated to be controlled by Mn oxidation. Thus, the presence of significant dissolved Mn in acid oxidized solution appears to be of critical significance for the mobility of Au in saline groundwaters.
16. Groundwater may be a useful exploration sample medium for primary Au mineralization in areas where the waters are neutral-alkaline, *i.e.*, where thiosulphate may be present as a mobilizing ligand. In areas where the waters are acid and saline, *i.e.*, where Au is dissolved as a chloride complex, groundwater sampling may only be useful at a regional scale.
17. Spectral techniques in the 0.4 to 2.5 μm wavelength region provide mineralogical information, particularly concerning the Fe oxides and clays, that appears to be useful for the characterization of soil and lag, and hence could have application in the classification and mapping of regolith materials. They can also be used to discriminate between different Fe oxides and clays when such distinctions are not always apparent using routine XRD analysis. However, spectral techniques are poor at detecting soil carbonates and hence cannot be used to identify areas where this important sample medium is present.
17. Spectral techniques can be used for the semi-quantitative estimation of micas, particularly muscovite, in fresh and weathered rocks and soils. This has potential for identifying alteration zones associated with Au mineralization and could have application in field logging or remote sensing. However, it is limited to materials containing more than about 20% mica, which may be too insensitive for practical application.

1 GEOCHEMICAL DISPERSION AND REGOLITH EVOLUTION

1.1 INTRODUCTION

Many of the investigations undertaken in the Project have determined the lateral and vertical distributions of Au and a wide range of other elements in the regolith close to mineralization. The principal objective has been to establish which elements may indicate or confirm the presence of mineralization where Au itself has been leached (*e.g.*, from near-surface depletion zones) or has a restricted or irregular distribution (*e.g.*, within saprolite). The data are also relevant to studies of the genesis of supergene Au deposits and to the evolution of the regolith. The sites investigated during the initial phase of the project were Reedy (Report 102R), Beasley Creek (Report 152R) and the Mystery Zone at Mt. Percy (Report 156R). Additional information was obtained from Callion, Panglo, Bottle Creek, Mt. Magnet and Telfer. Similar geochemical and mineralogical studies have been conducted in the second phase of the project at the Lights of Israel deposit, Davyhurst (Report 393R) and a background site at Mt. Percy (Report 389R), with a smaller investigation at Mulgarrie (Report 339R). The results of these studies are consistent with the features established previously, although the data refer to horizons beneath the mottled clay zone, for at neither Lights of Israel nor Mt. Percy (background) is there a lateritic gravel or duricrust horizon. The regoliths are thus assumed to be partially truncated, with a thin colluvial cover. The Mulgarrie site includes a palaeochannel infilled by clays; the adjacent residual area has a truncated regolith, whereas the channel clays are extensively mottled and have ferruginous horizons. However, the relationship of these to lateritic horizons developed in residuum is uncertain.

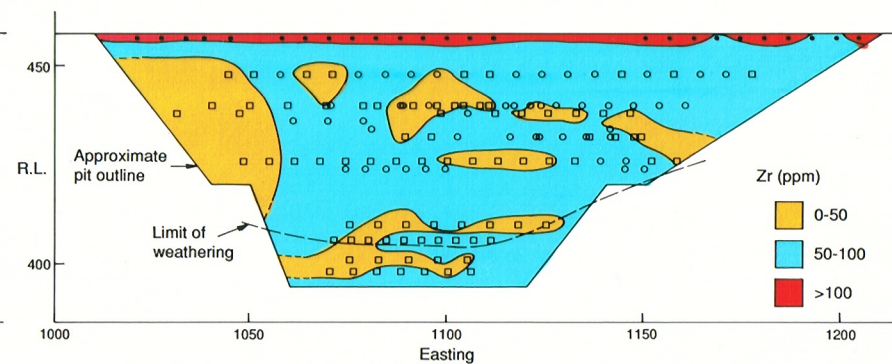
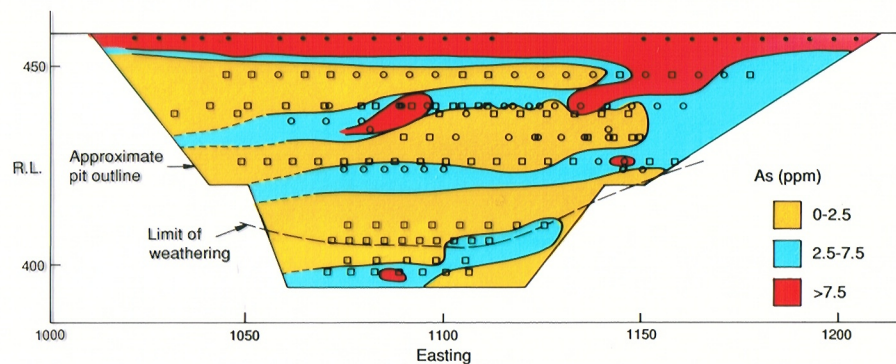
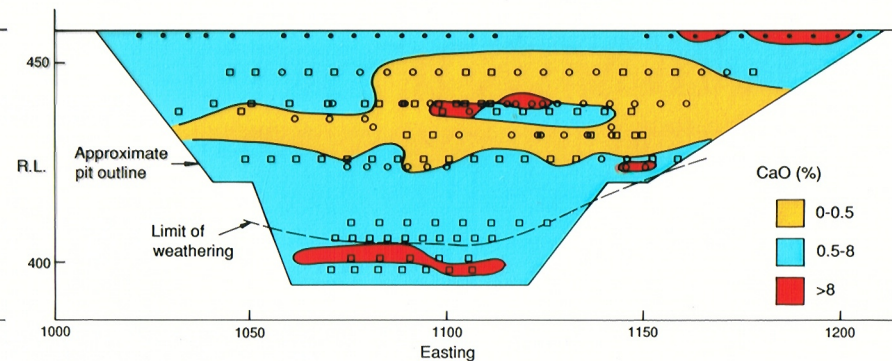
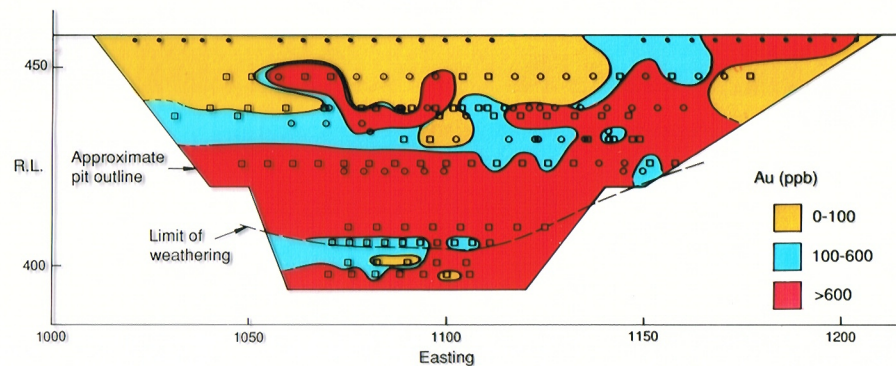
Element distributions in soils were also determined at Zuleika, south of Ora Banda, where they are developed over residuum and palaeochannel sediments, and at Granny Smith, where the soil is present above hardpan.

The distributions of selected data from Lights of Israel and the Mt. Percy background site are illustrated in Figures 1.1 and 1.2. Equivalent data were given in Figures 4.1 to 4.6 in the summary report for the earlier phase of the Project (Report 167R) and the following discussion is based on the findings of all the investigations.

The chemical and physical processes of weathering, soil formation and landscape development are essentially the same as those of secondary geochemical dispersion. Thus, the determination of weathering history and the recognition of the effects of past and present climates on these processes are fundamental to the interpretation of geochemical data. The distributions of elements in deeply weathered regoliths are determined by the stability of their primary host minerals, the presence or absence of possible secondary host minerals and the chemical mobilities of the elements in the changing weathering environments to which they have been subjected. The regoliths of the Yilgarn Block are products of a long history of weathering, during which two climatic regimes have been of particular significance. These were, firstly, humid, probably warm to sub-tropical conditions during the Cretaceous to mid-Miocene and, secondly, drier climates since the Miocene that have continued to the present. The former, which were probably equivalent to climates prevailing in the present wetter savannas, gave rise to extensive, deep lateritic weathering. The more recent arid to semi-arid climates, and some minor uplift, have resulted in a general lowering of water-tables, changes to, and slowing of, chemical weathering, and erosional modification of the landsurface. In general, only the processes that refer to past regimes of long duration, to extreme climates or to recent regimes have had a significant effect. Thus, many of the dominant geochemical (and mineralogical) characteristics of the regolith are related to the development of the lateritic profile under humid climates with high water-tables and generally acid conditions, whereas others are due to later, possibly still active, events related to arid, alkaline environments with lower water-tables. The features produced by these later events appear as modifications of the pre-existing lateritic regolith and tend to be reflected by the concentrations of its minor components. Research during the course of these projects has demonstrated the importance of currently active processes, not only with respect to Au, but to several other elements. These processes are discussed in more detail in later sections of this report.

LIGHTS OF ISRAEL

940N - 1050N



• Soil □ Amphibolites ○ Biotite schists

Figure 1.1 Regolith section, Lights of Israel mine; distributions of Au, CaO, As and Zr. The section is a composite between 940N and 1050N.

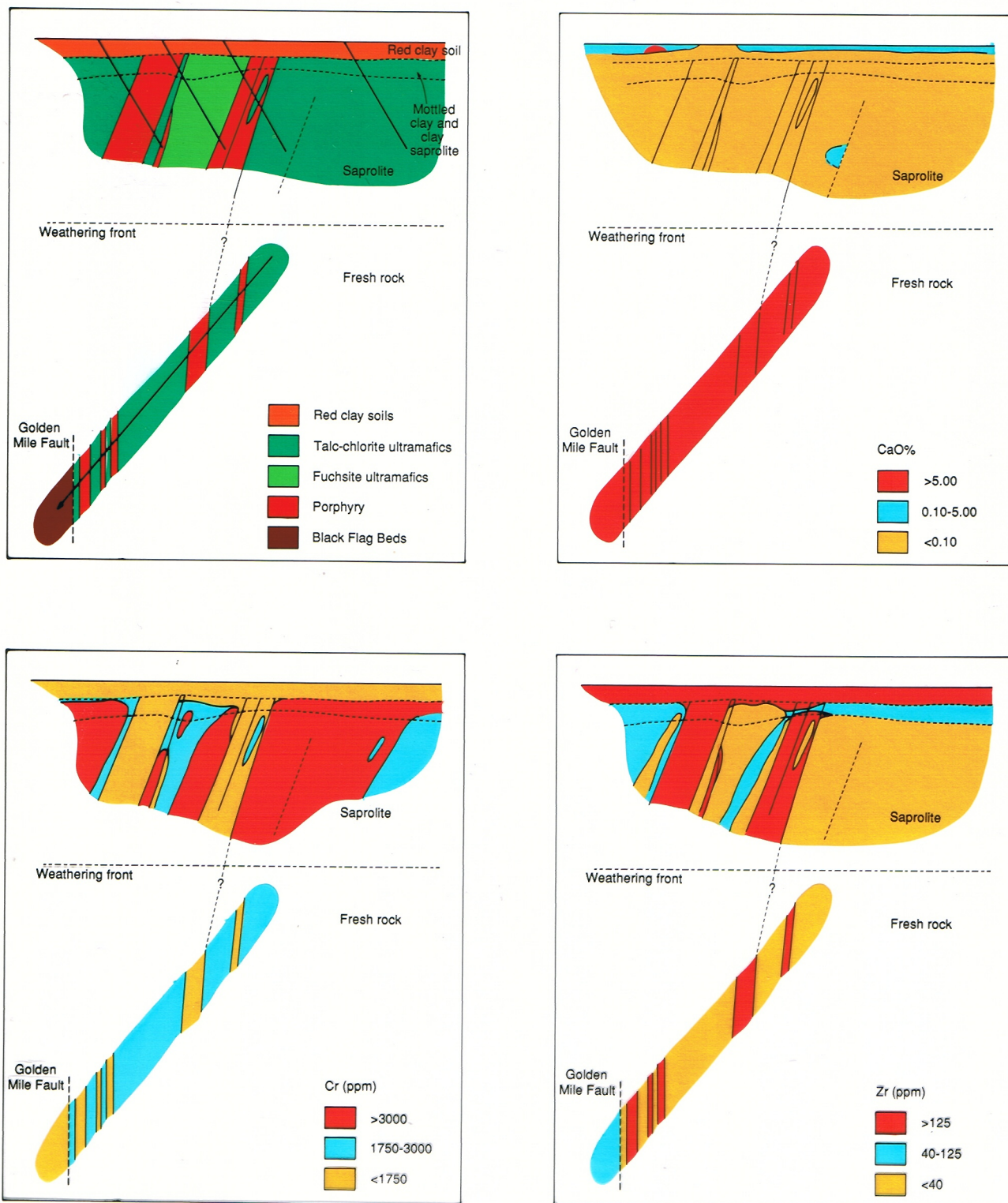


Figure 1.2 Section through a background area approximately 1 km north of the Mystery Zone, Mt. Percy. Geology and distributions of CaO, Cr and Zr. NB: there is a separation of 150 m between fresh rock and regolith sections.

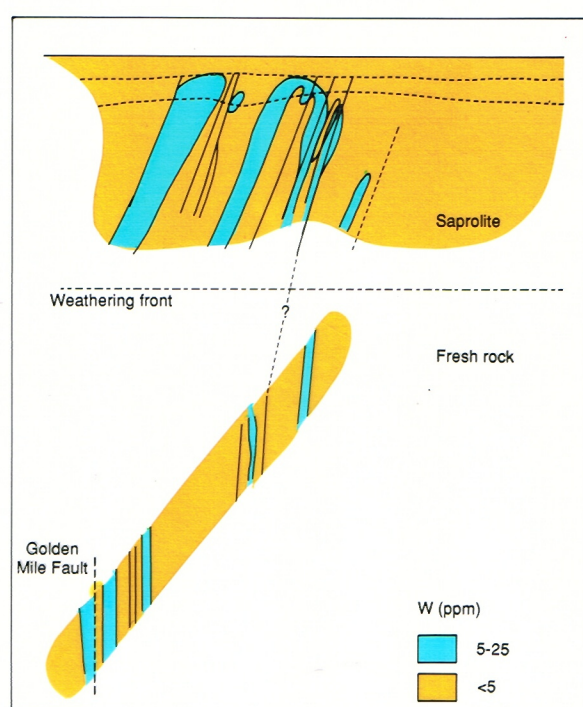
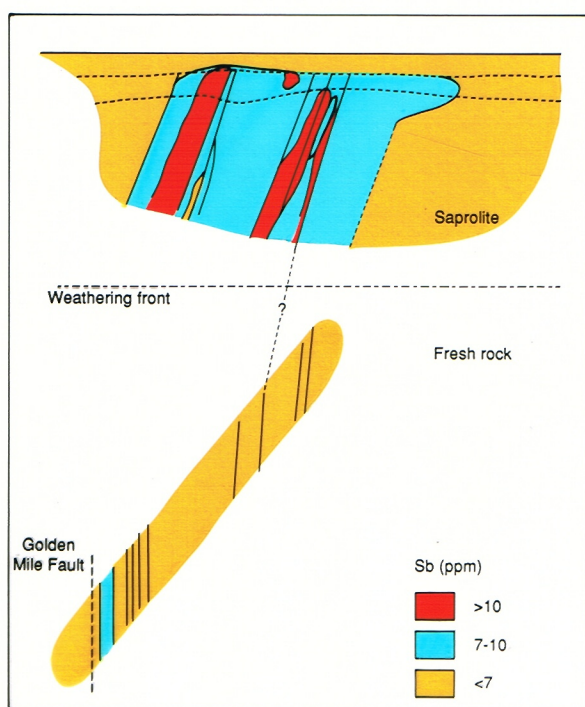
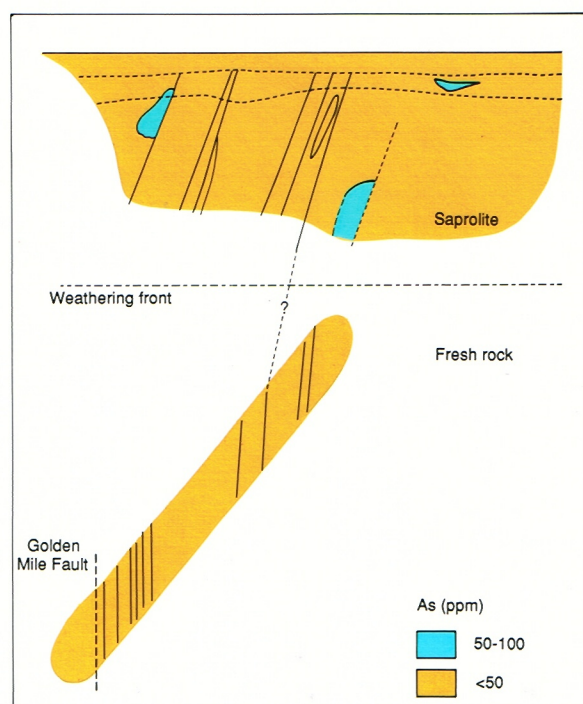
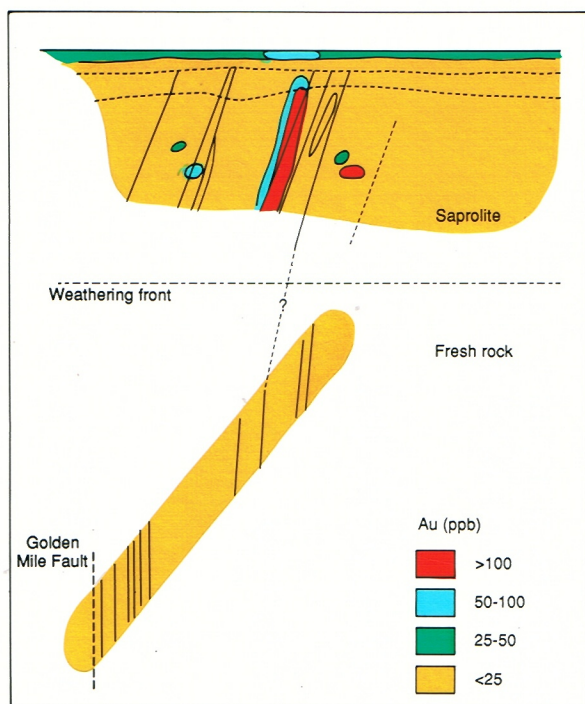


Figure 1.2 (continued) Section through a background area approximately 1 km north of the Mystery Zone, Mt. Percy. Distributions of Au, As, Sb and W. NB: there is a separation of 150 m between fresh rock and regolith sections.

1.2 LATERITIC WEATHERING UNDER HUMID WARM TO TROPICAL CONDITIONS

1.2.1 *Principal characteristics*

The principal effects of lateritic weathering on element distributions are summarized in Table 1.1, which relates leaching and retention of a range of elements to mineral transformations in the principal regolith horizons. This summary is, of course, a gross simplification and it must be noted that no mineral is entirely unaffected by weathering, no element is entirely leached from any regolith horizon nor is any element entirely immobile.

1. *Weathering front and saprock*

Sulphides are some of the most unstable minerals in humid, oxidizing environments and only persist high in the profile if preserved within vein quartz. This is consistent with the observation that S has been strongly leached from the deepest levels of the regolith and appears to be the element most susceptible to weathering. Many elements hosted by sulphides (Cd, Co, Cu, Mo, Ni, Zn) are also commonly strongly leached deep in the profile, although a proportion is retained in Fe oxides derived from the sulphides. Carbonates are similarly highly susceptible to weathering in humid, especially acidic, environments: hence elements dominantly or significantly hosted by them, such as Ca, Mg, Mn and Sr, are strongly leached. Calcium and Sr, for example, are thus commonly reduced to very low concentrations throughout most of the regolith.

2. *Lower saprolite*

Weathering in the lower saprolite causes the destruction of feldspars and ferromagnesian minerals. Sodium, Ca and Sr are leached from the former, with Si and Al retained as kaolinite (smectites may be intermediate products but are usually only retained in less freely-drained environments or in more arid environments). In addition, K, Rb and Cs will be lost if hosted by orthoclase or biotite, but if present mainly in muscovite, concentrations are maintained or residually increased through much of the regolith. Barium, commonly hosted by feldspars, is released early during weathering, but is reprecipitated as barite which remains stable through the regolith and is only partly leached in the duricrust. Weathering of less stable ferromagnesian minerals (pyroxene, olivine, amphibole, biotite) results in the formation of Fe oxides, partial retention of minor and trace elements such as Ni, Co, Cu, Mn and Ni, and progressive loss of Mg and Si, except where retained in smectite (Mg, Si), kaolinite (Si) or quartz (Si).

3. *Mid to upper saprolite*

The alteration of all but the most resistant primary minerals occurs in these zones; in addition, some less-stable secondary minerals such as smectites are also destroyed. Serpentine, chlorite and talc are progressively weathered through the zone, although talc and, in particular, muscovite may persist through to the mottled clay zone and, locally, to the duricrust. Ferromagnesian minerals are the principal hosts for transition metals such as Ni, Co, Cu and Zn in sulphide-poor mafic and ultramafic rocks and are retained higher in the profile than sulphide-hosted metals. Nevertheless, they become leached from the upper horizons and reprecipitate with secondary Fe-Mn oxyhydroxides in the mid to lower saprolite. Some leaching and redistribution of Ni, Co and Mn is probably related to post-lateritic periods of lower water-tables.

4. *Mottled and ferruginous zones*

Most remnant major primary minerals, except quartz, are commonly finally destroyed in these horizons, as is the primary fabric of the rocks. These horizons, in particular, demonstrate one of the principal characteristics of lateritic regoliths, which is to be dominated by Si, Al and Fe, resident in kaolinite, quartz, Fe oxides (hematite and goethite) and, in places, gibbsite. The abundances and distributions of Si, Al and Fe broadly reflect their source lithologies. Thus, kaolinization of saprolites is strongest over the felsic rocks, and only tends to be well developed over mafic and ultramafic rocks in the upper saprolite. Although some dissolution can occur in

Table 1.1 Element mobility during weathering

MOBILITY UNDER DOMINANTLY HUMID CONDITIONS

Host minerals	Leached	Partly retained in secondary minerals
Released at weathering front:		
Sulphides:	As, Cd, Co, Cu, Mo, Ni, Zn, S	As, Cu, Ni, Pb, Sb, Zn (Fe oxides)
Carbonates:	Ca, Mg, Mn, Sr	
Released in the lower saprolite:		
Aluminosilicates:	Ca, Cs, K, Na, Rb	Si, Al (kaolinite); Ba (barite)
Ferromagnesians (pyroxene, olivine amphiboles, chlorite, biotite)	Ca, Mg	Fe, Ni, Co, Cr, Ga, Mn, Ti, V (Fe and Mn oxides)
Released in upper saprolite:		
Aluminosilicates (muscovite)	Cs, K, Rb	Si, Al (kaolinite)
Ferromagnesians (chlorite, talc, amphibole)	Mg, Li	Fe, Ni, Co, Cr, Ga, Mn, Ti, V (Fe oxides)
Smectites	Ca, Mg, Na,	Si, Al (kaolinite)
Released in the mottled and ferruginous zones:		
Aluminosilicates (muscovite, kaolinite)	K, Rb, Cs	Si, Al (kaolinite)
Iron oxides	Trace elements	
Retained in stable minerals:		
B, Cr, Fe, Hf, K, Nb, Rb, REE, Th, Ti, V, W, Zr		

PRECIPITATED DURING ARID PHASES

Oxides:	Si, Fe, Mn,
Carbonates:	Ca, Mg, Sr
Sulphates:	Ca, Ba, K, Al
Halides:	Na

ferruginous zones, quartz is commonly only slightly weathered and most is left as a residual, resistate mineral, most abundantly over felsic igneous rocks and quartzose sedimentary rocks. The ferruginous horizon is commonly most strongly developed over ultramafic and mafic rocks, tending to be thinner, less ferruginous and less strongly cemented over other lithologies and almost absent over granitoids. Accumulation, partial dissolution and recrystallization of Fe oxides in the lateritic horizons results in the development of a variety of secondary fabrics (*e.g.*, pisoliths, nodules, vermiform voids) and the replacement of other minerals, particularly kaolinite. Released Si and Al either reprecipitates as kaolinite, *e.g.*, in the mottled clay horizon, or is leached.

The distributions of several minor and trace elements are controlled wholly or in part by the distributions of these major elements, due to substitution or coprecipitation. Thus, Cr, As, Ga, Sc, V, and possibly Au, tend to accumulate with Fe oxides; Cr, mainly derived from ferromagnesian minerals, is also associated with neo-formed kaolinite. Many resistate and immobile elements also tend to concentrate with Fe oxides in the lateritic horizons although, for most, no chemical interactions are involved. Thus, the distributions of Cr, K, Zr, Hf, Th, Nb, Ta, W, REE, Ti and V relate wholly or in part to their inertness during weathering, which is due to their relative chemical immobility (*e.g.*, V, Ti) and/or to the stability of their primary and/or secondary host minerals (*e.g.*, Zr and Hf in zircon; Ti in rutile and anatase; Cr in chromite; K in muscovite). Their abundances tend to increase upwards through the profile due to the gradual loss of other components, with marked accumulation in the ferruginous lateritic horizon, within which lateral dispersion by colluvial action can occur during the course of profile evolution.

1.2.2 Distribution of elements associated with gold mineralization

The behaviour of Au and possible pathfinder elements under lateritic conditions in the Yilgarn remains unclear, due to the overprint of remobilization under later arid conditions. However, some indications can be gained by analogy with humid lateritic environments (*e.g.*, Freyssinet *et al.*, 1989a and 1989b; Zeegers and Lecomte, 1992; Lecomte and Zeegers, 1992). These studies suggest that Au is essentially immobile throughout the saprolite but is physically dispersed in the lateritic horizons and chemically associated with Fe oxides, to give widespread surficial haloes. Similar dispersion haloes are present in the lateritic Au deposits in the Yilgarn Block but, whereas in humid areas, such as at Boddington, the Au-Fe oxide association is dominant, in arid areas there may also be a strong Au-carbonate association related to mobilization under semi-arid conditions. Nevertheless, relict primary Au particles in the ferruginous horizons, and the extent of the secondary haloes, are probably inherited from dispersion during lateritization. Pathfinder elements that are initially present in sulphide minerals are mostly leached at the onset of weathering at the base of the profile. Arsenic is an exception, because it concentrates with secondary Fe oxides; data from humid environments shows that it becomes widely dispersed at the surface, a feature also found in the Yilgarn Block. Silver, in primary electrum, is commonly retained until the grains themselves dissolve, commonly in the upper saprolite or higher. However, the fate of Ag in other minerals, including tellurides, is unknown, due to inadequate analytical sensitivities. Of other elements, Sb and W appear to accumulate residually, particularly in the lateritic horizons, and to be dispersed physically in the near-surface. There is no clear evidence for their dispersion within saprolite, although the Sb distribution appears to become more homogeneous.

1.3 WEATHERING UNDER SEMI-ARID AND ARID CLIMATES

1.3.1 *Principal characteristics*

Characteristics commonly associated with weathering under arid conditions are those related to the excess of evaporation over precipitation, which result in the accumulation in the regolith of weathering products that would otherwise be leached. Several of the resultant precipitates, such as silcretes and some calcretes, are stable and are an indication of stages in regolith evolution. Others are very soluble and hence may be transitory; however, these are associated with currently active processes, some of which have considerable implications for ongoing element dispersion and the development of certain exploration procedures. Aridity has also induced erosion, partly through instability produced by reduction in vegetation. The erosion, by sheetwash, wind and minor drainage rejuvenation, has been insufficient to remove most of the debris, which has been redeposited on lower slopes and in valleys, further reducing the already low relief. Accordingly, the precipitates may occur in any regolith horizon, diluting, cementing or replacing pre-existing materials, both residual and transported, and modifying their mineralogical and geochemical characteristics.

1.3.2 *Secondary accumulation and cementation*

1. *Accumulation of alkali and alkaline earth elements and sulphur*

These typically concentrate in groundwaters and their precipitation in the regolith results in the paradoxical accumulation of these highly mobile components in otherwise leached materials. They are derived in part from on-going weathering and in part meteoritically, with rainfall. In the southern Yilgarn Block especially, enrichment of Ca, Mg, S and Sr in soils and upper horizons, commonly in the top 2 m., relates to the precipitation of secondary sulphates and carbonates (*e.g.*, gypsum, calcite and dolomite in soils at Lights of Israel, Mt. Percy, Mt. Hope, Panglo, Mulline, Zuleika). In the north of the Yilgarn Block, carbonates are much less common in soils and have only a sporadic occurrence (*e.g.*, at Beasley Creek), but gypsum is widespread. Carbonates may also occur in upper saprolitic horizons, to depths of 10 m or more, as found at Granny Smith and Beasley Creek. Such carbonates were noted previously at Killara, near Meekatharra (Butt, 1979), but they are not present in all areas and the controls on their distribution are not understood. Sulphates may also precipitate in the mid saprolite, as alunite (*e.g.*, Panglo and the Mystery Zone, Mt. Percy) and halite is commonly present as a trace constituent throughout the regolith.

2. *Secondary silica cementation*

Silica induration of various types is a common feature of the regolith in semi-arid Australia. It is considered to be post-lateritic, although the conditions of precipitation are poorly known. Massively silicified saprolite and silica veins are characteristic of Al-poor ultramafic rocks (*e.g.*, dunites at Mt. Keith, Agnew and Siberia - see Butt and Nickel, 1981) and Ti-Zr-rich silcretes are present over granitoids (see Report 390R). More widespread and abundant, however, are the red-brown hardpans, which are developed extensively in the northern Yilgarn Block through partial cementation of the top 1 to 5 m of the regolith by hyalite (opaline silica). These may be confined to transported material but, where this is thin, the cementation may extend into residuum. The hardpan may thus include colluvium of diverse origins, semi-residual lateritic gravels (Bottle Creek) and/or soil and saprolite (*e.g.*, at Youanmi, Report 23R, Beasley Creek, Report 105R, Granny Smith, Report 385R;). At Bottle Creek, Beasley Creek and Granny Smith, the hardpan is also invaded by carbonate.

1.3.3 *Dispersion of minor and trace elements during arid weathering*

Other than the accumulation of alkalis, alkaline earths, sulphur and silica, discussed above, the change to aridity has not greatly affected the distributions of many elements in the regolith, because they are hosted by primary and secondary minerals that are stable in an arid weathering environment. Nevertheless, some remobilization has taken place as conditions changed, *e.g.*, in response to gradual lowering of the water-table. For example, the leaching of Cu, Co, Mn, Ni and Zn from upper horizons and their precipitation in the mid to lower saprolite in Fe oxides or smectites is probably a response to this change. Similarly, the

absolute accumulation of the light REE in the lower saprolite at Lights of Israel and the Mystery Zone, Mt. Percy, may be attributable to post-lateritic dissolution of primary minerals containing REE and the precipitation of these elements at a porosity barrier.

Active weathering and dispersion of several elements is evident from their presence in groundwaters and plants, high solubilities in soils and association with evaporite minerals such as carbonates. This most importantly affects Au but, at Mt. Pleasant, As, Cu, Mo and Zn also appear to have been dispersed into recent alluvium. Hydrogeochemical data from Panglo, Mulgarrie and Wollubar demonstrate that many elements, including Au, base metals and the REE, are highly mobile under the conditions prevailing in some highly saline drainages. In the regolith, these mobile elements may be detected by selective extraction analyses. Commonly, they represent only a small proportion of the total quantity of the element present, thereby not significantly altering the distributions inherited from the earlier lateritic weathering, as noted above. However, the proportion may increase in near-surface horizons, especially those characterized by recent precipitates: thus, at Granny Smith, up to 40% of the Au in some regolith materials is soluble in water.

1.3.4 Distribution of elements associated with gold mineralization

The effects of aridity on Au distribution can be determined by comparison with studies from humid lateritic environments (*e.g.*, Freyssinet *et al.*, 1989a and 1989b; Gray *et al.*, 1992; Lecomte and Zeegers, 1992; Zeegers and Lecomte, 1992). The most prominent differences are the development of a zone of marked depletion beneath the lateritic horizons, supergene enrichment deep in the saprolite, characterized by the presence of secondary Au of high fineness and, in the southern Yilgarn, enrichment in pedogenic carbonate. Depletion and enrichment in the saprolite are related to the salinization of the groundwaters and lowering of the water-table. The latter has probably been punctuated by still-stands or temporary rises due to reversals in climate. Such events have great significance, for the increased rainfall leaches precipitated salts and recreates redox conditions suitable for ferrolysis, thus producing saline and acid groundwaters. As these waters become more strongly oxidizing, they can become capable of dissolving Au and Ag as halide complexes. Evidence from Panglo (Report 125R) suggests that the Mn redox couple controls this oxidation step and that there, iodide may be more important than chloride as the complexing species. During these temporary humid periods, therefore, Au may be dissolved and mobilized, with precipitation taking place in response to a rise in pH or dilution of the halide concentration, both of which may occur when solutions percolating through the unsaturated zone reach the water-table. Precipitation is also caused by the reduction of the Au halide by ferrous iron, either at the water-table or at the interface between an upper oxidized aquifer and a lower reduced aquifer. The latter mechanism can account for enrichments parallel to, but below, the water-table. Repeated strong leaching of the upper saprolite leads to the formation of the depletion zone between the lateritic and saprolitic enrichments of Au. Mobilization of Au by plants under present-day conditions may also cause depletion, but is also implicated in the enrichment in carbonates. Minor dispersion of Au as a thiosulphate complex is suspected at Bottle Creek (Boags, Report 237R) and the Golden Hope mine, near New Celebration (Report 387R).

In areas where the lateritic horizons have been eroded, the depleted zone is the uppermost residual material, and either forms the parent material for the soils or, as at Panglo, Granny Smith and the background site at Mt. Percy, immediately underlies the transported cover. Gold enrichment in the pedogenic carbonates is particularly significant in such circumstances and results in the surface expression of the mineralization. Where there are no carbonates, however, Au concentrations may be lower by an order of magnitude; the high Au contents in hardpan at Granny Smith are unusual in this regard but may be due to local circumstances. The high solubility of Au in surficial materials demonstrates dispersion is active, although it is probable that the amount and, especially, the proportion of soluble Au may relate more to surficial environmental conditions than to the proximity of mineralization.

The overall effect of weathering on the distributions of As, Sb and W is homogenization and (residual) concentration. This is most noticeable for Sb and W at Mt. Percy, both in the Mystery Zone and in the slightly mineralized background site. Each of these elements, which indicate alteration associated with

primary mineralization, tend to persist through the depletion zone; K and Rb also persist, due to the stability of muscovite. However, none of these elements other, perhaps, than As, is dispersed into the transported overburden and none is universally applicable as a pathfinder. For example, at Reedy, only W is significantly enriched, and at Lights of Israel, there is no effective pathfinder. The presence of usable pathfinder elements is, of course, dependent on their abundance in primary mineralization and the associated alteration zone.

1.4 ROCK TYPE DISCRIMINATION

1.4.1 *Procedures for identifying parent lithology from weathered rock*

There are several procedures for determining parent lithology in the regolith, including colour, fabric, mineralogy and geochemistry. Fabric and, to a lesser extent, mineralogy, are very useful discriminators in fresh rock, saprock and saprolite, but their value diminishes as the degree of weathering increases. Mineralogy becomes dominated by Fe oxides, clays and silica, and, above the pedoplasation front, fabrics become altered by pedogenic processes. Nevertheless, relict fabrics survive in places, because of incomplete pedogenic processes, or have been protected by extensive ferruginization or silicification. Accordingly, accurate identification of parent lithology is possible by petrographic study, even at the low magnifications provided by a hand lens or binocular microscope. This has been demonstrated by the commencement in the Project of an Atlas of Rock Weathering (Report 390R), which displays the petrographic effects of weathering, at "hand lens" and "microscope" scales, for several lithologies, in some carefully selected profiles. The Atlas is not intended to be an exhaustive catalogue, but illustrates the type of information that can be obtained through careful observation. Nevertheless, the effects of intense weathering and/or pulverization of weathered material during drilling may destroy fabrics, so that it may be necessary to resort to geochemical procedures. Simple bivariate and trivariate analyses based on Ti, Zr (or Hf) and Cr are effective in subdividing the principal groups of igneous rocks (Hallberg, 1984), but they are insufficient to classify more complex lithologies, such as the fuchsite-altered ultramafic rocks and xenolith-contaminated porphyries from Mt. Percy, and quartz-rich mafic and ultramafic rocks from Reedy. Multivariate discriminant analysis was shown to have promise in the previous phase of the Project and this has been tested further with a broader data set and improved software.

1.4.2 *Geochemical database*

A database incorporating a wide range of igneous lithologies was compiled, incorporating samples from all regolith horizons (unweathered through to duricrust where available). Metasediments were not included because most immature clastics of the Archaean tend to reflect their provenance materials and any subsequent diagenetic alteration. The sizes of each segment of the data base and the sources are given in Table 1.2.

Most of the data are from samples collected within or close to mineralization. Hence, it was necessary to ignore target and pathfinder elements in the database as they are likely to be atypical, may vary with proximity to mineralization and may be independent of rock type. Other elements were excluded because their concentrations are very low, or the data are incomplete or too widely varied by weathering. Sixteen, mainly lithophile, elements (Si, Fe, Al, Ti, Ba, Ce, Co, Cr, Ga, La, Mn, Ni, Rb, V, Y and Zr) were chosen to be assessed with multivariate discriminant analysis.

Table 1.2 Geochemical database

Rock Type	Location	Number of Samples	Source
Fuchsite ultramafic	Mt. Percy	302	Report 156R
Talc-chlorite ultramafic	Mt. Percy	155	Report 156R
Pyroxenite	Ora Banda	11	Unpublished
Ultramafic Schist	Reedy	31	Report 102R
Amphibolite	Lights of Israel	123	Report 393R
Mafic Schist	Reedy	27	Report 102R
Porphyry	Reedy	7	Report 102R
Porphyry	Mt. Percy	111	Report 156R
Granite	Barr-Smith Range	30	Report 390R

1.4.3 Multi-element discriminant analysis

This technique attempts to maximize the differences between pre-determined groups. It is essential to supply well-controlled data in order to define these geochemically as training groups. It is limited by a number of assumptions that may be met only in part by geochemical data. It is assumed that the data have a normal distribution, but this is seldom true, so that log or power transformations may have to be applied. The data should have no extreme values, which, again, is seldom the case. The data should not sum to a constant value, consequently major elements should be excluded and only minor and trace elements used. The number of samples in each 'training group' should exceed the number of elements by a factor of at least three and preferably by ten. Multivariate analysis of the database was accomplished in steps using CSIRO software (Campbell, 1980; 1982; 1986).

Statistics and canonical variate analysis: Data for each element for each rock group were normalized by a series of power transforms. Robust estimations of means, standard deviations and correlations were followed by robust canonical variate analysis. The results of this canonical variate analysis of nine reference groups are eight canonical variates, of which the first five (CV1-5) contain most of the useful information. The extreme end members, granite and pyroxenite, are very well separated on the CV1-CV2 plot (Figure 1.3), as are the mafic amphibolites from Lights of Israel, which form a close group. As expected, the granitic porphyries from Reedy fall within the edge of the granite field. The orthogonal trend of some granite members reflect a high variance due to extreme weathering (arenose zone). The ultramafic rocks from Mt. Percy are extensively overplotted by their fuchsite-altered variants. All the well-contrasted types are quite distinct. The more difficult lithologies are not so distinct; the xenolith-contaminated porphyries from Mt. Percy form a trend between felsic rocks and the ultramafic rocks, with which they are contaminated. The quartz- and Zr-rich mafic schists from Reedy fall between the felsic rocks and the mafic amphibolites from Lights of Israel. Their ultramafic equivalents form a trend between them and the ultramafic rocks of Mt. Percy. Thus, if these difficult rocks are removed, the distinction would be good; their positions on the CV1-CV2 plot closely reflect their affinities.

Although they extensively overplot on the CV1-CV2 diagram, the fuchsitic and chloritic ultramafic rocks from Mt. Percy are largely separated by CV3. Similarly, the contaminated porphyries from Mt. Percy overplot the mafic schists from Reedy on the CV1-CV2 diagram, but considerable separation is also possible using CV3 (Figure 1.4).

Group membership and typicality: Group membership and typicality probabilities for individual samples were calculated using the 95% confidence level for the typicality. Assessment of the results (Table 1.3) showed that most rock types could be distinguished with 71-77% accuracy, the exceptions being the pyroxenite (36%) and the granite (23%). There were, inevitably, a number of cases that could not be classified; even though their membership probabilities indicated a particular group (almost always the correct *a priori* group), their typicalities were below the set confidence limit. The proportion of

unclassified cases was high for the high variance pyroxenite and granite; in each *there were no misclassified cases*. This is a far more statistically rigorous procedure than plotting the first two canonical variates but, as probabilities are used, data normalization is essential; it is also more effective as it makes use of the full dimensionality of the analysis. Having completed this type of analysis with a known training set, a group of unknowns may be appended and these identified in a similar manner.

The elements that contribute most to the classification are, in nearly equal proportions, Ni>Cr>Co>Rb>Zr>Ti>Ba, with a slightly lesser contribution from Y>Al>Mn>V>Ce>Fe>Si (Figure 1.5). The technique has selected elements already known to be useful for classification on a univariate and bivariate basis which, when combined, are even more effective. This has not been an easy classification, requiring at least seven elements to accomplish an imperfect result. These elements are those pertinent to the classification of the whole data set; their order would be modified if subsets of the data were considered alone and the classification may well be more efficient. For example, the earlier analysis of the Reedy data achieved 91% correct classification using seven elements and 85% with only four elements (Cr, Sc, Co, K) (Reports 102R, 167R).

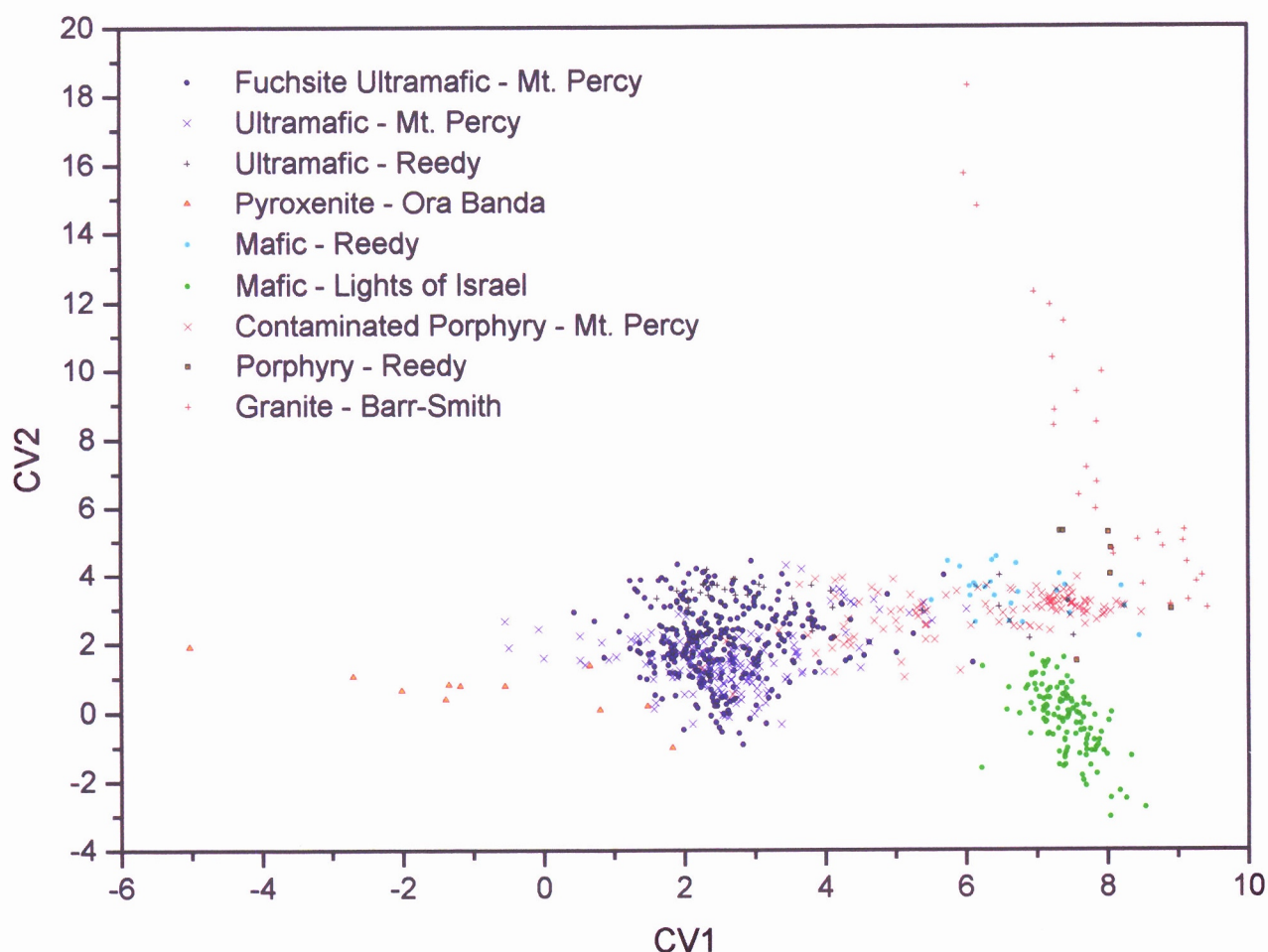


Figure 1.3. Plot of CV1 and CV2 for the whole data set, illustrating overlap between some groups.

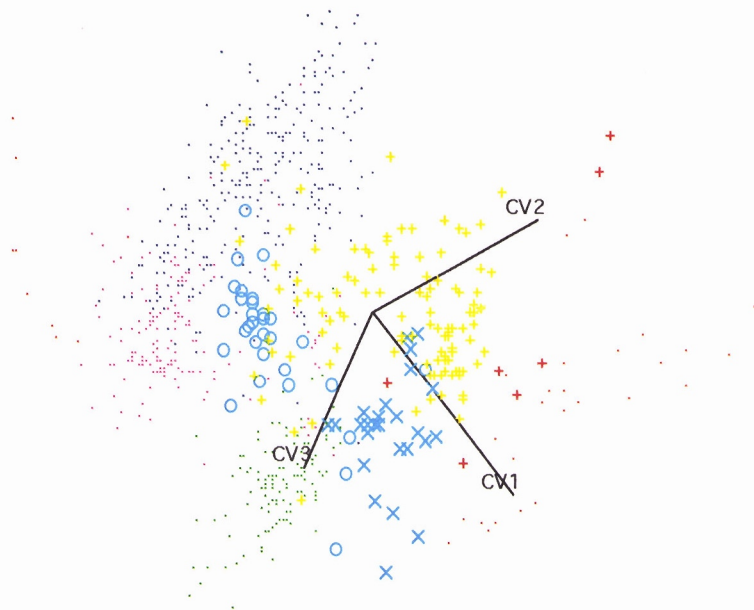


Figure 1.4. CV1 - CV2 - CV3 plot rotated to achieve maximum separation of all groups.

Table 1.3 Accuracy of classification of the database

<i>A priori</i>	<i>A posteriori</i>									
	FUMafic MtPercy	UMafic MtPercy	UMafic Reedy	Pxenite O Banda	Mafic Reedy	Mafic L.O.I.	Porph MtPercy	Porph Reedy	Granite Barr-Sm	Un- class'd
Fuchsite UMafic	76.74	12.29	0.33	0.00	0.00	0.00	2.65	0.00	0.00	8.31
UMafic MtPercy	0.65	76.77	0.65	0.00	0.65	0.00	0.00	0.00	0.00	13.55
UMafic Reedy	3.23	3.23	77.42	0.00	12.90	0.00	3.23	0.00	0.00	0.00
Pxenite O Banda	0.00	0.00	0.00	36.36	0.00	0.00	0.00	0.00	0.00	63.64
Mafic Reedy	0.00	0.00	7.41	0.00	81.48	0.00	3.70	0.00	0.00	7.41
Mafic L.O.I.	0.00	0.00	0.00	0.00	0.00	95.12	0.00	0.00	0.00	4.88
Porph MtPercy	5.41	5.41	0.90	0.00	0.90	0.00	71.17	0.00	0.00	16.22
Porph Reedy	0.00	0.00	0.00	0.00	0.00	14.29	0.00	71.43	0.00	14.29
Granite Barr-Sm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	23.33	76.67

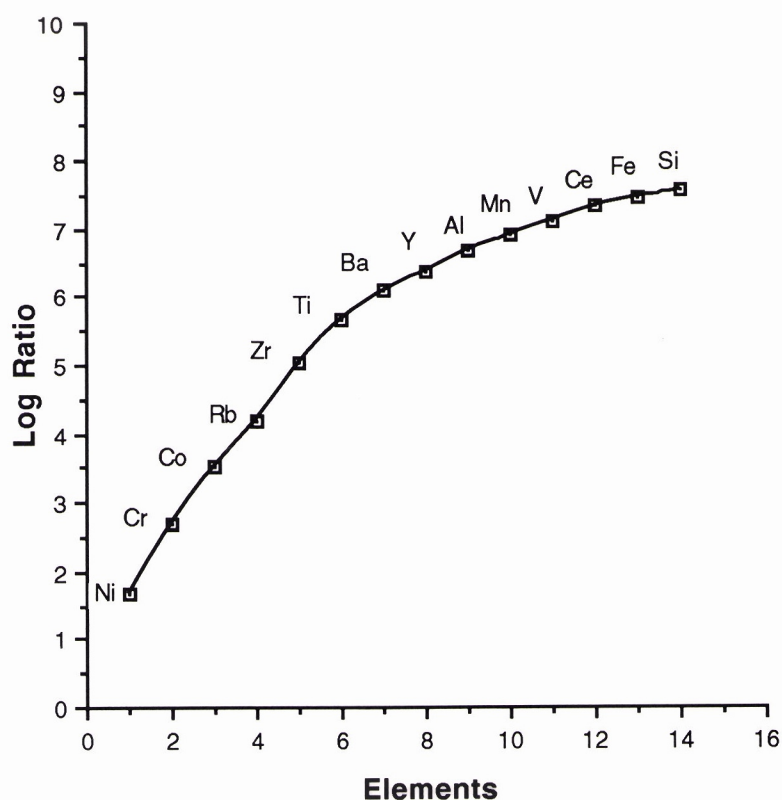


Figure 1.5. Element contributions to discriminant analysis.

1.5 IMPLICATIONS FOR EXPLORATION

The additional studies of multi-element dispersion patterns in the regolith and groundwaters, and the further investigations of Au mobility and extraction from soils confirm and extend the conclusions developed in the first phase of the Project. In summary, these are:

1. At local to sub-regional scales, Au itself is one of the best indicators of Au mineralization, despite (or perhaps because of) its chemical mobility during weathering.
2. Sampling must take account of the distribution of Au in the regolith. The accumulation of Au in calcareous and ferruginous surface horizons and its depletion for 5 to 20 m below them implies that sampling has to be carefully directed and that data interpretation will depend on the horizon sampled. Although Au may accumulate in some horizons of hardpan, this is not universally established and cannot be relied upon as a basis for sampling programmes.
3. Other elements commonly provide confirmatory evidence for the presence of mineralization and have particular value where Au either has been depleted or is patchily distributed, or where samples have been derived from the alteration zone rather than from the mineralization itself. The most suitable pathfinder suite is As, Sb, W, +/- Bi, Mo, Pb. Barium, K and Rb give a surface expression to some alteration zones, commonly wider targets than mineralization itself; K also offers potential for detection by radiometric surveys. However, these alkaline elements are not exclusively associated with mineralization and, in either event, the presence of K and Rb in the near-surface of intensely weathered regoliths is strongly dependent on the survival of the micas that host them, which is commonly the case.

4. Primary and supergene Au mineralization are indicated by broad Au anomalies in lateritic duricrusts and the lags and soils derived from them. These anomalies are comprised of (i) primary and (mostly) secondary Au associated with Fe oxides, presumably accumulated during lateritic weathering and (ii) principally in the south of the Yilgarn Block, secondary Au associated with pedogenic carbonates and accumulated during recent arid phases. Mineralization is also indicated by high concentrations of other ore-associated elements in these surface horizons, principally W, As and, less commonly, Sb, and alteration by K and Rb, but these do not appear to have wider or more consistent dispersion haloes than Au.
5. The depleted zone commonly occurs in the mottled and plasmic clay zones and the upper saprolite. At sites where the regolith has been truncated and the ferruginous horizon is absent, the depleted zone commonly outcrops (Parkinson pit, Mt. Magnet), or subcrops beneath transported overburden (Granny Smith, Panglo). The depleted zone is not always well developed (Callion, Beasley Creek, Reedy, Lights of Israel) but its common occurrence demands that care must be taken to avoid sampling within it. Gold contents are generally <100 ppb, even where there are quartz veins, and give little or no indication of the underlying mineralization. Other ore- and alteration-associated elements Sb, W, K, Rb, Ba and, to a lesser extent, As remain throughout the depleted zone. They may be anomalous in residual soils developed from Au depleted material in truncated regoliths even if Au contents are near to background values. If pedogenic carbonates are present, the Au depletion, or masking by transported overburden, may be offset by some surface enrichment, as at Panglo, Lights of Israel and Mt. Magnet.
6. Gold in the saprolite beneath the depletion zone is generally present at abundances similar to or greater than those in the fresh rock. Lateral dispersion and concentration commonly occur at one or more levels, thereby enhancing the weathered expression of the primary mineralization and becoming an exploitable resource in its own right; much of this Au is secondary. Recognition of the presence of an extensive, relatively thin (0-10 m) horizon of Au enrichment is important for data interpretation and in devising exploration strategies for further such deposits and for the primary mineralization from which they are derived. Sub-horizontal zones of supergene enrichment are best developed in highly saline environments (e.g., Hannan South (see Gray *et al.*, 1992, Figure V.3-4), Panglo), but are also apparent in the background site at Mt. Percy, close to minor Au mineralization.
7. The abundances of the elements associated with Au mineralization are very variable, so that no universal 'threshold' values can be proposed. Compared to the primary mineralization, element distributions (including Au) in the saprolite are more homogeneous, due to dispersion and reprecipitation during weathering. In general, dispersion and increase in size and coherence of secondary anomalies over primary distributions are:

$$S > Ag, Te \gg As > Sb > Au > W > Ba, K, Rb$$

Arsenic, Sb and W may give wider expression to mineralization in those saprolite zones in which Au has not been dispersed, whereas Ba, K and Rb indicate the broader target of the alteration zone. Silver, Te and S are very mobile and are generally leached to background values, although at Beasley Creek, Ag appears to be retained throughout the saprolite, indicating that, despite being weathered to a considerable depth, the mineralized unit has not been very severely leached. Sulphur in the mid to upper saprolite (Mt. Percy, Beasley Creek, Lights of Israel), present as alunite, gypsum or other sulphates, is meteoric and appears unrelated to mineralization, although there may be some bedrock-derived S at Lights of Israel.

8. The enrichment of Au in pedogenic carbonates provides an important sample medium in the southern Yilgarn Block. Most Au in soils appears to be associated with carbonates, where present; in lateritic gravels and duricrusts invaded by carbonate, Au is also associated with Fe oxides. The Au-carbonate association gives surface expression to basement mineralization concealed by at least 20 m of leached and/or transported overburden. In soil surveys, it is essential that the carbonate horizon, where developed, is preferentially sampled. This is best achieved using a power auger,

routinely sampling to a depth of about 1.5 m. However, the carbonate-horizon may occur as deep as 5 m, hence the sampling programme must be carefully monitored.

9. Pedogenic carbonates are only sporadically developed in the northern Yilgarn Block. Samples containing carbonates must be treated separately, since they may have a background Au abundance an order-of-magnitude greater than non-calcareous soils and hardpans.
10. Gold in hardpan at Granny Smith is present in lithorelics and in the siliceous cement. Gold enrichment occurs towards the base of the hardpan, overlying leached and possibly depleted saprolite. Secondary carbonate occurs in the lower hardpan and saprolite, commonly between 4 and 10 m depth. This carbonate is not so enriched in Au as pedogenic carbonates, but much of the Au is highly soluble.

2 SOIL AND LAG GEOCHEMISTRY

2.1 SITES SELECTED FOR STUDY

The multi-element geochemistry of soils overlying Au mineralization was investigated at five sites where the regolith is partially truncated and, in most cases, overlain by transported cover.

- 1 Lights of Israel: semi-residual calcareous soils, total thickness 2 m, overlying leached and depleted saprolite, with significant supergene mineralization below 15 m.
- 2 Mt. Percy: colluvial red clays, total thickness 4 m, overlying minor mineralization at the site selected to represent background.
- 3 Zuleika: calcareous soils developed on residuum and on barren palaeochannel sediments, mostly clays, overlying mineralization in coarse sands at 13-17 m depth.
- 4 Mulgarrie: calcareous soils developed on shallow colluvium and on barren palaeochannel sediments, mostly clays, 20 m thick, overlying mineralization in coarse sands at 30 m depth.
- 5 Granny Smith: red-brown hardpan in colluvium and saprolite; carbonates developed at base of hardpan (4 m) and extending to over 10 m depth.

At Lights of Israel and Mt. Percy, the geochemistry of the soil was studied as part of a more general investigation of multi-element dispersion in the whole regolith, whereas at Mulgarrie and Zuleika, the principal objective was to determine whether selective soil sampling could indicate the presence of mineralization concealed beneath barren sediments. Each of these four sites is south of the Menzies Line and the association with carbonate dominates the distribution of Au. In comparison, Granny Smith, well north of the Menzies Line, was selected to investigate Au distribution in hardpan. The very detailed study of different size and mineralogical fractions of the soils at the Lights of Israel provides a comparison with an equivalent study conducted previously at Beasley Creek, again contrasting environments north and south of the Menzies Line. The important contribution of vegetation, particularly deep-rooted species, to the formation and composition of soils, and to the geochemical cycling of Au and other elements, was recognized in the earlier phase of the project. Further studies were carried out at Zuleika, where vegetation could be involved in the development of a surface expression to the mineralization present within or beneath the palaeochannel sediments.

2.2 RELATIONSHIP BETWEEN GOLD AND PEDOGENIC CARBONATE

2.2.1 *Site studies*

The close association between Au and pedogenic carbonate, established in the earlier phase of the Project, has been confirmed and extended through further field investigations. These have concentrated on sites where the regolith is truncated and mineralization is depleted towards the surface and/or overlain by transported cover. The cover is very thin (<30 cm) at Lights of Israel, and residual areas were included at Zuleika. However, at Zuleika and Mulgarrie, the principal objectives were to determine whether mineralization in the palaeochannels has a distinctive surface expression. Results from these sites are outlined below, classified according to landform models (see Report 167R, p 71; Butt and Zeegers, 1992). The presence of carbonate at Granny Smith was unexpected and the relationship with Au is less clearly defined.

- a. Profile partly truncated, soils residual and semi-residual; (model code B1 Ca [1, 2])
Lights of Israel (Report 232R) and part of Zuleika (Report 328R).

At each of these sites, the Au distribution within the soil profiles is controlled by that of pedogenic carbonate. In the detailed study at Lights of Israel, it was found that mineralization was best expressed in the finer fractions of the soil (maxima >400 ppb Au in the minus 75 μ m fraction), which are the most calcareous. However, the total soil also gave a strong anomaly (maxima >200 ppb Au) and it is doubtful whether the additional sample preparation is of great value, particularly because, at other sites, carbonates

are coarser grained. Correct targeting of the carbonate horizon is of greater importance. The soil samples were collected from the top 25 cm, which, in places, is shallower than the most calcareous horizon. Thus, soil Ca and Sr anomalies directly overlying the mineralization are an artefact of sampling depth, with equivalent concentrations occurring deeper elsewhere on the traverse. Given the close association between Au and carbonate distributions, such an artefact could result in mineralization in areas with deep carbonate horizons being missed or having minor anomalies that are ascribed only low priority. At Zuleika, concentrations of 100-300 ppb Au, with a peak of 1670 ppb, occur close to subcropping mineralization in the calcareous top metre of the soil.

- b. Profile partly truncated, overlain by colluvium; (model code B1 Ca [2])
Mt. Percy background (Report 389R), part of Mulgarrie (Report 339R) and Granny Smith (Report 339R).

Gold concentrations of 30 to 52 ppb occur in the top 2 m of calcareous red clay soils developed on colluvium overlying minor mineralization (maximum 610 ppb Au at 12 m) in the background site at Mt. Percy. Underlying non-calcareous red clays and mottled clays contain <5 ppb Au. No soil survey based on carbonate sampling has been undertaken, so it is not possible to determine whether the anomaly represents a widespread enrichment or is related directly to the concealed mineralization deeper in the regolith, although the latter seems more probable. At Mulgarrie, Au is concentrated (maximum >400 ppb) in a calcareous horizon of a profile on colluvium 3-5 m thick, but it is unclear whether the Au is derived from underlying mineralized saprolite or by dispersion from outcropping mineralization and residual soils upslope.

Carbonates at Granny Smith differ from those at the other sites. They occur deeper in the profile, commencing from 3 to 9 m depth and continuing to below 12 m at some sites. They are diffused through the hardpan and underlying saprolite. There is no direct association between the distributions of total Au and Ca or Mg (*i.e.*, with secondary carbonate), although the proportion of water soluble Au in some of the carbonates is very high (nearly 40%).

- c. Profile partly truncated, thick alluvial cover; (model code B2 Ca [3])
Zuleika (Report 328R) and Mulgarrie (Report 339R).

At each of these sites, the principal objective was to determine whether mineralization within (Zuleika) or mainly beneath (Mulgarrie) alluvial clays and sands in palaeochannels had a surface expression. At Zuleika, anomalously high and statistically significant Au concentrations occur in the top metre of the alluvial soils over mineralization at 20 m depth in the palaeochannel (mean 28 ppb), compared to background samples to the west (13 ppb). However, the proximity of the palaeochannel to outcropping mineralization on a low hill to the west, where the mean Au content of residual soil is 140 ppb (maximum 1670 ppb Au, see above), suggests the possibility of downslope contamination. Gold is generally associated with the carbonates in the alluvial soils, but less strongly than in the residual soils; with some probably contained in detrital Fe oxide lag and as free Au grains. Similarly, at Mulgarrie, the proximity of the palaeochannel to outcropping mineralization at the Palm deposit and nearby colluvial soils (see above) suggests that the minor Au anomaly in the alluvial soils (maximum 55 ppb) is due to contamination from upslope. Thus, in neither case can it be shown that buried mineralization at these sites has a surface geochemical expression attributable to it. Nevertheless, evidence from exploration west of Panglo (Baseline) suggests that an anomaly detected by a shallow auger survey targeting calcareous soil horizons directly overlies mineralization occurring in saprolite beneath 20 m of barren sediments. Soils over the Baseline deposit contain approximately 50-250 ppb Au, with the higher values reported to occur directly over the strongest mineralization (Dr. I.G. Robertson, Pancontinental Mining Ltd., personal communication, 1992).

2.2.2 Mechanism of gold carbonate association

Dolomite and calcite form in the soil by the interaction of Ca^{2+} , Mg^{2+} , bicarbonate (HCO_3^-) and water. Calcium and Mg are derived directly or indirectly from bedrock, groundwater, vegetation, dust or rainfall and HCO_3^- from CO_2 gas produced by root and microbial respiration. Carbon dioxide dissolves readily in water and dissociates to HCO_3^- which, in turn, reacts with free Ca^{2+} and Mg^{2+} in soil waters and will precipitate calcite and dolomite when saturation is reached, probably due to water being removed by evapotranspiration. The reason for the dominant occurrence of pedogenic carbonates south of the Menzies Line is unclear, but is probably related to a number of interrelated regional differences, such as mainly winter rainfall, greater biomass (with abundant eucalypts), longer growing season and greater production of soil CO_2 .

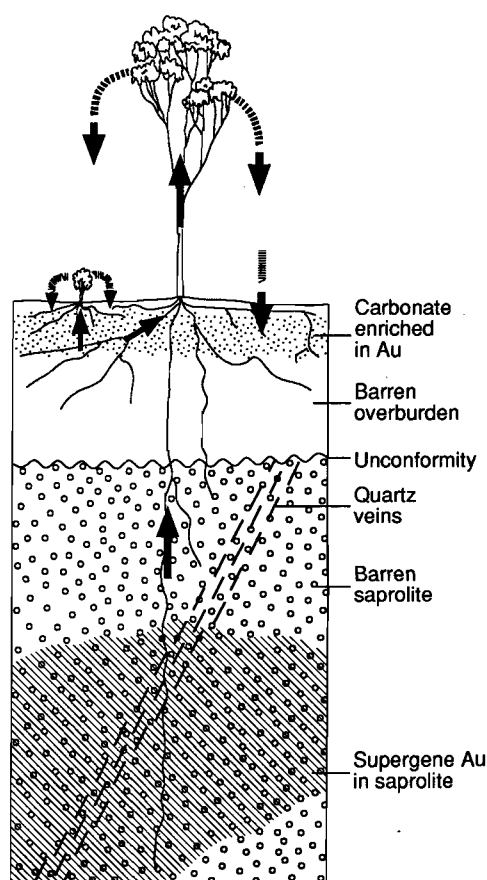


Figure 2.1: Possible pathways for surface enrichment of Au through leached and barren overburden by cycling via deep-rooted trees.

The Au distribution within soil profiles closely follows that of Ca, so it is reasonable to assume that it is controlled by a similar process, *i.e.*, dissolved Au is precipitated by the removal of water from the soil. Adsorption of Au on carbonate surfaces from migrating soil water is improbable at the prevailing high pH, and would also result in a Au-enriched zone at the top or base of the carbonate horizon, which is not observed. Furthermore, laboratory experiments (Reports 126R and 391R) have shown that the Au in soil, particularly that associated with the carbonate, is very soluble. Both Au and Ca are present in plants and this suggests the involvement of vegetation in the mobility and dispersion of these elements. It is postulated that both elements are taken up via roots, enter the plant tissue, ultimately to be returned to the soil surface

as litter and released by decay. Gold is probably mobilized in soil solution as an organic complex and Ca as a bicarbonate complex. They have concentration maxima at the same depth in the soil because each responds similarly to the dominant physico-chemical processes, namely the percolation of water (capillarity and gravity), evapotranspiration and evaporitic precipitation. Roots grow in zones that maximize their water uptake; they will also respire the greatest amount of CO₂ in the same zones. Averaged over many years, this will correspond to the zone of greatest carbonate concentration. Such a mechanism can explain the anomalies in the soils developed on transported overburden, with Au in underlying buried mineralization brought to the surface via deep-rooted trees (Figure 2.1); however, at Zuleika and Mulgarrie, it is possible that plants may merely be involved in surface cycling of Au derived from residual areas upslope.

2.2.3 *Implications for exploration*

The results from these investigations again strongly suggest that Au is associated with pedogenic carbonate and that the carbonate horizon should therefore be identified and preferentially sampled during exploration. Gold may be almost exclusively associated with carbonate in soils developed on highly leached and/or transported substrates although, where laterite is preserved, there may also be a pre-existing association between Au and Fe oxides. The nature of the regolith material and the geomorphic situation in which the carbonate is developed should, therefore, be noted and, if necessary, the data from different regolith-landform situations considered separately. The depth and thickness of the carbonate horizon may vary, but it is generally within the top 1 to 2 m of the soil and may readily be identified using dilute HCl. The most cost-effective sampling procedure is power auger drilling and compositing the cuttings through the carbonate-rich horizon. Anomalies are, however, restricted in lateral extent, so that close cross-strike sampling intervals should be used. Surficial soil sampling or drilling and routinely sampling at a specified depth may be inappropriate because Au anomalies may be overlooked. The results from this project do not unequivocally support the suggestion that mineralization within or beneath barren and/or leached sediments and saprolite over 20 m thick have a surface expression in calcareous soils. However, previous results from Panglo (Report 129R), and data from sponsor companies that have used this procedure demonstrate such a superjacent anomaly may be present and the results from the project are not inconsistent with such a mechanism.

2.3 GOLD DISTRIBUTION IN HARDPAN

2.3.1 *Introduction*

Red brown hardpans are widespread north of the Menzies Line in the Yilgarn Block, extending to the Pilbara and east to the centre of the continent. The hardpan is essentially a near-surface horizon of secondary silicification, usually in the top 1 to 5 m, that may develop in a wide range of precursor substrates, including colluvial or alluvial sediments, lateritic gravels and saprolite. The silica is typically opaline (as hyalite) and cementation is incomplete, that is, it does not completely infill voids, so that the material remains highly porous. Hardpan typically has a sub-horizontal laminar to pseudo-bedded fabric, with Mn oxides prominent as coatings (mangans) on fracture and lamination surfaces, and diffused into the substrate. Hardpans and their overlying soils are commonly reported as having Au contents an order of magnitude less than equivalent calcareous soils in the southern Yilgarn, even in the immediate vicinity of mineralization, with any anomalies being very restricted in extent. Detailed studies were carried out on five profiles at the Granny Smith deposit, south of Laverton (Report 385R), in order to investigate the distributions of Au and other elements in hardpan profiles and to determine whether any horizon or component has potential as a specific sample medium.

2.3.2 *Geochemistry and mineralogy of hardpan at Granny Smith*

The vertical distribution of Au in the near-surface at Granny Smith appears to be related primarily to the contact between transported and residual components of the hardpan (Figure 2.2) and is coincident with a trend towards increasingly alkaline conditions at depth. The latter is related to the appearance of secondary carbonates in the profile, usually between 4 and 10 m, but there is no apparent association with between the distributions of total Au and Ca or Mg. (South of the Menzies Line, there is no apparent relationship

between Au and a change in pH, but the distribution of Au is strongly associated with Ca and Mg). Maximum Au contents are in the range 80-190 ppb; segregations of the hardpan material from the enriched zones indicates that, although much of the Au is associated with the matrix, some is present in lithorelics. There do not appear to be any *general* mineralogical, geochemical or textural associations between Au and other components, although specific associations can be present in individual samples and profiles. Laboratory experiments show that some Au is associated with specific extractable phases within the soil such as Mn oxides, organic material and soluble silica but, compared with Au that can be leached with water or iodide, they do not represent a highly significant fraction. Gold is at least as soluble in water and iodide as in some soils south of the Menzies Line, particularly in the calcareous zone, but, in general, mobility in the surficial environment appears to be severely restricted due to encapsulation by the silica cementing the hardpan. Re-adsorption of dissolved Au by hardpan is possible, but is weaker than that occurring in ferruginous soils from Mt. Hope.

Arsenic, W, Mo and, perhaps, Sb are associated with primary mineralization, but only As is retained at detectable concentrations in the upper regolith. Barium, Cu and Zn are weakly enriched in bedrock and are retained in the upper saprolite; however, Ba may also indicate the presence of felsic rocks, such as granodiorite, rather than mineralization. The generally low abundances of Bi, Cd, In, Pb, Se and Ag in primary mineralization eliminate them as potential pathfinder elements.

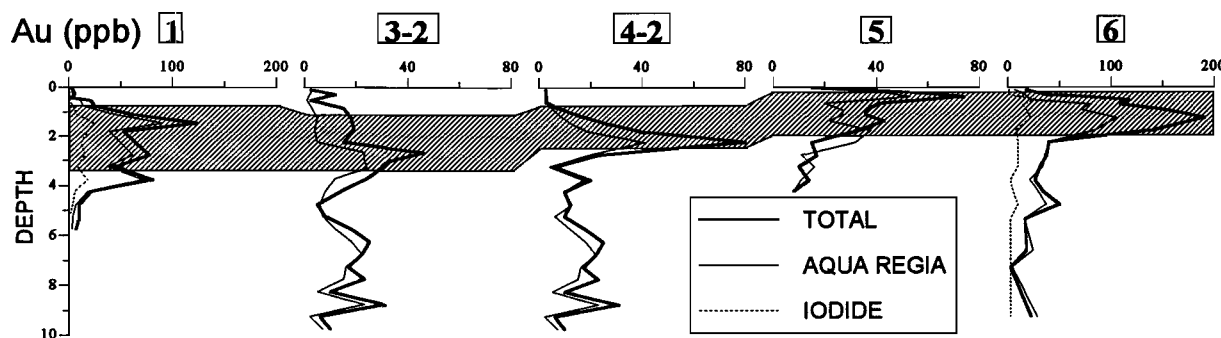


Figure 2.2: Gold distribution through hardpan, Granny Smith. Shading illustrates approximate position of hardpan.

2.3.3 Implications for exploration

The data from Granny Smith, and the limited results from the earlier study at Youanmi (Report 23R), show that appreciable amounts of Au can be present in hardpans, at concentrations similar to those in calcareous soils in the south. Nevertheless, the soils overlying these hardpans have very low Au contents. The partial and selective extraction results, in particular the high solubility in water (nearly 40% of the Au in some calcareous saprolite), demonstrate that Au in the hardpan is chemically active under present environmental conditions. The results suggest, therefore, that sampling of hardpan at the contact between transported and residual components may have some general application, although identification of this zone in drill spoil can be difficult. Such sampling would seem to target a possible zone of enrichment and be preferable over sampling soils, which have much lower Au abundances and a higher transported component, and sampling shallow saprolite, which is most probably highly leached.

These findings cannot be extrapolated uncritically to all sites where hardpan is present. Only five profiles were examined at Granny Smith, each being close to the subcrop of mineralization, with the hardpan being developed, at least partially, in residual material. Different characteristics may be exhibited where the hardpan is developed entirely within transported overburden, which itself may be 5-10 m or more thick and overlie leached saprolite. The high Au solubility suggests active mobilization and dispersion, but it is not known whether this is simply within the hardpan itself, for example release of Au from lithorelics and

reprecipitation in the hardpan matrix and underlying calcareous saprolite, or whether it represents, at least in part, upward dispersion from mineralization deep in the saprolite, in a manner analogous to that proposed for enrichments in carbonates. If the latter is true, then there is potential for developing selective sampling and/or analytical procedures.

The significance of the deep calcareous horizon below the hardpan is uncertain. Similar carbonate zones have been observed elsewhere, but they are not ubiquitous. Although soluble Au is associated with this material, the source of the Au and, in particular, its relationship with underlying mineralization, are unknown. Shallower pedogenic carbonates of the type common in the southern Yilgarn are not present at Granny Smith, but occur sporadically throughout the area where hardpan is the dominant surficial cemented horizon. The differences in characteristic and origin of these two carbonate types, other than their depth of occurrence, has not been established. However, the shallower "true" pedogenic carbonates do become enriched in Au, hence where they are present in hardpan regions and sampled during a soil or hardpan survey, care must be exercised in treating the data separately, since higher threshold limits will apply.

2.4 SOIL GEOCHEMISTRY NORTH AND SOUTH OF THE MENZIES LINE: COMPARISON OF BEASLEY CREEK AND LIGHTS OF ISRAEL

2.4.1 *Regional setting*

The Beasley Creek Au mine is 12 km WNW of Laverton. It is north of the Menzies line, in an environment having relatively fresh groundwater, soils that are mostly carbonate-poor and underlain by hardpan, and with vegetation dominated by acacia. The site occupied a low hill, flanked by wash plains, situated between broad drainage floors. The regolith has been partly stripped and lateritic duricrust was present only over the eastern flank of the hill, closely following the upper surface of the host rock. There are sporadic outcrops of ironstone and calcrete near the top of the hill, where the soil is thin and alkaline.

The Lights of Israel Au mine is 2 km NE of Davyhurst, south of the Menzies line, in an area of saline groundwater, calcareous soils and eucalypt-dominated vegetation. Erosion at the Lights of Israel site has been more severe than at Beasley Creek and the presumed pre-existing lateritic profile has been truncated to the saprolite. The soil is largely residual and has a calcareous upper horizon underlain by a discontinuous gypsiferous layer, and by carbonate-free, red-brown clays and saprolite.

Mineralization at Beasley Creek is enclosed in a presumed sulphidic black shale, very rich in pathfinder elements. Saprolites of Permian sediments overlap mafic and ultramafic saprolites in the eastern margin of the pit. The mineralized zone at Lights of Israel is a plagioclase-biotite-amphibole schist, poor in sulphides (1-3%; pyrite and trace chalcopyrite) and having low abundances of pathfinder elements. The wall-rocks at both sites are mafic amphibolites, intruded by felsic dykes, and the weathering front is at about 40-50 m depth. However, the depth of oxidation of the Au-rich sulphidic shale at Beasley Creek exceeds 200 m. Despite the great depth of weathering of the primary mineralization, the regolith at Beasley Creek is far richer in pathfinder elements than that at Lights of Israel. Background abundances of the pathfinder elements (except for Sb) in fresh rock and saprolite are similar, but the As and Sb anomalies are much stronger (1-2.5 orders of magnitude) at Beasley Creek (Figure 2.3). Zinc and Cu, which are depleted in the near surface, are slightly anomalous (<1 order of magnitude) at Lights of Israel.

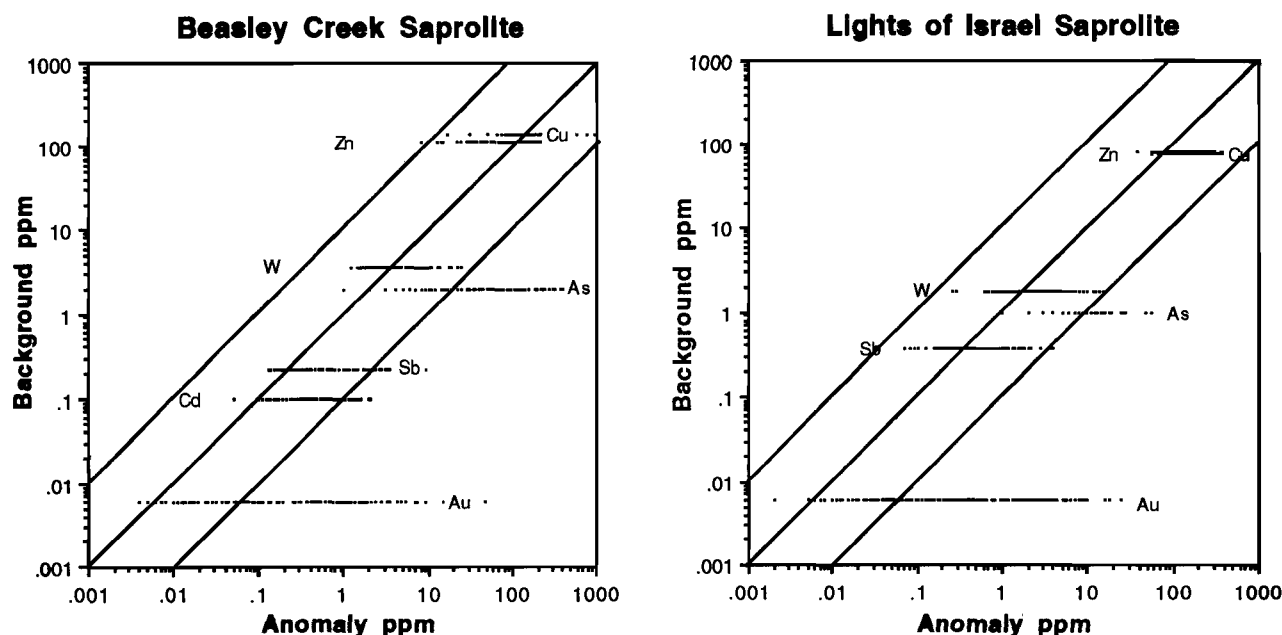


Figure 2.3. Comparison of abundances of Au and potential pathfinder elements in saprolite from background sites and mineralization at Beasley Creek and Lights of Israel. Elements with similar abundances plot on the diagonal; lines parallel to diagonal represent $\times 10$ enrichment (right) or depletion (left).

2.4.2 Size fractions and mineralogy of soils

The soils at each site were sieved to three contrasting fractions. At Beasley Creek, these are:

1. Coarse ($>710 \mu\text{m}$): dense, black, goethitic saprolite-derived granules, some of which are magnetic; red to yellow, less dense ferruginous, duricrust-derived clay granules and relatively rare, non-magnetic gossan fragments. The goethitic granules contain pseudomorphs after micaceous and kaolinitic lithorelics, set in a variety of massive, spongy, vesicular and colloform secondary goethite.
2. Sandy-silty fraction ($75\text{--}710 \mu\text{m}$): hematite-coated wind-blown quartz sand, with minor grains of feldspar. This is a dynamic, largely wind-blown fraction that dilutes the soil.
3. Fine fraction ($<75 \mu\text{m}$): quartz and small, locally-derived kaolinite and Fe oxide particles (mostly $<4 \mu\text{m}$).

Erosion by deflation and sheetwash has left a discontinuous desert armour of lag similar to the coarse soil fraction that also includes minor calcrete fragments and unevenly distributed coarse ($>15 \text{ mm}$), black, ferruginous fragments. Bedrock lithology can, in places, be identified by pseudomorphed and relict fabrics preserved in goethite and hematite that represent saprolites of mafic and ultramafic rocks, phyllites and Permian glacial sediments. Gossan fragments in the lag probably contain most of the geochemical signal.

The mineralogy of equivalent fractions at Lights of Israel is more complex:

1. Coarse fraction ($>600 \mu\text{m}$): dense, black, goethite- and hematite-rich nodules, some of which are magnetic, slightly less dense, red to yellow, ferruginous clay granules, quartz fragments and scarce, fresh, crystals of tourmaline and, near mineralization, gossan fragments. The Fe-rich fragments have lithorelics, containing microscopic relicts of smectites and kaolinite set in, and largely

replaced by, massive, spongy, vesicular or colloform goethite. The minor gossan fragments show pyrite pseudomorphs. The clay-rich granules consist largely of hematite- or goethite-stained kaolinite and some include goethite-rich lithorelics. Some upper soil horizons are rich in carbonates and contain crystals of pedogenic gypsum and halite.

2. Intermediate fraction (75-600 μm): sand and silt of bright, clear, angular, drusy quartz, with minor grains of feldspar, small ferruginous granules and fine pedogenic calcite. This is largely of local derivation, with very little aeolian input, although the aeolian content increases slightly in its finer parts.
3. Fine fraction (<75 μm): quartz grains and smaller kaolinite and Fe oxide particles (<4 μm), with minor sericite in the <4 μm fraction. Pedogenic calcite occurs as very fine-grained particles.

Tourmaline in the coarse and intermediate fractions has a composition indistinguishable from that in veinlets in the saprolite in the mine, suggesting that the soil at Lights of Israel is largely residual. As at Beasley Creek, the coarse and fine surface lag is identical to ferruginous material found within the soil and has accumulated on the surface due to loss of the fine fractions of the upper horizons by deflation and sheetwash. There is a much greater aeolian component in the silty fraction at Beasley Creek. At both sites, bioturbation and illuviation have mixed the aeolian material with the residual substrate.

2.4.3 Soil geochemistry

The lag, the complete soil and its coarse (>600 μm), intermediate (<75 μm) and fine (<4 μm) fractions were separately assessed. The quartz-rich 75-710 μm fraction was discarded. The lag was split into a coarse (>15 mm) and a fine component (<4 mm). The fine lag was further split into magnetic (maghemite-rich) and non-magnetic sub-components.

Gold: Gold is one of the best indicators of Au mineralization in lag and soil at both sites. At Beasley Creek, Au is slightly enriched (50-250 ppb) in the ferruginous, coarse fraction, relative to the complete soil (30-150 ppb), due to dilution of the latter by the sandy fraction (Figure 2.4). Enrichment in the coarse lag is locally much greater (13 ppm) but is very erratic. In contrast, at Lights of Israel, Au is largely associated with soil carbonates, here present particularly in the <75 and <4 μm fractions, with the soil anomaly reaching 230-750 ppb Au. Gold anomalies at Lights of Israel are small and lack an extensive dispersion halo. Anomalies in lag (80-72 ppb) are narrow (75 m) and erratic, particularly in the coarse materials, and not well-defined. In soil, the anomaly is about 125 m wide, little greater than the projection (40-60 m) of the relatively shallow-dipping primary and secondary mineralization that it directly overlies. At Beasley Creek, anomalies are broader (800 m), in part due to chemical dispersion of Au in the soil parent material, particularly the lateritic duricrust.

Pathfinder elements: Abundances of pathfinder elements in the soils and their size fractions are compared in Figure 2.5, relative to local backgrounds established from samples collected up to 800 m from the subcrop of mineralization. The multi-element signature is weak and subtle in all sampling media at Lights of Israel and is likely to be overlooked by exploration unless there is very careful control of the analytical process and geochemical background is properly established. Although some pathfinder elements (As, Sb, Cu and Cd) did not give a recognizable peak in the traverse, their general abundance is above the regional background. The only distinctive anomaly is given by Au, shown by the lag and, particularly, by the fine soil fractions. This contrasts with Beasley Creek, where there is a strong multi-element signature, particularly in the coarse, ferruginous sampling media. This difference in multi-element signature in lag is related to the higher primary abundances, and to the lesser degree of erosion. Only Au is enriched in the carbonate-rich fraction.

Because of its residual nature, lag is a convenient means of sampling the coarse, generally highly ferruginous soil fraction. Dispersion of the finer lag, by sheetwash, is generally greater than that of the residual soils and gives a larger target. The less-widely dispersed coarse lag (>15 mm) may have some advantages for follow-up, although the time-consuming collection and preparation required to obtain a sample large enough (several kg, to avoid erratic results) may outweigh its advantages. Comparison of the magnetic and the non-magnetic fine components of lag at both sites showed that the non-magnetic material,

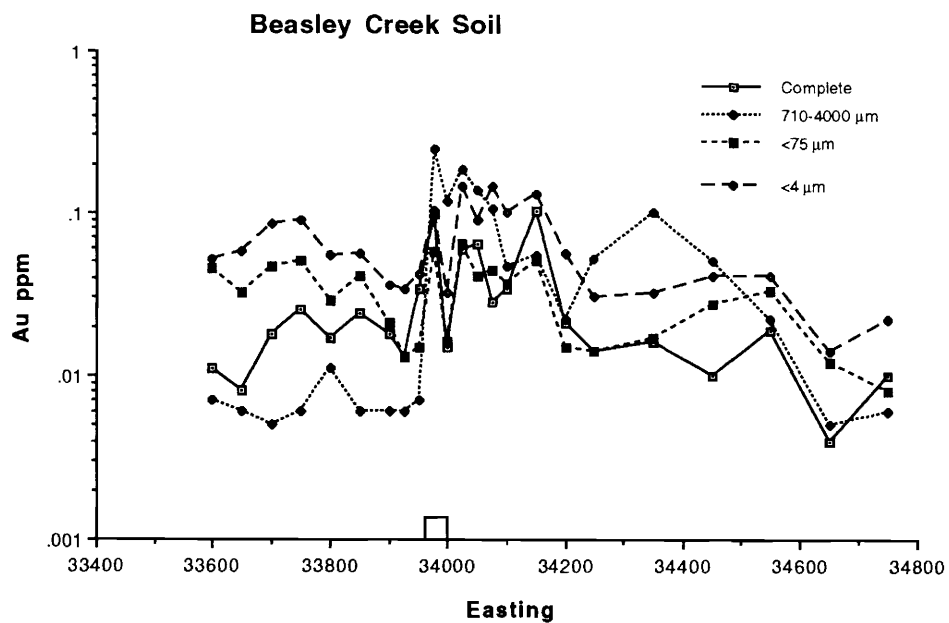
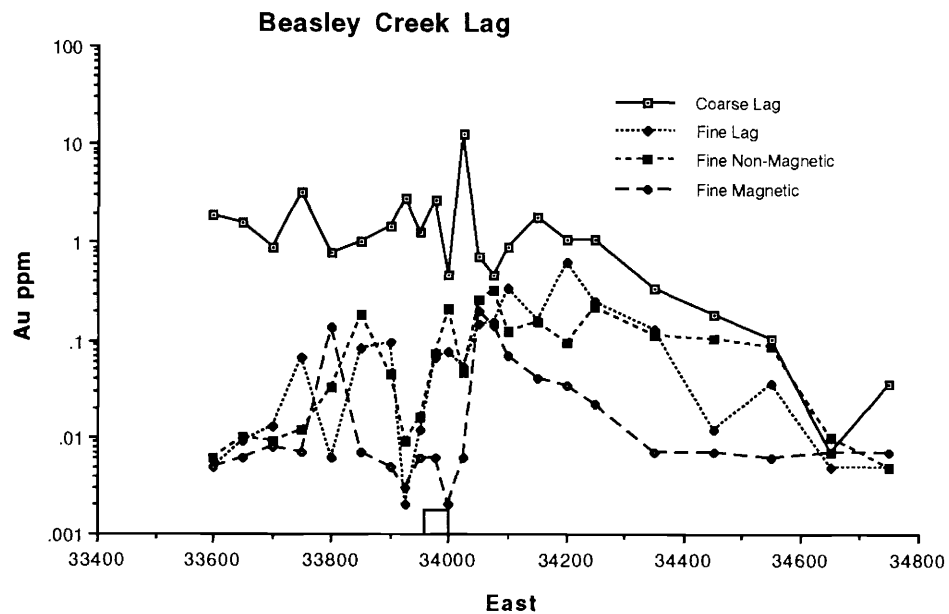
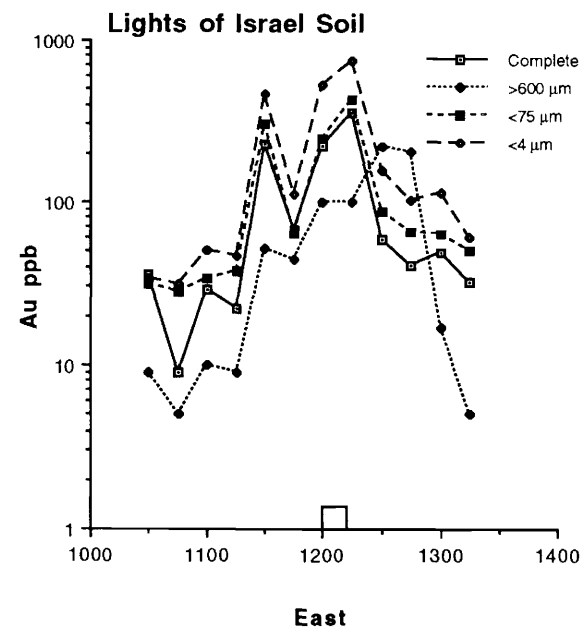
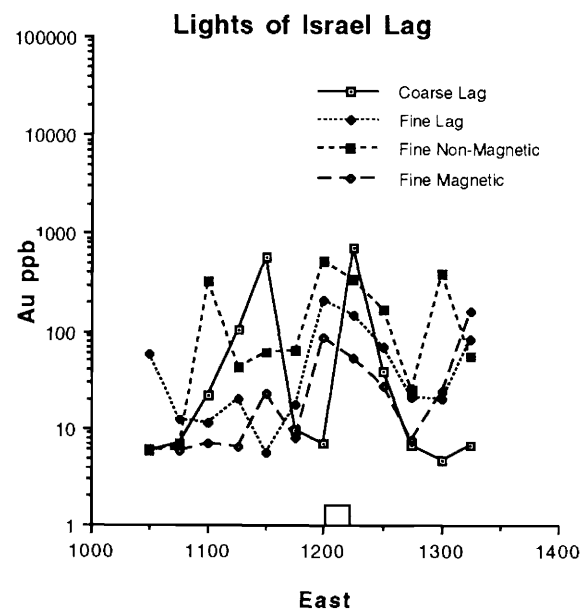


Figure 2.4. Traverses across mineralization at Beasley Creek and Lights of Israel, illustrating the distribution of gold in different soil fractions and lag.

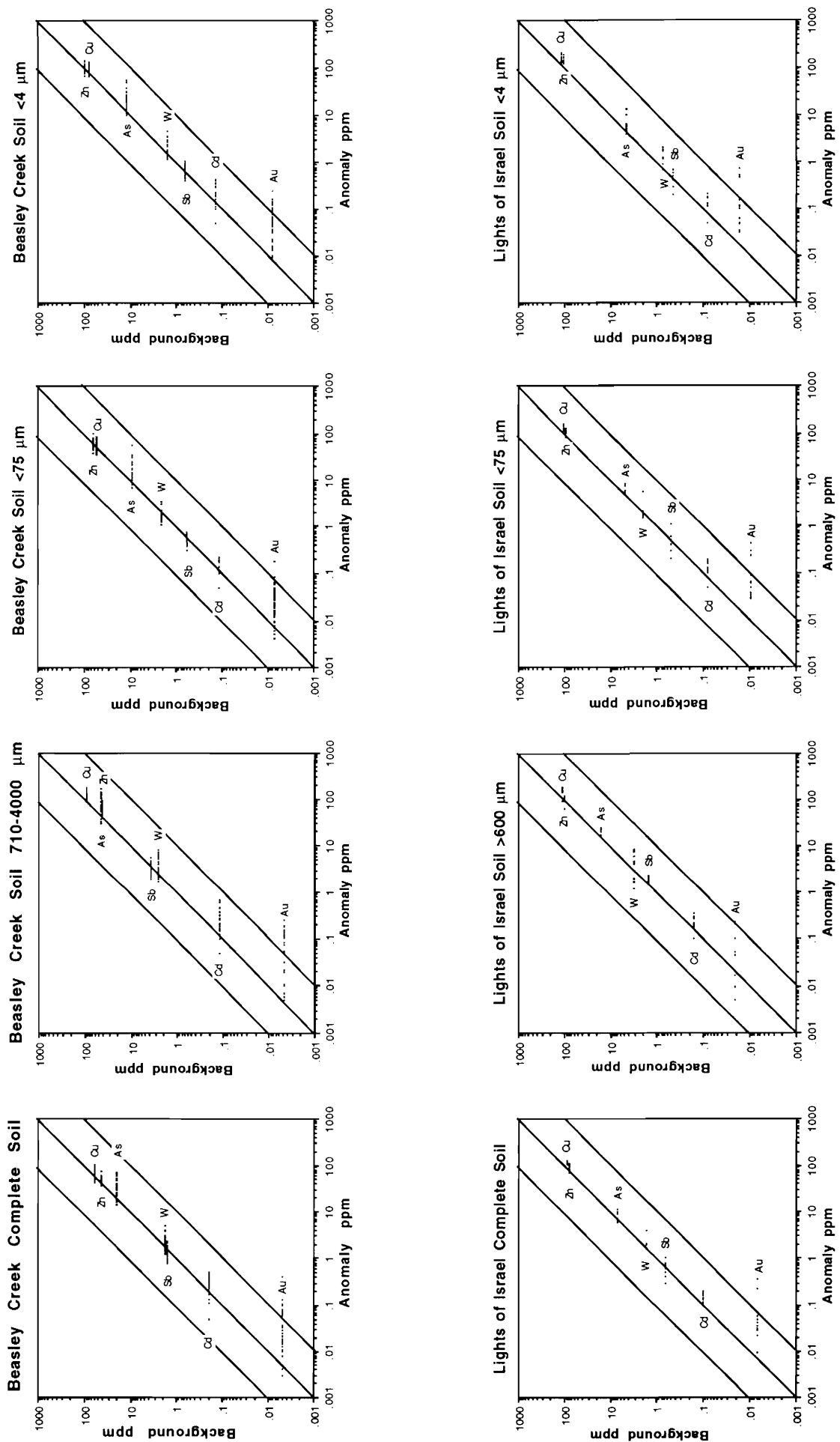


Figure 2.5. Comparison of abundances of Au and potential pathfinder elements in soil from background sites and mineralization at Beasley Creek and Lights of Israel. Elements with similar abundances plot on the diagonal; lines parallel to diagonal represent $\times 10$ enrichment (right) or depletion (left).

which contains the gossan fragments, displayed better pathfinder element anomaly contrasts although not necessarily enhanced abundances. Although magnetic samples provide a consistent, Fe-rich matrix, selective use of this material is not recommended. Conversely, its removal presents no significant exploration advantage either, as the proportion of magnetic material is relatively low (10-35%).

Sulphur: There are S anomalies in the soil over mineralization at both sites. At Lights of Israel, there is a layer of gypsum in the soil and at Beasley Creek, coarse gypsum occurs in the upper saprolite and minor barite is enclosed in the lag. Gypsum is generally common and widespread in the landscape and it is probable that the anomalies are coincidental. Nevertheless, at Lights of Israel, the isotopic composition of S is slightly heavier (1.2 per mil) than that expected if the S were derived from meteoric sources alone, thus there could be some bedrock S component - although the mineralization is sulphide-poor. At Beasley Creek, which is more sulphide-rich but more deeply weathered, the S isotopic composition is typically meteoric (15.2 ± 0.47 per mil) for that location (A.S. Andrew, written communication, 1992).

Ti-Zr ratio and origin of soil fractions: The coarse (Fe-rich) soil fractions from both sites have similar and relatively constant Ti/Zr ratios, reflecting an homogeneous material of mafic origin (Figure 2.6); similar linear trends, with lower Ti/Zr ratios, are apparent in the $<4 \mu\text{m}$ fractions. The silty ($<75 \mu\text{m}$) soil fractions at each site have contrasting Ti-Zr geochemistry; the wide scatter, with a generally low Ti/Zr ratio, at Beasley Creek reflects considerable input from transported zircon-rich granitic material whereas the slight scatter at Lights of Israel, superimposed on a trend more related to the coarse soil fraction, indicates little input from transported material, despite close proximity to the granite.

2.4.4 Implications for exploration

The results of these two detailed studies confirm the important regional difference in the occurrence of Au in soils, which has significant implications for Au exploration. North of the Menzies Line, Au is associated dominantly with the ferruginous, usually coarse, components in the soil, including lag, whereas, to the south, it is associated with pedogenic carbonates, which may either be dominantly in the fine fraction (as at Lights of Israel, Mt. Hope) or in all fractions, including very coarse nodules (e.g. Mulline, Mt. Percy). Of the ore-associated elements, only Au is enriched with the carbonates and, indeed, carbonate is a diluent for other elements. Despite the close associations of Au with the ferruginous and carbonate fractions, marked variations in background abundances, thresholds and anomaly dimensions can be anticipated in different parts of the landscape. Regolith-landform mapping, therefore, integrated with orientation studies or appropriate published case studies, should be used to design soil surveys and to control data interpretation.

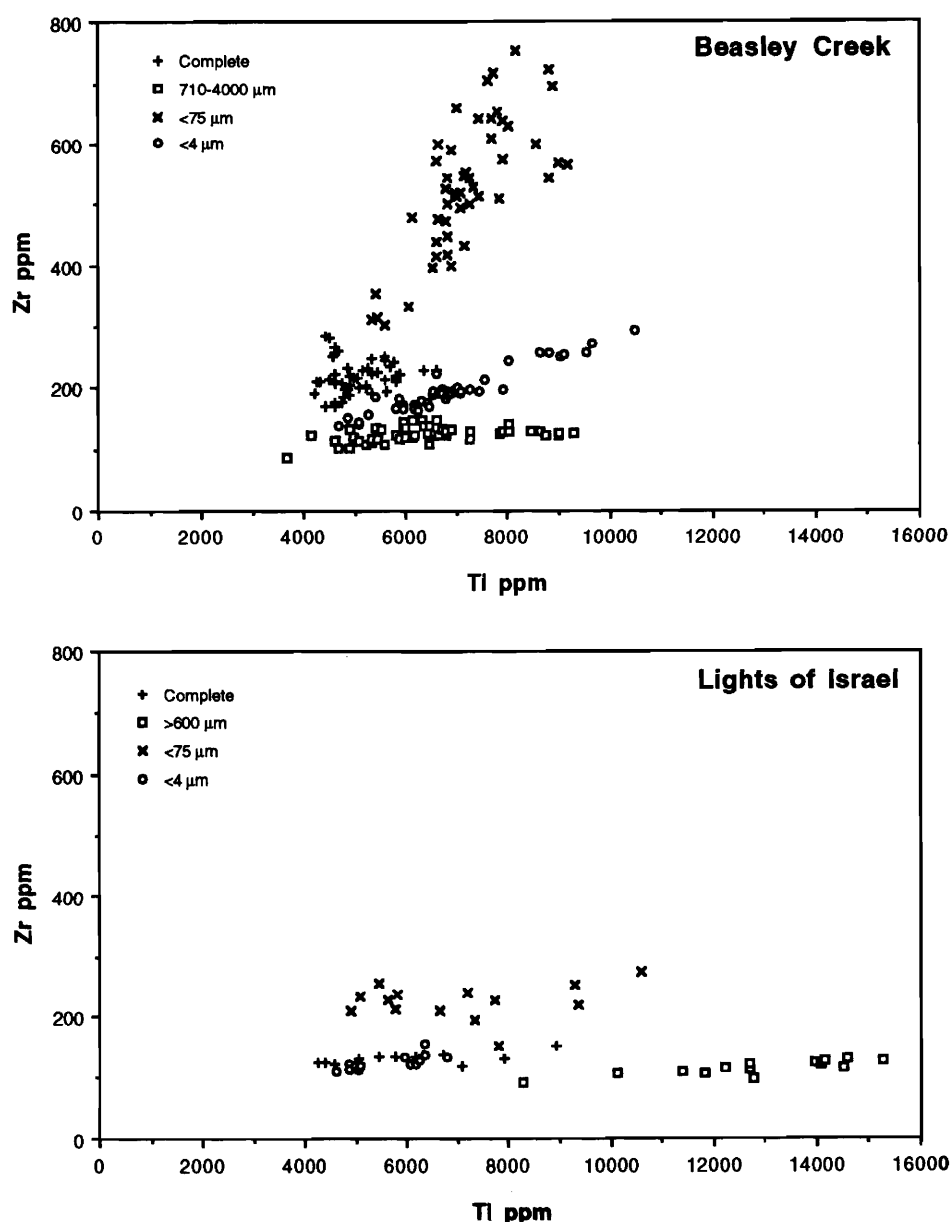


Figure 2.6: Binary plot illustrating differences in the Ti-Zr ratio in various soil fractions at **Beasley Creek** and **Lights of Israel**.

2.5 BIOGEOCHEMISTRY OF GOLD

2.5.1 Introduction

Biogeochemical studies have been of only secondary interest in the Project, but they are, nevertheless, of importance because vegetation is strongly implicated in the geochemical cycles of both Au and Ca, and vegetation sampling has some potential as an exploration technique.

Vegetation contributes significantly to soil formation and composition, and this role has been assessed during the Projects. The importance of plants in Au, Ca and Mg geochemistry with regards to soils is addressed in Section 2.2.2. The concentration of Au in vegetation reflects, to a great extent, (a) the availability of Au in the vicinity of the root system and (b) the ability of the plant to absorb, transport and

accumulate Au. The location of the root system of plants in semi-arid areas largely reflects the availability of water *i.e.*, rainfall, soil structure and drainage. Many plant species have adapted to dry conditions (*e.g.*, saltbush) with some of their roots very close to the surface to absorb minor rainfall before it evaporates. Other plants, such as *Eremophila* spp., have deeper penetrating root systems within the top metre. *Eucalyptus* spp., can have, in addition to a near-surface root system, a long tap root (a few tens of metres in length) capable of absorbing nutrients and water from deep in the profile. Shallow-rooted plants probably cycle Au and other elements already present in the soil, whereas deeper rooted plants, such as *Eucalyptus* and *Acacia* spp., can access components from greater depths. All will ultimately contribute this to the soil via the decay of plant material. Initial decay occurs at the surface, to form mull, which may contain concentrations of elements greater than that of the original plant, due to preferential leaching of mobile constituents.

The involvement of vegetation in the geochemical cycle of Au suggests its possible use as an exploration sample medium. The major perceived advantage that vegetation sampling has over soil sampling is that plants, particularly wide- and deep-rooted trees, have the potential to sample wider areas and, in particular, from greater depth, hence penetrating through transported overburden. Conversely, plants are ephemeral, whereas soils represent the combined accumulations of numerous plants (individuals and species), over a very long period.

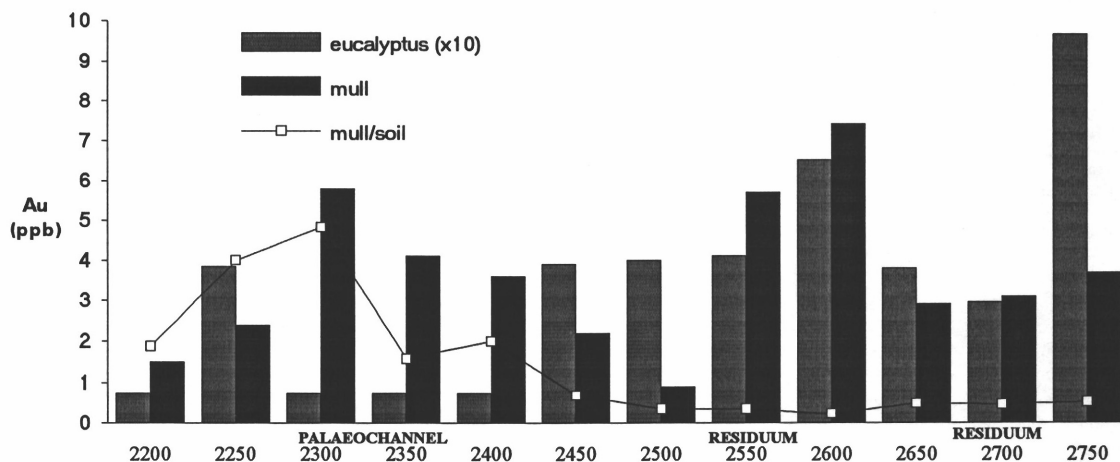
To be most effective, both media have to be sampled carefully, targeting specific components. It is essential to choose specific plant genera and, preferably, species, and to sample particular organs; similarly, it is desirable and, in some situations, essential, to sample specific soil horizons and to evaluate data in terms of the genesis of the soil, as indicated by regolith-landform relationships. This consistency is more achievable for soil sampling (and related surficial techniques), and it has delineated some concealed deposits. Available plant species can vary considerably, even within a few tens of metres, and plant species can be difficult to recognize. Thus, although biogeochemistry has not been widely used in exploration, limited testing has been conducted in a variety of environments. Earlier biogeochemical studies were conducted at Bounty and Panglo (Reports 24R and 129R). For Project P241A, a study was conducted at Zuleika (Report 328R) specifically to determine whether plant and mull sampling was better than soil sampling for detecting a Au deposit buried beneath barren transported sediments. A concentration technique was used to enhance detection limits and remove interferences from Na with INAA.

2.5.2 Biogeochemistry of Au at Zuleika

Samples of vegetation (leaves, small branches of eucalypts, and bluebush) and mull (decaying organic material on the ground, principally derived from eucalypts) were collected from two traverses; bluebush was collected from one traverse only. The traverses crossed two geomorphological units - residuum and floodplain. Although Au mineralization subcrops in the residuum, the principal exploration targets are Au deposits in palaeochannel sediments beneath the floodplain.

Strong Au anomalies occur in the soil and vegetation of the residuum, with the highest Au contents in mull and eucalyptus (19.2 and 1.2 ppb, respectively; Figure 2.7). The maximum Au content of bluebush (7.9 ppb) is located directly over the palaeochannel mineralization but other chemical evidence suggests this may be due to soil contamination. Lesser concentrations occur in vegetation over the floodplain and the buried mineralization but, although this essentially duplicates the soil geochemistry on the same traverses, the contrast is very much lower. On section 4490N (Figure 2.7), the mull shows a subsidiary peak over the palaeochannel mineralization and, on both traverses, the ratio $Au_{\text{mull}}/Au_{\text{soil}}$ (using soil from the top metre) is highest on the floodplain. This suggests that Au here is either (i) generally more chemically labile and/or (ii) more concentrated near the root zone. However, the data do not suggest that plant or mull sampling indicate the buried mineralization. This is similar to the conclusion from soil sampling.

4490



4705

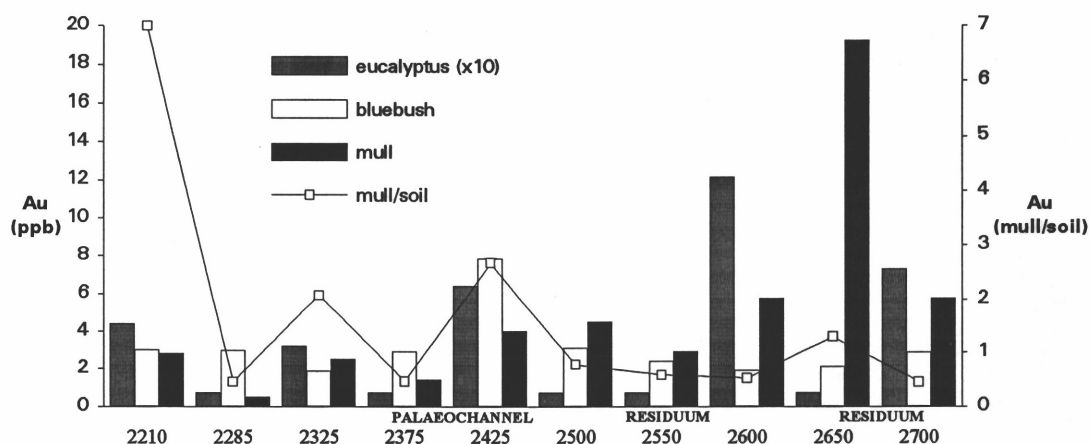


Figure 2.7: Gold in vegetation for 4705N and 4490N at Zuleika. Mull/soil ratios from the top metre of soil.

2.5.3 Discussion and conclusion

Maximum Au concentrations at Zuleika were lower than those found at Bounty (mull 71.2 ppb, eucalyptus 5.9 ppb) but similar to those at Panglo (eucalyptus ~2 ppb, saltbush ~3 ppb) and reflect the strength of, and proximity to, mineralization at each deposit. At Norseman (Smith and Keele, 1984), where only *Melaleuca* spp. were sampled, anomalous Au concentrations² were 5 - 7.5 ppb with a peak of 11.5 ppb and a background of <3 ppb. As at Bounty, Au contents of mull are considerably greater than those found in eucalyptus, suggesting there has been some retention of Au during decay.

As concluded in the earlier Project, biogeochemistry cannot be used alone as an exploration tool because it does not express mineralization in all cases. It tends to reflect the Au concentration of underlying soils, although at Zuleika, the contrasts between residual and floodplain environments are much lower in vegetation than in soil. Mull may be the best biogeochemical medium, because, (i) it has greater Au

² corrected to dry weight from ash weight by dividing by 20 (see Report 24R).

abundances and integrates Au from a larger mass of vegetation than that of an individual plant or organ and (ii) the ratio Au_{mul}/Au_{soil} may indicate buried mineralization. Difficulties of sample preparation, specifically to remove inorganic contaminants coupled with its poor sensitivity, may preclude its use for general exploration.

3 CHEMISTRY OF GOLD IN SOILS

3.1 INTRODUCTION

Soil sampling is extensively employed in modern-day Au exploration. A major part of Projects P241 and P241A has been to examine the distribution of Au in soils, to improve soil sampling and interpretation techniques. Although much is known about the chemistry of Au, in both the laboratory and the aqueous weathering environment (Report 4R), its chemistry and mobility in soils is generally poorly understood. Soils contain organic matter, amorphous Fe oxides and fine clays that are difficult to analyse for and have very complex interactions with metals. It has been necessary to devise specific techniques to investigate the chemistry of Au in soils (Reports 126R, 127R and 391R). This is briefly summarized. Soil and regolith samples were taken from the Bounty deposit, Mt. Hope (Reports 24R and 109R), Beasley Creek (Report 105R), Panglo (Report 129R), Mt. Percy (Report 156R), Mulline (Report 159R), Lights of Israel (Report 232R), Zuleika (Report 328R), Mulgarrie (Report 339R) and Granny Smith (Report 385R). These sites provide a wide range of soils of the southern Yilgarn Block, with two sites (Granny Smith and Beasley Creek) north of the Menzies line.

3.2 EXTRACTION METHODS

The objective of the experiments was to test the capacity of the soils to dissolve or precipitate Au. This would involve the interaction of the form of the Au in the soil, potential Au complexing ligands present and changes in the soil solution characteristics over time. Two different sample preparations were used prior to extraction:

1. using material jaw crushed to < 10 mm (coarse);
2. using material pulverized to < 75 μ m (fine).

Extractions were performed with (i) deionized water and (ii) an iodide reagent (1 M sodium bicarbonate and 0.1 M potassium iodide, saturated with CO₂ and taken to pH 7.5 with hydrochloric acid). A soil:solution ratio of 1:2 was used and the soil was extracted for 24 hr, unless otherwise stated. Gold was determined on the centrifuged solution. As some of the dissolved Au could reprecipitate or adsorb on soil surfaces, the Au in the solution is referred to as "net soluble Au". Similar experiments were set up, except that reaction conditions were changed so that the total amount of Au dissolved (including any that might be reprecipitated) could be determined. This "gross soluble Au" can be compared with "net soluble Au" and differences indicate the Au scavenging capacities of the soil. The experimental procedures are described in Report 391R (Section 3.2).

3.3 KINETIC STUDIES

The kinetics of Au dissolution were investigated for specific samples (Report 391R) to better understand the processes of dissolution and, for some samples, readsorption of Au during soil extractions. Typical results for iodide extractions of carbonate-rich (04-1206) and Fe oxide-rich (04-1251) samples are shown in Figures 3.1 and 3.2. Gross soluble Au was virtually 100% of the total Au in fine material of the carbonate-rich sample after 10 days (Figure 3.1). Only 85% of the Au was soluble in equivalent coarse material, suggesting that about 15% of the Au is occluded. However, only about half of the Au is net iodide soluble in the coarse sample, indicating significant readsorption of the extracted Au. When fresh iodide reagent is added, more of the Au is dissolved, indicating a shift in the equilibrium from adsorbed to dissolved Au.

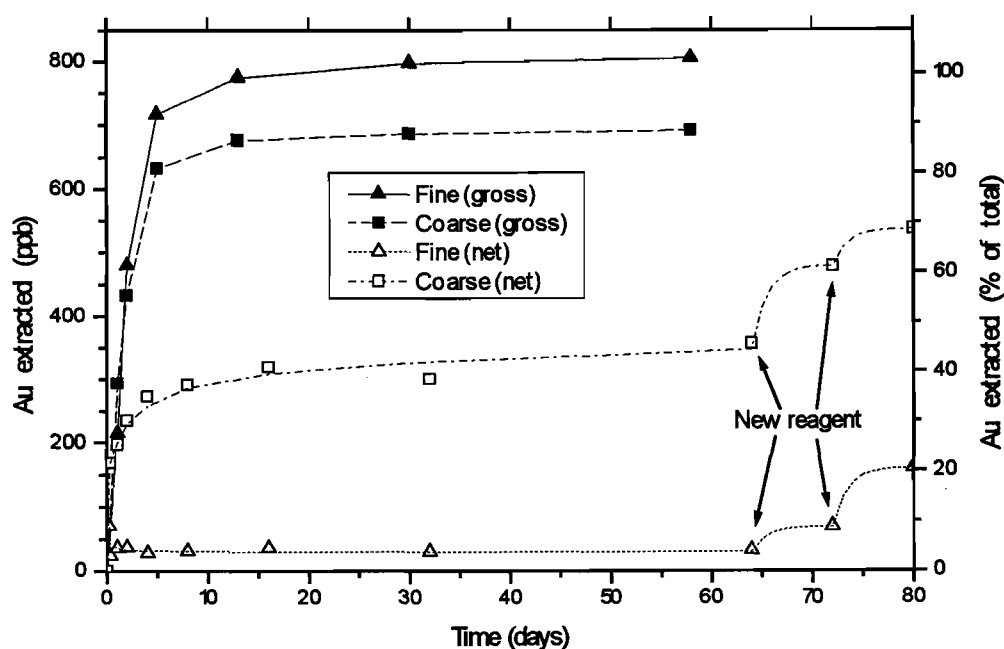


Figure 3.1: Iodide soluble Au in a carbonate-rich sample (04-1206).

Results for net iodide solubility for the fine material are particularly significant. During the first day, Au was dissolved at a similar rate to the other treatments. After the first day, net soluble Au decreased, reaching a constant low concentration of about 5% of the total Au. This compares with a gross iodide Au solubility (see above) for fine material of virtually 100%. Addition of fresh reagent increased soluble Au. This difference in behaviour between coarse and fine material is observed for other carbonate-rich material. It suggests that pulverizing exposes surfaces capable of adsorbing Au, whereas the surfaces exposed to solution in "natural" carbonate soils are poor at precipitating Au iodide. This low capacity of carbonates to adsorb Au was suggested previously (Report 126R), and indicates that the Au is potentially highly mobile.

Iron oxide dominated soils react differently. Gross iodide soluble Au of the finely pulverized Fe-rich sample reaches about 50% of total Au after 2 months (Figure 3.2), much lower than for the Ca-rich sample (Figure 3.1); gross iodide soluble Au for coarse material is similar for both samples. In contrast, net soluble Au is about 15% of gross soluble Au for the coarse material, whereas the fine material behaves similarly to fine carbonate soils. Initially, dissolution occurs at a similar rate to the other treatments, but the concentration of dissolved Au falls after one day, declining to about 1% of the total Au, indicating the high capacity of the soil minerals to adsorb Au iodide, particularly if pulverized to less than 75 μm .

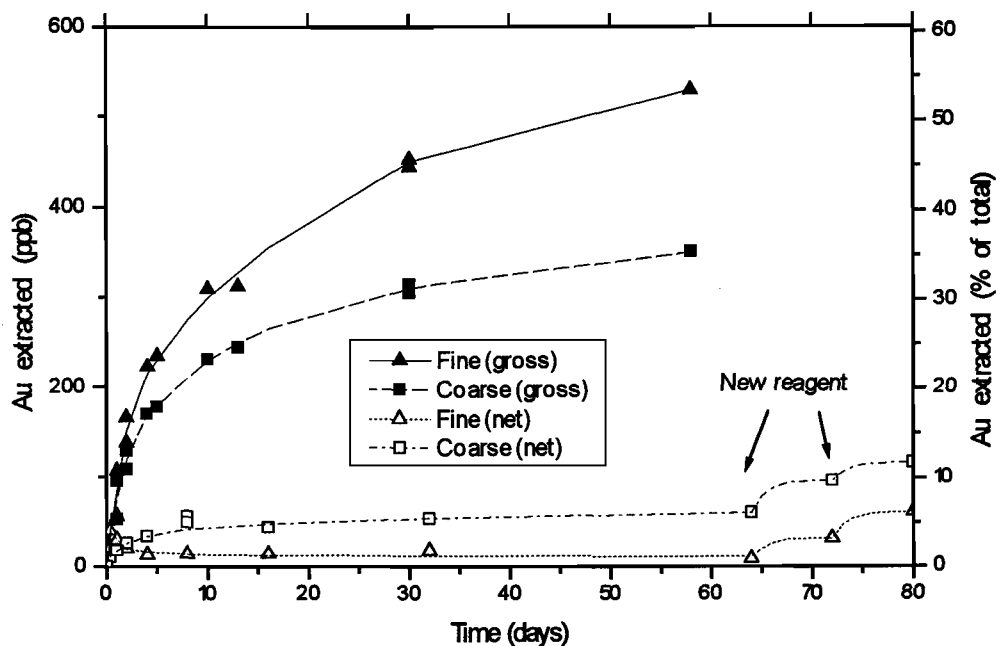


Figure 3.2: Iodide soluble Au in an Fe oxide-rich sample (04-1251).

For carbonate-rich materials, even deionized water is an effective extractant for Au; gross water soluble Au exceeds 10% for the fine material, and would be expected to be about 8% for the coarse material, over 70 days (Figure 3.3). This suggests either release of ligands able to dissolve Au and/or the presence of Au in highly soluble forms; it supports earlier results (Report 126R) that indicated a potentially high mobility of Au in natural carbonate-rich soils. This was further indicated by seepage waters in a 2 m trench in carbonate-rich soils at Panglo which contained 0.02 - 0.05 $\mu\text{g/L}$ (ppb) Au.

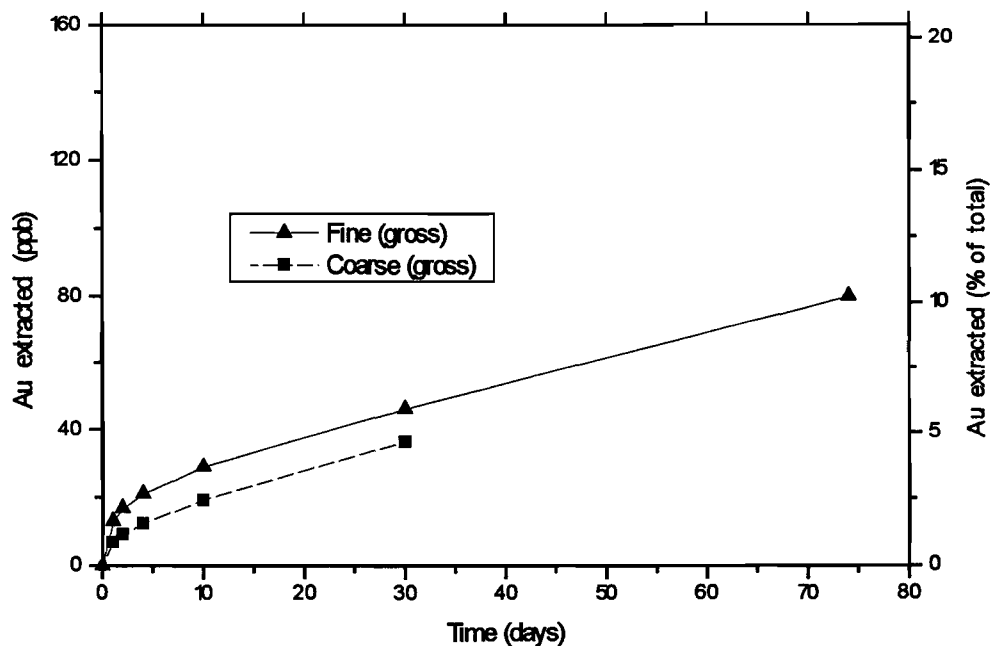


Figure 3.3: Water soluble Au in a carbonate-rich sample (04-1206).

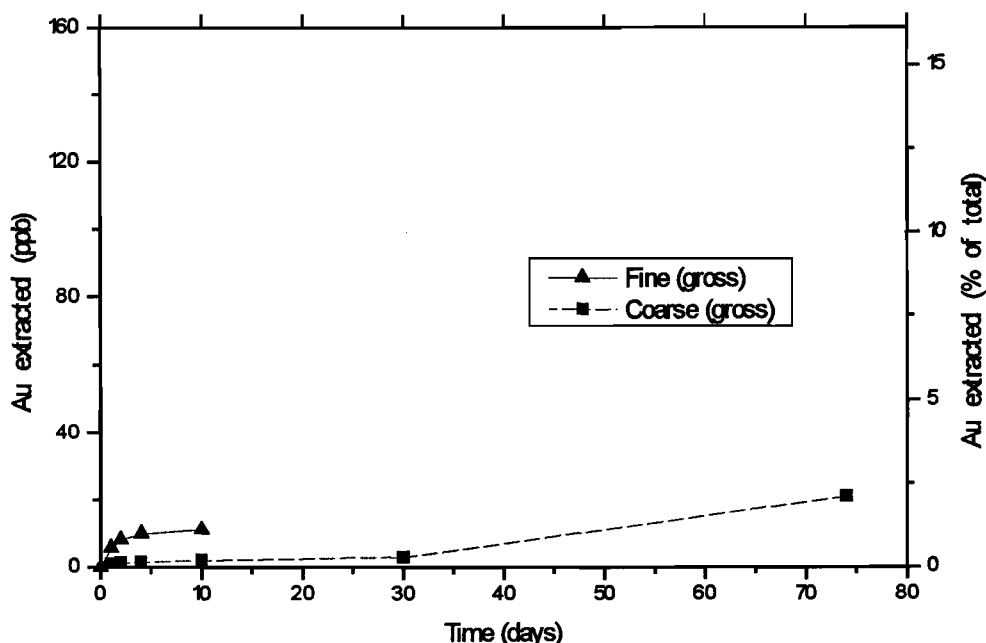


Figure 3.4: Water-soluble Au in an Fe oxide-rich sample (04-1251).

For Fe oxide-dominated soils, the proportion of water soluble Au is considerably less (Figure 3.4), implying poor mobility of Au in these soils. All this suggests that Au has a higher mobility in carbonate-dominated soils and that this high mobility is related to a carbonate "coating" which occludes minerals, such as Fe oxides, that would adsorb Au.

3.4 REGIONAL INVESTIGATIONS

From these results (discussed in detail in Report 391R, Sections 4 - 7), iodide soluble Au appeared to give a good distinction between differing soil types and has been used to investigate the regional geochemistry of Au in the Yilgarn, south of the Menzies line. These results are discussed below, in terms of regolith types, with similar studies at Granny Smith, north of the Menzies line, described separately.

3.4.1 *Unweathered rock and saprolite*

Extensive extractions of unweathered rock and saprolite from Mt. Percy and Mulgarrie indicated that, without exception, net and gross iodide-soluble Au was low (generally well below 1% of total Au), independent of the degree of sample crushing. This suggests that Au is in a relatively insoluble form such as primary and secondary metallic Au and/or tellurides, or occluded in sulphides or quartz.

3.4.2 *Laterite and lateritic soils*

Iron oxide-dominated systems have moderate Au solubilities in iodide solution (Section 3.3). This indicates some of the Au is soluble, perhaps partly due to the smaller grain size of secondary metallic Au.

3.4.3 *Manganese-rich horizons*

Manganese-rich materials from Mulgarrie yielded nearly 100% net iodide-soluble Au in fine materials and about 50% in coarse material, *i.e.*, the Au is particularly extractable and the Mn oxides are very poor at readsorbing the Au. This is illustrated in Figure 3.5, which shows soluble Au vs. time for a Mn-rich sample. About 90% of total Au was dissolved from the fine material within 5 days. In comparison, only about 50% of total Au was dissolved from coarse material. Results from other samples, and from differing degrees of pulverization prior to extraction, indicate that solubility is very high in all Mn-rich samples, with the degree of solubility primarily dependent on the degree of pulverization. This suggests that the Au is

chemically soluble, but occluded. This correlates with groundwater studies (Chapter 4) indicating the importance of Mn, as an oxidant, to the mobility of Au in Cl-rich groundwaters.

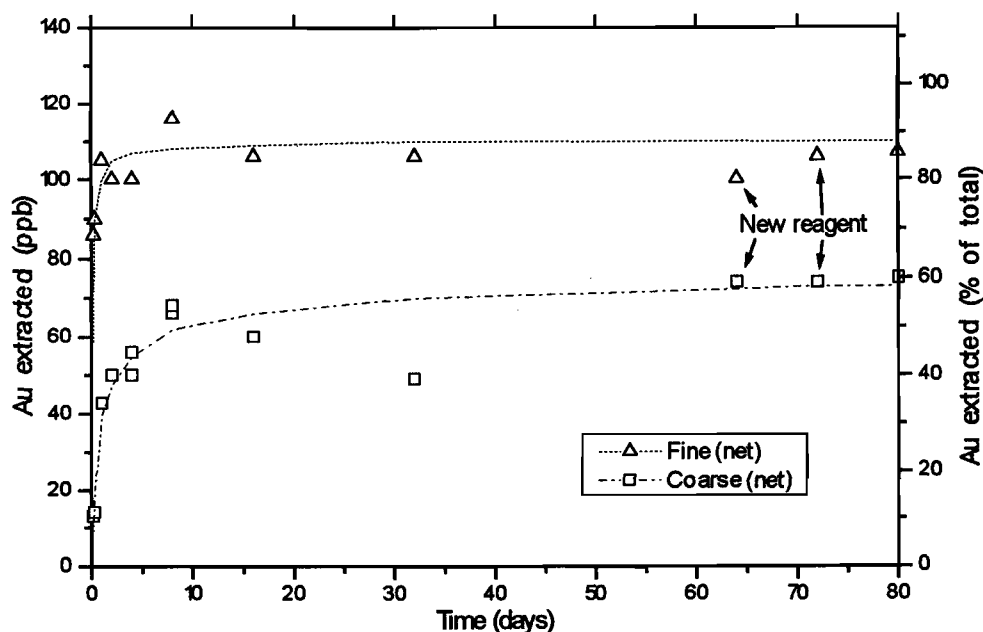


Figure 3.5: Iodide soluble Au for a Mn-rich sample (04-4023).

3.4.4 Calcrete and carbonate-rich soils

As discussed in Section 3.3, carbonate-rich soils commonly have high Au solubilities in iodide solution. Thus, for carbonate-rich soils of the southern Yilgarn (Figure 3.6), net iodide-soluble Au is about 30 - 50% of the total Au. More Au is extractable from coarse than fine material, suggesting much of the Au is in a highly accessible form. Both extractable and total Au are proportional to total carbonate, suggesting that soil Au and carbonate are precipitated by similar mechanisms or in response to similar conditions. This mechanism is unlikely to be adsorption of Au, given the high solubility of Au in carbonate-rich material. The most likely hypothesis appears to be that Au and Ca are soluble in soil solutions and both are precipitated by evaporative processes.

This remarkable Au solubility is contrary to the general "noble" characteristics of Au. However, evidence from a number of experiments (Reports 126R and 127R) indicates a high solubility of Au in Yilgarn soils, probably bound to biologically-derived ligands with a high Au affinity.

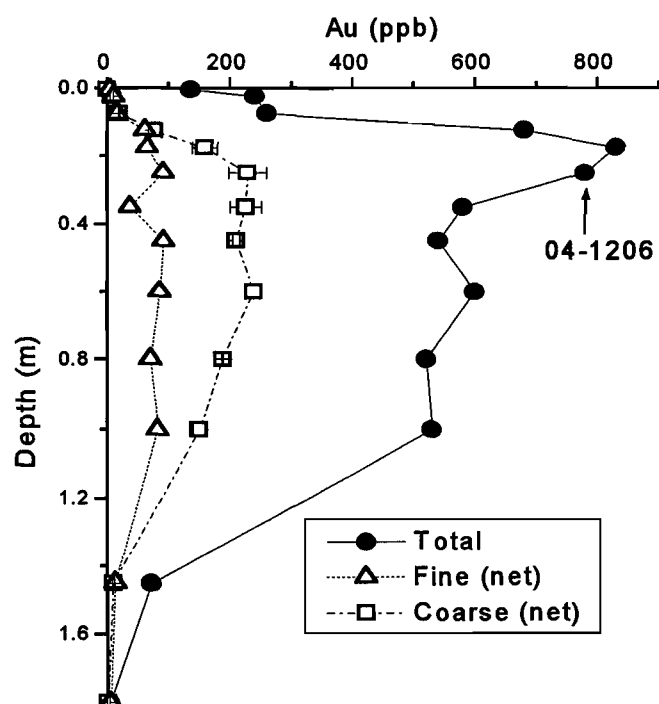


Figure 3.6: Total Au and iodide-soluble Au in samples from Profile B, Mt. Hope, with the position of sample 04-1206 (Section 3.3) shown. (Errors determined by duplicate extractions from coarse materials).

The relationship between Au and carbonate, observed for carbonate-dominated soils at Mt. Hope and Panglo, occurs in more complex profiles. At Mulline, Au shows a weak correlation with Ca in the top metre of the regolith, but is more strongly related to Fe oxides at greater depth (Figure 3.7a). However, net iodide-soluble Au correlates much more closely with Ca for the entire profile (example in Figure 3.7b). Similar results were obtained for Mt. Percy; Ca distribution correlated poorly with total Au but very well with net iodide-soluble Au. This is consistent with net iodide-soluble Au being an empirical measure of Au that is associated with carbonate.

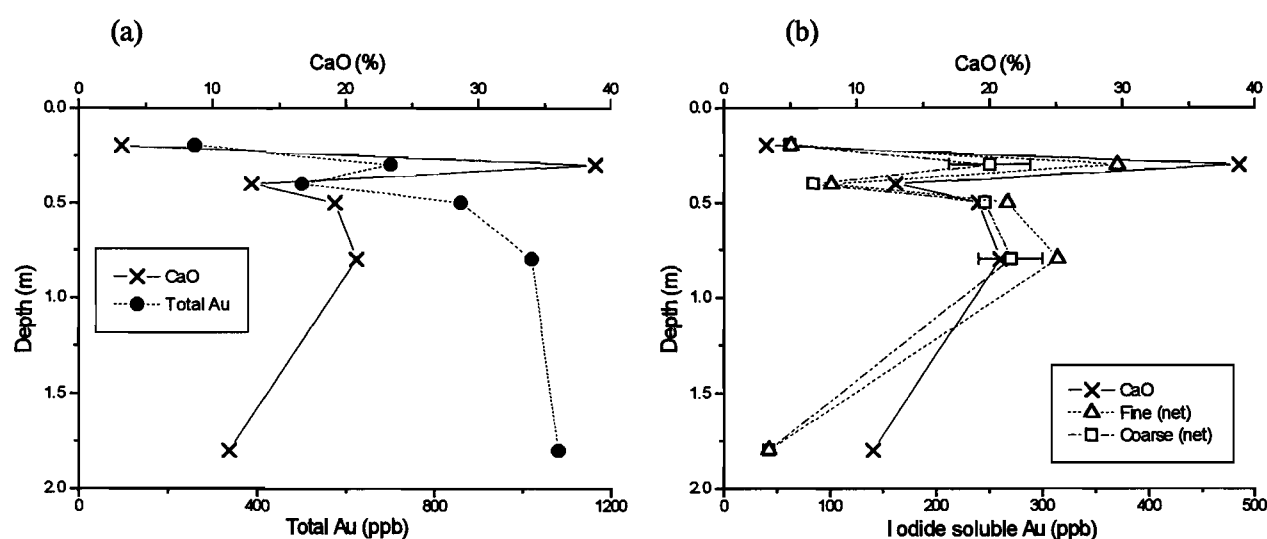


Figure 3.7: Depth distributions for Profile 4169, Mulline: (a) Ca and total Au; (b) Ca and net iodide soluble Au.

3.4.5 *Organic-rich soils*

The top 0.2 m of Yilgarn soils commonly contain 1-3% organic carbon. Net-iodide soluble Au is generally low for such surface samples (e.g., Figure 3.6), possibly due to readsorption of dissolved Au on organic matter. This is consistent with previous work (Report 126R) indicating that organic matter and/or biological materials are effective in readsorbing Au.

3.4.6 *Hardpan-dominated soils*

Granny Smith differs from the other sites investigated in that it is north of the Menzies line and has extensive development of hardpan (Report 385R). At this site, Au is most abundant in the hardpan, moderate in the saprolite and least abundant in the unconsolidated topsoil. There appears to be a generally weak association between Au and evaporite minerals e.g., halite and gypsum, in the topsoil and hardpan, but this association does not extend into the saprolite, nor does it occur in all profiles. Most calcite occurs at the top of, or within, the saprolite horizon, dispersed throughout the clay-rich matrix and as veins and concretions. However, although Au occurs in some carbonate segregations, there is no obvious relationship between the distributions of Au and Ca (Section 2.2.1).

A maximum of 30% of the total Au was net iodide-soluble, which is similar to the proportion from carbonate-rich material from soil profiles of the southern Yilgarn. Gross water-soluble Au was near 40% in some saprolite samples, where there is some indication that this is related to carbonate. There is strong evidence also that this Au is easily re-adsorbed by constituents present in the saprolite, as suggested elsewhere (Section 3.3). The low extractability of Au from hardpan supports the suggestion that a greater proportion of Au is immobile (even when pulverized) than from the saprolite.

3.5 DISCUSSION

Soil extraction procedures have distinguished differing chemical associations of Au with regolith materials in the southern Yilgarn. Presumably, many of these associations may be similar in north Yilgarn sites, although carbonate-rich soils are rare. The associations can be summarized as:

1. unweathered rock and saprolite - low Au solubility;
2. laterite and other Fe oxide-dominated regolith - moderate Au solubility;
3. Mn oxide-dominated regolith - high Au solubility when pulverized;
4. carbonate - high Au solubility even without pulverizing;
5. organic-rich - low Au solubility, possibly due to readsorption of dissolved Au.

These observations contribute to a better understanding of Au mobility during regolith development. Close to the regolith surface, and particularly in soils with present-day pedogenic activity, such as carbonate formation and/or movement of organic colloids, Au solubility increases. This could be due to two factors. Firstly, Au mobility can be enhanced by S-bearing biologically-derived molecules which can readily dissolve Au. This is suggested by incubation experiments that demonstrate the ability of deionized water to dissolve Au from organic surface soils. Secondly, closer to the surface, particularly in carbonate-dominated horizons, Au is highly soluble (indicated by iodide extraction).

It is expected that these two factors are related. Biologically-derived ligands bond with Au and make it highly soluble. This soluble Au may be highly mobile, depending on mineral charge characteristics, pore size and other soil properties. Gold may percolate down the soil profile, like Ca, until stopped by evaporation. Once precipitated, the Au may remain organically bound and may, once again, become highly mobile if the soil becomes wet. All the evidence suggests that Au in soils is in a highly dynamic state. Plant roots take up Au, which is then later shed onto the soil surface, thus beginning the cycling of soluble Au (Figure 2.1); unusually wet seasons could cause major Au redistributions in soils. Thus, it is not surprising that this Au mobility may cause enrichments, even in geologically recent overburden, that reflect buried mineralization.

Although many of the processes of soil redistribution of Au are now better understood, the process whereby Au is transported upward from mineralized rocks to the soil surface is not yet clear. Further work is required here, as it is critical to clarify further how soil or shallow regolith sampling can be used more effectively in Au exploration, particularly in areas dominated by hardpan and/or transported overburden.

4 HYDROGEOCHEMISTRY IN THE YILGARN BLOCK

4.1 INTRODUCTION

The objectives of investigating the hydrogeochemistry of mineralized areas are to advance knowledge of groundwater characteristics, particularly with reference to geochemical dispersions in the regolith, and to determine the potential for groundwater sampling as an exploration technique. Specific fields of interest are:

1. use of Au and pathfinder elements in water as an exploration tool;
2. which ions cause Au mobility, and how these ions are influenced by groundwater chemistry and water-rock interactions;
3. the chemical and geological factors that influence the chemistry of groundwaters in the Yilgarn Block;
4. development of techniques for analysis of groundwater data from mineralized areas.

Hydrogeochemical investigation areas have included:

- i Mount Gibson, a Au deposit about 100 km north-east of Dalwallinu (central-west Yilgarn; Project 240 - Report 120R);
- ii Panglo, a Au deposit some 30 km north of Kalgoorlie (south Yilgarn; Report 125R);
- iii Yalanbee, a non-mineralized area which lies some 50 km east of the western edge of the Yilgarn Block;
- iv Boags, a Au deposit at Bottle Creek, located 210 km north north-west of Kalgoorlie (central Yilgarn; Report 237R);
- v Mulgarrie, a neutral palaeodrainage system crossing mineralized rocks about 40 km north of Kalgoorlie (south Yilgarn; Report 339R);
- vi Wollubar, an acid palaeodrainage overlying mineralized rocks about 40 km southeast of Kalgoorlie, and Golden Hope, a nearby Au deposit (south Yilgarn; Report 387R).

Investigations of these sites have led to the hypothesis that the concentrations of major and minor elements are controlled by particular mechanisms, related either to hydrological phenomena, lithological effects, groundwater controls (*e.g.*, pH, Eh) and, in the case of Au, presence or absence of ligands (*e.g.*, chloride, iodide, thiosulphate) and or interfering ions (*e.g.*, Fe). Information on these controls and on general groundwater characteristics have contributed to the assessment and development of hydrogeochemistry as an exploration technique and enhanced understanding of regolith geochemistry.

4.2 SITE CHARACTERISTICS

Mount Gibson is about 300 km northeast of Perth and 200 km from the west coast; Mulgarrie, Panglo and Wollubar/Golden Hope are all near Kalgoorlie, and Boags is 210 km NNW of Kalgoorlie (Figure 4.1). All these sites have warm, semi-arid climates; Mt. Gibson has a mean annual rainfall of approximately 300 mm, and the Kalgoorlie sites and Boags about 250 mm. Most of the rain at these sites falls during the cooler months of May to August, although there is a significant component of summer rainfall from erratic thunderstorms. Yalanbee lies much closer to the coast (about 55 km east of Perth) and has a Mediterranean climate with higher rainfall (600 mm), also concentrated in the winter months. The sites are developed on a range of bedrock lithologies but all (with the exception of Yalanbee) are within or adjacent to greenstone belts. Sampling and analysis methods are described in detail in the various reports and are not discussed here.

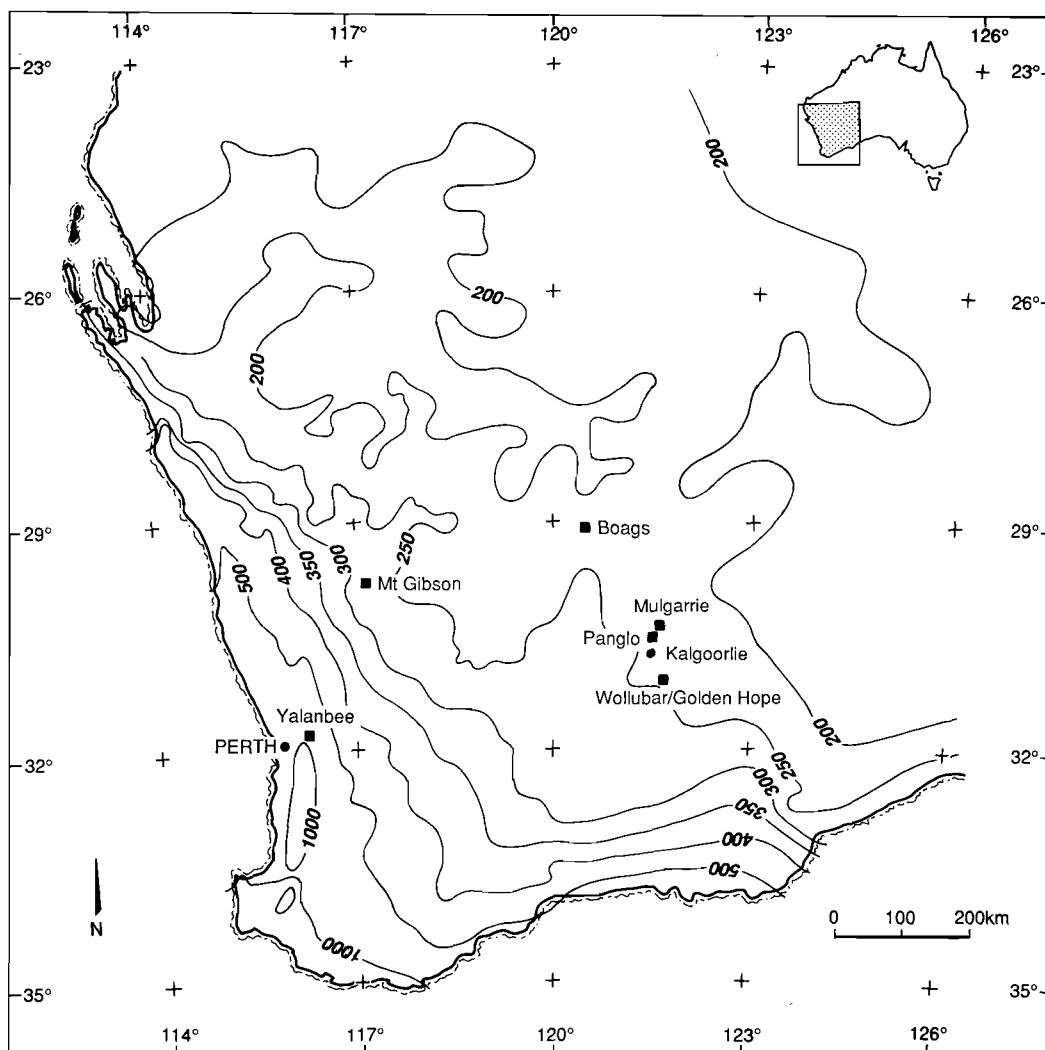
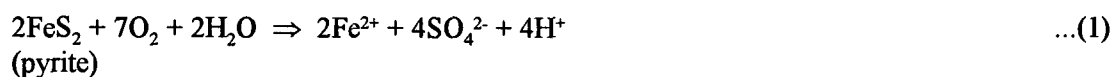


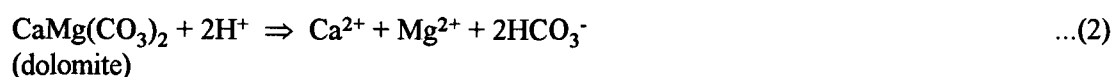
Figure 4.1: Groundwater investigation sites for AMIRA Projects 240, 241 and 241A.

4.3 EFFECT OF SAMPLE DEPTH

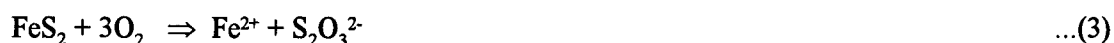
Most groundwaters at each of the sites are highly saline, the salinity arising from evaporative effects. Salinity increases with depth at several sites, with the lesser salinity of the shallower aquifers probably due to influxes from recent rainwater. Deep groundwaters in contact with mineralization (*e.g.*, Boags, Golden Hope and some from Mt. Gibson, Panglo and Mulgarrie) 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:



At depth, acid production is buffered by minerals such as carbonates or feldspar:



Under such conditions (*i.e.*, sulphides oxidizing in a neutral to alkaline environment), significant concentrations of the intermediate sulphur compounds thiosulphate ($\text{S}_2\text{O}_3^{2-}$) and sulphite (SO_3^{2-}) are commonly produced (Granger and Warren, 1969; Goldhaber, 1983; Mann and Webster, 1990):



Such conditions match the groundwaters at Boags and Golden Hope and deep groundwaters in contact with mineralization at Mt. Gibson, Panglo and Mulgarrie. This is important for the groundwater mobility of Au, as discussed in Section 4.7. For shallower groundwaters, the commonly observed higher acidity will destabilize thiosulphate. The more acidic shallow waters will be actively dissolving most elements from regolith material. Therefore, sample depth is an important parameter in groundwater sampling and should be considered in interpretation.

4.4 ACIDITY AND OXIDATION POTENTIAL

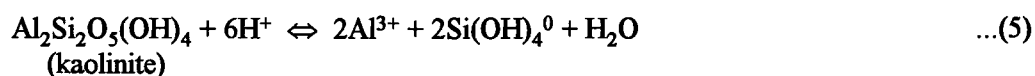
There are four types or groups of groundwaters, each having distinctive Eh/pH and geochemical characteristics (Figure 4.2).

Fe: these waters contain significant dissolved Fe (>0.1 mg/L) and are the most reduced. The primary Eh/pH control is the "ferrolysis" reaction (Brinkman, 1977):



This commonly generates highly acidic conditions in unbuffered systems. Because the reaction is governed by both Eh and pH, the ferrolysis control is an angled line on an Eh/pH diagram (Figure 4.2). All groundwaters with significant Fe concentrations (> 0.1 mg/L; solid symbols in Figure 4.2) congregate around this line.

Al: these are the most acid groundwaters, with the acidity probably caused by ferrolysis. Such conditions can only occur where minerals such as carbonates or feldspar are absent (*e.g.*, well above the weathering front, but below the zone of pedogenic carbonate). Here acidity (commonly generated by ferrolysis) is buffered by dissolving clay minerals:



which maintains the solution pH at about 3.2. As this is Eh independent, the Al control may be expressed as a vertical line (Figure 4.2).

HO: in the presence of buffering minerals, groundwaters are neutral to weakly acid (pH 4.5 - 7.5; Figure 4.2), and are denoted as the HO group. These waters do not appear to be strongly controlled by a redox couple, such as $\text{Fe}^{2+}/\text{Fe}(\text{OH})_{3(\text{s})}$ in the group Fe waters. Although there are redox couples within the range measured for these waters (the most probable is $\text{H}_2\text{O}_2/\text{O}_2$; 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 (group Fe), strongly acid (group Al) or strongly oxidizing (group Mn).

Mn: as discussed above, groundwaters become highly acidic as a consequence of ferrolysis. These groundwaters are depleted in Fe and, as they become further oxidized, Mn^{2+} may also oxidize and hydrolyse to solid Mn oxides and oxyhydroxides, *e.g.*:



This reaction is the Mn equivalent of ferrolysis and similarly controls the Eh and pH of a solution. The zone of Mn oxidation appears to be the upper limit for groundwater Eh. The oxidized acidic solutions, in particular, closely follow the line of Mn oxidation on the Eh/pH diagram (Figure 4.2). This reaction is critical to Au chloride mobility (Section 4.7) as it enables solutions to reach a sufficiently high Eh for Au oxidation.

These hypothetical controls appear to explain Eh/pH data from all Yilgarn sites investigated to date.

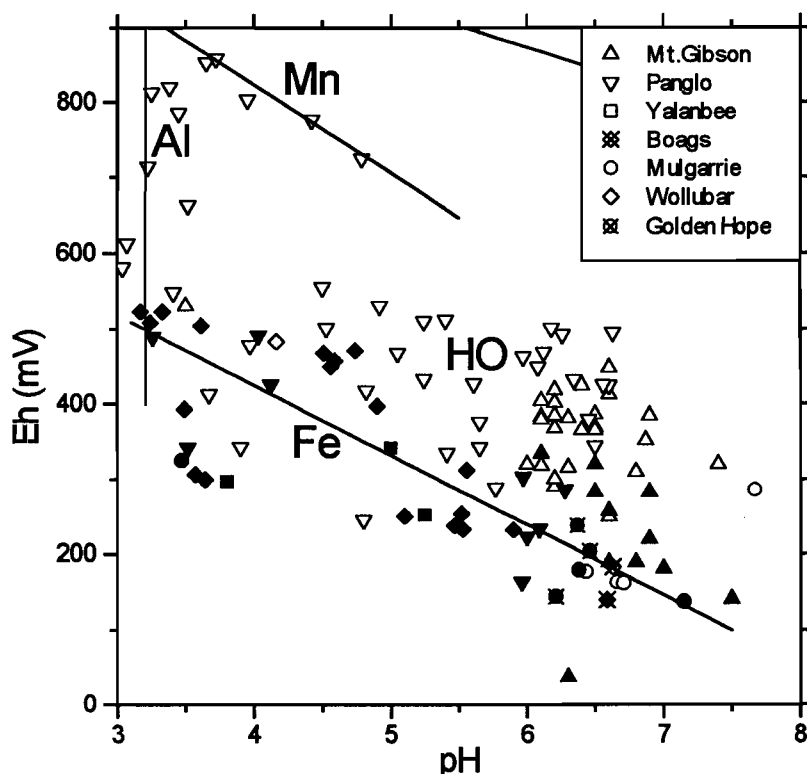


Figure 4.2: Eh and pH in groundwaters from research sites in the Yilgarn. Solid symbols indicate samples with Fe concentrations greater than 0.1 mg/L (ppm).

4.5 MAJOR ELEMENT HYDROGEOCHEMISTRY

Understanding Eh/pH and major element hydrogeochemistry, although not directly applicable to groundwater exploration may, nevertheless, help to place groundwater samples in context and help interpret the hydrogeochemistry of Au and other minor elements.

The saline Yilgarn waters are dominated by Na and Cl; most of the major ions show a very strong correlation with total dissolved solids (TDS), with the principal exceptions being Ca and HCO_3 , due to precipitation of calcite and/or gypsum and loss of HCO_3 with acidification. Therefore, the abundances of Na, Mg, Ca, K, Cl, SO_4 and Br are shown as proportions of total salinity (Table 4.1) so as to compare between sites. Thus, Golden Hope, Mulgarrie and Boags groundwaters are enriched in SO_4 and Mg, with SO_4 probably from dissolution of sulphides (Eqn. 1) and Mg from carbonates (Eqn. 2; Section 4.3). This is consistent with these being deep groundwaters in contact with or near to sulphides. The major depletions in K and Br, observed at Panglo and Wollubar in particular, are thought to be due to a significant proportion of the groundwater salinity resulting from halite (NaCl) dissolution rather than from evaporation.

Table 4.1: Mean major element compositions of groundwaters at research sites in the Yilgarn.

	Wollubar (19) #	Golden Hope (3)	Mulgarrie (6)	Yalanbee (3)	Boags (2)	Mt. Gibson (50)	Panglo (50)	Sea water
pH	4.5	6.35	6.8	4.7	6.6	6.5	4.9	nd
Eh (mV)	380	200	180	300	160	310	490	nd
Na *	0.31	0.27	0.29	0.28	0.25	0.32	0.32	0.31
Mg *	0.040	0.062	0.052	0.057	0.052	0.033	0.032	0.04
Ca *	0.006	0.013	0.012	0.02	0.032	0.009	0.008	0.012
K *	0.0032	0.0057	0.0041	0.003	0.0092	0.0112	0.0008	0.0112
Cl *	0.56	0.52	0.54	0.6	0.47	0.53	0.59	0.56
SO ₄ *	0.073	0.126	0.103	0.045	0.172	0.075	0.053	0.065
Br *	0.0012	0.0019	0.0016	0.0016	0.0024	0.0017	0.0005	0.0019
HCO ₃	20	690	398	nd	620	260	50	142
TDS	73000	45000	41800	8100	21000	24000	84000	34000

numbers in brackets denote the number of samples taken at each site.

* for the elements Na, Mg, Ca, K, Cl, SO₄ And Br, the ratio of the element concentration to TDS is used rather than the concentration. (see Section 4.5 for details.)

HCO₃ and TDS concentrations in mg/L (ppm).

nd not determined

4.6 MINOR ELEMENT HYDROGEOCHEMISTRY

Mean minor element concentrations in Yilgarn groundwaters are listed in Table 4.2. The last column gives the postulated control on groundwater concentration. Thus, for example, Al 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 minerals are not very useful for exploration, whereas other elements may give useful information as to lithology and/or presence of sulphides.

Table 4.2: Mean minor element compositions of groundwaters at research sites in the Yilgarn.

	Wollubar (19) #	Golden Hope (3)	Mulgarrie (6)	Yalanbee (3)	Boags (2)	Mt. Gibson (50)	Panglo (50)	Sea water	Conc. Control(s)
F	2.7	0.28	nd	nd	nd	nd	nd	1.3	Eq
Al	23	0.04	0.04	1.2	<0.01	0.3	8	0.01	Ac
Si	15	8	12	28	7	30	8	3	Ac/Eq
PO ₄	0.02	0.16	nd	nd	nd	nd	nd	nd	?
Sc	0.001	<0.001	nd	nd	nd	nd	nd	nd	?
Cr	0.012	0.002	0.032	0.003	0.002	0.004	0.04	0.00005	Um
Mn	3.4	0.32	4	1.2	0.035	1	3	0.002	Mf/Um
Fe	3	3	0.04	0.7	0.07	3	0.5	0.01	S
Co	0.20	0.00	0.06	0.012	<0.01	0.01	0.19	0.0003	Mf/Um/Ac
Ni	0.44	0.03	0.14	0.01	<0.01	0.01	0.26	0.005	Ac/Um
Cu	0.06	0.04	0.021	nd	0.007	0.01	0.08	0.003	Ac/Mf
Zn	0.11	0.04	0.033	nd	0.015	0.06	0.3	0.01	Ac
Ga	0.03	0.01	nd	nd	nd	nd	nd	nd	S
As	<0.02	<0.02	<0.02	nd	0.11	nd	nd	0.003	S
Sr	6.2	6.7	8.4	1.6	5.9	2.4	7	8	Eq
Y	0.39	0.00	nd	nd	nd	nd	nd	nd	?
Mo	0.01	0.02	nd	nd	nd	nd	nd	nd	S
Cd	0.003	0.002	0.002	nd	0.009	0.004	0	0.0001	?
Sn	0.006	0.003	nd	nd	nd	nd	nd	nd	?
Sb	nd	nd	<0.001	nd	0.17	nd	nd	0.0003	S
I	0.29	2.8	0.5	0.05	2.1	0.5	0.5	0.06	S
Cs	0.009	0.05	nd	nd	nd	nd	nd	nd	?
Ba	0.028	0.04	0.05	0.053	0.01	0.06	nd	0.03	Eq
REE (total)	1.6	0.004	nd	nd	nd	nd	nd	0.00001	?
W	0.031	0.06	nd	nd	nd	nd	nd	nd	S
Au	0.02	0.004	0.05	nd	0.5	0.13	0.3	0.01	Min
Hg	0.0020	0.0039	nd	nd	nd	nd	nd	nd	S
Tl	0.0010	0.0006	nd	nd	nd	nd	nd	nd	S
Pb	0.12	0.03	0.007	nd	0.005	0.13	nd	0.00003	Ac
Th	0.0005	0.0003	nd	nd	nd	nd	nd	nd	?
U	0.05	0.010	nd	nd	nd	nd	nd	nd	Ac

All concentrations in mg/L (ppm), except Au in µg/L (ppb).

Numbers in brackets denote the number of samples taken at each site.

nd not determined

Concentration controls

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

4.7 GOLD HYDROGEOCHEMISTRY

Previous research (summarized in Report 4R and Gray *et al.*, 1992) suggests that dissolved Au in deep, neutral groundwaters is probably present as the thiosulphate complex $[\text{Au}(\text{S}_2\text{O}_3)_2]^{3-}$, assuming buffered sulphide oxidation and the release of thiosulphate ions (Section 4.3). A plot of Au vs. Fe (present in solution as Fe^{2+}) for neutral to alkaline ($\text{pH} \geq 6$) groundwaters from several sites (Figure 4.3) shows that many of these samples have significant Au *and* Fe in solution. This indicates that, in these waters, Au is commonly in a form which will not be reduced, and therefore precipitated, by Fe^{2+} . Due to its high stability, the Au thiosulphate complex would show such a lack of effect of Fe^{2+} on dissolved Au content.

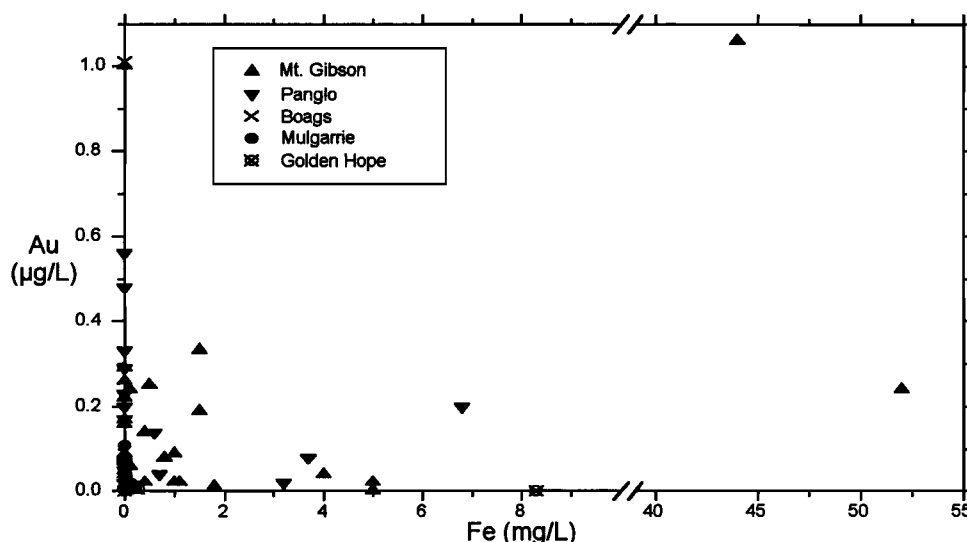


Figure 4.3: Gold vs. Fe for neutral to alkaline ($\text{pH} \geq 6$) Yilgarn groundwaters.

In comparison, in shallow acidic ($\text{pH} < 6$) groundwaters, dissolved Au would be expected to be present as the chloride complex (AuCl_2^-). Thus, in such groundwaters, there is a very strong antipathetic relationship between dissolved Fe and Au (Figure 4.4). This is because the ferrous ion has precipitated Au:

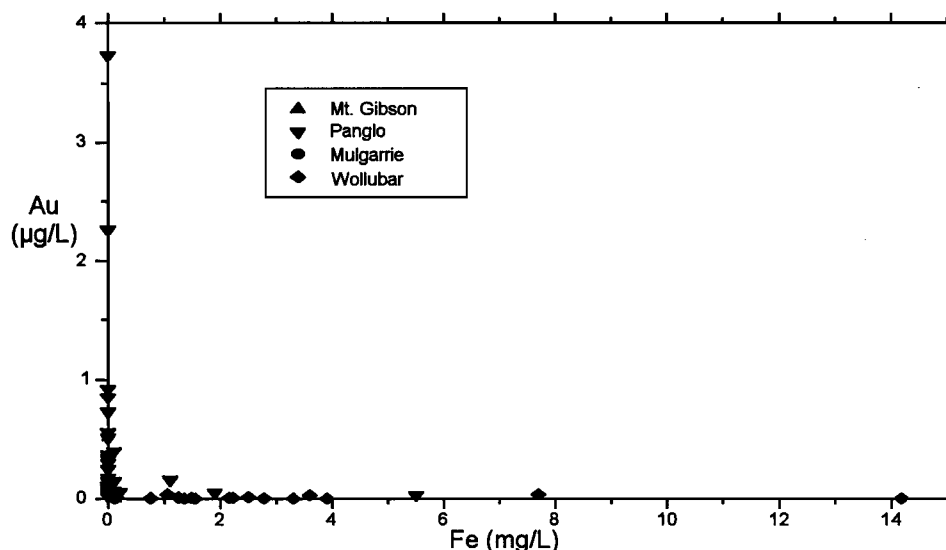
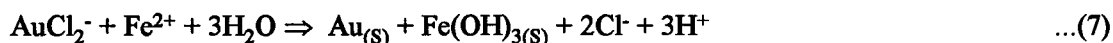


Figure 4.4: Gold vs. Fe for acid ($\text{pH} < 6$) Yilgarn groundwaters.

Thus, in acid solutions, groundwaters containing dissolved Fe will have low Au concentrations, even in the presence of mineralization. In addition to this negative control, there is a positive Eh control on Au chloride solubility. Gold is calculated to have a solubility of 2 ppb in a 3.5% Cl solution when the Eh is greater than 690 mV (Figure 4.5) and, indeed, of the acid groundwaters, those that are most oxidized do have the greatest Au concentrations. The only groundwaters sufficiently oxidized are those apparently controlled by Mn oxidation (compare Figures 4.5 and 4.2). Thus, significant dissolved Mn in acid, oxidized solution appears to be critical to the mobility of Au in saline groundwaters.

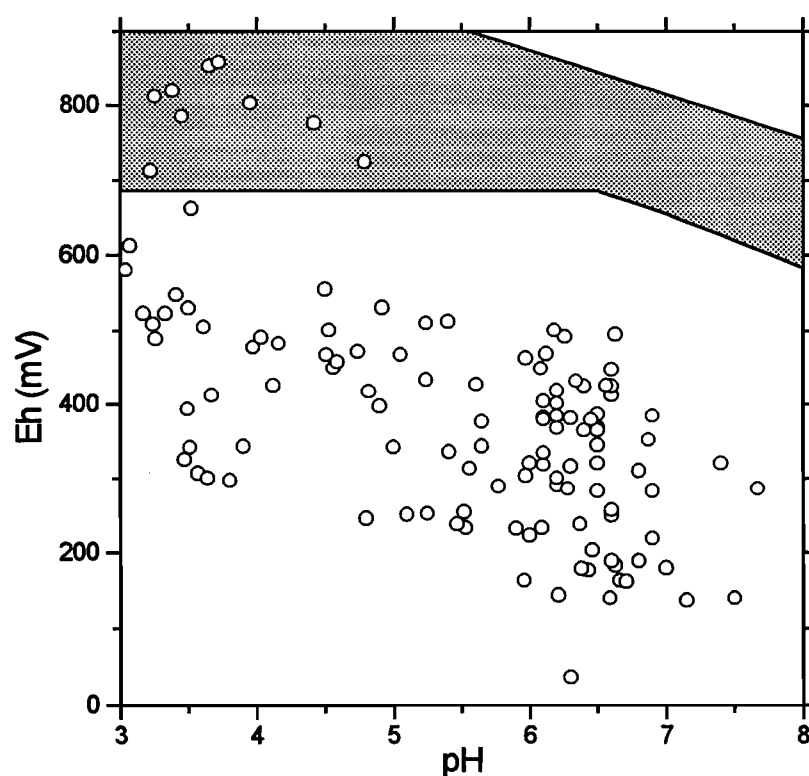


Figure 4.5: Eh/pH data for Yilgarn groundwaters, superimposed on the stability field for dissolved Au chloride for Au concentration = 10^{-8} M (2 ppb) and Cl concentration = 1 M (3.5%).

4.8 IMPLICATIONS FOR EXPLORATION

4.8.1 Possible applications

Hydrogeochemistry may be of value to exploration because:

1. geochemical anomalies may be broader in groundwater than in the regolith;
2. groundwater compositions are partly controlled by basement geology and, hence, may indicate lithologies not intersected or identified by drilling;
3. areas of high reactivity (e.g., faults and shear zones) may have distinct hydrogeochemical signatures even where they are unremarkable in terms of elemental abundances, and where drilling makes petrographic study difficult;
4. hydrogeochemical studies may yield further information on the processes of weathering, which may enhance understanding of saprolite geochemistry.

These possible applications for hydrogeochemistry are discussed below.

4.8.2 Lithological discrimination

The potential use of hydrogeochemistry in lithological discrimination (Section 4.6 and Table 4.2) is illustrated in Figure 4.6. Groundwaters at Panglo may be subdivided into those in contact with shales, mafic and ultramafic lithologies by plotting a mafic index ($Mn+13Co+9Zn+36Cu$) vs. an ultramafic index ($Ni+2Cr$). This discrimination is effective 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.

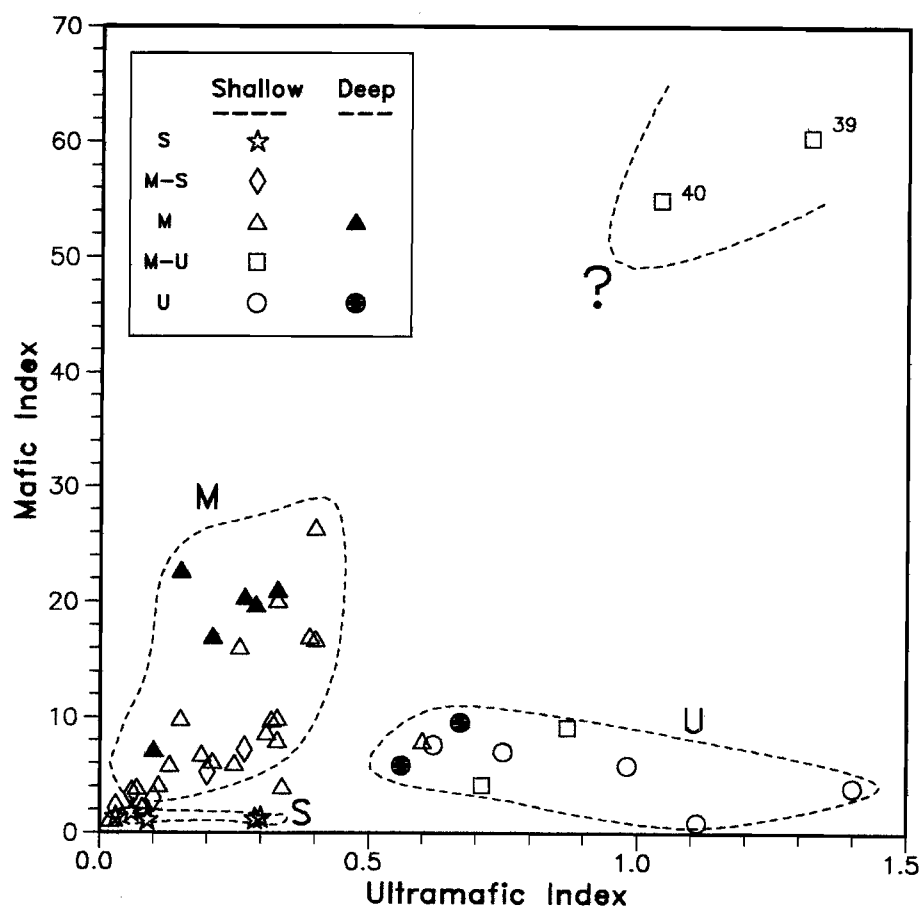


Figure 4.6: Mafic vs. ultramafic indices for groundwaters at Panglo.

Key: S - shale; M-S - at mafic-shale contact; M - mafic; M-U at mafic-ultramafic contact; U - ultramafic.

4.8.3 Presence of sulphides

As discussed in Sections 4.4 - 4.6, the weathering of sulphides under neutral to alkaline conditions may generate characteristic hydrogeochemical signatures. For example, deep groundwaters from Boags, Golden Hope and the Hornet pit at Mt. Gibson have characteristics in common including:

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 chalcophile pathfinder elements, including As, Mo, Ag, Sb, I, Hg and Tl.

4.8.4 Presence of Au mineralization

The clearest indication of Au mineralization in groundwater 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 two mechanisms for transport of Au in groundwater (thiosulphate and halide complexing, Section 4.7), with a third mechanism (organic complexation) specific to soils. Where Au appears to be dissolving in thiosulphate form, as at Boags and the Hornet pit at Mt. Gibson, the distribution of dissolved Au closely matches that of mineralization. Here the condition for thiosulphate formation (*i.e.*, sulphides weathering in a neutral-alkaline environment) is provided by the carbonate-rich alteration assemblage around the mineralization. Although this is encouraging, it should be noted that at Golden Hope and one other site (D.J. Gray, unpublished data), where the thiosulphate mechanism should be active, concentrations of dissolved Au are much lower than would be expected. The reason for this discrepancy should be determined before general application.

In acid, oxidizing environments, Au dissolves to form chloride or iodide complexes (Report 125R) and, where this mechanism is expected to be active (Panglo, Wollubar and some areas of Mt. Gibson), 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 4.7), and the distribution of dissolved Au does not match that of primary mineralization as closely as where Au is dissolving as the thiosulphate complex. At Panglo, for example, the highest dissolved Au concentrations were observed in groundwaters that appeared to be intersecting a shear.

5 SPECTRAL STUDIES OF REGOLITH MATERIALS

5.1 INTRODUCTION

High resolution spectral studies were conducted at the Beasley Creek, Bounty and Panglo Au deposits (Reports 160R, 169R and 234R), in collaboration with Mr T.J. Cudahy, through the CSIRO-AMIRA Project "Remote Sensing for Gold" Project P243. The objective was to determine the spectral characteristics of weathered materials to assist extraction of mineralogical information from remotely sensed data. In particular, the studies aimed to determine quantitative relationships between spectral features and mineralogy, and provide a basis to maximize the discrimination obtainable by remote sensing. The sites have different geological and geomorphological settings and, hence, different surface materials but collectively illustrate features common to many Au deposits. Full advantage was taken of undisturbed surfaces as mining activity had not commenced at the time of sample collection. This has allowed comparison between spectral information and other analytical data. These comparisons have been supported by laboratory experiments aimed at establishing quantitative relationships between spectral and physicochemical characteristics (mineralogy, geochemistry and morphology).

5.2 TECHNIQUES

The reflectance spectra of soil and lag samples were measured using either the Infrared Intelligent Spectrometer (IRIS) or the Portable Infrared Mineral Analyser (PIMA-II). The reflectance data were processed using CSIRO's PCSpectra software where the wavelength, symmetry and depth of absorptions were measured to provide information about the mineralogy, abundance and crystallinity of minerals. In addition, hull quotient curves (HQ) were used to enhance absorption features (Green and Craig, 1985). Ratios of reflectances were also used to measure the relative depth and geometry of selected absorptions and to measure changes in the wavelength of particular spectral characteristics.

Iron bearing oxides and silicates have diagnostic spectral characteristics in the 0.4 to 1.1 μm region, which are caused by the transfer of electrons to different orbits around a single atom (called a crystal field transition) or from the ligand to the iron atom (charge transfer). Dioctahedral and trioctahedral silicates (e.g., amphiboles, chlorites, micas, smectites, kaolinite), carbonates and sulphates produce characteristic absorptions in the 1.1 to 2.5 μm region. The wavelength and geometry of these absorptions are related to the composition and structure of the mineral lattice; e.g., absorption doublets at 1.39+1.41 and 2.17+2.21 μm are characteristic of octahedrally coordinated Al in kaolinite. The 1.4 μm pair are the first overtone of the O-H stretch whereas the 2.2 μm pair are a combination tone of the Al-OH bend with the O-H stretch. Figure 5.1 summarizes the major absorbances discussed above.

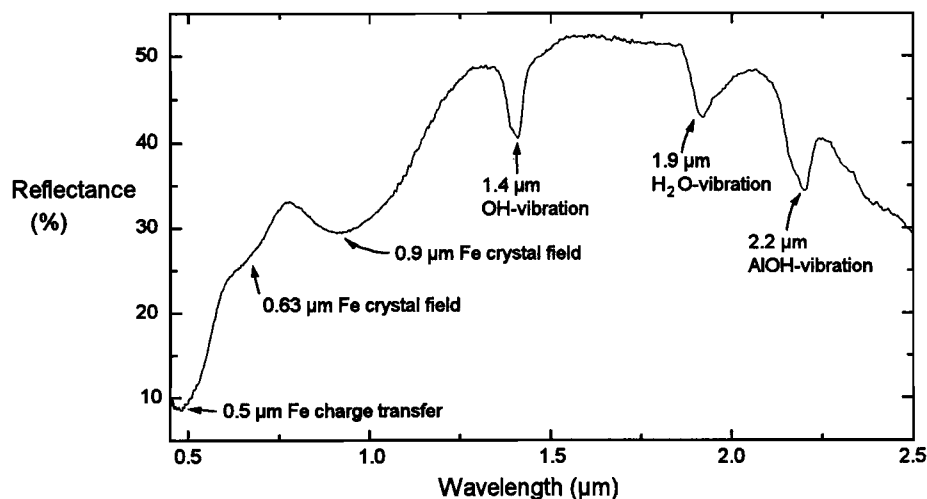


Figure 5.1: Reflectance spectrum of a typical soil showing the major absorbances with explanations.

The spectral studies concentrated on the 0.4 to 2.5 μm region, because it (i) provides information on two major weathering products (Fe oxides and clay minerals; see above), (ii) lies in an "atmospheric window" that allows sufficient energy to be detected remotely, and (iii) is covered by a variety of air- and space-borne remote sensing systems which are, or will be, made available to the exploration industry and include Landsat Thematic Mapper (TM), Daedalus Airborne TM, Geoscan Mk I and II, JERS-1, AVIRIS and ASTER.

In relating reflectance information to other analytical data it is essential to know what part of the sample has been measured. For example, spectral reflectance and scanning electron microscopy (SEM) measure the outer few microns, whereas X-ray diffraction (XRD) and chemical analytical techniques, such as inductively coupled plasma spectroscopy (ICP) and X-ray fluorescence (XRF), measure a bulk property. No correction can be made for this difference in approach.

5.3 PANGLO

5.3.1 *Introduction*

The potassian micas (muscovite, fuchsite, sericite) are common components of alteration assemblages associated with Au mineralization. These micas are also highly resistant to weathering and hence offer the potential for detection of an alteration zone by radiometric or remote spectral sensing techniques. This style of alteration occurs at the Panglo Au deposit, which was investigated during the earlier phase of the Project. Here, the regolith is truncated to the upper saprolite, and largely covered by a thin veneer of transported overburden. The alteration comprises muscovite (K-mica) associated with mineralization, and paragonite (Na-mica) in areas peripheral to mineralization. Spectral discrimination of these micas could be used to delimit the Au mineralization. The objectives of the study were to determine whether the micas (i) could be detected at the surface and (ii) could be discriminated using spectral techniques. This was investigated using a suite of surface and subsurface samples of weathered mafic rock, shale and soil.

The spectral investigation concentrated on the wavelengths of the OH-related absorption at 1.4 μm and the Al-OH absorption at 2.2 μm . These absorptions were expected to provide information on the composition of micas (size and composition of the unit-cell). In addition, the depth of the 2.35 μm absorption was expected to be related to the abundance of mica. Some consideration was given to the associated spectral mineralogy of clays, sulphates and water, and to possible relationships to the character of the regolith.

5.3.2 *Results and discussion*

The wavelengths of the 1.4 and 2.2 μm absorptions are approximately 0.010 μm longer than expected for muscovite and paragonite. In comparison, the spectrum of a kaolinite-poor, muscovite-rich shale sample showed wavelengths expected for muscovite; there is also no difference between paragonite-rich and muscovite-rich samples. The 0.010 μm difference could be caused by spectral contamination by other Al-OH minerals, such as kaolinite, which also absorb at 2.2 μm ;

The concentration of K_2O was used as a quantitative measure of the abundance of muscovite and was compared with the depth of the 2.35 μm absorption. The results showed significant correlation, though a threshold abundance of approximately 3% K_2O is required, below which the 2.35 μm absorption is no longer distinguishable. This threshold equates to approximately 25% muscovite. Note, however, that quartz-rich shales (> 60% SiO_2) have a threshold as little as 1% K_2O , which is probably related to the relative transparency of quartz. Analysis of the weathered, mafic subcrop showed a recognizable absorption at 2.35 μm ; therefore, any mica-bearing, mafic outcrop or float if present could be detected by spectral techniques. However, the soils did not show this absorption, suggesting that the mica concentration is too low; this is not unexpected, given the cover of transported material.

No quantitative relationship, analogous to that between the K_2O abundance, mica content and depth of the $2.35\ \mu m$ absorption, could be established for the Na_2O abundance and paragonite content, possibly because much of the Na is present as halite.

The mafic subcrops are characterized by strong absorption at 1.40 , 1.41 , 2.17 , 2.20 , 2.32 and $2.39\ \mu m$, producing absorption doublets at 1.4 and $2.2\ \mu m$ characteristic of relatively well-crystallized kaolinite. The associated soils are characterized by weaker absorption doublets at these wavelengths, indicating poorly crystalline kaolinite. The soil spectra also show small absorptions at 1.46 and $2.25\ \mu m$, possibly caused by water, Fe- or Si-cations in the kaolinite structure (typical of poorly crystalline clay). The shale subcrop shows weak to non-existent kaolinite absorption doublets.

These results can be applied to Au exploration strategies. The most important is the lower limit of 3% K_2O (*i.e.*, about 25% mica) before the absorption at $2.35\ \mu m$ becomes useable. The best application of these results field logging with a portable spectrometer, for detecting and estimating mica in subcrop and drill core. This would have particular application for mafic and ultramafic rocks in which K-rich minerals are unexpected, unless the rocks are known to have been affected by potassic metasomatism. Further work is required to establish whether phyllic altered, mafic saprolite is spectrally characterized by well-crystalline kaolinite and K-bearing mica.

5.4 BEASLEY CREEK

5.4.1 Introduction

The Beasley Creek Au mine is located in the Laverton area, north-eastern Yilgarn Craton (Report 26R). Gold mineralization is related to a deeply weathered carbonaceous shale, within an Archaean greenstone sequence. The deposit is located on a low erosional rise, characterized by largely residual material, but surrounded by depositional plains of colluvial and alluvial sediments. Laboratory reflectance spectra were measured from surface samples collected from two east-west traverses across Au mineralization and extending into background areas. The samples comprised soil, ferruginous lag and calcrete overlying subcropping lateritic duricrust, exposed saprolite and mottled zone.

5.4.2 Results and discussion

The spectral results show no evidence for sericite or other primary minerals previously identified in fresh rock but, instead, show information related to the principal weathering products, *i.e.*, Fe oxides and kaolinite.

The spectra of the coarser, ferruginous lag (10-50 mm diameter) show variations in the wavelengths of the charge transfer shoulder near $0.6\ \mu m$, and the crystal field absorption near $0.9\ \mu m$; these absorbances generally indicate hematite or goethite (Figure 5.1). The wavelengths of these parameters are invariant over broad zones ($>500\ m$ wide), consistent with hematite-goethite relationships measured by XRD and spatially related to particular, exposed, lateritic units. The goethitic lag is located over saprolite and mottled zone and is interpreted to be the residual product of selective erosion of the upper, lateritic horizons. The hematitic lag is located over lateritic duricrust. The soil has a relatively consistent spectral mineralogy comprising hematite and poorly crystalline kaolinite. The poor crystallinity of kaolinite is indicated by the weakly developed absorption doublets at 1.4 and $2.2\ \mu m$. Within a $100\ m$ wide zone over Au mineralization, there is an $0.008\ \mu m$ shift to shorter wavelengths of the charge transfer shoulder, indicating a slightly more goethite-rich soil. This shift in wavelength is much less than that shown by the coarse lag.

The soil and lag data indicate a weak relationship between Au distribution and the wavelength of the charge transfer shoulder, *i.e.*, between Au and goethite abundances, although there are too few data to consider this result as significant. The known increase in the overall abundance of Fe-rich lag close to Au mineralization (Report 26R) was not evident in the spectral data, although an increase in the total Fe^{3+}

content, based on the depth of the crystal field absorption near 0.9 μm , is weakly correlated with the total Fe_2O_3 concentration.

Calcrete is patchily developed in the soil at Beasley Creek, but spectral examination of carbonate-rich soil showed no evidence of the diagnostic carbonate absorption at 2.33 μm , even though SEM examination showed Ca-rich particles were well exposed at the surface of the soil minerals. This is consistent with studies at Bounty (see below and Report 169R), which found that a CaCO_3 concentration of 40% was required before carbonates are spectrally recognizable. This is much greater than the maximum carbonate content of the Beasley Creek soil. The only indication of carbonate in the spectra was an increase in the albedo, particularly the visible brightness.

The coarse, ferruginous lag commonly shows an upward ramp in reflectance from 0.9 and 1.3 μm which can dominate spectral properties in this region and will influence the geometry of the Fe^{3+} absorption at 0.9 μm . The intensity of this feature has been shown to be correlated with the depth and width of the 1.9 μm water-related absorption, suggesting that this water is either adsorbed on the surfaces of the Fe oxide crystals, by hydrogen bonding, or is intimately associated with more recently precipitated silica and Fe oxides. This spectral property may be related to desert varnish, although the mineralogy of the substrate is clearly evident in the spectra.

Subtle changes in the wavelength of the charge transfer absorption directly over the zone of mineralization indicate a weak but increased development of goethite in the soils. This 0.008 μm shift is detectable by field spectrometer and possibly with remote sensing systems such as Daedalus1268 and Geoscan Mk I and II. However, it must be remembered that hematite and goethite are pervasively developed throughout the weathered profile, hence this spectral information must be considered in the context of an appropriate regolith model.

5.5 BOUNTY

5.5.1 Introduction

The Bounty Au deposit is located in the Forrestania Greenstone belt. Clays, Fe oxides, pedogenic carbonate and quartz dominate the surficial horizons of the regolith. Surface soil samples were collected from three traverses across the zones of Au mineralization and extended far into background areas. These soils were developed from saprolite, lateritic duricrust, gravels and colluvium. The potential for the detection of pedogenic carbonate in these soils was of particular interest because of its value as a sampling medium for Au exploration.

5.5.2 Results and discussion

Pedogenic carbonate was investigated using the carbonate absorption near 2.33 μm , but it could not be detected spectrally even in the most carbonate-rich samples, including large nodules with thick carbonate skins. Laboratory experiments showed that a CaCO_3 concentration of over 40% (by mass) is required before the 2.33 μm absorption is apparent (assuming the carbonate particle size is less than 75 μm). SEM analyses of carbonate nodules showed the outer skin was carbonate-poor and contained abundant aluminosilicates.

The spectra provided information about clays not always evident in routine XRD analyses. These included the identification of smectite and relatively well crystallized kaolinite from changes in the geometry of the 1.4, 1.9 and 2.2 μm absorptions. For example, kaolinite has an Al-OH related absorption at 2.17 μm which produces diagnostic left-handed asymmetry in the 2.2 μm absorption, whereas smectite has an Al-Mg-OH related absorption at 2.23 μm , producing a right-handed asymmetry in the 2.2 μm absorption. These asymmetries were measured using a ratio of the reflectances at 2.17 and 2.23 μm . The spectra show that smectites are only developed in the Ca- and Mg-rich surface soils over stripped areas of residual and transported materials. In comparison, highly crystalline kaolinite is present in the Ca- and Mg-poor

residual soils over lateritic duricrust. Kaolinitic materials are also found at depths > 3 m below the smectitic soils.

The 1.9 μm absorption is more intense for the smectitic soils than for kaolinitic soils, due to the greater capacity of smectites to accommodate water molecules within the crystal structure. Hydrogen bonding of these water molecules is responsible for a distinctive absorption at approximately 1.46 μm , which produces a strong, right-handed asymmetry to the 1.4 μm OH-related absorptions for smectite-rich soils. This asymmetry was gauged using a ratio of reflectances at 1.65 and 1.50 μm .

The spectra are also able to discriminate between Fe oxides. This discrimination is reflected by changes in the wavelength of the 0.9 μm Fe^{3+} absorption minima. Goethitic soils are present in acidic environments over lateritic duricrust, whereas hematite is present in neutral to alkaline environments over areas stripped of lateritic duricrust and rich in Ca and Mg. Hematite is also abundant below 3 m in Ca- and Mg-poor zones beneath the pedogenic carbonate horizon.

The soils over the zone of mineralization also show a shift in the wavelength of the charge transfer shoulder to longer wavelength indicating relatively hematite-rich materials. This shift is opposite to that found by the Beasley Creek study and suggests that different weathering processes have occurred. Further work is required to establish the significance of this difference.

5.6 CONCLUSION

These investigations have increased the spectral data base for the Yilgarn and have also yielded information relevant to exploration:

1. Spectral characteristics in the 0.4 to 2.5 μm wavelength region provide mineralogical information, particularly of Fe oxides and clays, that appear to help characterize soil and lag, and could be used to classify and map regolith materials, using hand-held or remote sensing instruments. They may also discriminate different Fe oxides and clays when such distinctions are not always apparent using routine XRD analysis.
2. Spectral techniques can be used for the semi-quantitative estimation of micas, particularly muscovite, in fresh and weathered rocks and soils. This has potential for identifying alteration haloes around Au mineralization, although the technique is generally limited to materials with more than about 20% mica and could be applied to field logging or remote sensing.
3. Spectral techniques are poor in their discrimination of soil carbonates and hence cannot be used to identify areas where this important sample medium is present.
4. Subtle changes were noted in iron oxide-related spectral features spatially associated with gold mineralization. This needs to be followed up with further work to establish if it is characteristic of different weathering patterns (iron oxide development) over zones of gold mineralization and whether it is mappable using field and remote sensing techniques.

APPENDIX 1. REPORTS ISSUED BY PROJECT P241

Final Report

- 167R Gold and associated elements in the regolith - dispersion processes and implications for exploration. Final Report
C.R.M. Butt, D.J. Gray, M.J. Lintern, I.D.M. Robertson, G.F. Taylor and K.M. Scott.
September, 1991. 114pp.

Investigation Reports

- MG58R Morphology and geochemistry of gold in a laterite profile, Reedy Mine, Western Australia.
P. Freyssinet and C.R.M. Butt. April, 1988. 18pp.
- MG59R Morphology and geochemistry of gold in a laterite profile, Bardoc Mine, Western Australia.
P. Freyssinet and C.R.M. Butt. April, 1988. 28pp.
- MG60R Morphology and geochemistry of gold in a laterite profile, Beasley Creek, Laverton, Western Australia.
P. Freyssinet and C.R.M. Butt. April, 1988. 14 pp.
- MG67R A mineralogical, geochemical and petrographic study of the rocks of drillhole BCD1 from the Beasley Creek gold Mine - Laverton, W.A.
I.D.M. Robertson and S.F. Gall. June, 1988. 47pp. (Joint report with Project P240).
- 4R The aqueous chemistry of gold in the weathering environment.
D.J. Gray. December, 1988. 65pp. (Joint report with Project 240)
- 23R Occurrence of gold in hardpan, Youanmi Mine.
A.Z. Gedeon and C.R.M. Butt. May, 1989. 10pp.
- 24R Study of the distribution of gold in soils at Mt. Hope, Western Australia.
M.J. Lintern. May, 1989. 36pp.
- 26R The pre-mining geomorphology and surface geology of the Beasley Creek gold mine - Laverton, W.A.
I.D.M. Robertson and H.M. Churchward. July, 1989. 39pp. (Joint report with Project 240).
- 27R Geochemistry, petrography and mineralogy of ferruginous lag overlying the Beasley Creek Gold Mine - Laverton, W.A. Volumes I and II.
I.D.M. Robertson. November 1989. 181pp. (Joint project with P240.)
- 32R Mineralogy and Geochemistry of weathered shale profiles at the Panglo Gold Deposit, Eastern Goldfields, W.A.
K.M. Scott February, 1989. 21pp.
- 33R Mineralogy and geochemistry of mineralized and barren weathered profiles, Parkinson Pit, Mt. Magnet, WA.
K.M. Scott. February, 1989. 24pp.

- 36R Mineralogical and geochemical studies of gossan and wall rocks, Bottle Creek, Western Australia.
G.F. Taylor. July, 1989. 35pp.
- 41R Radioelements in weathered shales and mafic volcanics, Panglo gold deposit, Eastern Goldfields, W.A.
K.M. Scott and B.L. Dickson. April, 1989. 31pp. (Joint report with Project P263.)
- 42R Mineralogy and geochemistry of weathered mafic/ultramafic volcanics from section 4200N at Panglo, Eastern Goldfields, W.A.
K.M. Scott. April 1989. 22pp.
- 43R Mineralogy and geochemistry of some weathered rocks from Callion gold deposit, Yilgarn Block, W.A.
S.M. Llorca. April, 1989. 10pp.
- 58R Mineralogy and geochemistry of the Glasson gold deposit, Callion, Yilgarn Block, W.A.
S.M. Llorca. August, 1989. 33pp.
- 73R Mineralogy and geochemistry of mineralized and barren felsic volcanic profiles, Parkinson Pit, Mt. Magnet, W.A.
K.M. Scott. September, 1989. 18pp.
- 102R The petrography, mineralogy and geochemistry of weathering profiles developed on felsic, mafic, ultramafic and sedimentary rocks, Rand Pit, Reedy Mine, Western Australia.
I.D.M. Robertson, G.F. Taylor and M.A. Chaffee. December, 1990. Volumes I and II. 205pp.
- 105R Mineralogy and geochemistry of soils overlying the Beasley Creek gold mine - Laverton, W.A.
I.D.M. Robertson. September, 1990. Volumes I and II 158pp. (Joint report with Project 240.)
- 109R Multi-element soil survey of the Mount Hope area, Western Australia.
M.J. Lintern, H.M. Churchward and C.R.M. Butt. May, 1990. 76pp.
- 110R Gold morphology and composition at Panglo, Eastern Goldfields W.A.
K.M. Scott and J.J. Davis. April, 1990. 9pp.
- 124R Morphology and geochemistry of particulate gold in the lateritic regolith, Mystery zone, Mt. Percy, Kalgoorlie, Western Australia.
A.Z. Gedeon and C.R.M. Butt. October, 1990. 41 pp.
- 125R Hydrogeochemistry of the Panglo gold deposit.
D.J. Gray. October, 1990. 74pp.
- 126R Chemistry of gold in some Western Australian soils.
D.J. Gray, M.J. Lintern and G.D. Longman. November, 1990. 62pp.
- 127R The sorption of gold and silver on soil minerals.
D.J. Gray. December, 1990. 18pp.
- 128R Chemistry of gold-humic interactions.
D.J. Gray, M.J. Lintern and G.D. Longman. November, 1990. 32pp.

- 129R The distribution of gold and other elements in soils and vegetation at Panglo, Western Australia.
M.J. Lintern and K.M. Scott. October, 1990. 96pp.
- 143R The mineralogical and geochemical effects of weathering on volcanics from the Panglo deposit,
Eastern Goldfields, WA.
K.M. Scott. June, 1990. 47pp.
- 147R Electron microprobe studies of minerals from weathered profiles, Parkinson Pit and environs, Mt.
Magnet, WA.
K.M. Scott. July, 1990. 48pp.
- 152R Multi-element dispersion in the saprolite at Beasley Creek gold mine, Laverton, Western
Australia.
I.D.M. Robertson. April, 1991. Volumes I and II. 122pp.
- 156R Geochemical dispersion in the regolith, Mystery Zone, Mt. Percy mine, Kalgoorlie, Western
Australia.
C.R.M. Butt. January, 1991. Volumes I and II. 226pp.
- 159R Distribution of gold and other elements in soils from the Mulline area, Western Australia.
M.J. Lintern and C.R.M. Butt. February, 1991. 56 pp.
- 171R The mineralogical and geochemical effects of weathering on shales at the Panglo deposit, Eastern
Goldfields, WA.
K.M. Scott. August, 1990. 35pp.
- 178R The mineralogy and geochemistry of weathered mafic and ultramafic rocks, Parkinson Pit, Mt.
Magnet, Western Australia.
K.M. Scott and A. Martinez. October, 1990. 39pp.
- 187R Geochemistry of the gossans, weathered mineralization and host rocks, Telfer gold mine, Western
Australia.
J.R. Wilmschurst. March, 1991. Volumes I and II. 154pp.

APPENDIX 2. REPORTS ISSUED BY PROJECT P241A

Final Report

- 396R Gold and associated elements in the regolith - dispersion processes and implications for exploration. Final Report, Project P241A.
C.R.M. Butt, D.J. Gray, M.J. Lintern and I.D.M. Robertson. June, 1993. 64pp.

Investigation Reports

- 160R Spectral properties of soil and lag overlying the site of the Beasley Creek gold mine, Laverton Region, Western Australia. Volumes I and II.
T.J. Cudahy, I.D.M. Robertson and A.R. Gabell. September, 1992. 140pp. (Joint report with Project 243).
- 169R Spectral properties of soil overlying the sites of the Bounty and North Bounty Gold Mines, Forrestania Region, Western Australia.
T.J. Cudahy, M.J. Lintern and A.R. Gabell. September, 1992. 89pp. (Joint report with Project 243).
- 232R Petrography, mineralogy and geochemistry of soil and lag overlying the Lights of Israel Gold Mine, Davyhurst, Western Australia. Volumes I and II.
I.D.M. Robertson and M.F.J. Tenhaeff. October, 1992. 156pp. (Joint report with Project 240A.)
- 234R Spectral properties of muscovite- and paragonite-bearing rocks and soils from the Panglo Gold Deposit, Ora Banda region, Western Australia.
T.J. Cudahy, K.M. Scott and A.R. Gabell. September, 1992. 53pp. (Joint report with Project 243.)
- 237R Hydrogeochemistry of sulfide weathering at Boags Pit, Bottle Creek, Western Australia.
D.J. Gray. March, 1992. 18pp.
- 328R The distribution of gold and other elements in soils and vegetation at Zuleika, Western Australia.
M.J. Lintern and C.R.M. Butt. October, 1992. 90pp.
- 339R Geochemical and hydrogeochemical investigations of alluvium at Mulgarrie, Western Australia.
D.J. Gray. December, 1992. 66pp.
- 385R The distribution of gold and other elements in soils at Granny Smith, Western Australia.
M.J. Lintern and C.R.M. Butt. May, 1993. 73pp.
- 387R Investigation of hydrogeochemical dispersion of gold and other elements in the Wollubar palaeodrainage, Western Australia.
D.J. Gray. May, 1993. 100pp.
- 389R Geochemical background, Mt. Percy, Kalgoorlie, Western Australia.
C.R.M. Butt. May, 1993. 110pp.
- 390R Atlas of weathered rocks.
I.D.M. Robertson and C.R.M. Butt. June, 1993.

- 391R Further aspects of the chemistry of gold in some Western Australian soils.
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