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SUPERGENE MOBILIZATION OF GOLD AND OTHER ELEMENTS IN THE YILGARN CRATON - FINAL REPORT.

D.J. Gray, N.B. Sergeev, A.F. Britt and C.G. Porto

CRC LEME OPEN FILE REPORT 228

November 2008

(CRC LEME Restricted Report 152R / E&M Report 757R, 2001
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CRC LEME is an unincorporated joint venture between CSIRO-Exploration & Mining, and Land & Water, The Australian National University, Curtin University of Technology, University of Adelaide, Geoscience Australia, Primary Industries and Resources SA, NSW Department of Primary Industries and Minerals Council of Australia.

Headquarters: CRC LEME c/o CSIRO Exploration and Mining, PO Box 1130, Bentley WA 6102, Australia

The CRC LEME–AMIRA Project 504 "**SUPERGENE MOBILIZATION OF GOLD IN THE YILGARN CRATON"** was carried out over the period 1998 to 2001. Twelve reports resulted from this collaborative project.

CRC LEME acknowledges the support of companies associated with and represented by the Australian Mineral Industries Research Association (AMIRA), and the major contribution of researchers from CSIRO Exploration and Mining.

Although the confidentiality periods of the research reports have expired, the last in July 2002, they have not been made public until now. In line with CRC LEME technology transfer goals, re-releasing the reports through the **CRC LEME Open File Report (OFR) Series** is seen as an appropriate means of making available to the mineral exploration industry, the results of the research and the authors' interpretations. It is hoped that the reports will provide a source for reference and be useful for teaching.

OFR 217 – Characteristics of gold distribution and hydrogeochemistry at the Carosue Dam prospect, Western Australia – DJ Gray, NB Sergeev and CG Porto.

OFR 218 – Gold distribution, regolith and groundwater characteristics at the Mt Joel prospect, Western Australia – CG Porto, NB Sergeev and DJ Gray.

OFR 219 – Supergene gold dispersion at the Argo and Apollo deposits, Western Australia – AF Britt and DJ Gray

OFR 220 – Geochemistry, hydrogeochemistry and mineralogy of regolith, Twin peaks and Monty Dam gold prospects, Western Australia – NB Sergeev and DJ Gray.

OFR 221 - Supergene gold dispersion in the Panglo Gold deposit, Western Australia – DJ Gray.

OFR 222 – Gold concentration in the regolith at the Mt Joel prospect, Western Australia – DJ Gray.

OFR 223 – Gold dispersion in the regolith at the Federal Deposit, Western Australia – NB Sergeev and DJ Gray.

OFR 224 – Supergene gold dispersion in the regolith at the Cleo deposit, Western Australia – AF Britt and DJ Gray.

OFR 225 – Distribution of gold arsenic chromium and copper in the regolith at the Harmony Deposit, northern Yilgarn, Western Australia – AF Britt and DJ Gray

OFR 226 – Supergene gold dispersion in the regolith at the Kanowna Belle and Ballarat Last Chance deposits, Western Australia – DJ Gray

OFR 227 – Supergene gold dispersion, regolith and groundwater of the Mt Holland region, Southern Cross province, Western Australia – AF Britt and DJ Gray.

OFR 228 – Supergene mobilization of gold and other elements in the Yilgarn Craton, *Western Australia – FINAL REPORT* – DJ Gray, NB Sergeev, CG Porto and AF Britt

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EXECUTIVE SUMMARY

This report summarizes the three year CRC LEME/AMIRA Project P504 *"Supergene mobilization of gold and other elements in the Yilgarn Craton"*. This Project had, as its principal objective, "the determination of the mechanisms of supergene/secondary depletion, enrichment and dispersion of Au and other elements, so as to improve selection of drilling targets and further optimize interpretation of geochemical data". The principal fields of research and the outcomes are as follows:

1. Site studies

Five major study sites (Mt Joel, Carosue Dam, Twin Peaks/Monty Dam, Federal and Mt Holland) were selected across the Yilgarn and included detailed studies, 3D modelling and Au concentration calculations for 11 ore bodies. Another eleven deposits (Argo, Apollo, Kanowna Belle, Ballarat Last Chance, Golden Delicious, Cleo, Panglo, Mount Percy*, Harmony, Challenger and Comet*) were chosen for 3D modelling and Au concentration calculations. The project began with a review of supergene Au dispersion at 42 Yilgarn sites previously studied. Additionally, results from the Yandal Belt Project, along with extensions of the studies at Empire, Elliot and Gourdis, have also been used for this project.

2. Regional delineation of groundwaters in the Yilgarn Craton

Approximately 600 groundwater samples (130 within P504 with other data from previous projects) have been analysed by CSIRO/CRC LEME, with additional data from some 2000 sites on the Yilgarn obtained from other sources. These results have been used to delineate the variation in groundwater characteristics across part of the Yilgarn Craton and margins. The groundwaters are regionally grouped as follows, based on salinity and pH:

1. **Northern groundwaters** (Northern Yilgarn and margins)
   Groundwaters in these areas are fresh and neutral, trending to more saline in valley floors.
2. **Central groundwaters** (close to and north of the Menzies line; Butt *et al.*, 1977)
   Groundwaters here are neutral and brackish (commonly < 1% TDS) to saline (about 3% TDS), tending to hypersaline (10 to 30% TDS) at the salt lakes, generally with increasing salinity with depth.
3. **Kalgoorlie groundwaters**
   These groundwaters are commonly acid (pH 3 to 5), except where buffered by extremely alkaline materials (e.g., ultramafic rocks), and saline within the top part of the groundwater mass, trending to more neutral (pH 5 to 7) and hypersaline at depth and when within a few km of saline playas.
4. **Eastern groundwaters** (Eastern Yilgarn and Officer Basin)
   Groundwaters are saline to hypersaline, neutral to acid. Within palaeochannels they are reducing, presumably due to the presence of lignites and sulphides. The major ion chemistry is similar to that of the Kalgoorlie region, but, because of the lignites in the channel sediments, the dissolved concentration of many other ions is low.

As Au solubility is strongly enhanced in saline groundwaters, particularly when groundwaters are also acid and oxidizing, these variations have major effects on supergene Au mobility.

3. Geomorphological characteristics of the Yilgarn

Groundwater conditions, and therefore observed patterns of supergene Au mobility, can be related to geomorphology. In northern regions of the Yilgarn, where the main valleys have significant flow slopes and there are small, restricted areas of high salinity, supergene Au mobility is limited. In the

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* Site studies at Mt Percy and Comet were solely funded by CRC LEME. However, these results are included within this project report.

south and east, groundwater tends to pond (e.g., Lake Carey, Kalgoorlie) and salinity is much higher and more extensive and observed Au mobility is strong.

4. Catchment scale differences

Within each of the groundwater regions, the degree of Au mobility is affected by local geomorphological factors, though the magnitude of the variations depends on the particular region. In the Kalgoorlie region, strong Au depletion of the upper regolith is common, except along ridges or close to drainage divides. In the Central region, there is strong depletion at the valley floors, slight (< 50%) to moderate (50 to 80%) depletion along valley flanks, and little depletion in the uplands. In the Northern region, strong depletion is predicted to occur only in the local environment of the main drainage channels, or when enhanced by lithological factors (e.g., high sulphide ore bodies).

5. Geometry of the saprolitic Au enrichment zone

Supergene Au enrichment in the saprolite has a sharp upper contact with the overlying depleted zone. Typically, the highest Au concentrations occur in the top 1 to 5 m of the supergene Au enrichment zone, due to absolute chemogenic accumulation. Below this, enrichment appears to be almost exclusively residual. There appears to be no lateral dispersion and hence no increase in size, though the absolute concentrations are greater than in the unweathered rock. In general, Au distribution delineated by the saprolite enrichment roughly corresponds (at higher concentration) to that in the primary zone.

6. Control on depth of depletion

The mean depth of the saprolitic Au enrichment zone is similar at the majority of the sites (30 to 40 m). However, there can be considerable local variation, depending on lithology, structure and regolith preservation. Horizon boundaries in the regolith normally have a major control on the depth of the Au depletion front, which commonly occurs at the clay saprolite to mid saprolite regolith boundary, which is generally related to the alteration front of primary aluminosilicates to clay minerals, mostly kaolinite and Fe oxides. The regolith transition is roughly coincident with the Fe^{3+}/Fe^{2+} redox front, although these two transitions may differ by several metres.

The visual characteristics of the transitions are as follows:

1. Colour change, from red-yellow-cream in mafic, ultramafic and intermediate felsic rocks or white to pale-grey in granitoids, to grey-green weathered rocks.
2. Granulometric change, from clay-rich, soft regolith to saprolite with visible primary rock fabric. In the upper clay zone, there may be primary fabric, but this tends to be poorly distinguished in drill cuttings. Additionally, there is an clear reduction in rock hardness and in the upper zone regolith fragments can be broken by hand. In drill cuttings, 1-2 mm wet sieving of regolith portions can help resolve this critical transition, with a major increase in the proportion of coarse fragments beneath the transition.

7. Influence of primary mineralization and lithology

The nature and degree of supergene Au remobilization is influenced by primary mineralization and lithology. Free primary Au, partly locked within quartz-veins tends to remain stable in the regolith and can be residually concentrated near the surface with only partial depletion from the upper regolith. In contrast, Au associated with sulphides, particularly massive sulphides (>20% sulphides) is much more mobile in the regolith. Submicron particle size, easy access for supergene solutions and increased concentrations of S oxyanions favouring Au dissolution, generate highly corrosive conditions. Massive sulphide ore bodies show strong Au depletion and remobilization in the regolith, regardless of region or depth of water-table.

8. Gold redistribution within palaeochannels

Further studies are required to properly understand factors controlling dispersion of Au into palaeochannels, though results so far suggest the critical importance in differences in sediment material, particularly the presence of highly reduced material such as lignite or secondary sulphides. Lignite is primarily restricted to the SE of the Yilgarn Craton. By causing reducing conditions, lignite limits dispersion of Au into the palaeochannel sediments, although significant Au anomalies are observed in lignites close to the unconformity and in basal gravels and sands. In contrast, oxidized palaeochannel systems may show major Au dispersion, representing a potentially useful exploration medium.

9. Surface calcrete Au anomalies

Research within this and previous CRC LEME Projects indicates a coherent and physically connected source for Au in pedogenic carbonates. Although pedogenic carbonates are recommended as a preferred sampling media where they occur, due to ease of sampling and common broadening of the anomaly, interpretation of the Au source may be complicated. The magnitude of the surface Au anomaly, or indeed even the presence or absence of an anomaly, cannot be directly correlated with the size or grade of the primary mineralization. Surface or near surface carbonate sampling for Au exploration can "see through" transported cover only where the cover is less than 10 m, at best, or, more probably, less than 5 m. Thus, carbonate sampling represents a very useful "first pass" technique, which can then only be properly understood by understanding the regolith processes giving rise to the surface anomaly.

10. Different chalcophile solubilities

Groundwater analyses confirm that chalcophile elements, such as As and Sb, have different dissolution characteristics to Au, being less soluble in acid conditions. However insufficient data have been collated to develop a complete picture of chalcophile mobility. Limited results for acid groundwaters indicate little As leaching below the water-table; significant loss of As only occurs in the upper unsaturated portion of the regolith. In contrast, neutral groundwater sites north of Kalgoorlie might be expected to show more As depletion below the water-table, though available results do not strongly support this hypothesis.

11. Possible exploration uses for groundwaters

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

12. Gawler Craton

There are major similarities between the Yilgarn and Gawler Cratons, in terms of hydrogeochemistry and degrees and geometry of supergene Au mobility. Although significantly more investigations are required to understand the variation of groundwaters in the Gawler Craton and the importance of the various transported materials, it is expected that the models suggested for supergene Au mobility in the Yilgarn Craton should be applicable in the Gawler.

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1 INTRODUCTION

1.1 Exploration Issues

Supergene Au depletion and deeper dispersion haloes are well documented, especially in the Yilgarn Craton. They are the product of modification under saline and acid conditions of a pre-existing, deeply weathered regolith. An understanding of the processes that form them are of major importance for effective mineral exploration. Typically, lateritic residuum appears to maintain any pre-existing Au enrichment, but the underlying saprolite may be severely leached. If the laterite has been eroded there may be little or no Au in the upper regolith, presenting a major exploration difficulty. Conversely, if there has been Au dispersion in the saprolite, it may give a significantly broader target than the underlying mineralization. Supergene enrichment zones may represent useful drilling targets and, in some circumstances, may even be economic Au targets in their own right.

The processes of chemical dispersion of Au and other elements, particularly in the acid and saline groundwaters in the southern part of the Yilgarn Craton, have been intermittently studied prior to this project (abbreviated as P504), both before, and as part of, the various AMIRA projects undertaken by CRC LEME and CSIRO Exploration and Mining. However, the depletion and supergene enrichment zones, and the processes and timing of their formation, are insufficiently well established for optimum use in exploration. Accordingly, P504 research was directed at establishing their nature and origin and, using this information, to assist in optimizing exploration strategies and interpretation.

1.2 Objectives

The objectives of the project were:

Principal Objective
To determine the mechanism of supergene/secondary depletion, enrichment and dispersion of Au and other elements, so as to improve selection of drilling targets and further optimize interpretation of geochemical data.

Specific Objectives

1. Establish the extent, relative timing and patterns of supergene Au mobility.
2. Further investigate the mobility of pathfinder elements in the regolith and how they are influenced by acidity and/or salinity.
3. Establish whether there were specific differences in the degree, timing and form of supergene Au haloes, between different regions of the Yilgarn Craton, caused by the major differences in groundwater chemistry.
4. Compare results for the Gawler Craton with those observed for the Yilgarn.
5. Establish whether deposits within the same region give different supergene dispersion patterns due to local groundwater changes (e.g., depth to water, changes in salinity with distance from a salt lake system).
6. Investigate methods for determining changes in groundwater conditions over time.
7. Establish whether differences in the geology and alteration mineralogy of various deposits affect supergene processes.
8. Translate research results into more cost-effective exploration for Au.

1.3 Benefits

The expected benefits from the research included:

1. Enhanced understanding of the processes of supergene Au mobilization.
2. Greater understanding of the nature and origin of supergene gold deposits.
3. Methods for predicting the form of supergene Au, using available drill cuttings and core.
4. More cost-effective drilling and analytical strategies.
5. Prediction of the form of the Au target for exploration, based on determinable characteristics (e.g., region, water-table, lithology and alteration type).

1.4 Research strategy

To achieve the objectives of the project, five principal disciplines were used.

1. Weathering studies and regolith characterization

Drill cuttings, core and field exposures, mineralogical and micromorphological studies were used to characterize the regolith at the study sites. Careful characterization of regolith materials is essential for ensuring that samples are reliable for clarifying element dispersion patterns.

This discipline comprised approximately 20% of the activities of the project.

2. Gold and multi-element geochemistry, including 3D modelling

Previous regolith dispersion studies have been 1D (drill hole) or 2D (section or plan). Advances in software design and the availability of large amounts of logging and geochemical data have enabled intensive 3D investigations of regolith stratigraphy and the distribution of Au (and, in some cases, other elements). These 3D investigations have strongly enhanced our understanding and modelling of secondary dispersion.

Additional dispersion studies, based on a limited number of multi-element analyses, have provided information concerning the distributions of elements associated with mineralization. These include elements that may control distributions in the regolith (e.g., Fe, Ca, Mn) and those diagnostic for regolith stratigraphy or parent lithology (e.g., Al, Si, Fe, Cr, Ti, Zr). Dispersion studies at individual sites involved the analysis of fresh and weathered rocks, soils and selected fractions of these materials. This included partial extraction analyses (see below) to emphasize dispersion associated with specific minerals or organic phases, especially dispersion under present conditions. These investigations established the nature of geochemical dispersion patterns in various regolith units, the probable mechanisms involved and recommendations for exploration procedures.

This discipline comprised approximately 40% of the activities of the project.

3. Hydrogeochemistry

New hydrogeochemical studies, and use of a regional groundwater database from previous projects, were used to investigate dispersion, regolith evolution and the genesis of secondary mineralization. This also provided data on the potential of groundwater sampling in exploration for concealed mineralization. Although the most profound weathering of the Yilgarn and its environs is thought to have taken place under humid climates in the early Tertiary, weathering is still continuing, albeit under changed conditions, examples being the accumulation of carbonate at the near surface (Lintern *et al.*, 1997) and alunite lower in the regolith profile (Butt, 2001). This is particularly true in alluvial, commonly saline areas, low in the landscape, where water-tables are closer to surface and there is greater interaction between groundwater and the regolith. Hydrogeochemistry is fundamental to understanding active processes that may be giving rise to the supergene dispersion of Au and other elements.

This discipline comprised approximately 15% of the activities of the project.

4. Solution - solid interactions

The chemical behaviour of many elements in the regolith is still poorly known and laboratory studies were developed to assist interpretation of data from the study sites. Partial and selective extractions can indicate the distribution of elements between various solid phases and enhance understanding of dispersion processes.

This discipline comprised approximately 15% of the activities of the project.

5. Gold grain studies

Gold grain studies are critical for understanding supergene dispersion. Identification of primary grains are an unambiguous indicator that (at least some) Au dispersion is not hydromorphic. Thus, primary Au grains in transported material indicate physical transport. Primary Au grains within a supergene enrichment zone suggest residual accumulation rather than hydromorphic transport. Gold grain studies within this project have tested these potential processes.

This discipline comprised approximately 10% of the activities of the project.

1.5 Project Sponsors

The project commenced 1 July 1997. The first sponsors' meeting was held on 23 July 1997 and the project formally concluded with the Final Meeting (30 October to 2 November 2000). The 11 sponsors of the project were:

Aberfoyle Resources Ltd (now Western Metals Ltd)
Acacia Resources Limited (now Anglogold Ltd)
Aurora Gold Ltd
BHP Exploration
Delta Gold NL
Goldfields Exploration Pty Ltd
Great Central Mines Ltd (now Normandy Yandal Ltd)
MIM Exploration Ltd
Normandy Exploration Ltd
North Ltd (now Rio Tinto)
WMC Resources Ltd

1.6 Project Staff

Project Leader
Dr David J. Gray

Professional Staff
Dr Nikita Sergeev
Dr Claudio Porto (until February 1999)
Ms Allison Britt (from February 1999)

Support Staff
Mr Dale Longman

2 SUMMARY OF SITE STUDIES

Five sites for major study were selected across the Yilgarn and another eleven, including two in the Gawler Craton, were chosen for 3D modelling. The project began with a review of all available information on supergene dispersion from Au ore bodies in the Yilgarn Craton, to:

1. Compile information on regolith Au deposits. Characterize primary geology, regolith stratigraphy, hydrogeochemistry, Au distribution patterns and analyse the factors that control supergene Au dispersion.
2. Characterize zones of supergene Au depletion and enrichment, principal styles of the supergene Au enrichment and a scale of lateral Au dispersion.
3. Estimate achievements and gaps in understanding of processes of supergene Au mobilization, dispersion and enrichment.
4. Formulate the critical issues to achieve the project objectives.

The results of this study were released as a dataset with critical details documented in the report.

The review determined the principal styles of Au enrichment and investigated scales of lateral Au dispersion. It was generally difficult to quantify supergene Au mobility from qualitative description. To address this, emphasis was put on 3D visualization of the selected sites and calculation of Au concentrations within the regolith, using the program Mining Visualization System (MVS, © CTech), at all five major site studies and an additional eleven deposits. The sites investigated within P504 (Figure 1) were:

Major site studies:

1. **Mt Joel.** Five separate sites grouped within 3 km, with similar geological setting. The groundwaters are fresh. Transported cover varies from 0 - 80 m in thickness.
2. **Carosue Dam.** Mineralization is hosted by felsic rocks. Groundwater is saline, acidic and oxidizing. There is a pronounced surface Au anomaly in transported overburden.
3. **Twin Peaks and Monty Dam.** Similar to Carosue Dam in that mineralization is hosted by felsic rocks. Twin Peaks differs in being arsenopyrite-rich. Twin Peaks groundwaters are also similar to Carosue Dam, being saline, acidic and oxidizing. However, Monty Dam, immediately adjacent to Lake Rebecca, has groundwaters that are saline, neutral and less oxidizing.
4. **Federal.** Mineralization occurs in granitic rocks. Groundwaters are saline and neutral.
5. **Mt Holland.** Five separate sites, Bounty, Bounty East, Bush Pig, Twinings and Lounge Lizard were studied. The geology, mineralization, geomorphology and groundwater chemistries vary. Groundwaters can be acidic and oxidizing, but not as extreme as those in the Kalgoorlie area.

3D study sites:

1. **Argo and Apollo.** These two sites are approximately 2 km from Lake Lefroy and are hosted within two mylonitic shear zones in dolerite. Argo abuts a lignite-rich palaeochannel, whereas Apollo is dominated by residual regolith, away from the palaeochannel. Groundwaters are saline and neutral to acidic.
2. **Kanowna Belle and Ballarat Last Chance (BLC).** These two sites are in an area with saline groundwaters. Mineralization at Kanowna Belle is primarily hosted by feldspar porphyry and volcanic-related conglomerates. Upslope, mineralization at BLC is hosted by ultramafic lithologies.
3. **Golden Delicious.** Mineralization occurs along granite-greenstone contacts. The deposit is about 5 km E of Lake Carey and has saline, neutral groundwaters.

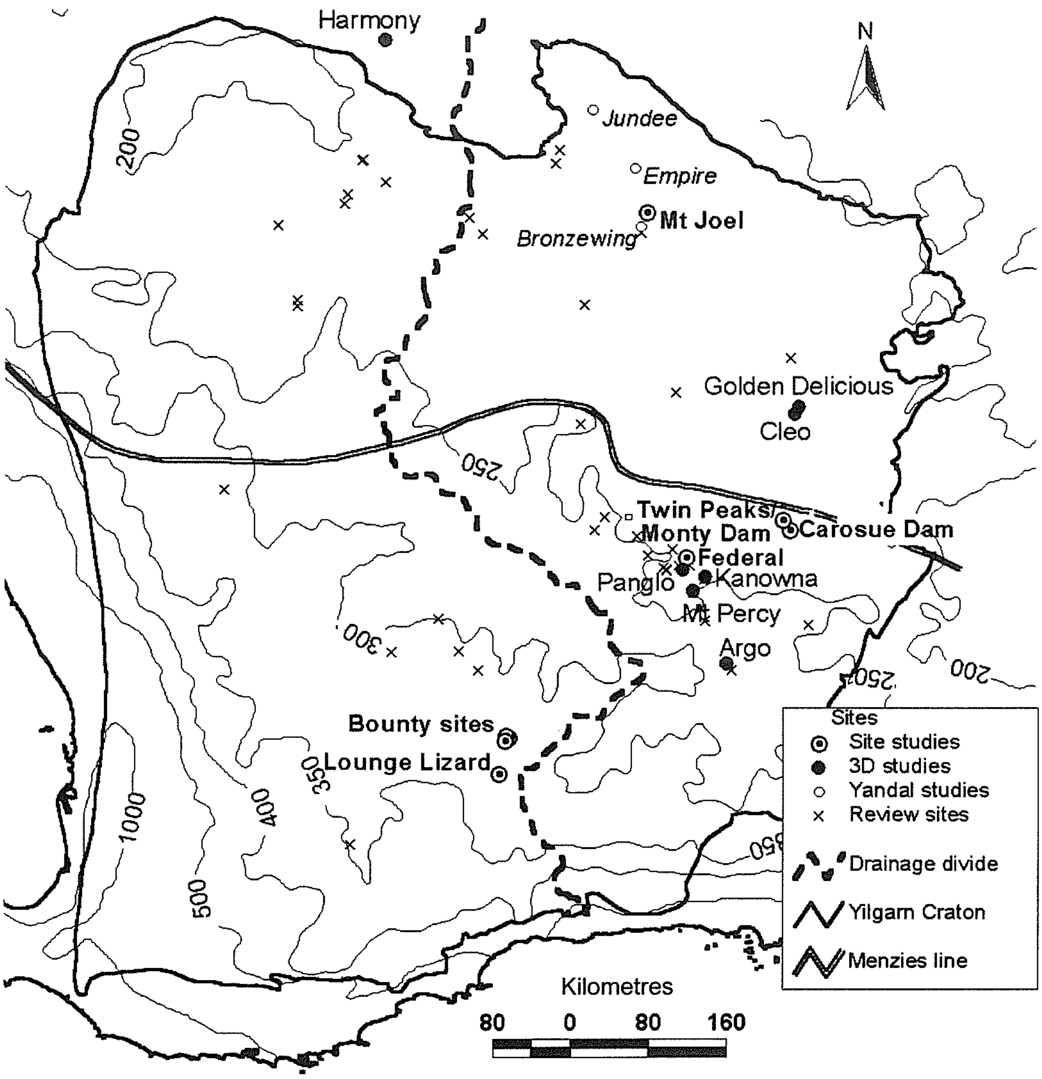

Figure 1: Location of Western Australian study sites, showing the boundary of the Yilgarn Craton, the major N-S drainage divide, the Menzies line and isohyets (courtesy Bureau of Meteorology).

4. **Cleo.** Mineralization occurs within volcaniclastic rocks of intermediate composition and is associated with pyrite replacement. The deposit abuts Lake Carey and is buried by transported overburden. The groundwaters are hypersaline.
5. **Panglo.** Mineralization occurs in carbonaceous shales and mafic to ultramafic volcanics. The groundwaters are saline and acid.
6. **Mount Percy[*].** Mineralization is located in the Hannans Lake Serpentinite in the Mystery Zone, with the chlorite talc carbonate rocks intruded by porphyries, with strong fuchsite-carbonate alteration occurring at their contacts. Mineralization is largely confined to the porphyries and adjacent ultramafic rocks. The water-table is below the base of weathering.
7. **Harmony.** The Harmony deposit is located at the contact between the Narracoota Volcanics and the Thaduna Greywacke, in an early Proterozoic sequence. Groundwaters are fresh and neutral.

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[*] Site studies at Mt Percy and Comet were solely funded by CRC LEME. However, these results are included within this project report.

8. **Challenger.** The Challenger Au deposit is located in the Gawler Craton, 750 km NW of Adelaide. Mineralization is hosted within Palaeoproterozoic meta-sediments. A vertical shoot was used for calculations of Au concentration variations within the regolith.
9. **Comet**[*]**.** The Comet prospect is located approximately 100 km NNW of Tarcoola in the Gawler Craton. MVS investigations of this site have included 3D visualizations and concentration calculations for Au, As, Cu, Zn, Ni, Co, Pb and Mo.

Additionally, results from the collaborative CRC LEME/Great Central Mines Ltd (now Normandy Yandal Ltd) project on the Yandal Greenstone Belt (Phillips and Anand, 2000) were available. Sites with useful regolith Au results are: Bronzewing, Jundee, Empire, Gourdis, Elliot, Callista and Mt McClure. Some of these sites included limited MVS analyses.

Major site study investigations generally included:

1. Characterization of the regolith.
2. Investigation of geochemical dispersion of Au (and other relevant elements) during weathering.
3. Selective extraction analysis of regolith materials in order to detect differences in potential Au mobility within regolith at each site, and between sites.
4. Groundwater geochemistry.

Other, complementary, research included:

1. Optimization of Au extraction techniques, as required.
2. Column investigations for the modelling of supergene Au mobilization processes.
3. Relevant hydrogeochemical studies to add critical data for understanding of regional groundwater patterns.
4. Using CRC LEME and/or other groundwater data, to model past groundwater regimes.

The site studies, and many of the MVS studies, are described in individual reports released during the Project. A list of the reports is included as Appendix 1.

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[*] Site studies at Mt Percy and Comet were solely funded by CRC LEME. However, these results are included within this project report.

3 METHODS AND MATERIALS

3.1 Logging and sampling

Drill hole or mine pit samples were selected at each site, and are described in individual reports. Logging was based mostly on bulk colour of the samples, guided by Munsell colour charts, and the nature of coarse fragments obtained by wet sieving of approximately 300 g of each sample. Selected bulk samples were collected for Au grain studies (Section 3.3).

Regolith and geochemical modelling used company-supplied logging. Where possible, company logging was checked against logging by CRC LEME staff and an equivalence table produced. Details of the correspondence between logging methods is given in individual reports.

3.2 3D gridding, visualization and Au concentration calculations

Regolith stratigraphy and geochemistry were studied with the 3D visualization program MVS (Mining Visualisation System, © C Tech Development Corporation), using company geochemical and logging information. There were major variations in logging quality and consistency. In general, the most problematic sites were those that had been explored over a long time. These generally showed major spatial and temporal variations, presumably due to changes in staff and different emphases on regolith units. The only logged regolith boundaries used were those that showed good stability, and/or a sub-sample of the logging was used (commonly the most recent). After careful checking and filtering of the logging, the regolith boundaries were delineated and used in later geochemical modelling.

Regolith horizons were gridded, and 'point' anomalies were removed from the input data prior to final gridding. Although this has the potential to bias the data, it was necessary to give coherent weathering horizons. For pictorial presentations, the Au data were log-transformed (base 10) before gridding (Porto *et al.*, 1999). Although this affects the magnitude of the mineralization, it enhances the detail of subtle supergene redistributions. For Au grade calculations (see below), untransformed data were used. In some cases, surface geochemical data were collected as 4 m composites, which can lead to deeper and weaker surface anomalies (e.g., a 4 m composite of a 1 m horizon at 0.5 ppm and a 3 m horizon at 0.1 ppm will give a single horizon of 4 m at 0.2 ppm).

Gold concentrations were calculated with untransformed data. No attempt was made to model different densities for different units. As the Au grade data are mass per unit mass rather than mass per unit volume, this can influence estimates of enrichment and depletion. Calculated concentrations do not compensate for leaching of mobile constituents: if half of the minerals have been leached then Au grade will double by residual concentration. Gold concentrations were calculated for slices defined either by elevation (e.g., 390-393 m RL) or distance from a regolith boundary (e.g., 3-6 m above the unconformity). Most investigations used 3 m vertical spacings. For some critical boundaries, where Au concentrations appeared to change more abruptly than could be accurately determined using a 3 m vertical spacing, the data were re-gridded and concentrations calculated using a 0.5 m vertical spacing.

Figure 2 illustrates nominal 3 m slices taken progressively down from the unconformity. These slices become truncated downwards at the base of weathering, as the analysis does not include the next regolith horizon. While this may be arithmetically correct, it can lead to over- or under-estimations of concentrations as the slices get further from the reference transition (in this case the unconformity). This is because, ultimately, the slice being analyzed is incomplete, again illustrated in Figure 2, as the slices becoming more and more truncated by the base of weathering. This is not a problem in calculation accuracy, but in the actual geometry of the study. It can be expressed as a reliability factor, which is the mass of the slice divided by the mass of an untruncated slice (Figure 2). A reliability index of 85% indicates that the slice is 15% truncated.

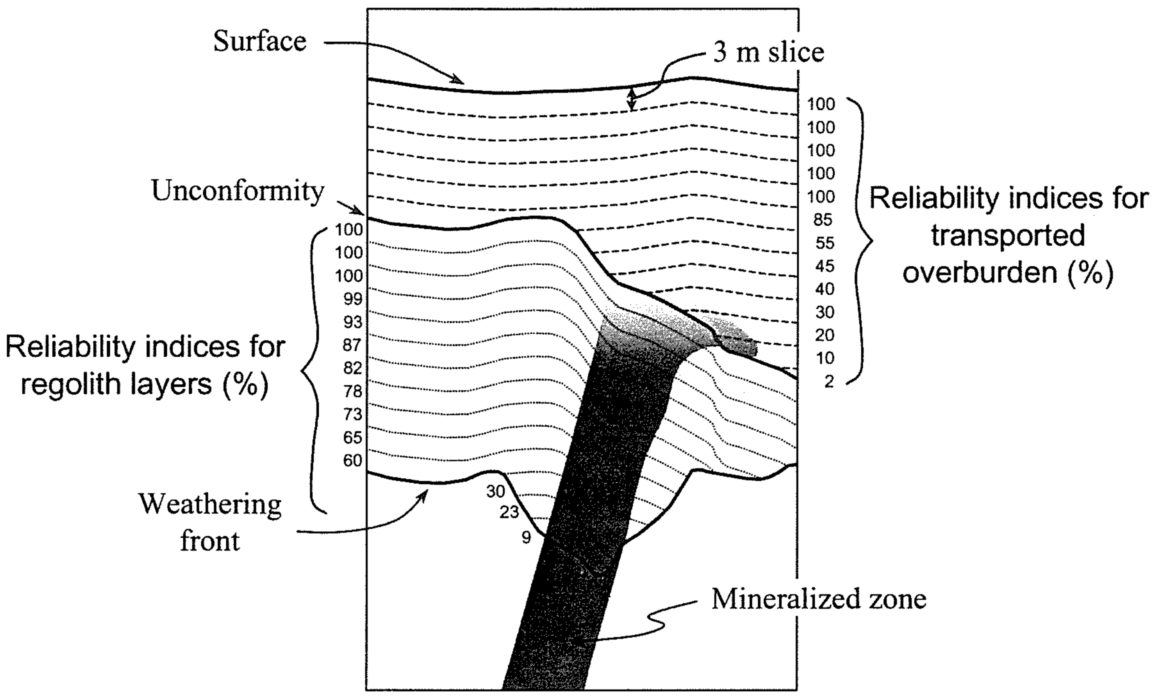


Figure 2: Diagrammatic representation of reliability indices and slices paralleling the upper surface and limited by the unconformity, as used in calculations of Au concentration shown in Figure 3.

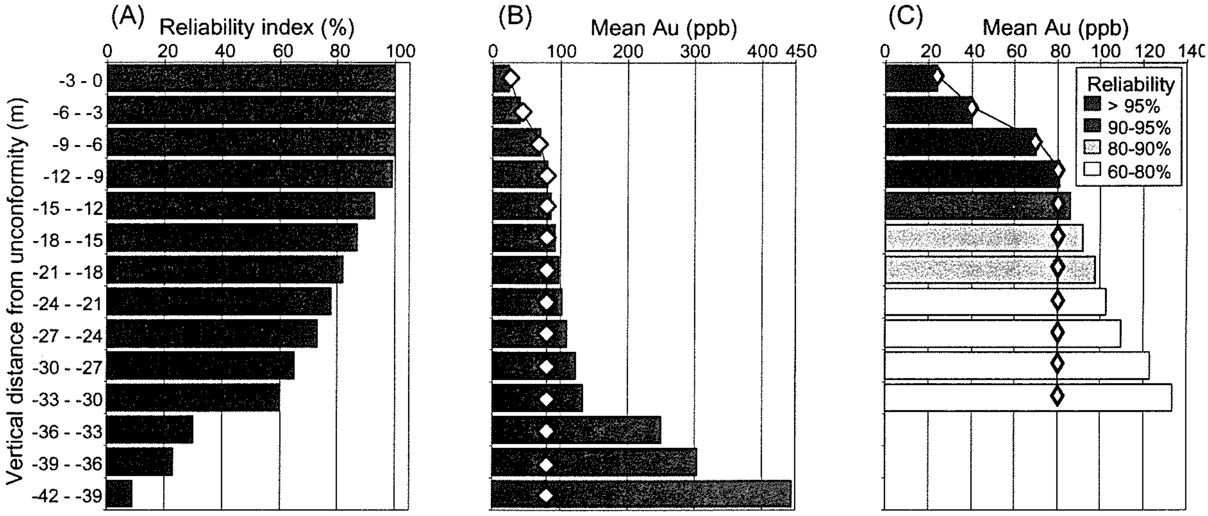


Figure 3: Calculated (A) regolith reliability, (B) unfiltered Au concentration and (C) filtered (> 60% reliability) Au concentration colour coded to reliability. Diamonds represent expected Au concentration is there were no truncation. Data based on situation represented in Figure 2.

As the reliability index decreases, significant errors begin to occur. Figure 3 shows the Au concentration measurement for each slice from the unconformity. Although the deeper slices are truncated (Figure 3A), they can still contain mineralized material, as in this example (Figure 2). Thus, a similar mass of Au is being divided by smaller and smaller amounts of regolith, which leads to anomalous Au concentrations (Figure 3B). In this example, the results indicate that the deepest slice has up to 440 ppb Au even though the "real" Au content is invariant at 80 ppb, except for the leached zone at the top of the *in situ* regolith.

When all the slices with reliability indices less than 60% are removed, the remaining results can be coded for reliability (Figure 3C). A much clearer picture of the Au trends is observed, illustrating the depletion at the unconformity. Note that this example is for the maximum possible overestimation of Au grade (the maximum overestimation = 100 ÷ reliability: e.g., when reliability is 60%, maximum overestimation is 1.67; when reliability is 90%, maximum overestimation is 1.11). In other cases underestimation can occur for low reliability samples (due to truncated intersection with mineralization). In summary, those samples with reliabilities less than 80% are suspect (but can still be valuable if treated with caution), whereas those with reliability less than 60% should generally not be used.

3.3 Gold grain separation and analysis

Bulk samples were collected for separation of Au particles (see individual reports). The morphology and size of the Au grains were examined by optical microscope. Following this, the morphologies of the selected particles were examined by scanning electron microprobe (SEM). Their Ag contents and the composition of neighbouring minerals were determined semi-quantitatively (limited by surface effects of the unpolished grains) using an energy dispersive detector. Selected Au grains were polished and analysed quantitatively by electron microprobe. Polished mounts were prepared by embedding in resin and carefully polishing down to expose the grains. Native Au was analysed for Au, Ag, Cu, Fe, Si and Pd.

3.4 Groundwater sampling and analysis

Groundwater samples were generally collected on site by pumping bailer or as pit seepages. Waters were analysed for pH, temperature, conductivity and oxidation potential (Eh), at the time of sampling. A 125 mL aliquot was collected in a polyethylene bottle (with overfilling to remove all air) for HCO_3^- analysis by alkalinity titration in the laboratory. About 1.5 L of water was filtered on site through a 0.2 µm membrane filter. About 100 mL of the filtered solution was acidified [0.1 mL 15 moles/litre (M) nitric acid], and analysed for a suite of elements by Inductively Coupled Plasma - Atomic Emission Spectroscopy, Inductively Coupled Plasma - Mass Spectroscopy and other colormetric or chromatigraphic techniques as appropriate.

The solution species and degrees of mineral saturation were computed from the solution compositions using the programs PHREEQE (Parkhurst *et al.*, 1980) and PHRQPITZ (Plummer and Parkhurst, 1990). These programs calculate the potential of a groundwater to be at equilibrium with various minerals. These modelling determinations are important for understanding solution processes at a site. They determine whether the spatial distribution of an element is correlated with lithology or mineralization, or whether it is related to weathering or environmental effects. Thus, if the Ca distribution is controlled by equilibrium with gypsum in all samples, the spatial distribution of dissolved Ca will reflect SO_4 concentration alone and will have no direct exploration significance.

4 TERMINOLOGY

Use of terms such as "blanket" or "halo", while common in many site descriptions, make specific assumptions about the genesis of the observed supergene Au pattern, rather than only record observations. It is considered critical to define descriptive and genetic terms, in order to clarify the observations and derived hypotheses given in this report. Critical terms are defined below.

Supergene – said of processes, deposits, blankets, minerals etc. formed under surface conditions. The term was originally proposed to distinguish *supergene* from *hypogene* processes. Used synonymously with the word *secondary*, and occurs within regolith. Note that supergene enrichment may be purely residual.

Enrichment and *depletion* – in this report, the terms refer to the ratio of the element concentration in the regolith to that in the equivalent fresh rock. This may well be relative or absolute (see below) as there is no correction for mass balance effects.

Relative or *residual enrichment* – accumulation of an element (e.g., Au) without transport, due to the leaching of other, more mobile components.

Absolute enrichment – element accumulation due to additional introduction of the element into weathered rock by chemical or mechanical (illuviation of host minerals) transport.

Residual – left in its original place. Residual regolith results from the *in situ* weathering of rock.

Dispersion – relocation of geochemical components by transport; either as particles or in solution.

Dispersion halo – field of higher concentrations of an element around mineralization, formed by epigenetic (here supergene) and hydromorphic dispersion.

Mushroom-shaped blanket – shape of a dispersion halo (Figure 4A), defined as subhorizontal broadening around the mineralization, with the top boundary limited by the surface of the profile.

Nail-shaped distribution - shape of the mineralization in the weathering profile (Figure 4B), defined as widening around the orebody limited by a sharp subhorizontal upper boundary with an overlying depleted zone, with the major factor being hydromorphic Au depletion.

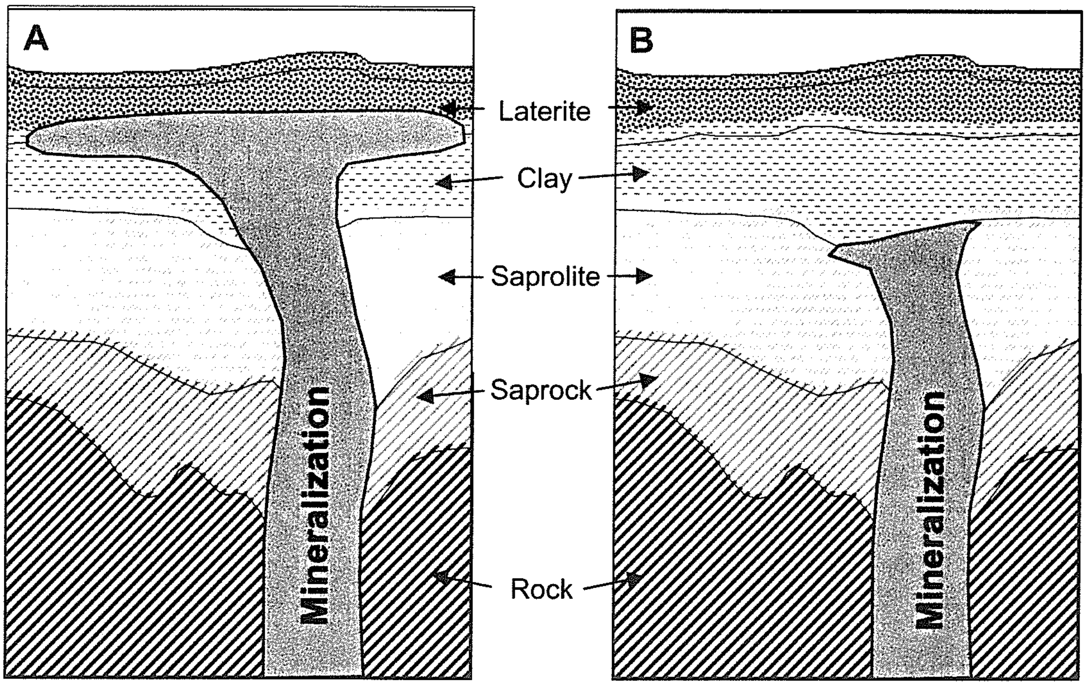


Figure 4: Diagrammatic regolith profiles, showing (A) Mushroom-shaped blanket and (B) Nail-shaped distribution

5 HYDROGEOCHEMISTRY OF THE YILGARN CRATON

The hydrogeochemistry of the Yilgarn Craton and its margins has been extensively investigated by CSIRO and CRC LEME, with particular emphasis on Au. Hydrogeochemistry may assist exploration for Au and other metals, and also provides information on how various materials are weathered. This enhances understanding of active dispersion and assists in development of weathering and geochemical models, which are essential for effective exploration in regolith-dominated terrain. The aims of the hydrogeochemical studies were to:

1. Provide information on whether groundwater can be used successfully as an exploration medium in the Yilgarn Craton and adjoining areas.
2. Yield data on geochemical dispersion processes.
3. Create a groundwater database on the characteristics of groundwaters at various sites.
4. Enhance understanding of groundwater processes in mineralized zones.
5. Develop techniques for interpretation of groundwater data from mineralized areas.

Systematic understanding of groundwater chemistry across the Yilgarn Craton is critical to comprehending the regional patterns of supergene Au mobilization. This section discusses important observations from these investigations, and provides a regional model of groundwater characteristics. Section 6 describes how these chemical variations affect the mobility of Au within the regolith.

5.1 Study sites

Groundwater data were collected from sites investigated by CSIRO Exploration and Mining and CRC LEME (Figure 5) both prior to, and as part of P504. Approximately 600 samples have been analysed with additional data from some 2000 Yilgarn sites obtained from the Water and Rivers Commission, open file mineral exploration reports from the Department of Minerals and Energy WA, CSIRO reports, WMC Exploration and Centaur Mining and Exploration. Data obtained from the non-CSIRO sources were commonly limited to a smaller analytical suite than used for the site studies. The groundwaters are regionally grouped as follows, based on salinity and pH (Figure 6):

1. **Northern groundwaters** (Northern Yilgarn and margins)
   Groundwaters in these areas are fresh and neutral, trending to more saline in valley floors.

   Examples: Baxter (Gray, 1995), Lawlers (Gray, 1994), Windara Well (Gray and Longman, 1997) and Mt Joel (Porto *et al.*, 1999).

2. **Central groundwaters** (close to and north of the Menzies line)
   Groundwaters here are neutral and brackish (commonly < 1% TDS) to saline (about 3% TDS), tending to hypersaline (10 to 30% TDS) at the salt lakes, generally with increasing salinity with depth.

   Examples: Granny Smith (Gray 1993a), Golden Delicious (Bristow *et al.*, 1996a), Mt Gibson (Gray, 1991) and Boags (Gray, 1992a).

3. **Kalgoorlie groundwaters**
   Groundwaters are commonly acid (pH 3 to 5), except where buffered by very alkaline materials (e.g., ultramafic rocks), and saline within the top part of the groundwater mass, trending to more neutral (pH 5 to 7) and hypersaline at depth and when within a few km of saline playas.

   Examples: Twin Peaks, Monty Dam (Sergeev and Gray, 1999), Carosue Dam (Gray et al., 2000), Mulgarrie (Gray, 1992c), Panglo (Gray, 1990a), Baseline, Steinway (Lintern and Gray, 1995a), Golden Hope, (Gray, 1993b), Wollubar palaeochannel (Gray, 1993b) and Lake Cowan (Gray, 1992b).

4. **Eastern groundwaters** (Eastern Yilgarn and Officer Basin)
   Groundwaters are saline to hypersaline, neutral to acid. Within palaeochannels they are reducing, presumably due to the presence of lignites and sulphides. The major ion chemistry is similar to that of the Kalgoorlie region, but, because of the lignites in the channel sediments, the dissolved concentration of many other ions is low.

   Examples: Argo (Lintern and Gray, 1995b), Mulga Rock palaeodrainage (Douglas *et al.*, 1993).

The Yilgarn Craton and surroundings were divided into 113 catchment domains, distinguished by drainage divides, restricted flow points and sites of major drainage bifurcation. These catchments are shown in Figure 7 and Figure 8, and the latter also shows, where known, the groundwater region that best fits that catchment.

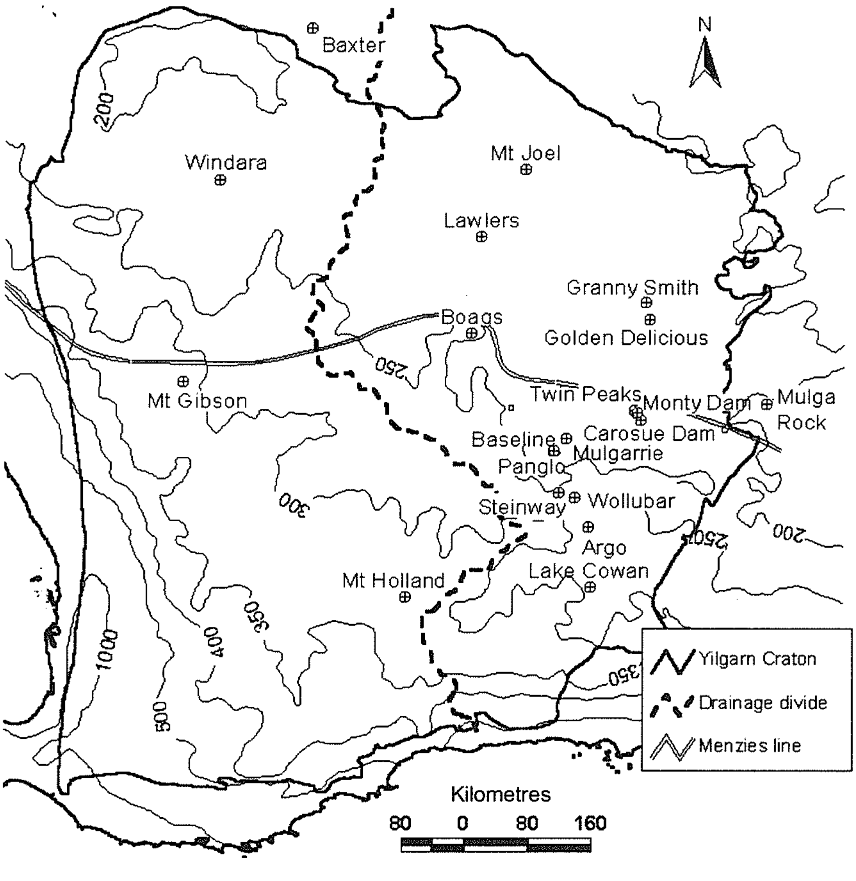


Figure 5: Location map of groundwater investigation sites with rainfall (mm) in isohyets (Australian Bureau of Meteorology).

5.2 Salinity variation across the Yilgarn Craton

As discussed above, four groundwater regions (Northern, Central, Kalgoorlie and Eastern) have been defined over part of the Yilgarn, as demonstrated in a plot of pH vs. TDS (Figure 6). Various researchers (e.g., Bestow, 1992) have also observed regional variations in groundwater salinities across the Yilgarn Craton. Commander (1989) modelled groundwater salinities (Figure 9), showing the highest salinities along the major drainages, which generally match palaeodrainage channels (Figure 10). The SE Yilgarn, roughly centered about the Kalgoorlie mining district, has the most saline groundwaters. Recent salinity modelling of this region (Kern, 1995a, b, 1996a, b) shows pervasive salinities > 30,000 ppm within the Kalgoorlie region and eastwards. The few Kalgoorlie groundwaters that are neutral and saline (rather than hypersaline) are shallow groundwaters in contact with weathered ultramafic rocks (Figure 6).

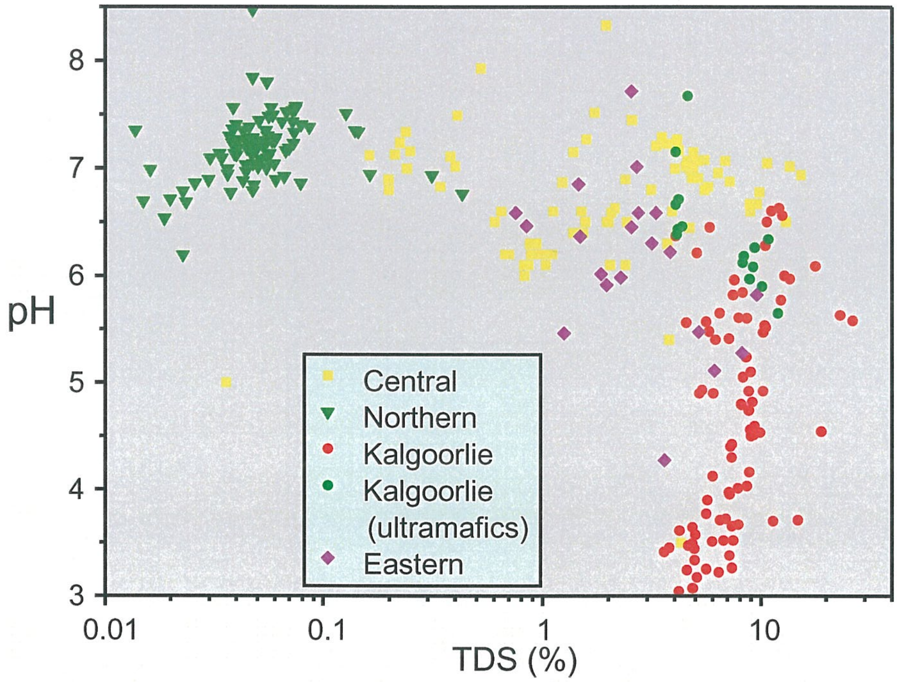


Figure 6: pH vs. TDS for groundwaters in Western Australian study areas.

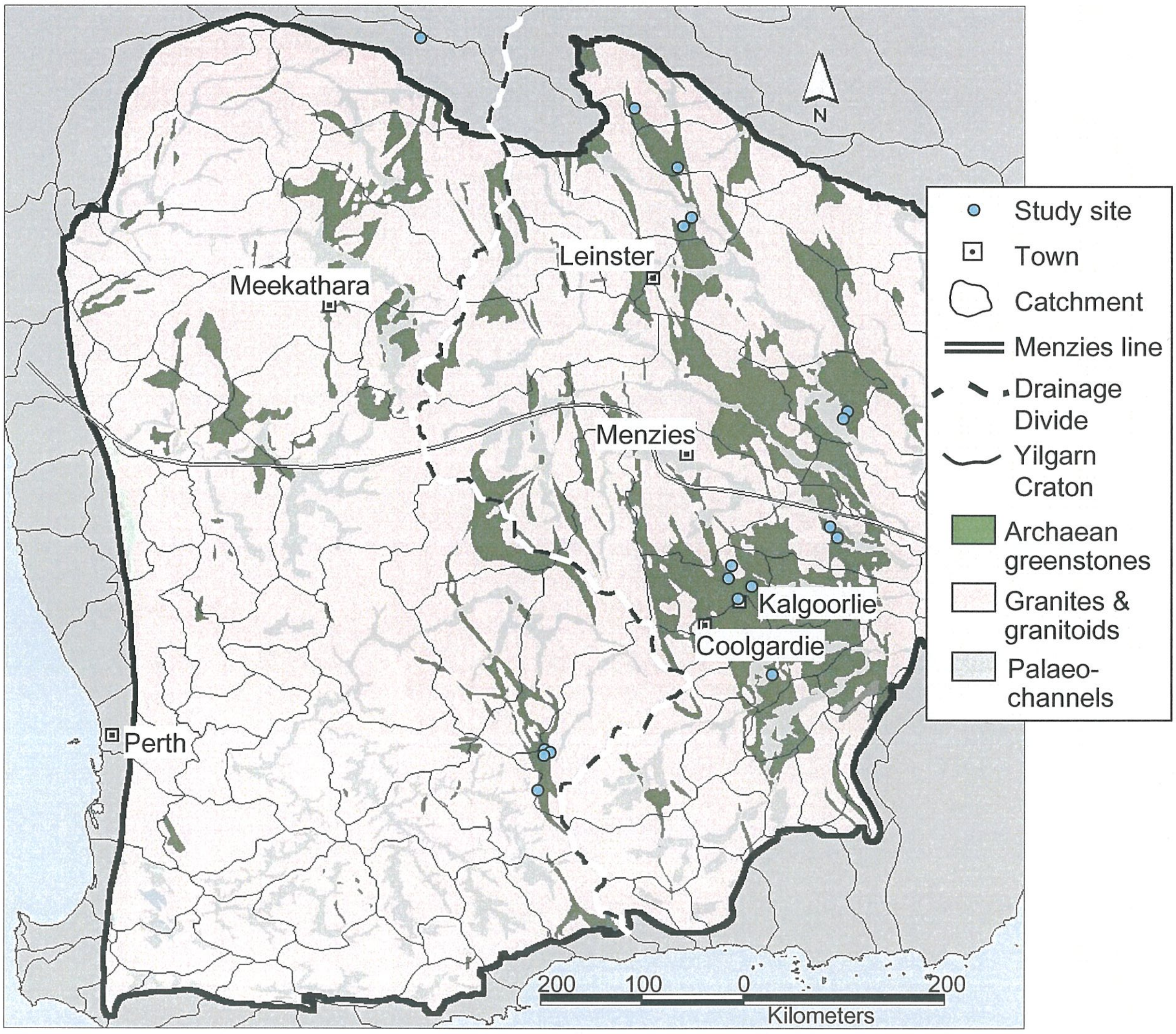


Figure 7: Defined groundwater catchment domains, with geology shown.

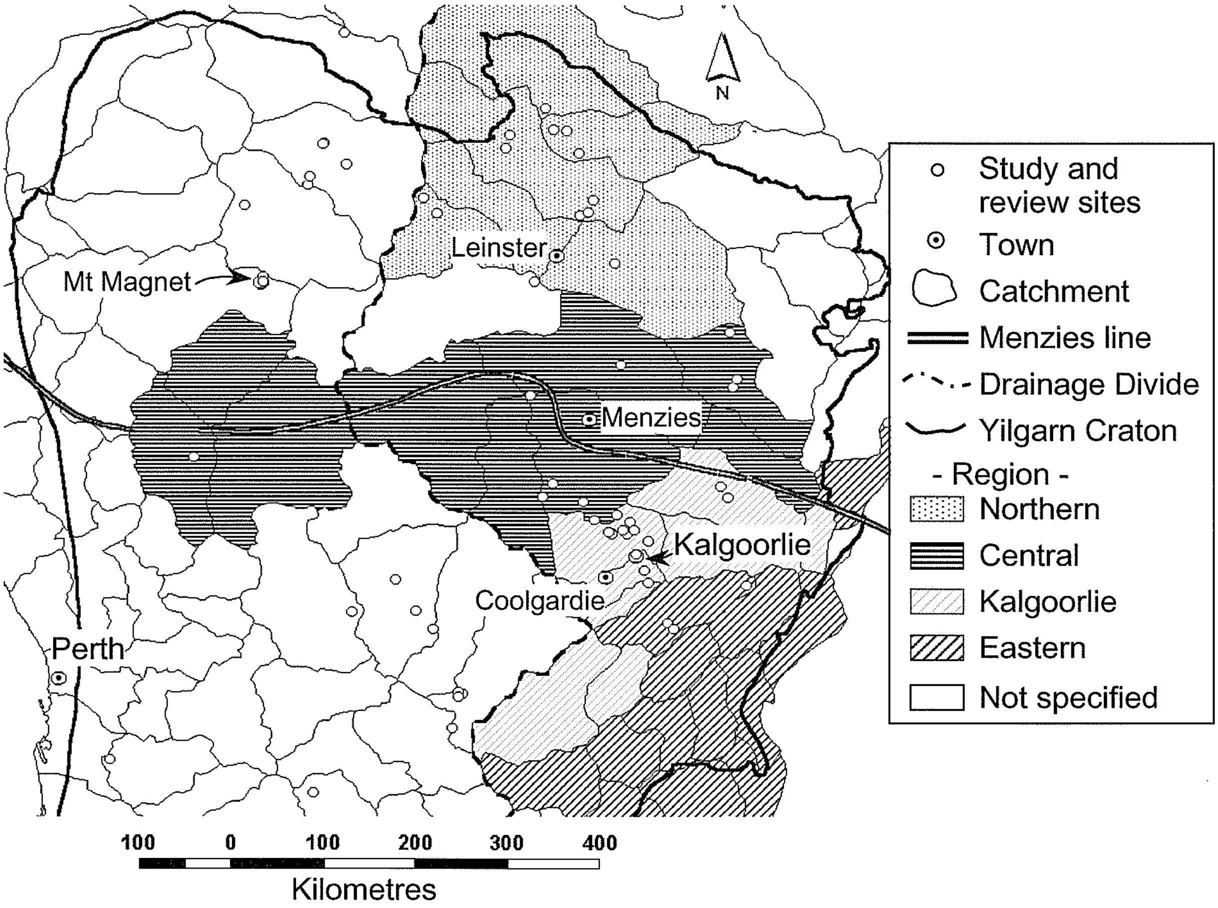


Figure 8: Defined groundwater catchment domains with groundwater regions shown.

North of the Menzies Line, an east-west transitional zone across which there are marked changes in soil types and vegetation (Butt *et al.*, 1977), groundwaters are significantly less saline and high salinities are confined to the immediate vicinity of major drainage channels. Compiled results from > 2900 salinity measurements (D. Gray, unpublished data) support these observations. In all but the Northern region, salinities show major increases with depth, probably due to back-flow from salt lakes (Figure 11).

The main source of the salt appears to be sea water, presumably imported by the wind as aerosols (McArthur *et al.*, 1989), with concentration by evaporation. Bestow (1992) calculated that salinities greater than 14,000 ppm (observed throughout much of the southern Yilgarn) would require loss of more than 99.9% of the rainfall through evaporation. One commonly suggested reason for the salinity differences from north to south are climatic differences from primarily winter rainfall in the south to irregular cyclonic summer rainfall, with high run-off, in the north. However, this factor alone could not cause the extreme differences nor the sharp gradients represented by the Menzies line. Elevation may be important, with the elevations along the drainage divide being at least 100 m higher in the northern Yilgarn (leading to much greater piezometric head differences), than in the south (Figure 10). Indeed, the extremely flat nature of the SE Yilgarn is demonstrated by the change in elevation of only 18 m over more than 300 km along the Johnston-Lefroy drainage system (Figure 12). Low piezometric head differences in the SE will cause very slow groundwater flows, with the high salinities due to evaporation of ponded waters.

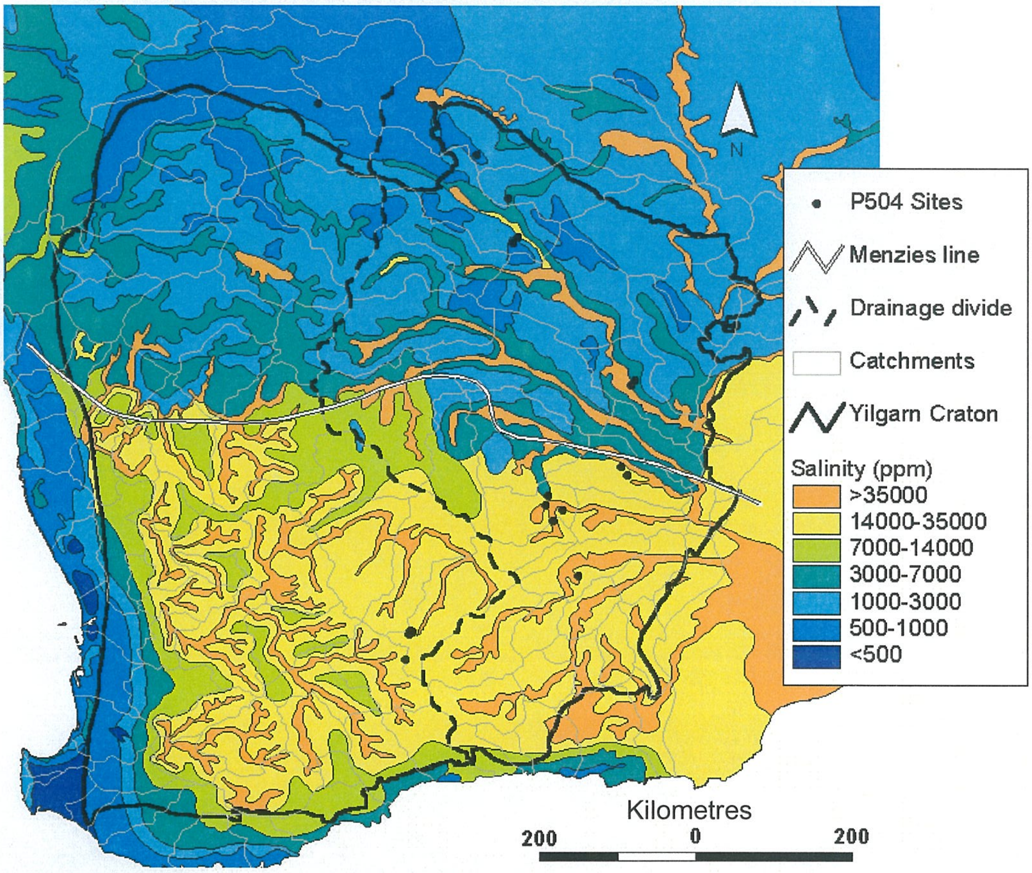


Figure 9: Modelled groundwater salinities in the Yilgarn Craton (Commander, 1989)

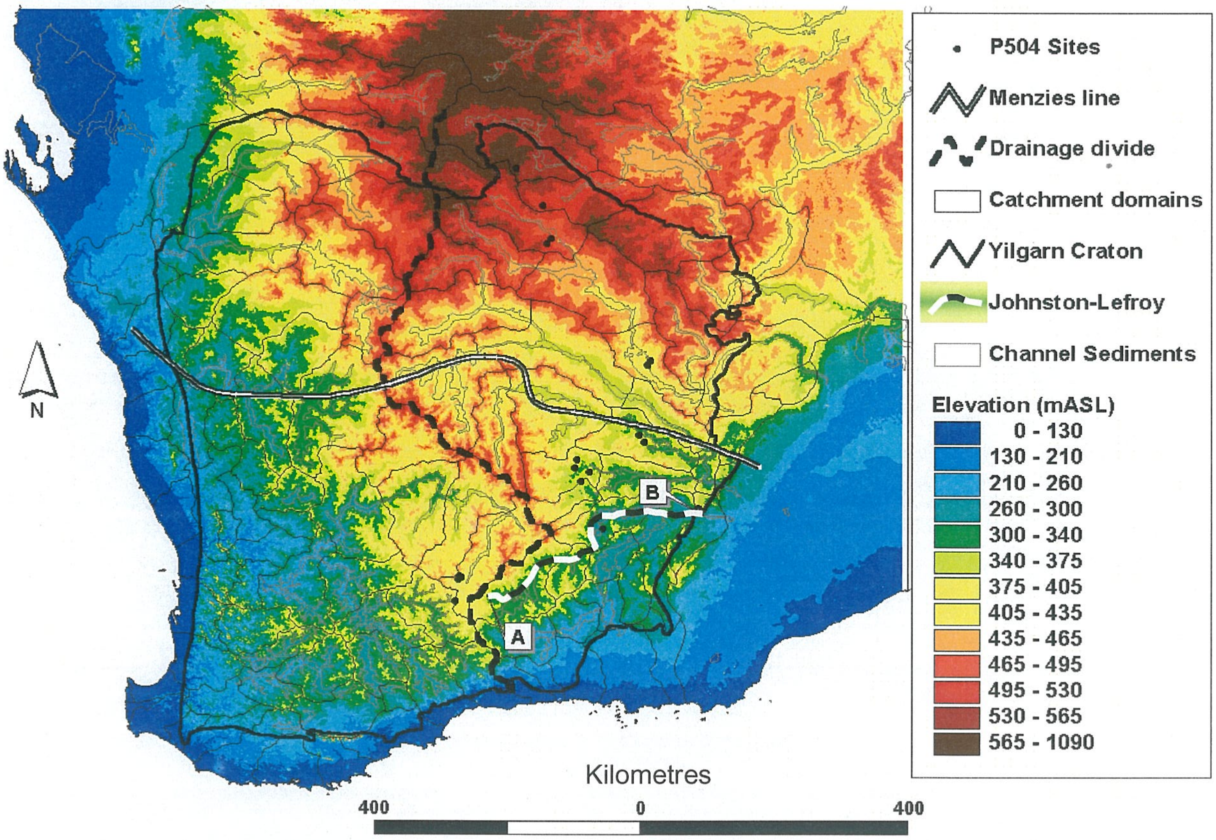


Figure 10: Elevation of the Yilgarn Craton, with P504 study sites, Menzies line, NS drainage divide catchment domains, Johnston-Lefroy drainage line (from locations A to B; Figure 12) and channels.

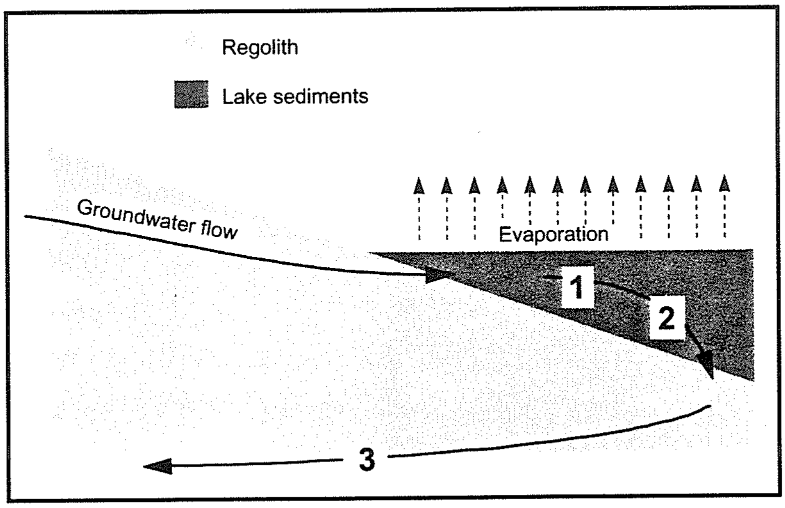


Figure 11: Diagrammatic representation of groundwater evaporation and flow at salt lakes: 1. Evaporation, leading to saline and dense groundwater; 2. Downward flow of dense groundwater; 3. Back-flow of saline waters, leading to higher salinity at depth.

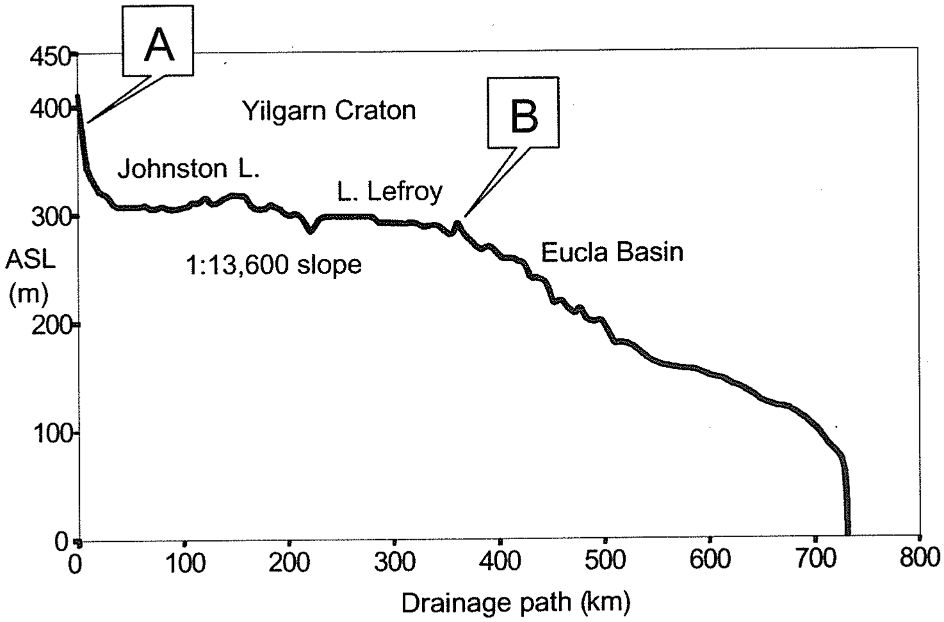


Figure 12: Change in elevation along the Johnston-Lefroy drainage system (dashed line in Figure 10) with locations A and B as marked on Figure 10.

5.3 Variation in acidity and oxidation potential

The major influence on salinity appears to be introduced sea water, but it is thought that there are strong local controls on acidity (McArthur *et al.*, 1989) and, presumably, oxidation potential. Deep groundwaters in contact with mineralization commonly have high concentrations of dissolved Fe and chalcophile elements, probably derived from the first stage of the oxidation of pyrite and other sulphides:

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

At depth, acidity is buffered by weathering of minerals such as carbonates or feldspars. These groundwaters contain significant dissolved Fe (> 0.1 mg/L) and are neutral and reduced [solid symbols in the neutral region ($6 < pH < 8$) in Figure 13], commonly having Eh values of 200 mV or less.

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

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

Because the reaction is governed by both Eh and pH, the ferrolysis control is an angled line on an Eh/pH diagram (denoted by the Fe line in Figure 13). All groundwaters with significant Fe concentrations (> 0.1 mg/L; solid symbols in Figure 13) congregate around this line.

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

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

This maintains the solution pH at about 3.2. The control is Eh independent (the Al line in Figure 13). In the more acidic groundwaters, dissolved Si is high, and they reach saturation with amorphous silica. Under these acidic conditions, Al is precipitated as alunite [$KAl_3(SO_4)_2(OH)_6$], with resultant major K and moderate SO_4 depletion (McArthur *et al.*, 1989). This is particularly marked in the Kalgoorlie area (Figure 14 and Figure 18) where groundwaters are acidic (Figure 6) and in the Gawler Craton (Figure 15).

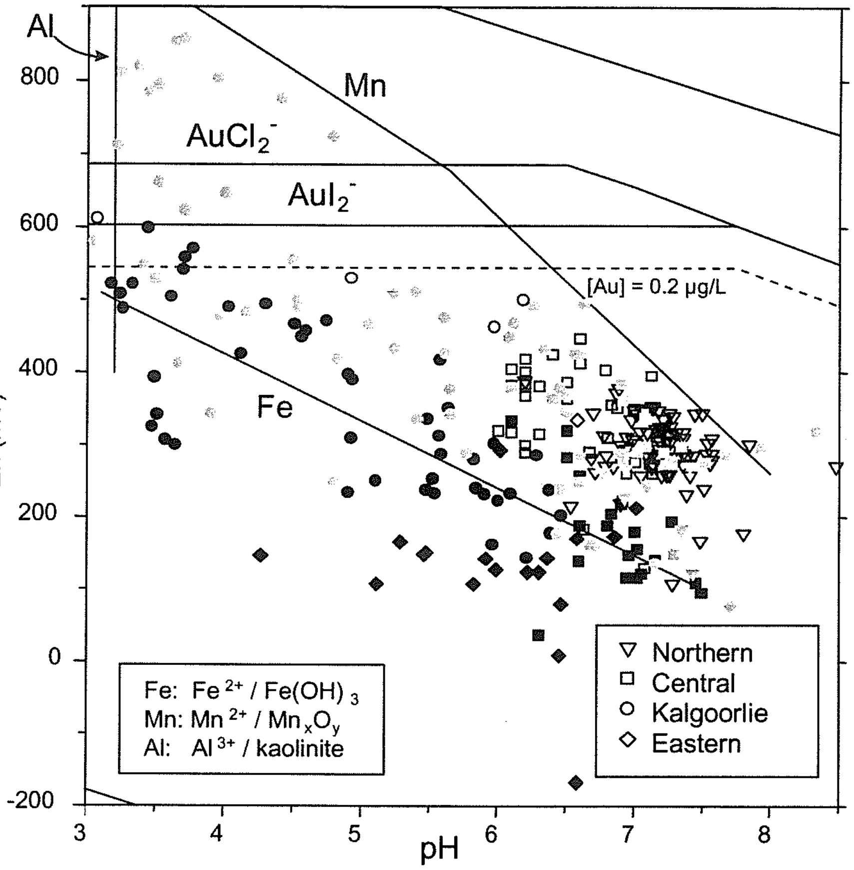


Figure 13: Eh vs. pH in groundwaters from WA research sites: solid symbols indicate samples with [Fe] > 0.1 mg/L (ppm); grey-filled symbols have [Fe] < 0.1 mg/L and [Mn] > 0.1 mg/L; open symbols have [Fe] and [Mn] < 0.1 mg/L. The Mn line is derived using data from Moussard *et al.* (1974), assuming [Mn] = 10^{-4} M (5.5 mg/L). The striped area is the zone where [Au] > 2 µg/L (ppb) in 1 M (5.7%) NaCl solution, with the stippled area showing the increased Eh field in which 2 µg/L Au will dissolve in the presence of 10^{-5} M (1.3 ppm) I^-. The dashed line is the lower Eh limit for [Au] = 0.2 µg/L in 10^{-5} M I^- / 1 M NaCl solution.

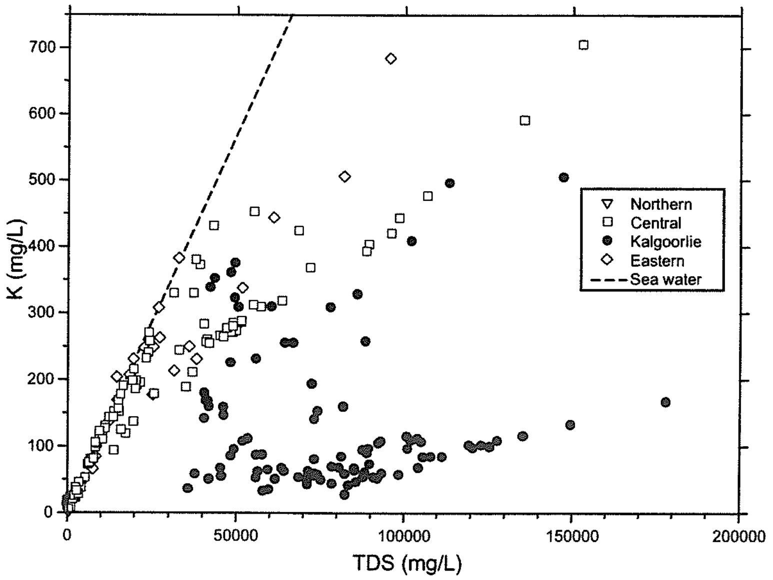


Figure 14: Dissolved K vs. salinity for Yilgarn groundwaters.

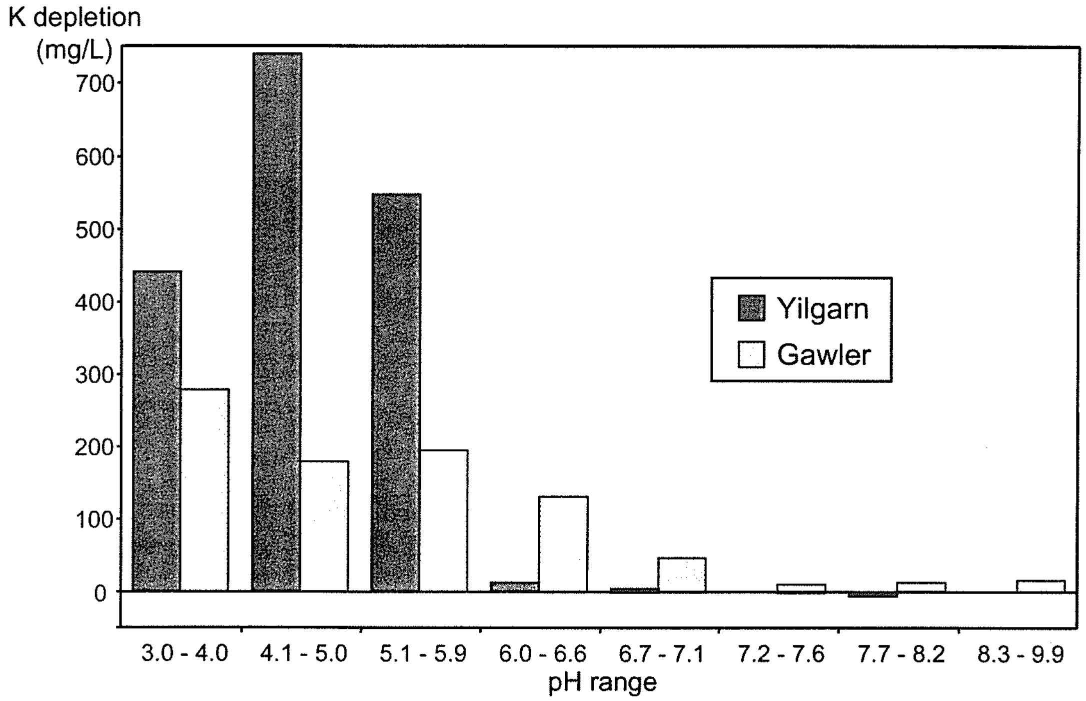


Figure 15: K depletion vs. pH for Yilgarn and Gawler groundwaters.

Many acidic groundwaters in the Yilgarn contain significant Mn, resulting in very high but stable oxidation potentials (up to 850 mV; shown as the Mn line in Figure 13) in the Mn analog to ferrolysis. As will be discussed later, this control is critical to the mobility of Au in the Kalgoorlie and, possibly, Central regions, as suggested by the relatively high Eh values in the Kalgoorlie region (Figures 13 and 17).

Lignites are common in the palaeochannels of the Eastern region (Figure 17) and have been dated as Eocene (Clarke, 1994). Where significant amounts of lignite or sulphides are present within palaeochannels, groundwaters can be highly reducing (< 0 mV; Figure 13). Though such deposition may previously have been more common than presently observed, lignite occurrences are rare elsewhere in the Yilgarn, possibly due to post-Eocene erosion and/or oxidation of the channel sediments (Morgan, 1993).

Groundwaters that contain neither significant Fe or Mn (open symbols in Figure 13), are denoted as the HO group. These waters almost exclusively have neutral pH (6 - 8.5) and include virtually all of the Northern, some Central, but few Kalgoorlie groundwaters. In the northern Yilgarn Craton, the only Fe-rich groundwaters observed are those contacting weathered massive sulphide orebodies, such as the Harmony Ni deposit near Leinster (Gray *et al.*, 1999). Although there are redox couples within the range measured for these waters (the most probable being H_2O_2/O_2; Sato, 1960), they have slow kinetics and the solution Eh will be weakly controlled. This group is the least chemically active of the waters, being neither strongly reducing (neutral group Fe waters), strongly acid (group Al) or strongly oxidizing (group Mn).

The five Eh/pH groups ($Fe^{2+}/Fe(OH)_3$; Mn^{2+}/Mn_XO_Y; Al^{3+}/kaolin; lignite-rich; and H_2O_2/O_2) discussed above appear adequate to model the Eh/pH data from all Yilgarn sites investigated to date. The Eh/pH characteristics vary from neutral to moderately acid and reducing at the extreme SE edge of the Yilgarn Craton (with extensive lignite in the palaeochannels), neutral to highly acid and oxidizing in Kalgoorlie, and neutral in the Central and Northern Regions.

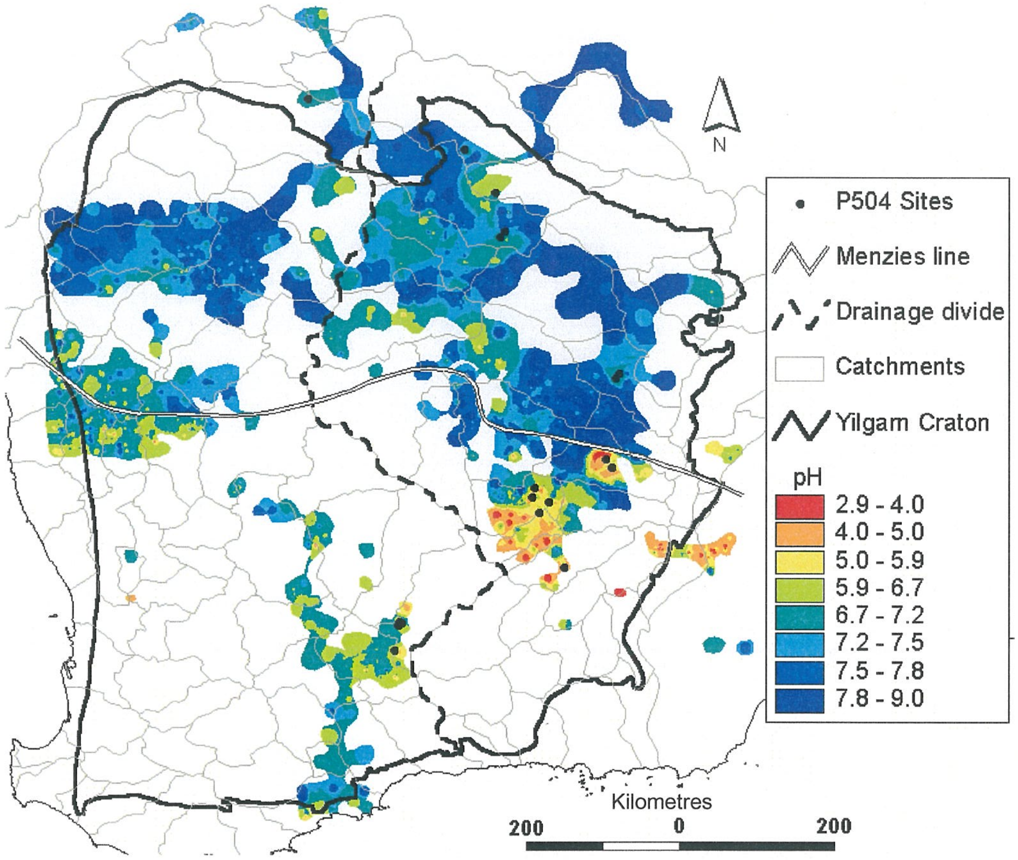


Figure 16: Groundwater pH distribution in the Yilgarn Craton (data sources given in Section 5.1).

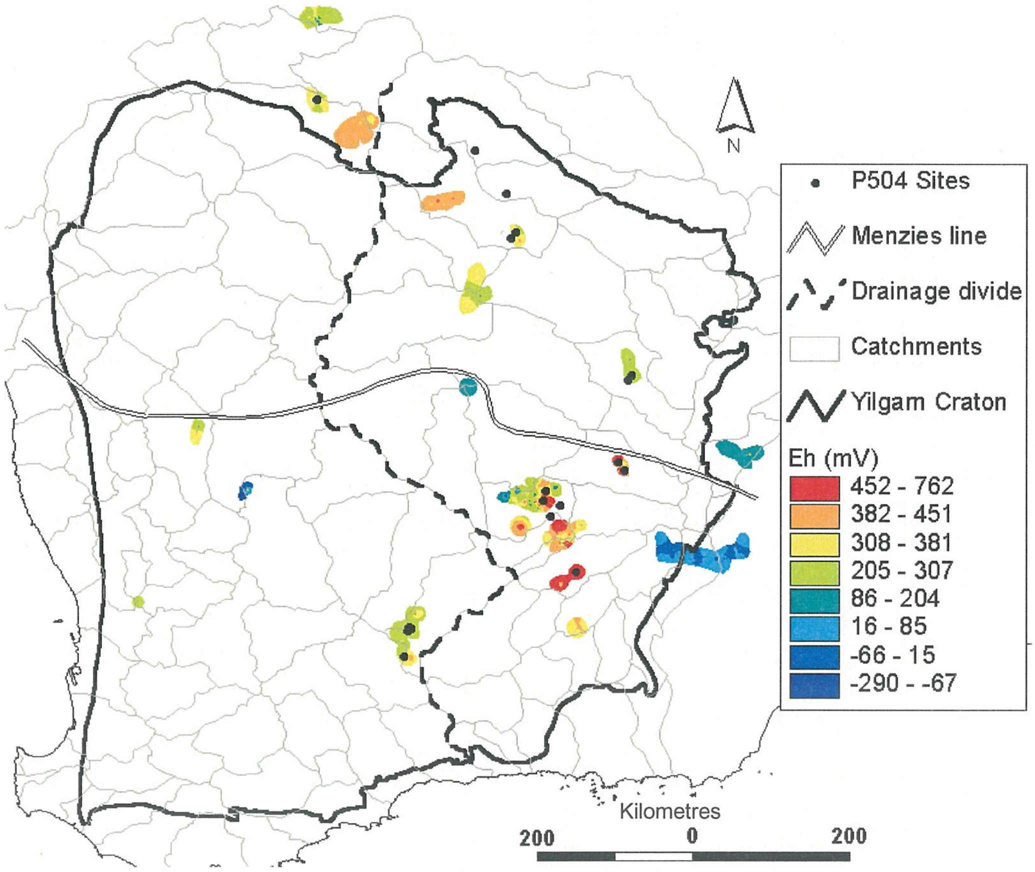


Figure 17: Distribution of groundwater oxidation potentials in the Yilgarn Craton (data sources given in Section 5.1).

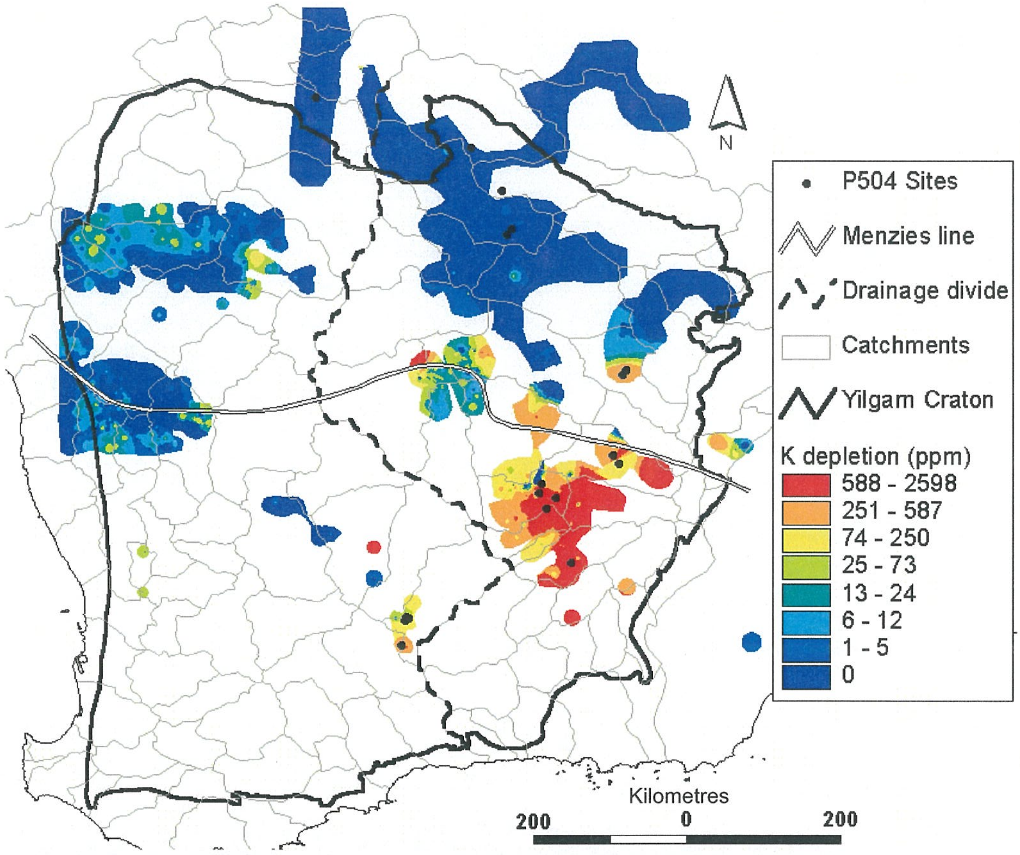


Figure 18: Distribution of Groundwater K depletion in the Yilgarn Craton (data sources given in Section 5.1).

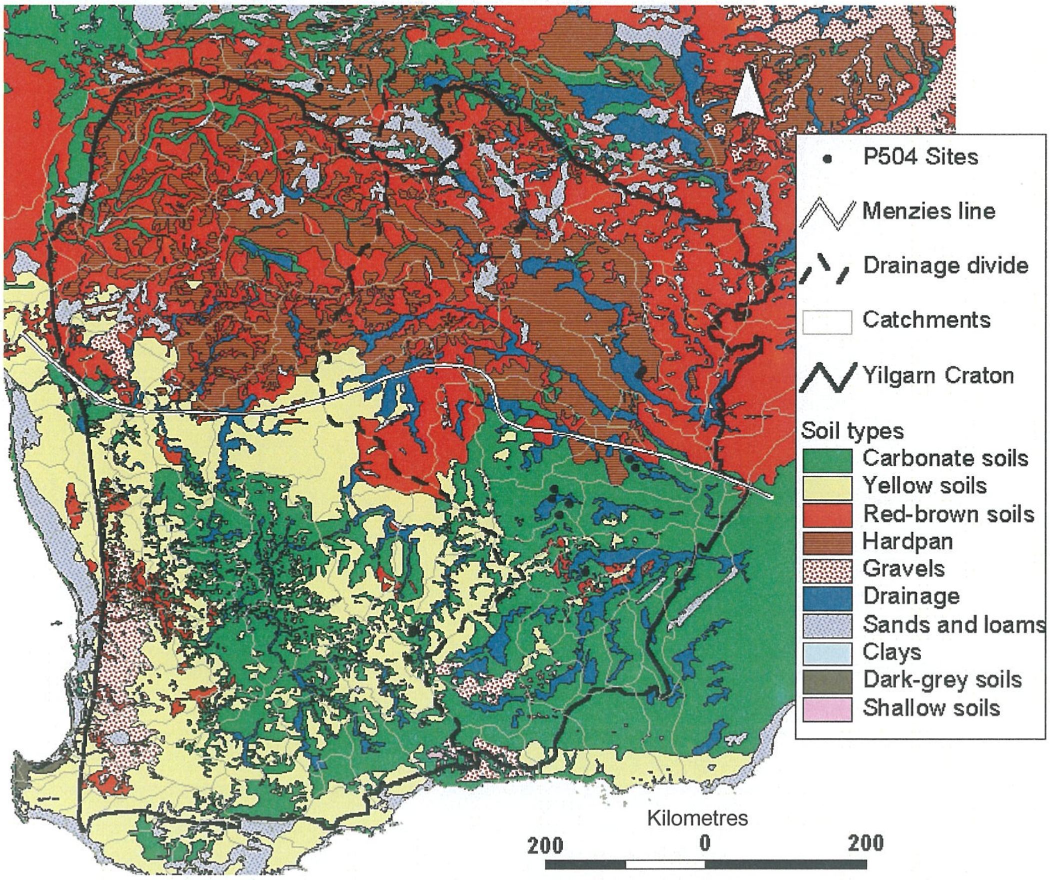


Figure 19: Distribution of major soil types in the Yilgarn Craton (modified from Northcote, 1979).

The reasons for this pH differentiation within the Yilgarn Craton is not as clear as the salinity effects (Section 5.2). There is an apparent correlation between carbonate-rich soils (Figure 19) and highly acid groundwaters (Figure 16). Carbonate precipitation, either as a result of precipitation of free Ca or as an alteration of blown-in gypsum will result in generation of acid equivalents (Equations 4 and 5).

Equation 4 $$Ca^{2+} + CO_2 + H_2O \rightleftharpoons \underset{\text{(calcite)}}{CaCO_3} + 2H^+$$

Equation 5 $$\underset{\text{(gypsum)}}{CaSO_4.2H_2O} + CO_2 \rightleftharpoons \underset{\text{(calcite)}}{CaCO_3} + SO_4^{2-} + H_2O + 2H^+$$

As weakly acid soil waters percolate to the groundwater and are evaporated they may become highly acid. For example, if a pH 6.5 meteoric water were to form a 14,000 ppm groundwater via evaporation of 99.9% of the water (Bestow, 1992; Section 5.2), with no pH buffering, this could result in a reduction of pH from 6.5 to 3.5. Of course, pH buffering from mineral surfaces and dissolved species such as bicarbonate will reduce this effect, though it is possible that this is a major, or even the dominant contributor to the low pH in the Kalgoorlie region.

Note that the K depletion is observed further north than the acid groundwaters (Figure 18). This may be a fossil groundwater, or may represent mixing of the Lake Rebecca and Lake Raeside groundwaters, which unite two separate catchments.

5.4 Minor and pathfinder element hydrogeochemistry

Many elements, including Al, F, Li, Ge, Y, REE and U, have high concentrations in acid groundwaters, such as those in the Kalgoorlie region, where there is extensive regolith redistribution of these elements. Groundwaters in the Kalgoorlie region have particularly high LREE concentrations (e.g., La and Ce), commonly being greater than those for most of the base metals. Calculations indicate that the water pumped from the Wollubar palaeochannel bore field contains approximately 4000 kg per annum of total REE (Gray, 1996). These high REE concentrations are primarily related to hydrogeochemical rather than lithological effects, presumably due to the interaction of regolith with highly acid and saline groundwaters. Because of these effects, REE, and most other metals, are not expected to be useful for Au exploration in the Kalgoorlie region, though REE depletion studies have potential as indicators of ancient acid groundwaters.

Dissolved concentrations of the base metals (Mn, Co, Ni, Cu and Zn) and Ga are less closely correlated with acidity than the REE. Chromium is surprisingly present as Cr^{6+} (i.e., CrO_4^{2-}) rather than Cr^{3+}, despite most groundwaters not being oxidizing enough to directly generate such an oxidizing form of Cr. This result is based both on direct analyses for Cr^{6+} and on the highly anti-pathetic relationship of dissolved Cr and Fe (Gray, 1996), possibly due to the capacity of dissolved Fe^{2+} to reduce CrO_4^{2-} to the less soluble Cr^{3+} ion. This result is potentially highly significant in terms of understanding the observed high concentrations of Au in the saline Central groundwaters, even though the observed Eh is not high enough to dissolve Au (see Section 6).

In contrast, a number of elements, including As, Sb Mo, W, Bi and, possibly, Zr and Tl, have low concentrations in acid groundwaters, but have higher concentrations above pH 6.5, particularly in the Central and Northern groundwaters (Figure 20). These elements commonly occur as oxy-anions (e.g., $H_2AsO_4^-$), which are better adsorbed by Fe oxide (or other) surfaces at low pH. This is because surfaces are positively charged when the pH is below the point of zero charge (PZC) of the mineral phase, and are, therefore, more effective at absorbing negative ions. This implies that the acid groundwaters (particularly those around Kalgoorlie) will be poor media for the use of these elements as exploration pathfinders. In addition, leaching of these elements should be much less below the water-table in areas that have maintained acid conditions. It is entirely possible that areas of present-day acid groundwaters may have been neutral or alkaline in the past, and leaching may have occurred at this point even if it is not occurring at present. There is insufficient information on As or Sb to reach even a tentative hypothesis. Results for Twin Peaks (Sergeev and Gray, 1999), which has As-rich mineralization and presently has highly acid groundwaters, indicates little As leaching below the water-table, and significant loss of As in the upper, unsaturated 10 m of the regolith. Molybdenum differs from the other elements in this group in having significant, though lower, concentrations at low pH. The reason for this difference is unclear, but this observation is consistent with the potential of Mo in groundwater as a pathfinder for Au mineralization.

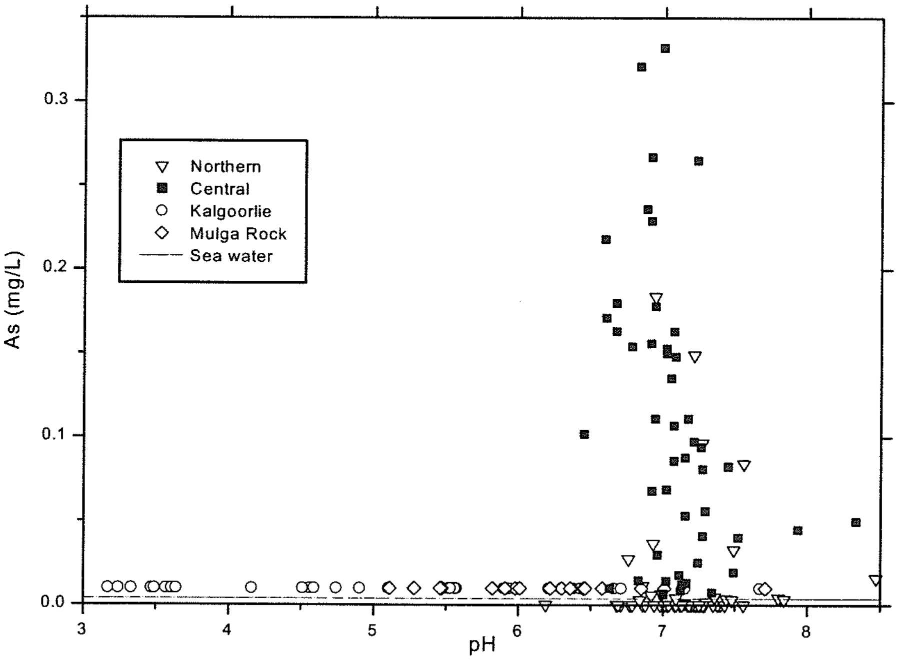


Figure 20: As vs. pH for Western Australian groundwaters.

The concentration and speciation of dissolved I may be important for the solubility of Au. Iodine may occur in a number of forms with contrasting oxidation states, including I^- (as free, weakly or strongly bound iodide), I_2, IO^- and IO_3^-. The I^- ion may be an important ligand for Au (Section 6), whereas the other, oxidized, forms could be important in maintaining oxidizing conditions for Au dissolution. Results to date indicate high groundwater iodine contents (commonly > 1 ppm), much greater than for sea water. Iodine may behave as a chalcophile element, with major enrichments associated with sulphides (Gray, 1996; and references given therein).

Relevant median concentrations of elements in Yilgarn groundwaters are listed in Table 1, with the last column giving the postulated control on their groundwater concentration. Thus, for example, REE concentration is primarily controlled by pH, whereas Co concentration is high in waters in contact with mafic or ultramafic rocks, with further enhancement in acid groundwaters. Elements whose concentration is controlled by equilibrium with specific secondary minerals are generally not very useful for exploration, whereas other elements may give useful information about lithology, presence of sulphides or degree of weathering. However, the usefulness of the latter elements depends on regional groundwater effects, detailed below.

Table 1: Median compositions and standard deviations of minor element in groundwaters.

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

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

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

6 GOLD HYDROGEOCHEMISTRY

6.1 Halide (iodide and chloride) dissolution

Groundwater observations indicate a major correlation between salinity and Au mobility – suggesting Cl rather than I (see below) to be the critical complex in saline/acidic/oxidizing groundwaters (Figure 13). The striped grey area in Figure 13 is the zone for which up to 2 µg/L (ppb) Au will be dissolved as $AuCl_2^-$ in a 1 M Cl solution (about twice sea water). This is approximately the mean salinity for Kalgoorlie groundwaters and the upper range for Central groundwaters. Also, a significant proportion of the Kalgoorlie groundwaters are within the Eh range required for Au dissolution.

However, I may be an important ligand for Au in sulphide-rich environments, as it may have a high groundwater concentration. This is because it behaves as a chalcophile element (Fuge and Johnson, 1984, 1986) and is extensively enriched in sulphide environments (Chitayeva *et al.,* 1971; Fuge *et al.,* 1988). Indeed, it may be a useful pathfinder for mineralization (Xie *et al.,* 1981; Andrews *et al.,* 1984; Fuge *et al.,* 1986). In a number of mineralized areas, available iodide (free plus loosely complexed iodide) may, in some cases, be greater than 10^{-5} M (1.3 ppm) (Gray, 1996). Because Au complexes strongly with iodide, this concentration of available iodide considerably extends the theoretical Eh range for the dissolution of at least 2 µg/L Au from 690 to 600 mV (Figure 13). If a lower dissolved Au concentration of 0.2 µg/L is used, the required Eh for Au dissolution is lowered to about 550 mV, which includes many of the Kalgoorlie groundwaters.

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

As expected, there is a weak correlation between dissolved Au concentrations and Eh (Figure 21). However, virtually none of the Central groundwaters have Eh values high enough to explain the observed concentrations of dissolved Au. One possibility is that mineral surface- or micro-processes generate transient, highly oxidizing conditions that can dissolve Au, consistent with observations of the common presence of dissolved Cr^{VI} in Yilgarn groundwaters (Section 5.4).

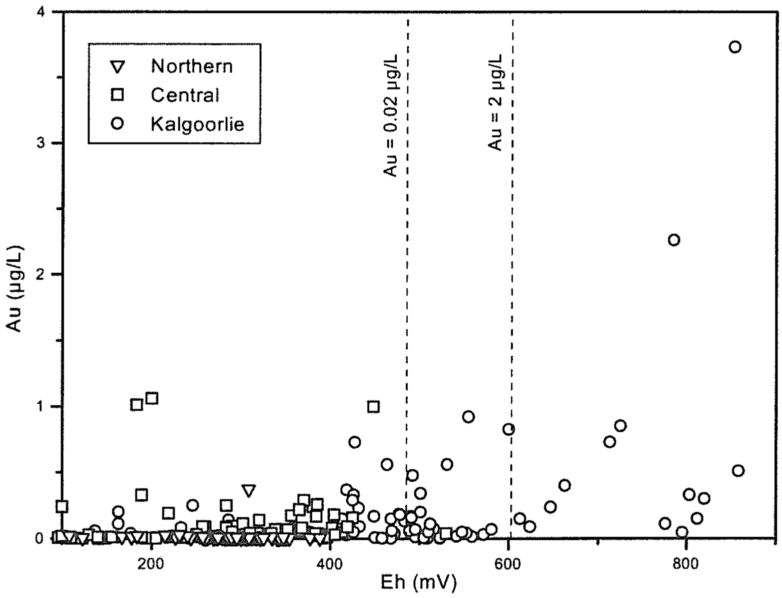


Figure 21: Dissolved Au vs. Eh for the Western Australian sites

Once dissolved, the Au-halide complex is meta-stable and, except in Fe-rich solutions, may be only slowly removed from solution. A number of acid groundwater sites (Gray, 1996) show a strong antipathetic relationship between dissolved Au and Fe, supporting the hypothesis that dissolved Fe is important in precipitating Au from halide complexes (Equation 6). Such a mechanism will have major implications for the control of supergene depletion and enrichment zones, and for the interpretation of drilling data. Such an environment may be more likely to show a significant Au supergene halo, in comparison to many groundwaters in the Kalgoorlie area where Eh conditions can maintain Au in solution and Au appears to be lost from the regolith in the mineralized area.

Equation 6 $AuCl_2^- + Fe^{2+} + 3H_2O \Rightarrow Au_{(S)} + Fe(OH)_{3(S)} + 2Cl^- + 3H^+$

6.2 Thiosulphate dissolution

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

Equation 7 $FeS_2 + 1^1/_2O_2 \rightleftharpoons Fe^{2+} + S_2O_3^{2-}$

In such conditions, Au can dissolve as the thiosulphate complex $[Au(S_2O_3)_2^{3-}]$. However, in acid environments, e.g., the shallow groundwaters of the Kalgoorlie region, thiosulphate is unstable. A few groundwaters sampled from rock or saprock within mineralized zones at Lawlers, Boags and Mt Gibson have anomalous Au (1 - 41 µg/L), but only in groundwaters from drill holes or seepages within the pits. It is possible that these high Au concentrations may be anthropomorphic, being caused by the release of very high concentrations of thiosulphate when pit excavation exposes bedrock. Groundwater sampling from drill holes in otherwise undisturbed ground at Lawlers and Mt Gibson indicate little dispersion of Au (Gray, 1991, 1994). Whatever the cause for the high dissolved Au concentrations in these conditions, it is probable that sampling deep groundwaters for Au will be an ineffective exploration method. It is expected that Au thiosulphate will only be important for mobilization of Au at the weathering front, and then only in very limited circumstances.

6.3 Regional differences in Au hydrogeochemistry and implications for supergene mobilization

The importance of halides for the dissolution of Au is illustrated by the low dissolved Au concentrations in the Northern region (Figure 22), which have groundwaters low in Cl, I and Eh. Over 80% of the Northern groundwaters have dissolved Au concentrations ≤ 0.01 µg/L, which is well within background for the other regions. The few Au-bearing groundwaters in the Northern region are from within pits and appear to represent localized thiosulphate dissolution (Section 6.2). The Kalgoorlie region has the highest mean dissolved Au content, consistent with the observed optimal conditions for dissolution (Section 6.1), with the Central region having moderate levels of dissolved Au. This implies significant differences in the degree of supergene Au remobilization in different regions of the Yilgarn, as discussed in Section 10.

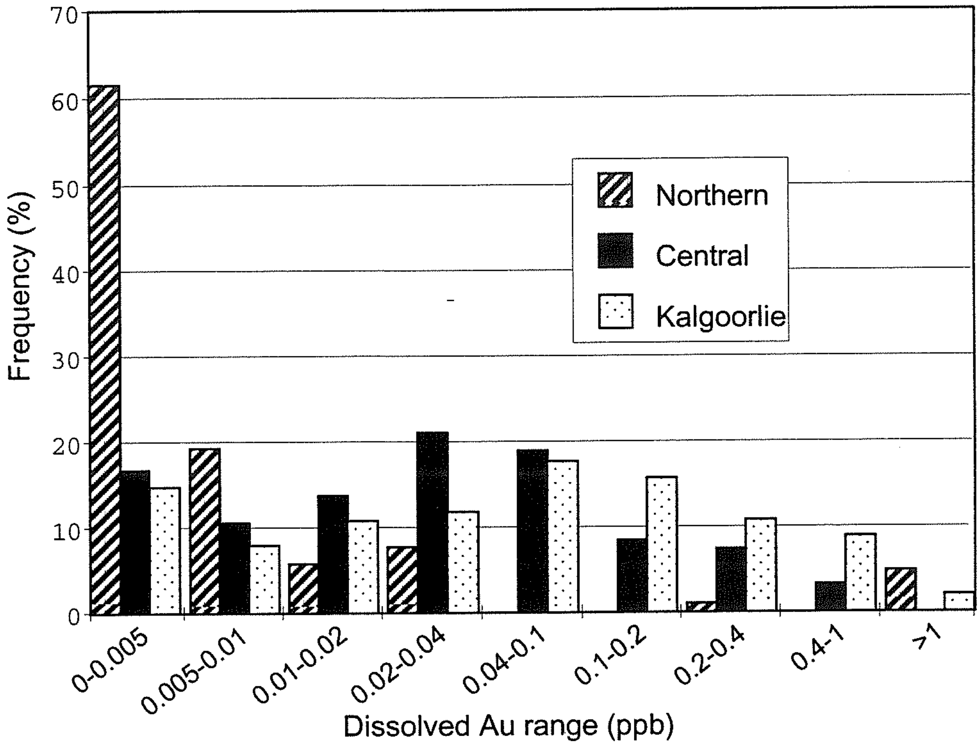


Figure 22: Distribution of dissolved Au concentrations for the Northern, Central and Kalgoorlie groundwater regions.

Extensive supergene mobilization of Au is expected to have occurred, and to be occurring, in the Central and Kalgoorlie regions. Oxidizing conditions in the upper parts of the groundwater should lead to major Au dissolution, which will diffuse though the water mass. Where dissolved Au halide interacts with dissolved Fe, possibly derived from weathering of saprolite and saprock, Au will be reduced in a redox front reaction (Equation 6). This results in characteristic horizontal and sub-horizontal supergene anomalies. The lower dissolved Au contents of Central groundwaters, which are postulated to be due to the less acidic groundwater conditions, suggests this process may take longer for this area, though extensive redistribution would still be expected given the long period of weathering.

7 GOLD DISPERSION IN THE REGOLITH OF THE YILGARN CRATON

7.1 Mechanisms for supergene remobilization of gold

Supergene remobilization of Au occurs more readily within the zone of groundwater saturation (Section 10), i.e., below the water-table and within the capillary fringe (the zone of water saturation above the measured water-table). The capillary fringe can extend several metres, or even tens of metres for clay-rich regolith, above the water-table. Gold solubility is very high in saline, acid and oxidizing groundwaters, moderate in saline and neutral groundwaters and low in fresh and neutral groundwaters (Figure 21). Based on these observations, and on data from this project, a model for supergene redistribution of Au is shown in Figure 23.

Initially, as the regolith profile forms under humid conditions, Au is slightly leached throughout the saprolite (Figure 23A), with no dispersion into wall rocks and little or no secondary Au (Gray *et al.*, 1992; Lecomte and Zeegers, 1992; Freyssinet, 1994; Freyssinet and Itard, 1997). Commonly Au concentrations are relatively high in rain forest soils (Freyssinet and Itard, 1997).

A later change to an arid climate has caused an increase in groundwater salinity, and major dissolution and mobilization of Au in the weathered profile. Gold dissolves where the saline groundwaters are oxidizing (i.e., the upper part of the groundwater mass). Above the capillary fringe, the regolith is unsaturated and water flow is reduced. Therefore, no matter how corrosive the solutions, Au mobility is limited compared to the saturated zone beneath. Thus, Au concentrations gradually increase again from the saturated depleted zone towards surface (Figure 23B). If water-tables later rise, then the upper boundary of the depletion will also rise.

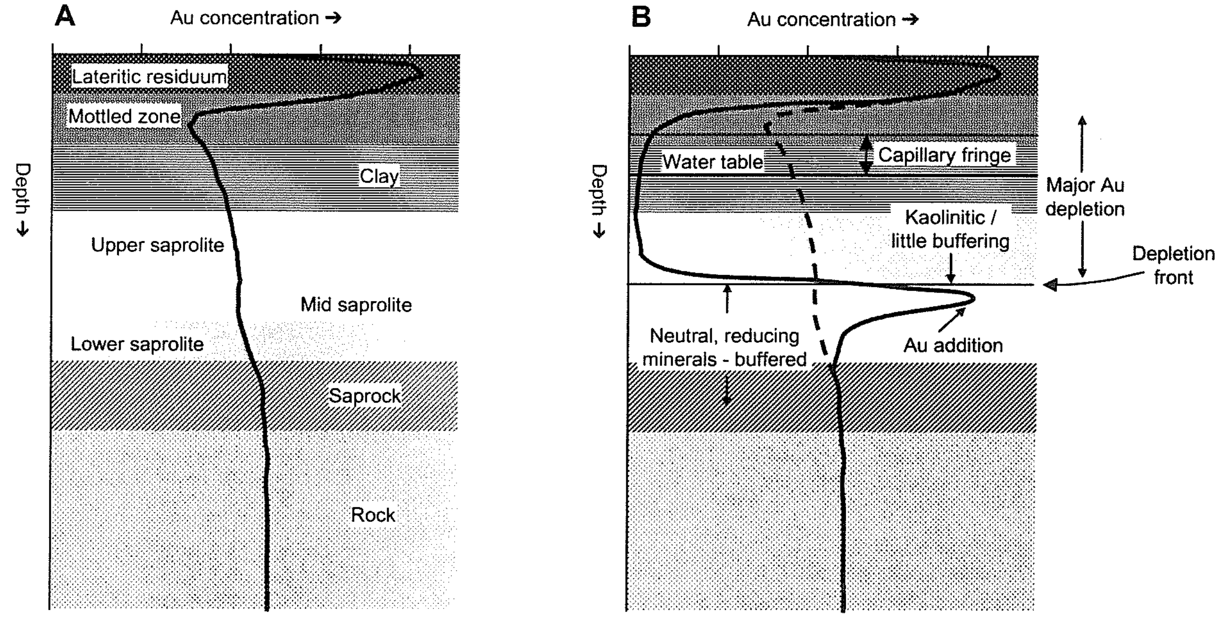


Figure 23: Diagrammatic representation of (A) supergene concentration (primarily residual) of Au during initial weathering , (B) supergene remobilization of Au due to saline groundwaters.

The lower depletion front is almost always sharp (Section 7.3.2). It commonly occurs (1) on a logged regolith transition, (2) a redox, or (3) a chemical change (Section 7.3.3), where the regolith locally controls groundwater chemistry. Above the depletion front, the mineralogy is commonly characterized by kaolinite, Fe oxide and quartz (in Figure 23B this is the upper saprolite). Below the depletion front, the regolith contains reduced swelling clays (e.g., nontronite) and/or primary minerals. These assemblages buffer the groundwaters so that they are less oxidized and contain minimal dissolved Au. Although some dissolved Au may reprecipitate directly below the depletion front, most is lost from the immediate environment of the mineralization. Possible exceptions are where oxidized and permeable palaeochannel sediments abut mineralization, such as at Cleo (Gray and Britt, 2000), and Federal (Sergeev and Gray, 2000) and Golden Delicious (Section 7.3.3), which have unusual structural and lithological characteristics.

Because there is little depletion in the upper, unsaturated horizons, there is a Au anomaly at surface, generally strongest where the laterite is present, but still apparent in truncated profiles. This surface Au may become chemically and mechanically dispersed, but forms the immediate source of Au in the soil environment, commonly associated with pedogenic carbonate or lateritic residuum. In carbonate-rich environments where the transported cover is not too thick (5 - 10 m), Au may move from the residuum into transported material and still form a surface anomaly. Various examples of this are given within P504 (e.g., Carosue Dam; Gray *et al.*, 2000) and previous studies (e.g., Safari; Bristow *et al.*, 1996b).

7.2 Gold dispersion in the regolith of the Yilgarn Craton

Models for Au dispersion are primarily based on those by Butt (1989a,b), though with some modifications. Palaeogeographic reconstructions indicate that parts of the Yilgarn Craton have been exposed to sub-aerial conditions since the mid or late Proterozoic (Daniels, 1975). The relatively high tectonic stability of the Yilgarn since the Permian has permitted widespread development and preservation of a thick regolith under changing climatic conditions. During the Mesozoic and Tertiary until the Mid Miocene, lateritic weathering developed under pervasive humid climates (Mabbutt, 1980). This period was followed by increasingly arid conditions, which have continued to the present.

Weathering of the Archaean rocks in the Yilgarn Craton and its Proterozoic surroundings has also altered primary Au mineralization within the weathered zone. Supergene behaviour of Au is partly as an inert (noble) element concentrated in the residual products of weathering and, partly, as a mobile element that has dissolved during weathering into supergene solutions, to migrate and be redeposited at geochemical barriers, as discussed above. The resulting Au distribution in the regolith is diverse with a combination of residual primary distribution with some supergene Au-depleted and enriched horizons. An idealized distribution in the complete profile (Figure 23B) includes two principal supergene Au enrichments and additional late surface processes:

1. An old (possibly Tertiary) lateritic anomaly occurs as a 'mushroom-shaped', subhorizontal Au blanket in the upper, ferruginous zone, generally spreading laterally up to several hundred metres from the mineralized structure (Figure 4A). This is mainly due to residual Au accumulation by substantial mass reduction in the laterite zone, though there may also be a chemogenic component. Gold commonly occurs as residual Ag-rich particles armoured by quartz and ferruginous fragments and as coarse nuggets, slightly modified by weathering, although fine secondary particles may also be present (Freyssinet *et al.*, 1989).

2. An arid-stage, saprolitic (and/or saprock) Au anomaly occurs as a 'nail-shaped' subhorizontal zone within the saprolite (Figure 4B) due to the influence of saline groundwaters. This saprolitic anomaly has a sharp upper contact beneath a strongly depleted zone. The top few metres of the anomaly are enriched and supergene Au particles occur widely, suggesting hydromorphic dispersion in the upper part of the anomaly. The higher Au concentrations surrounding the mineralization directly below the depletion front do not necessarily indicate dispersion of Au, as this could be due to residual enrichment of a low grade primary halo.

3. Later, arid-phase processes result in surface Au anomalies in the upper residual profile and/or transported overburden and soil. This is partly due to residual Au concentration. In addition, Au is mobilized, possibly as organic complexes, and redeposited within soil. Pedogenic carbonate anomalies are typical of the southern Yilgarn, with substantial local chemogenic Au due to remobilization under semi-arid conditions.

These three supergene zones are discussed below. The saprolitic enrichment is the primary focus of this Project and is discussed more in Section 7.3, though relevant observations on the lateritic (Section 7.4) and surface (Section 7.5) enrichments are also discussed.

7.3 Enrichment of gold in the saprock and saprolite

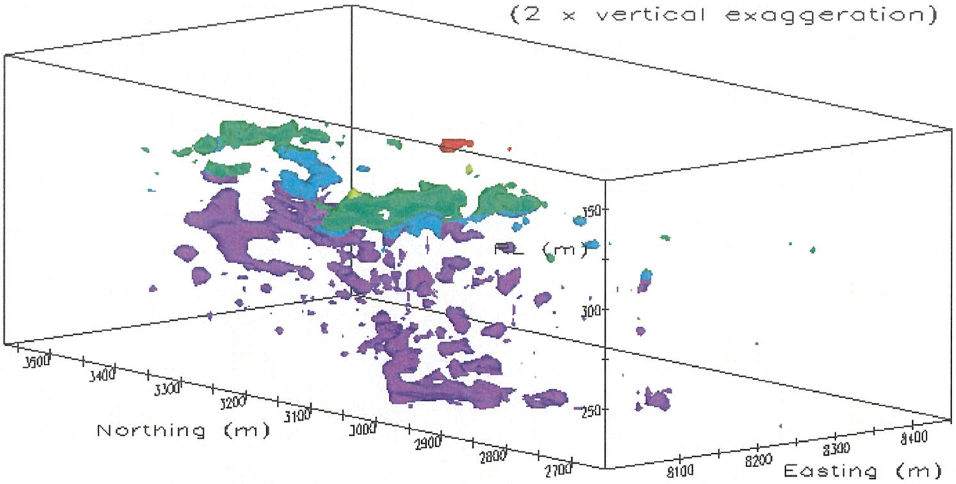
7.3.1 Introduction

Many Au deposits in the Yilgarn Craton demonstrate strong depletion in the upper clay-rich horizons of the regolith, with enrichment in the underlying saprolite and/or saprock. This enrichment, denoted in this report as the saprolitic Au enrichment zone, is generally a nail-shaped zone above the orebody, and is primarily due to residual enrichment (see below). The enrichment zones vary in depth, Au grade, size and orientation to the orebody from site to site. These anomalies have an approximately subhorizontal upper boundary with the Au-depleted zone, with considerably increased Au concentrations in the top few metres of the enrichment zone, including a substantial proportion of particulate secondary Au. The characteristics and variability of the anomalies are discussed below.

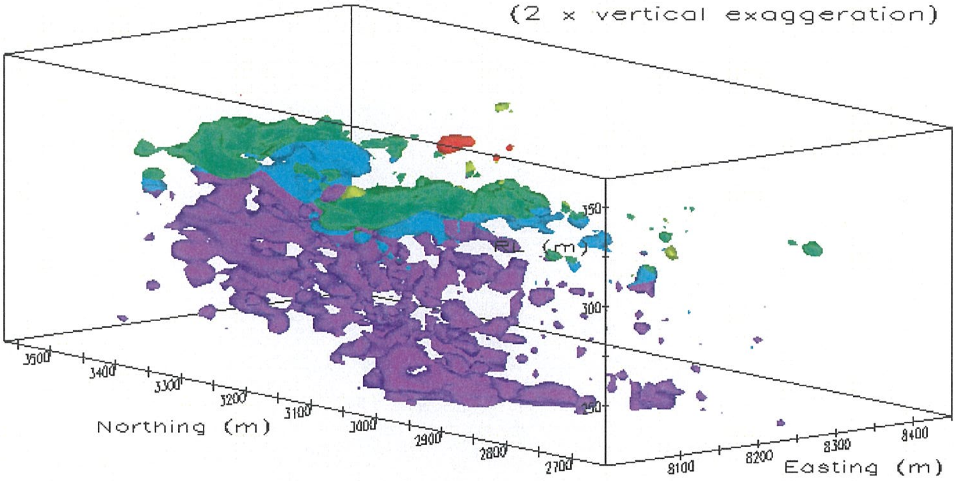
7.3.2 Geometry of the saprolitic enrichment zone

The boundary between the saprolitic Au enrichment zone and the overlying depleted zone is subhorizontal to horizontal. The width and thickness of the saprolitic Au enrichment zone varies from site to site, with the majority of the sites investigated in the Yilgarn, such as Carosue Dam (Figure 24), showing little (less than 100 m) or no broadening relative to the primary mineralization. A few sites (e.g., Twin Peaks (Figure 25), Kanowna Belle (Figure 26), Hannan South (Figure 28), Lounge Lizard (Figure 29) and Cleo (Gray and Britt, 2000) appear to show well developed broadening of the saprolitic Au enrichment, extending up to a few hundred metres from the main orebody. However, using 3D images, at least some of these supposedly well developed "blankets" as at Twin Peaks (Figure 25) become questionable. At a high (500 ppb; Figure 25A) Au cut-off, there is a small irregular broadening of the orebody below the depletion, similar to other sites. With a lower Au cut-off (50 ppb Au; Figure 25B), the anomaly shows a more classic "blanket" shape. However, the shape of the blanket is patchy and irregular, with the higher grades located above mineralization and mineralized structures. At an even lower cut-off (20 ppb Au; Figure 25B), the blanket shape of the halo becomes less clear still, with the anomaly commonly underlain by patchy low-grade Au mineralization. Similarly at Kanowna Belle, using a 100 ppb cut-off (Figure 26A), Au appears to form a blanket within the partially oxidized zone. However, when all contoured data are viewed (Figure 26B), the Au distribution in the partially oxidized zone is still closely correlated with underlying mineralization, though relatively enriched. Thus, it is suggested that the "blanket" appearance of the saprolitic enrichment zone is not due to hydromorphic dispersion. The geometry of the enrichment zone appears to be a consequence of residual enrichment up to the depletion front, a sharp depletion front, and some chemogenic enrichment within the top few (1 to 5) metres of the enrichment zone.

(A) 1 ppm Au cut-off



(B) 500 ppb Au cut-off



(C) 50 ppb Au cut-off

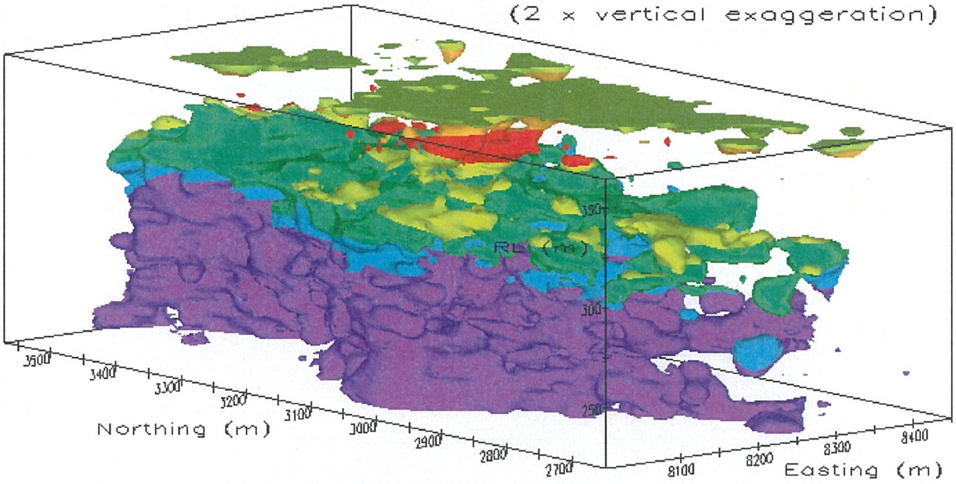
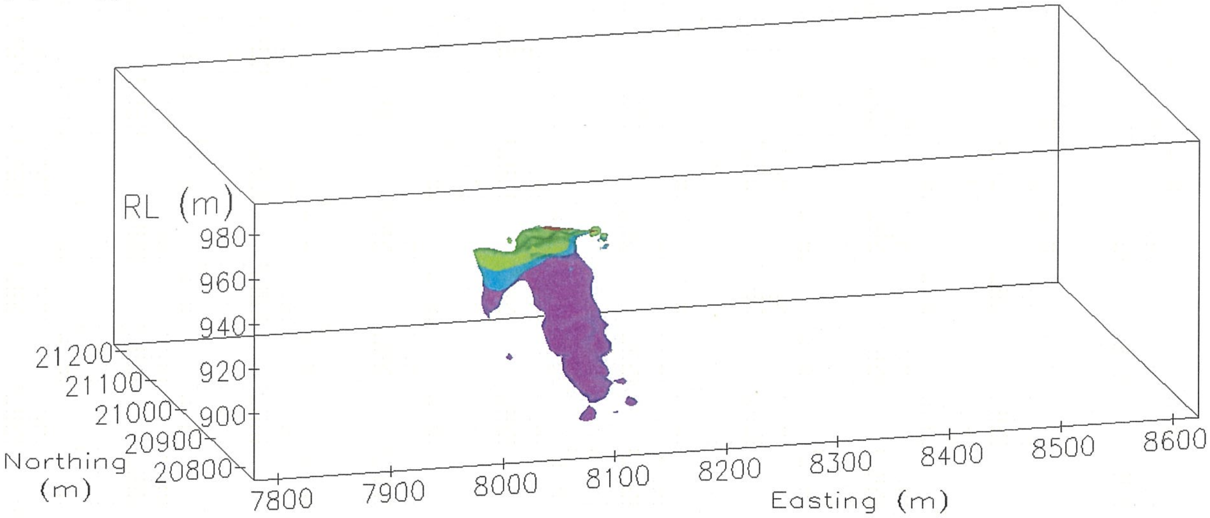
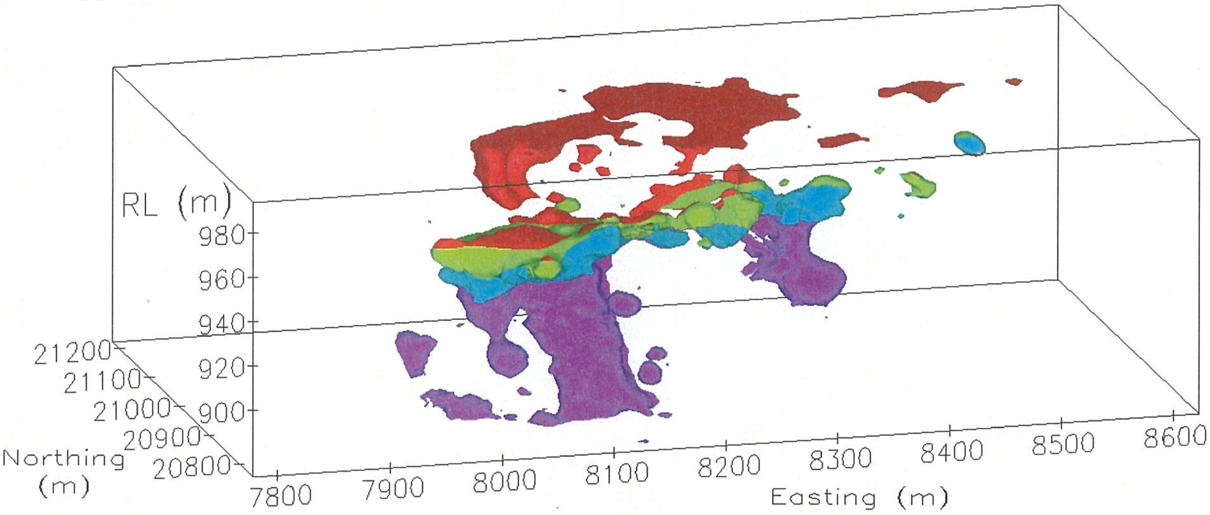


Figure 24: Gold distribution at Carosue Dam. Keys: purple - rock, blue - weakly oxidized saprolite, green - moderately oxidized saprolite, yellow - strongly oxidized saprolite, red - ferruginous zone, orange - transported cover, yellow/green - carbonate zone.

(A) 500 ppb Au cut-off



(B) 50 ppb Au cut-off



(C) 20 ppb Au cut-off

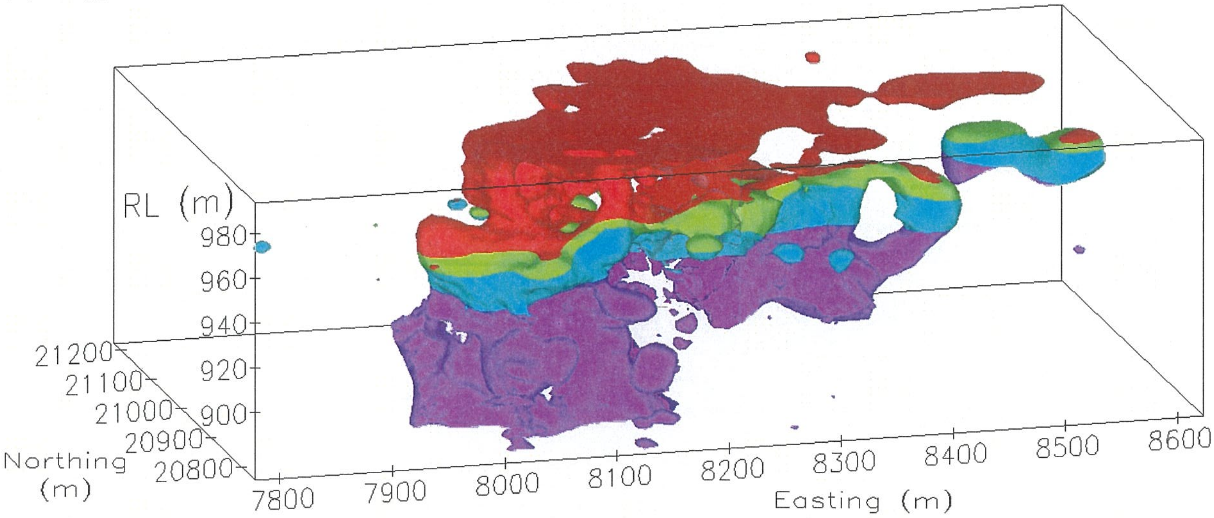
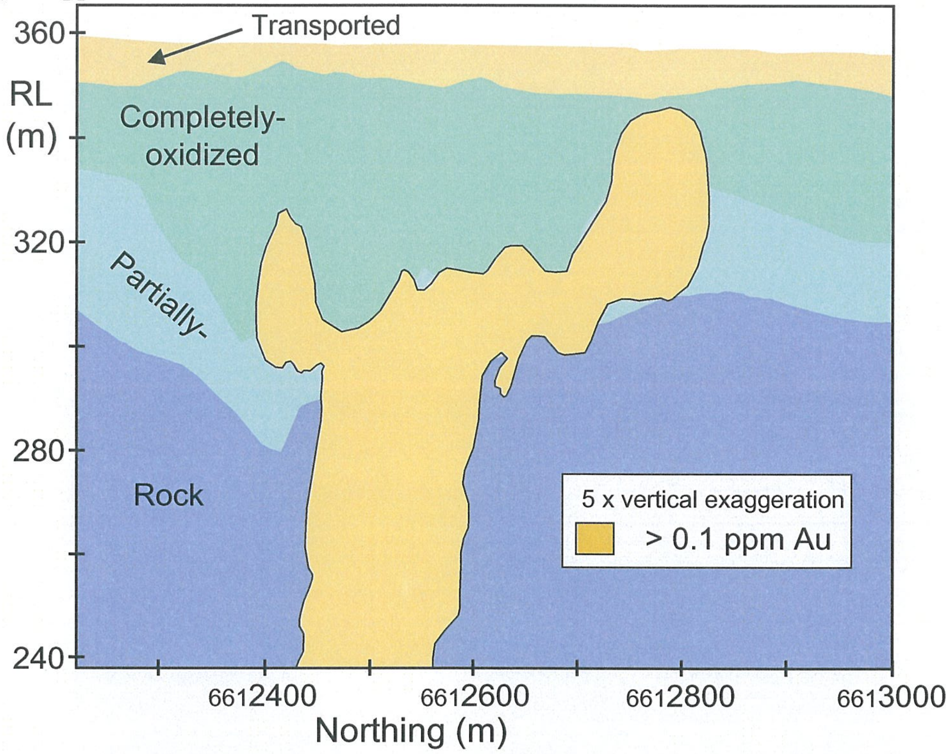


Figure 25: Gold distribution at Twin Peaks. Key: mauve - fresh rock, blue - slightly weathered, green - moderately weathered, red - highly weathered.

(A) 0.1 ppm Au cut-off



(B) All Au contours

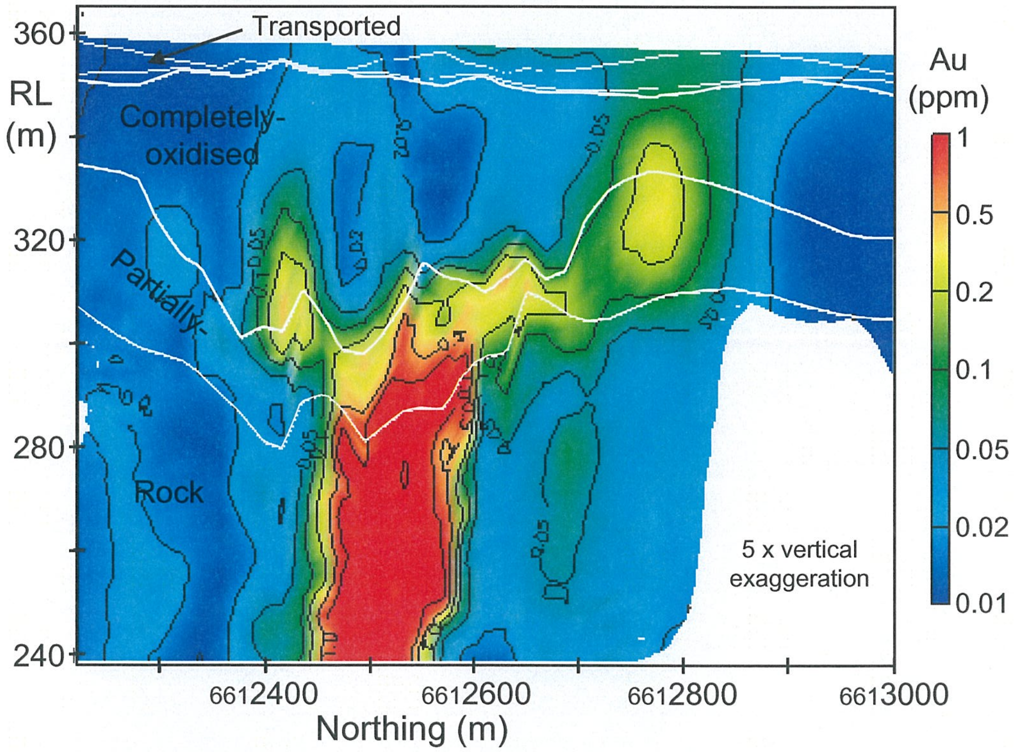


Figure 26: Kanowna Belle 363300 mN. (A) 0.1 ppm Au cut-off. Gold appears to form a blanket within the partially oxidized zone, but when contoured Au concentrations (B) are viewed it can be seen that, whilst enriched compared to the underlying rock, the Au distribution is still highly correlated with underlying mineralization.

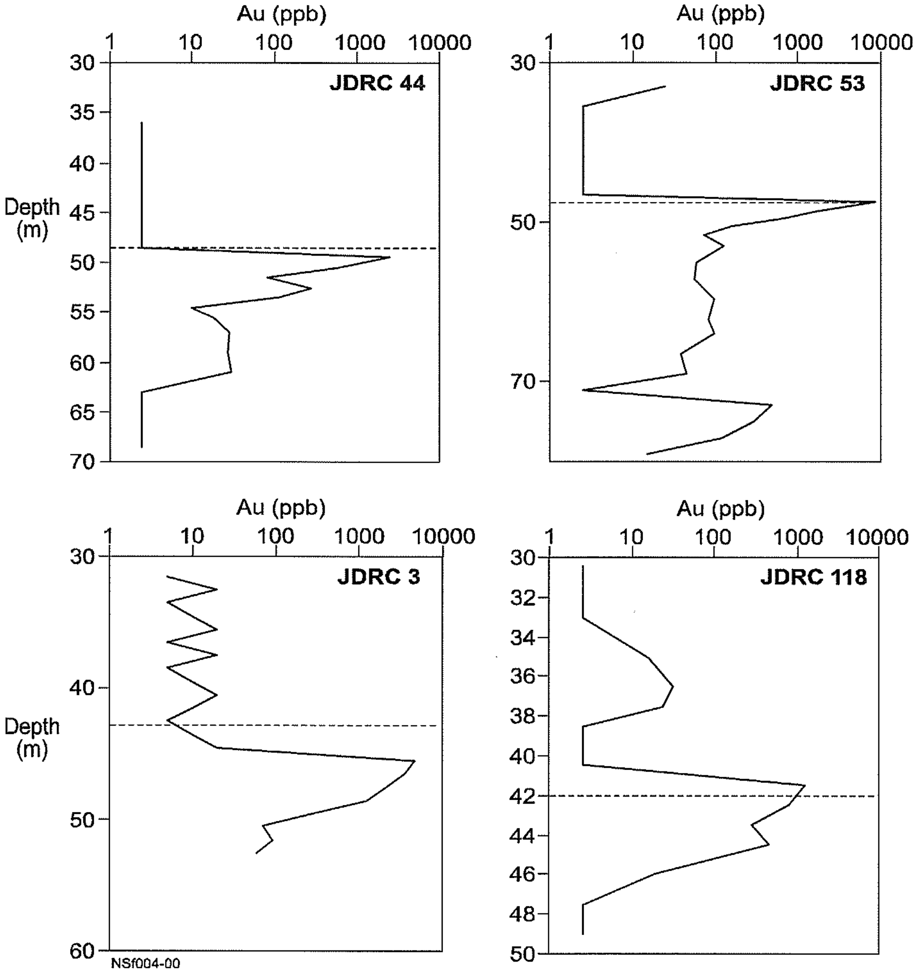


Figure 27: Gold distributions through the depleted zone and saprolitic enrichment at Twin Peaks. Dashed line represents transition from upper to lower saprolite.

There is a sharp contact between the depleted and the enrichment zones, with Au most strongly concentrated in the top 1 to 5 m of the supergene horizon, with a gradual decrease downwards. The MVS-generated images of Au distribution show a more gradual transition from the depleted to enriched zones, due to smoothing of the data during interpolation. Thus, at Twin Peaks, Au concentrations increase from below detection in the depleted zone to 10 ppm in the first few metres of the supergene orebody and 1 ppm within the halo (Figure 27). At Paddington, the boundary between the Au-depleted and enriched zones is sharp, and the Au content in the upper 1 to 2 m of the enrichment zone is commonly five to ten times greater than bedrock, gradually decreasing with depth (Hancock *et al.*, 1990). Similar Au distributions were also observed at Hannan South (Lawrance, 1991). This accumulation of Au in the upper portion of the saprolitic enrichment zone derives from the leaching of Au from the regolith above, but probably represents only a minor (estimated < 10%) component of the Au lost from the depleted zone.

Other features of the saprolitic enrichment zone are also difficult to explain by lateral Au transport. In plan the enrichment zone is generally oval, extending symetrically around the source. This is difficult to explain by lateral ground flow, which would have a preferred direction. At some sites (e.g., Kanowna Belle; Figure 26), the enrichment zone is upslope from the orebody, again contrary to an hypothesis of lateral Au redistribution. Thus, the data indicate that the saprolitic Au enriched zone is not a simple "blanket", formed by lateral dispersion, but was formed by a combination of three major processes:

1. Residual Au concentration due to rock mass reduction in the regolith.
2. Strong Au depletion above the anomaly.
3. Chemogenic Au accumulation at the very top (1 to 5 m) of the enrichment zone, presumably by downward Au migration.

7.3.3 Position of the saprolitic enrichment zone in the regolith

It is critical for Au exploration to understand the controls on the position of supergene Au enrichments in the regolith. Depth, regolith stratigraphy and groundwater level are obviously important parameters. They reflect changes in chemical and physical rock characteristics through a vertical profile, which may govern dissolution or deposition of Au in the resultant Eh-pH regimes.

Observations from P504 and earlier projects suggest that supergene enrichment zones commonly occur below the present-day watertable. Although other results [e.g., Lady Bountiful (Bartsch, 1990), Montague (Middleton, 1990), Edna May (Webster and Mann, 1984) and Lancefield Telegraph (Hronsky *et al.*, 1990) and studies by Mann (1984, 1998)) suggest co-location of the supergene enrichment zone and the present water-table at some sites, documentation is scanty. It appears that at nearly all sites, Au is actively being dissolved from the regolith in saline regions within the upper oxidized groundwaters. Gold enrichment due to residual (and, in some limited situations, hydromorphic) processes occurs in weakly oxidized/reduced zones, well below the water-table. To understand the influence of depth and regolith stratigraphy on the positioning of the supergene Au enrichment zone, data were compiled from various sources (Table 2).

Table 2: Calculated mean depth of the maximum Au concentrations within the saprolitic Au enrichment zone.

P504		Other sources		
Deposit	Depth (m)	Deposit	Depth (m)	Reference
BLC	16	Hannan South	20	Lawrance (1994)
Apollo	20	Paddington	30	Hancock *et al.* (1990)
Monty Dam	26	Bottle Creek	30	Legge *et al.* (1990)
Federal	30	Lights of Israel	30	Douglas *et al.* (1993)
Comet	34	Gourdis	30	Anand *et al.* (2000)
Mt Percy	35	Montague	20-35	Middleton (1990)
Golden Delicious	40	Gimlet South	35-45	Harrison *et al.* (1990)
Twin Peaks	42	Telegraph	38-40	Hronsky *et al.* (1990)
Kanowna Belle	44	Calista	40	Anand *et al.* (2000)
Panglo	30	Edna May	40	Webster and Mann (1984)
Carosue Dam	45	Bluebird	50	Walsh (1990)

The top of the saprolitic enrichment zone occurs at mean depths ranging from 16 to 20 m at BLC, Hannan South and Apollo to 50 m at Bluebird. Although the other deposits are similar (30 to 40 m), depths vary at each site, especially where regolith boundaries are undulating. Kanowna Belle has substantial deepening of the regolith over the mineralized structure, and there, the depth of the supergene enrichment changes considerably, being at higher levels over the weakly mineralized wall rocks (Figure 26). The top of the saprolitic enrichment zone coincides with the base of complete oxidation (possibly equivalent to the upper to lower saprolite transition). Other sites where regolith boundaries are not horizontal (e.g., Carosue Dam (Figure 24) and Hannan South (Figure 28)) also show variations in depth and coincidence of the Au enrichment zones with regolith boundaries.

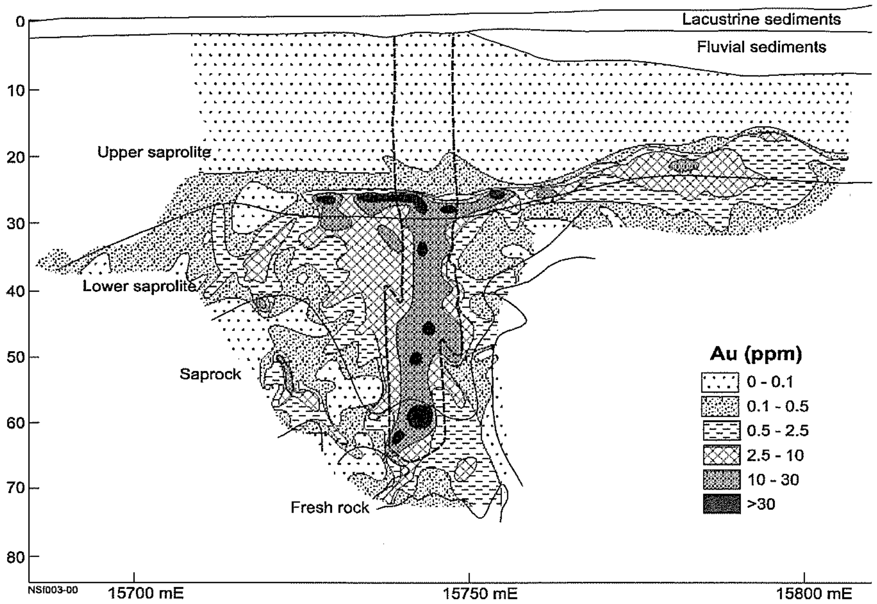


Figure 28: Gold distribution in the regolith at Hannan South (Lawrance, 1991).

Variations in bedrock lithology and differing exploration logging systems complicate comparisons of saprolitic Au enrichment zones between sites. Regolith transitions are mostly defined by colour change (redox front, base of complete oxidation), fabric transitions or mineralogical changes. Data on the Au depletion fronts for three major rock types (mafic and ultramafic rocks; intermediate felsic rocks; and granitoids) are presented in Table 3 and are discussed below. P504 observations and comparisons of exploration logging schemes show that, despite different definitions for regolith units, the data on critical regolith transition obtained, so far, show good agreement (Table 3).

Mafic and ultramafic rocks

At deposits hosted by mafic and ultramafic rocks, the supergene Au enrichment zone is confined to a regolith transition defined by a colour change from red, yellow or cream to green or grey. Thus, at Lounge Lizard (Figure 29), hosted by pyroxenite and dolerite, the enrichment zone occurs below the transition marked by regolith colour change from red-yellow to green. This boundary roughly corresponds to the transition from the clay zone to saprolite (Forrestania Gold NL logging) (Figure 29), although the boundaries do not always match completely.

At Hannan South (Figure 28), the supergene enrichment occurs at a sharp transition from red-brown to grey-green weathered rocks (Lawrance, 1994). The redox front also marks a sharp change in the weathering intensity and separates the lower saprolite from the upper saprolite. Lower saprolite consists of pale, greenish-grey rock, in which 20 to 80% of the primary minerals are replaced by clays, mainly kaolinite with minor smectite. In the upper saprolite, all primary minerals, except for quartz and some resistant accessory minerals, are completely weathered to clay and Fe-oxides, with preservation of the primary rock fabric.

At Mt Percy, hosted by felsic porphyries and meta-komatiites, the top of the weakly developed Au enrichment zone occurs at the transition from the upper, clay-rich regolith (i.e., the mottled and plasmic zones and some upper saprolite) to the saprolite (Butt, 1991). At Calista and Cumberland, at Mt McClure, hosted by meta-basalt, with komatiite at Calista and felsic tuffs at Cumberland, the depleted zone overlying the supergene Au enrichment similarly corresponds to the mottled and clay zones and some upper saprolite (Anand *et al.*, 1999). At Quarters, at Mt Pleasant, hosted by basalt, the top of the enrichment is at the BOCO (Foster *et al.*, 1997) which is mostly defined by a colour change from red-yellow to grey-green (redox front).

Table 3: Characteristics of the regolith transition coincident with the saprolitic Au enrichment zone.

Mafic and ultramafic rocks

Site	Transition	Colour transition	Regolith transition	Reference
Bounty, Bounty East, Lounge Lizard	Clay to saprolite	Red-yellow to grey	Clay without original primary fabric to saprolite	Britt and Gray (2001)
Hannan South	Upper to lower saprolite	Red-brown to grey-green	Clay with original primary fabric to saprolite	Lawrance (1991)
Calista, Cumberland	Clay-rich zone to saprolite		Clay to saprolite	Anand *et al.* (1999)
Quarters	BOCO*	Red-yellow to grey-green		Foster *et al.* (1997)
Mt Percy	Clay-rich zone to saprolite		Clay-rich regolith (mottled, plasmic zones, upper saprolite) to mid-saprolite	Butt (1991)

Intermediate felsic rocks

Site	Transition	Colour transition	Regolith transition	Reference
Twin Peaks, Monty Dam	Highly to moderately weathered	Orange-yellow-cream to grey-green	Clay with original primary fabric to saprolite	Sergeev and Gray (1999)
Carosue Dam	Strongly to moderately oxidized	Light-creamy to creamy-grey	Clay with original primary fabric to saprolite	Gray *et al.* (2000)
Kanowna Belle	BOCO*			Gray (2000)

Granitoids

Site	Transition	Colour transition	Regolith transition	Reference
Federal	BOCO*	White-pale-grey to grey-green-cream	Clay with original primary fabric to saprolite	Sergeev and Gray (2000)
Golden Delicious	Saprolite to saprock		?	

* BOCO – Base of complete oxidation

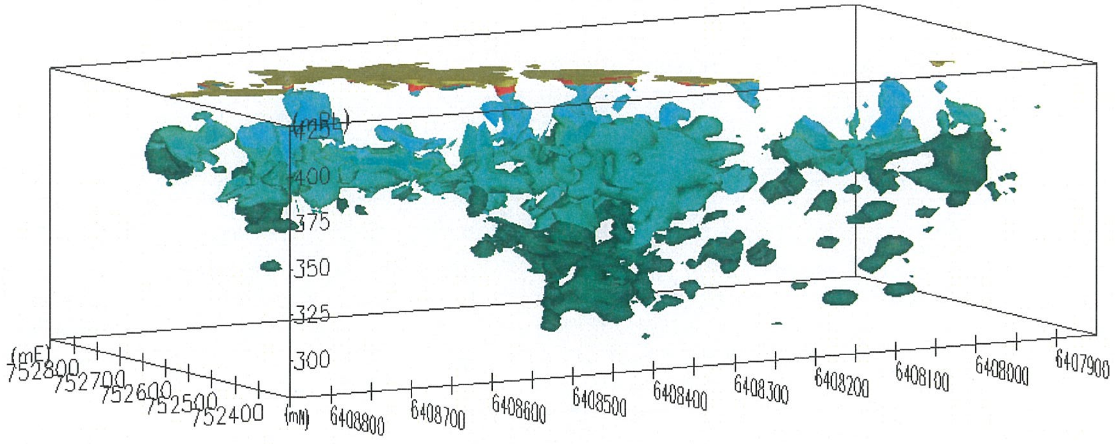


Figure 29: Gold distribution at Lounge Lizard using a 150 ppb cut off, showing the top of the supergene Au enrichment zone at the clay to the saprolite transition. Key: dark green – bedrock, green – saprock, bright green – saprolite, blue – residual clay, red – laterite, yellow – transported.

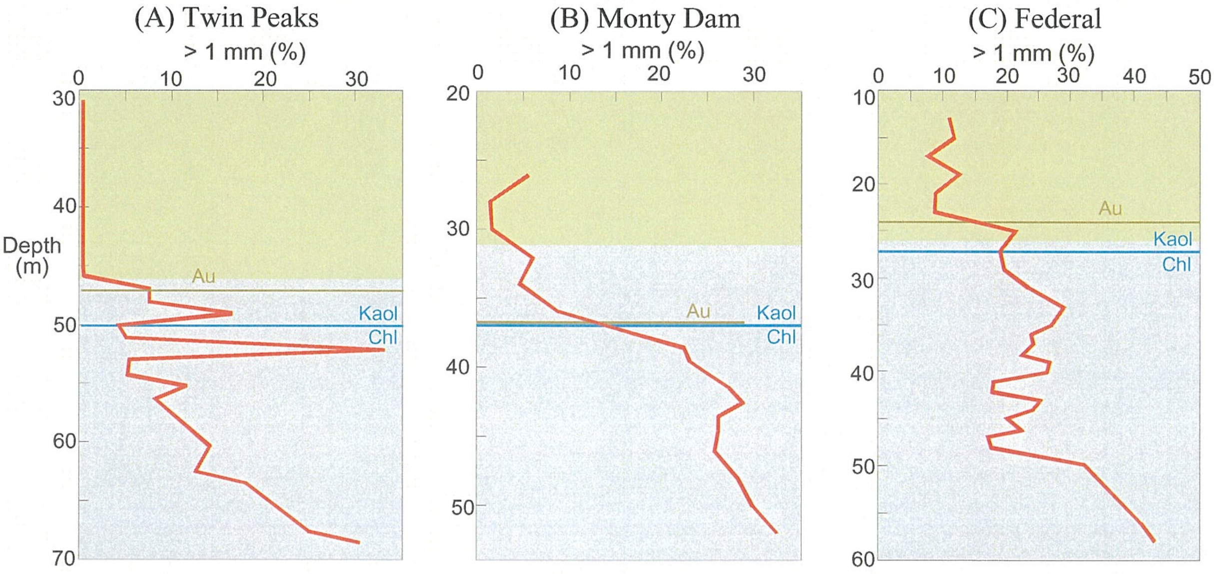


Figure 30: Variation with depth of the regolith colour change, Au depletion front (Au), mineralogical transition from kaolinitic to chloritic (Kaol / Chl) and the proportion of the > 1 mm fraction in drill spoil (red line) for representative drill holes from (A) Twin Peaks, (B) Monty Dam and (C) Federal.

Intermediate felsic rocks

As felsic rocks contain fewer Fe-bearing minerals than mafic and ultramafic rocks, the upper regolith is paler and the colour change that typically indicates the saprolitic Au enrichment zone is not so sharp. However, the position of the Au enrichment zone in the regolith over felsic rocks is similar. Twin Peaks and Monty Dam are hosted by felsic andesite to dacite. At Twin Peaks, the top of the enrichment zone is coincident with highly to moderately weathered rocks (the upper to lower saprolite; Figure 25). This transition is well defined by a colour change from creamy-yellow to greenish-grey and marks the complete replacement of primary minerals by kaolinite, but with preservation of original fabric. It is also defined by the proportions of size fractions in the drill spoil (> 1 mm); the clay-dominated rocks are soft and the drill spoil is finer grained (Figure 30A). The colour transition at Monty Dam is similarly defined (Figure 30B), but is not everywhere coincident with the enrichment zone, possibly because of later redox over-printing of the regolith with the development of the adjacent playa, Lake Rebecca. The Au enrichment at the nearby Carosue Dam deposit occurs at a similar position (Table 3; Figure 24).

Granitoid rocks

At Federal, about 40 km NNW of Kalgoorlie, hosted by granodiorites and monzogranites, the upper regolith is white to pale-grey, with gradual transition to a grey-green saprolite below. The Au enrichment zone is located several metres below the BOCO (Figure 31) corresponding to the clay to mid-saprolite transition. The transition is defined by a colour change from pale grey or white to creamy-grey or creamy-green. As at sites in mafic and intermediate felsic rocks, the colour change approximately marks the transition from kaolinitic saprolite to saprolite containing some primary minerals. The transition is also well defined by a sharp increase in proportion of the size fraction > 1 mm in drill cuttings (Figure 30C) downwards across the boundary. However, in contrast with other rock types, Federal also has a major enrichment (mean Au concentration twice that in the unweathered rock) in the saprock approximately 10 m above the weathering front. This possibly reflects primary mineralization or is specific to Federal's lithological and structural characteristics.

Golden Delicious, 5 km E of Lake Carey is also hosted by granitoid rocks. It is similar to Federal with the major depletion front occurring at the logged saprolite-saprock interface (Figure 32). The Au enrichment at both granitoid hosted sites is deeper in the regolith than for other host rocks. This may reflect the poorer buffering by granite-derived regolith. Golden Delicious also has Au enrichment at the mottled zone-saprolite transition (Bristow *et al.*, 1996; Figure 32). The mottled zone comprises large (up to 20 cm diameter) hematite-rich mottles in clay. Little primary fabric is preserved in the mottles or the clays except at the base of the unit. It is not clear whether the Au in this zone is residual or chemically transported. Golden Delicious is unusual in that weathering is shallowest in the mineralized zone. Thus, saprolite is only thinly developed over the main orebody with the mottled zone directly overlying a thin saprolite zone grading into saprock. The primary Au may be dissolving and re-precipitating along the mottled zone-saprolite contact, which is generally coincident with a red to green colour change in the regolith due to a redox (Fe^{3+}/Fe^{2+}) front. This hypothesis needs to be tested at other sites where weathering is shallower within the mineralized zone.

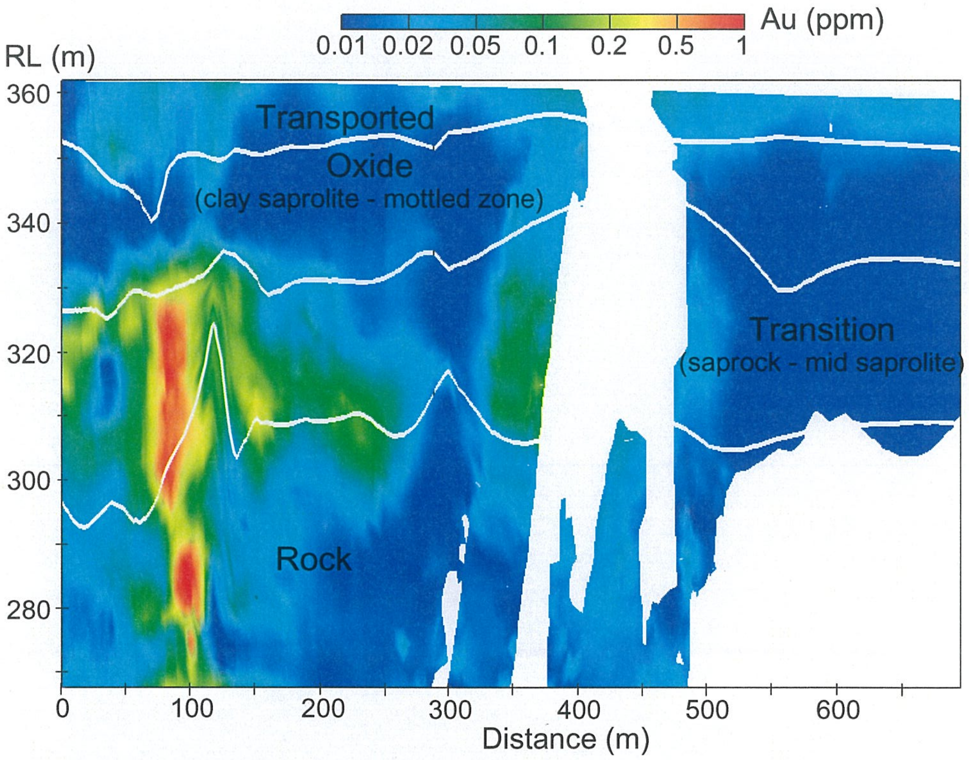


Figure 31: Gold distribution across a section through the Federal orebody, looking NW.

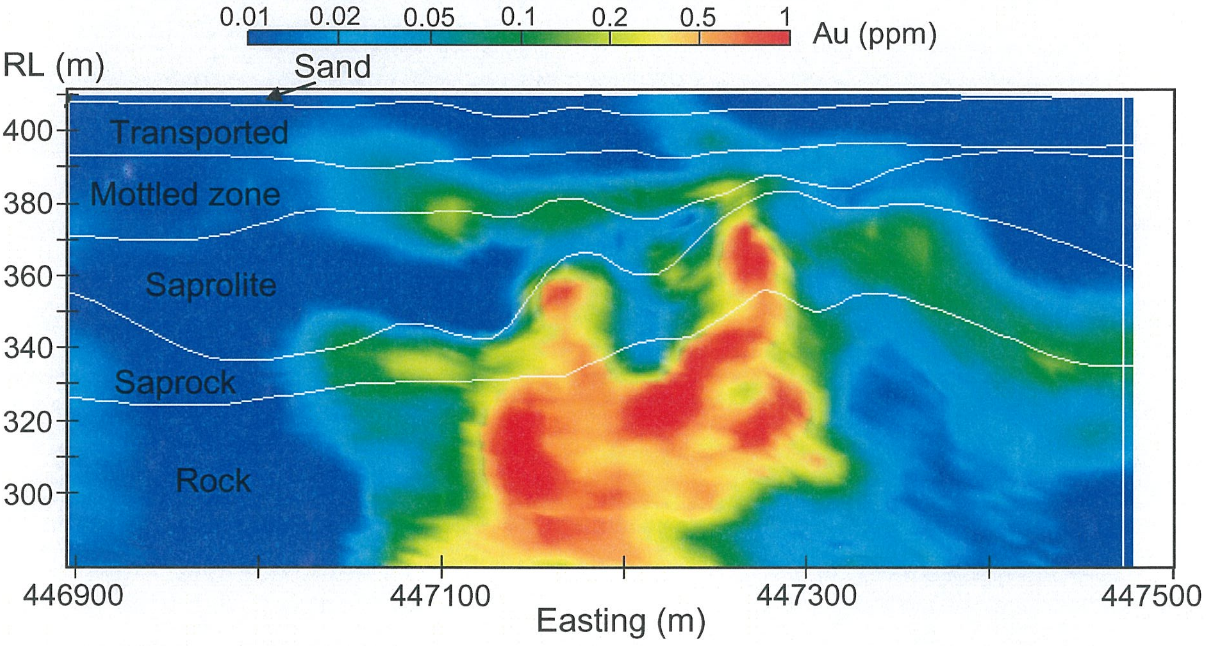


Figure 32: Gold distribution at Golden Delicious along Section 6790200 mN.

7.4 Lateritic Au enrichments

Lateritic Au enrichments and anomalies are commonly considered to be largely "fossil" anomalies generated during humid weathering in the Tertiary, although there may have been later reworking. Such enrichments have been investigated in earlier AMIRA Projects (240, 240A and 241), and are only discussed briefly here. Surface and/or subsurface Au concentration coincides with the lateritic residuum (unconsolidated lateritic gravel or massive, nodular or pisolitic duricrust) capping the lateritic weathering profile (Gray *et al.*, 1992). In humid, rainforest environments, these enrichments may be associated with stone lines (Essis *et al.*, 1993). In residual environments, the lateritic anomaly forms a "mushroom-shaped" subhorizontal blanket (Figure 4A), commonly spreading up to several hundred metres from the mineralized structure (e.g., Mt Gibson, Boddington). This anomaly is mainly due to residual Au accumulation resulting from substantial volume and mass reduction during the formation of lateritic residuum by chemical leaching and mechanical separation. Gold occurs as residual, Ag-rich particles within quartz and ferruginous fragments and as coarse nuggets, slightly modified by weathering. Some residual Au grains show significant surface chemical reworking (rounding and Ag-depleted rims). Supergene Au has a minimal contribution to total mass balance, occurring as small crystals, flakes, wires and dendrites of pure Au. Examples of major Yilgarn Au deposits with significant lateritic dispersion haloes are Boddington (Davy and El-Ansary, 1986; Anand, 1994), Bronzewing (Anand *et al.*, 1999), Mt Gibson (Anand *et al.*, 1989) and Callion (Glasson *et al.*, 1988).

7.5 Calcrete enrichments

Gold accumulations within pedogenic carbonates form an important surface to sub-surface dispersion halo in the semi-arid regions of the Yilgarn Craton, south of about 30°S. Pedogenic carbonates are formed in unsaturated soil horizons and differ from groundwater carbonates, which form in deeper, saturated environments. Pedogenic carbonates occur in many forms, e.g., massive duricrusts, nodules, powders, coatings and rhizomorphs and consist mostly of calcite and dolomite. Extensive research on Au calcrete anomalies undertaken by CSIRO and CRC LEME in Western and South Australia (e.g. Lintern, 1989; Lintern and Scott, 1990; Lintern and Butt, 1991, 1992; Lintern and Sheard, 1999) indicate that Au and pedogenic carbonate are commonly strongly correlated. Gold is concentrated with carbonate in the top 1 to 2 m of the soil (Lintern *et al.*, 1997). The correlation suggests combined, or parallel, chemogenic transport and deposition of Au, Ca and Mg near the surface. Vegetation and/or microorganisms may be involved in the mobility, dispersion and recycling of these elements near the surface (Lintern *et al.*, 1997), mobilizing this Au in soil solution as organic complexes, and precipitating it with the carbonates under evaporative conditions.

Within P504, detailed studies of carbonate Au anomalies were undertaken at the Federal (Sergeev and Gray, 2000) and Twin Peaks deposits (Sergeev and Gray, 1999) with minor research at Panglo (Gray, 1999) and Carosue Dam (Gray *et al.*, 2000). At the Federal deposit, found following discovery of a calcrete anomaly on an adjacent tenement, transported overburden is up to 16 m thick, with a pedogenic carbonate horizon located near the surface. A broad, patchy Au surface dispersion halo extends up to 600 m to the NE of the orebody at a 30 ppb cut-off (Figure 31). Gold is mostly concentrated within the calcareous soil and colluvium at 1 to 3 m depth and at the base of sediments within the lateritic colluvium. Gold distribution patterns in the residual regolith show numerous, narrow subvertical zones, which appear to "feed" Au to the surface, resulting in the carbonate Au anomaly.

In calcareous soil and colluvium, Au is strongly correlated with Ca, Mg, Sr and S (Figure 33 and Figure 34). Gold mass balance calculations (Sergeev and Gray, 2000) indicate that carbonate nodules contain 83 to 97% of the Au, suggesting chemical Au remobilization in the calcrete environment. Some of the Fe oxide nodules also have high (up to 400 ppb) Au concentrations, but their contribution to the total Au mass balance is negligible. Gold grains found in carbonate nodules are of high-fineness and different in shape from those in the primary mineralization and in the rest of the regolith. They are fragile, complex Au aggregates and possibly have a bacterial origin, though this needs further investigation.

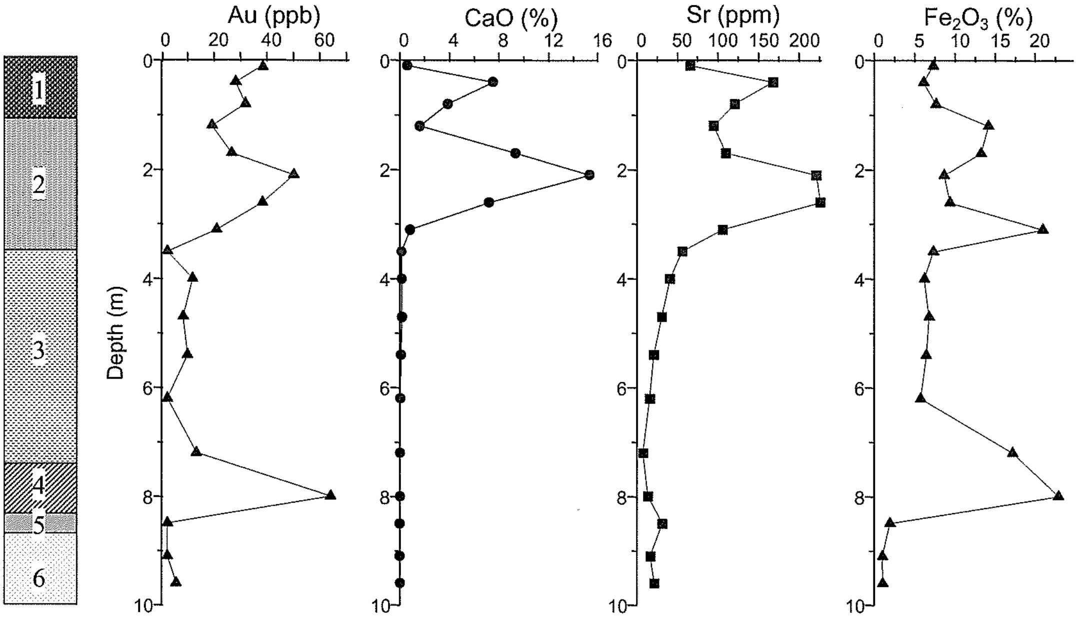


Figure 33: Distribution of Au, Ca, Sr and Fe with depth through transported overburden, NE wall of the Federal pit. Key: 1 – soil, 2 – hardpanized colluvium, 3 – silicified colluvium; 4 - duricrust colluvium, 5 – silicified clay saprolite, 6 – clay saprolite.

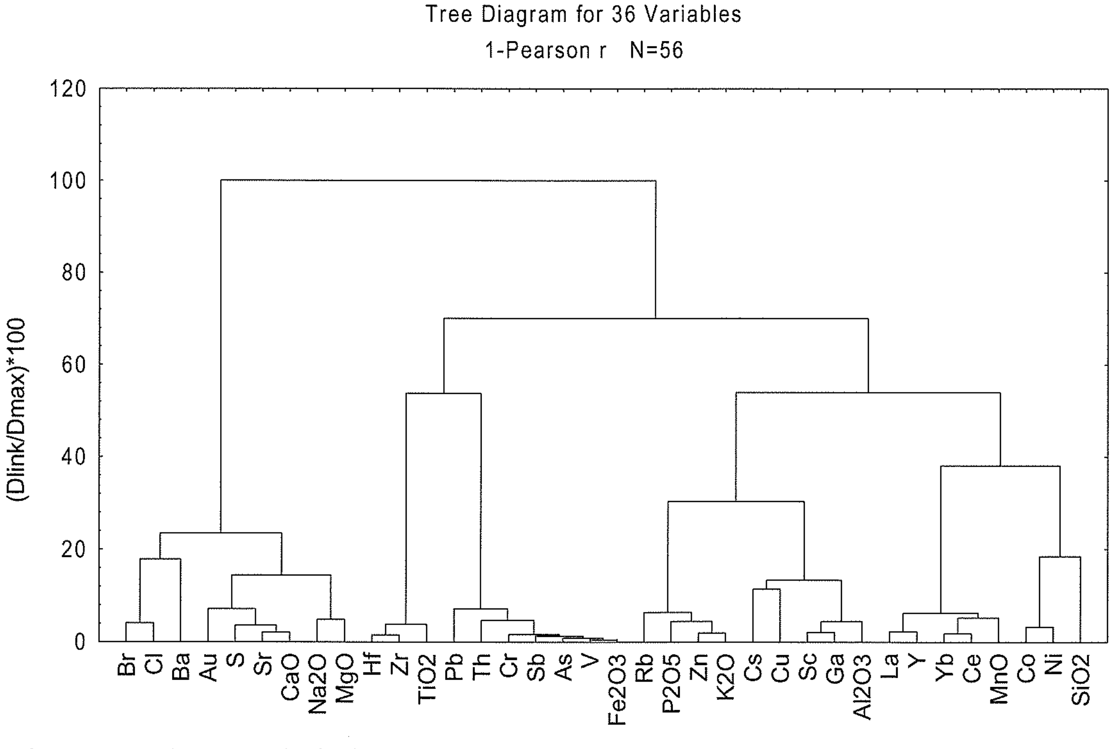


Figure 34: Cluster analysis demonstrating associations of elements within calcareous soil and colluvium, Federal.

These results contrast with Twin Peaks (Figure 25), the discovery of which is also attributed to calcrete sampling. This deposit is in an erosional regime, with pedogenic carbonates developed in the top 3 m. A Au anomaly (at a 20 ppb cut off) extends for 230 m, coincident with the NW-trending axis of mineralization and up to 350 m to the east. The average thickness of the Au surface anomaly is 2 m and, in places, Au concentrations are > 1 ppm.

Partial extraction analyses, Au mass balance calculations and Au grain studies (Sergeev and Gray, 1999) suggest a substantial (36 to 96 wt %, mean 60 wt %) contribution of residual Au in the anomaly. Thus, extractions on pulverized materials at Twin Peaks show a lower (50% mean) percentage of iodide-soluble Au than for other carbonate soils in the Yilgarn Craton (commonly > 80%; Gray and Lintern, 1993), indicating a lower proportion of mobile Au. Data from unpulverized subsamples demonstrate that cyanide extracts only 65% of the total Au, indicating that a substantial amount of Au is occluded by resistant minerals. Gold mass balance calculations performed on the calcrete residue after carbonate dissolution for major rock fractions support the results of partial extractions, showing that a substantial (mean 60 wt %) proportion of Au is occluded within saprolite and ferruginous fragments. Supergene Au is as high-fineness crystals with morphologies similar to those in the saprolite. No specific Au morphologies that could be related to Au redeposition in the calcrete environment were identified.

Evidence that residual primary Au "feeds" calcrete anomalies through the transported overburden was also found at Panglo (Gray, 1999) and Carosue Dam (Gray *et al.*, 2000). At Panglo, both 3D visualization (Figure 35) and calculations of Au concentrations in the regolith suggest that the Au anomaly in pedogenic carbonates in the overburden may be supplied from the residual Au concentrated at the unconformity. At Carosue Dam, where the residual profile is overlain by transported overburden up to 10 m thick, there is a Au anomaly near the surface with pedogenic carbonates (Figure 24). Gold grain studies (Gray *et al.*, 2000) demonstrate that a significant component of the Au is primary. The anomaly is "fed" through the sediments from the residual mineralization in the central part of the area which has not been Au-depleted, presumably preserved by local pervasive silicification, and has spread several hundred metres to the south (Figure 24). The surface Au distribution is statistically less skewed than at depth, indicating significant redistribution. Thus, a substantial part of the surface mobility of Au is by physical, rather than chemical, transport of the primary Au, presumably southwards.

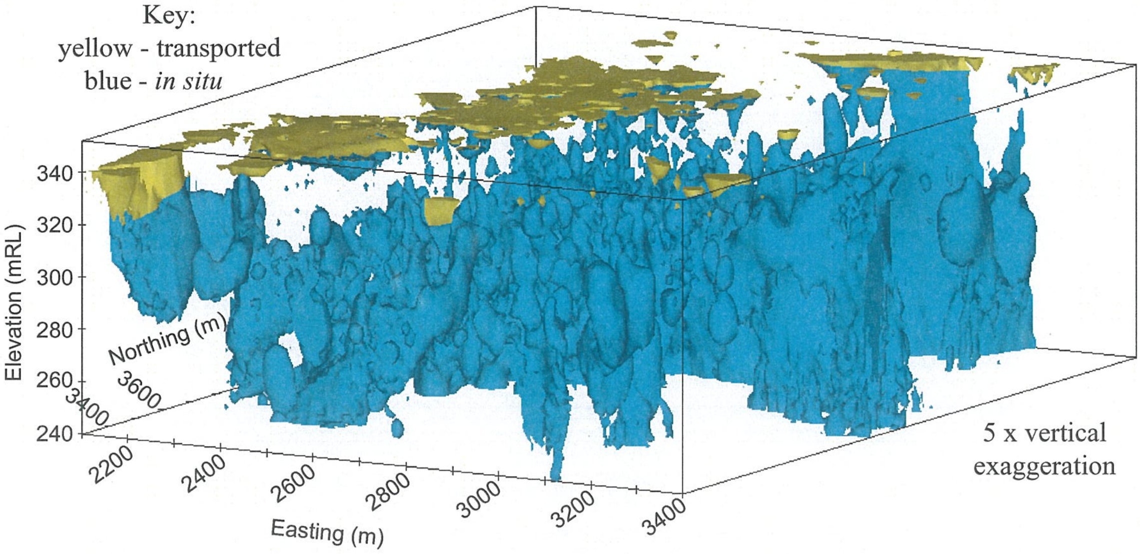


Figure 35: Gold distribution using a 50 ppb cut-off, Panglo.

The data indicate that the carbonate anomalies at these sites have been sourced from residual Au mineralization, with further Au remobilization and dispersion near the surface in the carbonate environment. The majority of the sites demonstrate clear superposition of the chemogenic calcrete dispersion halo above an enrichment in residuum or mineralized saprolite. Similar data were previously obtained at Mt Percy (Butt, 1991) and the Mulline prospect (Lintern and Butt, 1991), where Au, within the widespread surface enrichments, is partitioned between ferruginous and carbonate materials, indicating some residual component in the anomaly. At other sites, e.g., Carosue Dam and Federal, carbonate anomalies are supplied through generally depleted or barren regolith via few narrow subvertical residual Au zones. In these cases, the surface anomaly has resulted from further Au dispersion within pedogenic carbonates.

In summary, at all sites studied, there is a coherent and physically connected source for the Au, be it lateritic or surface Au, which was never depleted due to occlusion of the Au above the saturated zone, as resistant "units" in the upper regolith, or from outcrop up-slope. However, there is a limit to the vertical dispersion of Au. Numerous studies have indicated that surface sampling can "see through" transported cover only where the cover is less than 10 m at most, generally less than 5 m. This depth is significantly less in northern parts of the Yilgarn where pedogenic carbonate is absent. Despite this, pedogenic carbonates can be recommended as a preferential sampling medium. Physical and/or chemogenic Au dispersion from the residual source provide larger targets and more uniform Au distribution within the anomaly.

8 CHARACTERISTICS OF SUPERGENE PARTICULATE GOLD

8.1 Introduction

Properties of particulate Au are an important source of information on Au behaviour in the regolith. Detailed investigations in Western Australia, as part of AMIRA Project 241 (Butt *et al.*, 1991) at Bardoc, Mt Percy, Callion and Panglo in the Kalgoorlie area, Beasley Creek in the Eastern Goldfields, Reedy in the Murchison province, and studies at Hannan South (Lawrance, 1991) established important differences between primary and supergene Au particles. Primary Au grains tend to be irregular and xenomorphic, and the Au is alloyed with more than 1% of Ag and minor Cu, Hg and some other metals. In contrast, supergene particulate Au occurs mainly as small crystals of high fineness with no detectable Ag. However, so far, there is insufficient information on particulate supergene Au in various regolith environments (saprock, saprolite, laterite, calcrete), particularly on Au grain trace element composition and its mineral assemblages. This information is critical for understanding supergene Au mobilization and transport. Gold grain studies can also be used to estimate contributions of secondary and primary Au in the regolith anomalies.

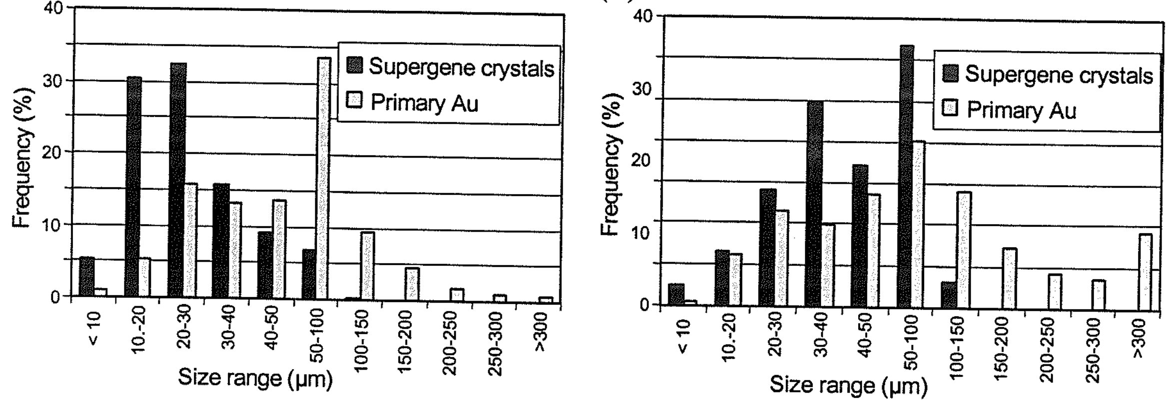
Research within this project has included studies of the variations in supergene Au morphology, composition and assemblages in different regolith environments. The Mt Joel prospect (Porto *et al.*, 1999), Twin Peaks and Monty Dam deposits (Sergeev and Gray, 1999) were investigated in detail, with additional studies at the Carosue Dam (Gray *et al.*, 2000) and Federal deposits (Sergeev and Gray, 2000). All involved the following techniques (Section 3.3):

1. selection of Au-rich samples from enrichment zones in the regolith and from primary mineralization;
2. two-step panning by Haultain Superpanner and micropanner;
3. removal of at least 100 Au grains and examining their sizes, morphology and mineral assemblages optically, and by SEM (selected particles); and
4. analyses of selected grains in polished sections by electron microprobe.

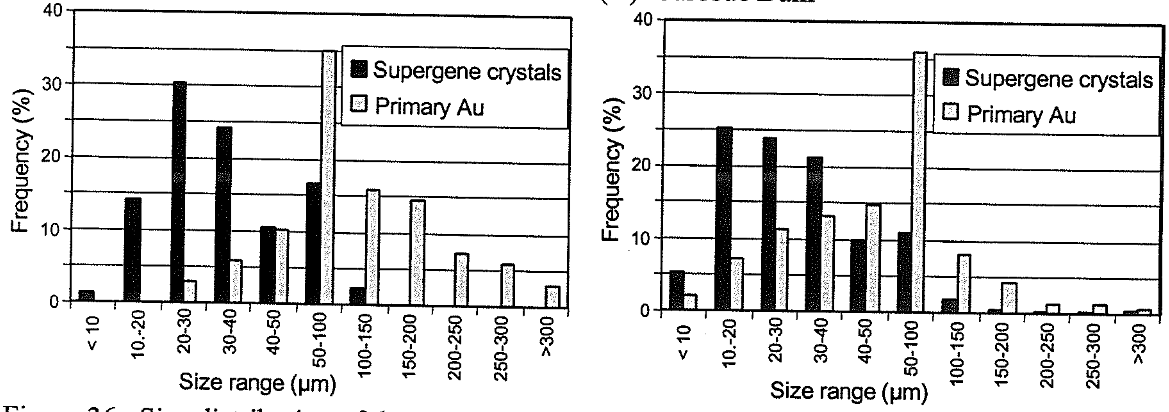
The results are summarized and discussed below. The data refer only to grains that can be recovered by mechanical panning. A substantial proportion of grains smaller than 10 μm will have been lost.

8.2 Gold grain size

At the sites studied, primary Au grains average 100 to 150 μm in length, with 8 to 30% of Au grains larger than 150 μm (Figure 36). In contrast, free supergene Au particles are smaller (Figure 36), being dominantly less than 100 μm, with mean lengths ranging from 25 to 50 μm. At Twin Peaks and Monty Dam, Au grains have bimodal size distributions due to a substantial number of large crystal aggregates. Size distribution curves for individual crystals are very similar: being unimodal with the peak at 10 to 30 μm (Figure 37). Similar results had been obtained at Bardoc, Reedy and Beasley Creek (Freyssinet and Butt, 1988a, 1988b, 1988c; Butt *et al.*, 1991), where Au grains in the saprolite were smaller than in primary rock or adjacent quartz veins.


(A) Mt Joel

(B) Twin Peaks


(C) Monty Dam

(D) Carosue Dam

Figure 36: Size distribution of the supergene and primary particulate Au at (A) Mt Joel, (B) Twin Peaks, (C) Monty Dam and (D) Carosue Dam.

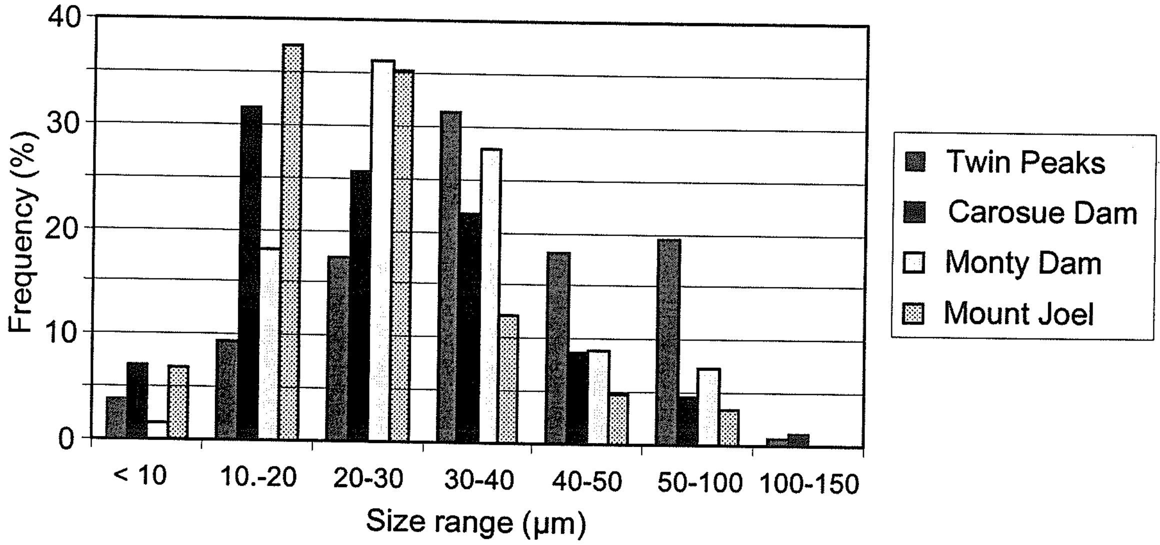


Figure 37: Size (length) distribution for individual supergene crystals, %.

All the studied and reviewed sites demonstrate the small size of supergene Au crystals. Although there are some larger supergene Au particles up to 3 mm diameter at Hannan South (Lawrance and Griffin, 1994), most are < 50 µm. Large Au particles occur as very thin (0.5 to 3.0 µm) pseudo-trigonal, hexagonal and dodecahedral plates with masses are comparable with smaller octahedra, or less frequently as dendrites > 10 mm.

8.3 Morphology

In the Yilgarn, supergene Au mainly occurs as euhedral and subhedral crystals with minor rounded or xenomorphic grains (Table 4). Pseudo-hexagonal tabular (e.g., flattened crystals with length/height ratio 1.5 to 3.0), platy (aspect ratios up to 100:1 or more) and prismatic crystals are the most abundant with minor, elongated crystals and combinations of cube and octahedra also present. Crystals are mainly pristine or slightly corroded within the saprolite and saprock, and strongly corroded in the depleted upper regolith and near the surface. Supergene reworking of Au within the saprolite enrichment zone is evident in some deposits, e.g., Hannan South (Lawrance and Griffin, 1994), and Bardoc (Freyssinet and Butt, 1988b).

Observations on morphologies of secondary Au in the saprock and at the weathering front are too limited for satisfactory conclusions on the mechanism of Au dispersion in these zones. The morphology of the supergene Au crystals does not change systematically through the regolith profile. Thus, at Mt Joel, secondary Au is present in various proportions (10 to 90%) throughout the regolith (Porto *et al.*, 1999) with mean data for each zone showing approximately similar percentages of the major crystal morphologies (Figure 38). This may indicate similar mechanisms of Au remobilization for both the upper and lower regolith. However, if Au had dissolved as thiosulphate or polythionate complexes in the lower regolith, the resultant supergene Au may occur as xenomorphic Ag-rich grains, which would be difficult to distinguish from primary Au.

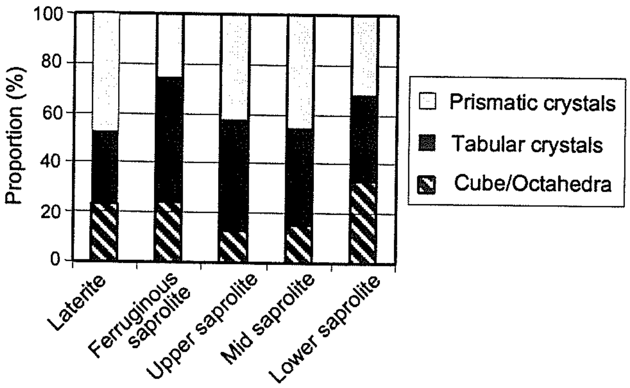


Figure 38: Morphologies of supergene Au crystals in the regolith zones of Mt Joel.

Anhedral supergene grains are less common, with Au occurring as wires, dendrites, spongy and mamillary aggregates, equant and irregular grains. "Coraline" and "cauliflower" aggregates are specific supergene Au morphologies abundant at Mt Percy (Gedeon and Butt, 1990). These may be *"in situ"* products of weathering of Au-bearing sulphides or tellurides (Wilson, 1984), or very strongly corroded, Ag-depleted grains after electrum, which is abundant at the site. Cryptocrystalline Au in intergrowths with goethite was also reported from Callion (Llorca, 1989).

Supergene Au morphology may be affected by the kinetics of Au deposition and growth, the geometry of crystallization and the compositions of supergene solutions. Rapid Au growth may lead to poorly crystalline aggregates, dendrites and skeletal crystals. Well-crystallized Au grows better in open spaces, whereas platy crystals and wires are constrained by narrow fractures and water films. The influence of solution composition on supergene Au morphology is still unclear. Thus, similar Au morphologies (e.g., tabular and prismatic crystals) were observed whether the groundwaters are highly saline (Kalgoorlie area) or almost fresh (Yandal Belt and Murchison province). Thin platy crystals mostly occur in the highly saline Kalgoorlie region, but they are associated with other Au morphologies (Table 4), further complicating interpretation.

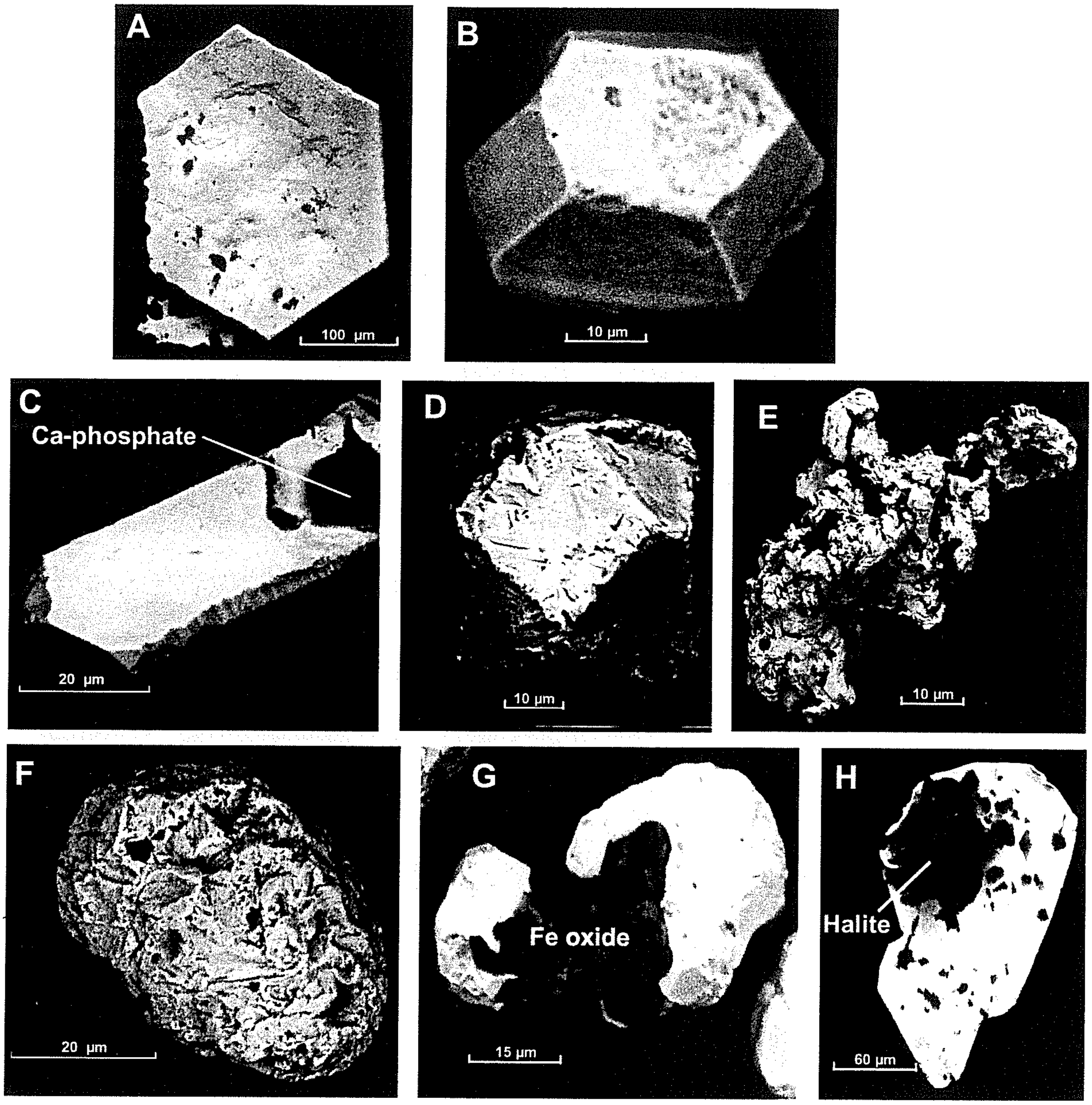


Figure 39: Typical morphologies and associations of supergene Au grains in the Yilgarn. A: pseudo-hexagonal platy crystal, Queen Lapage. B: pseudo-hexagonal tabular crystal, Mt Joel. C: prismatic crystal with an inclusion of Ca-phosphate, Carosue Dam. D: combination of cube and octahedra, Twin Peaks. E: irregular grain, Monty Dam. F: rounded grain, Twin Peaks. G: an intergrowth of Fe oxide and prismatic Au crystals, Mt Joel. H: Close intergrowth of halite and Au grains, Monty Dam.

8.4 Composition

In contrast to primary Au, which is commonly alloyed with more than 2% Ag and minor Cu, Hg and Te (Groves and Ho, 1990; Gedeon and Butt, 1990), supergene Au from Yilgarn sites is very pure. There are traces of Fe and Si in supergene Au at Hannan South (Lawrance and Griffin, 1994). As part of this project, microprobe analyses showed relatively high mean concentrations of Fe (up to 7140 ppm), Si (170-3200 ppm) and S (80-330 ppm) in supergene Au crystals (Table 5), presumably within inclusions. In comparison, mean Fe and Si concentrations in primary Au particles are a little lower at Mt Joel, whereas S concentrations (310 ppm) are similar. The elements are inter-correlated (Figure 40), which suggest they are micro-inclusions.

Table 4: Morphology of the supergene Au in the Yilgarn Craton.

Area	**Site**	**Morphology of supergene Au** **Typical**	 **Other**
Yandal Belt	Mt Joel	Prismatic and tabular crystals	Cubes, octahedra and round grains
Murchison	Reedy	Tabular, platy and prismatic crystals	Complex globular to hackly aggregates
	Mount Gibson	Rounded grains, square flakes and octahedra	Elongated platelets and wires
Laverton	Beasley Creek	Tabular and prismatic crystals	Rounded and irregular grains
	Twin Peaks	Prismatic crystals and combinations of cube and octahedra	Platy crystals, xenomorphic grains
Mulgabbie	Monty Dam	Prismatic and tabular crystals	Combinations of cube and octahedra
	Carosue Dam	Prismatic and tabular crystals	Elongated crystals, combinations of cube and octahedra
	Federal	Platy crystals	Prismatic and tabular crystals, rounded grains
	Mt Percy	Hackly, "cauliflower" aggregates	Tabular and prismatic crystals (secondary Ag halides)
Kalgoorlie	Hannan South	Cube-octahedra, platy crystals	Dendrites, wires and mamillary aggregates
	Bardoc	Prismatic and platy crystals	Irregular aggregates and dendrites
	Panglo	Tabular crystals	
	Callion	Polycrystalline aggregates	Films
Norseman	Princess Royal	Complex aggregates of tabular and prismatic crystals, dendrites	
	Queen Lapage	Platy crystals	
Southern Cross	Blue Turtle	Prismatic crystals and equant grains	Tabular and platy crystals, irregular grains
	Edna May	Octahedra, flat crystals and films	
	Griffins Find	Thin particles and films	

Table 5: Trace element compositions of the supergene Au.

Mount Joel

No	Regolith unit	Ag (ppm)		Cu (ppm)		Si (ppm)		Fe (ppm)		S (ppm)	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
8	L	<90	<90	<40	<40	460	410-510	150	80-390	310	270-400
1	US	<90	<90	<40	<40	490	490	130	130	330	330
6	S	<45	<45	25	bd (100)	3200	170-15500	7140	20-38120	80	70-170
24	LS	<90	<90	22	bd (70)	520	130-1240	810	bd (7720)	260	bd (370)

Carosue Dam

No	Regolith unit	Ag (ppm)		Cu (ppm)		Si (ppm)		Fe (ppm)		S (ppm)	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
5	S	<145	<145	<30	bd (35)	220	140-290	<30	bd (30)	nd	nd

Twin Peaks

No	Regolith unit	Ag (ppm)		Cu (ppm)		Si (ppm)		Fe (ppm)		S (ppm)	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
11	S	<145	bd (170)	<30	bd (30)	170	130-220	<30	bd (50)	nd	nd

Monty Dam

No	Regolith unit	Ag (ppm)		Cu (ppm)		Si (ppm)		Fe (ppm)		S (ppm)	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
17	S	<145	<145	<30	bd (40)	80	bd - 190	<30	bd (130)	nd	nd

L – laterite, US – upper saprolite, S – saprolite, LS – lower saprolite.
No – number of samples, bd – below detection (detection level); nd – not determined

Table 6: Trace element compositions of the primary Au.

Site	No	Ag (%)		Cu (ppm)		Si (ppm)		Fe (ppm)		S (ppm)	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Mount Joel	22	2.7	1.5-5.0	180	bd (300)	415	280-640	140	70-250	310	200-380
Carosue Dam	2	10.3	6.9-13.7	180	140-220	150	140-160	<30	<30	nd	nd
Twin Peaks	13	14.0	12.7-16.3	90	50-110	40	bd (80)	140	bd (160)	nd	nd

No – number of samples, bd – below detection (detection level); nd – not determined

Concentrations of Cl and I in the supergene Au are below detection (30 and 36 ppm respectively). Remnant Cl and I might be expected, as these elements are potential ligands for Au (Section 6.2), but Cl and I salts may have been removed in solution during polishing.

Primary Au is generally substantially modified in the upper regolith, being depleted in Ag and Cu near the grain surface and along fractures (Table 7). Thus, SEM determinations of high fineness of grain surfaces for some residual Au grains may be misleading. Data on surficial Au composition should be coupled with the morphology of the grain being studied, along with analyses of grain sections for a reliable conclusion.

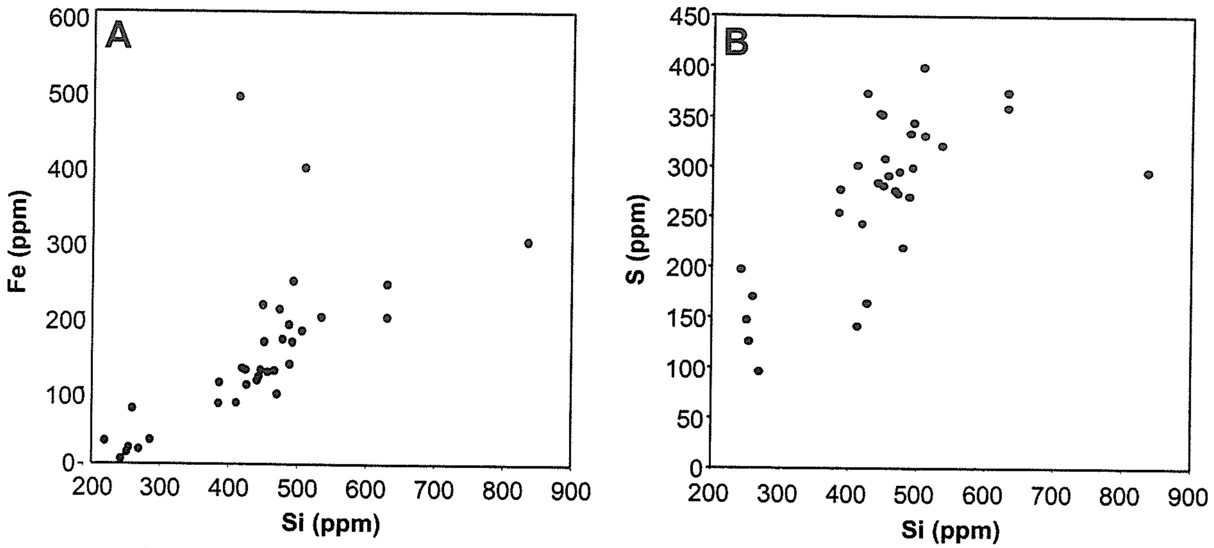


Figure 40: (A) Si-Fe and (B) Si-S concentration plots for supergene Au particles.

Suggesting micro inclusions.

Table 7: Electron microprobe analyses of cores and rims of the residual Au from the saprolite, Twin Peaks, (ppm).

Sample	Grain area	Ag	Cu	Si	Fe
1	Core	127760	80	<40	<30
	Rim	630	<30	70	30
2	Core	133760	70	60	<30
	Rim	230	<30	40	<30
3	Core	136980	60	40	<30
	Rim	170	50	40	<30

8.5 Mineral associations

Supergene Au is commonly associated with Fe oxides, which occur as intimate intergrowths and cover some of the surface of Au particles. Halite is also common, and has been documented at many sites, e.g., Hannan South (Lawrance and Griffin, 1994), Callion (Llorca, 1989), Monty Dam (Sergeev and Gray, 1999) and Queen Lapage. Surprisingly, intergrowths of halite with Au were found at Monty Dam even after long-term panning in water, which implies Au and halite may be a much more common association than previously realized. In addition, Ag halides coated in secondary Au were found at Mt Percy (Butt, 1991). However, the widespread halite occurrence in the regolith under modern semi-arid conditions, means that halite-Au grain associations could be coincidental, rather than indicating Au transport by Cl.

There are close associations of supergene Au with Ca-P and Ca-P-Ce-Fe-Yb-Sr phases at Twin Peaks (Sergeev and Gray, 1999) and Carosue Dam (Gray *et al.*, 2000). These minerals are probably related to apatite. This is consistent with observed correlations of Au with Ce, Y and Yb in the depleted and enriched zones. Gold and REE enrichment zones were noted at Mt Percy (Butt, 1991), though the distribution patterns did not match. There may be parallel (but not identical) Au and REE mobilization in acid oxidizing conditions of the upper regolith.

9 INFLUENCE OF PRIMARY MINERALIZATION AND LITHOLOGY ON SUPERGENE AU DISPERSION

The majority of the larger primary Au deposits in the Yilgarn are "mesothermal" (Perring *et al.*, 1990). The principal styles are: (1) alteration haloes with disseminated sulphide mineralization in shear zones, (2) large, laminated quartz reefs in shear or fault zones, and (3) quartz stockworks or vein sets in massive igneous rocks. Minor stratabound mineralization is developed in BIF.

The style of primary mineralization can affect supergene Au mobility by:

1. influencing the access of supergene solutions to the primary Au;
2. affecting the physical state of the primary Au;
3. controlling the chemistry of supergene solutions.

It is helpful to generalize primary Yilgarn Au deposits as a continuum of styles with quartz-vein mineralization as one end member and disseminated or massive sulphide mineralization as the other. Gold in quartz-vein deposits is mostly free and occurs as relatively coarse particles within quartz and infilling fractures in the quartz (Groves and Ho, 1990). In contrast, a high proportion of Au in sulphidic mineralization occurs either within the lattices of Fe and As sulphides or as submicroscopic inclusions. These differences in siting and association of Au affect its supergene mobility. Gold in sulphides becomes accessible to supergene solutions at early weathering stages. This Au may be highly mobile because of its small particle sizes and close association with sulphides. Weathering of sulphides leads to locally high concentrations of S oxyanions and other ligands capable of dissolving Au within the oxidizing sulphide "cell", even where the bedrock is relatively sulphide poor. For example, at the Calista deposit in the northern Yilgarn, there is strong Au remobilization in the regolith (Figure 41), independent of the surrounding groundwater regime. In contrast, Au in vein quartz is inaccessible to supergene solutions until the fragmentation of quartz in the upper regolith. Also, free, coarse Au is less mobile than submicron-size Au and is commonly only slightly corroded at its surface by preferential Ag depletion.

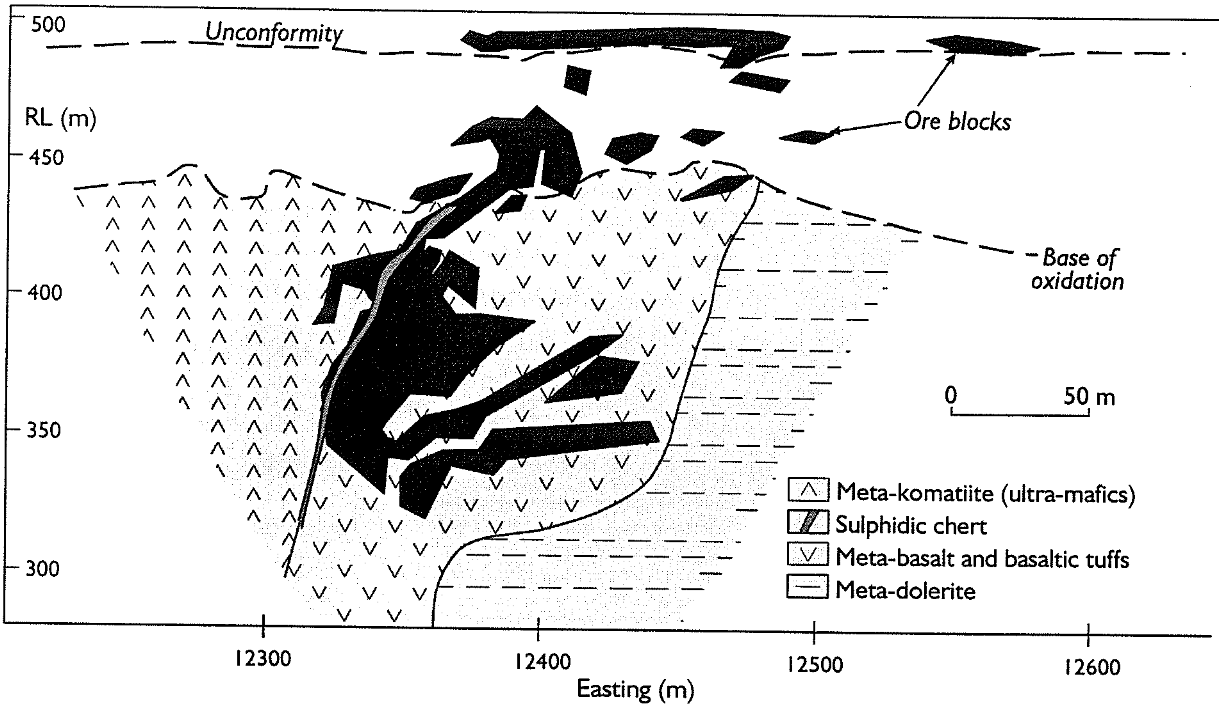


Figure 41: Gold distribution at the Calista Deposit, Section 51154 N, using a 0.5 ppm Au cut-off

Quartz vein and sulphide mineralizations commonly occur together in many Yilgarn shear zone deposits. These typically include a central high-grade quartz vein zone and a low-grade primary alteration halo with disseminated sulphide mineralization. Weathering results in obvious differences in supergene Au mobility. Supergene Au depletion is much more pronounced within the sulphide alteration zone, whereas high Au concentrations in quartz veins can be traced to the surface where they supply residual surface anomalies. This is seen in the Yandal belt, where sulphide-rich deposits have extensive supergene Au mobilization zones, whereas deposits which contain Au restricted to quartz veins have limited dispersion within saprolite and saprock (Anand, 2000).

Primary lithology also influences the degree of supergene Au mobility. Two adjacent deposits at Gourdis, in the northern Yandal belt, have contrasting lithologies and Au distributions in the regolith. The 81400 deposit, hosted by sheared quartz-feldspar porphyry and basalt contacts, has strong Au depletion in the upper regolith (Figure 42A). Four hundred metres away, the 81800 deposit, hosted by sheared mafic rocks, has Au enriched in the upper regolith (Figure 42B). Ultramafic and, to a lesser degree, mafic rocks buffer groundwaters more than other lithologies, leading to reduced Au depletion. Alternatively, the styles of mineralization at these deposits, which are unknown, might account for the differences.

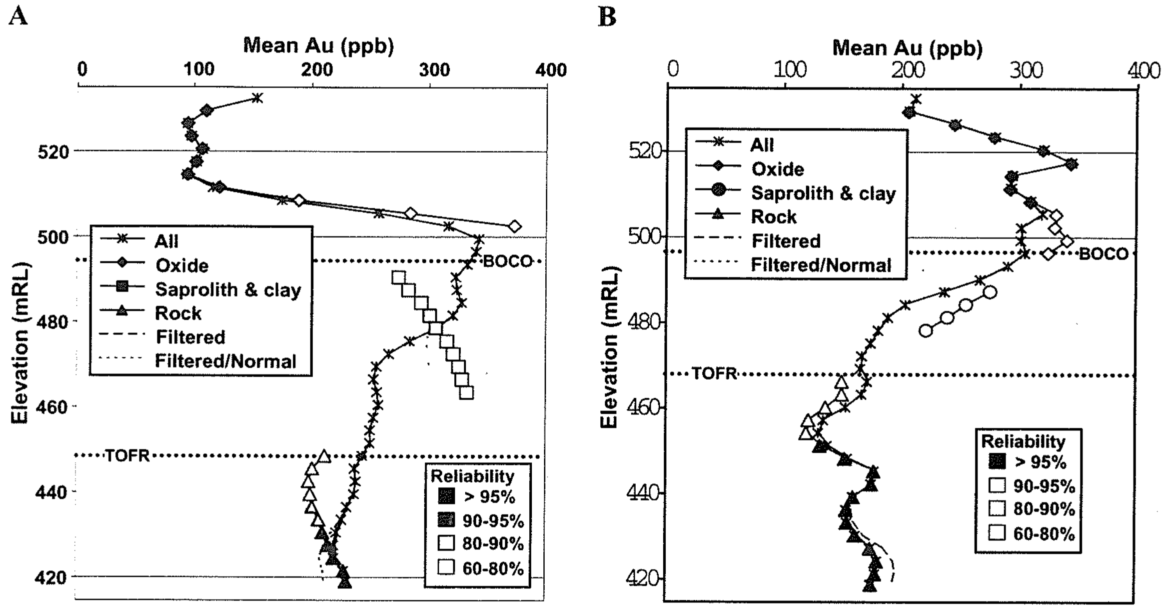


Figure 42: A) Au vs. elevation at Gourdis 81400, showing depletion in upper regolith.
B) Au vs. elevation at Gourdis 81800, showing enrichment in upper regolith.
Key: BOCO – base of complete oxidation, TOFR – top of fresh rock (weathering front)

Similarly, results for the adjacent Kanowna Belle and BLC deposits, 20 km NNE of Kalgoorlie, suggest primary bedrock influence on supergene Au mobility. The bedrock at Kanowna Belle is dominated by felsic volcanic rocks and the primary Au is associated with pyrite, minor arsenopyrite, chalcopyrite and sphalerite. Gold is strongly depleted in the upper regolith but concentrated below the base of complete oxidation (BOCO) (Figure 26). In contrast, mineralization at BLC is associated mainly with ultramafic rocks. Although the primary Au is free and associated with quartz veins (A. Aaltonen, Delta Gold N.L., personal communication, September 2000), there is considerably less Au depletion in the regolith, with Au mostly confined to primary structures (Figure 43). Geomorphology may also be an important factor in this area (Section 10), with BLC having a higher landscape position than Kanowna Belle (Gray, 2000).

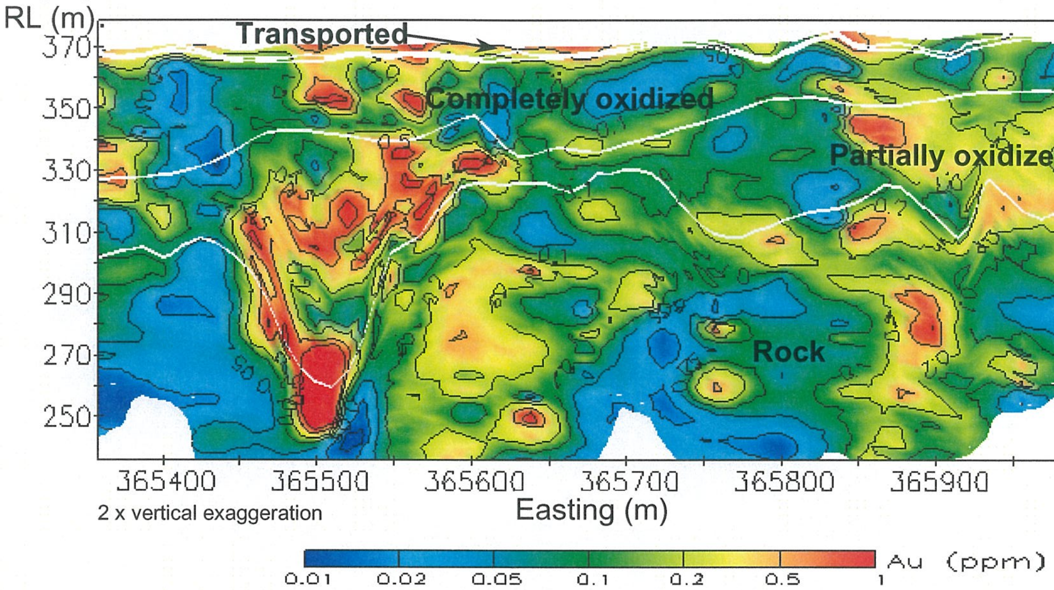


Figure 43: Gold concentration along Section 6614350 mN at Ballarat Last Chance (BLC).

Silicification may also reduce depletion by occluding the Au. Carosue Dam has very corrosive groundwaters with high dissolved Au contents, resulting in major depletion in the upper regolith (Figure 24). However, close to the centre of the orebody, silicification of the regolith has formed a resistant "chimney" of Au, resulting in a major surface anomaly.

10 REGIONAL PATTERNS OF AU SUPERGENE MOBILITY

Sections 5 and 6 present the results and hypotheses of regional groundwater studies in the Yilgarn Craton. It has led to a significant improvement in our understanding of regional variation in the degree of supergene Au mobility. This sections relates the observed patterns of supergene Au mobility to four groundwater regions of the eastern Yilgarn: Kalgoorlie, Eastern, Central and Northern.

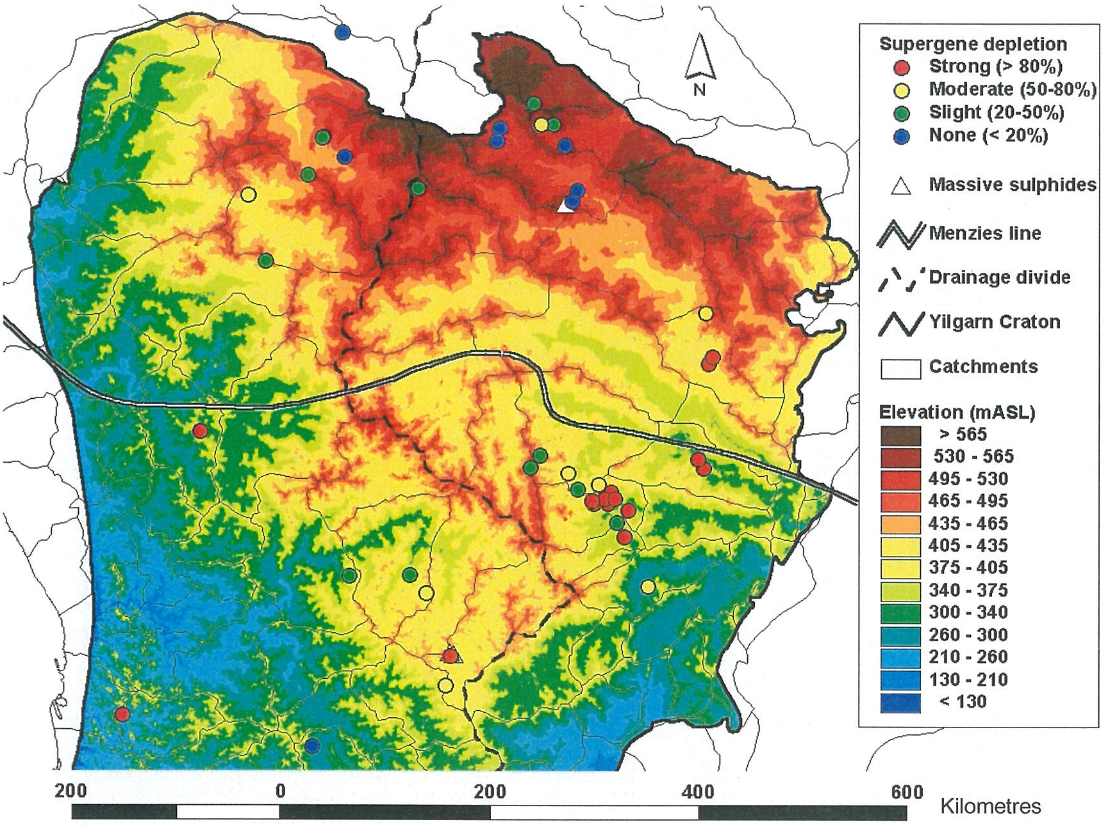


Figure 44: Observed supergene Au depletion (Section 4) for Au deposits in the Yilgarn Craton, with elevation, catchments, Menzies line and drainage divide.

10.1 Kalgoorlie Region

Sites studied within P504: Twin Peaks, Monty Dam, Carosue Dam, Federal, Panglo, Kanowna Belle and BLC.

Parallel CRC LEME studies: Mt Percy.

Review sites: Ora Banda, Zoroastrian, Lady Bountiful, Quarters, Mt Pleasant, Paddington, Havana, Hannan South, New Celebration.

The observed patterns of supergene mobilization of Au are described for the Gidge Lake catchment (immediately west of Lake Yindalgooda and north of Kalgoorlie; Figure 8), as there is sufficient information for useful comparisons. The catchment is dominated by a playa, which is typical of most catchments in the Kalgoorlie area, with the drainage divides commonly rising only 50 to 100 m to the north and south (Figure 45). There is more relief to the west, coinciding with the main continental divide (Figure 10). Groundwater salinities within the playa groundwaters are greater than 15% TDS, with most groundwaters in the area having > 1% TDS (Figure 10). These salinities, with acid and oxidizing conditions, are sufficient to mobilize Au. Because the water-table has a much lower relief than the land surface, depth to water-table increases from less than 10 m near the playa to 50 to 100 m below surface at the groundwater divides (Figure 46; Kern, 1995a, 1996).

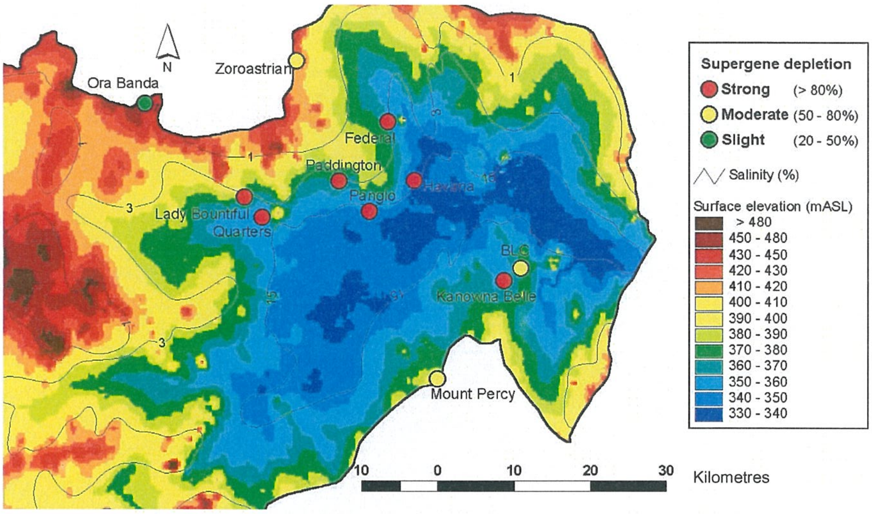


Figure 45: Observed supergene Au depletion of Au deposits within the catchment immediately west of Lake Yindalgooda (Figure 8), with elevation as colours and salinity (Kern, 1995a, 1996) as contours.

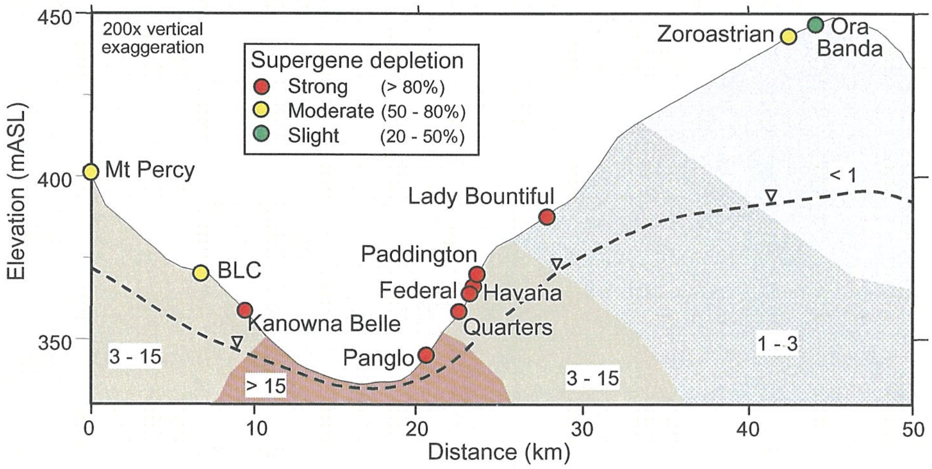


Figure 46: Diagrammatic traverse of the catchment immediately west of Lake Yindalgooda, showing relative locations and elevations, and observed supergene depletion of Au deposits. Numbers and shading represent groundwater salinity (%) and dashed line the water-table (∇).

Patterns of supergene Au depletion are strongly correlated with these geomorphological and groundwater factors. Gold mineralization in the lowlands and valley flanks is strongly depleted, whereas at higher elevations, where more of the regolith is above the water-table, there is less (though still significant) depletion. One minor exception is BLC, which is moderately depleted. It is at lower and similar elevations to Lady Bountiful and Paddington, respectively (Figure 46), both of which are strongly depleted. BLC is located on a ridge and groundwaters may be deeper in this landscape setting. Additionally, ultramafic lithologies dominate BLC and these buffer unsaturated waters to a more neutral, poorly oxidized form that is less likely to dissolve Au (Section 1).

In summary, results from the catchment immediately west of Lake Yindalgooda, and elsewhere in the Kalgoorlie area, indicate that Au deposits in the lowlands and valley flanks will be strongly depleted. Deposits close to groundwater divides will show less, though still significant depletion.

10.2 Eastern Yilgarn

Sites studied within P504: Argo and Apollo.

Review sites: Junction and Karonie.

Groundwaters in this region are similar to those within the Kalgoorlie area, though palaeochannel waters e.g., Mulga Rock (Douglas *et al.*, 1993) and Argo (Lintern and Gray, 1995b), tend to be reducing and neutral to acid. The *in situ* supergene behaviour of Au is similar to that in the Kalgoorlie region. Within the palaeochannels, significant Au is found in basal sediments. Gold also occurs in the channel sediments where they abut mineralization that once outcropped along the palaeovalley flanks (Britt and Gray, 1999). Otherwise, chemical transport into palaeochannels is expected to be minor, due to the past reducing nature of the sediments.

10.3 Central Yilgarn

Sites studied within P504: Cleo and Golden Delicious.

Review sites: Mt Gibson, Bottle Creek, Harbour Lights, Callion, Lights of Israel, Sand King, Telegraph.

There are insufficient sites from the Central region to characterize all geomorphological influences affecting the supergene mobility of Au. Data available indicate that sites adjacent (e.g., Cleo) or close to (e.g., Golden Delicious) saline playas are strongly depleted in Au, those on the valley flanks have moderate (e.g., Telegraph) to strong (e.g., Mt Gibson) depletion (Figure 44 and Figure 47) and mineralization close to divides are only slightly depleted. This suggest that the Central region, despite the lower acidity and oxidation potential of the groundwaters (Figure 13), has only slightly less supergene depletion than the Kalgoorlie region. Groundwater Au concentrations are approximately 2 to 5 times lower than those in the Kalgoorlie region (Figure 20), however this is still substantial and clearly sufficient to significantly mobilize Au over time.

10.4 Northern Yilgarn

Sites studied within P504: Mt Joel, Baxter/Harmony.

Sites studied within the Yandal Project: Jundee, Bronzewing, Callista.

Sites studied within the Yandal Project, with CRCLEME follow up studies: Elliot, Gourdis, Empire.

Review sites: Wiluna, Matilda, Gidgee, Montague, Darlot.

The Northern Yilgarn has saline groundwaters only within the central palaeochannels (Johnson *et al.*, 1999; Figure 48). In consequence, there is much less supergene Au mobility than elsewhere in the Yilgarn, with many sites (e.g., Mt Joel, Bronzewing, Matilda, Wiluna and Gabanintha) showing little or no supergene depletion (Figures 44 and 47). Other sites show slight or, rarely, moderate depletion, for reasons that do not seem to be associated with their geomorphological environment. It may be that lithological and/or mineralogical influences, "swamped" by the major acidity and salinity further south, are important in generating minor amounts of supergene Au mobility in the less reactive groundwaters of the Northern Yilgarn. One site, Callista, shows strong supergene Au depletion. This deposit is a massive sulphide ore body, and weathering of such a system appears to facilitate Au mobility, either due to extremely acid local environments, generation of ligands such as iodide (Section 5.4) and/or generation of thiosulphate (Section 6.2). The few massive sulphide ore bodies tested (Callista and three sites at Mt Holland) showed strong Au depletion, regardless of groundwater or geomorphological characteristics.

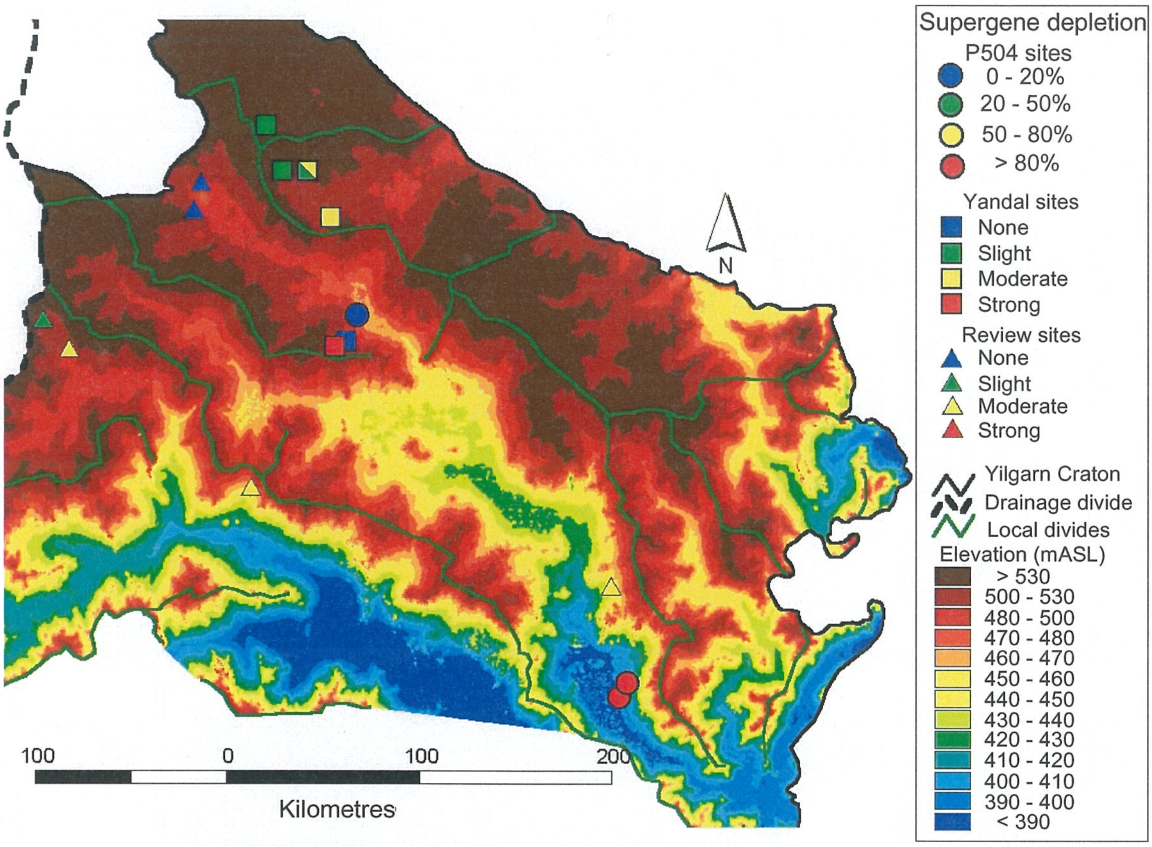


Figure 47: Observed Au depletion of deposits in the central- to north-eastern Yilgarn, with elevation, drainage divides and catchments shown.

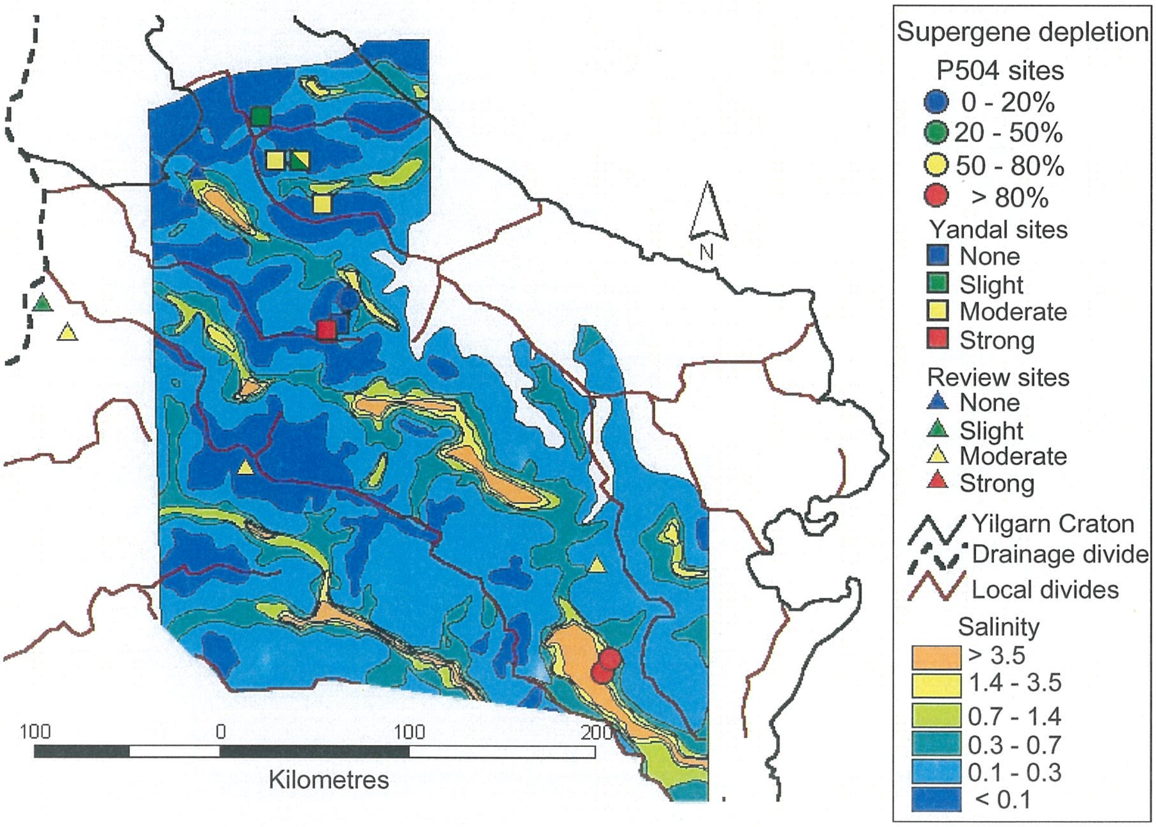


Figure 48: Observed Au depletion of deposits in the central- to north-eastern Yilgarn, with salinity (modified from Johnson *et al.*, 1999) and drainage divides shown.

11 SUPERGENE GOLD MOBILITY IN THE GAWLER CRATON

11.1 Geomorphology of the Gawler Craton

The Gawler Craton is extremely low-lying and flat, even relative to the Yilgarn Craton (compare Figure 49 with Figure 10). Minor rises, the Middleback Ranges and the Musgrave Block, occur in the central-east of the Eyre Penisula and the northwest of the Gawler Craton, respectively. Mt Lofty and the Flinders Ranges are a major feature to the east. The two study sites, Challenger and Comet, are located in a flat area near the centre of the Gawler Craton, with surface elevations of approximately 190 m and 160 m ASL, respectively. There is no consistent direction for surface flow in this region.

11.2 Hydrogeochemical investigations

Groundwater characteristics of the Gawler Craton appear similar to those of the Yilgarn Craton, both in terms of the different major pH and TDS regimes (compare Figure 53 with Figure 6) and other subsidiary processes such as K-depletion due to alunite precipitation (compare Figure 54 with Figure 14). Thus, a significant proportion of the groundwaters within the Gawler Craton have similar abilities to mobilize Au (i.e., high acidity and salinity) to those of the Kalgoorlie region of the Yilgarn Craton. Insufficient groundwater data from the Gawler Craton are available to comment on Au or trace elements, but the similarity of major element chemistry to the Yilgarn indicates that these elements should behave in a similar manner. Areas of the Gawler that are markedly more saline (Figure 50) and acid (Figure 51), are:

1. Along a northwest trend extending more than 200 km, approximately 100 km east of the western coast of the Eyre Penisula, on the sourthern edge of the Middleback Ranges.
2. West of Challenger, possibly an extension of the above trend.
3. Central-east Gawler Craton.

These areas are also highly depleted in K (Figure 54), again indicating highly corrosive groundwaters (Section 5.3). It is predicted that these areas, like the Kalgoorlie region in the Yilgarn Carton, will have high Au solubilities and strong supergene Au mobility.

11.3 Challenger 3D modelling

Detailed studies of the Challenger area by CRC LEME included 3D modelling of the surface regolith and transported overburden by van der Wielen (1999). Unfortunately, the only useable feature logged in the residual weathering profile and available during this study was the transition from saprolite (rock-type identified) to other residuum (lithology undetermined). This approximately matches the clay-saprolite boundary and correlates with the depletion front (Figure 55). Approximately 75% of the Au was depleted above this boundary.

11.4 Comet 3D modelling

CRC LEME also studied the Comet area in detail. The mineralization is low grade, but the site has the advantage of high quality logging. Depletion at this site is strong (> 80%) and occurs above the top of saprock (Figures 56 and 57).

11.5 Comparison with the Yilgarn Craton

Limited hydrogeochemical and site studies indicate major similarities between the Yilgarn and Gawler Cratons. Although significantly more investigations are require to understand the variations in groundwater characteristics in the Gawler Craton and the importance of the various transported materials, it is expected that the models suggested for supergene Au mobility in the Yilgarn Craton should be applicable in the Gawler Craton.

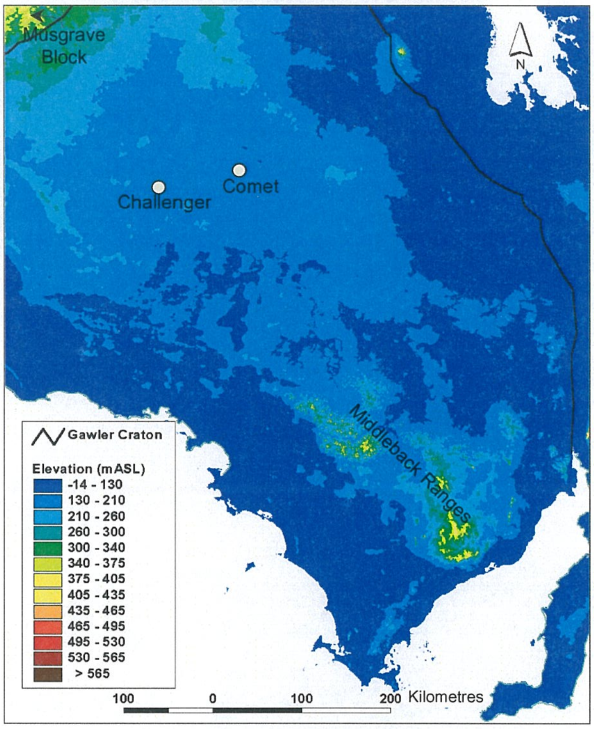


Figure 49: Elevation of the Gawler Craton, with Challenger and Comet sites shown.

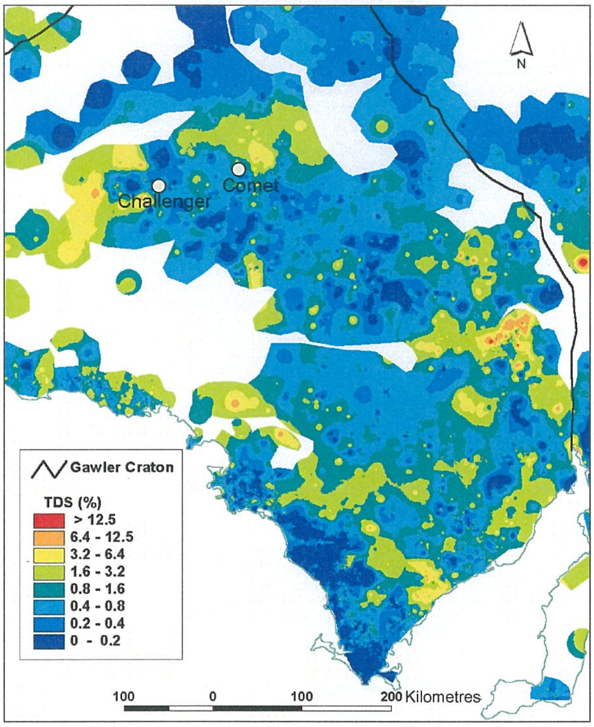


Figure 50: Groundwater salinity in the Gawler Craton.

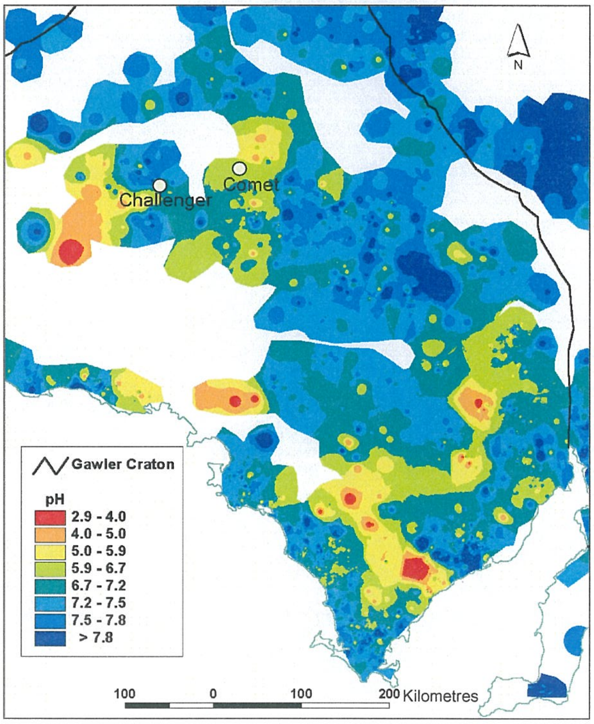


Figure 51: Groundwater pH in the Gawler Craton.

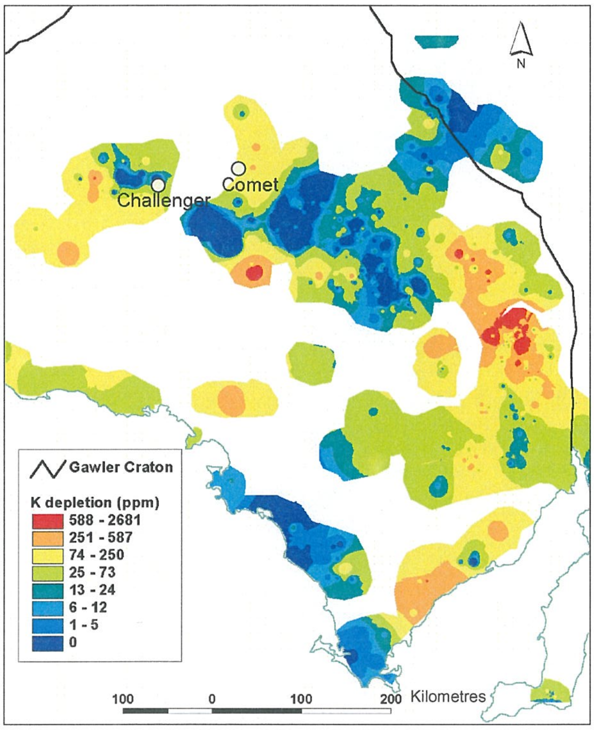


Figure 52: Groundwater K depletion in the Gawler Craton.

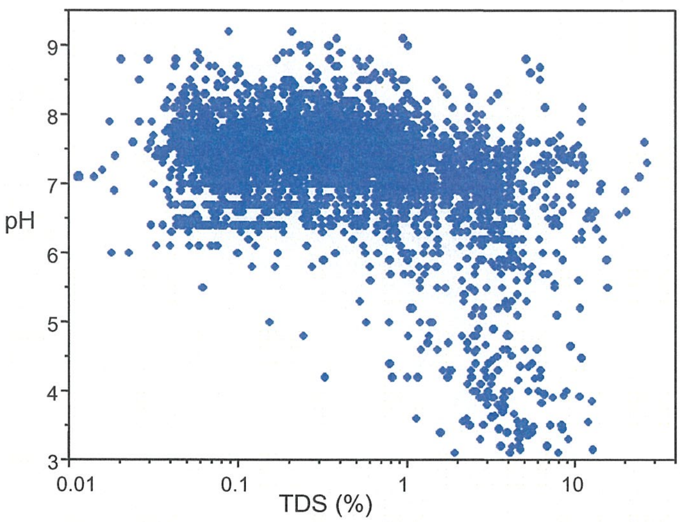


Figure 53: pH vs. total dissolved salts (TDS) for Gawler groundwaters

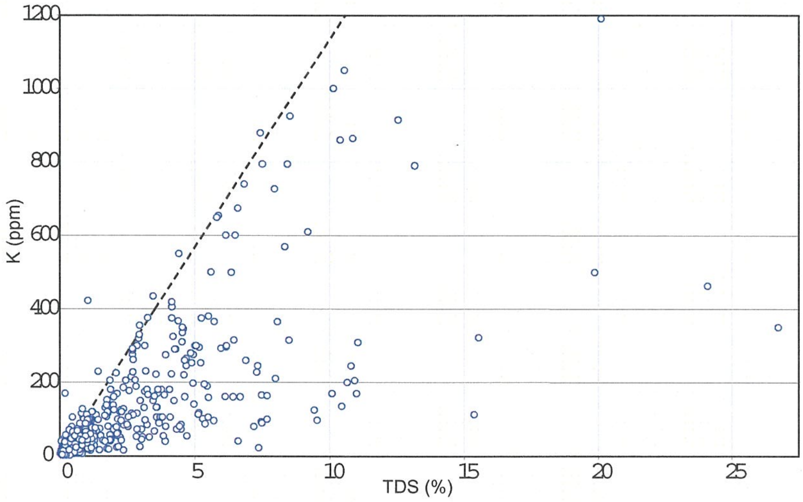


Figure 54: Dissolved K vs. salinity for Gawler groundwaters.

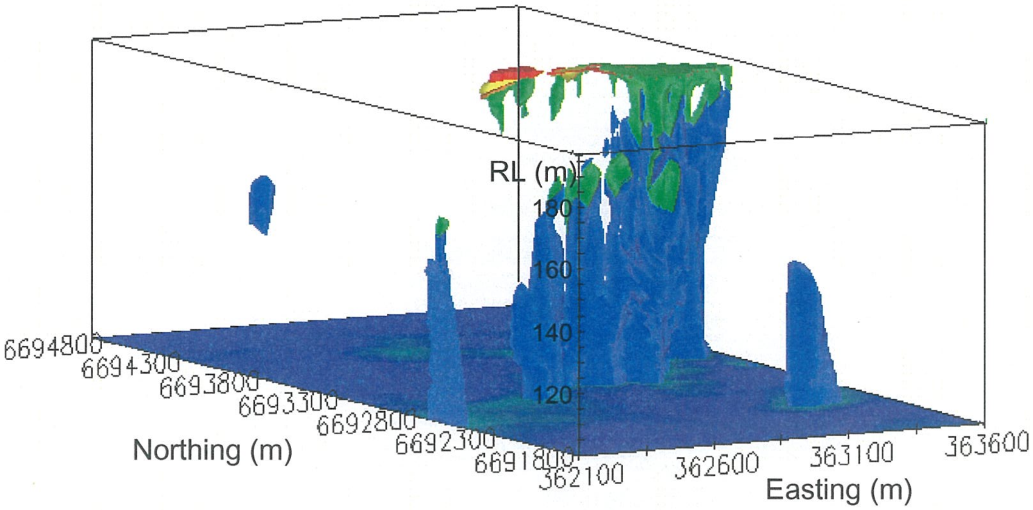


Figure 55: Gold distribution at Challenger using a 50 ppb cut off, showing the top of the supergene Au enrichment zone at the top of the recognizable lithology (clay to saprolite transition ?). Key: blue – recognizable lithology, green – residuum (possibly clay zone), orange/yellow/red – transported units.

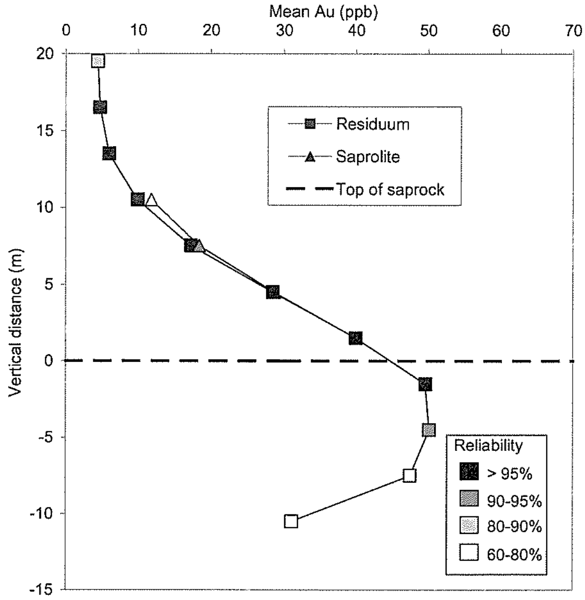


Figure 56: Mean Au vs. vertical distance from the top of saprock, Comet, S.A.

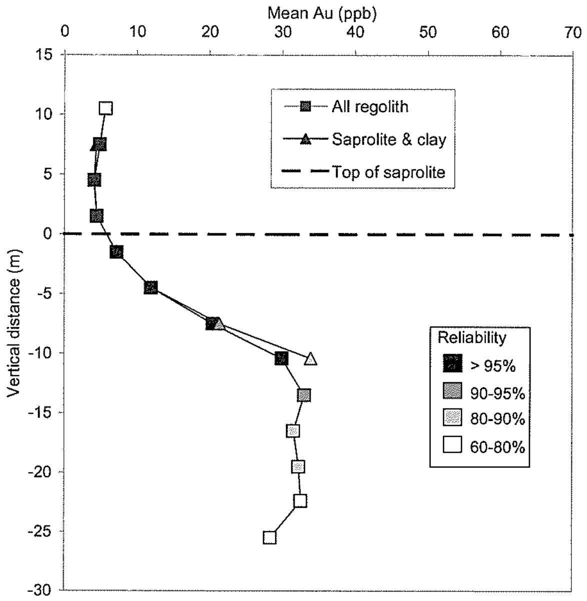


Figure 57: Mean Au vs. vertical distance from the top of saprolite, Comet, S.A

12 EXPLORATION IMPLICATIONS

12.1 Geometry of the saprolitic Au enrichment zone and direction of Au dispersion

The "blanket" shape commonly described for supergene Au enrichment in saprolite in the southern Yilgarn and Gawler Cratons is mainly due to a sharp upper contact with the overlying strongly depleted zone (Figure 4B), rather than a laterally extensive zone of Au dispersion and enrichment. The greatest Au concentrations occur in the uppermost 1 to 5 m of the enrichment zone, accentuating the contrast with the depletion zone. The top few metres of the enrichment zone have relatively high Au concentrations, and contain significant secondary Au particles, suggesting chemical addition of Au, but below this, Au enrichment appears to be almost exclusively residual.

Models of Au distribution in the regolith show that the apparent "blanket" shape of the enrichment zone can only be seen at high Au concentrations or cut-offs (Section 7.3.1). When lower concentrations of Au are included, the distribution is more columnar, indicating that the enrichment zone is actually the upper, residually enriched, extension of low-grade primary mineralization. Its position is determined by the location of primary mineralization both below (residual input) and, to a lesser extent, above (surface Au moving downwards). Within the saprolitic enrichment zone, the distribution roughly corresponds, at higher concentrations, to that in the primary zone. Therefore, the saprolitic enrichment zone is not a result of lateral dispersion and does not increase the anomaly size, although absolute concentrations of Au are greater than in the unweathered rock. The concentration of Au in the uppermost 1 to 5 metres of the enrichment zone means that Au concentrations in residuum are more likely to decrease than increase down to the weathering front.

12.2 Controls on the depth of depletion

The majority of the study sites show a similar (30 to 40 m) mean depth of the saprolitic Au enrichment zone. However, the depth can vary considerably at specific sites, depending on lithology, structure and the regolith preservation. Regolith transitions have a major control on the depth of the Au depletion front. The most common transition correlated with the depletion front is that from clay- to mid-saprolite (Table 3, Figure 58). This transition is generally related to the weathering front of primary aluminosilicates to clay minerals, mostly kaolinite, and Fe oxides and is often independent of lithological differences. It is also roughly coincident with Fe^{3+}/Fe^{2+} redox front (Figure 58), although these features may vertically separate by several metres (Figure 30).

At any one site, it is important to determine which regolith transition or redox front coincides with the supergene Au enrichment zone. In practice, regolith and redox transitions can be used in combination:

1. Colour change, from red-yellow-cream in highly weathered mafic, ultramafic and intermediate rocks, or white or pale-grey in highly weathered granitoids, to grey-green weathered rocks.
2. Grain size change, from clay-rich regolith to saprolite with visible primary rock fabric. In the clay zone, primary fabric is difficult to distinguish, especially in drill cuttings. However, there is a clear reduction in rock hardness and rock fragments can be broken by hand across the rock fabric. In drill cuttings, determination of the proportion > 1 mm by wet sieving can help resolve this critical transition (Figure 30).

It should be noted that in practice, successful logging of the transitions in drill cuttings is complicated by heterogeneity of the rocks, their deformation and variations in the degree of wallrock alteration.

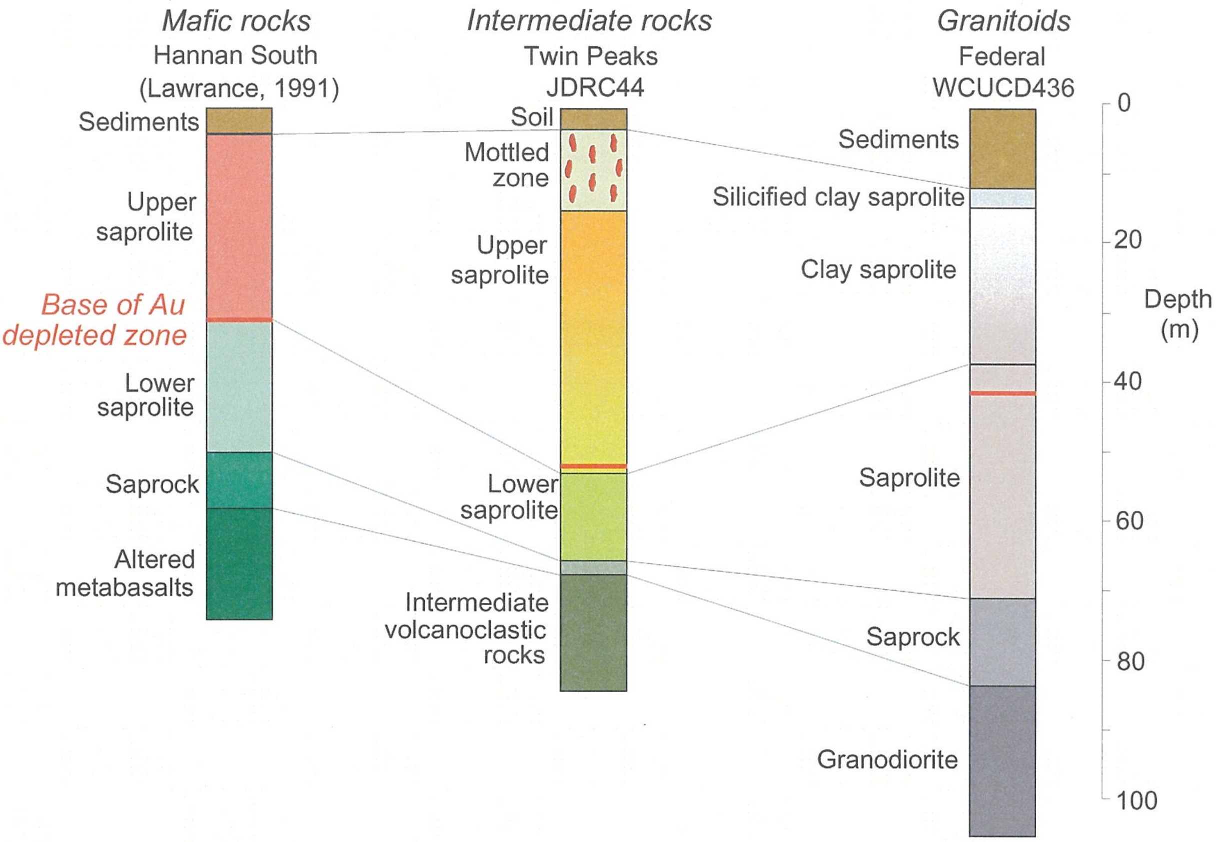


Figure 58: Correlation diagram for the regolith profile on different lithologies.

12.3 Influence of primary lithology and mineralization

The style of primary mineralization affects supergene Au remobilization. Free, primary Au, protected by vein quartz remains stable in the regolith and can be residually concentrated near the surface with only minor depletion from the upper regolith. In contrast, Au in sulphides is more readily depleted, due to its submicron particle size, easy access of supergene solutions and increased concentrations of S oxyanions, all favouring Au dissolution.

Lithology can be highly significant. Ultramafic rocks buffer groundwaters effectively, leading to reduced Au depletion. Thus, at BLC, on a subdued ridge where mineralization is in a mainly ultramafic package, Au depletion is considerably less than at nearby Kanowna Belle, with felsic to intermediate rocks. In contrast, highly corrosive groundwaters can "swamp" lithological influence. Panglo, for example, is close to the valley floor, with acidic and saline groundwaters close to the surface. Gold is strongly depleted from all lithologies, including ultramafic rocks.

Silicification will also modify the expected depletions by occluding the Au. Thus, at Carosue Dam, which has very corrosive groundwaters with high dissolved Au, there is, as expected, major depletion in the upper regolith. However, close to the centre of the orebody, major silicification of the regolith has occurred, leading to a resistive “chimney” of Au, resulting in a major surface anomaly (discussed further in relation to calcrete anomalies in Section 12.5).

There is strong Au depletion and remobilization in the regolith above sulphide-rich (> 20% S) ore bodies, regardless of region or water-table. Such materials locally generate highly corrosive conditions, leading to Au depletion in the upper regolith, independent of the surrounding groundwater regime.

Therefore, although there are standard Au depletion and enrichment predictions (Sections 12.1 and 12.2) that are independent of lithology, lithology can, in some circumstances, cause variations. These are mostly due to mineralization style, buffering and secondary silicification, and should be considered during orientation studies of an exploration site.

12.4 Gold redistribution within palaeochannels

Further studies are required to understand dispersion of Au into palaeochannels, although results, so far, allow tentative hypotheses. The materials within palaeochannels can differ significantly from the surrounding regolith, particularly in terms of redox characteristics, containing highly reduced material such as lignite or secondary sulphides. Within the Yilgarn Craton and Proterozoic margins, lignite is primarily restricted to the SE, though residual lignite is observed in isolated locations elsewhere. Results from Argo suggest that lignite, by causing reducing conditions, limits dispersion of Au into the palaeochannel sediments, although significant Au anomalies are observed in lignites abutting mineralization and in basal gravels and sands (Britt and Gray, 1999).

In contrast, the palaeochannel adjacent to the Cleo deposit in the Central region (Gray and Britt, 2000), in which the channel sediments are oxidized, has a major Au dispersion halo which appears to be chemogenic. The dispersion is at least several hundred metres across, and therefore represents a potentially useful exploration medium, as well as being a significant resource close to the orebody. Additionally, there are patchy enrichments along the unconformity, which may have complex origins.

Thus, results suggest that Au dispersion within palaeochannels is highly dependent on the nature of the infilling sediments. Possibilities for significant Au dispersion within the sediments, at the unconformity or even directly below the unconformity, seem good, related to enhanced permeability and strong water flow.

12.5 Shape and source of surface calcrete Au anomalies

Results from AMIRA Project 409 (Butt *et al.*, 1997) suggest that surface calcrete anomalies commonly have a direct source, followed by reworking within the top 1 to 5 m, resulting in a correlation between Au and carbonate content in the vertical profile. This hypothesis of a direct Au source is supported by results from P504. In all sites studied, there is always a coherent and physically connected source for the Au, be it lateritic/surface Au that was never depleted due to occlusion of the Au and its location above the saturated zone, resistant "chimneys" of Au within the upper regolith, or from outcrop up-slope.

Although pedogenic carbonates are a preferential sampling medium, due to ease of sampling and common broadening of the anomaly, tracing back to the Au source may be complicated. The magnitude of the surface Au anomaly or, indeed, even the presence or absence of surface Au, cannot be directly correlated with the size or grade of the primary mineralization. Techniques that use surface or near surface sampling for Au exploration to "see through" transported cover are only effective where the cover is < 10 m, at most, or more probably < 5 m. Thus, carbonates represent a very useful "first pass" technique, which can then only be properly interpreted by understanding the regolith processes giving rise to the surface anomaly.

12.6 Regional differences

Results shown in this report (Section 9), demonstrate major regional variations in the degree of supergene Au mobility. Thus, supergene Au depletion in the Kalgoorlie region (Figure 5) is commonly strong (> 80%), with the exception of sites close to drainage divides, such as Ora Banda (Figures 44 to 46). Within the Central region, the degree of depletion is highly variable, whereas further north, the depletion tends to be low (Figure 47). Characteristics of supergene particulate Au (e.g., low Ag content, pristine crystalline morphology, associations with Fe oxides and halite) support a hypothesis of Au remobilization as halide (Cl or I) complexes. This suggests dependence of the supergene Au depletion on groundwater salinity, and indeed the degree of Au mobility can be related to groundwater conditions (Section 6): Kalgoorlie groundwaters are acid/saline, Central groundwaters neutral/saline and Northern groundwaters neutral/fresh, with these changes resulting in variations in Au solubility (Section 6.3). This is an obvious initial factor to be used in orientation studies, although local factors, such as an high sulphide environment, can locally modify the groundwater regime.

12.7 Catchment scale differences and geomorphology

Within regions, the degree of Au mobility is affected by local geomorphological differences, although the magnitude of this depends on the region. In the Kalgoorlie region, strong Au depletion is common, with lesser depletion only occurring along ridges or close to drainage divides. In the Central region, Au mobility is highly dependent on geomorphological position, with strong depletion at the valley floors, slight (< 50%) to moderate (50 to 80%) depletion along valley flanks and little depletion in the uplands. In the Northern region, Au depletion is weaker, except in the local environment of the main drainage channels or where enhanced by lithological factors (e.g., high sulphide content as at Calista).

12.8 Different chalcophile solubilities

Chalcophile elements such as As, Sb or W have long been suggested as useful accessory elements for Au exploration. Not enough data has been collated to develop a complete picture of the mobility of these elements, though groundwater analyses (Section 5.4) indicate that they have different dissolution characteristics from Au, tending to have lower solubilities in acid conditions. Results from Twin Peaks (Sergeev and Gray, 1999), which is As-rich and has highly acid groundwaters, indicate little As has been leached below the water-table; significant loss of As has only occurred in the upper, unsaturated, 10 m of the regolith. In contrast, neutral groundwater sites north of Kalgoorlie might be expected to show more As depletion below the water-table, as shown by significant As depletion at Golden Delicious (Bristow *et al.*, 1996a). However, results from Reedy (Robertson *et al.*, 1990) and Beasley Creek (Robertson, 1991) appear to contradict the suggestion of enhanced As depletion north of the Kalgoorlie region. Considerably more work would be required.

12.9 Possible use of groundwaters in exploration

This topic has been developed previously (Gray, 1996). A brief summary is given below, along with cautions and recommendations.

Dissolved Au is the clearest indication of Au mineralization in Kalgoorlie and Central groundwaters. 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 complexes in groundwater (thiosulphate and halide; Section 6). Where Au appears to be dissolving as a thiosulphate complex, as at Boags and the Hornet pit at Mt. Gibson, the distribution of dissolved Au closely matches that of mineralization. However, this is very localized and would probably be missed in an exploration sampling program.

In oxidizing environments, Au dissolves to form chloride or iodide complexes (Section 6.1) and, where this mechanism is expected to be active, there are high concentrations of dissolved Au. However, Au concentration is strongly affected by factors not directly related to mineralization (e.g., Eh and dissolved Fe), and the distribution of dissolved Au only approximately matches that of primary mineralization. However, this technique would still provide extra information useful for exploration. A few other elements, such as As, Sb, Mo, I and various base metals may also have value as pathfinders, although they commonly have reduced concentrations in acid conditions and analyses for them in saline groundwaters may be difficult, expensive or of poor sensitivity. In the Kalgoorlie region, a limited suite of parameters, namely salinity, pH, Eh, dissolved Au, Fe, Cr and, possibly, other base metals, could be analysed cheaply (using standard probes, sorption onto carbon for Au, and ICP-AES and/or colorimetric analyses for Fe and Cr) but extending this to the other elements of interest will add considerably to cost, with little added exploration benefit. A threshold dissolved Au concentration of approximately 0.05 µg/L would appear to locate most mineralized areas. For the Central areas, a slightly lower dissolved Au threshold (0.02 µg/L) appears appropriate, and a number of chalcophile elements (e.g., As, Sb, Mo, W, Tl, Bi) may also give valuable exploration data. However, further work is required to study the relative degrees of groundwater dispersion of these elements.

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

Groundwater sampling seems to have limited ability to "see through" barren transported overburden, as opposed to its success when sampling groundwaters even from supposedly depleted *in situ* material (e.g., Panglo; Gray, 1990a). Results from groundwaters sampled above the unconformity appear most useful for the highly active Kalgoorlie groundwaters, but are poor for the least active groundwaters in the Northern region. It is recommended that, if possible, groundwaters be sampled below the transported overburden for optimum results.

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

12.10 Decision Tables

12.10.1 Overview

This section describes simple decision tables for exploration in the East Yilgarn Craton. This system is indicative only and should be used in conjunction with understanding of the lithology and regolith in the exploration area. Core parameters are the regolith landforms and the region of the Yilgarn, with the regional map repeated as Figure 59. A general decision table is given for each region. In the tables, BoD refers to the predicted base of depletion (whether of not there is Au mineralization to be depleted), based on the colour, grain size and mineralogical transitions as discussed in Section 12.2. 'P' and 'N' refer to positive and negative responses, respectively.

Commonly, the following sequence should be used:

1. Compile a simple regolith map, based on Residual Erosional Depositional (RED) or equivalent scheme.
2. Determine region of the Yilgarn, primarily based on location, but also correlating with other critical parameters, particularly presence of calcrete and any available groundwater data.
3. On the basis of these two parameters, use the relevant table for the region as a guide to exploration strategies.

   Example:
   1. Area is in the Central region, use Table 9.
   2. Area is erosional.
   3. Surface sample the lag and soil.
   4. If the response is positive, follow up with close spaced drilling to the BoD.
   5. Or if the response to surface sampling is negative, consider reconnaissance drilling to the BoD.
   6. If the response to Step 5 is positive, follow up with close spaced drilling.
   7. Or if the response to Step 5 is negative, stop and move on.

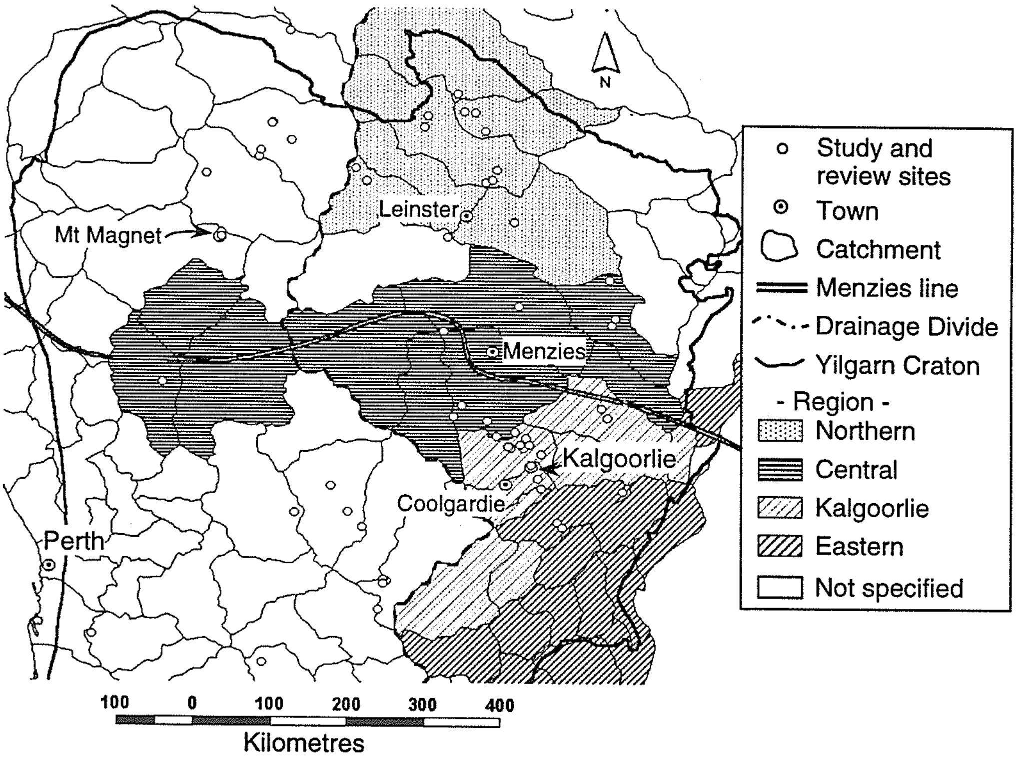


Figure 59: Defined groundwater catchment domains with groundwater regions shown.

12.10.2 Kalgoorlie and Eastern regions

Table 8. General decision table for the Kalgoorlie and Eastern Regions

Regime	**Test**		**Response 1**	**Response 2**
Relict		Surface sample (lateritic residuum)	**P**: close spaced drilling to BoD	
			N: STOP	
Erosional		Surface sample (carbonate)	**P**: close spaced drilling to BoD	
			N: Reconnaissance drill to BoD (based on cost benefit, depending on other geophysical or geological data)	**P**: close spaced drilling to BoD
				N: STOP
Depositional	Determine depth of transported cover and identify underlying regolith			
	< 5-10 m Underlying regolith = Buried lateritic residuum	Surface sample	**P**: close spaced drilling to BoD	
			N: STOP	
	< 5-10 m Underlying regolith = Buried truncated	Surface sample	**P**: close spaced drilling to BoD	
			N: Reconnaissance drill to BoD (based on cost benefit)	**P**: close spaced drilling to BoD
				N: STOP
	> 5-10 m Underlying regolith = Buried lateritic residuum	Interface sample	**P**: close spaced drilling to BoD	
			N: STOP	
	> 5-10 m Underlying regolith = Buried truncated	Interface sample	**P**: close spaced drilling to BoD	
			N: Reconnaissance drill to BoD (based on cost benefit)	**P**: close spaced drilling to BoD
				N: STOP

Key: **P** - positive, **N** - negative, BoD - base of depletion.

Notes:
Supergene Au depletion in this region is expected to be > 80% relative to primary grade, except at, or close to, drainage divides or when Au is "protected" (e.g., by occlusion). Therefore, follow-up drilling is required to the base of depletion.

Although further work is required to substantiate this hypothesis, the major difference between Kalgoorlie and Eastern Regions is that palaeochannels abutting mineralized regolith in the Kalgoorlie Region may well have anomalies within the sediments whereas, in the Eastern Region Au in palaeochannels is expected to be restricted to the immediate environment of the unconformity.

12.10.3 Central region

Table 9. General decision table for the Central Region

Regime	Test		Response 1	Response 2
Relict		Surface sample (lateritic residuum)	**P**: close spaced drilling to BoD	
			N: STOP	
Erosional		Surface sample (lag and soil)	**P**: close spaced drilling to BoD	
			N: Reconnaissance drill to BoD (based on cost benefit)	**P**: close spaced drilling to BoD
				N: STOP
Depositional	Determine depth of transported cover and identify underlying regolith			
	< 2-5 m Underlying regolith = Buried lateritic residuum	Surface sample	**P**: close spaced drilling to BoD	
			N: STOP	
	< 2-5 m Underlying regolith = Buried truncated	Surface sample	**P**: close spaced drilling to BoD	
			N: Reconnaissance drill to BoD (based on cost benefit)	**P**: close spaced drilling to BoD
				N: STOP
	> 2-5 m Underlying regolith = Buried lateritic residuum	Interface sample	**P**: close spaced drilling to BoD	
			N: STOP	
	> 2-5 m Underlying regolith = Buried truncated	Interface sample	**P**: close spaced drilling to BoD	
			N: Reconnaissance drill to BoD (based on cost benefit)	**P**: close spaced drilling to BoD
				N: STOP

Key: **P** - positive, **N** - negative, BoD - base of depletion.

Notes:

Supergene Au depletion in this region is expected to be > 80% relative to primary grade, except in uplands and close to drainage divides or when Au is "protected" (e.g., by occlusion). Therefore, follow-up drilling is required to the base of depletion.

Lateritic Au dispersion in soils may be limited in erosional areas.

The presence of carbonate should be monitored, as local carbonate may result in a high Au threshold.

Unless transported cover is less than 2 to 5 m, lags in depositional areas reflect sediment provenance, not underlying mineralization.

12.10.4 Northern region

Table 10. General decision table for the Northern Region

Regime	Test		Response 1	Response 2
Relict		Surface sample (lateritic residuum)	**P**: close spaced drilling to BoD	
			N: STOP	
Erosional		Reconnaissance drilling (based on cost benefit)	**P**: close spaced drilling to BoD	
			N: STOP	
Depositional	Determine depth of transported cover and identify underlying regolith			
	< 2-5 m Underlying regolith = Buried lateritic residuum	Surface sample	**P**: close spaced drilling to BoD	
			N: STOP	
	< 2-5 m Underlying regolith = Buried truncated	Surface sample	**P**: close spaced drilling to BoD	
			N: Reconnaissance drill to BoD (based on cost benefit)	**P**: close spaced drilling to BoD
				N: STOP
	> 2-5 m Underlying regolith = Buried lateritic residuum	Interface sample	**P**: close spaced drilling to BoD	
			N: STOP	
	> 2-5 m Underlying regolith = Buried truncated	Interface sample	**P**: close spaced drilling to BoD	
			N: Reconnaissance drill to BoD (based on cost benefit)	**P**: close spaced drilling to BoD
				N: STOP

Key: **P** - positive, **N** - negative, BoD - base of depletion.

Notes:
Under most circumstances, Au concentration in the regolith is at least 50% that in the primary rock, and deeper drilling is not required for initial exploration. Major exceptions are S-rich (approximately > 20% S) mineralization, though a small minority of sites (approximately < 10%) have greater than 80% depletion.

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