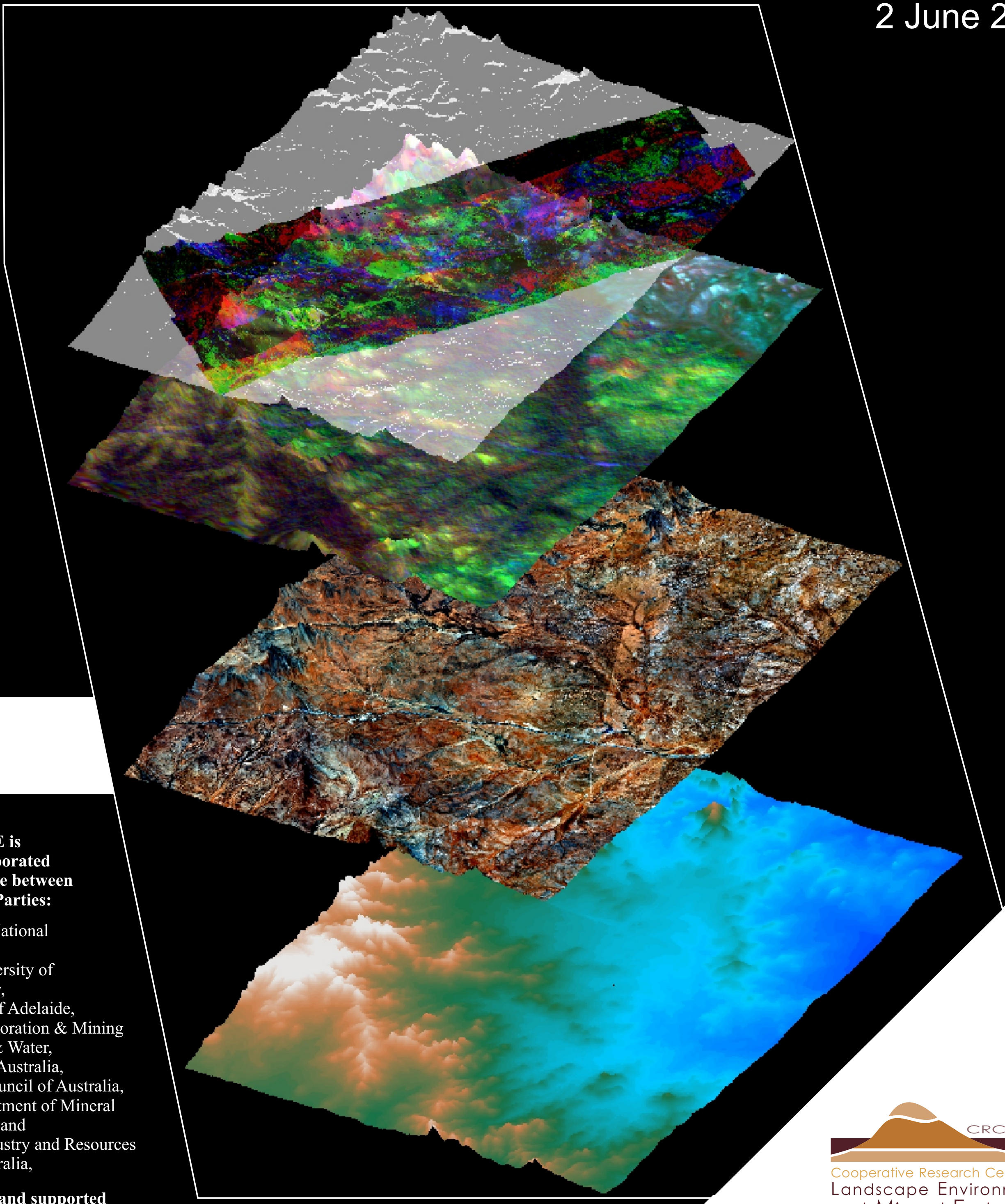
2004
MINERALS EXPLORATION SEMINAR
ABSTRACTS

Wednesday
2 June 2004



CRC

**CRC LEME is
an unincorporated
joint venture between
eight Core Parties:**

Australian National University,
Curtin University of Technology,
University of Adelaide,
CSIRO Exploration & Mining and Land & Water,
Geoscience Australia,
Minerals Council of Australia,
NSW Department of Mineral Resources, and
Primary Industry and Resources South Australia,

**established and supported
under the Australian Government's
Cooperative Research Centres Program**

CRCLEME
Cooperative Research Centre for
Landscape Environments
and Mineral Exploration

AMEC

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MINERALS EXPLORATION SEMINAR

ABSTRACTS

Convenor

Dr R Dennis Gee
CEO, CRC LEME

2 June 2004
Australian Resources Research Centre, Perth

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LEME PROGRAMS IN MINEX

Dr R Dennis Gee
CRC LEME

LEME's objective is apply regolith science to the problems facing Australia in the areas of mineral exploration and natural resource management. The two main research priorities are:

1. Understanding regolith architecture and processes in the third dimension
2. Making geochemistry work through transported regolith.

LEME has four core research programs which are, in effect, management units which allow considerable scientific interaction.

Program 1: Regolith geoscience
Leader: Ms Lisa Worrall (Geoscience Australia)
Objectives:

- Understand the nature and timing of regolith processes,
- characterise regolith materials,
- map 3D regolith architecture and
- integrate with landscape evolution models

Program 2: Mineral exploration in areas of cover
Leader: Dr Ravi Anand (CSIRO Exploration and Mining)
Objectives:

- Understand the chemical, biological and physical processes in anomaly formation, in order to provide better tools for mineral exploration in areas of regolith - especially transported regolith.

Program 3: Environmental application of regolith geoscience
Leader: Dr Steve Rogers (CSIRO Land and Water)
Objectives:

- Develop environmental applications for regolith science, including regional geochemical baseline datasets, mechanisms in acid-sulfate soils
- Provide geo-micro-biological input to minerals focussed projects.

Program 4: Salinity Mapping and Hazard Assessment
Leader: Dr Ken Lawrie (Geoscience Australia)
Objectives:

- Salinity and water - includes salinity mapping, hydrodynamic aquifer modelling, salt and metal mobility and AEM - of value of MINEX research

Program 5: Education and Training
Leader: Dr Steve Hill (Adelaide University)
Objectives:

- Ensure fundamental regolith geoscience knowledge and skills are used by the minerals industry and by the natural resource managers, now and by later generations. This is achieved through PhD and Honours student scholarships linked to LEME research projects, Minerals Tertiary Education Council courses, conferences and symposia.

LEME has a suite of integrated multi-disciplinary, multi-party, regionally based MINEX projects that span the programs and centres of activity and these all address the research themes.

LEME MINEX projects can be considered as

- generic process projects
- regional focus projects
- technology development

but the objective is for integrated, multi-party, multi-disciplinary projects across the country.

LEME research themes are:

- Regional mineral exploration
- Making geochemistry more effective
- Regolith Processes
- Landscape evolution
- Geophysical mapping and modelling
- Acid sulphate soils
- Salinity systems
- Regolith geoscience and urban Australia
- Environmental geochemistry

LEME research portfolio for 2004-2005 is currently being set. Details of our research projects will be on the web site by the 1 July 2004 - http://crcleme.org.au

GIRILAMBONE SYNTHESIS

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The Girilambone Project is one of CRC LEME's regional studies, centred in the western Lachlan Fold Belt of eastern Australia (Figure 1). It provides a model for an integrated, multi-disciplinary approach to understanding the landscape history and the major regolith controls on geochemical dispersion in an area of shallow to moderate regolith cover. The project is a collaborative venture between CRC LEME and the New South Wales Department of Mineral Resources and has involved a team of nine researchers from six core parties including geologists, geochemists a geomorphologist, geophysicist and soil scientist. The area has also been the focus for a number of student studies including five Honours and three PhD projects.

The area of study is located between Cobar, Nyngan, Bourke and Nymagee and is underlain by a poorly mapped and understood basement comprised of ?Ordovician Girilambone Group rocks with in-faulted slices of probable Early Devonian rocks, intruding granites and some Late Devonian outliers or down-faulted blocks. In the east there are a number of Alaskan-type mafic-ultramafic complexes. The Girilambone-Cobar-Nymagee region is one of the riches mineral provinces in New South Wales. Major deposits occur in the Cobar Basin, around Girilambone and at Canbelego and Nymagee. However, apart from the recent discovery of the Tritton polymetallic deposit, just south of Girilambone and the re-opening of the Mt Boppy gold mine as an open pit, there has been very little modern exploration activity in region of the Girilambone Terrain. This has been largely due to the extensive regolith cover as well as poor knowledge of the underlying geology. A major aim of this

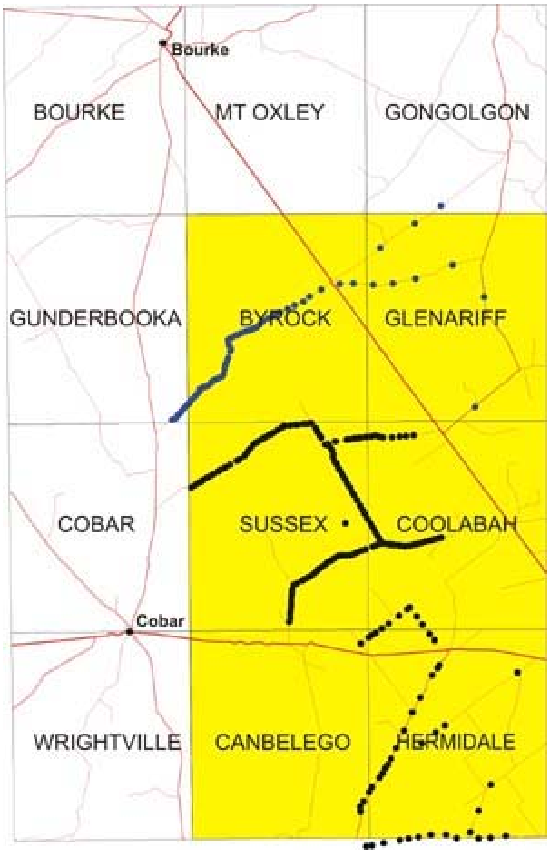

Figure 1: Location of the Girilambone Project in western New South Wales. Large map shows the position of air core drilling traverses and the 1:100 000 sheet areas.

project was to stimulate and assist exploration activities in this region through better knowledge of the regolith and the covered basement rocks.

The extensive regolith of the Girilambone region has formed during more than 60 million years of exposure, weathering and erosion. The cover includes intensely weathered *in situ* regolith and, superimposed transported materials of variable thickness, commonly in complex palaeochannel systems. The latter are preserved at different levels in the present landscape. Detailed regolith-landform mapping of key areas, combined with palaeomagnetic and apatite fission track dating, has established the landscape history and provided a framework for interpreting the regolith evolution. Better knowledge of the mineralogical and geochemical features of different regolith components (particularly the recognition and characterisation of the widespread transported regolith, not previously identified) can now greatly assist sampling and data interpretation for improved geochemical exploration.

A key feature of the project was the use of shallow air core drilling along a series of approximately east-west road traverses (Figure 1). This was designed to gain 3D information on the regolith, including petrographic, mineralogical and geochemical data down the profiles. It also allowed sampling of fresher saprock to help with bedrock mapping. A total of 247 holes were drilled and over 3360 samples analysed. This has provided a large data base of background geochemical compositions. This in turn has provided the opportunity to assess the level of background variation and establish element associations related to normal regolith-forming processes and different regolith host minerals. Some of these give rise to highly variable background levels for ore and pathfinder elements in different parts of the regolith, which may be confused with ore-related anomalies. The main associations include:

- an “evaporitic” association of Ca-Mg±Au, in some cases with Ba-Sr, related to regolith carbonate and barite accumulation in the near-surface regolith and at the base of palaeochannels and transported regolith;
- an association of Mn-Co-Zn±Ni-Cu±Au developed in redox boundary accumulations of manganese oxides/oxyhyroxides (particularly lithiophorite), commonly at around 20-30 m and at the present, deeper water table;
- an association of Fe-Cu-Zn with goethitic accumulations in the regolith;
- an association of Fe-As-Pb±Sb±Bi with hematite, particularly in ferruginous lag, paleochannel sediments containing ferruginous lag and in hematite rich mottles in the upper saprolite.

These and other regolith-controlled element associations can account for some of the background variation encountered when sampling the regolith of the region. Combined with information from previous case studies around Cobar and at Tritton it is now possible to develop a series of geochemical templates for different regolith materials that identify trends in multi-element relationships reflecting mineralised environments as distinct from normal background regolith concentrations and variations. This work has also established the important regolith host minerals and traps for dispersed pathfinder and target elements. With this knowledge it is possible to target the most appropriate sampling media for a given area and apply appropriate normalisation procedures to the data.

A number of different regolith materials are appropriate for sampling in areas of *in situ* or shallow transported cover in the Girilambone region. The typical soil is a relatively homogeneous red silty loam. It contains a major aeolian component of mainly quartz, clay and other resistate minerals such as zircon. In this region the aeolian component is mainly in the 60-80 µm size fraction and the +100 µm fraction is the most appropriate for geochemical sampling. Deeper sampling (>0.3 m) or sampling of the C horizon are other options, as the abundance of aeolian additions decrease with depth. Despite aeolian dilution and soil reworking/redistribution there is a significant bedrock-derived component in soils over *in situ* regolith related to bioturbation. In these settings soils are an appropriate and convenient sampling medium.

Lag is widespread in the region, is easy to sample and has been widely used as a sampling medium (generally the 3-15 mm size fraction), particularly at the reconnaissance level of exploration.

However, in many situations it has a complex transport history and variable mineralogy that can affect its usefulness. Bulk lag containing lithic and ferruginous fractions with a high goethite content is most useful where locally derived from *in situ* regolith. Lag transported directly from *in situ* regolith is useful for regional anomaly detection. Significant ore and pathfinder element fractionation has occurred during lag maturation and transport and some elements require normalisation to iron (hematite) content before interpretation. Micro lag (<150 µm) which includes dense and resistate mineral grains is also a useful sampling medium, particularly for gold.

Regolith carbonates are widespread in the lower part of the soil profile and as coatings on saprock/bedrock. This material accumulates gold and other elements and is useful for both regional and local anomaly detection. In areas with thin saprolite the upper generally more ferruginous zone below the soil or transported regolith can be a good geochemical sampling medium. In very strongly weathered profiles or where there has been marked erosional stripping saprolite geochemistry requires more careful interpretation. Iron oxide/oxyhydroxide concentrations in deeper saprolite commonly retain ore and pathfinder elements. Redox boundaries in well developed weathering profiles commonly show a regolith generated association of manganese and cobalt in some cases with zinc, copper and gold accumulation.

As part of the project we have developed a methodology for regolith-landform mapping appropriate to the minerals industry and also suitable for routine application by government mapping agencies. Methods have also been developed to build derivative maps or exploration "go" maps, which highlight particular regolith attributes (e.g. *in situ* vs. transported origin; thickness of transported cover, source of transported regolith). These can be included in a GIS available for explorers and used in combination with the regolith landform base map to provide direct guides to sampling strategies.

An approach which integrates knowledge of the regolith and landscape setting, direct 3D information on the regolith, geophysical data on the surface and near-surface regolith and geochemical techniques is summarized schematically in Figure 2. Good regolith-landform mapping and visual, textural and spectral logging of regolith cuttings is essential for the appropriate 3D knowledge of the regolith and to identify consistent and appropriate sampling media.

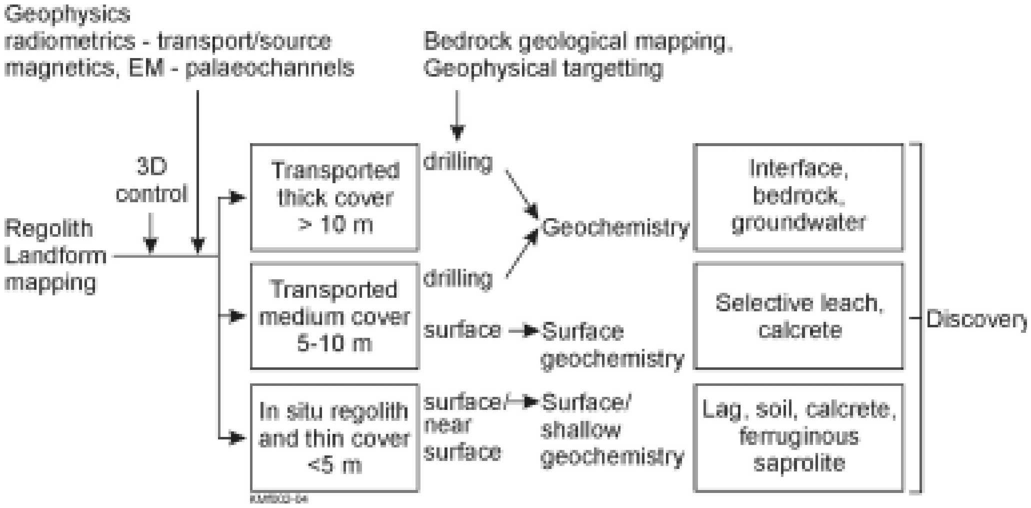

Figure 2. The role of regolith-landform mapping in an integrated approach to mineral exploration in regolith-dominated terrain.

Acknowledgments: The work reported here was supported by the Australian Government's Cooperative Research Centre Program within CRC LEME and by the New South Wales Department of Mineral Resources. A team of more than fifteen LEME researchers, students and technical staff working on the Girilambone Project, have contributed to the findings described in this article. I also thank the various land owners and mining companies in the Girilambone-Cobar region for providing access to their properties.

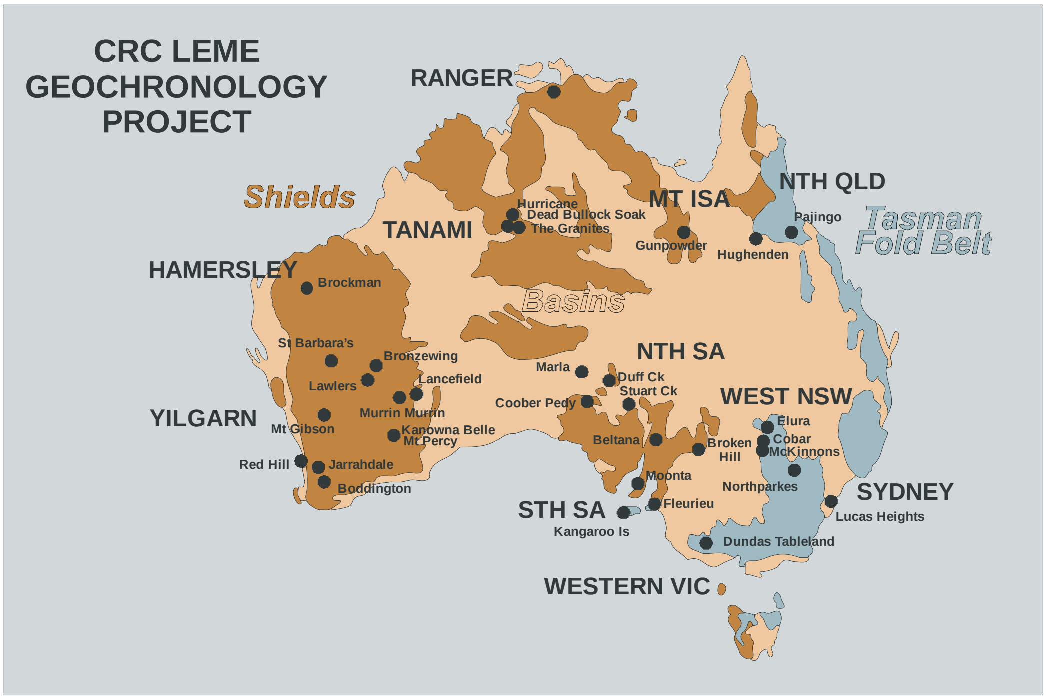

Figure 2. Location of sites where regolith ages have been obtained or which are currently being studied.

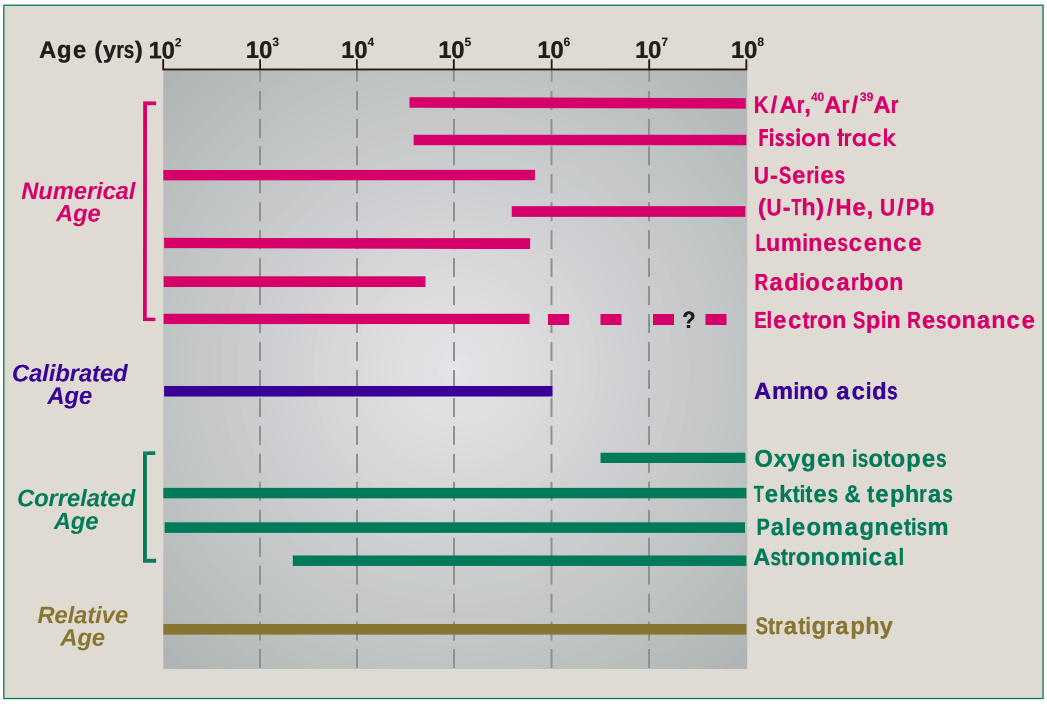

Figure 3. Age ranges over which regolith dating methods can be applied. Methods are grouped according to type of age result produced (after Pillans 1998).

REGIONAL LATERITE GEOCHEMISTRY OF THE CENTRAL YILGARN

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Many areas of lateritic residuum in greenstone belts have been tested for Au, and many for Ni, over the past 20-30 years; is laterite geochemistry now passé? We think not!

The use of laterite geochemistry for mineral exploration in Western Australia was first investigated by Mazzucchelli and James (1966). Smith et al. (1984) built on this with multi-element geochemical studies of dispersion in gossanous material from the Gossan Hill Deposit at Golden Grove, and the nearby Scuddles Prospect (Smith and Perdrix, 1983). Subsequent studies of the Greenbushes rare metal pegmatite district showed a massive multi-element anomaly of approximately 20 x 12 km (Smith et al., 1987). Between 1980 and 1993, a regional geochemical database (CSIRO-AGE) of several thousand laterite samples was generated (Grunsky, 1991; Grunsky et al., 1988; Grunsky et al., 1989; Geological Survey of Western Australia, 1998), covering substantial parts of the Yilgarn Craton, mainly greenstone-dominated areas. Between 1997 and 2000, a collaborative research project between CRC LEME and Astro Mining NL, generated a further 3900 laterite samples over approximately 100,000 km^2 of the central Yilgarn Craton, mainly in granite-gneiss terrain (Cornelius et al., in prep.). In addition to these regional surveys, exploration companies have been exploring tenements all around the Yilgarn Craton, mainly for Au and Ni, using laterite geochemistry.

With this amount of work both from exploration and research organizations, a large find such as the Boddington Au deposit would now appear rather unlikely in terrain with a lateritic mantle preserved at surface. However, that does not negate the possibility of a Boddington-size deposit or a VHMS base metal deposit under transported cover.

Lateritic duricrust and gravel, apart from being well documented widely tested sample media in the Yilgarn Craton, reflect the geochemical composition of mineralisation and its host rocks. They have a relatively uniform matrix and can contain precious, base and rare metals, as well as many pathfinder elements. Geochemical dispersion halos in lateritic residuum due to a combination of mechanical transport and hydromorphic processes can be many times larger than the target. Lateritic materials mainly occur at surface as duricrust or sandplain.

Could laterite geochemistry play a role in exploring areas of transported cover? Lateritic gravel derived from the erosion of nodular and/or pisolitic lateritic duricrust forms beds within alluvium or colluvium, together with sand, clay and lithic materials (newly formed nodules and pisoliths within sediments (ferricrete) are not discussed here). The lateritic gravel appears to retain geochemical characteristics despite removal of cutans and fracturing into smaller pieces. However, the sedimentary process mixes the geochemical signatures both from mineralization and from country rock, thereby diluting the target signature. Mixing may also be beneficial, particularly during a first pass regional geochemical survey, as the sample will represent a far greater area than lateritic residuum. Conventional exploration commonly disregards transported materials and, where transported sequences have been falsely characterized as residual and yield anomalous results; follow-up drilling commonly fails to detect the source of the anomaly as the material may have been transported for some distance. Such anomalies are considered ‘false’ anomalies. However, selective analysis of lateritic gravels within colluvium and alluvium could expand the application of laterite geochemistry from residual terrain to areas of transported cover.

What does an anomaly or geochemical trend in transported gravel mean and can anomalies be converted into targets which can be ranked and prioritized? Several case studies in the Yilgarn Craton have shown multi-element signatures of mineralization in nearby transported ferruginous gravels and particularly at the residual regolith – colluvium interface (e.g., Harmony (Robertson, 2004) and Calista (Anand, 2001)). Current studies at the Jaguar and Teutonic Bore base metal deposits found multi-element geochemical signatures in transported gravels that appear to show the Teutonic Bore mineralization displaced at least 4 km downstream from the deposit. Critical for the interpretation are knowledge of:

- regional geochemical patterns in lateritic residuum (background signature)
- geochemical signature of the targeted mineralization in lateritic residuum (target signature)
- palaeotopography and dispersion direction

Exploratory statistical techniques such as score indices, and multivariate discriminant analysis can then be applied to identify targets in transported materials (and residuum) and to vector towards these targets by, for example, contouring score indices or statistical parameters.

CSIRO/CRC LEME and GSWA have commenced laterite geochemical mapping of the western Yilgarn Craton, to establish geochemical background over the entire Yilgarn Craton, and to identify and delineate broad geochemical trends. Sampling is on a 9 km triangular grid, sufficient to show regional geochemical trends (Cornelius et al., 2001). For the western Yilgarn, the total number of samples will be 5000 of which 1900 are available from existing collections. This leaves approximately 3100 locations but it is estimated that, due to difficult access and other problems, only about 2350 will be sampled. To date, approximately 500 samples have been collected.

Representative geochemical signatures of various deposit types are currently being compiled. Most data are already available as part of previous LEME or AMIRA projects and require compilation. Some samples will have to be re-analyzed to be compatible with the regional data sets. Where geochemical signatures in residual and locally transported ferruginous nodules suggest proximity to a target, preserved micro fabrics within the nodules may give further clues as to their origin. At Golden Grove, Gossan Hill, textural information from lateritic nodules and clasts can be diagnostic (Smith, 2004).

Understanding the palaeotopography and therefore probable dispersion directions is essential for interpretation of the laterite geochemical data and vectoring towards mineralization. Company drill information (depth of transported cover) and the landform will, in many cases, be sufficient to interpret geochemical trends. Where there is insufficient information, some stratigraphic drilling or geophysical surveys may be required to fill gaps.

In summary, the significant benefits that lateritic residuum has had for surface exploration in the past and the enormous knowledge base that exists suggest that it and its transported components have been underutilized in exploration under cover and that these media may be used to explore areas of colluvium and alluvium more effectively.

Fifteen years ago, Canada had no economic primary diamond deposit. It was the efforts of some determined companies, geologists and prospectors who unraveled the indicator mineral trails in glacial tills. Glaciofluvial sediments have now led to the discovery of diamond pipes and the start of what is now one of Canada's most important mineral industries. The transported cover of the Yilgarn Craton could be similarly utilized rather than seen as an impediment to exploration.

Acknowledgements

Reviews and comments by R.E. Smith and I.D.M. Robertson are appreciated.

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MINERAL MAPPING FROM BEDROCK TO PLAYA SEDIMENTS: EXAMPLES FROM ST IVES

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Introduction

Portable visible and shortwave-infrared spectroscopy is a reliable and fast technique for mineralogical analysis of regolith and primary lithology. The technique is sensitive to clays, hydrous silicates, other hydrous minerals and carbonates, and may recognise regolith type, primary lithology and gold associated alteration. It can provide valuable support to visual logging of drill core or chip tray material. However, the technique does not recognise feldspars, quartz, sulphides and other non-hydrous minerals present in many rocks. Spectra were taken from down-hole samples from two traverses over Au deposits in Lake Lefroy, Western Australia, courtesy of St Ives Gold Mining Company Pty Ltd. The equipment used was the ASD[1], which has a wavelength range from 350 to 2500 nm, followed by input into “The Spectral Geologist”[2]. The “Spectral Assistant” module was used to derive mineral compositions. Aims were to map fresh rock alteration, to test the capacity to “objectively” log regolith stratigraphy, and to investigate spectral parameters for the determination of lithological features from highly weathered samples.

[1] Analytical Spectral Device – Fieldspec Pro ©

[2] © Ausspec International Pty Ltd

Intrepide Traverse

The east-west Intrepide traverse extends for 730 m, with approximately 200 m of ultramafic flanked by intermediate rocks (Figure 1). The regolith consists of 10-12 m of sediments over saprolite and saprock weathered to 50 m. Gold distribution is erratic (Figure 2), but appears to be locally higher along lithological contacts.

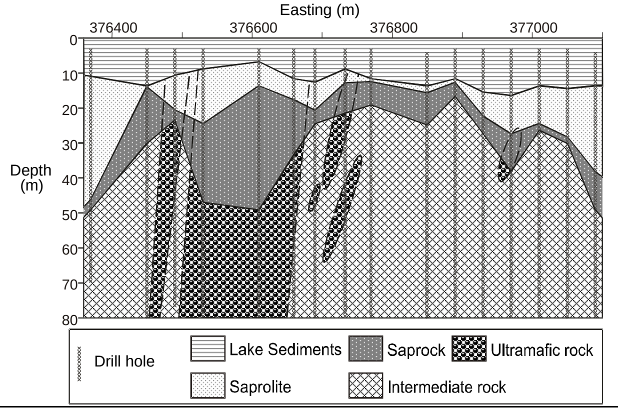


Figure 1: Geology and regolith stratigraphy of the Intrepide traverse

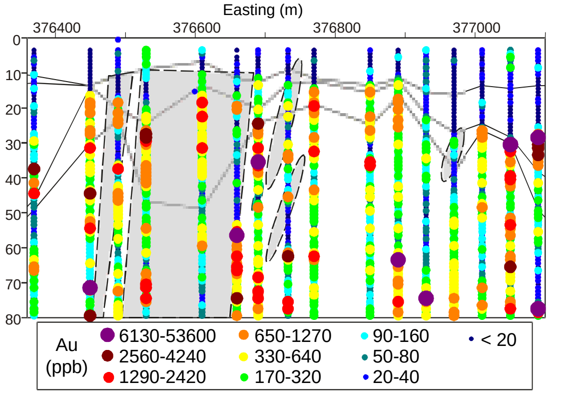


Figure 2: Gold distribution for the Intrepide traverse

Mineral maps and mineral assemblages obtained from the ASD are consistent with, and enhance visually logged geology. Intermediate rocks are distinguished by muscovite (Figure 3) and phengite (Figure 4) The phengitic zones, not observed by visual logging, may be a useful alteration indicator. Chlorite is a major mineral in ultramafic regions (Figure 5) with an outer chlorite/talc zone, and then carbonates observed (Figure 6) along the contact between ultramafic and intermediate rocks. On this basis, some drill holes appear to have been incorrectly logged as intermediate, with their chlorite-rich and mica-poor mineralogy indicating ultramafic rocks. In addition, the apparent deeper weathering on the western and eastern parts of the traverse may represent lithological contacts, weathered along fault.

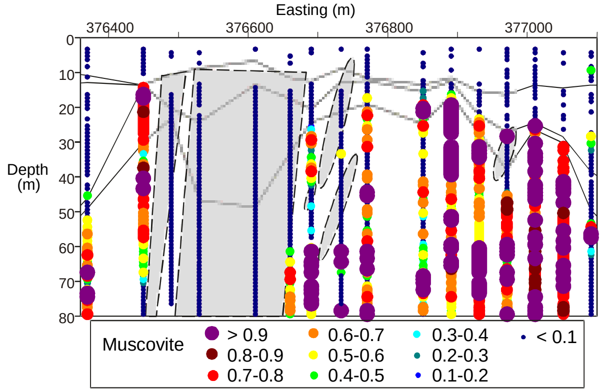


Figure 3: ASD-derived muscovite distribution for the Intrepide traverse

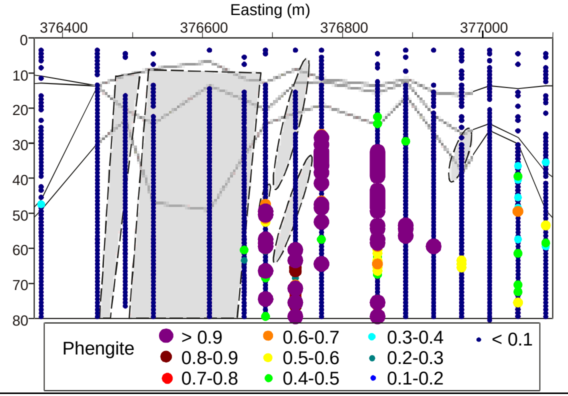


Figure 4: ASD-derived phengite distribution for the Intrepide traverse

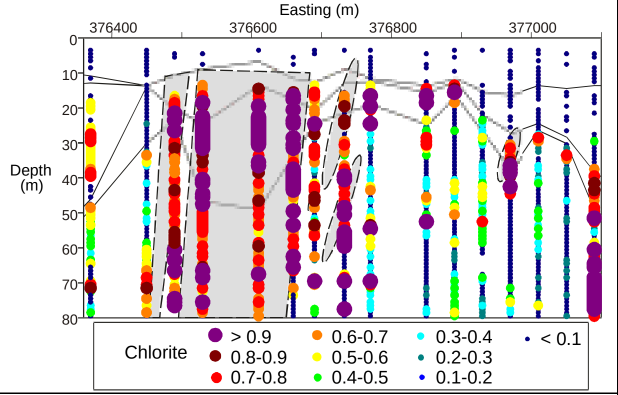


Figure 5: ASD-derived chlorite distribution for the Intrepide traverse

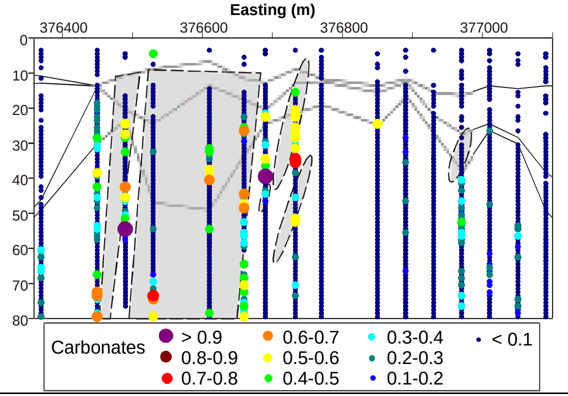
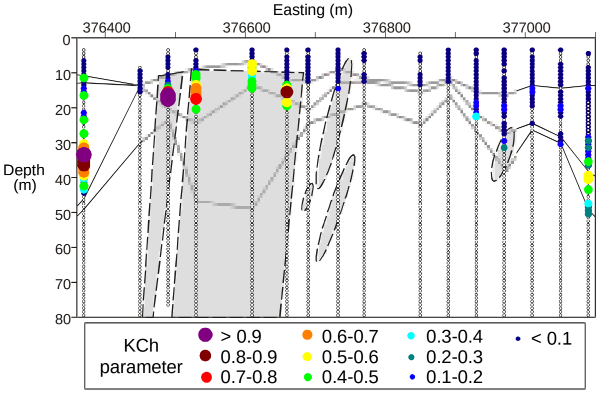


Figure 6: ASD-derived carbonate distribution for the Intrepide traverse

	Weathering of basic rocks commonly produces Fe-rich kaolinite, measured using the in-house derived KCh parameter. For the Intrepide traverse, this parameter (Figure 7) successfully indicates ultramafic rocks from analysis of overlying saprolite. As mentioned above, the high KCh parameter values on the eastern and western margins of the traverse indicate a contact with ultramafic rocks not identified in visual logging.
Figure 7: ASD-derived KCh parameter distribution for the Intrepide Traverse	

Using spectral data, areas of sediments (Figure 8), regolith (Figure 9), and rock (Figure 10) are distinguished respectively using the 500, 1950 and 2200 nm spectral regions. An overlap between regolith and rock indicates saprock (Figure 11). The spectrally interpreted zones agree well with those determined by visual logging, as indicated by the lines on Figure 11.

Revenge Traverse

The Revenge traverse is primarily composed of mafic rocks, with weathering down to 70 m below surface, and up to 25 m sediments. The presence of muscovite (Figure 12) is indicative of mineralization, with various alteration effects, such as Fe oxides at depth (Figure 13), also observed. Not surprisingly, high Fe oxide contents are also observed in the saprolite and clay.

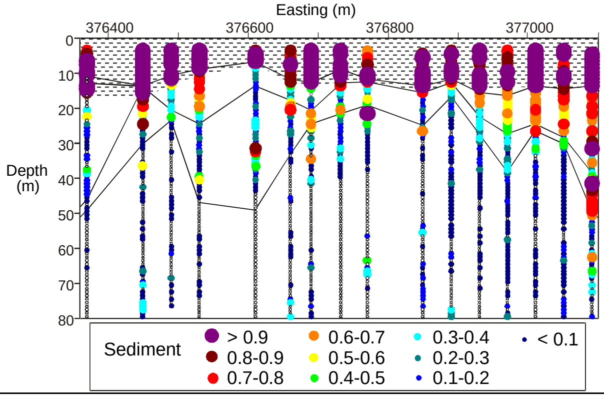
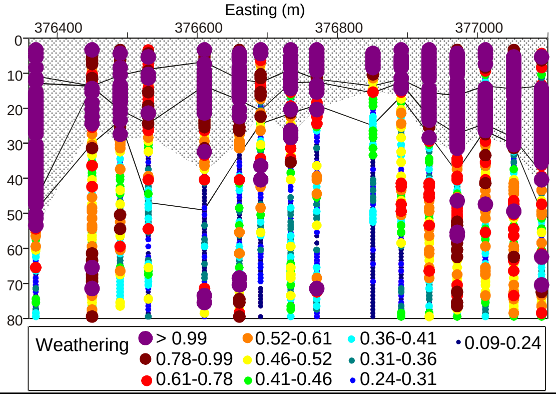
	

Figure 8: ASD-derived sediment distribution for the Intrepide Traverse	Figure 9: ASD-derived weathering distribution for the Intrepide Traverse

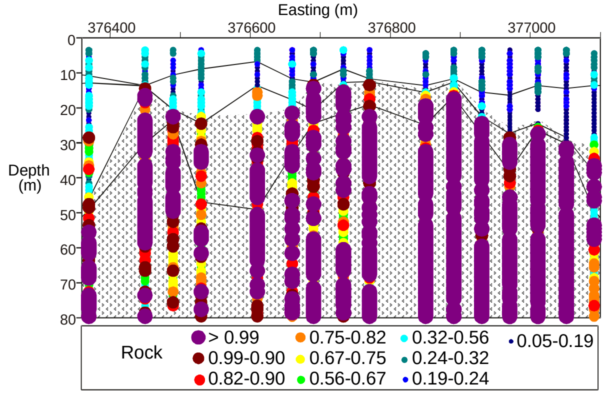


Figure 10: ASD-derived rock distribution for the Intrepide Traverse

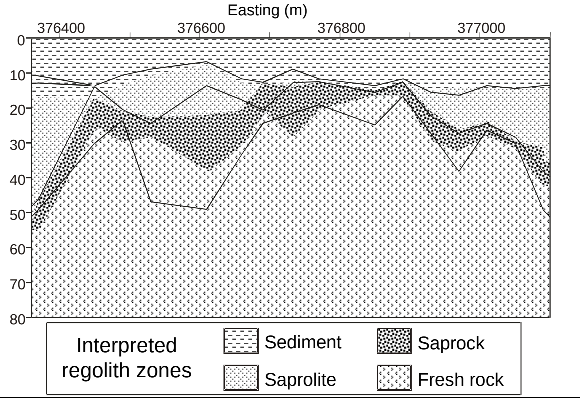


Figure 11: ASD-derived regolith zones for the Intrepide Traverse

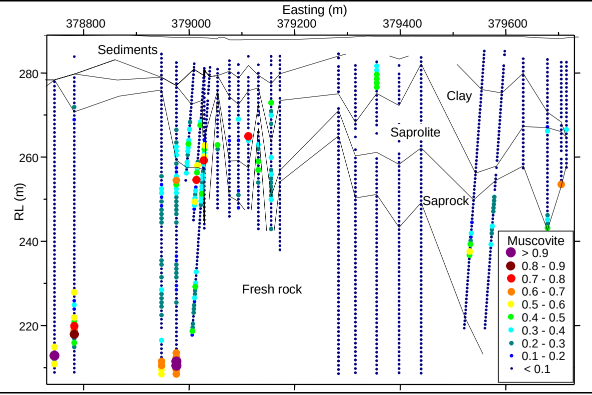


Figure 12: ASD-derived muscovite distribution for the Revenge traverse

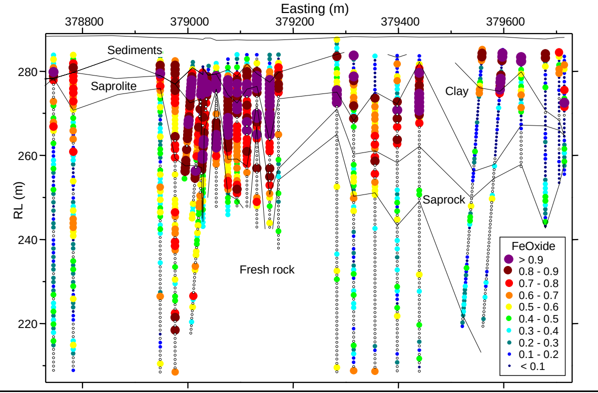


Figure 13: ASD-derived Fe oxide distribution for the Revenge traverse

Conclusions

Spectral analysis can recognise rock types, regolith units and differentiate sediments from in situ regolith. Alteration zones are clearly defined. Kaolinite chemistry of near surface zones, interpreted from the reflectance spectra, indicate underlying Fe-rich ultramafic parent rocks, with crystallinity measures indicative of transported materials. Reflectance spectral analysis can also recognise zones of oxidation and reduction in fresh rock and regolith. This study demonstrates the potential utility of rapid spectroscopic techniques for mapping mineralogical parameters in rock and regolith.

HYPERSPECTRAL REGOLITH AND ALTERATION MINERAL MAPPING

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New remote hyperspectral sensing technologies can now provide seamless maps of abundances and physicochemistries of alteration and regolith minerals like iron oxides (hematite and goethite), clays (kaolinite, illite, smectites), chlorite, micas, amphiboles and talc as well as green and dry vegetation.

New methods for addressing the effects of obscuring materials like vegetation and kaolin to retrieve the desired “absolute” abundances and chemistries of target minerals have now been developed.

One of the main challenges has been accurately measuring “relic” alteration minerals within the regolith in the more weathered parts of Australia.

Furthermore, mapping the regolith mineralogy provides a valuable information for more accurately mapping the regolith, including transported from in situ materials.

These new technologies are now been tested for the 1:100 000 scale mapsheet centered over Kalgoorlie as part of a LEME-GSWA-CSIRO-HyVista-PDAP collaborative project.

REGOLITH GEOCHRONOLOGY AND MINERAL EXPLORATION

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Geological evidence suggests that many parts of the Australian continent have experienced subaerial exposure over hundreds of millions of years (Fig.1). Consequently, there has been a long and complex history of weathering and landscape evolution, some of which occurred under climates quite different from the present. Given the long history of subaerial weathering in many regions, polygenetic weathering profiles are likely to be the rule rather than the exception. Consequently one should expect a range of ages from a single profile, whether determined by a single method, or by more than one method. Furthermore, different ages should be expected from different mineral phases, because each mineral can form under differing environmental conditions.

The LEME Geochronology project is applying regolith dating methods at sites across Australia (Fig. 2) to provide the chronologic framework for this long history of weathering and landscape evolution. Many sites are located in open pit mines, where results have implications for the age and genesis of supergene mineral deposits and associated geochemical haloes.

Reliable numerical estimates of regolith age, using isotopic dating techniques, are often difficult to obtain. Typical problems include the lack of suitable minerals and uncertainties regarding closed system assumptions. Furthermore, the generally unfossiliferous nature of much of the Australian regolith means that traditional methods of biostratigraphic dating cannot always be employed. Despite these problems, a number of dating methods have been successfully applied. On timescales of less than 10^5 years, radiocarbon and thermoluminescence have been extensively used to provide a robust chronology for late Pleistocene regolith. On timescales beyond 10^5 years, paleomagnetism, oxygen isotopes, K/Ar (including $^{40}Ar/^{39}Ar$) and stratigraphic dating have been employed. Recently, U-series, (U-Th)/He and U/Pb dating methods have been investigated, with promising results. Cosmogenic isotopes are also increasingly important for measuring long-term erosion rates.

In this talk I will illustrate some ways in which regolith geochronology can be significant the context of mineral exploration. The age ranges over which various regolith dating techniques can be applied, are summarised in Fig. 3.

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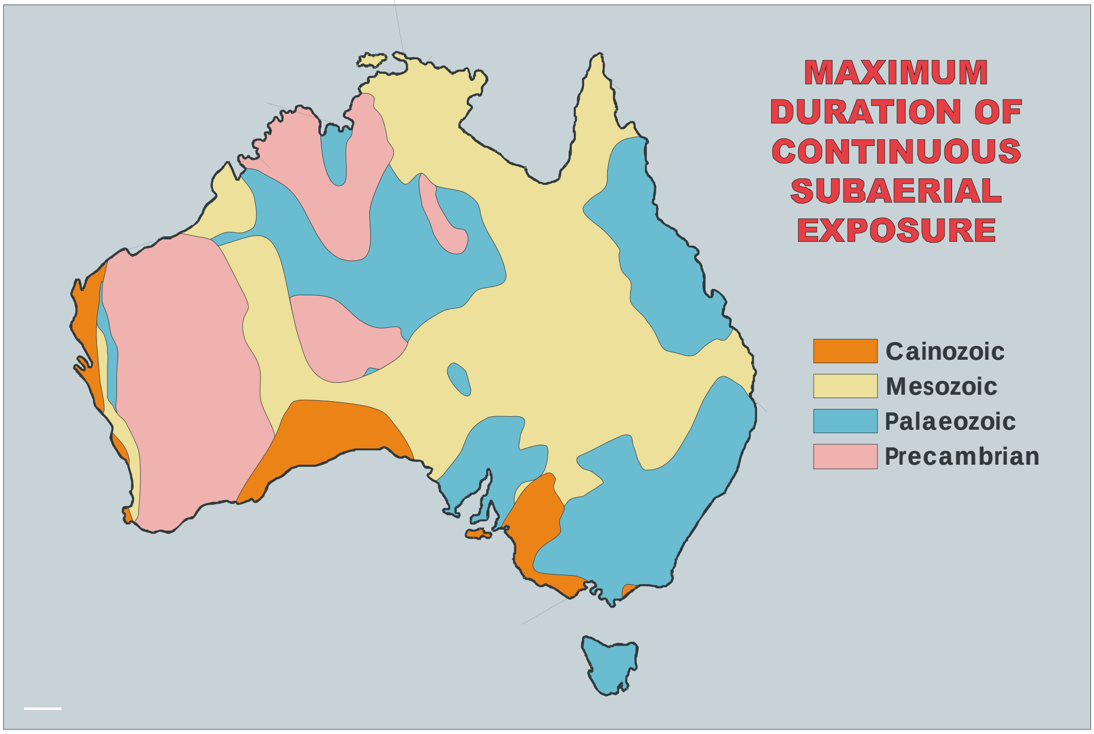

Figure 1. Duration of continuous subaerial exposure from paleogeographic reconstructions by BMR Palaeogeographic Group (1990).

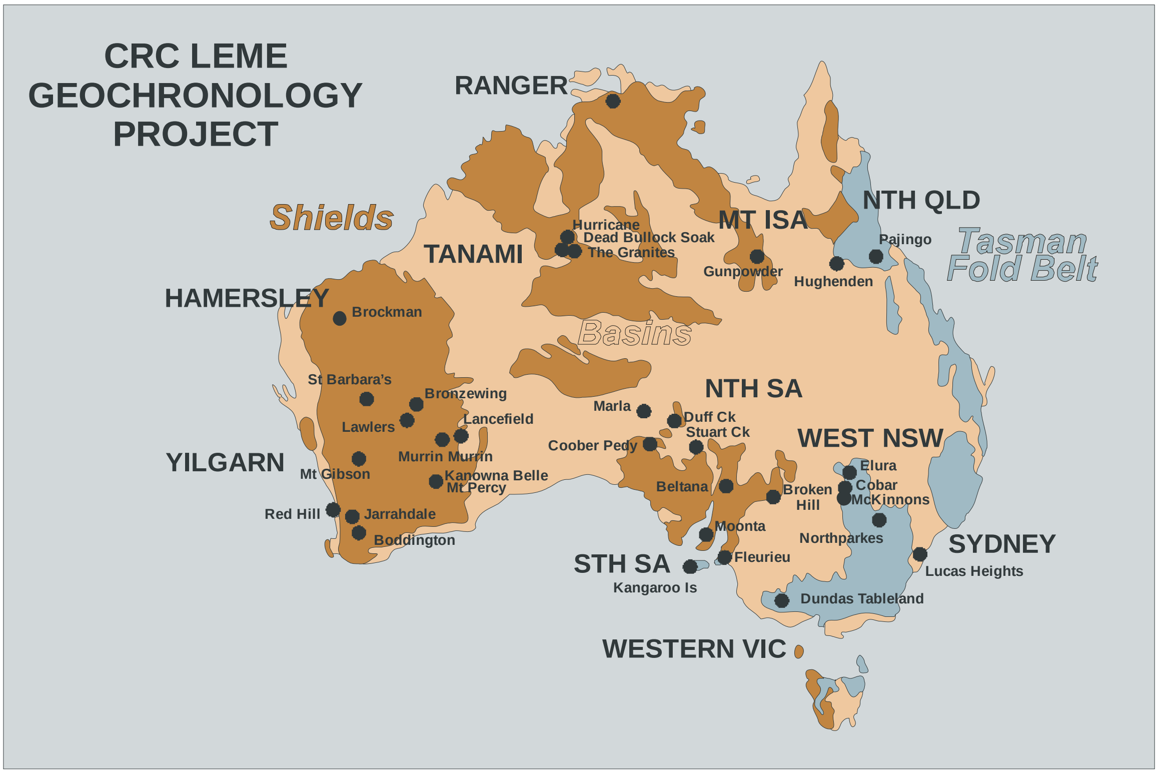

Figure 2. Location of sites where regolith ages have been obtained or which are currently being studied.

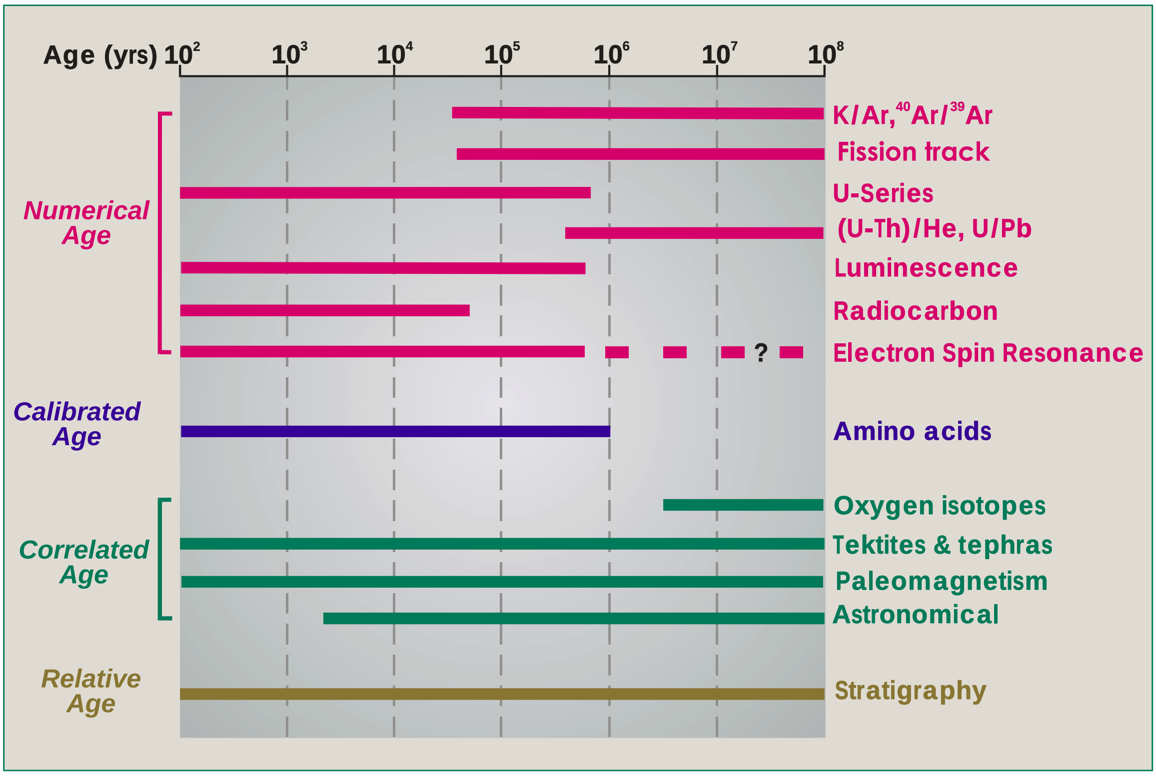

Figure 3. Age ranges over which regolith dating methods can be applied. Methods are grouped according to type of age result produced (after Pillans 1998).

ELEMENT FRACTIONATION AND MINERAL HOSTS IN THE REGOLITH

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INTRODUCTION

There are two fundamental questions in regolith geochemistry of importance to geochemical exploration:

- How does an element move through the regolith (i.e. what are the processes and controls on element mobility and immobility)?
- Where does an element reside in the regolith (i.e. what are the mineral hosts in different parts of the regolith)?

Answers to the first question provide us with vectors towards mineralisation. Answers to the second tell us what to sample.

Fully understanding element-host mineral associations will provide breakthroughs in fine-tuning geochemical exploration techniques and improve exploration success, particularly in the regolith. This can be considered as “mineralogical exploration”, involving analysis and characterisation of specific mineral hosts. Targeting specific mineral hosts has the advantages of providing a consistent sampling medium, reducing geochemical “noise” and selecting for element concentrations directly related to mineralising processes or dispersion from mineralisation. There are three main approaches to establishing and utilising element-host mineral associations:

- Direct analysis of specific minerals (now largely possibly through low detection level microbeam analytical techniques);
- Selective extraction methods designed to release elements hosted or attached to specific minerals or phases;
- Numerical modelling of bulk geochemical data to reveal relationships of elements with particular minerals known or suspected to be present in ore or associated alteration.

During weathering of ore deposits, elements may follow a trail of hosts, being held or released from different minerals in different parts of the profile depending on chemical parameters. This can be considered a type of weathering-controlled fractionation process. The study described here examines the effects of this process up the weathering profile to the surface for a number of sites in the Cobar gold field of western NSW (Figure 1).

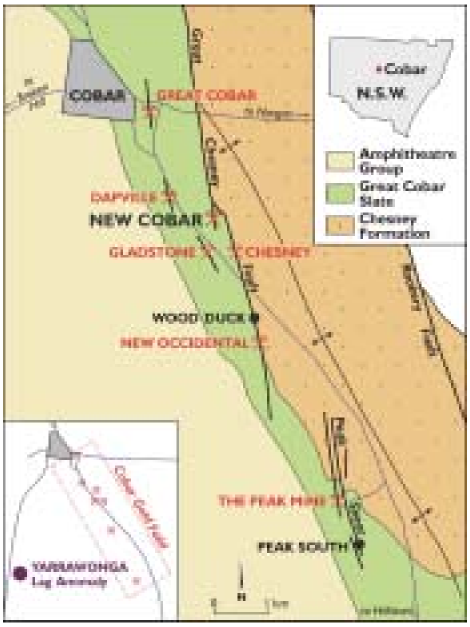

Figure 1: Location and geology of the Cobar gold field also showing known ore deposits and sites examined in this study. Insert shows the location of the Yarrawonga lag anomaly.

Polymetallic sulfide ores in the Cobar gold field have undergone prolonged weathering where they have been exposed at the surface or intersected by the water table. This has led to oxidation, chemical leaching and element dispersion, variable supergene enrichment and eventual mechanical dispersal of the weathering products across an evolving landscape. In addition to predominant Au and Cu the ores have associated Zn, Pb, Ag, Bi, As, Sb and W, which provide useful pathfinders for geochemical exploration.

IN SITU PROFILE

Mineralogical and geochemical trends at the New Cobar Au-Cu deposit indicate a progressive change in mineral hosts from primary sulfide and specific secondary minerals (particularly Pb and Cu arsenates) in the lower part of the weathering profile to more generic Fe and Mn oxides/oxyhydroxides towards the top (Figure 2). Goethite is an important host for Zn, Cu, As and to a lesser extent Pb, Bi and Sb. Hematite, where predominant, is an important host for Cu, Pb and Sb. Cryptomelane and alunite-jarosite group minerals are important hosts for Pb and As and lithiophorite for Co, Cu and Ni. Geochemical data on bulk samples from the lower part of the oxidised zone show very poor correlation of ore and pathfinder elements with Fe because they are hosted by a range of secondary minerals and not just the iron oxides/oxyhydroxides. Closer to the surface where most of the intermediate secondary minerals have been broken down, goethite and hematite are more important host minerals and a stronger correlation between these elements and Fe is evident in the bulk geochemical data.

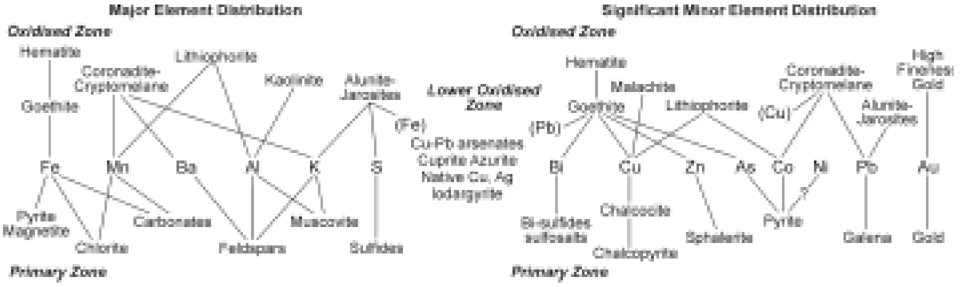

Figure 2: Connectagrams showing the mineral host pathways for major and minor elements through the primary and oxidised zones at the New Cobar deposit.

NEAR SURFACE PROFILES

At the Wood Duck and Peak South prospects detailed mineralogical and geochemical investigation of the upper 20 m of the weathering profile indicates that there has been significant leaching of metals and sequestering of the remnant geochemical signal in goethite and hematite. Bulk samples from near-surface RAB drilling at the Wood Duck prospect contain less than 450 ppm Cu, 100 ppm Zn, 150 ppm Pb, 10 ppm As and generally less than 20 ppb Au (with up to 180 ppb in several samples near the very top of the profile). Primary mineralisation contains 1.75% Cu and 2.23 g/t Au, with trace Pb and Zn. Marked positive correlations between Cu and Fe in the near surface oxidised zone are consistent with concentration of Cu in abundant hematite within the profile. Lead and Zn contents are not significantly correlated with Fe. Similar sampling at the Peak South prospect indicates less than 100 ppm Cu, 250 ppm Zn, 100 ppm Pb, 300 ppm As and less than 100 ppb Au. Primary mineralisation here contains 4.24% Zn, 1.72 Pb, <0.02% Cu and 0.4 g/t Au. Goethite is the predominant Fe phase in the weathering profile and there is marked positive correlation of Zn and As with Fe. Copper is low in abundance and does not show significant correlation with Fe. There is no apparent correlation between Pb and Fe contents. Ferruginous lag immediately overlying the mineralisation at these sites contains variable mixtures of hematite and goethite and anomalous concentrations of Cu, As, Zn, and in some cases Au and Ag. These concentrations are significantly greater than in the underlying regolith. Sequential leaching analysis of these lag samples indicates that these elements are largely bound within the crystalline component of the iron oxide/oxyhydroxides.

DISTRIBUTED LAG

A detailed study was made of lag from the Yarrawonga anomaly located down catchment of the Cobar gold field Lag collected from 8 sites was subdivided into a number of different fractions including: a micro lag component (<120 μm), quartz lag, lithic lag, ferruginous lag and magnetic ferruginous lag. The last three categories were further subdivided into angular and rounded categories as an approximate means of separating the less reworked lag from the more reworked or transported. Geochemical trends in the lag indicate progressive increase in Fe content with rounding and presumably exposure and transport/reworking. Some other elements including As, Pb, Sb and Ba show a similar increase suggesting that these elements are being stably fixed in the more Fe-rich lag and their relative abundance increased as the non Fe oxide components of the lag are leached and removed. This represents a type of weathering fractionation of these particular trace elements driven by chemical leaching and mechanical reworking. A good marker for this process is the Th vs Fe fractionation trend (Figure 3). Quantitative XRD analysis of representative lag samples from the

Yarrawonga sites indicates that hematite (19-64 wt%), quartz (16-54 wt%) and muscovite (3-14 wt%) are the dominant mineral constituents. The magnetic lag contains up to 15 wt% maghemite, which is generally more abundant in the rounded fraction. Amorphous (poorly crystalline) components comprise 5-17 wt% and lesser kaolinite up to 6.5 wt%. Goethite comprises less than 2 wt% in this lag. There is a strong correlation between increasing Fe content and hematite abundance, which contrasts with the pattern for lag at the Wood Duck and Peak South sites. The abundance of maghemite is not significantly correlated with Fe content. Sequential extractions on the hematite-rich lag indicate that most of the trace elements of interest are strongly bound in the crystalline phases with virtually none in weakly adsorbed sites.

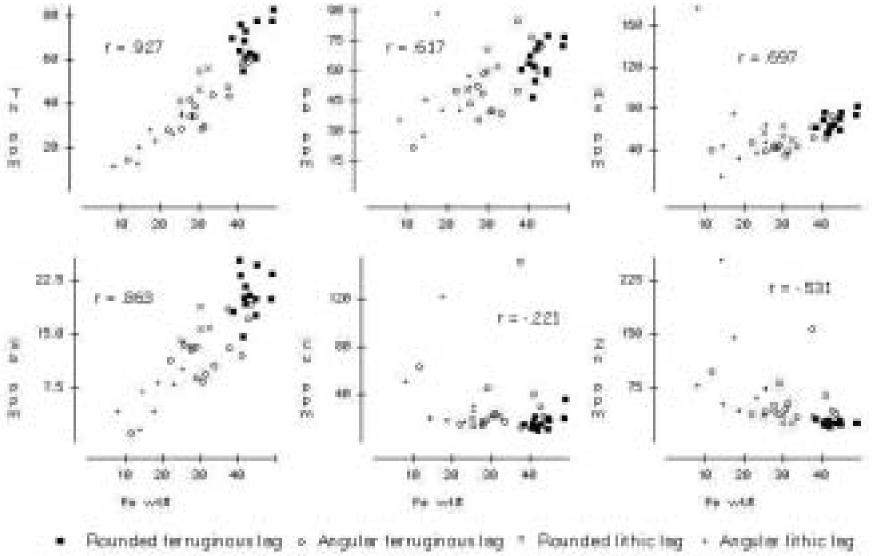

Figure 3: Bivariate plots of Fe versus pathfinder elements for lag samples from the Yarrawonga area. Each lag type has been subdivided into angular and rounded variants (r = correlation coefficient). Geochemical analysis was by INAA and ICP OES.

CONCLUSIONS

To understand the behaviour of pathfinder elements in intensely weathered terrains it is important to identify their host minerals and understand how geochemical dispersion and weathering fractionation have affected the development of these. The story can be complex. For example, in the Cobar gold field, Pb and As within deposit profiles show limited chemical mobility, but once fixed in goethite/hematite near surface become mechanically widely dispersed. The Cu and Zn signature can be broad around the deposit but become progressively leached towards the top of the profile, where the metals are strongly correlated with Fe due to association with goethite and hematite. Prolonged surface exposure of ferruginous materials leads to progressive conversion to hematite±maghemite, increase in overall Fe content and retention and relative concentration of Pb, As, Sb and Ba. This represents the end stages of a weathering fractionation of trace elements driven by chemical leaching and mechanical reworking. The process is indicated by a marked Th vs Fe fractionation trend. Interpretation of lag geochemistry should take into account the tendency for As, Pb and Sb in particular to be relatively concentrated in the ferruginous component during surface exposure and transport. The relative enrichment of Th in the more hematite-rich, transported lag may provide a means for mapping out areas dominated by this material using detailed analysis of the Th channel in radiometric imagery.

Acknowledgments: I thank my co-workers and students from CRC LEME, particularly Keith Scott and Dougal Munro, who have helped with their ideas, data collection and analysis. The Cobar study was encouraged and supported by Peak Gold Mines Pty Ltd, special thanks to Rex Berthelsen, Peter Leah and Craig Roberts from the company.

THE FORMATION OF GEOCHEMICAL ANOMALIES IN THE EASTERN GOLDFIELDS: THE ROLE OF AN EOCENE ACID WEATHERING EVENT

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The southeast margin of the Yilgarn Craton, in southwestern Australia, was inundated by marine transgressions during the Middle and Late Eocene. These transgressions resulted in the deposition of marine sediments in the shallow Eucla Basin and its marginal palaeovalleys, commonly for distances of several hundred kilometres from the palaeo-shoreline.

The Eocene palaeo-shoreline, at the onlap of the Eucla Basin with the Yilgarn Craton, was deeply embayed during this period. Organic and pyrite-rich, fine-grained, non-marine sediments, including locally thick peat accumulations, were deposited in the incised palaeovalleys and coastal plains during the early stages of the Middle Eocene transgression. Continued transgression drowned the palaeovalleys, forming estuaries that supported the extensive development of fringing mangrove communities and temperate rainforest. Terrigenous sediments accumulated in most estuaries and embayments during the Middle Eocene. The exception was in the Cowan Palaeovalley where reduced terrigenous influx allowed the deposition of shallow-marine, cool-water carbonates

When the sea regressed during the Middle Eocene and sea levels fell by at least 80 metres the estuarine sediments were drained, resulting in oxidation of the pyrite rich profile; generating sulphuric acid and precipitating haematite. The development of acid sulphate soils in reclaimed coastal wetlands is a contemporary analogue for this process. We speculate that acidification of the saline groundwater draining from the estuarine sediments would have resulted in dramatic leaching of the surrounding country rock, generating deep weathering profiles. Silica would have flooded the near-shore marine environment as a consequence of this deep weathering "event", providing key nutrients for the extraordinary proliferation of marine sponges that formed the extensive coastal spiculites and spongolites of the Late Eocene transgression. Onshore, metal ions would have been released by weathering of the country rock and may have been fixed with precipitating haematitic iron.

If these speculated changes in the nature of the regolith in environments marginal to the unconformity of the Eucla Basin and the Yilgarn Craton during the mid Tertiary can be substantiated then geochemical exploration models in the Kalgoorlie region will need to be reviewed. Our hypothesis presents new and very different possibilities regarding the timing of deep weathering associated with acid leaching, and the age, style and distribution of metal traps within the regolith. Traps which may be the source of anomalies and secondary deposits.

Although this hypothetical model pertains to the southeastern Yilgarn Craton, it is also applicable to other margins of the Eucla Basin. It is especially applicable to the eastern margin, where similar Eocene sediments filled the same type of palaeo-landscape of coastal embayments and drowned estuaries of the Gawler Craton. Thus, we expect similar implications for the development and modification of geochemical signatures of ore bodies, and their supergene expression, in the Gawler Craton.

MECHANISMS OF METAL TRANSFER THROUGH SEDIMENTARY OVERBURDEN

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As mineral exploration moves into regions dominated by shallow sedimentary cover (5-50 m), bulk surface geochemical techniques are considered less applicable, and partial, selective and sequential leaches and gas analysis are increasingly employed to delineate anomalies. However, the application of these techniques have found mixed success, because the particular mechanism(s) and their effectiveness in transferring metals associated with mineralization upwards through transported overburden is poorly understood, thereby complicating and limiting the interpretation of datasets, and precluding the discrimination of negative and false anomalies. There is a major need to critically study potential mechanism capable of transferring metals from buried mineralization upwards through barren cover to the surface. This review assembles a list of potential mechanisms and their application to surface geochemical techniques.

The main mechanisms potentially capable of transferring metals upwards are groundwater (hydrogeochemical), gases, vegetation and bioturbation; most having variants or sub-mechanisms within them, and each being influenced by positive and negative effects of microbial processes.

Groundwater in association with infiltrated water is the main agent of chemical weathering, and facilitates the dispersion of metals from the ore body. Flow directions, solution properties, aquifer heterogeneity, adsorption, complexation and inherent interactions and feedbacks between these processes influence the extent of *lateral and vertical dispersion* within the unconfined aquifer. Redox processes and formation of a possible stagnant zone at varying depths affect vertical migration of specific elements and can lead to the fractionation of specific elements (rare earths, Fe, Mn, V, As) at or within the fluctuating zone of the water table. *Capillary* forces at and above the water table can induce upward migration of solutes, with the rise being dependant on aquifer grain size and evaporation rates. *Seismic* or *dilatancy pumping* occurs in neo-tectonic active areas where faults and fractures act as conduits for upward transfer of mineralized groundwater. Earth tremors promote compressional stresses along faults and force groundwaters upward, with surface discharge after the earthquake, resulting in a near surface anomaly. This mechanism is limited to low-rainfall and neo-tectonic areas that have regular seismic activity after overburden deposition. *Free convection* or buoyancy driven currents within the groundwater can arise due to density differences induced from point sources or subtle heat sources. These can promote faster solute migration in a particular direction and the possible formation of irregular fronts. The denser fluids arising from salt lakes are known to cause convective mixing of mineralized groundwaters in surrounding regions. The applicability of convective flow mechanism to rapidly transfer solutes upwards up to the water table remains unexplored and has only been investigated via simulations and laboratory tests for point source contaminant transport. The formation of *electrochemical cells* around an oxidizing-reducing sulphide body within groundwater can provide excess cation concentrations at the oxidized upper edges of the sulphide body, and the proposed pattern of (“rabbit ear”) surface anomalies in regolith suggests its possible operation. An advanced version of the electrochemical cell model posits the onset of redox anisotropy between the buried sulphide body (reducing) and water table (oxidizing) after the deposition of sediments. Self-potentials arise and are maintained due to reducing conditions at the sulphide body front and oxidizing conditions at the water table, leading to upward and outward migration of reduced species and their subsequent oxidation and formation of a reduced column above the ore body. This voltaic cell model is capable of rapidly transferring metals upwards through thick (30 m) saturated cover. The limitation of all the groundwater supported transfer mechanisms is the upward limit to which groundwater rises or the water table (and capillary fringe), except that of seismic pumping. In the Australian landscape, groundwaters reside are commonly more than 5 m below surface except in lower, discharge landform sites, and other mechanisms are necessary to transfer metals from the water table upwards.

Gases migrate via molecular diffusion, advection and gas streaming, out of which advection and gas streaming appear the main sources of rapid upward migration of ore related gases (CO_2, SO_2, COS) and possibly of metals. *Atmospheric pumping*, the depression front set up by large barometric pressure change, causes rapid upward migration of air present in pores and conduits, and is a primary mechanism causing upward migration of trace gases from nuclear blasts, with the capability to transport volatile and radiogenic elements (Hg, Rn, He, As) and also gas bubbles. The effectiveness of atmospheric pumping is restricted to fractured media and possibly operates in a connected, heterogeneous sedimentary overburden. Other mechanisms that may cause advective gaseous migration are thermal convection on hillsides (only along inclined slopes) and rapid fluctuations of the groundwater, the latter being valid only in shallow water tables and high permeability zones. *Gas streaming* or bubble migration is the upward transfer of gases in the form of microscopic bubbles that form within the groundwater due to overpressure and are released from the water table. Specific metals (Cu, Zn, Pb, Hg, actinides) and ultra-fine particles (clays, oxides, bacteria) can attach to the surfaces of ascending gas bubbles (dominantly composed of CO_2) and be transported upwards to the near surface environments, where pressure changes induce bubble instability and cause release of metals. Gas streaming, in combination with atmospheric pressure changes, is a potential mechanism of transferring metals upwards, although the capacity to absorb and carry metals, and their fate during transfer through a clay bearing overburden requires further testing. In any case, most, if not all, studies of gas anomalies at the surface indicate rapid migration along conduits such as faults, fractures and shears, above which the anomalies are present.

Vegetation or plant physiological uptake of elements from subsurface and their release to the surface via litter over time is a potential mechanism of rapid metal transfer. In drier climates, many pheratophyte plants have dimorphic roots systems with laterals and sinker or tap roots (vertical), the latter roots acquiring water from deeper groundwater source, especially during summer (as demonstrated by deuterium isotopic studies). However, the uptake of specific metals, besides the macronutrients, from the groundwater remains untested. Furthermore, the operation of hydraulic lift – redistribution of deeper water acquired by sinker roots to near surface soil horizons to be used by laterals, is a process capable of rapid transfer of water and nutrients within the overburden. The depth of rooting of vegetation is critical to the ability of vegetation in transferring water and possibly ore metals, and a global rooting depth survey suggests that deep roots, especially sinkers, are ubiquitous with 10 m plus depths regularly reached and confirmed in several climatic settings. Vegetation is known to uptake specific mineralization associated elements (Au, Ni, Cu, Pb, Zn, As) with specific flora being adapted to substrates of high concentration of these elements, and use of plants in phytoremediation stands as a testimony. The vegetation uptake can also affect the species of the element. For example, gold absorbed as dissolved form can be converted into colloidal form. The effectiveness of phreatophytes and other vegetation in acquiring mineralization associated metals from the groundwater and releasing them to surface via litter and within the soil via hydraulic lift, has not been intensively tested, but holds promise.

The operation of **bioturbation** process within the biomantle underlying the surface is capable of moving huge amounts of soil material, and thereby bringing up anomalous material from depth to the surface. Ants, termites and earthworms are the main bioturbators, and combined with rainwash are the primary cause of soil (and anomaly!) homogenization and lateral dispersion of surface anomalies over time. However, unlike the other biological pathway of vegetation, the effectiveness of bioturbation decreases rapidly downwards, with activity mostly ceasing at a depth of 2 m. The role of **microbes** in transferring metals upwards is restricted, but they affect most of the processes responsible for metal transfer. Microbial metabolism affects the kinetics of many hydrochemical processes, especially redox and sulphide oxidation. Microbial metabolism can negatively impact on gaseous migration of elements by generating methanogenic, CO_2 and sulphur gases. They can influence the efficiency of metal uptake by roots via redox reactions, symbiotic associations and organic secretions. And they can participate in intracellular and extracellular formation of minerals (and gold particles) within the saturated zone and soil, irrespective thermodynamic solubility products of those minerals, and can affect efficiency of partial and selective leaches.

While all the mechanisms described above have potential to create surface anomalies, it is likely no one mechanism may be singly responsible, and a combination of mechanisms may be pertinent in the Australian environment. The critical, but often neglected aspect of evaluating the operation of the diverse mechanisms responsible for upward metal migration is the **nature** of the transported overburden (pre and post weathering) and its **depth**. Related to the nature of the overburden is the **time** and **landscape** factor that are equated to the age and type of weathering. Weathering of the overburden with development of a weathering profile (sometimes multiple weathering profiles are superimposed) and concomitant water table increases the possibility to transfer metals upwards via a combination of mechanisms such as vertical hydrogeochemical gradient and electrochemical effects, vegetation uptake and bioturbation, to form “incremental” anomalies over time. Alternatively, younger, fresh to slightly weathered sediments, even of shallow depth, will afford a much lesser opportunity for diverse mechanisms to operate, except gas advection and possibly vegetation uptake. However, specific partial leaches, gas measurements and electrochemical techniques, work on the principle of a rapid migration mechanism even in recent, fresh cover, and therein lies the need to understand the rate, extent and overall effectiveness of the mechanism(s) to mobilize ore metals upwards under different transported cover settings, so surface geochemical techniques can be efficiently and predictively applied, or discarded.

REGOLITH MINERAL HOSTS FOR GOLD AND OTHER BASE METALS

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INTRODUCTION

During the weathering of mineral deposits, trace elements are displaced from their original host minerals, are dispersed, and can subsequently occur in newly formed secondary phases in the regolith. In sedimentary cover, post-depositional weathering and diagenesis lead to the formation of a variety of secondary minerals. Of most interest are clay minerals, poorly crystalline minerals and Fe and Mn oxides. Such mineral phases will interact geochemically with weathering fluids, and so have the potential to trap trace elements. This may create an anomaly in a specific mineral phase. The associations between trace elements and minerals can be partially derived using statistical analyses of bulk geochemical data supported with a relatively simple qualitative study of the mineralogy of the regolith. Selective sampling such as size fractions or selective extraction techniques improves the result but in these techniques it is generally not known which mineral is hosting the anomaly. In this study, the physical location of the trace elements in the regolith was directly determined using *in situ* techniques. A combination of conventional, bulk (XRF, INAAA) and micro-analytical techniques covering a wide range of observation scales (X-ray diffraction, Scanning Electron Microscopy) have been used to characterize the mineralogy and trace element distribution. *In situ* geochemical analyses were performed on polished thin sections by electron microprobe and laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS). Le Gleuher (2003 a; b) and references therein, provide a full description of the LA-ICPMS technique and the development of its application to regolith samples.

This paper reports preliminary results on mineral-trace element associations in regolith developed over mineralized rocks at the Lancefield South and Enterprise (Mt Gibson) Gold Deposits.

LANCEFIELD SOUTH GOLD DEPOSIT

Geology and mineralization

The Lancefield Gold Deposit is located 8 km north of Laverton. The bedrock assemblage consists of komatiites, Mg basalts, massive to pillowed mafic volcanics, carbonaceous shale and chert. The ore body consists of a mineralized zone some 140 m in strike length and 7 to 12 m in width, enveloping a 5 m wide chert unit. The chert unit has a sulphide content of around 15% near the ore zone and near to the chert the regolith developed on ultramafics also contains significant supergene gold mineralization (Hronsky et al., 1990).

Regolith

The deposit is situated in a sheet flow plain. The *in situ* weathered profile on the Archaean is overlain by up to 20 m of sediments. The depth of weathering exceeds 50 m on basalt. By contrast, talc-chlorite ultramafic is weathered to some 20 m. Palaeomagnetic dating of hematite indicates a long and complex weathering history with different weathering ages (Late Carboniferous to Late Miocene) in different parts of the profile (Dr Brad Pillans, CRC LEME/ANU, written communication, 2004).

There are three principal types of sediments.
(i) The basal Permian fluvioglacial deposits range in thickness from 10 to 20 m and are partly covered by Tertiary palaeochannel clays and hardpanised colluvial deposits. There is a strong tendency for the Permian channels to follow ultramafic lithologies. A thick, deeply weathered Permian fluvial sequence is exposed abutting, and unconformably overlying Archaean ultramafic rocks on the SW

wall of the pit. The wall of the channel is steep, to overhanging, in places. The base of the Permian consists of a matrix supported, coarse, bouldry conglomerate, consisting of a variety of rounded and angular metavolcanic and granitic boulders and some BIF, set in a gritty matrix of similar material, interbedded with gritty cross-laminated sandstones. The base of the channel sediments are largely dominated by quartz, kaolinite and smectite and are derived from a mixed felsic-mafic provenance. Higher in the profile, the sediments are mottled; the mottles accentuate the gritty, polymictic fabric of the Permian sediments but this is less obvious in the surrounding matrix. The megamottles consist of goethite, hematite with kaolinite aggregates, and fine-grained ilmenite. Some are of hematitic kaolinite with ilmenite and muscovite. Others consist of kaolinite, quartz and minor muscovite.

(ii) A 3-8 m thick Tertiary palaeochannel clay overlies mottled Permian sediments. Post-depositional weathering, in particular, megamottling (>200 mm) has obliterated much of the primary sedimentary fabric. Many of the megamottles have a kaolinite and/or smectite-rich zone around their margins. Kaolinitic zones contain rare, milky, extremely fine grained quartz grains. In the upper part, hematite has altered to goethite. Biota appear to have played an important role in ferruginisation of sediments. Judging from the elongate form of the mottles, their dominantly vertical orientation, their decrease in abundance with depth, and the fairly uniform depth to which they occur, it can be inferred that mottles formed by the removal and reprecipitation of iron around tree roots. The removal of iron around tree roots was probably affected by the microbial decay of organic matter, which generates reducing conditions under which Fe^3 oxides can be dissolved and redistributed.

(iii) A 0-2 metre thick layer of soil and hardpanised colluvium overlies the Tertiary palaeochannel clays. It consists of quartz, hematitic clasts, kaolinite and poorly crystalline goethite and opaline silica formed as coatings around the quartz grains.

Bulk geochemistry and *in situ* microanalysis

The bulk samples of saprolite contain high concentrations of As (90-600 ppm), Cu (40-620 ppm) and Zn (50-430 ppm). Gold ranges in abundance from 11-196 ppb. Mottled Permian and Tertiary sediments were separated into Fe-rich and clay-rich components. The Fe-rich part consists of goethite, hematite, quartz and kaolinite whereas the clay-rich material contains kaolinite, smectite and quartz. Gold occurs in both the materials, but is slightly more elevated in the clay. By contrast, As (43-899 ppm), Cu (21-115 ppm) and Zn (10-140 ppm) are enriched in the Fe-rich material but the clays are very low in these elements. The Fe-rich materials of Tertiary palaeochannel clays are enriched in Cu (25-160 ppm) and Zn (10-85 ppm) but contain low levels of As (14-67 ppm) compared to the underlying mottled Permian sediments. Bulk samples of hardpanised colluvium are relatively low in these elements.

The trace elements used as pathfinders have multiple hosts. The saprolite largely consists of talc and kaolinite with small amounts of smectite, interstratified minerals, goethite, ilmenite and chromite. Kaolinite is the main weathering product in the saprolite, but hosts only small quantities of trace elements as indicated by *in situ* microanalysis. In the saprolite, trace elements are concentrated in minerals of marginal abundance such as Fe oxides, smectite and interstratified. The trace elements directly related to mineralization (As, Cu, Zn) released by the dissolution of sulphides are incorporated in goethite and smectite. A significant amount of Cu and Zn occurs in smectite. Manganese oxides also contain Zn. Trace elements related to the host rock occur as residual in primary minerals (e.g., chromite) or mobilized and integrated into other secondary phases in their alteration products.

In the mottled Permian sediments, As is strongly concentrated in Fe oxides. Copper and Zn, both present in the primary mineralization in sulphides, are hosted by Fe oxides. Kaolinite is extremely low in trace elements. Mottled Tertiary clays are very low in As but Cu and Zn are present in significant amounts in Fe oxides. In the overlying hardpanised colluvium, Cu and Zn are concentrated in poorly crystalline goethite. Copper and Zn are absent in opaline Si.

ENTERPRISE DEPOSIT (Mt Gibson)

Geology and regolith

The Enterprise Pit Gold Deposit is about 300 km NNE of Perth and is located within the colluvial-alluvial plains. The Au-bearing bedrock comprises quartz veining in sheared basalt with mixed sulphides of pyrite, pyrrhotite, chalcopyrite, sphalerite and galena. This is overlain by some 20 m of bleached saprolite composed of white kaolinitic clays and occasional green smectitic clays together with quartz veins (up to 1 m thick) and occasional ferruginous dykes, presumably from the alteration of basic dykes. In situ regolith is overlain by transported overburden principally consisting of two Tertiary and Quaternary sedimentary units. Slabby to pisolitic ferricrete is formed in Tertiary sediments. These were originally sandy-clay to clay-rich sediments that have been modified to form pisoliths by the introduction of hematite and goethite. The pisoliths consist of hematite, kaolinite, quartz and goethite. The matrix and nodules of the ferricrete contain fine clay spherites thought to have been derived from granites. The uppermost sandy to sandy-clay unit is 3-4 m thick and has been subjected to calcification and silicification to produce calcrete and hardpans, the top 1-2 m is hardpanised. Within this unit sub-horizontal to horizontal laminations have developed commonly marked by thin coatings of precipitated Mn-oxides.

Bulk geochemistry and *in situ* microanalysis

The bulk sample of sulphide rich bedrock of basalt contains high concentrations of Au (>20 ppm), Ag (88 ppm), As (363 ppm), Zn (954 ppm), Cu (375 ppm) and Pb (1120 ppm). These elements are generally depleted in the saprolite though localised concentrations do occur associated with sub-vertical quartz veining and isolated ferruginised zones. The slabby, ferricrete is anomalous with up to 587 ppb Au detected in one sample, and white clay in-between slabby layers containing 112 ppb Au. Arsenic concentrations occur in areas of ferruginisation (20-50 ppm), even in the saprolite, and reach 85 ppm in slabby sediments. The hardpanised sediments and calcrete near the top of the profile yield little As but appreciable Au concentrations (128-436 ppb). Using this bulk geochemistry, we targeted polished thin sections of Au and/or As rich samples for *in-situ* micro-analysis using LA-ICPMS.

The *in-situ* analyses are able to identify areas of Au enrichment in the samples and in most the trend mirrors that of the bulk geochemistry with As, Cu and Zn all having a preference for Fe-rich areas. In the slabby ferricrete the Au, As, Cu and Zn are contained in the minor hematite rich clasts rather than the dominant matrix which comprises quartz, goethite, kaolinite and hematite. Interestingly, the white clay within these slabby zones contains appreciable Au. LA-ICPMS identified the kaolinite as a local host for Au but with little As. The Fe-stained kaolinite shows a slightly higher enrichment in Au together with higher As and Cu.

The gravelly red-clays that contain clasts comprising small clay and hematitic spherites or balls in a matrix of hematite, kaolinite and quartz show As closely associated with Fe-rich areas, but both mineralogies of spherite are relatively Au-poor. In the uppermost sequence of hardpanised colluvium and calcrete high concentrations of Au are found in the calcareous matrix. Silica-rich areas in the matrix of the hardpan (kaolinite+ amorphous silica) are also rich in Au and the hardpan analyses yield more Cu than in calcrete. Some highly anomalous values were obtained using LA-ICPMS on the calcrete, preliminary observations would suggest this represents grains of Au in the sample to produce a nugget effect in the analyses. It should be noted however, that Au grains were not observed in these samples during SEM observations indicating they may still be very fine-grained.

CONCLUSIONS

Sediments at the Lancefield and Entreprise deposits display complex history of kaolinisation, ferruginisation, calcification and silicification, with Au and trace metals being concentrated in several mineral hosts. In most cases *in-situ* analysis was able to identify the mineral or mineralogical structures that act as hosts for Au, As, Cu and Zn at the thin section scale. It has been shown that targeting individual minerals and mineralogical phases provide a potential tool to enhance geochemical anomaly detection.

It appears that metal enrichment in various mineral phases developed in sediments at Lancefield and Entreprise have resulted from dispersion from the underlying mineralization. Possible mechanisms of dispersion and its implications to exploration will be discussed.

ACKNOWLEDGEMENTS

We wish to thank management and staff of Metex Resources and Oroya Mining for their cooperation and hospitality without which this study would not have been possible. Assistance on the SEM and electron microprobe was given by Greg Hitchen and Michael Verall.

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BACTERIAL LEACHING AND OTHER TECHNIQUES TO IDENTIFY GOLD UNDERCOVER (N.W. VICTORIA)

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As mining industries move into the 21st century new economic mineral deposits are becoming more difficult to locate. Exploration for major ore bodies is progressing under various depths and types of regolith cover. As this trend in exploration continues, geochemical investigation will play an important role in the success of exploration, particularly in regions of transported overburden and poor geophysical response.

Partial chemical extraction techniques have been widely employed as a geochemical exploration tool. Partial extractions seek to remove part of a mineral phase or phases into solution rather than a specific chemical species that is targeted by selective extraction techniques. Similar techniques used in other studies have had some ability to locate buried ore bodies in specific environments and can provide a rapid and cost effective method for geochemical exploration under regolith cover (Bajc, 1998; Williams and Gunn, 2002). Although previous studies have found the information gained from partial chemical extractions beneficial, they have also concluded that such extractions are of limited use as 'stand alone' procedures (Bajc, 1998).

The use of bacteria in partial extractions of regolith samples has the potential to greatly magnify the geochemical signature imparted on the sample by the underlying mineralisation. The bacteria cause dissolution of only ultra-thin surface layers of mineral particles, so the geochemical signature is not diluted in the sample matrix. The objective of this investigation is to understand the efficacy of bacterial leaching in locating gold mineralisation under regolith in the Stawell goldfield of western Victoria, approximately 230 km northwest of Melbourne. The Bacterial Leach (BL) will also be compared more common techniques including HF acid total digestion (T), weak H_2O_2 leach (HP), H_2O leach, and hydroxylamine hydrochloride leach (HA) analyses.

The study region is situated on the boundary of the Ballarat Trough and Murray Basin and comprises predominantly sandstones, mudstones, shales and slates, with some regions of basalt, overlain by Quaternary alluvial sands, silts, and clays (Douglas and Ferguson, 1976). Recent efforts have been made to explore the region to the NNW of Stawell where potentially gold bearing units occur under a varied thickness of regolith. The regolith cover overlying the mineralised zone at site 1 and 2 is 30-110 m thick. Murray basin alluvial sediments at this location overlie basalt, volcanogenic sediments and psammopelitic rocks. The regolith can be categorised as a thin, uppermost layer (5 m) of weathered soil underlain by up to 40 metres of Loxton/Parilla sands, above Geera clays and a thin layer of saprolite. Site 3 is believed to contain a potentially economic Cu-Au ore body. Analysis of the soils at site 3 was conducted as a blind experiment without prior detailed knowledge of the underlying geology, regolith, or target ore. The regolith thickness generally increases to the north.

Soil sampling was undertaken along traverses across areas overlying known gold ore bodies (Site 1 and 2). Samples were subjected to BL analysis and the results combined in geochemical element suites to predict the underlying mineralisation. The combining of potentially anomalous elements suppresses the background and increases expression, thus enabling recognition of an anomaly where it may have been overlooked in investigations using single elements only. The element combinations are typically necessary given the bacterial mechanisms for non-preferential, incomplete, partial digestion. The element suites in this study used combinations of the following: As, Bi, Cu, Ga, Ge, Ni, Sb, Se, Te, Ti, V and W. No single element anomalies were evident at site 1 and 2. The resulting groupings were subsequently applied to BL results of soil samples of three separate traverses in the vicinity of a suspected buried ore body (Site 3).

An empirical assessment of anomaly expression of the BL over Site 1 and 2 was conducted using hypergeometric statistics (Stanley, 2003). This method requires an orientation survey using prior knowledge of the underlying geology to predicted sites of anomalous response. The following hypergeometric formula relates the probability of the anomalous points and false positives to the successful detection of mineralisation (Stanley, 2003).

$$P(x) = \frac{\begin{pmatrix} a \\ x \end{pmatrix}\begin{pmatrix} t-a \\ k-x \end{pmatrix}}{\begin{pmatrix} t \\ k \end{pmatrix}} \times 100\%$$

a = number of predicted anomalous points
x = number of correct anomalous points
t = total sample points
k = number of anomalous points (true and false)

Hypergeometric statistics allow a rigorous comparison of conventional and new exploration techniques. Site 1 BL significantly predicted mineralisation (*P(x)*<3%) on 2 of the 5 assessed traverses (Figure 1), while Site 2 was successfully predicted with *P(x)*<0.5%). The lower the probability the more successfully the mineralisation is predicted (Stanley, 2003). The results indicate that the BL is providing some beneficial results, but is not consistently identifying the mineralisation under cover.

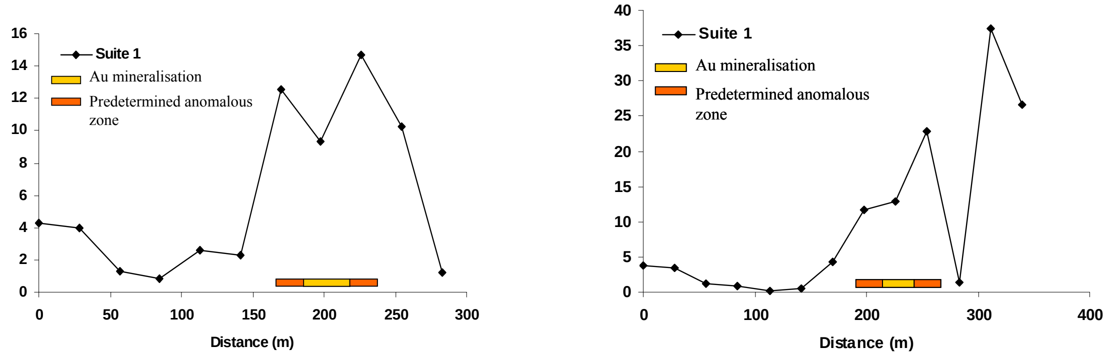

Figure 1. Two successfully predicted traverses from Site 1 using BL.

The BL geochemical suites respond similarly over the traverses, which is expected since certain elements are used in all derived groupings, however suite 1 provided the best results in the form of higher contrast anomalies and fewer false positives. The BL also possibly indicates fault zones at Site 2, as well as zones of mineral depletion that can be characteristically adjacent to those of enrichment (Figure 2).

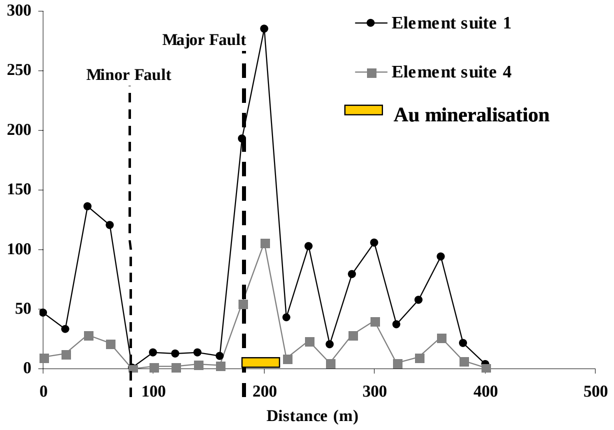

Figure 2. Geochemical suites developed for Site 2 with underlying mineralised zone and faults.

There is a potential presence of a Cu-Au ore body in the vicinity of site 3 (J. Dugdale, SGM, pers. comm., 2003). When applied to the site 3 soils, the geochemical suites provide similar results. There is, however, a distinctive zone at the end of the third traverse (samples 23-32) of very different chemistry (Figure 3). Unfortunately, this region has not yet been drilled to assess the underlying geology and, in turn, the effectiveness of the element groups. Single element data, particularly Cu, from the third traverse also indicates an anomaly in this region from all analytical techniques (Figure 4). Interestingly, soil pH values for the third traverse of site 3 were lower than the other locations, perhaps indicating that soil pH may provide an indication of underlying geology, a change in regolith, or influence factors that may affect the proficiency of the BL. Future research on the influence of soil properties and anomaly expression will be required to better understand the BL and other techniques in this region.

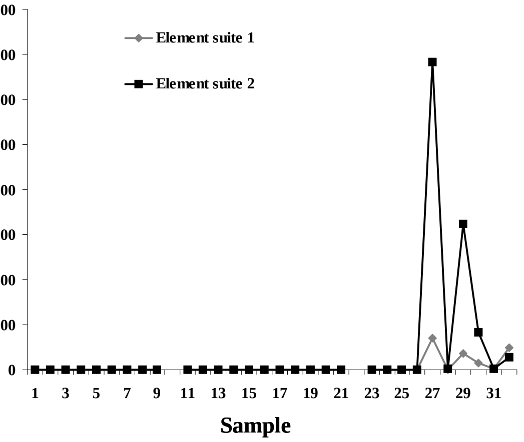

Figure 3. Site 3 BL element suite responses.

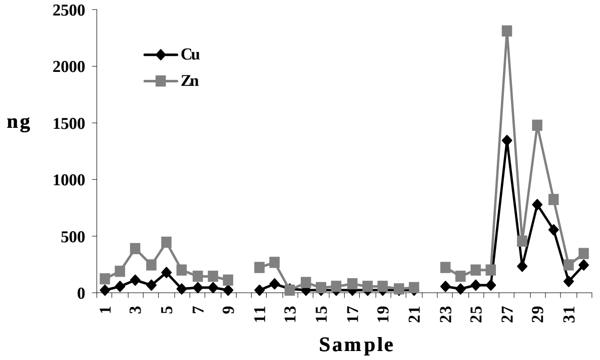

Figure 4. Site 3 BL responses for Cu and Zn.

Further investigation of the soils was undertaken using the previously mentioned leaches (T, HP, H_2O and HA) to compare the results of these chemical extractions with those of the bacterial treatment. Comparing the responses for elements based on the various leach treatments by correlation and principle component statistical analysis indicated that the BL was most similar to the HA leach. The HA specifically targets the amorphous Mn oxide phases and implies that the BL may be slightly selective towards the same phases. The H_2O and HP leach were also very similar in their responses for these soils.

The results of BL experiments have allowed for identification of possible areas of buried mineralisations that were not apparent through other chemical extractions. However, the success is inconsistent. The BL significantly provided different geochemical information than the other techniques, although HA was similar. In traverses where single element anomalies occurred the other techniques would have also worked. Whether BL has superior qualities as an individual ‘stand alone’ technique is yet to be determined. Bacterial leaching, nevertheless, is likely to be a beneficial tool in future geochemical exploration in areas of regolith cover.

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Acknowledgements: The support of MPI mines, Stawell Gold Mine, CRC LEME and the Departments of Applied Chemistry and Applied Geology at Curtin University is appreciated.

MINERAL MAPPING AND SPECTRAL LOGGING OF THE GAWLER CRATON

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Between 29 September 2003 and 25 January 2004 a major campaign of spectral core logging was undertaken at PIRSA's Glenside Core Storage Facility using the prototype *HyLogger* core scanner developed by CSIRO's Mineral Mapping Technologies Group. The *Hylogger* offers a cost effective, objective means of capturing detailed mineralogical data while providing a high-resolution digital image of the drill core. The instrument is built around a visible to short wave infrared spectrometer coupled with a quality linescan camera. A sophisticated computer-controlled X-Y table is used to manage the rate of core feed and provide the precision needed to integrate the data sets. Development of the current operational system was achieved with company sponsorship through AMIRA International (Project P685), a project in which PIRSA was an active participant.

Of the 357 holes scanned with the HyLogger in the recent campaign, 201 were from the Gawler Craton. 155 were from the Central Gawler Gold Province. Those that engaged regolith issues - 106 of which 58 where chip trays. All together some 60 Gigabytes of data were acquired over the Gawler Craton. Products generated include high resolution images of the core trays and automated mineralogical logs plotted by depth. With ancillary information provided, assay data, lithological logs and petrophysical logs can be integrated with the display.

A number of Central Gawler Gold projects were identified for this analysis including: Barns Prospect, Tunkillia, Lake Harris Greenstone Belt and the Tarcoola Gold Mine. By way of demonstration this presentation will focus on the Barns Prospect. In this example a strong correlation has been found between the chemistry of the white mica assemblage and the distribution of Au. In addition a comparison can be made between diamond core and drill cuttings which show that the diagnostic alteration assemblage can be traced into the lower saprolite where there are also elevated levels of Au mineralisation.

EXPERIMENTAL METHODS IN GEOCHEMISTRY AND MOBILITY OF METALS IN THE REGOLITH

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INTRODUCTION

The mobility of metals in the regolith controls their dispersion, or concentration, and the formation of geochemical anomalies, especially in areas covered by transported regolith. Understanding mobility requires knowledge of the geochemistry of the metals and the leaching, transport and trapping processes. We need a much deeper understanding of all parts in order to develop successful exploration methods that allow us to decipher anomaly patterns, and to distinguish anomalies indicating ore bodies and those that do not. Metal mobility is important more generally to geologists and geochemists, both exploration and otherwise, because it is a critical link in the formation of laterite and hydrothermal ore deposits. In addition, understanding the mobilisation and trapping of metals is important to many aspects of mineral processing, *e.g.,* hydrometallurgy, and environmental science, *e.g.,* potential contamination of regolith and waterways and impacts on ecology. This means that exploration geochemists, economic geologists and environmental scientists need to understand how metals exist in the regolith, different lithologies and water, how they are mobilized or trapped, how far they can be transported and whether they are bioavailable and act as micronutrients or toxins to plant and animal life.

Although the mobility of metals in the regolith depends on the transporting process(es), *e.g.,* groundwater advection or convection, diffusion, gaseous, sediment or airborne physical transport, micro- and/or macro-biotic, it depends substantially on the geochemistry of the individual and collective metals, *i.e.,* how do they exist in groundwater and regolith materials and what are the controlling geochemical reactions between water and minerals, organic matter and biota. It is clear that we need to know the aqueous speciation of metals, the solubilities of metal-bearing minerals and sorption of metals to mineral surfaces, in order to understand and predict how metals behave during weathering and diagenetic processes in the Earth's crust.

How do we gain the necessary knowledge and understanding of metal geochemistry and mobility? Detailed field studies have been done and are currently underway, especially in LEME, to research how metals exist in regolith material, groundwater and plants – largely made possible by advances in the microanalytical technology, *e.g.,* Laser Ablation Inductively Coupled Plasma Mass spectrometry (LA-ICP-MS). This is important in understanding which minerals host which metals and what the best sampling media are for geochemical exploration. Although part of the puzzle, field studies and sophisticated analytical techniques are insufficient to understand how metals have dispersed and concentrated in the regolith, and in turn how geochemical anomalies have formed. Experimental studies provide another approach that leads to understanding how elements are transported. In this presentation, I highlight several examples of current experimental studies in LEME that are focused on understanding the geochemistry of metals in waters and the reactions between dissolved metals and regolith materials.

GEOCHEMISTRY AND MOBILITY OF GOLD

Gold geochemistry is complicated because it has three valence states in natural systems, *e.g.,* Au(0) in native gold, electrum and colloids, Au(I) in waters under reduced conditions and Au(III) in waters under very oxidized (atmospheric), acidic conditions. Dissolved gold can exist as ions (Au^+, Au^{3+}) or as many possible complexes with, for example, chloride, iodide, sulphide, thiosulphate, cyanide, ammine and other organic ligands and chelates. The nature and properties of colloids and other particles and the dissolved gold complexes affect how much gold can be leached, transported and precipitated. These depend directly or indirectly on several geochemical variables, *i.e.,* temperature, pressure, pH, redox (*e.g.,* Eh, log $f_{O2\ (g,\ aq)}$), concentrations of elements, ions or compounds that complex with gold (*e.g.,* Cl^-, I^-, HS^-, SO_4^{2+}, and more), and partial pressures of gases (*e.g.,* O_2, CO_2, H_2S, S_2, NH_3). In addition to the physical and chemical variables, biota can affect gold geochemistry and mobility. At the ANU, there are several current experimental and field projects focused on some of the important aspects.

EFFECT OF BIOTA

Ph.D. student, Frank Reith, is studying how microbiota (bacteria and fungi) affect gold mobility in the regolith. He has two main field sites in areas of gold mineralisation, one at Tomakin, NSW and the other at Palmer River, Qld, chosen to compare areas with different climates. His results show a strong correlation between gold concentrations and populations of *Bacillus cereus* in both areas. Individual microcosm experiments with natural samples have either no added material, added gold (dissolved or solid) and/or added organics (energy source for bacteria). The results are exciting and show that gold is mobilised after several to tens of days, in contrast to samples that were sterilised and show no gold mobilisation. In his most recent experiments, Frank has monitored not only gold mobilisation, but also changes in microbial ecology, probably the first ever experiments of this kind. Preliminary interpretation of the results suggests the microbial ecology does change during the course of the experiments; however, more interpretation is necessary to confirm the nature of the changes. His current, equally exciting research is focussed on molecular microbiology studies to identify particular DNA sequences of the microorganisms from field and experimental samples. Frank Reith's research has already enhanced our understanding of how microbiota affect gold mobility in the regolith and there is potential to develop exploration methods using bioindicators.

GEOCHEMISTRY OF GOLD IN SALINE TO HYPERSALINE BRINES

The geochemistry of dissolved gold is being studied by several experimental methods, mainly by Ph.D. student Alistair Usher. UltraViolet-Visible (UV-Vis) spectrophotometry is being used to identify oxidised Au(III) chloride complexes in NaCl and LiCl solutions. These complexes may be important in transporting gold in acidic, very oxidised (atmospheric conditions), but the experiments also provide a window into the more complicated Au(I) complexes, more likely to be the transporting gold complexes under many regolith conditions. Other experimental methods are currently being developed, *i.e.,* mineral solubility (native gold) under well controlled atmosphere (redox) and pH conditions with variable chloride, thiosulphate and iodide salts used to understand the importance of all three types of complexes. Spectro-electrochemical methods are also being investigated. Another part of Alistair Usher's Ph.D. research is focussed on alternative and improved methods of analysing low concentrations (ppt) of dissolved gold in groundwater.

GOLD MOBILITY

We are developing experimental methods to study how gold moves through regolith material. Frank Reith's research includes column experiments under abiotic and biotic conditions, and the results already show that gold can be mobilised in the presence of microbiota. These experiments are run under similar conditions to his microcosm experiments but with solutions flowing through columns, a more dynamic system that approaches field conditions. Although in preliminary stages, we intend to use column, and perhaps tank experiments for 2-dimensional flow, to study how gold and other elements are leached, transported and trapped in synthetic and natural regolith. The results will be used to test reactive transport models, also being developed at the ANU. As we get to the stage where model and experimental results agree, the models can then be applied more confidently to predicting gold mobility and anomaly formation in the regolith.

SORPTION OF METALS ONTO IRON OXYHYDROXIDES

The concentrations of metals in solution can be controlled by sorption onto mineral and/or organic matter surfaces, but there is much more research necessary to understand the importance over the wide ranges of conditions found in the regolith. We have completed an experimental study of the impact that salinity has on the sorption of copper on goethite, with some surprising results.

Ph.D. student Chris Gunton is studying the effect of salinity on the sorption of oxidised copper (CuII) on goethite. The experimental conditions cover a range of pH (~2-7) and NaCl concentration (~0 to 5 m, or 0 to >30 wt%). The results show the well known behaviour with pH, but the effect of increasing NaCl concentration, a controversial topic in the literature, has important ramifications for metal transport in the regolith, particularly the in prospective saline and arid Australian environments. With increasing NaCl concentration, the amount of copper sorbed onto goethite increase by a factor of two or more over the pH range typically encountered in the regolith. Preliminary quantitative interpretation of the data indicate that one or more copper chloride complexes form on the goethite surface and they are more stable than those in aqueous solutions. The increased sorption suggests that copper haloes are likely to be intense and small during weathering of sulphide ore bodies in saline to hypersaline environments.

We are extending these experiments to study zinc sorption on goethite under similar ranges of conditions, although the pH range important for the sorption of zinc is higher than for copper. We may also use different morphologies and compositions of goethite, *e.g.,* Al-bearing goethite found commonly in the regolith. Depending on time and resources, we will also extend our studies to gold; however, the concentrations of gold that can be obtained are low and may prevent us from obtaining reliable results.

GROUNDWATER FLOW AND ELEMENT DISPERSION

The geochemistry of metals and other elements is critical in understanding the dispersion and anomaly formation in groundwater systems, but the other necessary part is knowing the groundwater flow, *i.e.,* pathways, volumes and velocities.

Although not part of LEME, recent experimental studies at Monash University by Michelle Carey (Ph.D. supervised by Dr. McPhail) demonstrate how hypersaline plumes form under playa lakes and can affect the dispersion of gold and other elements in groundwater systems. This was part of her Ph.D. research on the use of hydrogeochemistry as an exploration tool. She studied the St. Ives gold fields near Kambalda, WA, installing a well field of approximately 100 km^2, sampling and analysing the saline to hypersaline groundwater, numerically modelling the geochemistry of gold under hypersaline conditions and experimentally dertermining and numerically modelling the density-driven convective flow around the playa lake and the gold mineralisation.

The experiments were conducted in a tank 105 cm long, 60 cm high and 5 cm thick, filled with 100 µm diameter glass beads and constant head was imposed on each end of the tank, one end to simulate regional flow of saline brine and the other end to result in the hypersaline, and higher density, brine convecting. The experimental conditions are scaled to represent the conditions in St. Ives goldfields bordering Lake Lefroy. The results demonstrated the shape and extent of the hypersaline plume, as well as the timeframe of the plume development. Numerical models were used to predict the density-driven convection and then the results were compared with the experimental data. Once good agreement was obtained, the numerical models were applied to the field area. In combination with the detailed geochemistry, measured and modelled, we now understand much better the dispersion of gold in groundwater in the St. Ives area.

SUMMARY AND FUTURE STUDIES

A combination of experimental techniques is being used to understand the geochemistry of gold, copper, zinc and other elements, as well as their mobility and dispersion patterns in the regolith. Although there are already some direct links to field studies, *i.e.,* Frank Reith's research on microbes and gold, we need to take the results from experimental studies to help understand the dispersion patterns observed in the field. For gold mineralisation, the likely field areas we will focus on are in the Yilgarn (*e.g.,* Lancefield, Mt. Gibson, St. Ives, Whirling Dervish), Gawler Craton (*e.g.,* Tunkillia), Lachlan Fold Belt and the Tanami. In other studies we are measuring the solubilities of low-temperature zinc minerals (*i.e.,* hemimorphite, a hydrated zinc silicate) and researching the dispersion of zinc around zinc oxide deposits in the northern Flinders Ranges, SA. In all cases we strive to choose field areas to combine forces with other LEME projects and scientists working on different aspects of regolith science, especially so we can build our understanding in the context of landscape and regolith evolution. In addition to studies focussed on aspects related to mineral exploration, we are also studying with experiments the impacts of biota (microbial, fungal, tree and their roots) and organic acids on weathering processes in the regolith (Drs. Sue Welch, John Field and others), mobility of salt in regolith (Drs. Andrew Fitzpatrick, Dirk Kirste and others) and the formation and degradation of acid sulphate systems in inland areas (Drs. Sue Welch, Sara Beavis, Steve Rogers, Rob Fitzpatrick, and others). What we learn from mineral exploration studies will help in environmental and salinity studies, and *vice versa*.

GROUNDWATER ISOTOPIC GEOCHEMISTRY

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Groundwater chemical and isotopic composition: a mineral exploration tool for areas of regolith cover – Lessons from the Curnamona Province

EXTENDED ABSTRACT

The Curnamona Province is endowed with the supergiant Pb-Zn-Ag Broken Hill orebody and numerous minor mineral deposits (Pb-Zn-Ag, Cu-Au, Sn, W, U, etc.). These occur mostly within the limited outcrop of the Proterozoic Willyama Supergroup. Yet, the vast majority of this Province is concealed by transported regolith, hampering the success of exploration based on conventional strategies.

Groundwater is a geochemical sampling medium that moves through the subsurface, is easily collected and can be analysed with great accuracy and sensitivity. It may have flowed near mineralisation and retained a chemical ‘memory’ or fingerprint of such an encounter. Can one detect such fingerprint in groundwater collected from existing pastoral and exploration bores? Can it be used to target exploratory drilling in areas of transported cover? These are some of the questions our study in the Curnamona Province attempts to answer.

We have collected about 300 groundwater samples to test whether this medium could be helpful in the search for hidden mineral deposits in the Broken Hill region. We determined the major, minor and trace element concentrations of the groundwaters (by ion chromatography, inductively coupled plasma-atomic emission and inductively coupled plasma-mass spectrometry, ion specific electrode, photospectrometry and titration) as well as the isotope compositions of H, O (of H_2O and SO_4^{2-}), C, Cl^-, S, Sr and Pb (by mass spectrometry after various preparation methods). We also analysed several rain and surface water samples to better constrain the starting point of the evolution of the groundwater.

The groundwaters have undergone a range of processes; their present-day composition is the end product of a complex and, in many instances, long evolution. Using hydrogeochemical principles and modelling, we have been able to identify and, in some cases, quantify these processes. Thus, we have been able to recognise that a number of the groundwaters have a sulfur excess (S_{XS}), ie an amount of S that can be ascribed neither to evaporation nor to mixing. Many of these samples have a low $\delta^{34}S$ composition, which possibly results from oxidation of sulfides with a Broken Hill type $\delta^{34}S$ signature (average ~0 ‰ V-CDT). Further, the $\delta^{18}O$ composition of the SO_4^{2-} helps discriminate whether sulfide oxidation occurred near the groundwater table or in deeper settings. Sr isotopes identify the broad types of bedrock that the groundwater has been interacting with, from less radiogenic Adelaidean rocks (and minerals) in the west to highly radiogenic Willyama Supergroup in the east (groundwater $^{87}Sr/^{86}Sr$ ratio up to 0.737). The groundwaters have $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios comparable to, or intermediate between, various mineralisation types recognised in the area (Broken Hill, Rupee, Thackaringa, etc. types).

The oxidation of any sulfide mineralisation will result in increased concentrations of Cu, Pb and Zn (and other trace elements) in solution in the groundwater. To predict the behaviour of these trace metals during transport along a flow path, we have generated a 1-D reactive transport model. The basic initial assumptions in the model are:

- the transporting fluid is a typical groundwater equilibrated with galena, chalcopyrite and sphalerite, with no secondary mineral precipitation allowing for a maximum metal content in the groundwater,
- the flow path has ion exchange sites and adsorption sites, which are initially equilibrated with the unreacted groundwater, and
- flow and transport occur at 1 m/yr for 4,000 years.

The results show that elevated Cu and Zn concentrations extend to ~150 m down the flowpath, while Pb values are attenuated already within ~50 m of the deposit. Perhaps the most important outcome of this exercise is to illustrate that trace metals do not travel far in such groundwater systems and that Zn and Cu have a higher mobility than Pb. We cannot expect high metal contents at any great distance from the deposits, but where we have higher amounts of specific metals it may indicate proximity to mineralisation, depending on the aquifer mineralogy and the hydrogeology. However, other groundwater constituents (such as SO_4^{2-}) may present a much larger footprint of a buried deposit.

Of the 23 real groundwater samples taken in the vicinity of known mineralisation in the Curnamona Province, 21 yield positive indicators, that is:

- positive S_{XS},
- low $\delta^{34}S$,
- $^{87}Sr/^{86}Sr$ signature consistent with bedrock type,
- Pb isotope fingerprinting consistent with mineralisation type, and
- elevated Zn and/or Cu concentrations.

This study also highlights several new locations under sedimentary cover where our vectors suggest interaction with mineralisation. We conclude that hydrogeochemistry is a very useful tool in the search for mineralisation under cover, particularly at the regional scale for area selection or target ranking, and should be part of any multi-disciplinary mineral exploration campaign.

Acknowledgments
This study was funded by an Australian Government Cooperative Research Centre grant to CRC LEME. The New South Wales Department of Minerals Resources is warmly thanked for its financial and moral support to this project.

ROLE OF BIOTA IN MINERAL TRANSFORMATIONS AND TRANSPORT

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Microorganisms are likely to have played a significant role in the formation of the Australian regolith and in the transport and transformation of minerals within regolith materials. Single celled bacteria were the only forms of life on the planet for approximately 50% of earths history, first appearing about 4000 x 10^6 years before present (BP). More complex eukaryotic organisms such as fungi first appeared around 2000 x 10^6 years BP. Fossil records suggest that these early single celled organisms had similar cell structure to modern bacteria. In contemporary regolith environments about 5000 microbial species have been isolated and identified, with one gram of surface regolith material containing between 10^6 - 10^9 cells. However, estimates of the total number of microorganisms in the regolith range from 100,000 to 1 x10^6 species, suggesting up to 95% of regolith microorganisms are unknown to science.

There is much evidence to suggest a role for microbial processes in shaping contemporary regolith environments. For instance, the weathering of rocks as a result of microbial activity is thought to be the dominant form of chemical rock weathering in both geological and contemporary environments. Production of organic acids by bacteria (formic, acetic, lactic, pyruvic, succinic, 2-ketogluconic) and fungi (nitric, sulfuric, citric, oxalic, gluconic), is a biological mechanism these organisms have evolved in order to solubilise and obtain trace elements such as P and S from minerals.

Geochemical transformations resulting from microbial activity in the regolith are also well established. One of the most well known is the biological oxidation of pyritic and sulfide minerals, carried out by a group of bacteria known as chemolithoautotrophes. These organisms are highly adapted to low pH environments, and utilise Fe or S as electron donors in their respiratory chain, catalysing Fe and S oxidation through the production of iron or sulfur oxidase enzymes, bacteria are therefore the key biochemical catalysts of geochemical transformations in these environments. Bacteria responsible for the oxidation of sulfide minerals including As, Cu, Co, Fe, Ni, Mo, Pb, Zn have been isolated from sulfidic environments and historically classified as members of the Thiobacillus genus notably (*Thiobacillus* sp., *Acidothibacillus* sp. *Sulfobacillus thermosulfidooxidans* and *Acidanus brierleyi*). (Mukhopadhyaya *et al*., 2000).

Whilst biological processes responsible for mineral weathering and geochemical transformations have been identified we still lack a sound mechanistic understanding of the principle biological processes underpinning biogeochemical dispersion, mobilization, transport, and mineralisation of minerals & trace elements in the Australian regolith. A more important question is what is the relative role of biological and non-biological (abiotic) processes driving mineral transport, transformation and accumulation in the regolith.

BIOLOGICAL ACTIVITY AND BIOGEOCHEMICAL TRANSFORMATIONS

Much of the current approach to the study of microbial transformations of minerals has focussed on the identification of organisms, species diversity and population dynamics, (Baker and Banfield, 2003) and their relationship to rates of mineral transformation. In fact environmental microbiology research concerning defining the role of biota in driving biogeochemical transformations in general has focussed on establishing the relationship between bacterial diversity and rates of biogeochemical processes (Rogers and Colloff, 1999). In general there is a paucity of evidence from available studies linking changes in species diversity or shifts in microbial populations to changes in biogeochemical functionality. Traditional microbiological techniques applied to the study of regolith microbial populations fail to identify more than 5% of the species present. They also fail to determine the 'functional attributes' of microbial populations responsible for geochemical transformations.

FUNCTIONAL MOLECULAR TOOLS

An alternative approach to determining the mechanistic relationship between microbial activity and biogeochemical transformations is to target the 'molecular genetic' attributes of microbial populations as opposed to their phylogenic attributes (Rogers et al. 2002). We have developed a new generation of molecular biology techniques to study the role of biota in mineral biogeochemical transformations, based on the direct extraction of nucleic acids (DNA and RNA) from regolith samples that remove the need to isolate/culture and identify individual organisms. They allow direct comparison of biogeochemical reaction kinetics, gene expression and biotic diversity of organisms, all in the same sample, and represent a major advance over traditional microbiology methods.

Examples of the application of molecular tools to the study of Regolith biogeochemical mineral transformations

i. Identification of chemolithotropic microbial functional genes involved in Sulfide mineral oxidation

The suite of genes encoding for sulphide mineral oxidation in bacteria has recently been identified. The soxB gene encodes for a diheme cytochrome c enzyme and has been shown to be essential for chemolithotrophic sulfide mineral oxidation. This functional gene has also been identified in representatives of all known groups of chemolithotrophic sulfur oxidising bacteria, making it an ideal candidate for our functional molecular approach. Polymerase chain reaction (PCR) techniques have beed designed that amplify a 1000 base pair region of the soxB gene sequence (Petri et al. 2001), allowing us to apply our existing functional molecular techniques to the study of sulfur oxidising chemolithotrophic bacteria activity and presence in sulfidic sediments.

In brief, DNA and RNA were extracted from sulfidic sediments using established techniques. Oligonucleotide primers were designed to amplify through PCR *sox*B gene sequences in sample DNA extracts. The presence of functional genes indicates the presence of the biological potential for S mineral oxidation reactions. Figure 1 summarises the detection of the *sox*B gene in sulfidic sediments actively oxidising in the River Murray Floodplain.

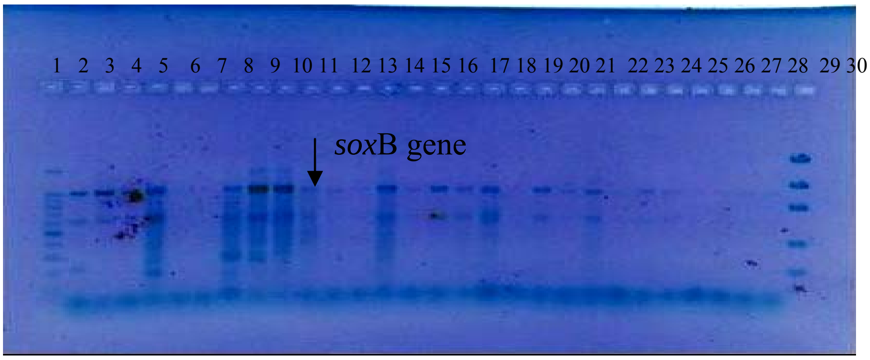

Figure 1 *soxB* functional gene DNA detected in extracts from sulfidic sediments . 1000 bp PCR product visualised on 2% agarose gel. **Lane 1** 100bp DNA ladder; **Lane 2-4** *A.caldus* soxB positive control 1000bp product; **Lanes 5-29** presence of *sox*B gene in sulfidic sediments; **Lane 30** DNA quantification marker

ii. Microbial ecology/population diversity of Bacteria Associated with Gold solubilisation and precipitation

A current LEME PhD project has identified the role of bacteria in gold precipitation and solubilisation. In order to identify microorganisms present on gold flakes, numbers of species and if the organisms are living, the molecular technique 16S rRNA Density Gradient Gel Electrophoresis (DGGE) analysis has been used (Muyzer, 1999). In brief a region of the bacterial 16S gene can be amplified in DNA extracts. PCR products are separated on a DGGE electrophoresis gel, that separates double stranded DNA. Each different bacterial species has a unique 16S gene sequence, therefore each band on the gel represents an individual bacterial species. Individual sequences (bands) from the DGGE gel can be further analysed by sequence analysis in order to identify the species present. This technique allows the analysis of all organisms present, as no culturing and isolation of cells is required. Figure 2 shows a representative DGGE acrylamide gel showing bacterial species 16S gene diversity in DNA extracted from a single gold flake collected from the Tomakin Park gold mine. The successful extraction and amplification of DNA from single gold flakes, confirms that the microbial biofilm thought to be responsible for solubilisation and precipitation reactions is 'alive'.

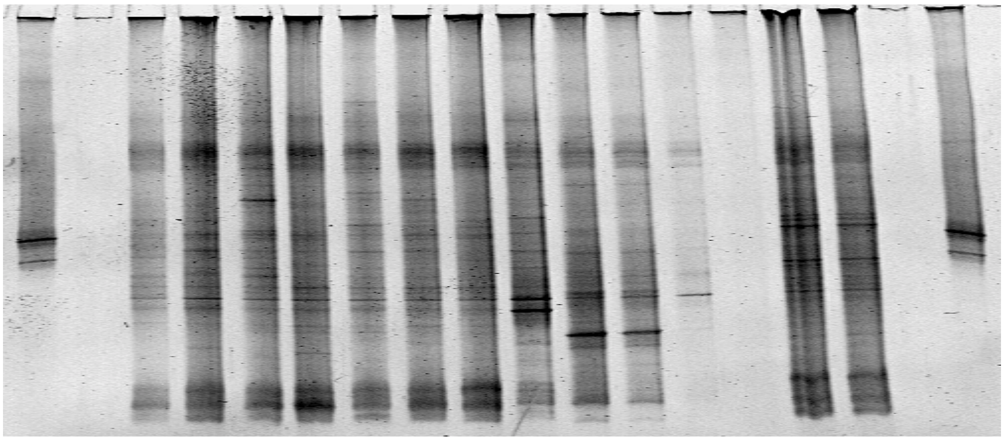

Figure 2. 16S rRNA Density Gradient Gel Electrophoresis profiles of bacterial populations on gold flakes collected at the Tomakin park gold mine. 16S V3 region amplified in soil DNA extracts with degenerate oligonucleotide PCR primers 27FGC and 534R. PCR product visualised on a 35-60% urea/formamide acrylamide gel (8%), 120V 20hrs.

Both these CRC LEME sponsored studies have demonstrated the application of new molecular techniques to the study of biological mineral transformations in the regolith. The core aim of LEME activities in this area is the identification of mechanisms, processes and physico-chemical conditions in contemporary environments where biogenic weathering, biogeochemical transformations and dispersion dominate. Allowing the development of predictive models to identify where in the regolith biological mineral transformation and transport processes have occurred in the geological past.

Acknowledgements

Frank Reith CRC LEME PhD student for the gold flake DGGE figure, Naomi Grey for technical assistance with the sulfidic sediment *sox*B work

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THE TUNKILLIA EXPERIENCE

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The Central Gawler Gold Province is poorly known and poorly explored principally because of the extensive development of regolith.

CRC LEME is collaborating with Geoscience Australia and the Minerals Resources Group in the South Australian Department of Primary Industry and Resources to reduce the risk attached to exploration through cover in this terrain.

We have integrated the interpretation of geological, geophysical and calcrete geochemical data at known prospects to develop a strategy for generating ranked drilling targets.

The strategy which has been developed is illustrated using data drawn from the Tunkillia Prospect.

SUB-AUDIO MAGNETIC (SAM) GEOPHYSICAL TECHNOLOGY FOR MINERAL EXPLORATION AND SUBSURFACE REGOLITH MAPPING

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1. SAM Methodology

SAM is an active source geophysical method that channels current into conductive sub-surface features, generating an electromagnetic field that is detected at the surface. The transmitter is a time variant electrical source using a frequency of 1 to 20 Hz, injecting 2 to 10 Amps of current into the ground over a survey area. The electromagnetic field generated at right angles to the flow of electrons is usually less than 5 nT, and is measured at surface by a very sensitive magnetometer that takes more than 200 readings per second. The part of the time varying signal relating to conductivity in the ground is called the total field magnetometric resistivity (TFMMR). Another part of the SAM signal relates to induced polarization (IP) effects, and is called total field magnetometric induced polarization (TFMMIP). Useful TFMMIP data cannot always be extracted from SAM field data, but efforts are underway to improve SAM TFMMIP data acquisition and processing. Total field magnetic data are also recorded during SAM surveying.

SAM surveys are usually carried out within a 1 by 1 km area, and transmitter current electrodes are placed along geological strike, at least 500 m from the edges of the survey area. The electrode wires and transmitter system are also set at 500 m or more from the edge of the survey area (Figure 1). Survey transect lines are oriented perpendicular to the strike of the transmitter electrodes, and transect line spacing can vary from 100 m to less than 10 m, depending on survey requirements. After data stacking and noise editing, along line sample readings become spaced at about 0.5 m to 1 m, depending on the walking speed of the field crew.

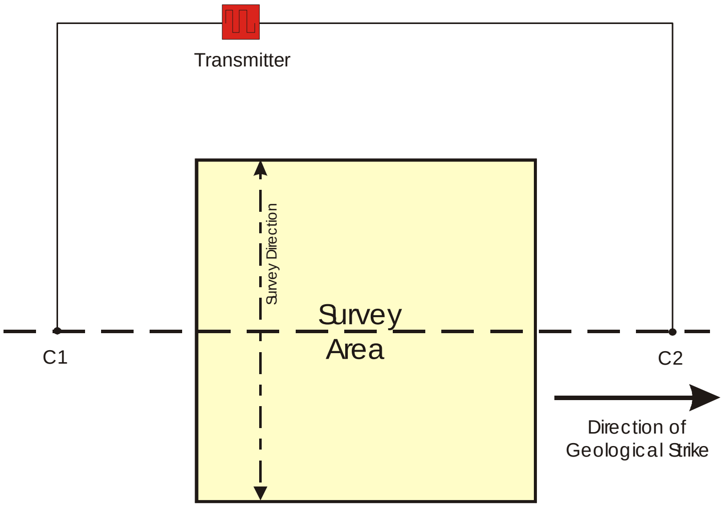

Figure 1. Typical ground layout for a SAM survey area of 1 by 1 km.

The forward calculated fields from the transmitter wire and electrodes are removed from the data, and the residual TFMMR, TMI, and TFMMIP data are gridded and imaged to show patterns relating to subsurface geology, regolith, and mineralisation. Depth information cannot be directly estimated from the TFMMR data, but the data can be treated like a monopole potential field and modeled to predict subsurface geometry of conductive sources.

2. SAM Data

The TFMMR response is provided in units of pT/A (pico-Teslas per Amp), and the subsurface pattern is very similar to apparent conductivity that can be obtained from gradient array IP surveys. The advantage that SAM has over gradient array IP surveying is that stations are collected at intervals of 1m or less, while operators walk over the ground carrying a magnetometer and DGPS. Gradient array IP stations require electrical contact with the ground, dipole receivers, and heavier equipment, which all limit station spacings to usually greater than 20 m. Therefore, SAM surveys are more time efficient, collect data at much higher resolution, are not greatly effected by bad readings, and can be run over areas where it is difficult to apply electrodes. TMI data is also provided. Furthermore, SAM TFMMR measures the relative changes in current density as a potential field, and therefore it can be used in highly conductive areas such as salt lakes, where gradient array IP will not work. A major advantage that gradient array IP surveying has over SAM is that reliable IP data can be collected, whereas the TFMMIP data generated from SAM surveying is not always reliable, and is measuring a weaker signal.

The ability of SAM to detect shallow, subsurface conductivity at such high resolution means that this technology can be used to fill the gap in survey resolution between conventional surface and airborne geophysical methods and very localised downhole and in-mine geophysical methods.

3. SAM and the Regolith

The SAM TFMMR response detects variations in current channeling in the strike direction of the transmitter electrodes, and can penetrate down to 200 m in some areas. Figure 2 shows an idealised cross section of the regolith over a gold mineralized shear zone and a steeply dipping black shale unit. Electrons flowing out of the page become channeled into more conductive regions in the subsurface, such as paleochannels, zones of deeper weathering, conductive bedrock lithologies, and conductive minerals. The amplitude of the TFMMR anomalies, and their shapes reflect information about the geometry of the subsurface conductors. Highly chargeable features, such as carbonaceous shales and sulphide deposits, may also produce TFMMIP anomalies.

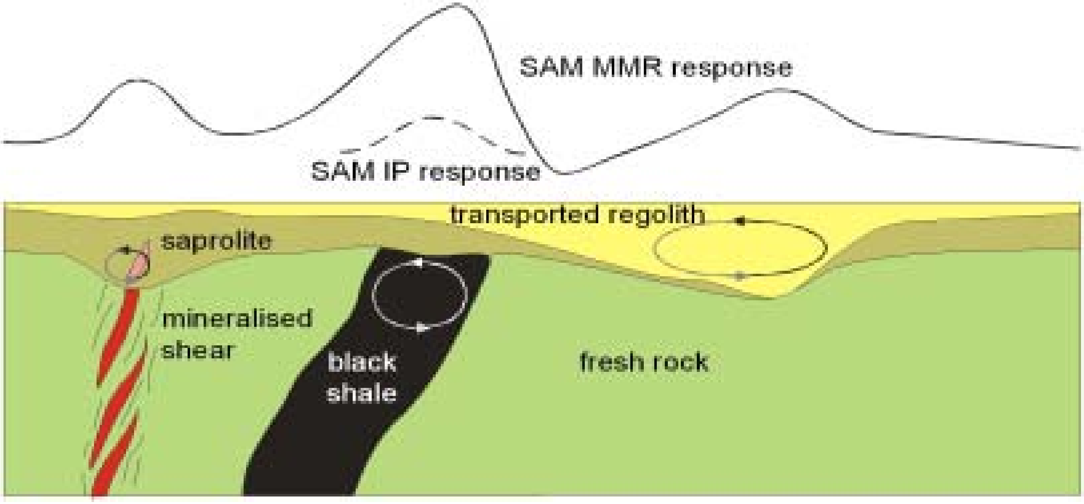

Figure 2. Schematic profile of simplified regolith and the shape of SAM anomalies expected to be caused by current channeling in conductive subsurface features.

4. SAM Case Studies

Several case studies of recent SAM surveys will be shown during the oral presentation. The SAM data in all cases are compared to other geophysical data, such as: gradient array IP, transient electromagnetics, gravity, magnetics, and downhole logging. Geology and drillhole data are also used to validate the sources of the SAM responses.

Results are shown from a number of SAM surveys collected over the same area, where different transmitter and survey line geometries produced radically different results. This includes the use of downhole transmitter electrodes to get TFMMIP images of sulphide bearing gold ore at greater than 100 m depth. Examples of geophysical interpretations using SAM and other complementary data sets will be presented to show how such high-resolution data sets can be used to greatly enhance the understanding of the subsurface geology and regolith at prospect scale. Below is a list of case studies to be presented:

4.1 Woodie Woodie Manganese Mine: The SAM TFMMR shows the location of conductive manganese ore where it is shallower than 50 m. When pods of manganese ore sit below 50 m, they are not detected in the TFMMR data, and this is likely due to current channeling being focused in the regolith above the ore bodies, and weak signal from the ore bodies being masked by the shallower regolith features.

4.2 Songvang Gold Deposit: The SAM TFMMR has identified a gold mineralised shear zone, as well as zones of deep weathering over ultramafic rocks. The TFMMR response is very similar to apparent conductivity obtained from gradient array IP surveying, but the SAM data has much greater resolution. Rotation of the SAM survey grid by 90 degrees over the same area shows radically different results, where only conductive features running sub-parallel to the direction of the transmitter electrodes become detectable, due to the preferred orientation of current channeling. Downhole transmitter electrodes were placed into the ore zone, and the TFMMIP response was recorded at the surface using 25 m line spacing. The overall outline of the ore zone is similar between the gradient array IP chargeability and the SAM TFMMIP, but there is much more of detail in the TFMMIP data. Localised TFMMIP highs were drilled and shown to correlate to increased pyrite alteration and high gold grades. Therefore, the TFMMIP and TFMMR at Songvang were useful for planning resource definition drilling (Figure 3).

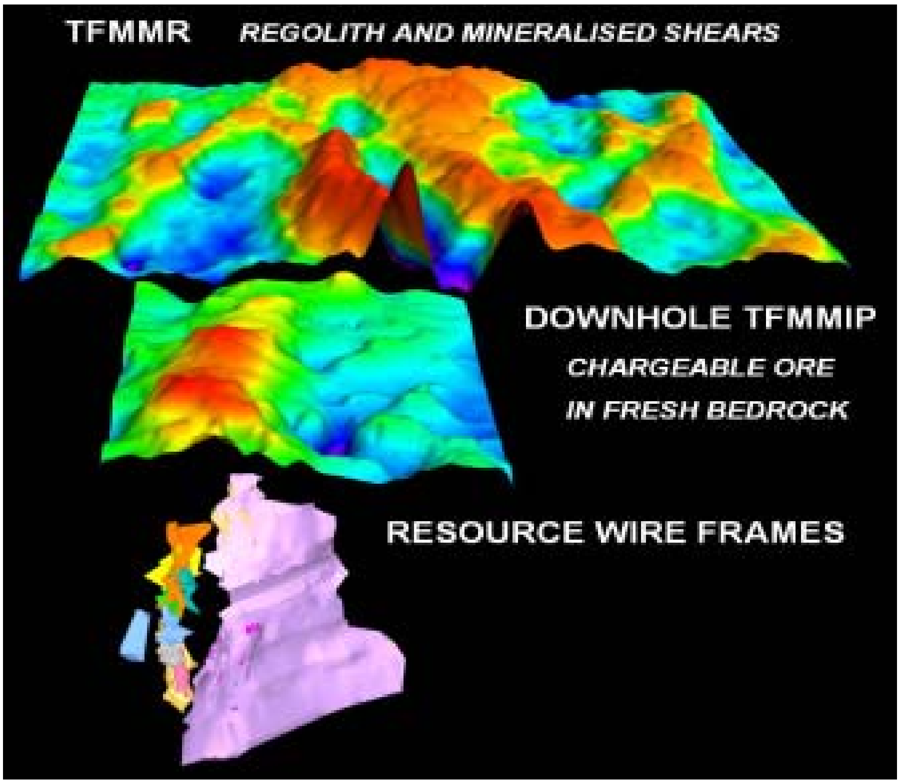

Figure 3. Three dimensional perspective of SAM responses over the Songvang gold deposit near Agnew, WA.

4.3 St. Ives Gold Mine: This is an example of how SAM can work in salt lake environments.

4.4 Indee Gold Prospect: The examples show similarities between gradient array IP and SAM results, and integrated geophysical interpretation for gold deposits in highly weathered siliciclastic sediments.

4.5 **Bogada Bore Gold Prospect:** This is an example of an integrated study using several high-resolution geophysical data sets, where differential weathering between rock types allows for geophysical detection of the regolith to help interpret bedrock geology and structures in covered and deeply weathered terrains.

EM TORCH

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The EM Torch is an electromagnetic (EM) based geophysical tool designed for finding small pods of nickel within a 20 metre search radius. This tool is the idea of Peter Williams, a geophysicist with Independence Group (IGO), who envisaged a rapidly deployable EM tool that could locate many of the small pods of nickel ore in the Longshaft Mine missed by previous mining. As the tunnels and development drives are already in place and paid for the small incremental cost of mining out small pods near such infrastructure makes the search for such pods very profitable. The trick is in finding these ore pods in an economic manner.

Massive nickel sulphide ore is a very good electrical conductor and so it is relatively easy to induce electrical currents into the ore via rapidly changing magnetic fields from a current transmitter. These electrical currents produce a secondary magnetic field that is detected by the Torch system. Luckily for IGO the ore pods are more conductive than all the other conductive bits and pieces within the mine, such as wire mesh, pipes and electrical wiring. Thus, the induced electrical currents last longer in the ore pods and can be seen as distinct conductors.

Development of the Torch system was not without tears however, as it is difficult to detect the small magnetic fields from the ore pods without resorting to enormous transmitter currents. Being able to work in an underground mine is a significant constraint as the system must have a cross-section less than 2 by 2 metres. Thus, it is hard to obtain a significant transmitter moment to excite detectable currents in pod some 20 metres distant. A compromise solution is to use a multi-turn transmitter loop with a moderate amount of current (less than 20 Amps) combined with very sensitive magnetic field sensors. A customised system incorporating these concepts was developed at Curtin University and mounted upon a wooden trailer. The use of wood was necessary as steel and other metals produce a spurious response that masks the effect of distant ore pods. In addition, the cart mounted system cannot have a vehicle within 10 metres for the same reason.

Within six months of use the Torch system has paid for itself more than ten times over, and is well on its way to delivering more than $1-10 million dollars to IGO shareholders by year end. It is a perfect example of the judicious use of a mature technology in an innovative way.

LIGHTING UP THE REGOLITH WITH ELECTRICAL GEOPHYSICS

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ABSTRACT

Downhole-to-surface electrical geophysics provides a rapid and cheap approach to determine the spatial extent of mineralisation beneath cover. In this method, sometimes known as mise-à-la-masse, a downhole current electrode provides a source, and a roving surface electrode measures the resulting electrical potential. The method is particularly applicable at brown-fields exploration sites where mineralisation or alteration has been intersected by one or more drill holes, as it indicates continuity of electrical interconnection of mineralised regions, extending exploration targets away from drill holes.

To date, interpretation methods have been mostly qualitative, involving plots of gridded surface electrical potential data, with little or no processing. This CRC LEME funded study provides a quantitative means of interpreting data, through (a) a numerical approach to separate the surface potential into contributions from the source current electrode and sub-surfaces charges at resistivity boundaries in the Earth, and (b) a simple three-dimensional (3D) imaging method to determine the lateral and vertical extent of the conductive mineralisation. The methods described work in both the case where a drill hole intersects mineralisation and the source current electrode is directly connected to the conductive ore, and in the "near-miss" scenario in which the drill hole does not intersect mineralisation. Data from the Golden Grove VMS deposit in Western Australia are shown for example.

INTRODUCTION

The downhole-to-surface electrical technique is under utilised given the simplicity of the method, and the possible information that can be extracted from resulting data (Ketola 1972). Data are generally collected in a pole-pole configuration (Eloranta 1985) by placing a current electrode in contact with, or close by, a conductive target, either downhole or at an outcrop. A return current electrode is located as far as possible to simulate a point current source (Figure 1). Surface potentials are mapped using a roving electrode relative to a reference potential electrode placed some distance away.

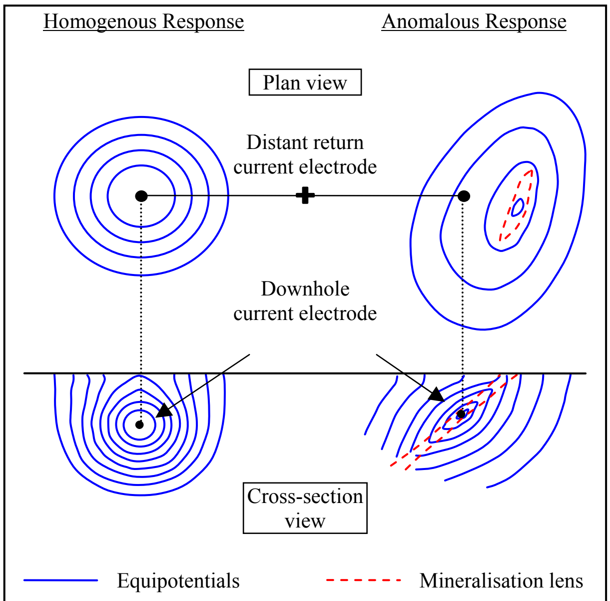

Figure 1: Surface and sub-surface equipotential contours for (left figure) homogenous media, and (right figure) anomalous structure, such as a mineralised lens.

Equipotentials about an energised current electrode are approximately spherical in a homogenous and isotropic half-space. Surface potential responses are symmetrical, centred above the current electrode (Figure 1). Any resistivity changes within the Earth distort the potentials, and on the surface the maximum potentials are centred over the top of the conductive body. Surface potentials may therefore indicate the lateral and depth extent of a conductive structure and can provide information on the continuity of ore between borehole intersections or outcrops. However, data do not readily provide unique depth constraints to the target, as is the case with all surface potential field measurements.

LOCALE AND GEOLOGICAL DESCRIPTION

Field data were obtained by Newmont Australia at the Scuddles Mine, Golden Grove tenement, Western Australia (approximately 225 km inland from Geraldton) (Boyd and Frankcombe 1994). The location hosts a base metals operation involving a volcanogenic massive sulphide (VMS), with the primary target being a massive pyrite. Covering the region is a conductive weathered overburden of thickness 80-100 m. The target is a conductive band 80 m wide, steeply dipping 80° to the west, striking north-south, with a plunge of 5° to the north (Boyd and Frankcombe 1994). The conductive body has been extensively drilled, and downhole electrical surveys conducted at numerous drill holes. The region has low topographical relief with the only prominent feature being a low-lying hill situated over the ore body, aptly named Gossan Hill. More details of the field area are given by Carey (2003).

METHODS

The area surveyed measured 750 by 1000 m. The transmitter used was an Iris VIP-4000 that supplied between 2-5 A on a two second cycle at 200 volts. The receiver used was an Elrec 6 IP. The distant return electrodes were placed more than 2 km from the survey area. Most surveys were conducted in a pole-pole configuration with the current electrode placed at the depth of lowest resistivity of the target formation to ensure a good coupling to the conductive body. However, several surveys were also conducted in a near-miss configuration, where the current electrode was outside the target formation's known depth, as identified from drill logs.

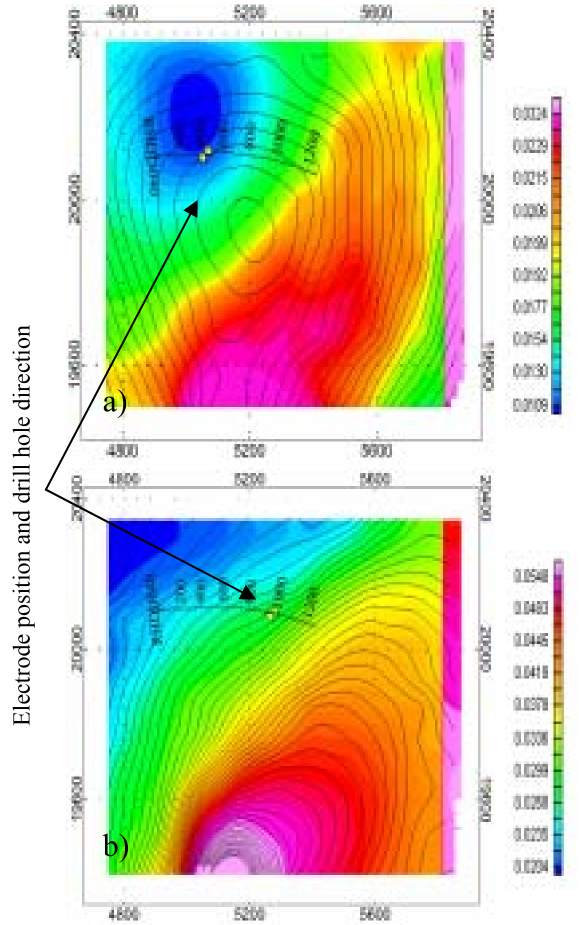

Figure 2 (a) Line contours of observed surface potentials (current electrode at 450 m), superimposed on a colour map of residual potentials after the removal of the electrode effect. (b) As for (a) but for the current electrode at 850 m.

Electrode Effect Removal

Electric potential fields produced by a buried current electrode inside any complex geologic resistivity structure can be described as part of a geoelectric construct, where the potential U at point P is due to integral sum of all point current sources and or sinks (Keller and Frischknecht 1966).

$$U(P) = \frac{1}{2\pi}\left[\int_V \frac{\rho\,\mathrm{div}\,\mathbf{J}}{r}\,dV + \int_V \frac{\mathbf{E}\cdot\mathrm{grad}\,\rho}{\rho r}\,dV\right] \quad (1)$$

In equation (1) **J** and **E** are the electric current density and electric field vectors, r is the distance from point P to the volume element dV, and ρ is the resistivity. The **first integral** is the primary input to U(P) from a divergence of electric current density (div **J**) from the downhole current electrode; the **second integral** is due to the electric charges accumulating at any gradient in electrical resistivity (grad ρ) within the subsurface.

From equation (1) we can calculate the first integral simply using the image-current technique (Telford et al. 1990) from a buried electrode in a homogenous half-space. Assuming we can measure U(P) on the surface of the Earth, we can re-arrange equation (1) to yield just the contribution due to subsurface resistivity changes $U^r(P)$:

$$U^r(P) = \int_V \frac{\mathbf{E}\cdot \operatorname{grad}\rho}{\rho r} dV = \left[\int_V \frac{\rho \operatorname{div}\mathbf{J}}{r} dV - 2\pi U(P)\right] \qquad (2)$$

This technique was applied to sets of data from the same drill hole but at different depths of 450 m and 850 m. The gridded surface potentials from the shallow survey are shown as solid contour lines (Figure 2a), and are significantly different to the contours from the deep survey (Figure 2b). The shallower potential response is a broad anomaly, with highest values to the southeast of the current electrode location, while the deeper response yields the highest values far to the south of the current electrode. The shape of the surface potential contours is also different.

The current electrode effect was modelled using the image-current technique (Telford et al. 1990) with a half-space of 1000 Ω.m. Modelled surface potentials were subtracted from observations, and residual potentials are shown in Figures 2a,b as colour maps. In Figure 2a, residual potentials from the 450 m current electrode case no longer have a peak anomaly centred in the survey area; the maximum potentials now occurs on the southern margin of the survey, similar to field data collected with the deeper current electrode. Applying the same technique for the case with the current electrode at 850 m in Figure 2b shows minimal change to the surface potentials. We note now that the residual potential maps in Figures 2a and 2b are quite similar, indicating that the sources of the residual potentials are due to subsurface resistivity variations and not the location of the source current electrode.

Image Reconstruction Method

A strategy to determine quantitative information from the residual surface potentials has been developed by Patella (1997) and Hämmann et al. (1997). Surface potentials can be represented by the integral sum of potentials from all sub-surface charges that occur at locations where there is a resistivity gradient (ie. grad $\rho \neq 0$). An electric charge at a point in the sub-surface (x,y,z) generates a modelled potential V^m at a surface location (a,b,0) that has the form

$$V^m(a,b,0) = \frac{2\rho I}{4\pi\sqrt{(x-a)^2 + (y-b)^2 + z^2}} \qquad (3)$$

where I is the current at the charge location, and ρ is the average resistivity of the sub-surface. We can define a cross-correlation coefficient $\hat{C}(x,y,z)$ between the modelled potentials V^m and residual potentials U^r after electrode effects have been removed, for all measurement positions (a,b,0) as

$$\hat{C}(x,y,z) = \sum_a \sum_b V^m U^r \qquad (4)$$

Equation (4) can be normalised by the square-root of the sum-squared components of observed and modelled potentials as

$$C_{norm}(x,y,z) = \frac{\hat{C}(x,y,z)}{\sqrt{\sum_a \sum_b V^2 \sum_a \sum_b U^2}} \qquad (5)$$

We note that the normalised function C_{norm} has no dependence on I or ρ, only on the distances between the point source and the surface locations. The function C_{norm} is defined to range between –1 and 1; strong positive correlations (0.8 to 1) indicate the probable location of positive point-charges, while negative correlations (-0.8 to -1) show probable negative point-charged sources. Numerical scanning through a range of source locations (x,y,z) in equation (5) produce a matrix that can be contoured as a 'map' of sources correlations.

Figure 3 shows two iso-surfaces of the normalised correlation function C_{norm} for the residual potentials in Figure 2a. The upper iso-surface is for $C_{norm} = 0.9$; while the more spherical surface is for $C_{norm} =$

0.95 (implying a 95% correlation with the observed residual potentials). The figure is orientated with the southern margin on the right side, suggesting that the ore body is at a depth of about 500 m, and is not continuous from south to north, possibly terminated by east-west striking faults. The choice of a suitable cut-off value of C_{norm} is somewhat arbitrary. However, we find experimentally that 0.95 is often appropriate.

CONCLUSION

We conclude that the use of gridded maps of surface potential is outmoded and insufficient, as the potential field due to the electrode can significantly distort and dominate the surface response. With an image current approach, it is very easy to remove the electrode potential, and the residual potential map is a better representation of the subsurface charge distribution that occurs at resistivity boundaries. Rather than 3D forward and inverse modelling, we recommend an alternative approach of defining a 3D scanning function and determining a spatial correlation with the measured fields. As targets are bounded by changes in resistivity, it is of interest to know where charges are located spatially rather than in terms of their electrical potential response.

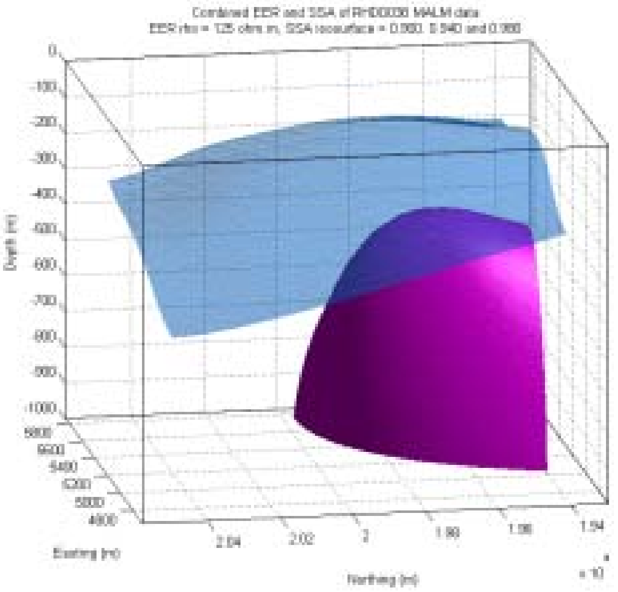

Figure 3: Iso-surfaces of the correlation function C_{norm} for the area of survey shown in Figure 2. The figure is orientated such that the north-direction is from right to left. The two surfaces are for C_{norm} = 0.9 (upper), and C_{norm} = 0.95 (lower).

ACKNOWLEDGMENTS

We thank Newmont Australia Ltd for financial and in-kind support during this project. Additional funding was supplied from the CRC LEME. The work in this abstract formed part of an M.Sc. thesis undertaken at the University of Adelaide (Carey, 2003).

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