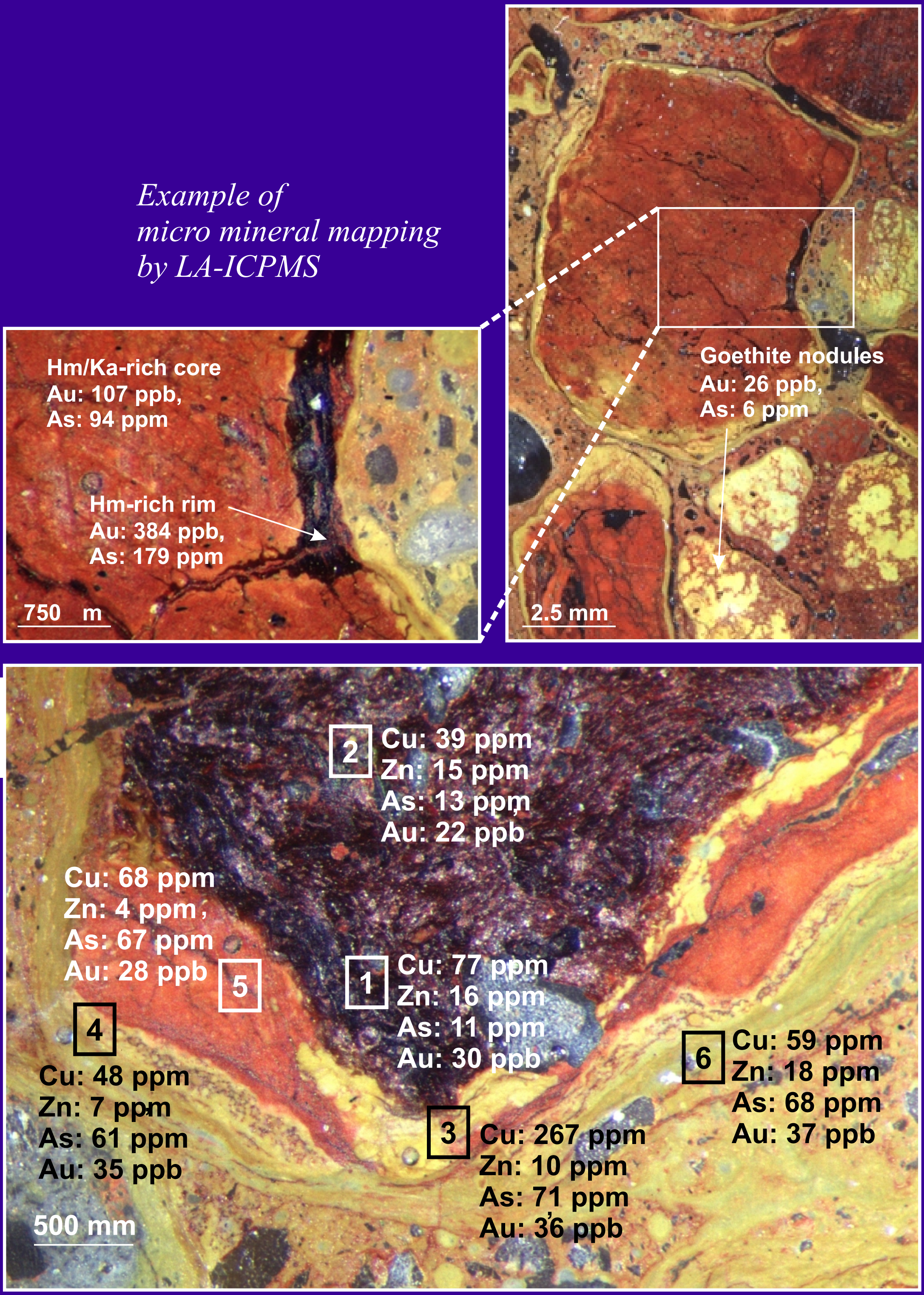
2005
MINERALS EXPLORATION SEMINAR
ABSTRACTS

14 - 16 February 2005

Example of
micro mineral mapping
by LA-ICPMS



CRC AUSTRALIA

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Australian National University,
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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,

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Geological Survey Western Australia

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Convenors

Ravi Anand, CRC LEME/CSIRO Exploration & Mining
Paul Morris, Geological Survey of WA

14 - 16 February 2005
WA School of Mines, Conference Centre, Kalgoorlie

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ADVANCES IN REGOLITH RESEARCH

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Recent research by CRC LEME from an Australian mineral exploration perspective, has focussed on regolith architecture and mechanisms of geochemical anomaly formation, within transported regolith.

Methods have been developed for the rapid production of regolith-landform maps which is the starting point for understanding regolith architecture in the third dimension. Methods for development of 3D regolith models are less well advanced, and require integration of all available geological and geophysical datasets, but still with a heavy reliance on drill-hole information. The base of the transported regolith – the unconformity – remains the most important regolith boundary for geochemical sampling in transported regolith terrains.

A new generation portable spectral logger, employing a broader spectrum can interpret important features from drill chips within the regolith. This allows internal architecture, redox fronts and the all-important interface to be objectively identified. Transported lateritic components can provide vectors to mineralisation in depositional regimes. Palaeomagnetic and new radiometric methods which date individual phases of the regolith provide evidence of different episodes, each characterised by different geochemical dispersion patterns in transported regolith.

Along with lateritic residuum, calcrete is prime sampling medium. Calcrete is probably enriched in gold through physical and biological processes, rather than straight chemical processes. In South Australia, the lowermost calcrete layer buried within the depositional regime, especially where it lies directly over the silcrete layer at the buried interface, is the desired sampling medium.

Certain gum trees, with deep roots in transported regolith have been shown to record anomalous values of gold and basemetals in leaves, twigs and bark. Anomalous metals in acid-sulfate soil seeps can also provide a window through sedimentary cover in respect of mineralisation in the basement.

A number of Yilgarn occurrences of gold anomalies in transported cover, strongly infer hydromorphic and biological mobilisation of gold. This inference is supported by micro-analyses of regolith mineral hosts in hardpans and mottled sediments, which show gold and pathfinder elements prefer to reside in goethite and specific types of clay minerals. This creates anomalies in specific mineral phases. However the inference that that these are sites of mobile or labile metal ions remains enigmatic. Similarly there is inconclusive evidence that selective extractions will provide an anomaly not otherwise detected by conventional total dissolution methods.

Hydrogeochemistry is a promising exploration tool for basemetal exploration.

The importance of microbes in both the dissolution and precipitation of gold in the Australian regolith is demonstrated. We are on the verge of identifying the functional gene sequence of individual active microbes. A consideration of possible mechanisms for creating anomalies in soils above transported regolith, presents difficulties in facilitating upward movement of ions from the watertable to the surface. Perhaps the best avenues of research lies with surrogate soil gases, and biotic transfers.

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. As a result 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 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 erosion rates on 10^5-10^6 year timescales (Bierman & Caffee 2002), while apatite fission-track ages constrain regional denudation rates on longer timescales (see Kohn et al. 2002). The age ranges over which various regolith dating techniques can be applied, are summarised in Fig. 3. See also Pillans (in press) for an overview of regolith geochronology in Australia – available for downloading from http://leme.anu.edu.au/Pubs/Monographs/RegLandEvol.html

In this talk I will illustrate some ways in which regolith geochronology can be significant in the context of mineral exploration.

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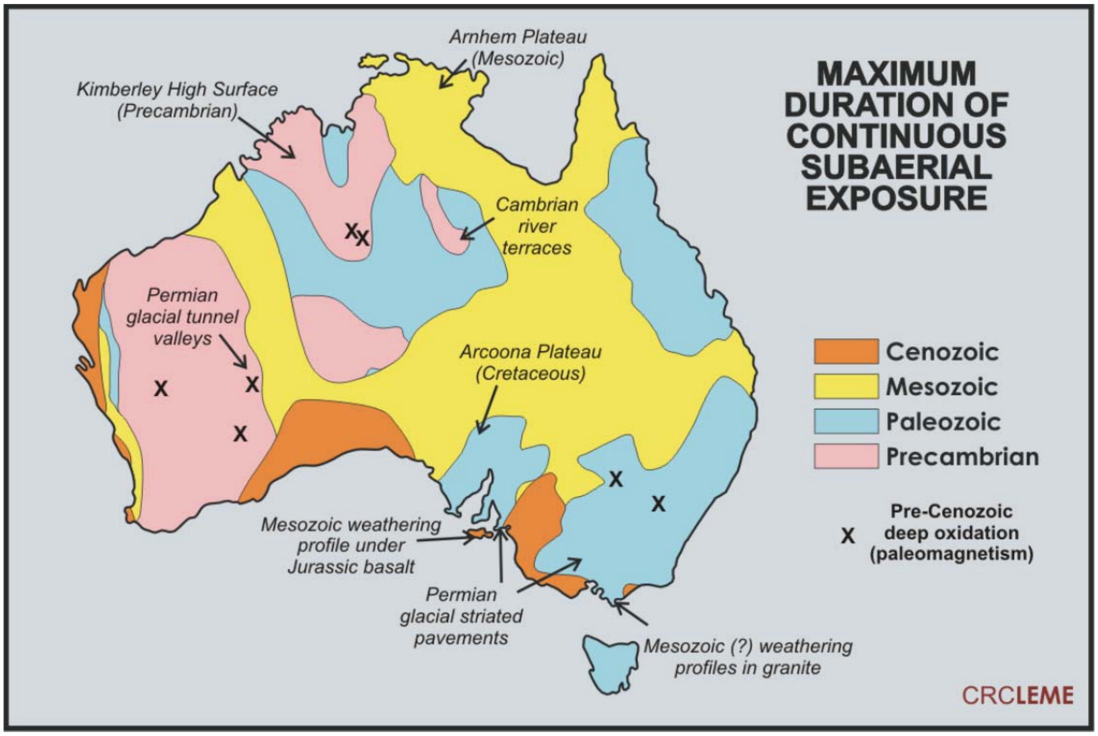

Figure 1. Duration of continuous subaerial exposure from paleogeographic reconstructions by BMR Palaeogeographic Group (1990) and locations of selected sites with pre-Cenozoic regolith and landforms.

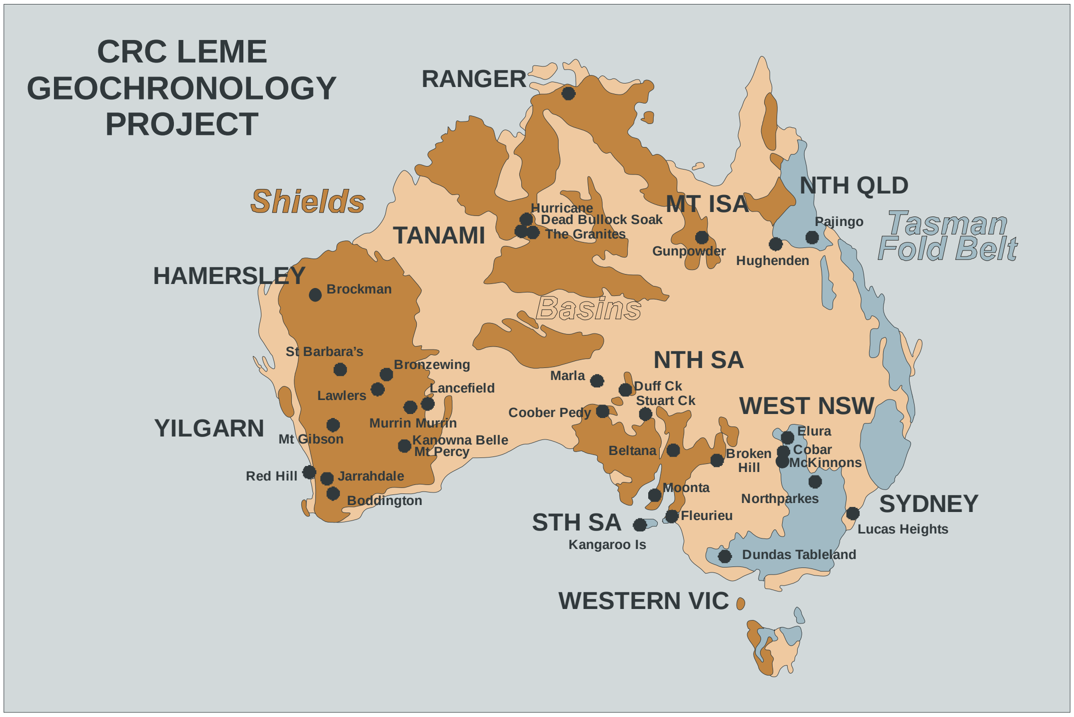

Figure 2. Location of sites where regolith ages have been obtained or which are currently being studied.

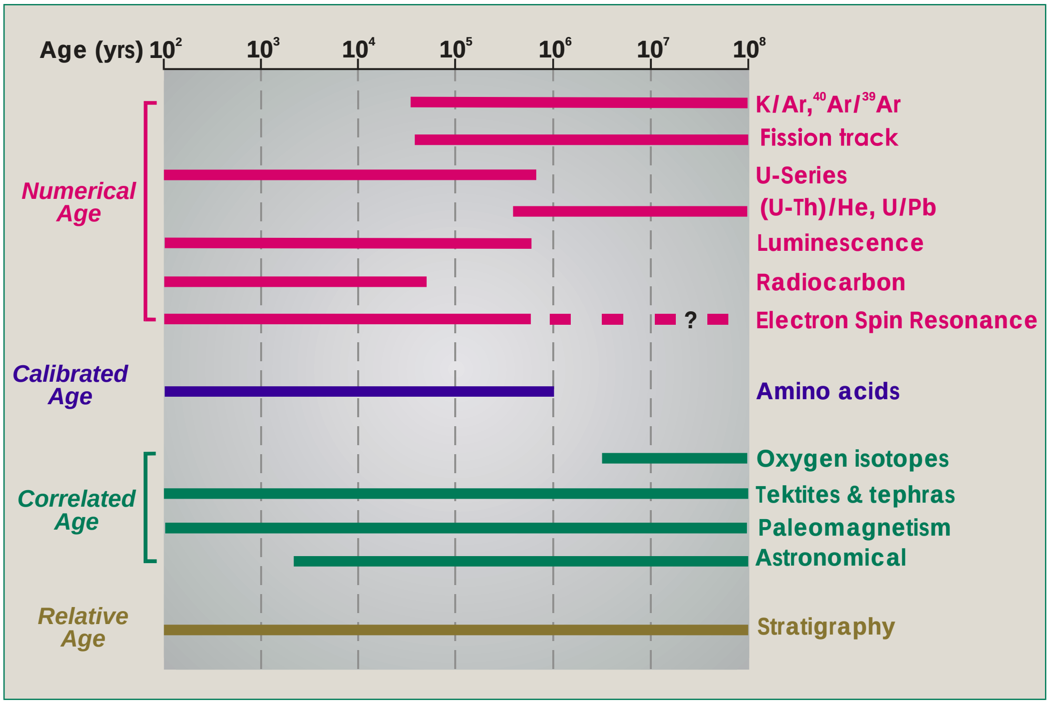

Figure 3. Age ranges over which regolith dating methods can be applied. Methods are grouped according to type of age result produced (after Pillans 1998).

REGOLTIH-LANDFORM MAPPING, YILGARN CRATON

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This presentation provides a brief overview of regolith-landform mapping practices and products, past and present, from the Yilgarn Craton and outlines new data collection techniques currently being developed.

Regolith-landform mapping for mineral exploration in Australia has developed from early approches to land systems mapping in the 1950s to 1960s by CSIRO. Many of the fundamental developments in regolith-landform mapping for mineral exploration have taken place in the Yilgarn Craton of Western Australia during the period between 1980 and the late 1990s by BMR/AGSO, GSWA, CSIRO/AMIRA and, more recently, CRC LEME. The development is driven by a range of needs arising from geochemical exploration, especially for gold. Regolith-landform mapping approaches have developed beyond basic inventories and have also been influenced by needs arising from outside mineral exploration activities. The ready availablility of supplementary and complementary data, and an increasing need to understand and provide more detailed information about the four-dimensional distribution of regolith and landforms have fuelled greater diversity in mapping techniques and map presentation.

Regolith-landform mapping, such as in the Yilgarn Craton, routinely involves multi-dataset integration and analysis, and presentation of maps and initial field data, all within a GIS framework. Landsat Thematic Mapper, HyMap™, Aster, radar, airborne electromagnetics (AEM), geochemistry, biogeochemistry, geological data and digital elevation models (DEM) are becoming standard datasets consulted during the production of regolith maps. These data are critical for a comprehensive understanding of regolith-landforms in relation to mineral exploration. Regolith-landform maps and their complementary databases now routinely include information about the nature and distribution of geochemical sample media, such as surface lag and, increasingly, geobotanical data.

Continued developments in digital data-collection techniques by CRC LEME now provide seemless integration of field data into spatial analytical software for map production and regolith material characterisation. Critical observations can now be recorded readily in the field onto a variety of image backdrops fully integrated with site photography and all wirelessly connected with GPS technology. Hand-held devices are now cabable of storing compressed imagery, tracklogs and site records in excess of 1GB. This automates field data collection in a revolutionary way, and allows for much easier tranfer of field data to larger national databases.

End-users have, in the past, tended to regard a single printed map as the most desirable outcome for characterising the nature and distribution of regolith and landforms. However, increasingly we recognise the restrictions and limitations of one simple product. Multiple thematic regolith-landform maps, digital or hard-copy, that are based on a variety of data associations and correlations now provide us with a wider range of contexts to gain a better understanding of regolith-landforms. Regolith-landform mapping for mineral exploration in the Yilgarn Craton continues to provide the lead especially in GIS-derived thematic maps.

REGOLITH-LANDFORM MAPPING OF THE KALGOORLIE-KANOWNA AREA

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Regolith-landform mapping of the Kalgoorlie area commenced in 2001 as part of the Development Areas Resource Mapping (DARM) project. The object of the DARM programme is to undertake detailed regolith-landform mapping and resource delineation in regional areas of Western Australia that are likely to undergo significant development and where landuse planning would benefit from the availability of digital and hard copy geoscience datasets. Compilation and release of available digital datasets (including digital 1:25 000 digital orthophotography, Landsat TM images, magnetic (TMI) and Bouguer gravity images, and spatial data for regolith-landform features, abandoned mine sites, and mine and mineral deposits (MINEDEX)) was completed in 2004 (GSWA Record 2004/12). During the 2004 field season, regolith-landform mapping of the Kalgoorlie and Boulder sheets was reassessed and fieldwork was completed for the Kanowna and Golden Ridge 1:50 000 sheets. The release of the digital regolith-landform map, covering an area of 1512 km^2 (42 km by 36 km), including the Kalgoorlie-Boulder townsite and the mining areas of Golden Mile-Mount Charlotte, Kanowna, Binduli, Panglo, Golden Ridge and Nimbus, together with any updates of Record 2004/12, is planned for June 2005.

Methodology

The regolith-landform polygons were drawn in ArcMap onto a rectified orthophotograph base with an overlay of height contours at 0.5 m intervals derived from the digital elevation model. The Geological Survey of Western Australia (GSWA) regolith classification system (Hocking et al., 2001), based on landform position and regolith composition, was used to code the polygons. Supporting digital datasets were used, including Landsat, HYMAP, and field observations from the corporate database (WAROX). The map was produced as a digital product nominally at 1:25 000 scale, with digitizing of individual polygons at 1:5 000 scale.

Regolith-landform map units

Two principal regolith-landform domains occur: (i) a dominant relict-colluvial domain characterized by low hills and rises (commonly with outcrops of weathered to almost fresh bedrock), skirted by a broad pediment and fringed by a transitional zone, exhibiting the underlying pediment structure but overlain by up to 25 m of transported material, and alluvial plains; and (ii) the playa-eolian domain overlying dominantly alluvial deposits.

Regolith-landform units can be assigned to seven primary landform categories (Figure 1): residual or relict; exposed; colluvial (proximal slope); alluvial; lacustrine; eolian; sandplain. Three additional non-regolith categories (mining; gravel pit or quarry; infrastructure) have been used to classify other components of the map.

Colluvial-relict domain

The principal components are ranges of low hills and rises surrounded by a gently inclined to flat pediment (or peneplain), which have been incised by major northerly or northwesterly drainages and northeasterly to southwesterly tributaries, and by playas. Secondary (rejuvenated) pediments, typically fringed by linear breakaways, may be cut into the older pediment by this drainage system. The materials of the older pediment were derived from the weathering and erosion of the ranges and have blanketed pre-existing topographic relief. Thin (generally <2 m), more recent alluvial and/or eolian cover may form a veneer.

Ferruginous materials are ferricretes (probably ferruginized saprolite) occurring on hill crests and rises, overlying saprolite, and cemented polymictic ferruginous gravels that occur either along former drainage lines or as scree deposits (valley-fill) along hill slopes. The latter occur at various levels in the landscape, from playa-eolian domains to the crests of the higher hills along the ranges (e.g., to the north of the Golden Ridge mine). In the latter instance, weathering of these gravels has given rise to local glacis pediments (i.e., pediments formed by secondary products derived from the gravels).

Playa domain

This domain corresponds to the Kunanalling, Black Flag, Hannan and Yindarlgooda arms of the Roe Palaeochannel (Kern, 1995, 1996), an arcuate northeasterly to easterly belt to the north and northwest of Kalgoorlie, and smaller sections further south. The main components are: playas and playa margins, playa plains (which appear to be zones where playa/alluvial processes are relatively active), dunes and eolian sandplain. Internal drainage is via linear depressions/swales. Hills (with outcrop) may occur at the western margins of some playas. Silcrete and ferruginous deposits (typically hematite-cemented coarse quartz sand) are restricted to this domain and fringe some of the playas.

Significance of results

Landform-based regolith-landform mapping, together with field observations, indicates that there is a close association between geology and landforms and this can be used to derive an interpretation of near-surface regolith (Figure 1). Pediment and hills outline areas of outcrop, colluvium and thin transported cover. The topographic contour patterns of the relict-colluvial domain disappear where cover is significantly thicker in the playa domain. From a mineral exploration perspective, such maps give a clearer indication of which sampling techniques can be applied.

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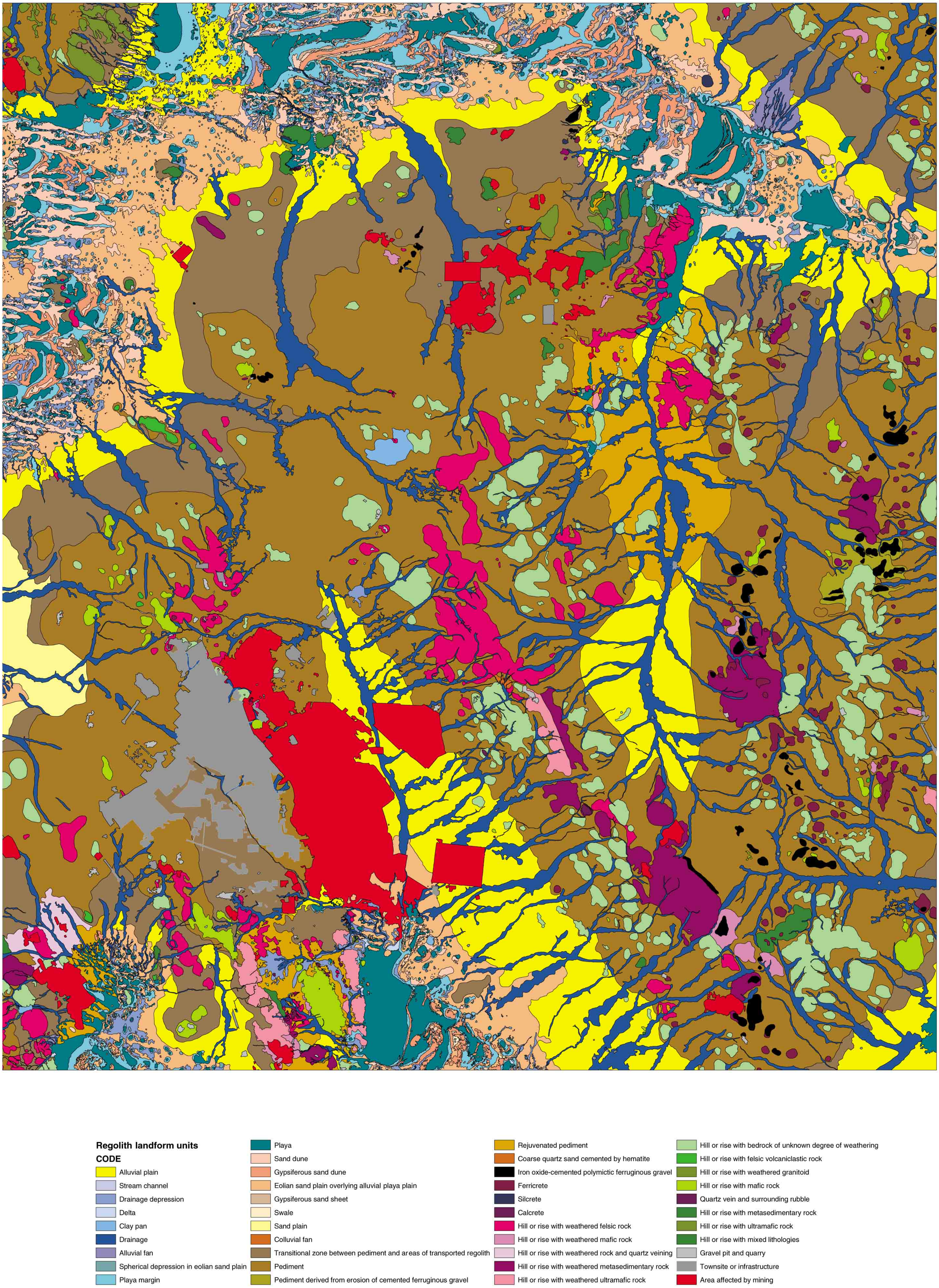

Figure 1. Provisional regolith-landform map of the Kalgoorlie-Kanowna area; the area of the map is 42 km by 36 km.

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 base metals, 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 et al., 1988; Grunsky et al., 1989; Grunsky, 1991; Smith et al., 1992; Anand et al., 1993; 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 at the base of 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 of the bedrock it formed on 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 multi-element analysis of lateritic gravels within colluvium and alluvium combined with the use of microprobe analysis and microscopy 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 and Bronzewing (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 900 samples have been collected and the SW quadrant of the Yilgarn Craton will be completed by July 2005.

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, I.D.M. Robertson and R.R. Anand are appreciated.

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GSWA'S REGIONAL REGOLITH GEOCHEMISTRY PROGRAM: AN OVERVIEW

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Introduction

The Geological Survey of Western Australia's regolith geochemistry program (1994 – 2001) provided baseline information on the distribution and composition of regolith for the mineral exploration industry. At its inception, the program focussed on parts of the Eastern Goldfields, but most projects were carried out in 'greenfields' areas, particular the Capricorn Orogen. Each of the twenty projects involved systematic sampling of regolith on a nominal 4 x 4 km grid over 1:250 000 map sheet areas, equating to approximately 1000 sites per sheet. Each sample was analysed for more than 50 analytes using a 'total' analytical approach, with these data presented as both a digital dataset, and as a series of element concentration maps shown in relation to regional geology. At each sample site, information was recorded about regolith, landforms, and bedrock geology, which was used to ground-truth regolith-landform maps, compiled from remotely-sensed data such as aerial photographs, Landsat and radiometric imagery.

Explanatory notes accompanying each set of maps contain a summary of geology and mineralization, the approach to regolith sampling, geochemical analysis, and regolith map compilation, and discussions dealing with the relationship of regolith chemistry to different regolith-landform types and regional geology. A compilation of all open file exploration company activity dealing with surface geochemistry, extracted from GSWA's WAMEX database, is summarised in a spreadsheet and a related activities map.

Regolith Mapping

The approach to regolith classification is based on the landform position and composition of regolith (Hocking et al., 2001). Apart from showing the distribution of various regolith types, regolith maps can also show the genetic relationship between different regolith types. For example, regolith over part of the Murchison Granite-Greenstone Terrane on the eastern part of the Byro 1:250 000 map sheet (Morris and Verren, 2001) comprises granitic rubble and areas of silicified granitic rock on or near outcrop. Adjacent and downslope is proximal colluvium with abundant granitic detritus, flanked further downslope by lower-gradient deposits, which are better sorted, finer grained and lacking lithic fragments. In areas of minimal slope, two types of alluvium is found in drainage channels; older deposits are consolidated and locally incised, whereas younger deposits are unconsolidated, and found in active drainage channels.

Regolith sampling and geochemistry

For GSWA's regolith geochemistry program, the preferred sample medium is stream sediment, but where streams are poorly developed, colluvium or sheetwash, sandplain, or lake sediment has been sampled. At each sample site, an analytical and archive sample of approximately 2 kg and 4 kg respectively of the <6 mm material was collected. The < 2 mm and + 0.45 mm fraction of the analytical sample was subsequently milled and analysed. This size fraction was chosen to minimise the nugget effect of coarse-grained fragments, and the dilution effect of aeolian material. Data recorded at each site includes the GPS location, site and sample number, the position of the sample in an idealised landform profile, an estimate of the regolith clast, matrix, and cement proportions and type, and the presence of secondary units (e.g. silcrete, calcrete) and bedrock nearby.

Analyses were carried out by commercial laboratories. To monitor any inter-laboratory variation, samples were analysed using the same analytical conditions where possible, and a series of in-house standards were used throughout the program. To achieve suitably low detection levels at the lowest price, most analyses were carried out using inductively-coupled plasma (ICP) spectrometry for a total of more than 50 analytes. Gold and platinum-group elements (PGEs) were analysed by fire assay preconcentration and an ICP or atomic absorption spectrometry (AAS) finish.

In addition to providing the analytical data as a digital data file, a series of spot concentration maps against bedrock geology were produced. The size of the spot is proportional to the concentration of the element, apart from statistically anomalous concentrations, which are shown as a star. In some cases, certain combinations of elements were used to construct an index to highlight the potential for certain types of mineralization, following the approach of Smith and Perdrix (1983) and Smith et al. (1989) for the detection of chalcophile element corridors in parts of the Yilgarn Craton.

Statistical analysis of regolith geochemical data

Regolith chemistry can be statistically examined to determine the relationships of different regolith types, and the relationship of regolith and underlying bedrock. This approach has been used to identify a residual or transported origin for two different types of sandplain on the Byro 1:250 000 map sheet, and to track the relative proportions of mafic and felsic rocks from two different Archaean terranes on the same map sheet (Morris and Verren, 2001). In another application, Morris et al. (2000) used clustering to estimate the relative contributions of residual and transported regolith to sandplain deposits in the Fraser Range area.

Integration of Regolith Geochemistry with Other Datasets

Since 1997, a measurement of the Earth's gravitational field was made at each regolith sampling site during GSWA's 4 x 4 km spaced regolith geochemistry program, greatly improving the quality of gravity data in most areas, where regional coverage was typically at 11 x 11 km grid spacing. These data have been combined with aeromagnetic data, regolith and bedrock mapping, and regolith chemistry to identify different styles of Proterozoic mineralization in the eastern part of the Capricorn Orogen (Morris et al., 2003). Sanders et al. (1997) combined Landsat imagery, airborne radiometric data and regolith chemistry for the Mt Phillips map sheet, noting a high correlation between potassic granitic rocks and K_2O in regolith, and a coincidence of enhanced radiometric uranium with greater U concentrations in areas of silicified regolith.

Conclusions

The GSWA's regolith geochemistry datasets provide comprehensive information on the distribution and composition of regolith in Western Australia, and an up to date summary of exploration activity, geology, and mineralization. By sampling at a uniform sample density over areas unconstrained by bedrock geology or structure, any bias in sampling is minimised. The regional coverage and sample density allows integration of regolith chemistry and mapping with other similar-scale datasets such as gravity, aeromagnetics, and bedrock mapping to produce derivative studies highlighting areas of potential mineralization.

Regolith geochemical data are available from GSWA as digital GIS datasets for each 1:250 000 sheet covered by the program, at $100 per map sheet.

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TOWARDS UNDERSTANDING THE FERRUGINOUS COMPONENT OF THE REGOLITH

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INTRODUCTION

The Earth is a wet, iron-rich planet and for much of its history has had an oxidising atmosphere. Oxidation of ferrous (Fe^{2+}) to ferric iron (Fe^{3+}), followed by hydrolysis and formation of insoluble oxide/oxyhydroxide minerals from soluble species is a major aspect of weathering and the regolith. Iron oxides/oxyhydroxides (principally goethite and hematite) are major end products of near surface chemical weathering and because of their ability to take up a wide range of cations these minerals exert a significant control over the fate of many trace elements, including target and pathfinder elements used in geochemical exploration (Figure 1).

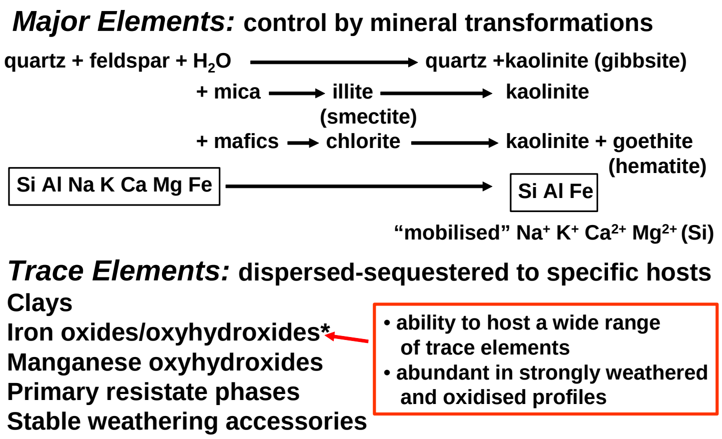


Figure 1: The basics of element fractionation during chemical weathering of silicate rocks.

It is important to understand the mineralogical-chemical characteristics and evolution of ferruginous weathering products because:

- they are a major component of the surface and near surface regolith, affecting its chemistry and landscape stability;
- they can provide a record of certain environmental and chemical conditions (e.g. Eh);
- they have advantages/disadvantages as a geochemical sampling medium in mineral exploration.

SOME CHEMICAL CONSIDERATIONS

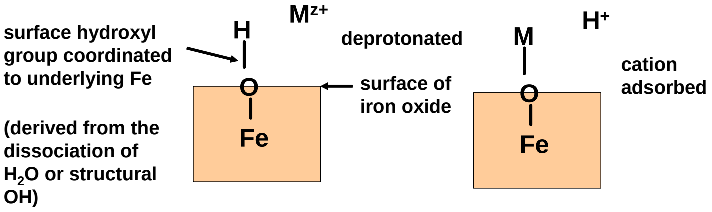
The most abundant iron oxides/oxyhydroxides in the regolith are goethite (α-FeOOH) and hematite (α-Fe_2O_3). Both these minerals are very stable under ambient conditions. Ferrihdyrite (ca. $Fe_5HO_8.4H_2O$) is a widespread but unstable compound in surface environments, generally transforming into more stable iron oxides/oxyhydroxides. Although not as abundant as goethite and hematite, lepidocrocite (γ-FeOOH) is common in non-calcareous soils and other ferruginous weathering products (Cornell and Schwertmann, 1996). Maghemite (γ-Fe_2O_3) is commonly present at and near the surface, particularly in ferruginous lag, where it is thought to form from the other iron oxides/oxyhydroxides by heat transformation.

Minor and trace elements can be incorporated into iron oxides/oxyhydroxides by the following mechanisms:

- adsorption/desorption followed by structural substitution or neo-formation of trace-element specific minerals;
- isomorphous substitution from a precursor phase (e.g. ferrihydrite to goethite);
- coprecipitation/introduction of new trace-element specific minerals;

- overgrowth and inclusion of other resistate minerals.

Under aqueous conditions, heavy metal cations (and complexes) adsorb onto the surface of iron oxides/oxyhydroxides by interaction with deprotonated, surface hydroxyl groups to form mono- and binuclear inner sphere complexes (Cornell and Schwertmann, 1996; Figure 2). The extent of this adsorption is strongly pH dependant, increasing with increasing pH over a narrow range. Increased temperature and addition of anions (e.g. thiosulfate, chloride) can also enhance cation adsorption, in the latter case by formation of mixed metal/ligand surface complexes (e.g. Schindler, 1990; Gunton, 2004). The available mineral surface area is a major control on the level of adsorption. Adsorption characteristics are different for the different iron minerals (e.g. in typical near surface environments and soils the relative strengths of metal adsorption on goethite are Cu>Pb>Zn>Co>Ni>Mn and for hematite Pb>Cu>Zn>Co>Ni>Mn; McKenzie, 1980).



$$\ddagger FeOH + M^{z+} = \ddagger FeOM^{z-1} + H^+ \quad \text{mononuclear}$$

$$\ddagger (FeOH)_2 + M^{z+} = \ddagger (Fe\text{-}O)_2M^{z-1} + 2H^+ \quad \text{binuclear}$$

Figure 2: Summary of heavy metal cation adsorption onto the surface of iron oxides/oxyhydroxides under aqueous conditions.

Under dry conditions, surface Fe atoms in the iron oxides/oxyhydroxides may be coordinatively unsaturated with respect to hydroxyl groups, affecting the level of adsorption. Periodic wetting and drying may therefore have an effect on the adsorption capabilities and behaviour of the minerals. During deposition of iron oxides/oxyhydroxides adsorption is probably a preliminary step in the substitution of cations for Fe^{3+}.

A wide range of cations can isomorphously substitute for Fe^{3+} in iron oxides/oxyhydroxides including, Al, Cd, Co, Cr, Ga, Ge, Mn, Ni, Pb, Sc, Zn in goethite and Al, Cu, Cr, Ga, Ge, In, Mn, Rh, Si, Sn, Ti in hematite (Cornell and Schwertmann, 1996). Isomorphous substitution commonly changes the cell dimensions of the iron oxides/oxyhydroxides. The main controls on substitution possibilities are ionic radius and charge characteristics of the substituting elements.

FERRUGINISED LANDSCAPES

The formation of iron oxides/oxyhydroxides by weathering processes can have major effects on landscape evolution. This occurs through:

- induration of porous lithologies, surfaces and structures by chemically and physically stable iron oxide (mainly hematite);
- formation of iron oxide dominant rocks/regolith, such as ironstones, gossans, ferricretes and duricrusts.

Ferruginisation involves both vertical and lateral transport of dissolved iron in groundwater and in some cases surface water. The ferruginous component can also be added mechanically as detritus (e.g. aeolian dust and fluvial sediments). Ferruginous materials may be contributed to the soil, concentrated in surface lag and recycled through different components and levels of the landscape as the latter evolves.

Ferruginous induration and deposition commonly occur below the surface and in low parts of the landscape and these resistant materials may then become topographically inverted. They form chemically and physically stable features that can persist for long periods. Ferruginisation can armour the landscape (e.g. ferruginous duricrusts). Under arid and semi-arid conditions hematite is inherently more stable and probably more persistent than goethite. Many porous, ferruginised lithologies are quartz-rich and this adds to their stability. In these landscapes ferruginised materials can dominate what is available at the surface for observation and sampling. They dramatically affect the chemical characteristics of surface and near surface regolith. Ferruginised surfaces may also become buried.

FERRUGINOUS MOTTLING

Ferruginous mottling is a feature of many weathering profiles above the water table. These mottles are yellow to reddish brown segregations with more abundant iron oxides/oxyhydroxides. They take many forms including:

- light staining or impregnation/cementation of saprolite by minor amounts of the iron minerals;
- more concentrated nodular and concretionary accumulations of goethite/hematite with well defined outlines;
- goethite/hematite infillings of fractures, cavities and porous zones or beds.

The mottles form by patchy or localised precipitation of Fe^{3+} oxidised from Fe^{2+} and complexes dissolved in deep and shallow groundwater. The initial precipitate is probably ferrihydrite, which then transforms to goethite-hematite. In many cases biological activity plays a role in precipitation. Infilling of pore space may be followed by replacement of clays to produce more iron-enriched masses (Nahon, 1991). Ferrolysis (which lowers the pH) assists the dissolution of clay minerals. The relative proportions of goethite and hematite depend largely on the level of local hydration. Typically goethite is more common deeper in the weathering profile and closer to the water table, whereas hematite is generally more abundant at and near surface. More concentrated accumulation of iron oxides/oxyhydroxides results in nodules and pisoliths.

Strong mottling results in significant local enrichment in Fe^{3+}. Adsorption/incorporation of other elements typically results in an overall increase in their abundance in the ferruginous mottles but relative to Fe these enrichments may be small, particularly in environments where the elements are present at background concentrations (e.g. Figure 3). The dominant process is clearly oxidative deposition of Fe^{3+} and accumulation of iron oxide/oxyhydroxide from a large source volume. Other dissolved elements are extracted from solution and their level of adsorption/substitution varies with the type of host iron oxide/oxyhydroxide as well as their concentration. In some cases minor and trace elements are precipitated as secondary minerals incorporated into and protected by the ferruginous mottles (e.g. secondary sulfates phosphates, chlorides and manganese minerals).

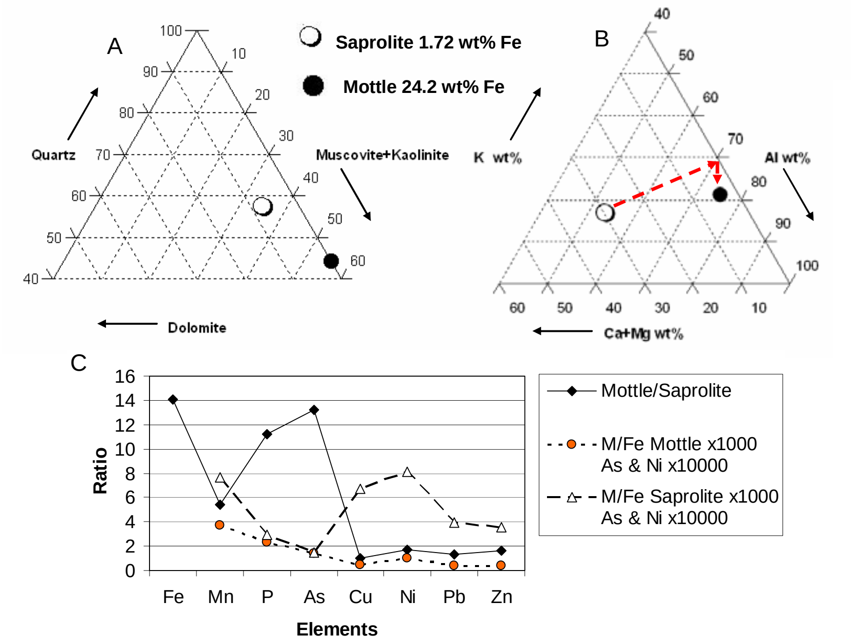


Figure 3: Compositional differences between ferruginous mottled and adjacent non-mottled saprolite/saprock from Pine Tree Tank quarry northeast of Cobar. Bedrock is fine grained, quartz-rich sandstone (ca. 40% quartz).
A. shows the major (non-iron) mineral differences.
B. shows major element differences (less Fe and Si)
C. line plots show ratios of element abundance, including relative enrichment and ratios of elements over iron for the mottled and non-mottled material.

In mineralised environments, ferruginous mottles can fix target and pathfinder elements that may be leached from the surrounding saprolite or introduced by groundwater. If these elements become substituted/incorporated they are then less leachable compared to adsorbed or weakly bound cations (e.g. on clays). The mottles are therefore a useful sampling media if appropriate threshold values and the history and degree of transport of the elements can be established. A number of parameters indicate that goethite is generally the better ferruginous sampling medium.

IRONSTONES, FERRICRETES AND FERRUGINOUS DURICRUSTS

Surficial and near-surficial accumulations of iron oxides/oxyhdroxides can form where groundwater flow has been focussed and where dissolved Fe^{2+} can be oxidised to Fe^{3+} (e.g. along structures or where groundwaters are exposed). This can produce massive ironstones or ferruginous, cemented sands and gravels, generally referred to as ferricretes. Extreme or prolonged concentration of iron oxides/oxyhdroxides by precipitation or residual enrichment above or within deeply weathered profiles gives rise to ferruginous duricrusts.

These ferruginous materials can scavenge and trap available cations in a similar fashion to ferruginous mottles. It is important to know the source vectors of the precipitating groundwater to interpret any geochemical anomalies present. For example, elements may have been transported in a vertical, residual or lateral sense. Some ironstones and ferricretes superficially resemble gossans and many have been “tested” by early prospectors. In mineralised environments they can occur with, and even mask gossans.

WEATHERED ORE PROFILES AND GOSSANS

Weathering profiles through ores exposed at the surface or intersected by the water table generally show strong ferruginisation (depending on iron content and extent of weathering). In these profiles there is a progressive change in the major mineral hosts for ore and associated elements from primary minerals (mainly sulfides and oxides) below the weathering front, to supergene assemblages around the water table, to secondary oxides and oxysalts (sulfates, carbonates, phosphates, arsenates) in the lower oxidised zone, to residual iron and manganese oxides/oxyhydroxides in the upper oxidised zone. This trend is reflected by an increasing positive correlation between many of the elements and Fe up the profile (e.g. McQueen and Munro, 2003). Due to their greater overall abundance, the ferruginous minerals generally retain the bulk of the remnant (unleached) ore elements. 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, As and Sb. The relative proportions of the major iron oxides/oxyhdroxides vary within the profile depending on chemical conditions (pH, Eh, activity of H_2O and O_2) during profile evolution and position relative to the surface and water table (Figure 4). Transformations between the iron oxides/oxyhydroxides result in release/redistribution of adsorbed and substituted elements.

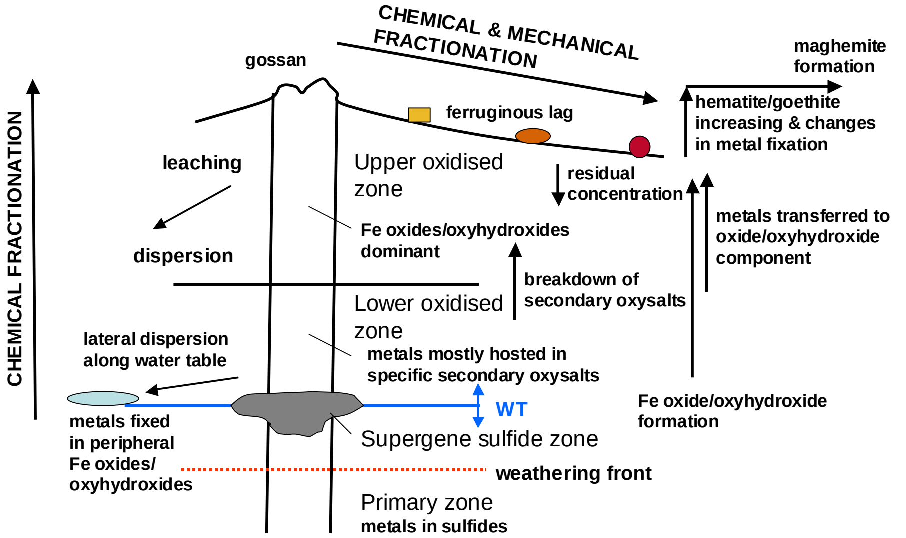


Figure 4: Schematic summary of a well developed weathering profile through sulfide mineralisation, showing major mineralogical transitions, the distribution of different ferruginous components and their role in hosting target and pathfinder metals.

Changes in mineral hosts, accompanied by element leaching, vertical and lateral dispersion and selective sequestering by particular minerals in different parts of the weathering profile, result in an overall chemical fractionation. The nature of this fractionation varies with the style of mineralisation and history of weathering. Once the profile is exposed at the surface, erosion results in mechanical dispersion of the gossan and its contained ore and pathfinder elements. Further transformations in the ferruginous component (notably conversion of goethite-hematite assemblages to hematite±maghemite) are accompanied by additional chemical fractionation of the associated ore and pathfinder elements.

FERRUGINOUS LAG

The most chemically and physically resistant components of the regolith commonly form a layer of surficial lag, particularly in areas where normal surface runoff is unable to remove the coarser or more dense fractions. In deeply weathered, arid or semi-arid environments much of this lag is highly ferruginous. It can be derived from all the various ferruginous materials of the regolith but especially the underlying mottled zone, or where present, ferruginous duricrust. Lag has been widely used as a sampling medium in geochemical exploration (generally the 3-15 mm size fraction) on the assumption that it retains ore and pathfinder elements present in the underlying bedrock.

Detailed investigations in the Cobar area of western New South Wales have established that lag undergoes physical and chemical maturation as a result of mechanical reworking, transport, conversion of residual goethite to hematite, loss of soluble components and precipitation of additional hematite (McQueen and Munro, 2003; McQueen *et al.*, 2004). This maturation is accompanied by significant fractionation of trace elements. The contents of some elements including Th, Hf, Pb, As, Sb, Bi, Ba and Cr systematically increase with increasing Fe (and hematite) content and with degree of rounding and physical maturation of the lag. This results in significant concentration of these elements. Thorium shows the strongest correlation with Fe and hematite and is a good marker for the fractionation. Other elements (including Cu and Zn) do not show this relationship and in some cases are negatively correlated with hematite content. The mechanisms for this control on element fractionation in ferruginous lag are not fully known. For some elements, positive correlation with Fe reflects residual concentration in separate resistate minerals (e.g. Ba in barite) that accumulate with residual hematite. Sequential leaching experiments also indicate that most concentrating elements are largely bound in the crystalline component of the lag and appear to be dispersed within hematite (Cairns et al., 2001, McQueen et al., 2004). Significant amounts of Cu and Zn are present in exchangeable or loosely bound forms (including in the amorphous and manganese oxide components).

Fractionation of pathfinder and ore elements needs to be taken into account when interpreting lag geochemical data, particularly where the lag contains variable mixtures of different lag types. Normalisation against Fe content for those elements that concentrate with hematite is one approach to reducing this geochemical noise. Typical background trends for elements against Fe can be recognised and preliminary results indicate that these are different from trends found in areas of known mineralisation and for lag sourced from gossan (Figure 5). This suggests that regional templates could be constructed for background ratio trends, which could then be applied to lag geochemical data to isolate and detect truly anomalous values.

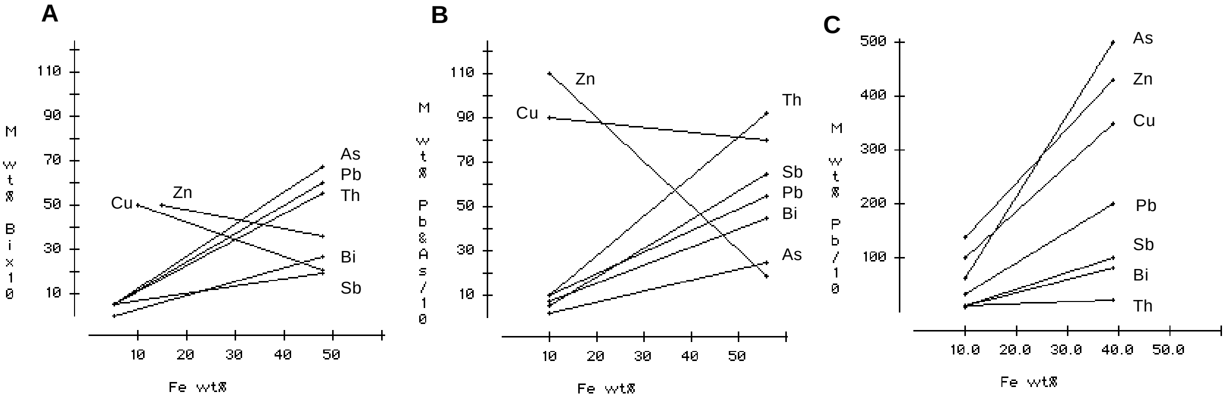


Figure 5: Ratio trends for some target and pathfinder elements in ferruginous lag from the Cobar area, NSW. A. is for lag from a background (unmineralised) site. B. is lag from the Cu-Pb-Zn mineralised CSA area. C is lag derived from gossan near the CSA mine (note plotted values have been increased by an order of magnitude for Bi in A and reduced by an order of magnitude for Pb and As in B and for Pb in C).

CONCLUSIONS

Ferruginous materials are a major but diverse physical and chemical component of the regolith. To effectively use these materials in mineral exploration it is important to understand their origin and mineral-chemical characteristics in the context of their landscape setting and the landscape evolution. Interpreting source locations of target and pathfinder elements in ferruginous materials depends on identifying the history, directions and extent of hydromorphic and mechanical transport of the elements during and after formation of the host iron oxides/oxyhydroxides. Possibilities include:

- "*in situ*" incorporation of elements from either mineralisation or the primary dispersion halo into adjacent or nearby iron oxides/oxyhydroxides in the weathering profile;
- limited lateral hydromorphic dispersion of dissolved elements along the water table (or palaeo water tables) and incorporation into precipitated iron oxides/oxyhydroxides;
- extensive lateral dispersion of dissolved elements by groundwater to sites where iron oxides/oxyhydroxides have precipitated and where the elements are adsorbed/incorporated;
- mechanical transport and reworking of eroded ferruginous materials containing target and pathfinder elements;
- subsequent incorporation of cations into transported ferruginous materials from a local or distal source.

Trace element fractionation can occur as ferruginous materials undergo transformation near and at the surface. This needs to be taken into account when interpreting geochemical data derived from these materials, particularly hematite-rich ferruginous lag.

More research is required to fully understand the mineral-chemical and biological controls on trace element behaviours and distributions in the ferruginous regolith.

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HYPERSPECTRAL REGOLITH AND ALTERATION MINERAL MAPPING OF THE KALGOORLIE-KANOWNA 1:100 000 SCALE MAPSHEET

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Summary

Accurately determining the surface mineralogy of the using remote spectral technologies, such as the airborne HyMap system, can complement conventional mapping methods for not only improving the efficiency and accuracy of geological and regolith maps, but in the delivery of a new range of alteration maps (metamorphic and/or metasomatic). To demonstrate this potential, a collaborative research and demonstration project was established to evaluate whether airborne and satellite spectral data could be processed to deliver a series of regolith and alteration mineral distributions for a 1:100 000 scale special mapsheet (2500 km^2) centred on the Kalgoorlie township. Data processed to date for the 26 HyMap flight-lines demonstrate that seamless maps can be derived for regolith mineral distributions (e.g. kaolinite abundance and crystallinity, iron oxide abundance and hydration state, hematite-goethite ratio, gypsum) and alteration mineral distributions (e.g. white mica abundance and chemistry [effectively the mica Al-content], talc, chlorite, amphibole). Field sampling, ground spectral measurements, XRD and geochemistry, is validating the accuracy of these mineral information products. The real significance or opportunity for these mineral information products is when they are incorporated into regolith and alteration mineral models. Previous models indicate that kaolinite disorder would be useful for mapping transported versus in situ materials. The associated laboratory study of field samples shows that the relative depth of the kaolinite 2160 nm absorption is correlated to changes in kaolinite crystal structure (that is, disorder), as shown in XRD patterns. The application of this parameter to the HyMap data broadly separates erosional from depositional areas and thus is consistent with the regolith model. Previous alteration studies (models) have shown that the white mica chemistry, measured using the wavelength position of the 2200 nm absorption, is useful for defining alteration zonation in the region, including within weathered ferromagnesian host rocks, which is a critical indicator for superimposed K-metasomatism.

Introduction

A 12 month MERIWA (www.doir.wa.gov.au/meriwa/) project, called “Regolith, Geology and Alteration Mineral Maps from New Generation Airborne and Satellite Remote Sensing Technologies” (Project Number M370) was established in mid-2004. The main remote sensing data used for the project are from the hyperspectral airborne HyMap (www.intspec.com) and the multispectral, satellite-borne ASTER (www.ersdac.or.jp/projects/aster/asterpro_e.html) systems. The vision is that project will herald a new generation of publicly available maps of regolith, geology and alteration mineralogy tiled across large parts of WA and Australia, showing mineral abundances and mineral physicochemistries at scales from 1:25 000 to 1:250 000. This new pre-competitive geoscience information will empower exploration geologists and regolith geoscientists to more effectively explore in terms of mineralogy and will complement their current use of conventional data sets including geochemistry, geophysics, aerial photography and Landsat satellite imagery. The collaborators/stakeholders involved in the M370 project include: CSIRO Exploration and Mining; HyVista Corporation; Geological Survey of Western Australia; CRC LEME; Placer Dome Asia Pacific and MERIWA. The Kalgoorlie-Kanowna 1:100 000 map area was chosen because it coincides with a special map release of this area by the GSWA; the wealth of existing data in the area; and because of the challenge for this new “surface sensitive” technology to provide valuable information for more efficient exploration in deeply weathered (covered) environments.

Results

Twenty-six flight lines of airborne HyMap data were collected in May 2004 over an 11 day period and under very poor conditions (constant high-level cloud; drying ground and vegetation flush after significant earlier rainfall; variable sun angle). These data were delivered by HyVista Corporation (www.hyvista.com) to CSIRO as surface reflectance data. Processing to mineral information products was conducted using both ENVI™ (www.rsinc.com) and CSIRO's in-house "Stygosauras™" software.

Theoretically, 127 unique variables can be generated from HyMap's 126 spectral bands, but because of natural spectral variability of surface materials, typically 30-40 surface types can be discriminated. Of these, 15-20 components can usually be identified and mapped accurately and of these just a handful (1-3) will be critical for a given application. From previous studies of Yilgarn regolith spectral-mineralogy (Cudahy, 1992, 1997), kaolinite disorder is considered important for regolith materials classification, especially distinguishing transported from *in situ* materials, and even for determining weathered host rock composition (Figure 1). For example, soils and transported materials tend to have poorly ordered kaolinite in contrast to saprock and saprolite over felsic and mafic rocks which typically have moderate to well ordered kaolinite. The degree of iron substitution in the kaolinite helps separate weathered felsic from ferromagnesian rocks. Other clays may also be present depending on host rock composition.

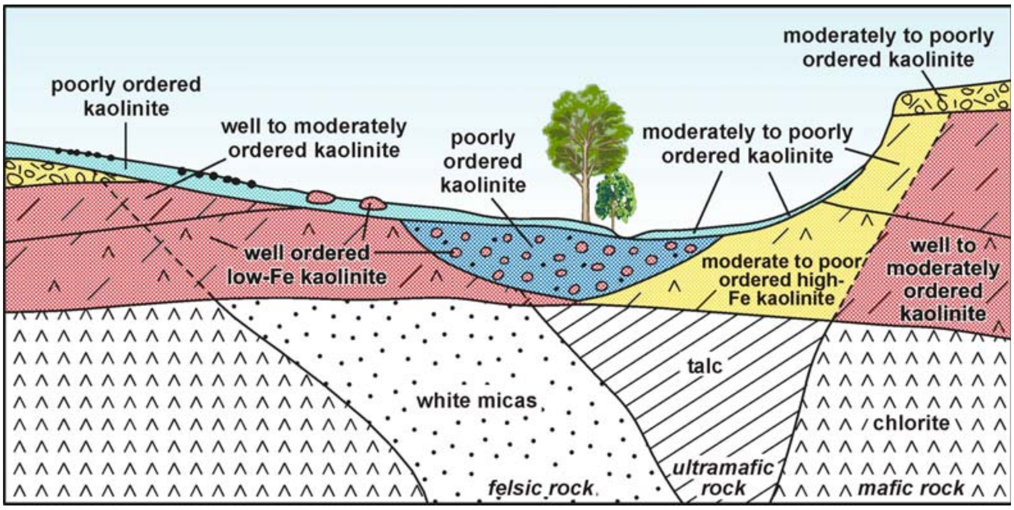

Figure 1: Schematic spectral-mineralogy regolith model for the Yilgarn focusing on kaolinite crystallinity (from Cudahy, 1997).

Cudahy (1997) established correlations between spectral parameters and XRD data that relate to kaolinite crystallinity. A similar correlation was found for the current M370 project, especially for the depth of the 2160 nm kaolinite absorption (Figure 2).

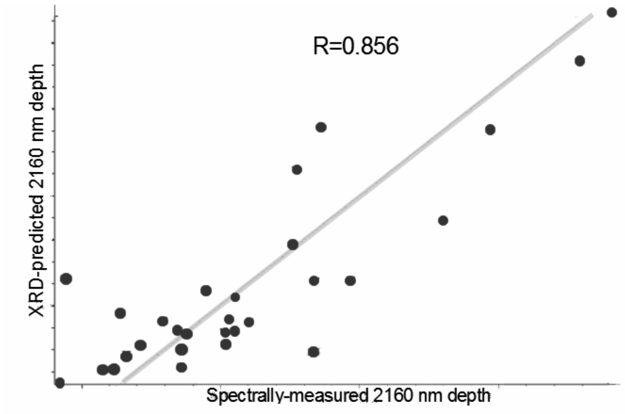

Figure 2: Partial least squares correlation established between a spectral parameter sensitive to kaolinite disorder, namely the depth of the 2160 nm absorption, and associated XRD data of field samples.

Even though HyMap has a spectral resolution of approximately 18 nm in the 2200 nm region compared with field spectrometers like the Analytical Spectral Devices Fieldspec Pro (www.asdi.com/products-FSP.asp), which has a spectral resolution of approximately 8 nm, there is little loss in precision when measuring the depth of the kaolinite 2160 nm absorption (Figure 3a) as a measure for kaolinite crystallinity. Cross-validation of the field spectral data and processed HyMap mineral maps is proceeding with due consideration given to problems in relating a single rock or soil spectral measurement with an integrated 5*5 m HyMap pixel and collocated using a GPS ground accuracy of 15+ m. Nevertheless, the emerging project results show correlation, albeit with some notable outliers (Figure 3b).

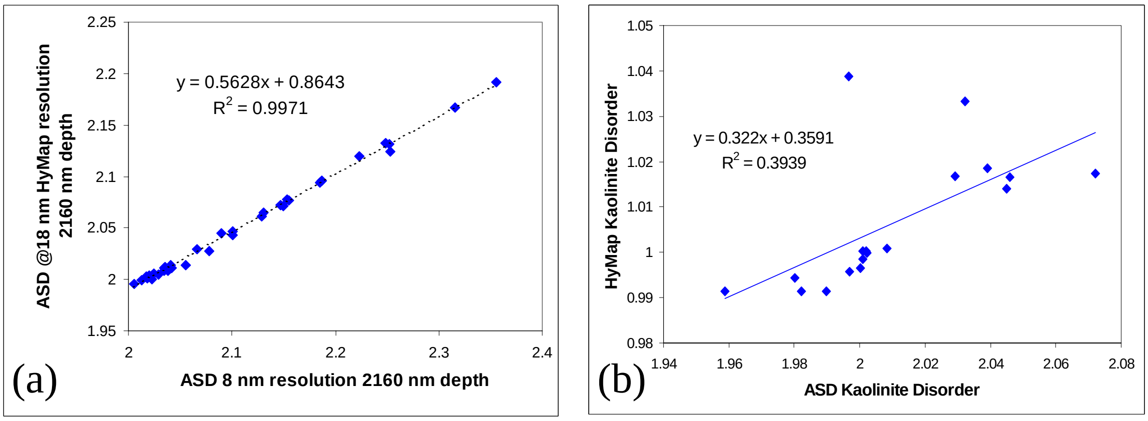

Figure 3: (a) Comparison of the measured depth of the 2160 nm absorption for field ASD spectra (8 nm spectral resolution) versus the same ASD spectra but convolved to airborne HyMap spectral resolution (18 nm) data; (b) Comparison of the measured depth of the 2160 nm absorption for actual HyMap data versus ground validation ASD results.

With the HyMap imagery processed to deliver both a measure of the kaolinite crystallinity (depth of the 2160 nm absorption) and the kaolinite abundance (depth of the 2200 nm absorption), with both products masked for white mica, green and dry vegetation and low albedo (dark) surfaces (e.g. shadow) and then draped over a high resolution digital elevation model (Figure 4), a pattern emerges that is consistent with the schematic model presented in Figure 1 and with the published regolith. That is, areas of saprolite and saprock show abundant well to moderately ordered kaolinite (“A”) whereas soils and/or alluvium/colluvium comprise more poorly ordered kaolinite (“B”). Some anomalous areas, such as “C”, comprise saprock over a white mica-rich felsic unit. The HyMap processed data show that this area contains little kaolinite of apparent poor to moderate crystallinity. From the schematic regolith-model in Figure 1, weathered felsic rocks should produce well-ordered kaolinite. This negative result is largely a function of unresolved spectral mixing problems and incomplete masking of Al-rich white mica which would theoretically degrade the 2160 nm feature to appear as a poorly ordered kaolinite. Clearly, more research is required to generate even more accurate mineral extraction methodologies.

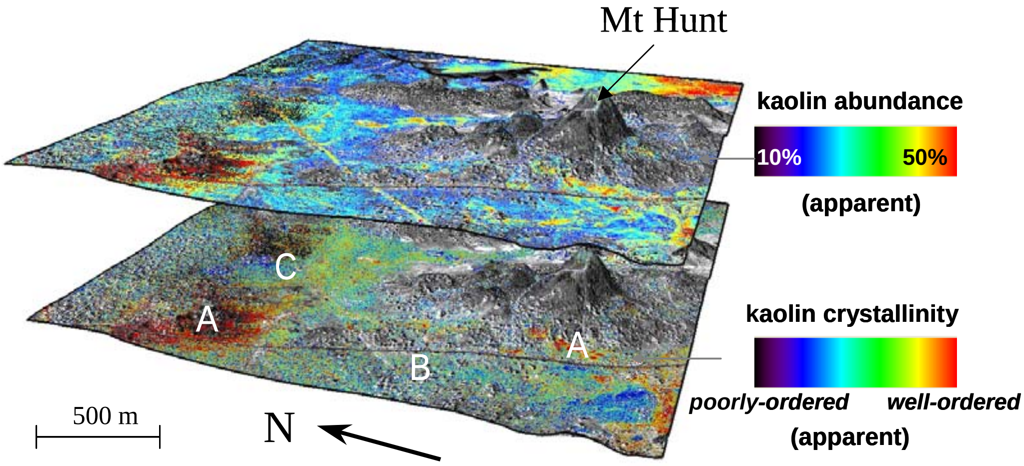

Figure 4: HyMap mineral maps of kaolinite abundance and kaolinite crystallinity draped over a DEM for the Mt Hunt area south of Kalgoorlie.

A composite mineral map that features the HyMap-derived kaolinite crystallinity as well as a range of other regolith mineral products for the entire coverage of the 1:100 000 scale mapsheet is presented in Figure 5. This is one of two hardcopy products to be generated from the M370 project. This one being the “Regolith Mineral Map Theme” and the other is an “Alteration Theme” based on white mica chemistry. The important observation to be made from the kaolinite crystallinity product in Figure 5 and the existing published regolith landform map (second from the top series of tiles in the centre of the figure) is that red areas are essentially associated with erosional regimes (cyans and purples on the regolith map) and blue-cyan area associated with depositional areas (yellows and greens on the regolith map). Armed with this type of mineralogical information (not just kaolinite crystallinity but also iron oxide mineralogy and the presence of primary minerals), regolith mapping would in theory be more efficiently achieved for at least separating transported from *in situ* materials, especially when combined with a DEM and information about vegetation type (also from the spectral data and aerial photography) and radiometrics. Furthermore, within the erosional areas there is the potential to map mineral alteration including metasomatic minerals associated with hydrothermal Au and potentially base metal mineralisation. This has also been achieved with these HyMap data but is not presented in detail in this paper.

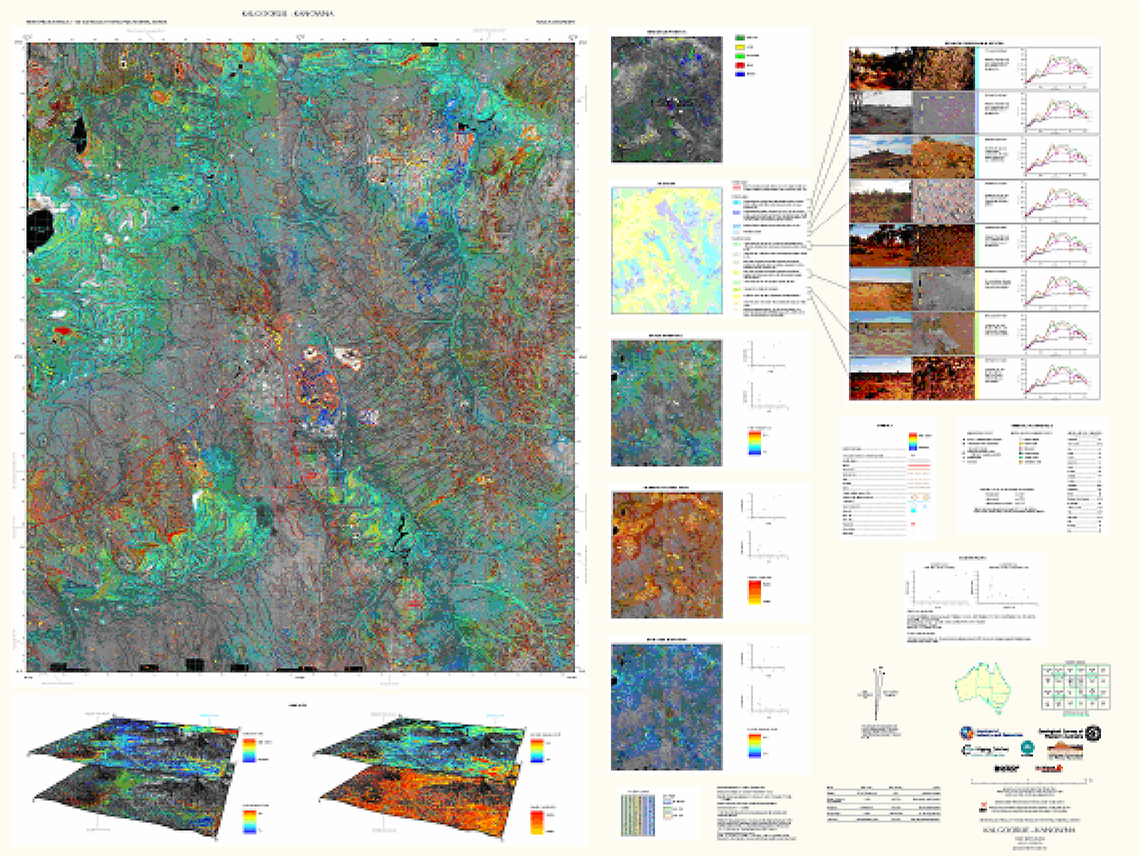

Figure 5: One of the final M370 project deliverables, namely the composite 1:100 000 mineral map for the Regolith Theme featuring kaolinite crystallinity.

Acknowledgements

This work has been possible through the efforts and resources of the MERIWA M370 Project team, including CSIRO Exploration and Mining, GSWA, MERIWA, CRC LEME, Placer Dome and HyVista Corporation. To these organizations we give our sincere thanks.

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AUTOMATED REGOLITH LOGGING – A REALISTIC PROPOSITION?

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INTRODUCTION:

With substantial parts of the Australian landscape covered by regolith, drillhole information remains critical to the discovery of buried mineral systems. As the exploration for blind or obscured mineral systems increases, so does our dependence on data from drilling and the need to offset the added costs to exploration. In part this can be achieved by increasing the value of geological information derived from boreholes, drill core, powders and chips. The advent of rapid, objective logging technologies based on the spectral measurement of geological materials (eg. Huntington et al., 2004) heralds an opportunity to use spectrally derived mineralogy in addition to other petrophysically based measurements (eg magnetic susceptibility) to generate new geological information by discriminating bedrock type from its weathered counterpart, distinguishing between transported and in situ regolith and separating hydrothermal alteration from weathering mineralogy.

From a regolith perspective, the automated and objective interpretation of drill hole cuttings and core is attractive for a number of reasons, not least for consistency when trying to interpret geochemical data in the context of a complex regolith setting, but also because potentially valuable geological information may not be evident through simple visual interpretation. Currently CRCLEME is collaborating with CSIRO Exploration and Mining, AusSpec and several mining companies to determine the potential of spectral methods for the automated logging of regolith, founded on a better understanding of their spectral properties. The prospect of automatically defining regolith units is predicated on different regolith materials having distinct physico-chemical properties that can be measured and interpreted quickly.

We are currently trialing computationally fast, readily adaptable software developed to assist in the automated interpretation of petrophysical logs. These procedures, which are in common use in the petroleum and coal industry, are increasingly being adapted for use in metalliferous and mineral exploration and mining sectors and have potential for application in exploration through the regolith. Several packages are available including LogTrans (www.minserve.com.au/software_logtrans.htm) and VIEWLOG (www.viewlog.com) which have been specifically developed for the rapid analysis of multi-parameter drillhole logs.

This paper reviews the application of the LogTrans software package in a simple case study concerned with discriminating between transported and in situ regolith materials in drill core collected from a mineralized system located in the Eastern Goldfields of Western Australia.

METHODOLOGY:

Spectral measurements of drillchips for a number of holes drilled through a complex and varying regolith in the Eastern Goldfields of Western Australia, were measured using an ASD Spectroradiometer (www.asdi.com) measuring reflected light in the visible, near and shortwave infrared (350-2500nm). Spectral analysis and interpretation was completed using The Spectral Geologist (TSG) software. Mineralogical interpretations of those minerals that are spectrally active over the range of the spectrometer are calculated using “The Spectral Assistant” (TSA™) Algorithm (Berman et al., 1999), along with their relative proportions and an interpretation error. User defined functions for the mapping of selected minerals species and defining crystallinity can be readily computed and saved for future use.

A range of spectral indices were determined, including the kaolinite crystallinity index which involves determining the depth of the so called "ordered kaolinite spectral feature" at 2160nm relative to the depth of the "disordered kaolinite feature" at 2180nm. Several workers (eg. Merry and Pontual, 1997, and Phang and Anand, 2000) have observed that this index can be used to identify regolith type, namely transported materials over in situ saprolitic clays. However, it has been recognized that this index alone cannot be used in reliably discriminating between regolith units and therefore other measures also have to be employed (Scott, 2003). In testing the use of spectral indices as a basis for the automated discrimination of regolith units, several other indices were determined, including a "Brightness index" based on the overall spectral albedo of the material being measured, A "Colour Index", A hematite:goethite ratio, an AlOH intensity index and a Fe2+ intensity index (C. Phang, *pers comm* 2004).

The automated interpretation of drill hole materials was undertaken using LogTrans, which performs automated interpretation of drillhole data, and was originally developed to interpret geophysical borehole logs (Fullagar et al., 1996). It has since been adapted to facilitate joint interpretation of logs and core-based data such as geochemical assays.

LogTrans exploits contrasts in the petrophysical, mineralogical and/or chemical properties of different rock types and presents the results in a form readily understood by geologists. The procedure involves the statistical characterisation of a representative set of geological units based upon the measured properties of those units. Then "unknown" materials collected from drilling elsewhere are assigned to a particular class of materials or units according to their proximity to known classes in "parameter space". The parameter space is determined by the rock properties being measured and in the spectral sense consists of spectral indices, or spectrally determined mineralogy. A more complete summary of the LogTrans Algorithm is provided in Fullagar et al., (1999).

RESULTS AND DISCUSSION

Fundamental to the adoption of a quantitative approach for automatically discriminating between regolith materials is the assumption that particular units can be defined by relatively invariant properties or parameters which in turn can be determined rapidly. In this study spectral indices which may differentiate between in situ and transported regolith materials have been used. Control data, based on "reliable" regolith logging are plotted in spectral "parameter space" defined by a kaolinite crystallinity index and a measure of brightness (Figure 1) with the different regolith units represented by various colours. Each of the units occupies a relatively distinct part of the scattergram, although an overlap between the saprolite and transported classes suggest that differentiation of unknown units based on these two spectral indices alone may be compromised in certain circumstances given the non-uniqueness of the two-parameter interpretation in this example. Where possible, control data should be consistent and representative and for the purposes of differentiation should be distinct. Results to-date suggest that more consistent differentiation of transported and in situ regolith requires a range of spectral indices including depth/width of the 1900nm water feature, the kaolinity crystallinity index, some measure of brightness and colour. Further studies are underway to determine what influence particular regolith settings and control materials have on the automatic differentiation of these material types.

Figure 2 illustrates the results from a LogTrans interpretation of regolith materials for one drillhole using control data from others in the area. The interpreted log is defined from the classification of regolith materials based upon a three spectrally derived parameters, a kaolinite crystallinity index, "brightness" and "colour". The result indicates that LogTrans can be used to make a reasonably stratigraphic interpretation on the basis of spectral indices, although further work is required to understand how reliably this can be used in other settings.

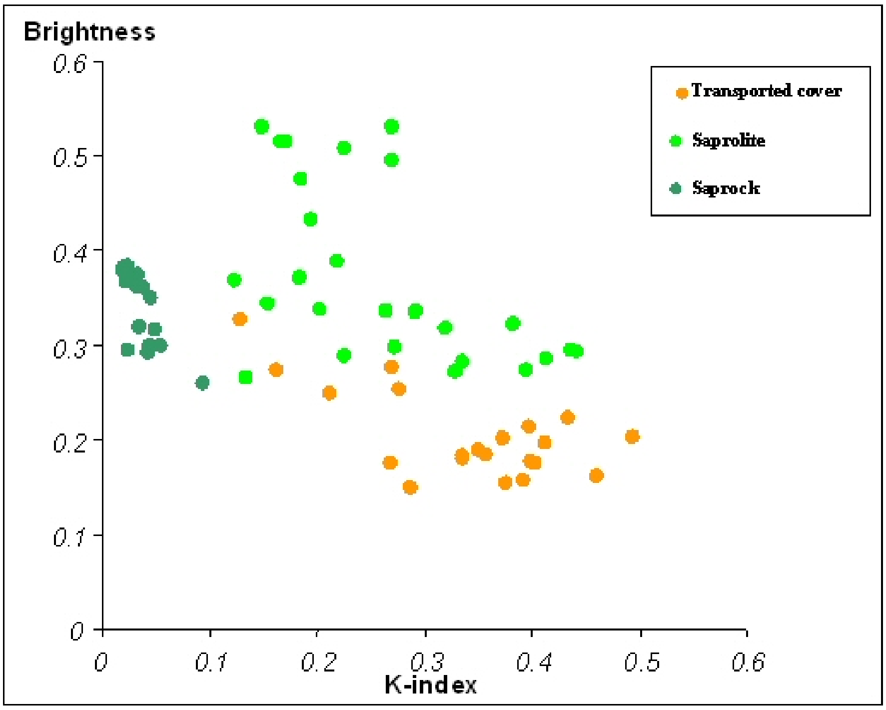

Figure 1: Spectral indices determined from the spectral measurement of drill chips, classified according to general regolith material type. Each material occupies a different "domain" in a "parameter space" as defined by these two spectral indices.

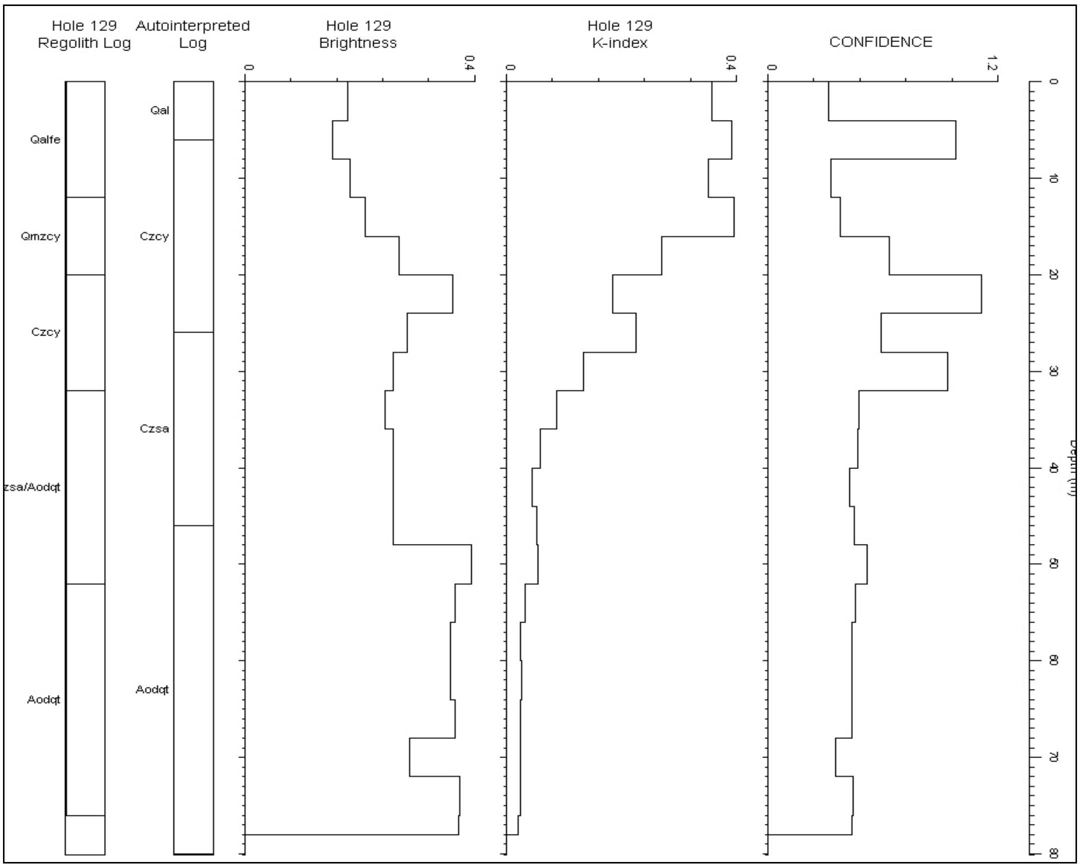

Figure 2: Actual and LogTrans interpreted geological log for drillhole #129, with corresponding spectral indices for "Brightness" and Kaolinite Crystallinity on which the automatic interpretation was based A measure of confidence for the derived interpretation is also plotted. Qal = alluvium; CzCv = colluvium, Cza= saprolite, Aodqt=saprock

LogTrans calculates a measure of confidence in the derived interpretation using a measure of standardized distances to assess the membership of particular groups (or in this case stratigraphic units). This feature is similar to that employed in cluster analysis and provides a measure of how effective the classification has been. In this example the most reliable classification is observed at the top of the profile where the most marked differences in the spectral indices are observed.

SUMMARY

Potentially drillhole returns as core, chips or powders are amenable to automated spectral analysis and interpretation, with results that could be returned in timeframes that would suit exploration. Rapid and detailed, spectrally determined mineralogical logging has already been demonstrated with the CSIRO HyLogging technologies and spectral data derived from these and other systems lend themselves to automated interpretation. However, as regolith materials are characterized by varying spectral responses, careful choice of spectral indices along with the measurement of other petrophysical properties is required for robust and reliable discrimination between particular regolith units. That said however, the principles involved in using relatively simple, computationally fast, statistically-based classification procedures such as employed in the LogTrans package, hold considerable promise for the development of automated regolith logging methods, which in turn would add value to information currently returned from exploration drilling through the regolith.

ACKNOWLEDGEMENTS

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MINERAL MAPPING AND SPECTRAL LOGGING OF THE GAWLER CRATON

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A major campaign of spectral core logging was undertaken between 29 September 2003 and 25 January 2004 at PIRSA's Glenside Core Storage Facility using the HyLogger core scanner developed by CSIRO’s Detection Technologies Group. The HyLogger offers an 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 high quality linescan camera. A computer-controlled X-Y table manages the rate of core feed and provides the precision needed to integrate the data sets. PIRSA was an active sponsor in the development of the system undertaken by CSIRO with AMIRA International (Project P685) sponsorship.

106 of the 357 holes scanned with the HyLogger in the recent campaign addressed regolith issues. 58 of the holes where chip trays. High resolution images of the core trays and automated mineralogical logs plotted by depth constitute the main products. With ancillary information provided, assay data, lithological logs and petrophysical logs can be incorporated with the interactive display.

Central Gawler Gold projects identified for this analysis included the Tarcoola Gold Mine, Barns Prospect, Tunkillia, and Lake Harris Greenstone Belt. By way of demonstration this presentation will focus on the Tarcoola Gold Mine. In this example a strong correlation has been found between the mineralogy of the weathering/alteration profile and the distribution of Au (Mauger et al., 2004).

Selected to investigate the relationship between recorded Au values and alteration minerals, 12 diamond holes from the Perseverance Prospect, BHP holes TD001-TD012, were scanned during the campaign.

Analysis of individual holes revealed the overriding spectroscopic pattern to be controlled by weathering and host lithology (Figure 1). Depth of weathering, indicated by the presence of kaolin and goethite, is variable but extends to around 70m. Host lithologies beyond the base of weathering show evidence of hydrothermal alteration in the form of hematite and phengitic white mica. Mineral species identified from HyLogger which were found to be common across holes included kaolin, illite, muscovite, phengite, montmorillonite, hematite, goethite, chlorite, carbonate, alunite, and jarosite.

Given their close spatial proximity, it proved possible to merge all 12 holes in a single file for analysis emphasising mineralogical associations and trends. Kaolin and goethite clearly characterise the weathered zone to 70m. This zone also includes sulphate species alunite and jarosite (Figure 2) – both weathering products of sulphides. Near the base of the weathered zone there is a distinct smectitic zone which corresponds with high iron oxide

(FeOx) intensity and the highest recorded Au values (max 64 ppm). Variation in wavelength of the Al(OH) absorption, which reflects changes in white mica geochemistry, does not correlate with variations in Au grade (Figure 3). Although overall white mica composition is predominantly phengitic a negative correlation between the presence of illite and Au was observed in unweathered rock.

The presence of hematite and phengitic white mica in cores of unweathered rock are indicative of hydrothermal alteration (Figure 3). Chlorite, carbonate and epidote and the depletion of Al(OH) minerals correlate with thin intrusions of diorite.

The understanding of the regolith at this stage is that there exists a zone of supergene Au enrichment near the base of the weathered zone characterised by the presence of highly crystalline kaolinite, smectite and alunite interpreted as the products of weathering an illite and sulphide primary assemblage. Below the supergene zone weathering continues but with little or no sulphate. Au values are elevated below the supergene zone but there has yet to be identified a clear correlation with alteration mineralogy. Further work is needed to verify the mineralogical trends further a field within the mineralised zone and to better quantify the alteration system at depth.

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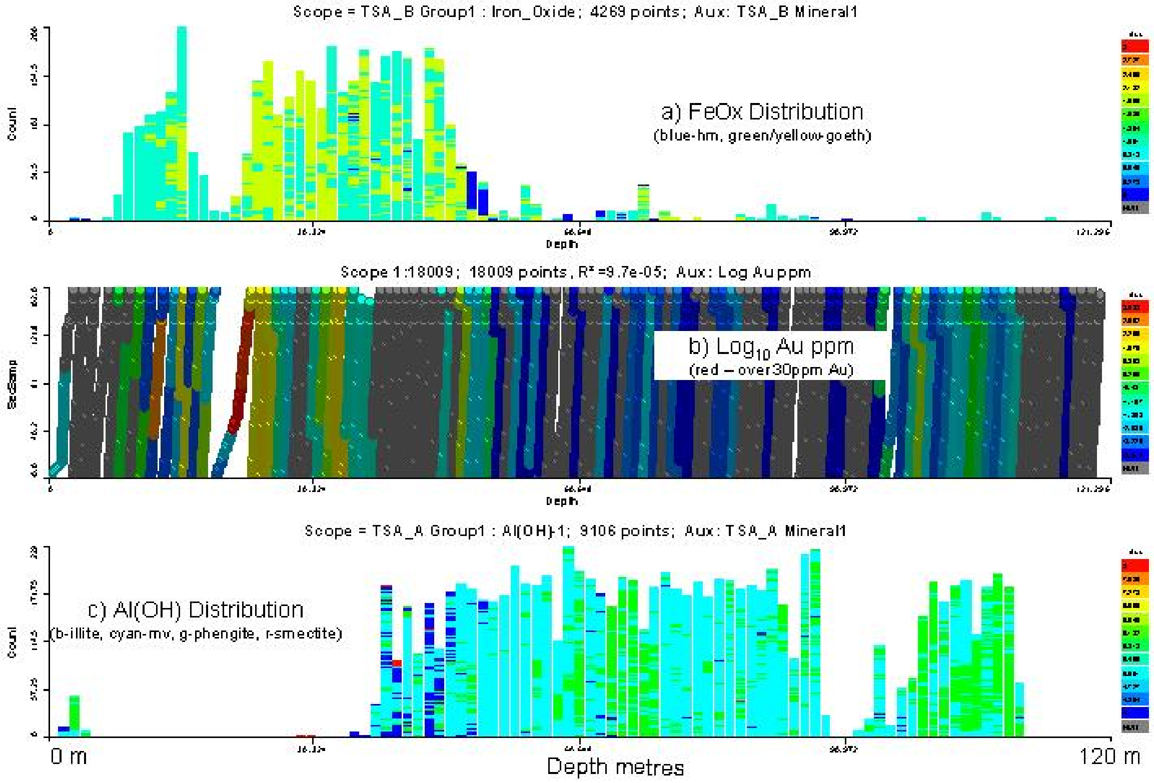
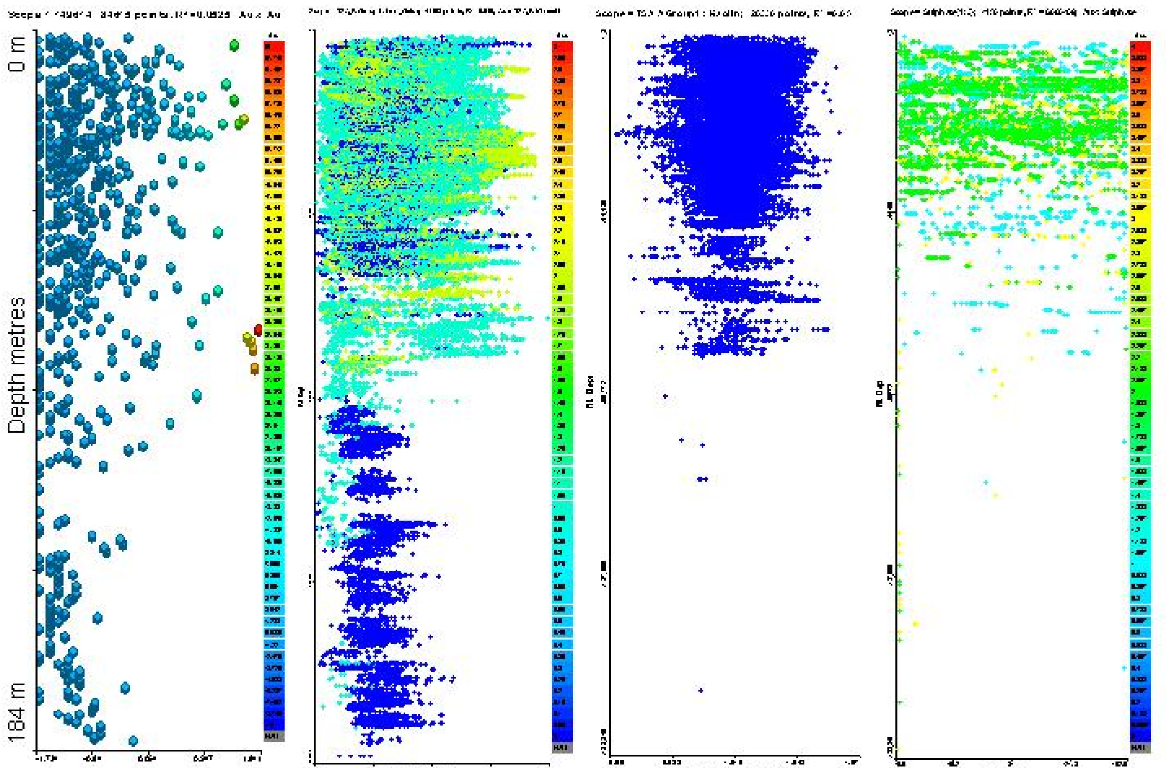


Figure 1: Tarcoola Ridge Drillhole TD001: Histograms showing downhole mineral distribution.



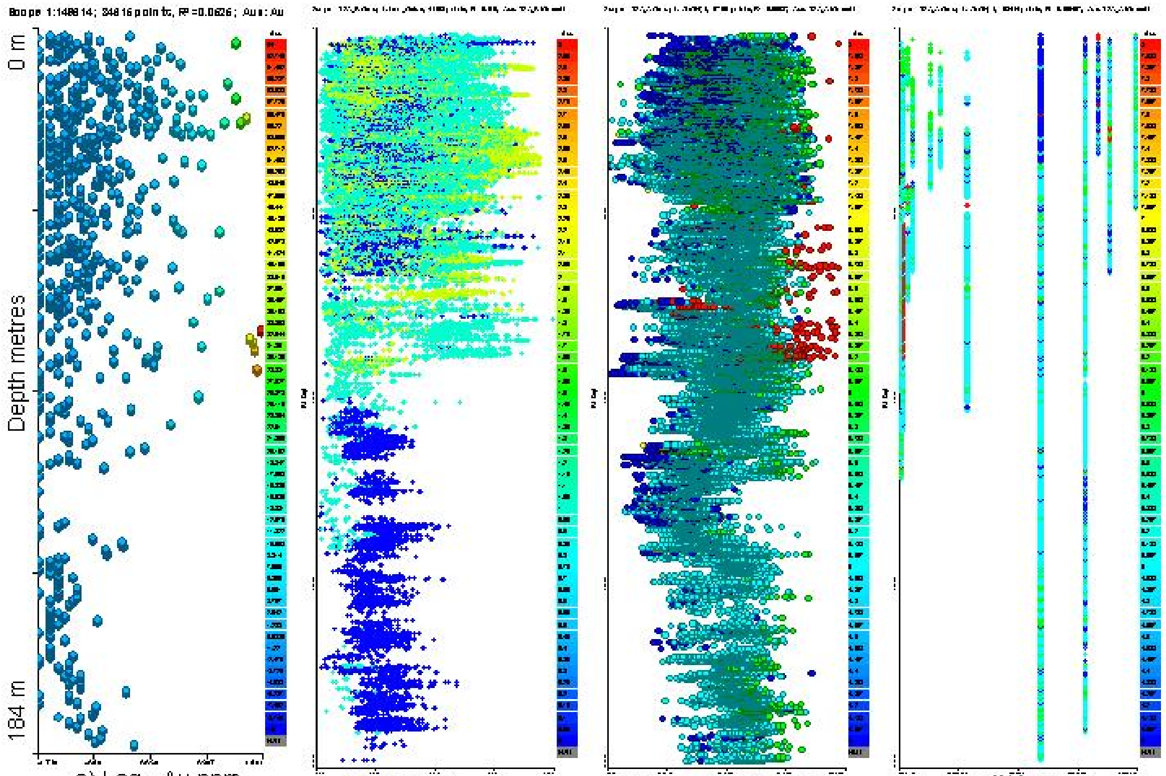
a) Log_{10} Au ppm (coloured by Au ppm 0-64)

b) FeOx Intensity (blue-hm, green/yellow-goeth)

c) Kaolin Distribution

d) Sulphate Distribution (y-Na-Alunite, g-K-Alunite, b-Jarosite)

Figure 2: Tarcoola Ridge Drillholes TD001-TD012 combined showing weathering



a) Log_{10} Au ppm (coloured by Au ppm 0-64)

b) FeOx Intensity (blue-hm, green/yellow-goeth)

c) Wavelength Al(OH) (ed-smect, blue-illite, cyan-mv, green-pheng)

d) Collar Easting (drillholes coloured by Al(OH))

Figure 3: Tarcoola Ridge Drillholes TD001-TD012 combined showing Al(OH) & FeOX distribution.

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

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Introduction

Visible and shortwave-infrared spectroscopy is a reliable and fast technique for mineralogical analysis of fresh and weathered rocks. The technique is sensitive to clays, hydrous silicates, other hydrous minerals and carbonates, although it does not recognize feldspars, quartz, sulfides and other non-hydrous minerals. The data may be used to identify regolith type, primary lithology and gold associated alteration, and thus provide valuable support to visual logging of drill cuttings and core. The study had the objectives of using IR spectroscopy to map fresh rock alteration, to test the capacity to log regolith stratigraphy "objectively", and to investigate spectral parameters for the determination of lithological features from highly weathered samples. Spectra were taken from down-hole samples from two traverses over Au deposits in the St Ives Mining Camp, Lake Lefroy, Western Australia (Figure 1), 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.

Figure 1: Location of the St Ives Mining Camp

Intrepide Traverse

The east-west Intrepide traverse extends for 730 m, with approximately 200 m of ultramafic and flanking by intermediate rocks (Figure 2). The regolith consists of 10-12 m of sediments over saprolite and saprock weathered to 50 m. Gold distribution is erratic (Figure 3), but appears to be locally higher along lithological contacts.

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[1] Analytical Spectral Device – Fieldspec Pro ©

[2] © Ausspec International Pty Ltd

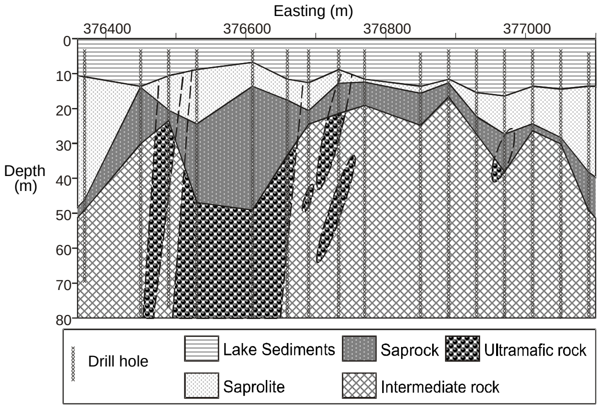

Figure 2: Geology and regolith stratigraphy of the Intrepide traverse

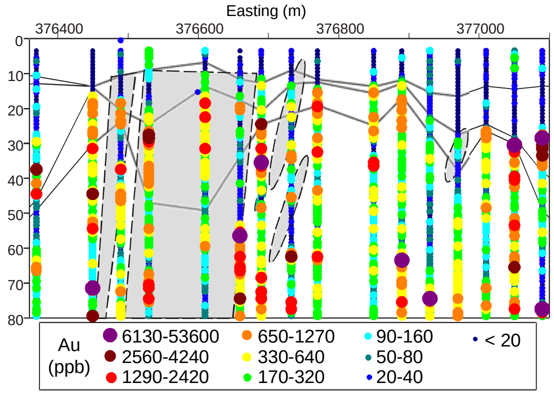

Figure 3: Gold distribution for the Intrepide traverse

Mineral maps and mineral assemblages obtained from the ASD are consistent with, and enhance visually logged geology. Intermediate rocks are distinguished by common muscovite (Figure 4) and the Si- and Mg-rich muscovite, phengite (Figure 5). The phengitic zones, not observed by visual logging, may be a useful alteration indicator. Ultramafic rocks are characterized by chlorite as a major mineral (Figure 6), they have an outer chlorite/talc zone, with carbonates (Figure 7) along the contact with intermediate rocks. On this basis, the rocks in 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 and fault, with weathering along faults.

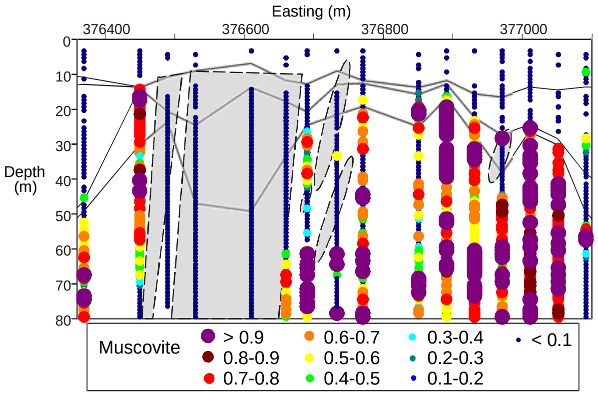

Figure 4: ASD-derived muscovite distribution for the Intrepide traverse

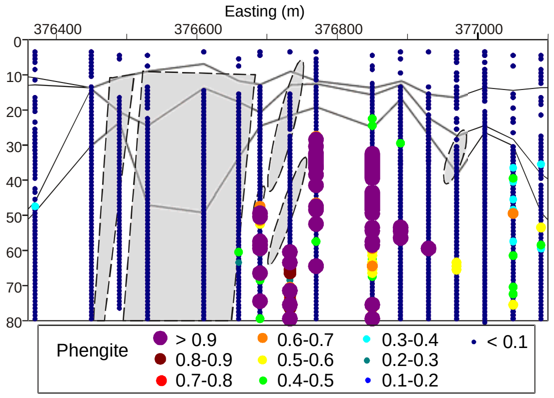

Figure 5: ASD-derived phengite distribution for the Intrepide traverse

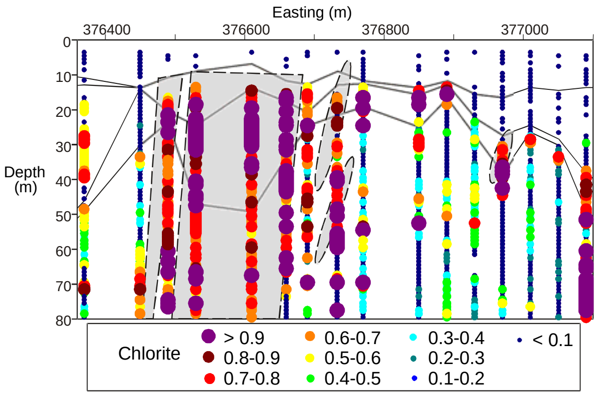

Figure 6: ASD-derived chlorite distribution for the Intrepide traverse

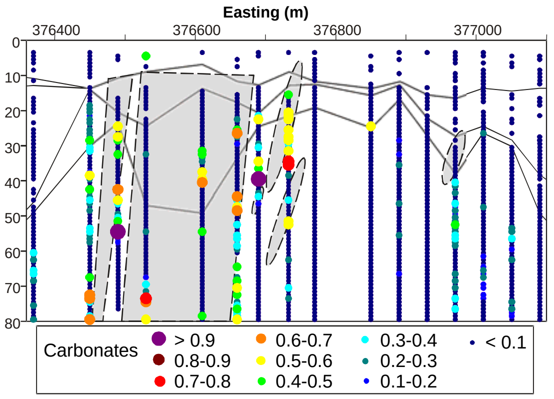

Figure 7: ASD-derived carbonate distribution for the Intrepide traverse

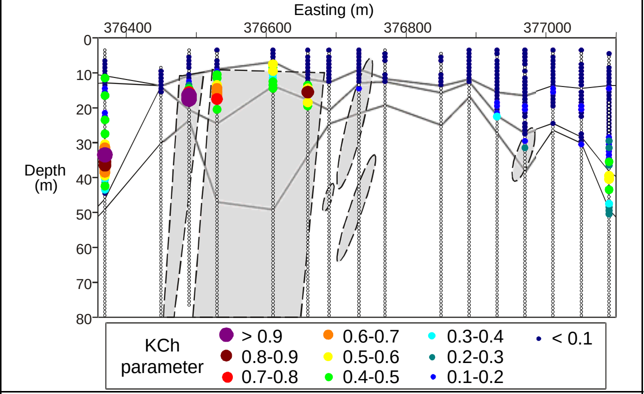

Figure 8: ASD-derived KCh parameter distribution for the Intrepide Traverse

Weathering of basic rocks commonly produces Fe-rich kaolinite, which is characterized by a minor, though readily observed peak at approximately 2240 nm. This is measured using the in-house derived KCh parameter. For the Intrepide traverse, this parameter (Figure 8) successfully recognizes ultramafic rocks from analysis of overlying saprolite. 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 (as also indicated by chlorite analyses; Figure 6).

Using spectral data, areas of sediments (Figure 9), residual regolith (Figure 10), and fresh rock (Figure 11) are distinguished respectively using the 500, 1950 and 2200 nm spectral regions. An overlap between regolith and rock indicates saprock (Figure 12). The spectrally interpreted zones agree well with those determined by visual logging, as indicated by the lines on Figure 12.

Revenge Traverse

The Revenge traverse is composed dominantly of mafic rocks, weathered to 70 m below surface, and overlain by sediments up to 25 m thick. The presence of muscovite (Figure 13) is indicative of mineralization, with various alteration or weathering effects, such as Fe oxides at depth (Figure 14), also observed. Not surprisingly, high Fe oxide contents are also observed in the saprolite and clay.

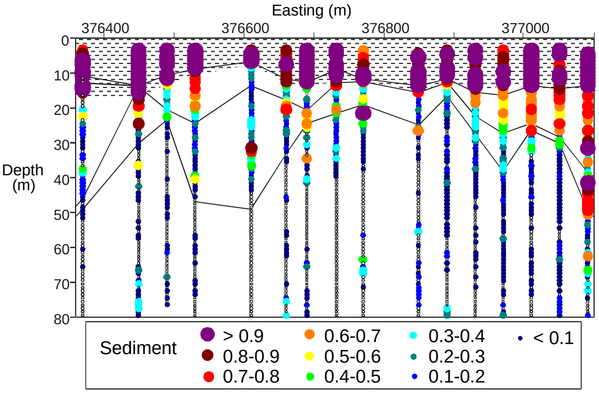

Figure 9: ASD-derived sediment distribution for the Intrepide Traverse

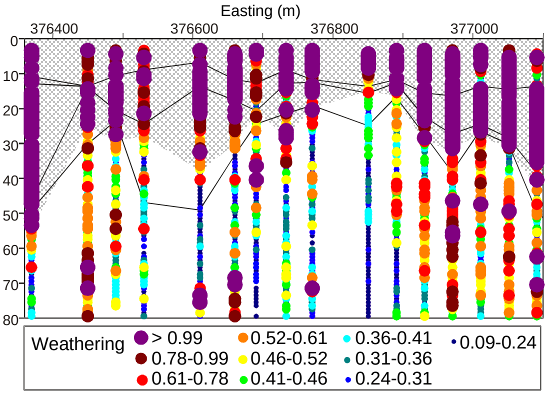

Figure 10: ASD-derived weathering distribution for the Intrepide Traverse

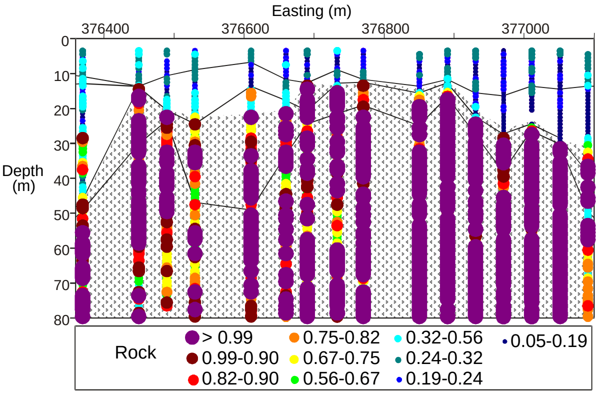

Figure 11: ASD-derived rock distribution for the Intrepide Traverse

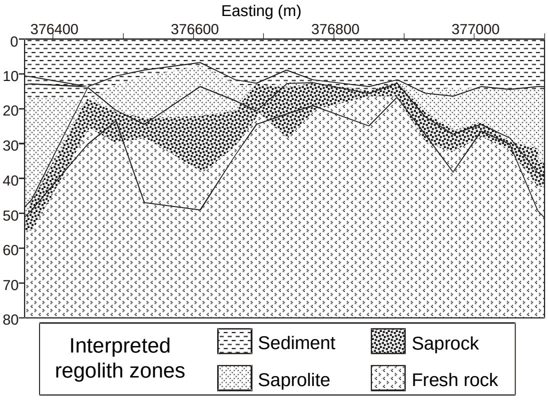

Figure 12: ASD-derived regolith zones for the Intrepide Traverse

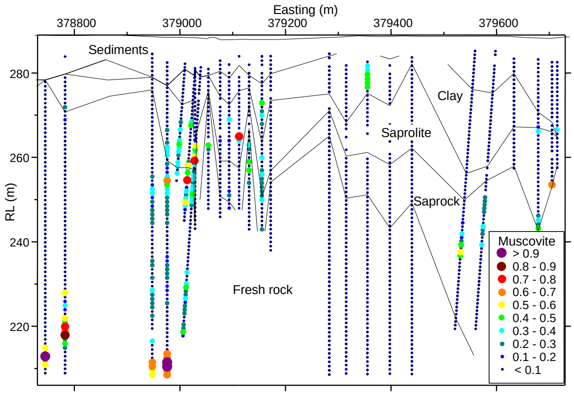

Figure 13: ASD-derived muscovite distribution for the Revenge traverse

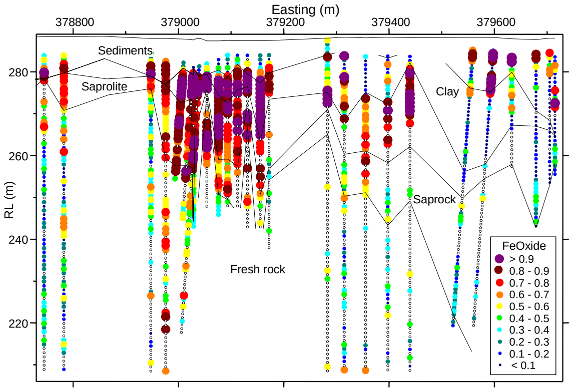

Figure 14: ASD-derived Fe oxide distribution for the Revenge traverse

Conclusions

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

GSWA MAPPING OF OUTCROP AND BEDROCK GEOLOGY

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Introduction

The geological mapping of Western Australia is a principal function of the Geological Survey, with coverage of the State at 1:250 000 completed in the early 1980s and some 20% of the State mapped at 1:100 000 scale to date. Until recently, maps were published as high quality lithographic products, providing a valuable foundation to mineral exploration and the general development of the State. A principle adhered to in this mapping has been the recording of outcrop geology and regolith in accurate detail to provide quality maps of the surface geology and, consequently, allow accurate **interpretation** of the basement geology — a vital aspect given the limited bedrock exposure in much of the State.

Recent advances in information technology have lead to enormous changes in map production and vast improvements in the use of spatial information. These advances allow more efficient collection and interpretation of geological map information, the release of maps in digital format, and the production of maps on demand from a corporate database. New products such as the 1:100 000 Geological Information Series (GIS) that provide seamless digital geology, geophysical and satellite imagery, and associated structural and petrographic data over large areas are proving to be invaluable in mineral exploration targeting.

Procedure

Mapping projects are undertaken by GSWA in regions that are economically important or are considered to have high potential for new discoveries– such as the Eastern Goldfields, the Capricorn Orogen or the west Musgrave Complex. Initial work on new mapping areas now routinely involves the collation of legacy data generated during earlier mapping by GSWA and by external academic and commercial organisations, and acquisition of regional aeromagnetic, radiometric and high resolution orthophotographic coverage. Legacy data from existing maps, notebooks, petrographic studies, and exploration reports requires transformation into digital format, with verification of spatial accuracy an essential.

Accurately rectified digital aerial photography is studied stereoscopically at 1:25 000 to allow 3-D visualisation of the area and identification of outcrop and regolith distribution, allowing the entire area to be mapped provisionally before fieldwork is undertaken. A pre-mapping compilation of all the available geological information, together with an interpretation of bedrock geology based on this in combination with geophysical and sub-surface data (exploration drilling), is now planned for release as an Exploration Data Package as soon as possible, typically a year or more before the new geological map becomes available.

GSWA fieldwork is conducted using fly-camping on traverses that allow confirmation of the outcrop distribution and rock type characteristics, collection of structural measurements, and petrological samples for further work. The amount of fieldwork required for each mapsheet, typically equivalent to a quarter degree rectangle (~45x55 km), depends largely upon the ease of access, extent and distribution of outcrop, and the complexity of the geology. For Western Australia this can vary from about 2 to 20 weeks.

The new mapping process currently being rolled out in GSWA incorporates digital data capture in the field using hand-held iPAQ palm top computers, with progressive compilation of the map to identify and solve any problems early. These data are then incorporated into the project GIS database, from which the required maps may be extracted.

Digital map packages

Digital compilation of maps involves data in diverse formats, linked by spatial attributes, and this requires the subdivision of data into different information themes or layers. Much of the power of GIS stems from this subdivision in that it enhances selective access to data for detailed analysis. The layers used in GSWA digital map packages include the following:

Geology

- Distribution and nature of outcrop and regolith units are recorded as polygons, each with a rocktype code for which standardized definitions are provided in look-up tables;
- Outcropping faults or shears, lineaments, and joints are provided as a line data layer.
- Point records represent sample sites or field observation sites.
-

Field observations – WAROX

All field observations are recorded in GSWA's corporate database, WAROX, from which appropriate records are extracted for inclusion in digital map products. The observations include rock type identification, structural measurements, petrographic description and photomicrographs (if a thin section has been made), and photographs of outcrops.

Geochronology and geochemistry

All available geochronology data are provided as points with links to records of the original analyses and interpretation. Similarly, geochemical analyses of rocks and regolith are also provided in point datasets — including the results of GSWA regolith geochemical mapping projects.

Sub-surface observations

Sub-surface records of rock types from drillholes and costeans are provided in a point dataset. Exploration drilling data is extracted from the statutory reports in the Department of Industry and Resources (DOIR) Western Australian mineral exploration database (WAMEX).

Regional interpreted bedrock geology

The bedrock geology layer provided in the databases is a map of the interpreted distribution of Precambrian rock types beneath younger cover. This is based on interpretation of detailed airborne magnetic surveys integrated with the observed outcrop geology. Polygon and line data are in separate layers.

WAMIN

The Western Australian mineral occurrence database (WAMIN) comprises the localities and commodity groups of currently operating and abandoned mines, all mineral deposits for which there is an established resource estimate, and prospects that have reported mineralization but from which there is no recorded production.

MINEDEX

The extract from the mineral deposits database (MINEDEX) provides information, either directly as point attributes or in look-up tables, for commodity groups, projects, and sites, corporate ownership, site type and stage of development, site coordinates, and current (at date of compilation) mineral resource estimates.

MITIS

The tenement information within the database is extracted from DOIR's electronic tenement graphics system (MITIS). The information includes extent and location of tenements, with identity, status, and commencement and expiry date information.

Airborne magnetic survey

Total magnetic intensity and radiometric images are provided if such data are publicly available.

Landsat 7 TM

The Landsat 7 TM layers comprise images prepared using data collected in 2002. Data from several Landsat scenes have been merged using robust regression techniques, to provide a seamless image. Spatial accuracy better than 50 m, with a pixel size of 25 m, has been preserved.

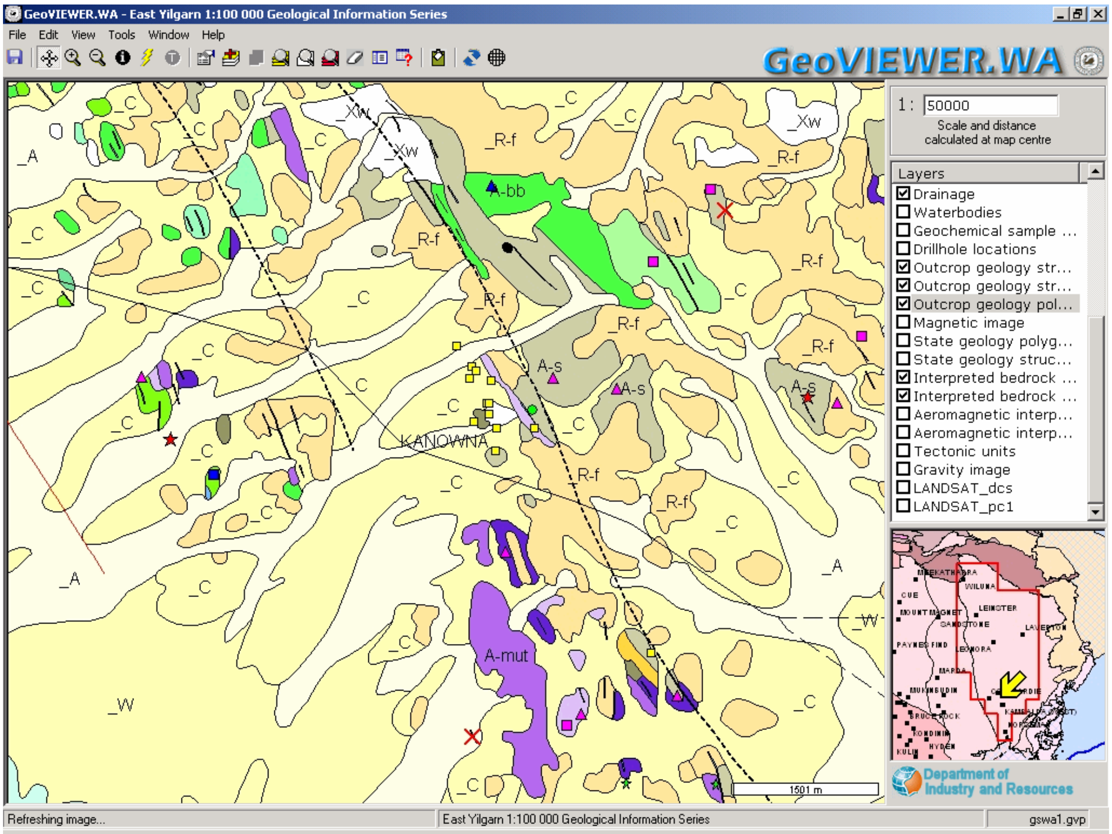
Topocadastral data

Topocadastral data are provided as separate layers for rivers and creeks, roads and tracks, airfields, railways, homesteads, townsite locations, other localities (hilltops), and waterbodies.

Software and application

The mapping and associated data are collated using software such as ArcGIS and MSAccess, and provided in formats suitable for use with GIS software such as ArcView, ArcInfo and MapInfo. To allow direct visual access to the data, GSWA has developed GeoVIEWER.WA software that allows the user to select and customize layers for viewing (Fig. 1). This software is distributed free on Geological Information Series CDs or DVDs.

An example of GSWA digital data map products is the 1:100 000 East Yilgarn Geological Information Series which comprises fifty-seven map sheets that cover 150 000 km^2 in the Eastern Goldfields region. The collation of geoscience information in this database provides a cornerstone for mineral exploration targeting in the region.



1 : 50000

Scale and distance calculated at map centre

Layers

- ☑ Drainage
- ☐ Waterbodies
- ☐ Geochemical sample ...
- ☐ Drillhole locations
- ☑ Outcrop geology str...
- ☑ Outcrop geology str...
- ☑ Outcrop geology pol...
- ☐ Magnetic image
- ☐ State geology polyg...
- ☐ State geology struc...
- ☑ Interpreted bedrock ...
- ☑ Interpreted bedrock ...
- ☐ Aeromagnetic interp...
- ☐ Aeromagnetic interp...
- ☐ Tectonic units
- ☐ Gravity image
- ☐ LANDSAT_dcs
- ☐ LANDSAT_pc1

Refreshing image... | East Yilgarn 1:100 000 Geological Information Series | gswa1.gvp

Figure 1. A typical screen view of GSWA geological map data in the Eastern Goldfields provided by GeoVIEWER.WA software.

MECHANISMS OF METAL TRANSFER THROUGH TRANSPORTED COVER WITH THE AUSTRALIAN REGOLITH: A REVIEW

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Mineral exploration programs in Australia are faced with multiple challenges when it comes to exploring across landforms underlain by “transported” and complex regolith, the main challenge being the successful application of surface geochemical techniques to identify buried deposits. A growing trend to make surface geochemistry effective in exploring across depositional landforms underlain by shallow to deep sediments is the use (and abuse!) of partial and weak selective extractions (SWE), gas analysis and biogeochemical surveys to delineate anomalies in depositional landforms (some of these techniques have been in application for over 30 years). However, these techniques have found mixed success in delineating buried ore bodies and not merely ‘anomalies’, especially in Australia, because the particular mechanism(s) and their effectiveness in transferring metals associated with mineralization upwards through the often complex transported overburden is poorly understood, thereby complicating and limiting the interpretation of datasets, and precluding the discrimination of negative and false anomalies. To address the lack of understanding of various upward metal transfer mechanisms through transported regolith (as opposed to the metal concentration in residual regolith), a review was conducted to evaluate the potential mechanisms effective in the Australian environment. In general, besides solid state diffusion, which is extremely slow for most metal cations except H^+ (Smee, 2003), four dominant mechanisms with potential to transfer metals upwards through barren cover were identified (some covered by Cameron, et al. 2004): groundwater, gases, vegetation and bioturbation. Most of these categories have variants or sub-mechanisms, and may be influenced by microbial processes, and all are summarized below.

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 and 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. Keeling (2004) has suggested capillarity as the main driver for dispersion Cu through 5-8 m of transported cover at Moonta, SA. *Seismic* or *dilatancy pumping* occurs in neo-tectonic active areas where faults and fractures act as conduits for upward transfer of mineralized groundwater (Cameron, et al. 2002). Earth tremors promote compressional stresses along faults and force groundwaters upward, with possible surface discharge 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 or diffuse heat sources. These can promote faster solute migration in a particular direction and the possible formation of irregular fronts. The oxidation of sulphides in an ore body is an exothermic reaction that produces heat and is capable of increasing groundwater temperatures and facilitating rapid increases of solute concentrations above ore bodies. The ability of convective flow 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 (Govett, et al. 1984). Another variant of the electrogeochemical 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 (Hamilton 2000). This model is considered to account for the rapid transfer metals upwards through thick (30 m) saturated cover (Cameron et al 2004). All the groundwater supported transfer mechanisms are limited to the upward limit to which groundwater rises or the water table (and capillary fringe), except that of seismic pumping. In the Australian environment dominated by Mediterranean, semi-arid, and arid settings, groundwaters are commonly more than 5 m below surface except in lower, discharge landform sites, and other, or additional, mechanisms are necessary to transfer metals from the water table upwards.

Gases migrate via molecular diffusion, advection and gas streaming (Hale 2000). Diffusion and advection appear to be the main sources of rapid upward migration of ore related gases (CO_2, SO_2, COS) and possibly of volatile metals. The upward *diffusion* of gases and volatiles that are produced as a result of weathering of ore body (COS, CO_2, H_2S, Hg) has been experimentally shown to be viable mechanism of volatile metal transfer but has limitations in individual gas stability and tortuosity of the weathered and often cemented regolith medium. *Atmospheric pumping*, the depression front set up by large barometric pressure change, causes rapid upward migration of air present in pores and conduits, and has the capability to transport volatile (I, Hg) and radiogenic elements from nuclear blasts (Cameron, et al. 2004). Atmospheric pumping is restricted to fractured media, and whether it may operate in a connected heterogeneous sedimentary overburden needs testing. *Gas streaming* or bubble migration is the upward transfer of microscopic gas bubbles that form within the groundwater due to overpressure, and are then 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), especially if the gas bubbles have an organic coating acquired from trace organics in groundwater. The bubbles can then be transported upwards to the near surface environments, where pressure changes are proposed to induce bubble instability and release metals. The stability of bubbles during their transfer from a saturated to an unsaturated medium as well as the fate of adsorbed matter on bubbles when the bubbles destabilize is unclear. 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 gas anomalies are present, and this confirmation holds promise to at least accurately demarcate local structural features.

Vegetation or plant physiological uptake of elements from subsurface and their release to the surface via litter is a potential mechanism of rapid metal transfer. However, proof is required that plants tap into deeper water sources for their nutrient content, otherwise higher metal content in plant tissues merely may indicate recycling of a soil anomaly. The potential of plant assisted metal transfer from deeper groundwater comes from deuterium isotopic studies on facultative pheratophytes – plants having dimorphic roots systems with laterals and sinker or tap roots (vertical), the latter roots acquiring water and nutrients from deeper groundwater source, especially during summer (Pate, et al. 1999). Recent work on plant metal relationships in Northern Yilgarn suggests plants do uptake ore related metals from groundwater at depth. Additionally, hydraulic lift – redistribution of deeper water acquired by sinker roots to near surface soil horizons to be used by laterals (Caldwell, et al. 1998) - is capable of rapid transfer of water and possibly metals within the overburden. Diurnal uptake and transfer of water groundwater to surface soil has been confirmed, but no data exist on ore metal transfer.

The depth of rooting is critical to the ability of vegetation in transferring water and possibly ore metals upwards. A global survey indicates that deep roots, especially sinkers, are ubiquitous with > 10 m depths regularly reached and confirmed in several climatic settings (Canadell, et al. 1996). Plants are known to take up mineralization associated metals that are essential micronutrients (Zn, Mo, Se) plus other ore metals (Au, Ni, Cu, Pb) and even potentially toxic metals such as As in significant concentrations (Meharg and Hartley-Whitaker 2002). Plant physiological processes biotransform specific metals within their tissues, thereby influencing the effectiveness of selective leaches and element mobility once the metals are released on the surface via litter. For example, gold absorbed by roots in the dissolved form can be converted into colloidal form within the plant tissues, and arsenic and other elements are combined with phytochelatins to reduce toxicity. The subsequent release of these organo and colloidal species on the surface and their impact on partial or selective leaches needs further evaluation. Preliminary results point to the potential of phreatophytes and other specific plants to transfer metals from 10 m deep, current or paleo groundwater tables (redox fronts) or capillary fringes, but identifying the role of plant species, the rate and amount of metal transfer to the surface via particular plants and the regolith and groundwater environments (perched or permanent, saline or fresh) under which plant transfer is operative requires extensive testing.

Bioturbation within the biomantle 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 in the Australian environment, but only ants and termites have the capacity to penetrate deeper into the transported regolith (> 1 m). These bioturbators, in combination with rainwash, are the primary cause of soil (and anomaly!) homogenization and lateral dispersion of surface anomalies over time. Although bioturbation on freshly deposited sediment begins within years with 1 m penetration achieved randomly, it is the development and evolution of the biomantle across the depositional landform that needs to be considered for anomaly homogenization and true anomaly detection, and the rate of biomantle homogenization varies from hundreds to thousands of years depending on the interplay between deposition rates on the landform and climatic/biotic factors. Furthermore, barring a few exceptions from the Kalahari in Africa, the effectiveness of bioturbation decreases rapidly downwards, with activity mostly ceasing at a depth of 2 m, which is likely to be the limit for uniform biomantle homogenization in most landforms.

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 sulphide oxidation and other redox transfers (Edwards, et al. 2000). Microbial metabolism can impact on gaseous migration of elements by generating methanogenic, CO_2 and sulphur gases, and by generating volatile metal species via biomethylation (As, Se, Sb, Mo). They can influence the efficiency of metal uptake by roots via redox reactions, symbiotic associations and organic secretions. Microbes participate in intracellular and extracellular formation of minerals (and gold particles) within the saturated zone and soil, and can influence the efficiency of partial and selective leaches (Figure 3). Microbial induced biomethylation (with As, Sb, Se, Hg) can significantly affect the “loosely” bound metal fraction or the efficacy of selective or partial leaches. For example, recent studies demonstrate microbial role in biomethylation of commonly used pathfinders with some of the metal differentiating into volatiles (Craig, et al. 2003), possibly followed by demethylation. Microbial roles need to be investigated to address the question of whether the results of selective leaches or gas analysis are dependant on microbial populations and soil conditions rather than transfer mechanisms.

The vital parameter that influences 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,** both factors in turn affected by time and landscape evolution. Weathering of the overburden and formation of concomitant water table within the sedimentary overburden 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. This has been shown to occur at a couple of sites in Western Australia. Alternatively, younger, fresh to slightly weathered sediments, even of shallow depth, will afford a much lesser opportunity for diverse mechanisms to operate, except mechanisms capable of rapid metal transfer such as gaseous diffusion and advection and possibly plant uptake, depending on porosity, anisotropy and hardness of the transported material. However, specific partial leaches, gas measurements and electrochemical techniques, rely 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.

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Figures

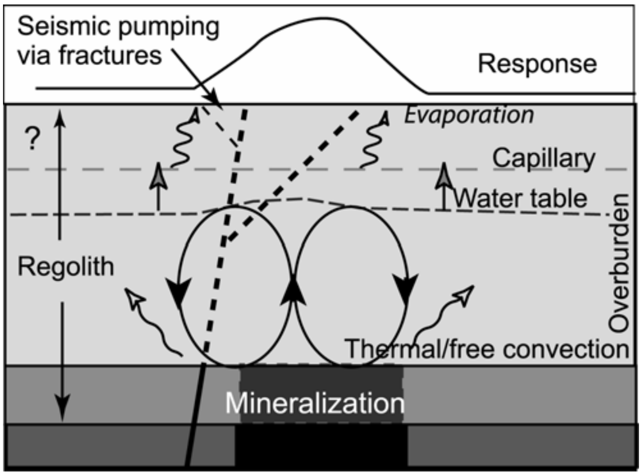

Figure 1. Some potential hydrogeochemical mechanisms for dispersion through transported regolith. The genesis and evolution of electrochemical processes within saturated transported cover are covered by Hamilton (2000).

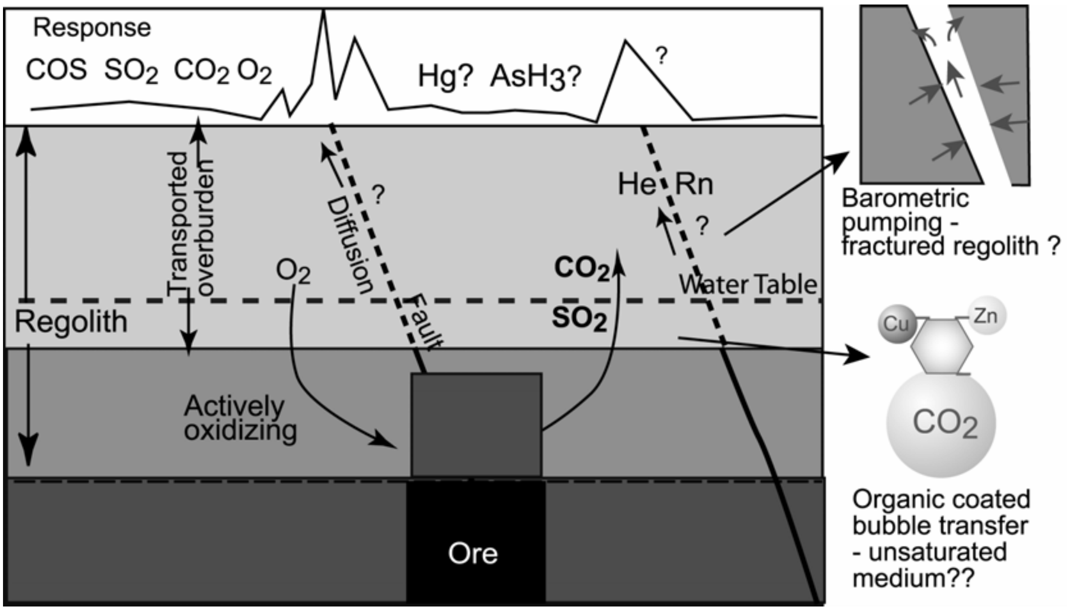

Figure 2. Illustration of potential gas based migration mechanisms through transported regolith.

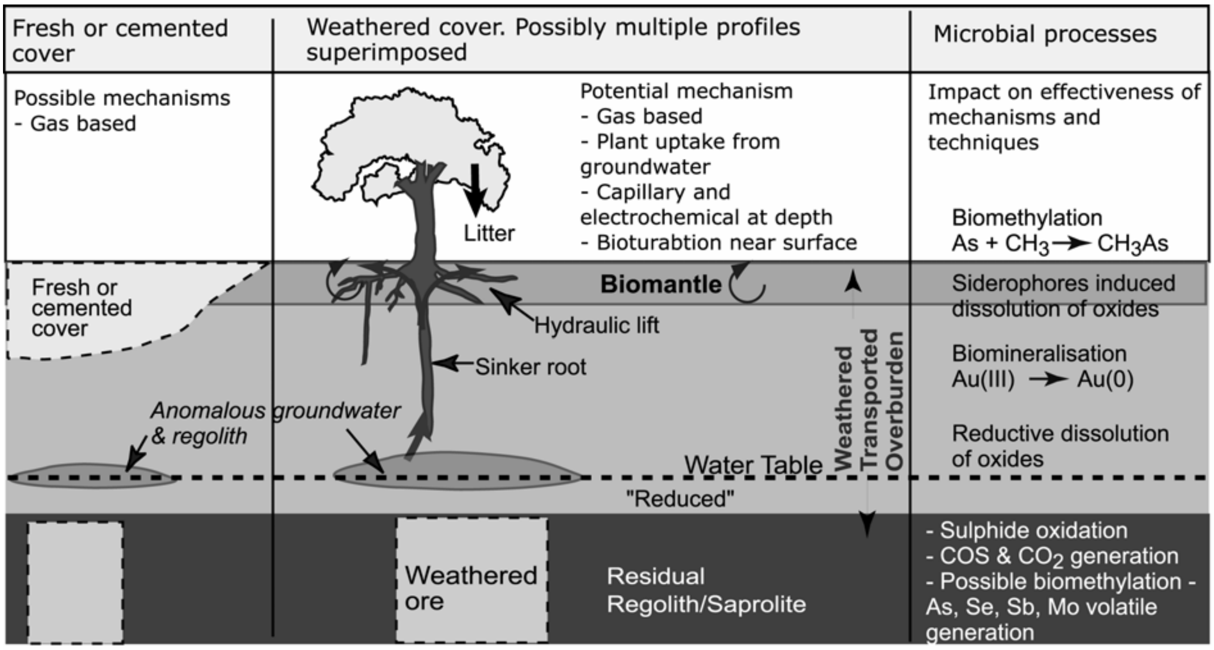

Figure 3. Illustration showing the operation of potential mechanisms depending on nature of cover (fresh or cemented as compared to deeply weathered with minimal cementation) and influences of microbial processes.

IN-SITU MICROANALYSIS TO STUDY REGOLITH MINERAL HOSTS IN FERRICRETE FROM THE ENTERPRISE PIT, MOUNT GIBSON GOLD DEPOSIT

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INTRODUCTION

Insitu geochemical microanalysis is a powerful method to search for specific mineral and regolith features that act as hosts for ore related elements (e.g. Au, Cu, Pb, As and Zn) and we have applied this approach to a pit-wall regolith profile from the Enterprise Pit, Mount Gibson gold deposit. The physical features of the landscape, bedrock geology and regolith profiles of the Mount Gibson gold deposit (300 km NNE of Perth) and its environs, have all been studied extensively (e.g. Anand et al., 1989; Yeates and Groves, 1998). Transported overburden at the Enterprise pit at Mt. Gibson has been subjected to ferruginisation, calcification and silicification. As previously reported (Hough et al., 2003) these sediments, and their weathering products, provide a good setting to study mineral and regolith features that act as hosts for ore-related elements, and may provide pathfinders for underlying mineralisation. Ultimately such studies are expected to identify minerals that act as deep geochemical sensors and are therefore, exploration sampling media in areas of deep cover.

ENTERPRISE PIT: Transported overburden.

In the Enterprise pit in-situ regolith is overlain by Tertiary and Quaternary sediments. Slabby to pisolitic ferricrete is formed in the Tertiary sediments with anomalous (up to 587 ppb Au), whereas white clay between the slabby layers contains 112 ppb Au and 85 ppm arsenic. The uppermost sandy to sandy-clay Quaternary unit is 3-4 m thick, and has been calcified and silicified to produce calcrete and hardpans with 128-436 ppb Au.

Building on our previous study (Hough et al., 2003) we have conducted XRD analyses of the ferricrete, this revealed that it contains alunite, a potassium aluminium sulphate that is commonly precipitated from acidic groundwaters, kaolinite, and only minor goethite. Alunite occurs within the matrix of the sample, and is very fine grained with a red-brown colour. It appears as a late stage, pervasive precipitate that surrounds clay spheres and clasts.

We have also performed new laser ablation ICPMS (LA-ICPMS) and electron microprobe studies on the ferricrete, LA-ICPMS has been shown to be a powerful technique in the analysis of regolith samples, especially for Au (Le Gleuher, 2003a; b; Hough et al. 2003). Our previous LA-ICPMS analyses on the kaolinite-rich matrix from this ferricrete sample revealed that it contained 1-1.5 ppm Au, 290 ppm Cu and 360 ppm As. At this stage we interpreted that kaolinites within the matrix were authigenic, and as such were trapping hydromorphically dispersed Au from underlying mineralisation. Minor iron oxides in the matrix were thought to be preferential sinks for the Cu and As. Our new XRD data and some SEM work suggest this matrix is dominated by alunite.
An electron-microprobe transect from the core of a clay sphere into the alunite rich matrix reveals the sharp change in trace element concentrations with substantial Cu (290 ppm), Pb (500 ppm), and As (360 ppm) in the alunite rich areas. The new LA-ICPMS analyses confirm the probe data and building on our preliminary results (Hough et al., 2003) several analyses found 1-2 ppm Au within alunite rich areas. Hematite veins and large kaolinite rich clasts within the ferricrete are devoid of Au and have much lower levels of Cu, Pb and As.

Butt (2001) reported a similar alunite Au association in the mid-upper saprolite at the Mount Percy gold deposit near Kalgoorlie, bulk S contents of 0.5-5% were reported in this horizon.

During LA-ICPMS spot analyses we were able to monitor the count levels for the Au isotope in the mass spectrometer as the laser gently ablated the samples. This allows us to reveal if the Au is present as small grains, whereby it would give peaks, or is homogeneously distributed giving a constant plateau. Within the alunite matrix Au counts formed a constant plateau suggesting the Au is homogeneously distributed throughout the ablated material, and is therefore likely to be either extremely fine grained or chemically bound within the alunite mineral lattice. In the near future we hope to utilise X-ray adsorption spectroscopy using synchrotron radiation to investigate this further, and to attempt to identify the oxidation state of the Cu, Pb and As.

We have also recently employed laser transect analyses in combination with ICPMS, here the laser continuously ablates as the sample moves on a motorised stage creating a transect. The neoformed sample travels through, and is analysed by, the mass spectrometer in the same way as for single spot analyses. This method creates large datasets as many elements can be collected contemporaneously and over a relatively long time scale, but is a rapid means of identifying the location of anomalously high levels (largely qualitative) of specific elements including Au in a heterogeneous sample e.g. regolith samples. Some new results from this technique will also be presented.

SUMMARY

Minerals precipitated from groundwaters in the upper sediments of regolith profiles could provide an interesting sample medium to search for hydromorphic dispersion from underlying, and deeply buried mineralisation. Alunite appears to be one such mineral occurring in the regolith profile of the Enterprise pit, Mount Gibson that contains appreciable Au, Cu, Pb and As.

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PROGRESS ON ANOMALY FORMATION IN CALCRETE

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Work on calcrete in CRC LEME continues on many fronts. This talk will try to summarise some of the more interesting or important findings that have been made within the last two years. Work is continuing on mechanisms as to how anomalies form in calcrete and how best that these may be used to refine the exploration methods that use this geochemical sampling medium. Current or recently completed CRC LEME research on calcrete that can be found on the CRC LEME website (LEME symposia) includes:

Finding blind orebodies: geochemical exploration for large nickel-copper PGE sulphides on the western Gawler Craton: **A. Lockheed & K.M. Barovich**.

Geology and geochemistry of regolith carbonate accumulations of the southwestern Curnamona Province, SA: implications for mineral exploration: **P.D. Wittwer, K.M. Barovich & S.M. Hill.**

Gold mobility within dune systems on the Barns prospect, Wudinna, South Australia: a partial extraction approach: **L.B. McEntegart & A. Schmidt Mumm.**

Key findings from the South Australian regolith project: **M.J. Lintern, M.J. Sheard & G. Gouthas.**

Origin and genesis of calcrete in the Murray Basin: **L.N. Tylkowski, D. Chittleborough & K.M. Barovich.**

Strontium isotopes as an indicator of the source of calcium for regolith carbonates: **R.C. Dart, P.D. Wittwer, K.M. Barovich, D. Chittleborough & S.M. Hill.**

The biogeochemistry of calcrete forming processes: **A. Schmidt Mumm & F. Reith**.

By the far the largest of these studies was “The South Australian Regolith Project” that concluded recently with the issuing of a final report. Sixteen or more case studies involving calcrete were undertaken and a series of exploration models for different settings were constructed. Briefly, conclusions were similar to those found for AMIRA-CSIRO Yilgarn studies undertaken last decade:

1. Calcrete is the best near surface sampling medium for Au and should be used as a first pass geochemical sampling technique.
2. It usually occurs within a metre of the surface and is readily identifiable using dilute acid.
3. It works best as a guide to mineralization where transported overburden is absent or thin (<10 m), and when there is saprolite (weathering) rather than fresh bedrock in the residual regolith.
4. Local topography may lead to the development of transported anomalies located away from their source mineralization.

In addition, it was shown that in specific environments (high water table, acidic groundwaters and <10 m of transported material), upward dispersion and co-precipitation of Cu and Au with alunite may occur at the base of the calcrete horizon due to a pH change.

Exploration companies are still faced with the dilemma of which of their many calcrete anomalies should be drilled first – how do we rank geochemical anomalies? It is now considered that to move forward on this problem, the research emphasis must be directed towards understanding the process and a number of projects have been completed, or are under way, that shed light on the way calcrete anomalies form.

GOLD NUGGETS: FORM AND COMPOSITION.

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INTRODUCTION

Gold nuggets have long captured the imagination of exploration geologists, prospectors and the general public and have an important role in public perception not only of the gold sector, but of the mining industry in general. Western Australia, and particularly the Eastern Goldfields, is one of the principal locations in the world where nuggets have been, and are, relatively abundant. However, as time passes, they are becoming more difficult to find and their commercial significance has increased accordingly. Nevertheless, despite this widespread interest, the origin of gold nuggets is controversial and their geological significance is uncertain. In particular, it is uncertain whether some or all nuggets are partially or wholly "primary", that is, formed during the emplacement or metamorphic alteration of the ore, or whether a proportion are "secondary", formed at the earth surface during weathering.

The term 'nugget' is poorly defined as "a large lump of placer gold" (AGI Glossary). In Western Australia, the term is applied to masses of gold from a few millimetres to tens of centimetres in size. Few, if any, are found in placer deposits and, as such, have a rather different origin from that implied by this definition.

In Western Australia, most gold nuggets have been found at or near the soil surface. Others have been found deeper within the regolith and at the weathering front. Smaller nuggets, in particular, may be intimately associated with, and even enclose, soil materials and weathered rock. Even large nuggets are reported to have surface features and/or gross morphologies that suggest chemical reworking in the regolith. In addition, large masses of gold have occasionally been found at considerable depth, in completely unweathered, primary environments.

Gold is a noble metal, implying that it is inert under most ambient, earth-surface conditions and commonly considered chemically immobile in the weathering environment. Consequently, gold nuggets, especially those found in placers, have generally been regarded as primary in origin. Those in placers are considered to have physically eroded from the original ore and subsequently transported and deposited under fluvial conditions, and those in deep regolith accumulated by residual concentration during weathering. These views have been held especially by geologists working in temperate regions in the Northern Hemisphere. However, for over 100 years, Australian geologists and chemists have recognized that gold can be chemically mobile under some weathering conditions (Liversidge, 1893a, b), and could therefore form "secondary" nuggets in zones of supergene enrichment.

We will present our new data on the form and composition of a selection of gold nuggets from Western Australia. These results provide a valuable contribution to the debate on the origin and weathering of gold nuggets.

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DEVELOPING ENHANCED HEAVY MINERAL EXPLORATION STRATEGIES – LESSONS LEARNT FROM THE MURRAY BASIN IN WESTERN VICTORIA

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Introduction

Recently, due to the discovery of several heavy mineral deposits such as Wemen, Murrayville and the WIM 150 deposits (Figure 1), the Murray Basin has been identified as a new and important heavy mineral province where mid-continental beach placers associated with the Loxton-Parilla sands contain economic concentrations of ilmenite, rutile, and zircon (Roy et al., 2000). One such deposit, the Bondi Main heavy mineral beach placer deposit (currently operated by Iluka Resources), was the subject of a number of detailed studies. As a result of these studies, a number of findings were generated, many having some obvious benefits in the development of future exploration activities. These include the development of a palaeogeographic model, establishing a stratigraphic framework, rapid heavy mineral identification and provenance studies.

Regional setting

The intracontinental Murray Basin occupies over 300 000 km^2 of inland southeastern Australia (Figure 1) and contains an extensive preserved strandplain that provides a remarkable record of sea level change throughout the Late Miocene and Pliocene (Figure 1). This variably buried strandplain is characterised by a series of dominantly northerly to northwesterly trending ridges and swales that extend over a strike length of some several hundred kilometers. Although previously noted by earlier workers, these linear features were first interpreted by Blackburn (1962) as representing successive coastlines. These and associated sediments are now referred to the Loxton-Parilla sands, which were deposited in association with the regressive phase of a short-lived marine incursion into the western Murray Basin by a shallow epicontinental sea during the Late Miocene to Pliocene.

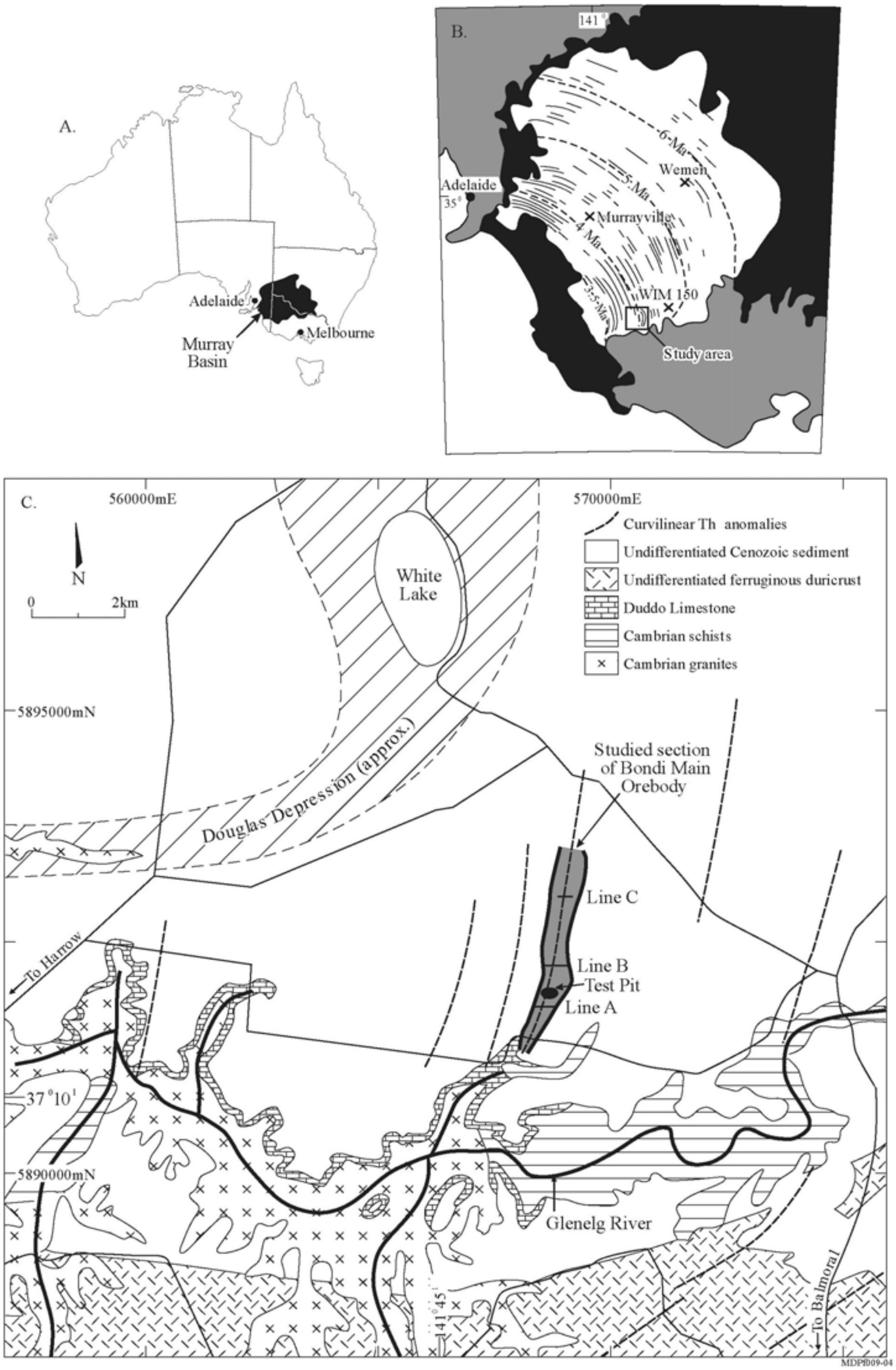

Figure 1. (A) Location of the Murray Basin within southeastern Australia. (B) Distribution of the Loxton-Parilla-sands within the Murray Basin (shaded black). Orientation of the strandlines and their assumed ages modified after Kotsonis (1995) and the location of some of the many heavy mineral placer deposits within the basin. (C) Location of the studied portion of the Bondi Main heavy mineral deposit, the three drill traverses used in this study and the location of the test pit. Curvilinear Th/U anomalies traced from radiometric imagery for the area provided by the Department of Primary Industries, Geological Survey of Victoria. After Paine (2005).

Palaeogeographical modeling

Most heavy mineral deposits form in conjunction with some form of heavy mineral trap that concentrates heavy minerals in favorable settings along the coast. Accordingly, the recognition of these traps forms an important component of a heavy mineral exploration campaign. For example, heavy mineral deposits such as the Yoganup, Capel, Minninup and Eneabba in Western Australia have all formed in “J” shaped bays with headlands at their southern ends. These headlands presumably acted like a riffle to trap heavy minerals on the updrift side but allowed less dense quartz-rich sand to bypass to the south (Lissiman and Oxenford, 1975; Shepherd, 1990). Similar geographical settings have also been noted at other heavy mineral deposits e.g. Geelwal Karoo deposit in South Africa (Macdonald and Rozendaal, 1995). Similarly the coastline hosting the Bondi Main deposit was truncated by a rocky headland in the form of the elevated Dundas Tableland (Figure 2) at its southern end. In the absence of such a prominent trap, which is often the case for the remaining Murray Basin deposits, other physical barriers are required. Consequently Whithouse et al. (1999) proposed (a) the growth faulting model or (b) the substrate erosion model as likely heavy mineral concentration mechanisms.

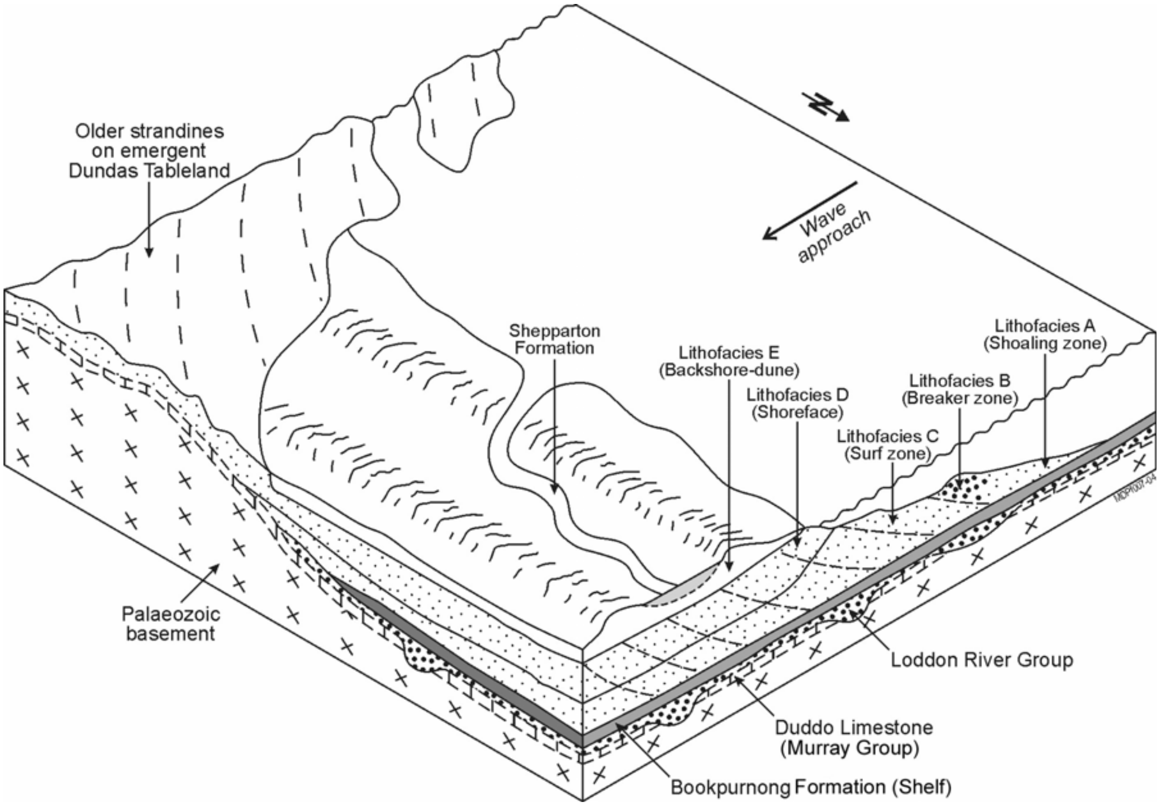

Figure 2. Palaeogeographical model for the Bondi Main deposit showing depositional environments for the units and established lithofacies studied. After Paine (2005).

Stratigraphic framework

The majority of the worlds heavy mineral resources occur as placer deposits hosted by coastal sediments. More specifically, heavy mineral deposits commonly occur within facies deposited in the more energetic environments such as the swash zone. Site-specific stratigraphic models however often reveal a more complex story, demonstrating their necessity at individual sites.

Complications such as stacked heavy mineral lenses, re-mobilisation of heavy minerals into the adjacent aeolian dunes and storm wash overs are some of the features encountered. Indeed this is the case at the Bondi Main deposit, where a detailed lithofacies analysis demonstrated (a) both individual and stacked heavy mineral rich swash zone facies (Lithofacies D, Figure 3), (b) remobilization of heavy minerals into aeolian sediments and (c) the establishment of a basal unit (the Bookpurnong Formation) that effectively represents the base of the heavy mineral-bearing sequence.

Rapid heavy mineral identification

Commonly, heavy mineral analysis of both modern and ancient placer deposits has relied upon either magnetic separation (Franz Isodynamic Separator, Rapid Magnetic Separator), point counting techniques or a combination of the two. These techniques have been used to provide both weight % and/or frequency % data where typically 300 grains are counted per sample. The Automatic Geological Scanning Electron Microscope (AutoGeoSEM) offers an alternative to these techniques and has some advantages in that (a) it is fully automated, (b) it produces objective compositional data and (c) it is capable of analysing large numbers of grains (Robinson et al. 2000). By utilizing the AutoGeoSEM, down hole heavy mineral concentrations were plotted for studied sections through the Bondi Main deposit (Figure 3). Following this, a number of implications relevant to exploration were deduced. Firstly, it was found that the weathering overprints at the Bondi Main deposit, such as ferruginous pisoliths, nodules and hardened mottles, have contributed significantly to the heavy mineral suite. It is prudent therefor not to rely solely on heavy mineral grade; varietal studies are also required when assessing the economic potential of a deposit. Secondly, it was found that the swash zone sediments not only contain the greatest quantity of heavy minerals, they also contain greater proportions of the valuable heavy minerals such as ilmenite, the intermediate titanates, rutile/anatase and zircon. This renders them as the most favourable lithofacies to target for sourcing economic concentrations of heavy minerals. Thirdly, it appears that there are no significant differences in the relative proportions of heavy minerals between the transgressional and regressional swash zone Lithofacies (Lithofacies D, Figure 3). Finally, the fact that at least locally the interpreted dune sediments contain a heavy mineral suite that is representative of the heavy minerals in the underlying swash zone deposits, presents an interesting implication for at least local scale heavy mineral exploration. Backshore-dune deposits generally occur at the top of regressive coastal deposits (as they do here) and consequently, present an accessible sample medium, which in this case would provide a representative sample of the various heavy minerals in the underlying swash zone.

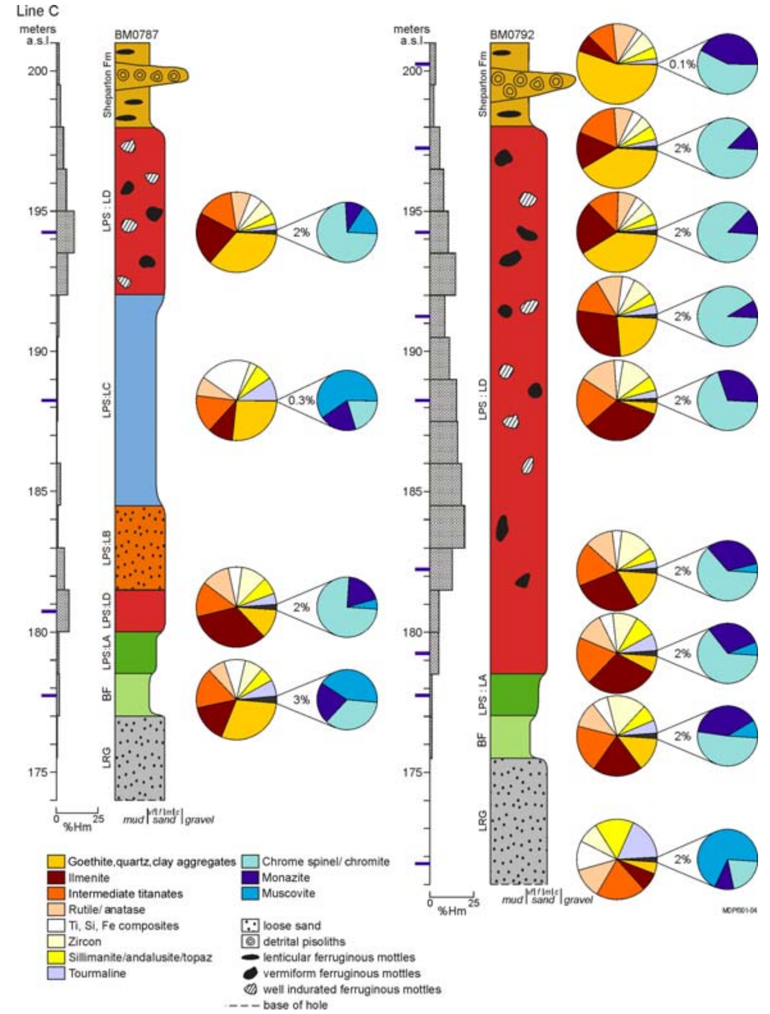

Figure 3. Vertical stratigraphic sections for drill holes along Line C across the Bondi Main deposit and associated heavy mineral type and concentration. BF = Bookpurnong Formation, LPS = Loxton-Parilla sands (Lithofacies A to E), LRG = Loddon River Group, SF = Shepparton Formation. Iluka Resources supplied hole names, collar elevations and total heavy minerals as weight % for each drill interval. After Paine et al. (2005).

Heavy mineral provenance

One of the principal factors contributing to the modern interest in provenance studies is the affect that source rocks have on the overall quality of the detrital heavy minerals they produce. For example, Basu & Molinaroli (1989) found that detrital ilmenites derived from igneous source rocks show a wide range of TiO_2 contents with a mode of about 47 % whereas those from metamorphic source rocks show a tighter cluster around 52 %. Belousova et al. (2002) demonstrated that trace elements such as Y, Ce, U, Eu, Yb, Sm, Nb, and Ta, in igneous zircons were also influenced by source rock type. They found that there is a general trend of increasing REE abundance in zircons from ultramafic through mafic to granitic rocks. Consequently the provenance and composition of both zircons and rutile from the Bondi Main deposit were investigated using Laser Ablation ICPMS analysis. These results will be presented at the conference.

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NICKEL LATERITES

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Nickel laterites are regolith materials, derived from ultramafic rocks, that contain economically exploitable reserves of nickel (and, commonly, cobalt). They are found where the ultramafic rocks outcrop over a wide area and the regolith is well preserved. The deposits are developed on olivine-bearing ultramafic rocks, mainly dunite and olivine-pyroxene peridotite, and their serpentinized equivalents. The nickel is derived principally from forsteritic olivine ($>Fo_{75}$), which commonly contains 0.16-0.40% Ni.

The nickel concentrations generally occur in one or more horizons or units within the profile and the ores can be classified according to their mineralogy (Brand *et al*, 1998):

> *Oxide:* dominated by iron oxyhydroxides, principally goethite, forming the mid- to upper saprolite and extending to the pedolith. Nickel is hosted mainly in goethite, by substitution for iron and/or by adsorption. Manganese oxides (*e.g.*, asbolan, lithiophorite) are commonly abundant and are enriched in both cobalt and nickel. Deposits developed over dunites (adcumulates) may contain abundant secondary silica. Mean grades are about 1.0-1.6% Ni; examples include Cawse, Ravensthorpe, Goongarrie.
>
> *Clay silicate:* dominated by Ni-rich smectites such as nontronite and saponite, commonly in the mid to upper saprolite and pedolith. Nickel in these minerals is fixed between structural layers or substitutes for ferric iron in the octahedral layer, with concentrations up to 4%. Mean grades are generally 1.0-1.5% Ni. The deposits form from peridotites (mesocumulates and orthocumulates) and are exemplified by Murrin Murrin and Bulong.
>
> *Hydrous Mg silicate:* dominated by hydrous Mg-Ni silicates in the lower saprolite. The silicates are mainly nickeloan varieties of serpentine, talc, chlorite and sepiolite, many of which are poorly defined and are known informally as “garnierite”. Globally, these ores have the highest grades (mean 1.8-2.5% Ni), and are typically found in areas of high relief. In Western Australia, they are represented only by low grade altered serpentines (e.g., at Ravensthorpe). Similar minerals also occur in saprolite at the Mt. Keith MKD5 deposit, but this does not constitute a nickel laterite resource.

The deposits formed under the humid climates prevailing in the Cretaceous to mid-Tertiary, but have been modified under later arid conditions by the precipitation of secondary silica, especially over dunites, and magnesite in saprolite.

Enrichment of nickel occurs in the regolith on all originally olivine-bearing ultramafic rocks, although the amount varies according to the mineralogy of the protolith and its metamorphic history. The high grade, hydrous-silicate deposits in high relief areas of the humid tropics are typically developed on ophiolitic olivine-orthopyroxene peridotites (harzburgites). Conversely, talc-carbonate rocks never give rise to economic concentrations of nickel in the regolith, although contents are elevated compared to the primary abundance and to other lithologies.

In addition to bedrock lithology, the formation of nickel laterite, including the type and grade, is controlled by geological structure, tectonism, climatic and weathering histories, regolith-landform setting and topography (Table 1). These influence the intensity of weathering, the drainage status of the regolith at different stages of its development, and the degree of preservation of the profile.

TABLE 1: Summary of controls on nickel laterite formation

	Hydrous Mg silicate	Clay silicate	Oxide
Climate	Humid savanna – rainforest	Humid savanna; possibly formed or modified in semi-arid climates	Savanna; modified in semi-arid climates
Relief	Moderate	Moderate to low	Moderate to low
Drainage	Free	Impeded	Free or impeded
Tectonism	Promoted by uplift	Inhibited by uplift.	Promoted by uplift
Primary structure	Promoted by increased weathering and Ni enrichment along open fractures	Enrichment on some fractures. Possibly promoted where faults impede drainage.	Promoted by increased weathering and Ni enrichment along open fractures
Primary lithology (only olivine-rich ultramafic rocks).	Peridotite>dunite.	Peridotite>>dunite	Dunite and peridotite. Component of all deposits.

Knowledge of the characteristics of nickel laterites is essential for effective exploration for nickel sulphides in deeply weathered terrain. Higher concentrations of nickel may be developed in the regolith over barren adcumulates than over similar rocks containing disseminated or matrix mineralization. Secondary enrichment is commonly focussed along fractures and shears, and the geochemical data alone may simulate the distributions associated with weathered sulphide mineralization and associated wall-rock. Discrimination can be made by use of abundances and ratios of pathfinder elements, such as copper and the platinum group elements, but the solutions are not unique and wholly reliable diagnostic criteria have yet to be found.

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LOCATING ORE UNDERCOVER USING LOCATORE® AND OTHER GEOCHEMICAL TECHNIQUES. EXAMPLES FROM STAWELL, VICTORIA AND HONEYMOON WELL, WA

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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 a new bacterial leach LocatOre® and other more common geochemical techniques to identify mineralisation undercover. Two very different prospects are investigated; Wildwood, gold mineralisation in north western Victoria and Honeymoon Well, nickel mineralisation in central Western Australia.

The Wildwood Au prospect is located 250 km northwest of Melbourne and is situated on the boundary of the Ballarat Trough and Murray Basin, comprising 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 where potentially repeating gold bearing units occur under a varied thickness of regolith. The regolith cover overlying the mineralised zone is 25-75 m thick. Murray basin alluvial sediments at this location overlie basalt, volcanogenic sediments and psammopelitic rocks. The regolith can be categorised as a thin, weathered soil underlain by Loxton/Parilla sands, above Geera clays and a thin layer of saprolite. The regolith thickness generally increases to the north.

The Honeymoon Well Ni prospect is located 45 km south of Wiluna in the Agnew-Wiluna greenstone belt. Disseminated and massive sulphide deposits are hosted in the ultramafic sequence of diverse metamorphosed komatiite lithologies (Gole and Woodhouse, 2000). The regolith in the study site is 15-40m depth of mixed transported material.

Soil sampling was undertaken along traverses across areas overlying known mineralisation. Samples at Honeymoon Well were taken at the surface and at 30-40 cm below the surface, while samples from Wildwood were taken at the argillic horizon 30-85 cm below the surface. Samples were subjected to LocatOre® 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.

Empirical assessments of anomaly expression of the geochemical techniques over the two sites were 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).

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

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. LocatOre® significantly predicted mineralisation ($P(x)$<3%) on 2 of the 5 assessed traverses at Wildwood (Figure 1), but none of the 3 traverses at Honeymoon Well were successfully predicted. The lower the probability the more successfully the mineralisation is predicted (Stanley, 2003). The results indicate that LocatOre® is providing some beneficial results, but is not consistently identifying the mineralisation under cover. The LocatOre® geochemical suites respond similarly over all traverses. This trend 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. Other geochemical techniques were not successful in detecting the mineralised zone undercover; however some techniques still need to be applied to the Honeymoon Well samples. No single element anomalies were evident at Wildwood, but some inconsistent single element anomalies were found at Honeymoon Well. These anomalous points at Honeymoon Well also require further investigation. Values of the surface materials were much lower than those collected at depth at Honeymoon Well location which could be of significant importance in future soil sampling exploration in the area. Future research on the influence of soil properties and anomaly expression will be required to better understand LocatOre® and other techniques in this region.

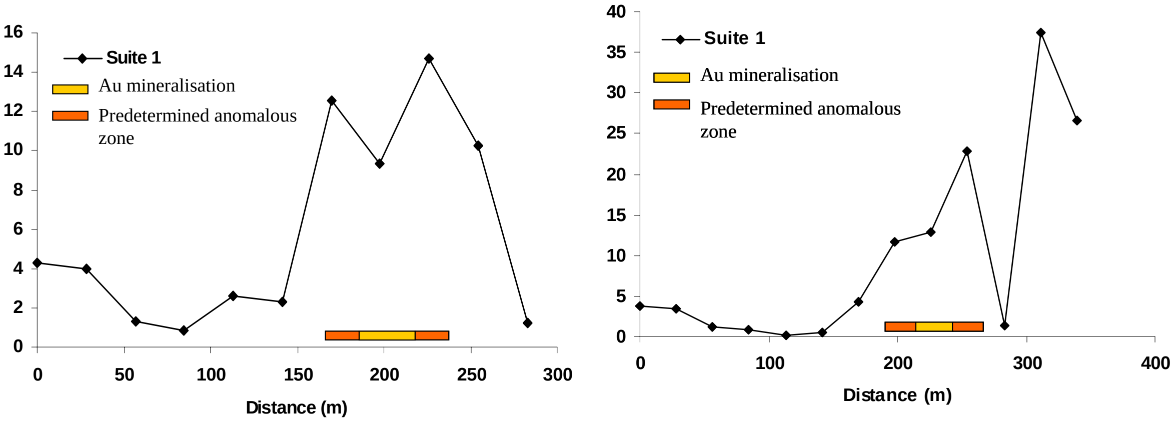

Figure 1. Two successfully predicted traverses from Wildwood using LocatOre®.

Further investigation of the soils was undertaken to compare the results of these chemical extractions with those of the LocatOre®. Comparing the responses for elements based on the various leach treatments by correlation and principle component statistical analysis indicated that LocatOre® was most similar to the weak hydroxylamine hydrochloride leach. The hydroxylamine hydrochloride specifically targets the amorphous Mn oxide phases and implies that LocatOre® may be slightly selective towards the same phase.

The results of this study have allowed for identification of possible areas of buried mineralisations using LocatOre® that were not apparent through other chemical extractions in Victoria. However, the success is inconsistent and was not successful in the different climate of Honeymoon Well. LocatOre® significantly provided different geochemical information than the other techniques, although hydroxylamine hydrochloride was similar. Whether LocatOre® has superior qualities as an individual 'stand alone' technique is yet to be determined. Regardless of this fact, LocatOre® and other partial or selective extractions are likely to be a beneficial tool in future geochemical exploration in areas of regolith cover.

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USE OF BIOTA IN MINERAL EXPLORATION IN AREAS OF TRANSPORTED COVER IN THE YILGARN CRATON

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Biota geochemistry has not been widely used as an exploration technique for Au and base metals in Western Australia because sampling of soils and other surface materials has been reasonably effective in finding new mineral deposits in deeply weathered areas with or without shallow transported overburden. Future discoveries of base metal and Au resources in deeply weathered terrains are likely to occur under several to many metres of transported overburden where soil and lag sampling are likely to be ineffective. As the focus of exploration shifts to these more difficult terrains, biota geochemistry needs to be investigated. This paper presents findings of some recent LEME work on biota that form geochemical anomalies at surface over buried deposits.

We are investigating several gold and base metal deposits in the Yilgarn Craton and of these we will discuss two sites. At these locations, transported cover ranges in thickness from 8 to 20 m. A variety of biota samples were collected at each site and procedures were developed for their preparation and analyses. Soil samples were also taken 5-10 cm below surface at each site to compare the chemistry of the biota and soil. In contrast to soil data, biota geochemistry shows unequivocal evidence of buried mineralisation and therefore appears to be more effective in certain environments than conventional soil and selective extraction of soil.

Present biota geochemistry results are most encouraging and may lead to a practical method for locating mineralisation under transported cover in greenfield areas. We consider this a highly perspective field for future research which LEME is therefore addressing as a matter of priority.

A NEW UNDERSTANDING FOR THE USE OF BIOGEOCHEMISTRY TO EXPRESS MINERALISATION THROUGH TRANSPORTED COVER IN REGIONAL AND PROSPECT SCALE MINERAL EXPLORATION

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INTRODUCTION

In recent years a range of regolith biogeochemistry research projects have been undertaken in the Curnamona Province and immediately adjacent areas in western New South Wales and eastern South Australia. The biogeochemistry of tree and shrub species (as summarised in Hill & Hill, 2003) has been the main focus of the research although increasing consideration is being given to faunal biogeochemical characteristics. This manuscript provides a brief overview of some of the highlights of this research program.

RESEARCH STRATEGY

The ultimate aim of the research program has been to develop the application of biogeochemical sampling media for use in mineral exploration and environmental chemistry sampling programs (Hill, 2004). There is more to this than simply picking parts of plants and sending them off to the laboratory for analysis. Biogeochemical sampling media are typically dynamic and complex, however by having some respect for the characteristics of the media to be sampled a suitable sampling strategy can be developed. The sampling strategy needs to be rigorous and robust, with a major aim being the collection of consistent and therefore comparable sampling media. Once the sampling and then the sample preparation and assay technique have been decided upon the assays generated can be used for establishing knowledge of the biogeochemical characteristics and then interpretations of biogeochemical mechanisms and controlling factors. These are important because they are major aspects of biogeochemical dispersion and residence models, which ultimately determine the type of application that particular biogeochemical media can be used for, and how the assay results will be interpreted.

One way to consider the array of biogeochemical sampling available in most landscapes is that once characterised and understood, each medium can be seen as a sampling and chemical processing tool within the larger biogeochemical toolbox within the landscape.

Some media will be best used for regional sampling media programs. These will typically have a widespread distribution across large geographical areas and either occur within a range of regolith-landform settings or within a widespread regolith-landform setting which is of regional significance (e.g. along major drainage channels). They will also derive their biogeochemical signatures from broad areas (kilometre to 100s of metres dispersion pathways), either through amalgamation of the chemistry from a large area (such as extensive root systems) or else from a substrate that is an amalgamation of regional chemical signatures (e.g. stream sediments, particularly fine-grained overbank deposits). These attributes produce regional sampling media that derive their biogeochemical signatures from broad areas and can be sampled on relatively large sample spacing, to efficiently account for large regions. Examples of regional sampling media developed by this research program include regional river red gum sampling and macropod (red and western grey kangaroo) scat sampling.

Other media are best suited to local-scale, detailed sampling programs. They are typically sensitive to local substrate chemical changes (e.g. plants with restricted root systems), and are best sampled at relatively close sample spacings. It is recommended that these media may be used to refine and further constrain interesting regional sampling media results, rather than being used on a regional scale sampling programs, where they are associated with dispersion pathways operating on the scale of metres to 10s of metres. Plants used in this way may have root systems restricted to either mostly vertical penetration of the regolith to the underlying bedrock or aquifer systems, or else have root systems that amalgamate chemical signatures from locally derived regolith materials. Examples of locally applicable sampling media include prickly wattles (*Acacia victoriae*), mulga (*Acacia aneura*), and chenopod shrubs (e.g. *Maireana spp.* and *Atriplex spp.*).

SAMPLING AND ASSAY APPROACH

The early stages of this research program have focussed on establishing a robust and rigorous sampling strategy. This included extensive reading and review of previous literature as well as the trial of different approaches specific to both the particular indigenous flora being sampled, and the specific goals of particular sampling programs. Many of the details of this stage of project development are outlined in L.Hill (2002), with more recent accounts specific to particular species such as river red gums (*Eucalyptus camaldulensis*) (Hulme & Hill, 2003; 2004). Sample preparation approaches adopted are outlined and discussed in L.Hill (2002; 2003) and Hulme & Hill (2003). One component that has been found to be extremely important as a framework for conducting and then interpreting biogeochemical surveys is the provisional of a suitable regolith-landform map. Regolith-landform setting is a major control on the biogeochemical assay results (e.g. Hill, 1995; Brown & Hill, 2003; 2004). The regolith-landform maps used need to have meaningful descriptions and subdivision of the regolith-landform units as well as the potential to show dispersion pathways, and hopefully some vegetation community and dominant species information (S.Hill, 2002; Brown & Hill, 2003).

BIOGEOCHEMICAL CHARACTERISTICS

In order to establish some of the chemical and parameters specific to individual biogeochemical sampling media, sampling studies have been undertaken in both ‘background’ and ‘extreme’ chemical landscape settings. These ‘extreme’ settings have included sites overlying or proximal to mineralisation (e.g. Jones, 1999; Debenham, 2000; Senior, 2000; Dann, 2001; Hill & Hill, 2003; Hulme & Hill, 2003; Brown & Hill, 2004), or bedrock types with extreme rock chemical compositions such as serpentinites and other ultramafic rocks (Hill 1998; Hill & Hill 2003; Barratt & Hill 2003). An summary of some of the ‘extreme’ assay results from trees and sampled near the Junction Mine on the Broken Hill Line of Lode are given in Table 1. For the biogeochemical sampling media and elements listed here, many of the elements (e.g. Ag, Pb, Cd, Sb) are typically in concentrations below the detection limits of the assay techniques, or in the case of Zn, are typically in concentrations of 10s of ppm rather than the elevated figures shown here.

Determining meaningful Au assays of many biogeochemical media has been a major challenge for characterisation in areas prospective for Au (such as Tibooburra and at the Williams Peak Prospect near Kayrunnera. Firstly many media assayed for Au have also have high Na contents, which interfere with obtaining Au assays at low detection limits. This was a major problem for bladder saltbush (*Atriplex vesicaria*) and many other chenopod leaf assays that feature salt secretion glands, and has been overcome by preferentially sampling the twigs from these shrubs (Brown & Hill, 2004). The Au content also appears to be extremely heterogeneous and seasonally variable within many plants, such as river red gums (Hulme & Hill, 2003; 2004), and large robust sampling approaches within optimal seasonal conditions have been recommended when sampling for Au assays (Hulme & Hill, 2004).

LOCAL SAMPLING MEDIA: TENEMENT & PROSPECT SCALE BIOGEOCHEMISTRY

Many of these studies have been based on characterising and testing the biogeochemical expression of a site of known mineralisation or a substrate of ‘extreme’ chemical characteristics such as ultramafic bedrock. At the local-scale, plant biogeochemistry may be useful for chemical characterisation at the individual tenement- or prospect-scale by providing a chemical signature that:

1. amalgamates the chemical characteristics of an otherwise heterogeneous sampling media; and,
2. penetrates the regolith substrate and extracts a chemical signature from specific materials that may be otherwise covered (e.g. covered bedrock or aquifers).

Many of the chenopod shrubs appear to be chemical amalgamators from within the regolith substrate overlying bedrock, such as black bluebush (*Maireana pyramidata*) at the Flying Doctor Prospect (Hill *et al.* in press), and to some extent bladder saltbush (*Atriplex vesicaria*) at the White Dam prospect, although the bladder saltbush also appear to gain chemical signatures from below the base of the transported regolith interface (Brown & Hill 2004).

Two of the best examples of plants that are deriving chemical signatures derived from weathered bedrock underlying shallow transported regolith are the prickly wattles (*Acacia victoriae*) at the Flying Doctor Prospect (Hill *et al.* in press), and the mulgas (*Acacia aneura*) that colonised aeolian regolith that overlies mafic and ultramafic bedrock. In these cases the surface and near surface regolith materials have either a poor or insignificant chemical signature of the underlying bedrock, however the trees appear to have ‘penetrated’ this shallow (< 5 m thick) regolith and contain chemical signatures indicative of the underlying bedrock. This characteristic is extremely important for mineral exploration programs based in areas with shallow transported regolith that extends over a very large proportion of the Curnamona Province and adjacent areas. It suggests that these trees are recommended sampling media ahead of surface transported regolith materials and the more expensive shallow drilling and costean digging.

REGIONAL SAMPLING MEDIA: WIDE-SPACED CHARACTERISATION

The two main regional biogeochemical sampling media that have been developed within this research program are river red gums (*Eucalyptus camaldulensis*) and macropod scats.

River red gums form extensive riparian woodlands along many of the major drainage lines in the region. Their root systems extend for many 100s of metres laterally and 10s of metres vertically, where they may interact with regolith substrates (mainly stream sediments), shallow aquifer systems and the underlying bedrock (Hulme & Hill, 2003). Hill (2004) shows some exciting assay results from a river red gum leaf sampling survey conducted along Pine Creek and extending past the Pinnacles Mine, west of Broken Hill. The very high Pb content in the leaves at the Pinnacles Mine sample (over 300 ppm!) and the exponential decrease in Pb assays to eventually reach background levels (below detection limits) downstream, are typical of the results that would be expected if this chemical signature reflects a downstream dispersion plume within the stream sediment substrate. Further research by Karen Hulme has re-sampled leaves from these trees and further assays not only repeat these results, but further assays following ultra-sonic washing of the leaves also repeated these assay results (indicating that the Pb is not due to Pb-rich detrital contamination on the leaves). The geochemical ‘footprint’ associated with other elements such as Zn covers a much greater area multi-element assays of this media may be the most useful approach in regional sampling programs.

Western NSW has been the location of some very detailed study by ecologists based at the Fowlers Gap Arid Zone research Station, who have been trying to better understand the behaviour of kangaroos. Particular attention has been given to understanding their grazing preferences and home-range (via radio tracking). Based on some of the results from this ecological research, sampling of scats from red and western grey kangaroos has been undertaken on an approximately 5 km sample spacing across large parts of western NSW. The assay results show high trace metal contents for elements such as Pb, Cd and Zn in the vicinity of Broken Hill and some high contents near the Pinnacles (Hill, 2004). These chemical signatures reside within the macerated vegetation fraction of the scats, however it is unclear whether the high assay results centred on Broken Hill are detecting a centre of mining and previous smelting, or if they represent a natural chemical 'footprint'. Further work is being undertaken to better understand these results, however they show enormous potential for possibly being able to:

- be used as a regional chemical sampling media across large parts of Australia to detect mineralised provinces, or chemical pollution;
- reflect chemical background levels of important trace metals (e.g. at the very least the results so far show a measure for the environmental metal enrichment in the Broken Hill landscape); and,
- show that if macropod droppings are included in surface regolith samples they may account for some of the trace metal contents.

CONCLUSIONS

The results from this research have led to the development of several new and innovative biogeochemical sampling media and approaches that could be adopted in mineral exploration and environmental chemistry sampling programs, particularly based in areas with shallow transported regolith. Different biogeochemical media may be adopted for different roles including local and regional surveys, as well as for the amalgamation of otherwise heterogeneous chemical signatures with the regolith, or the penetration of transported regolith and expressing chemical signatures from the underlying bedrock.

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DETERMINING THE ROLE OF BIOLOGICAL MECHANISMS IN MINERAL TRANSFORMATIONS AND TRANSPORT IN THE AUSTRALIAN REGOLITH-PUTTING THE ‘BIO’ BACK INTO ‘BIOGEOCHEMISTRY’

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Recent work in the CRC has for the first time categorically demonstrated the key role of bacteria in the solubilisation and precipitation of Au in the Australian regolith, the role of microbial and plant organic acids in mineral weathering around the roots of native eucalypt species, and is further elucidating the role that bacteria play in the oxidation and reduction of sulfidic materials. Biogeochemical research in CRC LEME is developing a sound mechanistic understanding of the principle biological processes underpinning biogeochemical dispersion, mobilization, transport, and mineralisation of minerals & trace elements in the Australian regolith, as well as determining the relative role of biological and non-biological (abiotic) processes driving mineral transport. The core aim of LEME activities in this area is the development of predictive models to identify where in the regolith biological mineral transformation and transport processes occur.
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 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 a million and a billion cells. However, estimates of the total number of species in the regolith range from 100,000 to 1 x10^6, suggesting up to 95% of regolith microorganisms are unknown to science.

Geochemical transformations resulting from microbial activity in the regolith are also well established. One of the most well known is the biological oxidation of sulfide minerals, carried out by a group of bacteria known as chemolithoautotrophes. These organisms are highly adapted to low pH (highly acid) environments, and utilise Fe or S as part of their energy generating processes, 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).

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). Unfortunately, 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.

APPLICATION OF NEW MOLECULAR BIOLOGY TOOLS

CRC LEME is developing an alternative approach to determining the mechanistic relationship between microbial activity and biogeochemical transformations, targeting the ‘molecular genetic’ attributes of microbial populations (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 and culture 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. A major advantage of these techniques is the rapid analysis of samples, to determine microbial attributes responsible for mineral transformation, and identify organisms responsible. Molecular techniques can provide details within a matter of days, compared to weeks or months when traditional microbiology techniques are used.

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 *sox*B 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 been designed that amplify the *sox*B gene sequence (Petri *et al.* 2001), allowing us to 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. *sox*B gene sequences were amplified 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.

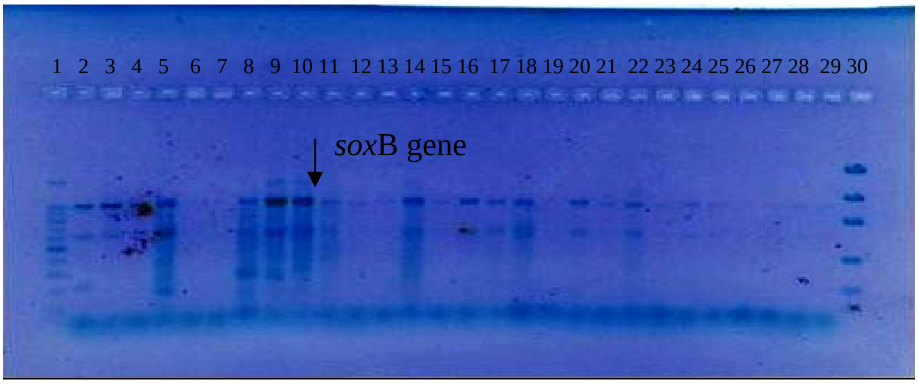

Figure 1 *soxB* functional gene DNA detected in extracts from sulfidic sediments . 1000 bp PCR product visualised on 2% agarose gel. **Lane 1** 100bp DNA ladder; **Lane 2-4** *A.caldus* soxB positive control 1000bp product; **Lanes 5-29** presence of *sox*B gene in sulfidic sediments; **Lane 30** DNA 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, which 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’. DNA sequencing, the determination of the individual species DNA structure has identified the bacteria responsible for Au precipitation/solubilisation in auriferous regolith materials. This same species of bacteria is responsible for Au biomineralisation in both sites studied (Queensland and NSW).

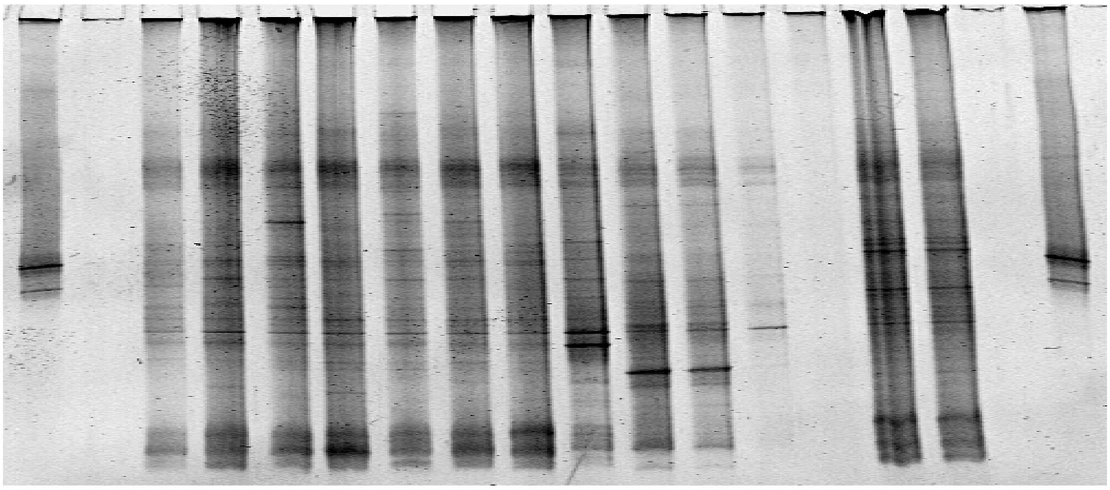

Figure 2. 16S rRNA Density Gradient Gel Electrophoresis profiles of bacterial populations on gold flakes collected at the Tomakin park gold mine. 16S V3 region amplified in soil DNA extracts with degenerate oligonucleotide PCR primers 27FGC and 534R. PCR product visualised on a 35-60% urea/formamide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

Both these CRC LEME sponsored studies have demonstrated the application of new molecular techniques to the study of biological mineral transformations in the regolith.

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EOCENE CHEMICAL WEATHERING IN SOUTHEAST YILGARN BLOCK

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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.

EXPERIMENTAL METHODS IN GEOCHEMISTRY AND MOBILITY OF METALS IN THE REGOLITH

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INTRODUCTION

The dispersion of metals in the regolith around ore deposits, and hence the formation of geochemical anomalies, is controlled by metal mobility. Understanding mobility requires knowledge of the geochemistry of metals in regolith, water and biota (i.e., what mineral and aqueous species of metals are important, not just their concentrations), and the leaching, transport and trapping processes. We need a much deeper understanding of the mineralogy and speciation of metals and related elements as well as the processes, in order to develop successful exploration methods that allow us to decipher observed geochemical patterns, and to distinguish between anomalies indicating ore bodies and those that do not. In Australia, this is especially important because of the need to explore in areas covered by transported regolith. Metal mobility is important more generally to geologists and geochemists because it is a critical link in the formation of lateritic and hydrothermal ore deposits. In addition, understanding the mobilisation and trapping of metals is important to 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, water and vapour, how they are mobilized or trapped, how far they can be transported and whether they are bioavailable and can be transported by biota and/or 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 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 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 critical in developing our understanding, 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 the geochemistry of 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, i.e., the speciation of gold in solid and aqueous forms, is complicated because it is affected by pH, redox, salinity and organics, as well as temperature. Gold 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, 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 BACTERIA ON GOLD MOBILITY

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 show that gold is mobilised into solution after several to tens of days, in contrast to sterilised samples that showed no gold mobilisation (Figure 1). In more 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/RNA sequences of the microorganisms from field and experimental samples. He has found that there are different microbial populations associated with gold grains from the different field areas, and he has evidence of microorganisms that have not been identified anywhere else. 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 and iodide complexes in chloride and iodide solutions. Iodide forms strong complexes with Au, and could be important in transporting gold in saline brines. Oxidised Au(III) complexes may be important in transporting gold in acidic, very oxidised (atmospheric conditions), but the results will also provide a window into the more complicated Au(I) complexes, more likely to be the transporting gold complexes in many groundwater environments. 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. Another part of Alistair's Ph.D. research is focussed on improved methods of measuring low levels of dissolved gold in water, something that will benefit mineral exploration using hydrogeochemistry.

SORPTION AND MOBILITY OF BASE METALS ONTO IRON OXYHYDROXIDES

The concentrations of metals in surface and groundwater can be controlled by sorption onto mineral and/or organic matter surfaces, and therefore could be the controlling process in metal dispersion in the regolith around ore bodies. We are using experiments to study the effect of pH and salinity on the sorption of Cu and Zn on goethite, and have found some surprising results.

Ph.D. student Chris Gunton has completed a study of how NaCl affects 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 that adsorbed copper increases with increasing pH, where the sorption edge is approximately pH = 4.5. This is well known behaviour, but we have found that copper sorption increases up to 20-fold with increasing NaCl concentration (Figure 2), a result of Cu chloride complexes on the goethite surface. The increased sorption with NaCl has important ramifications for metal transport in the regolith, particularly in prospective saline and arid Australian environments. For instance, it suggests that copper haloes are likely to be intense and small during weathering of sulphide ore bodies in saline to hypersaline environments where goethite and likely other iron oxyhydroxide minerals are present.

We have extended these experiments to study zinc sorption on goethite under similar ranges of conditions. The results show that zinc is adsorbed to goethite at higher pH (i.e., pH approximately 7 for the sorption edge) than copper (Figure 3), and that the effect of NaCl is smaller. This means that zinc will likely disperse farther than copper during the weathering of an ore body and that zinc will be less affected by salinity. We have also completed preliminary experiments to study the effect of sulphate on the sorption of zinc, which suggest that sulphate has little or no effect. These results suggest that metal ratios in goethite could be a useful indicator in exploring for new ore deposits, but further research is needed to understand how different metals react with goethite.

New experimental techniques are now being established to study how metals can move through the regolith. Column experiments will be used to pump metal-bearing solutions through regolith material (e.g., goethite- and hematite-coated sand) under different pH and salinity conditions to study how the metals are trapped and/or released under dynamic flow conditions. This is a step towards taking our knowledge of sorption from batch experiments to help understand how metals move in groundwater and the regolith.

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 determining and numerically modelling the density-driven convective flow around the playa lake and the gold mineralisation. Figure 4 shows an example cross-section indicating the variation in groundwater salinity, schematic groundwater flow directions and groundwater region where elevated levels of dissolved gold were found (Condenser survey on Figure 4)

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 simulate the playa lake. 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 (Figure 5), as well as the timeframe of the plume development, and the process of density-driven convection. Numerical models were used to predict the density-driven convection and then the results were compared with the experimental data. The comparisons allowed us to refine and verify the numerical models, so that we could apply them to the field area with more confidence. The applications showed that the present playa lake could form in a timeframe of tens of thousands of years, a short time compared to the millions of years of relatively stable geological environment in the area. The results of experiments and field studies indicate that any gold signature in the groundwater is affected by the extent of the convection cell.

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 regolith and groundwater. For gold mineralisation, the likely field areas are in the Yilgarn (*e.g.,* Lancefield, Mt. Gibson, St. Ives, Whirling Dervish), Gawler Craton (*e.g.,* Tunkillia), Lachlan Fold Belt (e.g., Cobar basin, Lake Cowal) and the Tanami, in collaboration with Drs. David Gray and Mark Pirlo of CSIRO Exploration and Mining in Perth, and Dr. Dirk Kirste (ANU) and Dr. Patrice de Caritat (Geoscience Australia). 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. 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 of geochemical and physical processes of dispersion in the context of landscape, regolith and climate 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, Sebastien Lamontagne, Steve Rogers, Rob Fitzpatrick, and others). What we learn from mineral exploration studies will help in environmental and salinity studies, and *vice versa*.

ACKNOWLEDGEMENTS

I thank all the people with whom I collaborate in LEME, many of which are mentioned above. In particular, I thank my post-graduate students, Frank Reith, Chris Gunton and Alistair Usher, who work with me on this project and do much of the hands-on research and challenge me regularly with new ideas. This research is funded by CRC LEME, which I gratefully acknowledge.

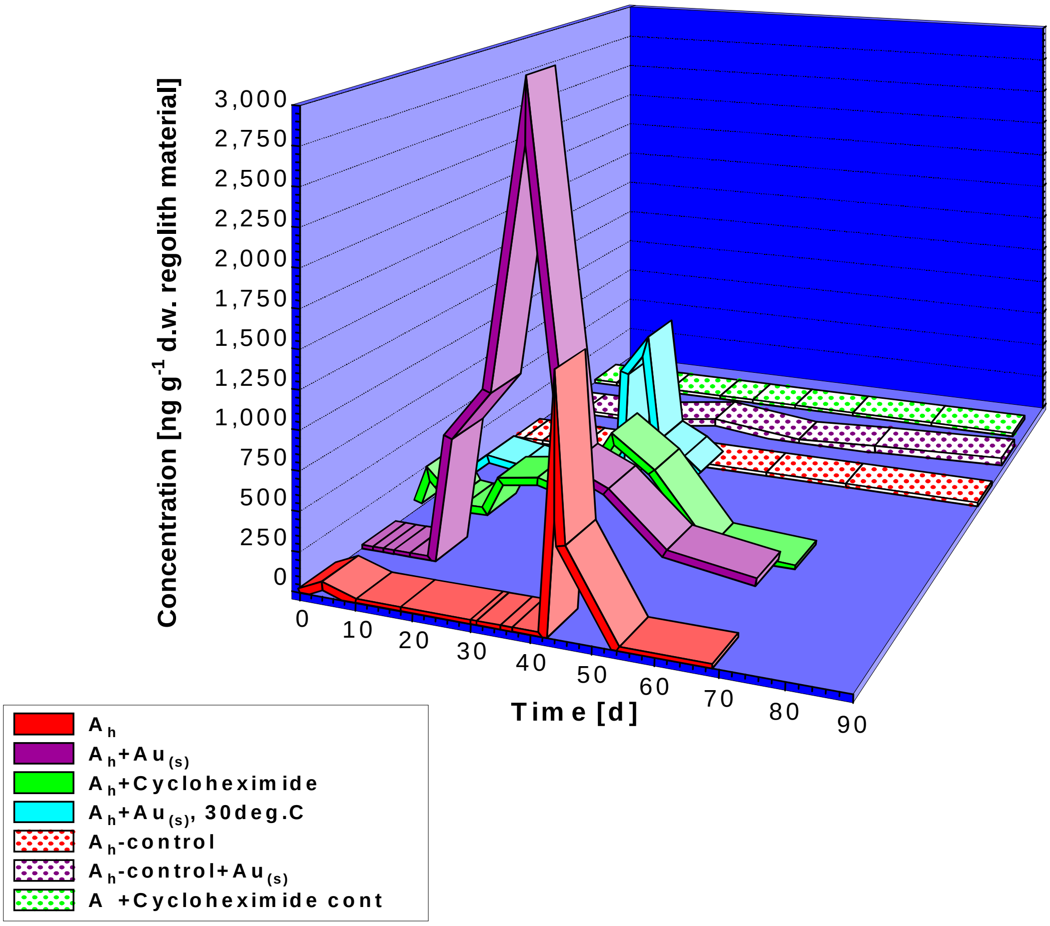

Figure 1. Results from microcosm experiments at mainly 25°C showing gold solubilisation in samples from the Mogo Gold Mine, Tomakin, NSW. A$_h$ refers to samples from that soil horizon. Cycloheximide limits organisms other than bacteria. Samples from the 3 control experiments were sterilized before running.

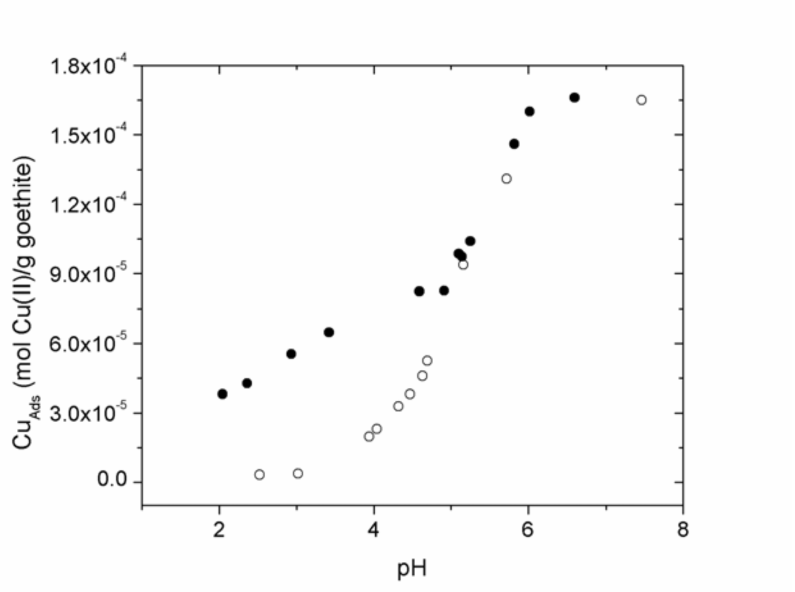

Figure 2. Effect of NaCl on the adsorption of copper onto goethite at 25°C. The open circles are for experiments with no NaCl and the filled circles are for experiments with 5 molal NaCl (seawater is 0.6 molal and halite saturation is approximately 6 molal). Note that most of the increase in adsorption occurs between 0 and 1.5 molal NaCl. Initial dissolved copper concentration in experiments was 10 ppm.

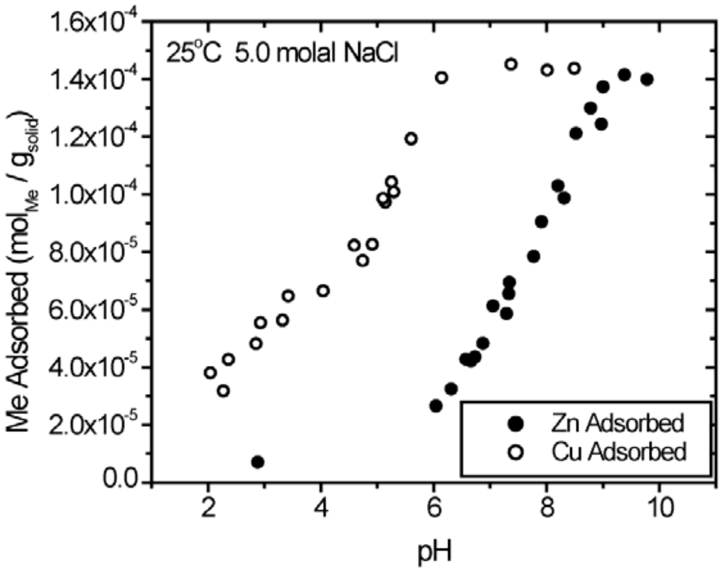

Figure 3. The effect of pH on the adsorption of copper and zinc on goethite. Initial dissolved metal concentrations in experiments was 10 ppm. Note that the effect of NaCl on copper adsorption is less than it is for zinc.

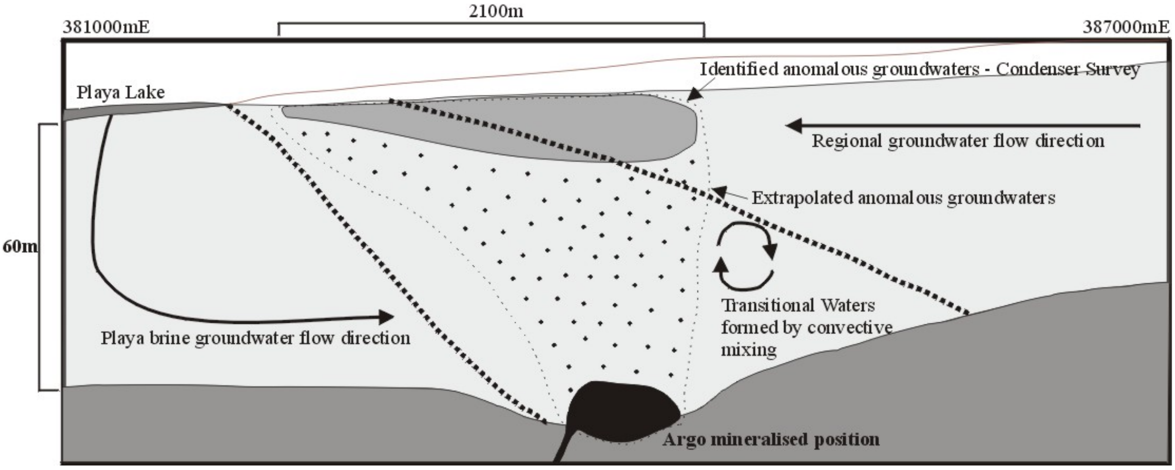

Figure 4. Schematic diagram of density-driven convection under Lake Lefroy and the St Ives area, Western Australia. (Taken from Carey et al., 2003; Geochemistry: Exploration, Environment and Analysis, 3, 57-71).

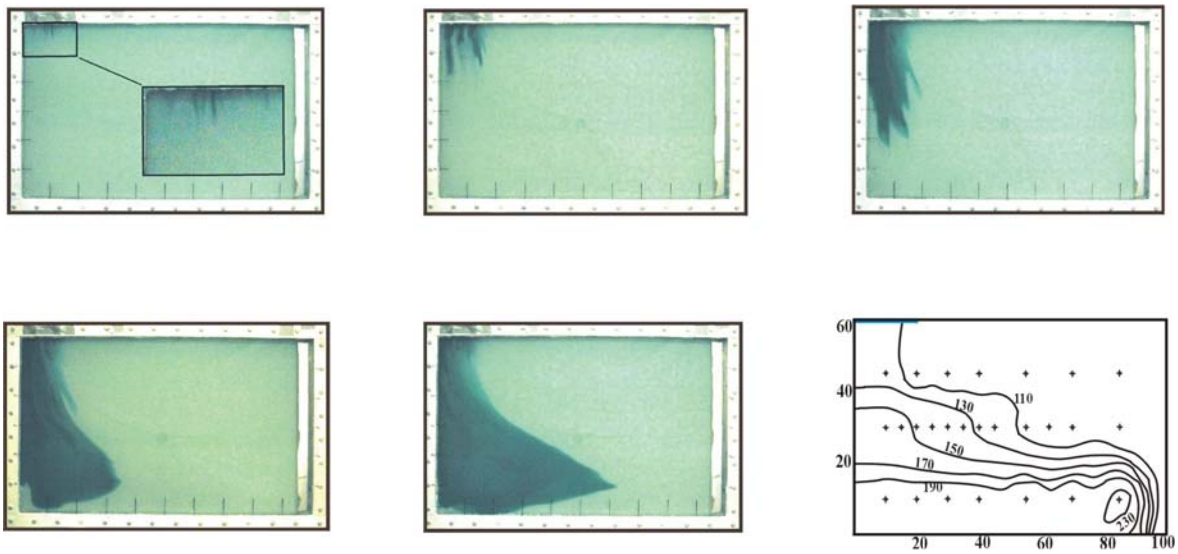

Figure 5. Snapshots of plume development in a 105 cm wide and 60 cm high tank. Total length of time for experiment was approximately 24 hours. The bottom right diagram shows contours of salinity measured at points shown in diagram at the end of the experiment.

GROUNDWATER CHEMICAL AND ISOTOPIC COMPOSITION: A MINERAL EXPLORATION TOOL FOR AREAS OF REGOLITH COVER – LESSONS FROM THE CURNAMONA PROVINCE

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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 come in contact with mineralisation and retained a chemical 'memory' or fingerprint of such an encounter. Can one detect such fingerprints 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 350 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}), i.e., 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 determine 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 (e.g., Broken Hill, Rupee, or Thackaringa types). For further details, the reader is referred to the recent publication by Caritat et al. (Applied Geochemistry, 2005, in press).

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 away from mineralisation (down the flowpath), while Pb values are already attenuated within ~50 m of mineralisation. 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 dissolved metal contents at any great distance from the deposits. Therefore, higher amounts of specific metals dissolved in groundwater may indicate proximity to mineralisation, depending on aquifer mineralogy and 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 southern Barrier Ranges (Broken Hill Domain), 16 yield positive indicators, that is:

- positive S_{XS},
- low $\delta^{34}S$, and
- elevated Zn and/or Cu concentrations.

This study also highlights several new locations under sedimentary cover in the Curnamona Province 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. We thank Frank Krikowa, Steve Taylor, Malcolm McCulloch and Graham Carr for assistance with analytical components of this study.

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. It produces high-resolution images of conductivity structure in the regolith and bedrock that is very useful for mineral exploration at prospect scale.

The SAM 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 small 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.

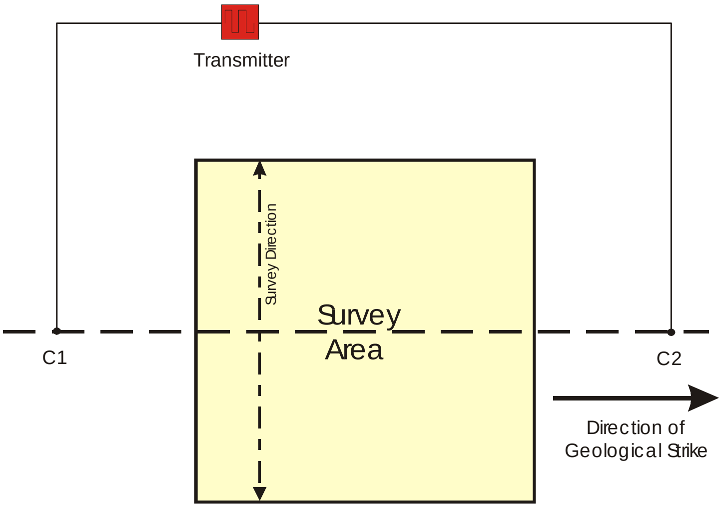

Figure 1. Typical ground layout for a SAM survey area of 1 by 1 km.

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 then 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 anomaly 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 1 m 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. The use of real time DGPS also means that cost there is no need for putting in surveyed grids used for IP surveys. 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. SAM can also be collected using a low flying helicopter, and an example from the Eastern Goldfields will be presented.

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 the very localised forms of 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.

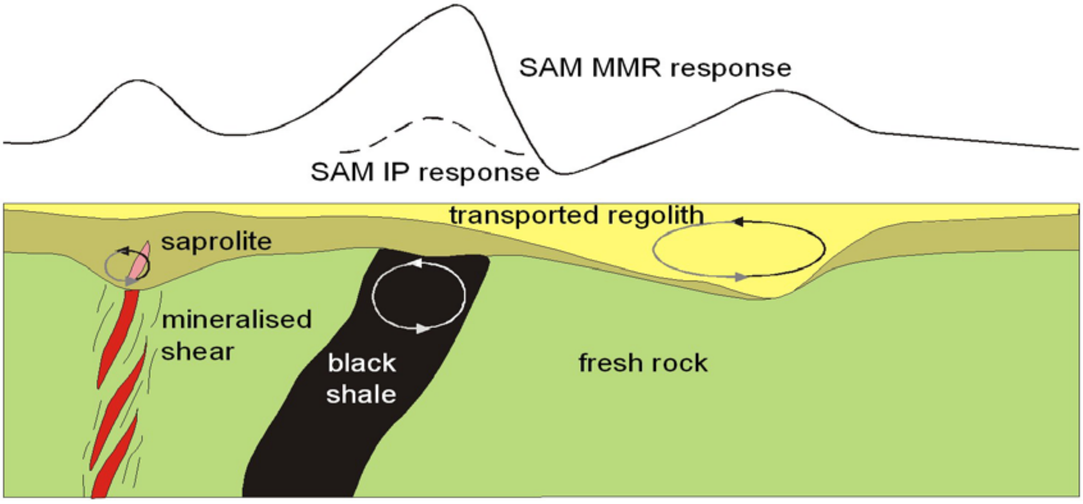

Figure 2. Schematic profile of simplified regolith and the shape of SAM anomalies expected to be caused by current channeling in conductive subsurface features.

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 in resistive bedrock 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: 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).

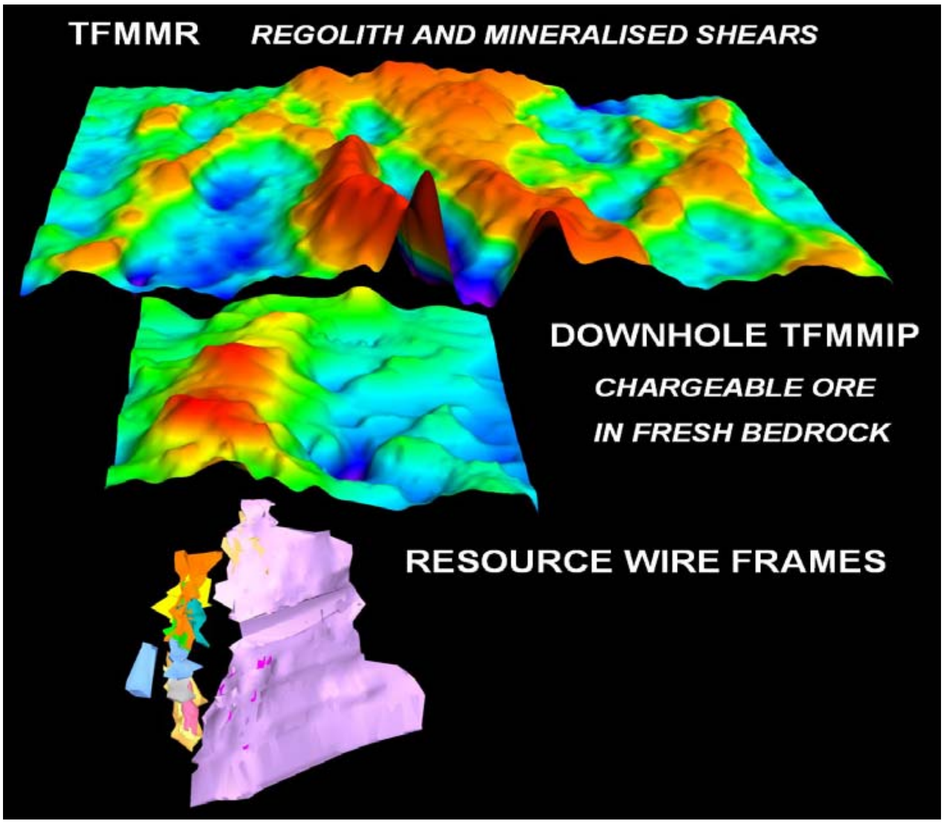

Figure 3. Three dimensional perspective of SAM responses over the Songvang gold deposit near Agnew, WA.

4.3 St. Ives Gold Mine: This is an example of how SAM can work in salt lake environments, and how high-amplitude SAM anomalies are related to wider and deeper zones of weathering. An example of HeliSAM will also be shown.

4.4 Indee Gold Prospect: Surveys carried out over Archaean turbidite deposits hosting epithermal gold in quartz veins show similarities between gradient array IP and SAM results. Integrated geophysical interpretation has generated structural targets in the 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 greenstone terrains.

INNOVATIVE GEOPHYSICAL TECHNIQUES FOR MAPPING REGOLITH

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Abstract not available