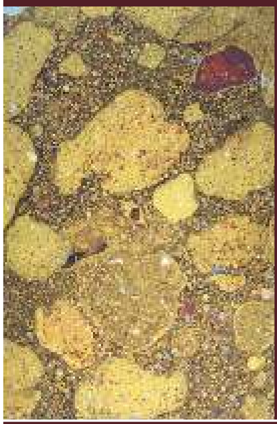
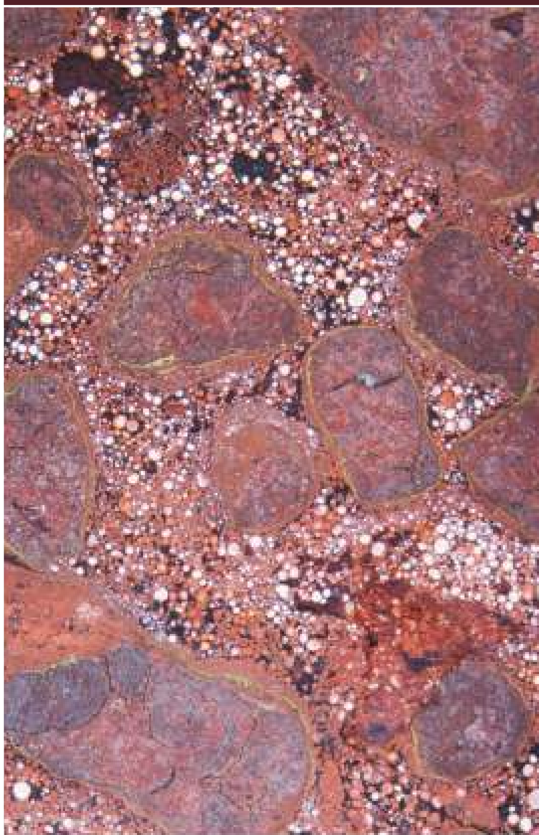
2005
MINERALS EXPLORATION SEMINAR
ABSTRACTS

25 May 2005

Regolith sections courtesy of I.D.M. Robertson, CSIRO



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Curtin University of Technology,
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CSIRO Exploration & Mining and Land & Water,
Geoscience Australia,
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CRC LEME
Cooperative Research Centre for
Landscape Environments
and Mineral Exploration

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ABSTRACTS

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25 May 2005

Australian Resources Research Centre
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CONTENTS

REGOLITH EXPRESSIONS OF AUSTRALIAN LANDSCAPES AND ORE SYSTEMS

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Two thematic volumes are being released as monographs. These are: -

- Regolith expression of Australian Ore Systems,
- Regolith-landscape evolution across Australia.

Regolith expressions of Australian ore systems: Edited by Butt, Robertson, Scott and Cornelius
This is a systematic compilation of about 100 highly condensed, three page geochemical case studies and conceptual models covering the geological, geomorphological and environmental characteristics of individual deposits and occurrences and their expression in residual and transported regolith. The case studies come from all over Australia, although the bulk is from WA, NSW and Queensland. Although many are gold, copper-gold and base metal case studies, there are a few for nickel, PGEs, molybdenum uranium and vanadium. These are being summmarized into a suite of dispersion and exploration models to anticipate the surface expression of mineralization for a given area and commodity, help design exploration programs and evaluate anomalies. This monograph will expand and update earlier compilations and models by Butt and Smith, (1980) and by Butt and Zeegers (1992). Although the monograph is being compiled and edited by CRC LEME staff, the case studies are from a wide range of published and unpublished sources, many from industry, and include hitherto unreleased exploration data.
It is intended that the monograph will provide a substantially improved understanding of the effects of weathering and transported cover on exploration methods, leading to reductions in the cost of exploration for concealed base metal, polymetallic, uranium and gold deposits in areas of residual and/or transported regolith. Case studies have been progressively released as .pdf files on the CRC LEME website prior to the final release as hardcopy, scheduled for the IGES in September. It is encouraging that this part of the website has had over two million hits in the past year.

At this stage, we have completed 87 case histories and another fifteen are in advanced stages of preparation. A computerised database has been constructed, which can be readily searched and will be included with the hardcopy. Supporting chapters are nearly complete, covering physiography, drainage, climate, vegetation, ore deposits and sample media.

Regolith-landscape evolution across Australia: Edited by Anand and de Broekert
This is a compilation of regolith-landscape case studies and landscape evolution models. This volume integrates the regolith-landscape evolution studies of many investigations at various scales provided by LEME and others. The volume will also include regional landscape models, and weathering and denudation histories of selected regions. These case studies are being progressively released as .pdf files on the CRC LEME website and a hard copy will be released in September. Fifty-one case studies have been completed and they contain information on physical setting, regolith-landform relationships, regolith characteristics, dating and regolith evolution. Most are from WA and NSW, although the other states are well represented. Supporting chapters covering geochronology, regional synthesis, weathering history, landscape evolution and implications for exploration are being prepared.
Generally, regions of outcropping bedrock and *in situ* regolith are well explored; the greatest potential for future discoveries lies beneath substantial, largely transported cover. These under-explored areas are complex. The cost of future discoveries will be reduced by understanding the regolith and landscape evolution processes and improving interpretation of geochemical dispersion from ore deposits. This understanding will also aid environmental research and management.

Access
Case studies from both monographs can be accessed at http://crcleme.org.au → Publications → Monographs. Pick the monograph and download the case study needed.

NORTHERN TERRITORY REGOLITH PROJECT - A PROGRESS REPORT.

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Project Scoping

The beginning phase of this project involved a major scoping meeting in Alice Springs with staff from the Northern Territory Geological Survey and CRCLEME. This meeting was responsible for establishing the overall strategic plan and general work plan for the life of the project. Staffing mix, individual roles and responsibilities within the life of the project were clearly defined at that meeting. The task was essentially to provide a framework map of the Northern Territory with supportive regolith characterisation, shed some light on the evolution of major landscape domains and their associated weathering history. he initial task of surveying and consolidating relevant published and unpublished datasets the characteristics and distribution of Northern Territory regolith was achieved.

A key decision of the scoping meeting was to undertake a Trans-NT regolith traverse. Its purpose was for team embers to observe, first hand, the major regolith-landscape variations (domains) from south to north, with lesser excursions east and west as time permitted and needs dictated. All aspects of logistics for the Trans-NT regolith traverse, which began from Alice Springs on 21st September 2003, were provided by the NT Geological Survey. This was a unique exercise that was going to provide a broad view of the regolith-landform domains across the territory, provide insights to regolith material characterisation needs for the project and allow us to target representative and complex domains that required more intense fieldwork.

Deliverables

The main deliverables from this project are:

1. A Northern Territory Regolith framework map (1:2,500,000)
2. A regolith Atlas of NT regolith materials
3. Summary report.

Getting Started

A simple geomorphic "provinces" map was prepared as a result of decisions at the scoping meeting. It was prepared at the meeting from some existing data at hand for later use during the traverse and to serve as a general guide for later fieldwork. The geomorphic provinces map served as a general guide for field mapping operations and provided the project with its initial working context.

The Trans-NT traverse was completed during September-October 2003. The Stuart Highway was the major access route from south of Alice Springs through to the Darwin coastal plain. Such a large-scale regolith calibration traverse has not been previously undertaken in the NT or, perhaps, anywhere else in Australia. A wide range of imagery e.g., Radiometrics, Landsat TM, Magnetics, Elevation data and Aster imagery was used during the traverse to assist in recognising regolith variations and sampling contexts.

Early traverse results suggested that particular regolith materials and landscapes have complex relationships, and that some materials are likely to be more widely distributed in some areas than has been previously recorded. Of the two samples collected during the Trans-NT regolith traverse for trial age determination, one sample from a road cutting north of Tennant Creek proved to be highly successful, the other from near Mataranka was not. Further samples were then planned for collection during the main project fieldwork in mid to late 2004. The results are outlined later in the project highlights section of this manuscript.

Telling our Secrets

A regolith materials and mapping workshop was conducted, in Darwin, at the end of the NT Gabfest from January 18th to 21st 2004. The audience was essentially NT Geological Survey staff and invited industry representatives. The workshop focus was on regolith materials and mapping techniques and was presented by Mike Craig, Ravi Anand and David Gray. Feedback indicates that NTGS staff and industry participants gained better and wider understanding of regolith materials, regolith in the context of exploration, and regolith mapping approaches.

Early Results

Immediately following on from the 2003 traverse, 58 regolith specimens underwent X-ray diffraction mineralogical analysis and X-ray fluorescence analysis at the Perth CRC node. Thin and polished sections were prepared. The XRF analysis was for 21 major and minor elements and LOI (loss on ignition). This enabled the team to generate a simple overview of the range of materials that we would be dealing with during the major fieldwork program. Two palaeomagnetic samples were sent to ANU for age determination. Datasets from field capture and some 500 photos were then edited for later integration into project datasets. The field data help form the basis of planning later major field work and identifying any complementary data that would be required. The traverse results also identified an issue with our digital data collection strategy. The issue was that the existing platform and software was not up to the size of the task. A new platform and software was urgently required for the successful field operations at the NT scale.

The Big Push

The major field work phase was conducted during May 2004 through to September 2004. Again, field logistics were provided by NTGS. The work was divided into four distinct regolith domains as determined from scoping results and the Trans-NT regolith traverse. The first area was centred on the Harts Range. The second area was centred on the Barrow Creek-Tennant Creek districts. The third area involved the Darwin coastal plain and immediate hinterlands. The fourth and final area focussed on the Tobermorey district, ending with minor visits to Glenn Helen and a traverse along the Tanami Road. This work was not intended to repeat existing detailed work but act as a supplement to it.

Project Milestones

1. Known data compiled and consolidated;
2. Additional support data generated;
3. Trans-NT regolith traverse was undertaken;
4. Traverse results used for area selection;
5. Pilot samples processed - guide sample program;
6. Pilot paleomag. program successful;
7. Atlas data collected -materials being prepared; and
8. Product generation now in progress.

Selected Project Highlights

Over 250 regolith samples were collected during project fieldwork and are currently undergoing analysis, sectioning or slabbing and will form the basis of entries in an NT Regolith Atlas. All the sites visited are supported by a photo database containing about 2000 entries. Some entries will become part of the Atlas and the others will become part of the overall digital record of the project.

A pilot palaeomagnetics sample program was conducted to help address the issue of the lack of age control in NT regolith materials and landforms. Overall palaeomagnetic ages ranged from 2Ma in a weathering profile along the Darwin foreshore to 295Ma in a road cutting at Tennant Creek. A small cluster of ages occur around 5-10Ma, from samples taken from the hinterland of the Darwin coastal plain. A single age of 47Ma comes from near Glenn Helen Gorge west of Alice Springs. Project results generally fall within three major age clusters determined from a very much larger range of samples being amassed by Brad Pillans (pers. comm). In view of the results of our pilot program, a much clearer understanding of the timing NT regolith, weathering and landscapes development can be derived from a more focussed palaeomagnetic age determination program across the Territory and would be a welcomed addition to the understanding of NT regolith.

Not all our efforts have lead to the results we had first hoped for. Some considerable effort was focussed on attempting to find a way to determine a "base" of regolith through the processing of magnetics data. In the Tennant Creek region this exercise did not prove to be successful. Instead, the investigations were able to highlight, in 3D, the major ironstone bodies in the area. Another test area is to be considered soon. However, on a more positive note, the magnetics data do contain information about magnetically signatured subsurface palaeodrainage lines. This should prove to be a valuable element in any future palaeochannel investigations within the Northern Territory.

Project members are confident that our results will lead to better guidance and understanding of regolith-related issues especially for mineral exploration in the Territory.

NT Regolith Project Team:

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REGOLITH AND GEOCHEMICAL DISPERSION MODELS, NORTH QUEENSLAND

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INTRODUCTION

Extensive, variable, and generally thick regolith is a major impediment to mineral exploration in parts of northern Queensland, as in many other parts of Australia. The Mount Isa and Charters Towers - north Drummond Basin regions host numerous base-metal and gold deposits and have a long history of mineral exploration. The well-exposed parts of these regions have been effectively explored by traditional methods. Exploration is now concentrating on areas obscured by deep weathering or by transported cover.

The main aim of the 1994-1997 LEME/AMIRA project "Geochemical exploration in Regolith-Dominated Terrain of North Queensland" was to develop suitable geochemical exploration methods for regolith covered areas based on an improved knowledge of the nature and evolution of the regolith and landscape. To achieve this, the project undertook regolith-geochemical dispersions studies in a variety of geomorphological and sedimentary environments with particular emphasis on distribution, characteristics and origin of the regolith. The activities of the project ranged from regional to district-scale investigations, with more detailed studies at specific sites or prospects. Sites were selected to address specific problems and, in many cases, mapping was extended to place them in their regolith-landform context. The outcomes of district-scale and specific studies are available as investigation reports. The purpose of this paper is to summarise the results and to develop models, conclusions and recommendations.

MT ISA REGION

Regolith

As an aid to geochemical dispersion studies, a regolith-landform framework was established for the Mt Isa region. There has been complex erosion, deposition and weathering during the Mesozoic and Cainozoic forming complex landscapes and regoliths. Mesozoic sediments were deposited on a landsurface of broad river valleys with low hills and interfluves. By the early Cainozoic most of the Mesozoic sediments had been eroded except in the southeast and north of the region. Field relationships and dating of Mn oxides strongly suggest that evolution of the weathering profiles spans the Tertiary, possibly extending into the Cretaceous. Weathering of Cambrian, Mesozoic and Proterozoic bedrocks left lateritic profiles capped, in places, by ferruginous or siliceous duricrust. The depth of weathering varies and is controlled largely by landscape position, bedrock, structural features and any overlying sediments at the time of weathering. Palaeoplains and topographic lows are more deeply weathered than the erosional plains and hill belts. At many locations, Proterozoic bedrocks are weathered to greater depths where overlying Cambrian or Mesozoic sediments have been removed or were never deposited. In places, remnant river channel and sheet wash deposits have been silicified and ferruginised.

Massive, fragmental and nodular duricrusts have formed *in situ* on Fe-rich weathered rocks by accumulation of ferruginous materials from mottled saprolite and were left by down-wasting of the profile as clays and soluble elements were removed. Slabby duricrust formed on lower slopes by induration of locally derived colluvium and saprolite with lateral accumulation of Fe. Slabby duricust can be distinguished by its landscape position on plateau edges, micromorphology (platy), geochemistry (Mn and P-rich) and its goethite-rich mineralogy.

Silcretes have formed on a variety of bedrocks but are most common on siliceous materials. In places, silica has cemented alluvial sands or sheet wash sands and gravels. Silicified alluvial sands and gravels now occupy topogaphically higher areas, because of relief inversion since induration.

The plains have variable thicknesses of Cainozoic and Mesozoic sediments, underlain by weathered or fresh Proterozoic bedrock. Soils have formed on fresh and weathered Mesozoic and Cainozoic sediments and Proterozoic bedrock. Lithosols are associated with resistant rocks, areas of high relief and steeper slopes. In depositional areas, the soils vary from black through brown to grey sandy clay, sands or clays and generally contain polymictic gravels. Some soils have been weathered (mottling, silicification) since their deposition. Black and brown soils have developed extensively on Cainozoic and Mesozoic sediments. Black soils were developed progressively from brown soils where the alluvium was fine, water was retained and kaolinite was transformed to smectite.

Recommendations for exploration

Several geochemical sample media were demonstrated to have specific application in exploration in the Mt Isa region. Appraisal of geomorphology and regolith at a district scale is an important pre-requisite for efficient exploration of a regolith-dominated terrain. Regolith-landform maps and regolith stratigraphy should guide the selection of sample media, sample interval, sampling procedure, analytical method, element suite and data interpretation. A regolith 'fact map' is produced to describe regolith materials in a landform framework and to divide these broadly into duricrusts, saprolites and colluvium-alluvium. Each, with the exception of colluvium and alluvium, are subdivided according to their bedrock (Proterozoic and post-Proterozoic). The bedrocks have different prospectivities and require different interpretation.

Residual ferruginous materials (massive, fragmental or nodular duricrusts), where they occur, should be collected for district- to prospect-scale surveys. Data from partly transported slabby duricrust should be interpreted with care, as their Fe and trace element (Cu, As) content may have been derived laterally.

Soil sampling is effective in areas of shallow overburden (1-5 m). The best materials are mottles or the soil matrix rather than clastic grains. Where Fe and/or Mn oxides have adsorbed significant quantities of indicator elements (e.g., Cu, Zn) multiple regression, followed by a residual treatment of these indicator elements would remove the effects of adsorption and draw attention to anomalies that would otherwise remain hidden.

Areas dominated by thick (>5 m) Cambrian, Mesozoic and Tertiary sediments present significant exploration problems. Coarse sediments should be collected at and just above the unconformity (interface sample) in areas of unweathered or slightly weathered Mesozoic cover to detect a near-miss when drilling a geophysical target. When sediments have been weathered, buried ferruginous bands at palaeosurfaces or at watertables may provide a continuous sampling medium. Horizontal ferruginous bands, formed within sediments, should be preferentially collected. These are more useful than structurally controlled sub-vertical ferruginous veins within the Mesozoic sediments.

CHARTERS TOWERS - NORTH DRUMMOND BASIN

Regolith

The landscape of the region is a product of several sedimentation and weathering episodes. The dominance of a southerly flowing river system in the early Tertiary, the formation of a large lake system in the middle Tertiary, and the reversal of the river system in the late Tertiary are the main episodes of landscape evolution in the north Drummond Basin. Deposition and erosion in the north Drummond Basin has been dictated by drainage changes. When the southerly drainage was choked during the Tertiary, rapid sedimentation formed the Suttor Formation in the south and the Southern Cross Formation in the north. In view of their extent and fluvial nature, these sediments were deposited over a considerable time span and were not restricted to a single event.

Deep weathering of both the fluvial sediments and the basement formed duricrust, red earths and, to a lesser extent, yellow earths. Campaspe Formation sediments were deposited on the Southern Cross Formation. In areas where intense erosion of the Southern Cross Formation occurred, Campaspe Formation sediments were deposited in lower levels in the landscape. Yellow and grey earths with ferruginous pisoliths are developed on the Campaspe Formation.

In drill spoil, the Southern Cross Formation is more clay-rich than the Campaspe Formation and contains clasts of basement rocks. The Campaspe Formation is sand-rich and more sorted than the Southern Cross Formation. The Campaspe Formation may contain detrital nodules and pisoliths throughout the sediment, whereas most of the pisoliths and nodules in the Southern Cross Formation are concentrated near its top. There are no consistent mineralogical and geochemical criteria but sharp changes in feldspar and kaolinite abundances, appearance of round quartz grains and geochemical parameters such as sharp changes in Ti/Zr ratios can be used to distinguish the Campaspe Formation from basement volcanics.

Recommendations for exploration

The focus of most of the geochemical studies in the Charters Towers - north Drummond Basin was on investigating dispersions in sedimentary cover. Regolith-landform procedures are similar to those described for the Mt Isa region with the exception that regolith units should be divided into Palaeozoic or post- Palaeozoic. The geochemical dispersions appear to be similar to those of the Mt Isa region, with geochemical responses where the cover is shallow (1-5 m). Here, soil sampling (including specific sampling of mottles) would be effective. The probability of hydromorphic dispersion is better in sediments that have been weathered since deposition.

In areas dominated by a thick (>5 m) regolith on Campaspe, Southern Cross and Suttor Formations, dispersion is predominantly mechanical near the base. There was some hydromorphic relocation of Au during subsequent weathering. Dispersion may be traceable for 100-300 m downslope from mineralization, or from areas of numerous sub-economic auriferous quartz veins. Large dispersion patterns are most likely where mineralization was exposed for a long period during sedimentation (e.g., Scott Lode, Pajingo) and less likely where mineralization was covered by early sediments or quickly smothered froom upslope so an understanding of palaeotopography is essential. Elevated Au at 25-35 ppb may indicate distal mineralization, whereas anomalies of 35-70 ppb, and more specifically , >70 ppb Au may indicate proximal mineralization. Total Au analysis of the Southern Cross Formation is important as about half of its Au is occluded from cyanide attack. In places, elevated indicator elements and Au are hydromorphically dispersed with Fe oxides and dolomite-rich bands at least 10 m above the unconformity. Thus, basal sediments and ferruginous bands (redox products) should be sampled preferentially. Extensive sheets of ferruginous pisoliths, developed in the Campaspe Formation, also appear to be a promising sampling medium in the region.

TERTIARY "PALAEOCHANNEL" FILLS, KALGOORLIE, WA

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Comprising a major component of the sedimentary cover in the Eastern Goldfields are sequences of Tertiary continental to shallow marine sediments hosted within networks of palaeovalleys cut deeply into the weathered surface of the Yilgarn Craton. Owing to their entrenched position within the bedrock surface of a much broader and older system of valleys, the palaeovalleys are more appropriately referred to as "inset-valleys" rather than their traditional name "palaeochannels".

Based on transects of cored boreholes and extensive open-cut exposures of the inset-valleys and their fills at the Lady Bountiful Extended and Kanowna QED gold deposits, the inset-valleys have been subdivided into two major unconformity-bounded packages (alloformations). The basal alloformation can in turn be subdivided into a number of "fill-styles" reflecting changes in source-rock composition and position within the inset-valley network. Unlike at Lakes Lefroy and Cowan, where the inset-valley fills have also been extensively studied, deposition of the sediments appears to have been dominantly controlled by changes in climate, suggesting that marine-influenced deposition was restricted to the lower reaches of the inset-valleys or that such sediments were eroded in the upper valley tracts and are now represented by an unconformity.

The inset-valleys and their fills thus provide a rich record of tectonics, climate and sea-level change in eastern Yilgarn Craton during the early Cenozoic, which is of relevance to models of palaeonvironmental change and ore deposit generation.

YILGARN RED-BROWN HARDPAN AND EXPLORATION IMPLICATIONS.

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Red-brown hardpan occurs extensively in Western Australia in the arid and semi-arid regions of the Murchison, Pilbara and Eastern Goldfields divisions, between longitudes 115°E and 124°E and latitudes 23°S and 30°S. It occupies an area of about 360,000 sq. km, two thirds of which occurs in the northern Yilgarn Craton, predominantly in regions with <250 mm annual rainfall. In present-day higher rainfall (400 to 500 mm) regions, red-brown hardpan is being weathered to form the top soil.

Red-brown hardpan occurs at or near the land surface and may vary from less than one metre to more than 10 m thick. It is exclusively developed in colluvium containing a minimum of 20% quartz, 15% clays and 2% iron oxides. It is bright reddish brown to reddish brown, earthy, with a sandy loam texture, blocky structure and porous. Red-brown hardpan is hard and characterised by sub-horizontal laminations predominantly of uncemented kaolinite. Ped surfaces are often coated by Mn oxide. Red-brown hardpans show varying stages of cementation ranging from weakly cemented through moderate to strongly cemented. In addition, calcrete and red-brown hardpan occurs together in many places, south of the Menzies line, and this distribution suggests that red-brown hardpan was once more extensive and has been subsequently replaced by carbonate to form calcareous red-brown hardpan and calcrete.

The mineralogy of the cement is complex. Data from XRD, SEM, TEM, EFTEM, FTIR and NIR investigations show poorly-ordered kaolinite and opal-A as the main components of the cement. These results suggest that red-brown hardpans were formed where there was sufficient water during the wet season to dissolve alumina and silica, but insufficient to leach them. During the subsequent dry season, the dissolved alumina and silica was precipitated as poorly-ordered kaolinite and opal-A. Successive dissolution and precipitation led to the fusion of poorly-ordered kaolinite and opal-A at a nanometre scale to progressively cement the colluvium. The age of the red-brown hardpans, estimated by paleomagnetic dating of hematite, is from Pleistocene to present.

Geochemical investigation at the Federal Open Pit Gold mines, Broad Arrow, north of Kalgoorlie indicate that there are Au anomalies in red-brown hardpan. Gold concentration is up to 50 ppb against the background anomaly of 10 ppb. Sequential and partial extraction analyses show significant correlation of Au with Ag, Ca, Ce, Co, Mg, Mn and Ni. This suggests that the Au concentration in red-brown hardpan is due to: (a) mechanical dispersion due to reworking of Au-bearing clasts in the sediment and (b) hydromorphic dispersion from the underlying mineralisation. It can therefore be used as a useful sampling medium for gold exploration.

ELEMENT DISPERSION IN THE FOURTH DIMENSION

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INTRODUCTION

Despite nearly 70 years of modern geochemical exploration and related research there is still much that we don't know about the processes of weathering-related element dispersion and the formation of secondary geochemical anomalies. Many questions relate to time, and the history of geochemical anomalies. The following questions spring to mind.

- How fast are different target and pathfinder elements 'mobilised' under different weathering regimes and what is the flux ?
- How long does it take to form (and destroy) a detectable secondary geochemical anomaly under different weathering conditions ?
- Is secondary geochemical dispersion a continuous process or is it episodic ?
- The geochemical anomalies that we find – when did they form and how have they been modified ?
- How have changes in the biota through time affected element dispersion ?
- Are anomalies spreading at the present time ?
- Mobile metal ions - do they effectively exist ?

In areas with variably preserved old regolith where there has been opportunity for multiple or continuous geochemical dispersion under a range of weathering regimes (i.e. most of Australia), answers to these questions could improve exploration success. For example, if the relative expression of a geochemical anomaly is markedly different under different weathering regimes, setting the appropriate anomaly threshold and recognising the appropriate multi-element association will depend on knowing when the anomaly formed and under what conditions. Understanding particular element behaviour under different weathering regimes and recognising these can also help predict the formation and location of important supergene and residual ore deposits.

Dating of regolith by various methods now provides time constraints on materials associated with element dispersion at a number of important sites. Detailed studies of the dispersion patterns at these sites can start to answer some of the fundamental questions listed above.

WEATHERING EPISODES AND LANDSCAPE EVOLUTION

Weathering profiles and their contained geochemical anomalies are preserved according to their position in the regolith and the history of landscape development, relative uplift, erosion and deposition (Figure 1). Different weathering features and episodes may be manifest and preserved in separate parts of the weathering profile if there has been erosional lowering of the land surface or burial of older profiles. Alternatively younger and older features may be superimposed if the land surface has been relatively stable. Each episode may be characterised by different geochemical dispersion and fixing processes, particularly if climatic, hydrologic and biological conditions have changed. In many cases the earlier dispersion patterns are overprinted by patterns developed during contrasting conditions. This combination can result in very low concentrations of many target and pathfinder elements over mineralised sites, particularly in the non-ferruginous saprolite (i.e. a double or multiple 'whammy' dispersion scenario).

Materials exposed at the surface (e.g. lag) undergo a range of transformations with time and changing environmental conditions. These include variable transport and physical degradation as well as chemical leaching and precipitation. This results in element fractionation by combined mechanical and chemical processes. The degree of fractionation will vary depending on the age or life cycle of the material and commonly there is intermixing of materials with differing maturity.

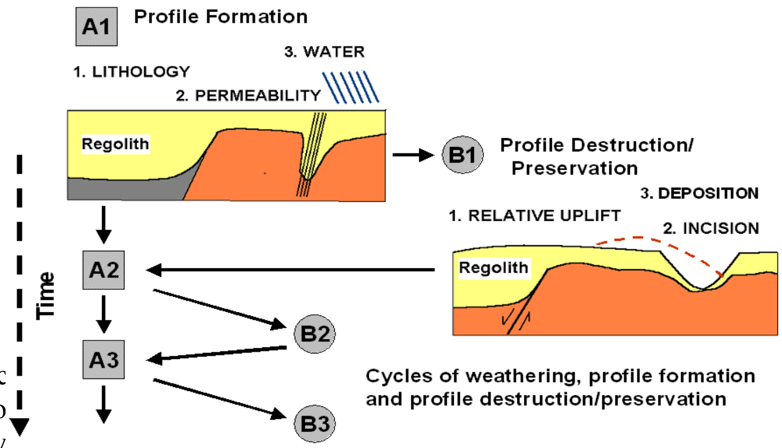

Figure 1. Basic c ... ng profiles. Cycles of these pro ... er different, climatic, hy ... volving element dispersion, fixation and fractionation accompany these cycles.

SOME SITES AND EXAMPLES

Ongoing work in the Cobar region of western NSW (including work in collaboration with Dr Brad Pillans and PhD student Martin Smith) has established a framework of dates related to weathering processes. These include:

- Palaeomagnetic dates of major oxidation, ferruginisation and hematite fixation across the region and at several ore deposits;
- Dates inferred from the monsoon effect and δO^{18} values of kaolinite in weathering profiles;
- Dates based on stratigraphic relationships and radiometric dating of Miocene leucitite flows;
- Ar-Ar dates of manganese oxides (cryptomelane-coronadite) associated with gossans.

Results to date indicate two major periods of deep oxidation and ferruginisation in the Early Palaeocene (60±10 Ma) and Miocene (12±3 Ma). These two periods are preserved at the McKinnons gold deposit in different parts of the profile. At other sites the two dates occur superimposed in the same mottled zone or are singly preserved at particular locations. Profiles buried and preserved by leucitite flows (dated at 17±0.25 Ma, McQueen *et al.* in prep.) also show the Miocene dated ferruginisation. At the New Cobar open pit, palaeomagnetic dating of the top 40 m of the oxidised saprolite gives a Jurassic age (ca. 180 Ma; McQueen *et al.*, 2002). Oxygen isotope studies of kaolinite in saprolite at several sites suggest ages consistent with the early (Palaeocene to Eocene) ferruginisation period (M. Smith pers. comm.). Manganese oxides in the upper part of the gossan at New Cobar yield Ar-Ar dates of 15.9±0.5 Ma (Vasconcelos. 2004).

Similar to many parts of southern Australia, the weathering history of the Cobar region has been strongly influenced by major climatic variations through the Cainozoic. In general terms this has resulted in deep chemical weathering under predominantly warm humid conditions (with high availability of organics) in the Early-Mid Tertiary and superimposed drier chemical weathering under increasingly arid conditions from the Late Tertiary. In detail the picture is more complex with fluctuations to at least two cooler-dry episodes prior to the Oligocene (McGowran and Li, 1998). Over this period humid conditions with high water table levels would have favoured hydration/hydrolysis reactions and mobility of reduced species, particularly Fe^{2+}. Groundwater pH conditions would have been neutral to acid, the latter particularly where sulfides were oxidising. It is also likely that high organic content would have favoured organo-complexing of many elements. Arid climatic conditions, with falling and fluctuating watertables, favoured oxidation reactions and a change to more complex, groundwater compositions, particularly with higher salinity, increased activity of carbonate and sulfate and regional neutral to alkaline pH. Under these superimposed arid conditions the solubility and mobility of some elements, particularly Au was increased where chloride and thiosulphate complexing occurred, whereas other elements, especially Pb, Ag, Ba and Hg became relatively fixed as insoluble chlorides and sulphates. Marked pH gradients around sulfide deposits that continued to weather resulted in dispersion of elements such as Cu and Zn to form broad anomalies.

McKinnons gold deposit

The McKinnons gold deposit is a supergene-enriched, epigenetic pyritic-quartz veinlet style gold deposit. Exposures in the open pit and information from the regional landscape history indicate that the deposit has undergone prolonged weathering and some erosional stripping of the upper part of the profile. A Palaeocene ferruginisation is preserved in the upper part of the profile and a younger Miocene ferruginisation occurs below this (25 m). Individually dated sample cubes of mottled saprolite from these two zones show some major differences in their trace element contents (Figure 2). The older part of the profile has significantly elevated As and samples with significantly higher Pb contents. The zone of younger ferruginisation has very low As and Pb contents but the highest Cu contents. Hematite is the principle iron oxide in both zones and its bulk abundance is similar for both (Figure 2). Higher As and Pb in the older part of the profile may reflect early intense weathering under humid conditions with widespread release of these elements from the sulfides, enhanced mobility and subsequent accumulation in hematite during oxidation. Elements such as Cu and Zn were not accumulated by hematite or if they were they were not strongly fixed in this mineral (studies on ferruginous lag in the Cobar area confirm that these elements are not as enriched or as strongly bound in hematite as As and Pb). Low pH conditions would also have favoured greater mobility of Cu and Zn. Later weathering under arid climatic conditions resulted in overall lower release of metals from already partly weathered sulfides but some local accumulation of Cu and Zn in hematite, possibly enhanced by neutral to alkaline groundwater conditions.

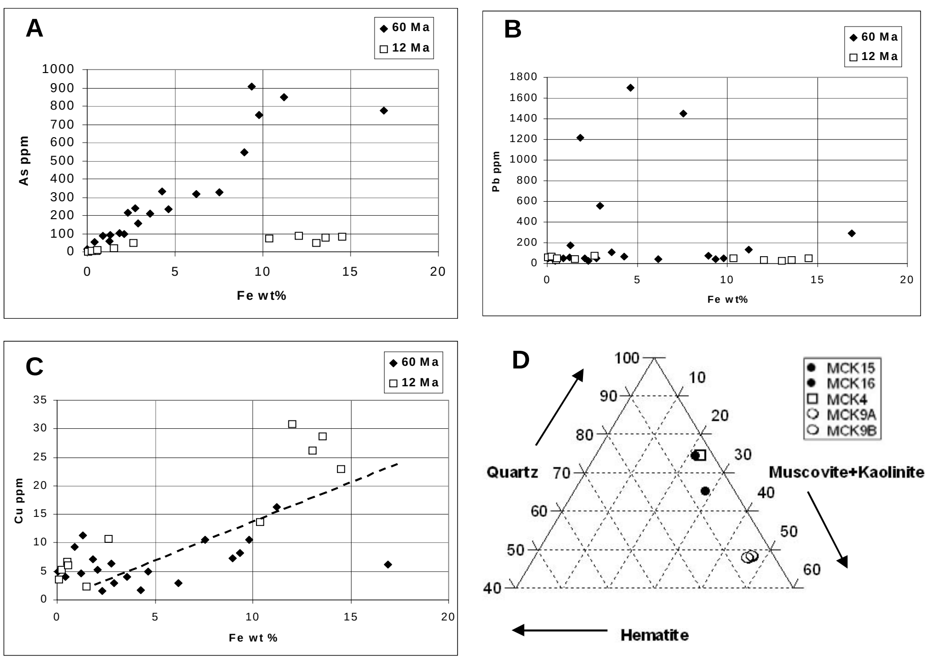

Figure 2. Geochemical and mineralogical characteristics of palaeomagnetically dated ferruginous saprolite from the McKinnons gold deposit near Cobar. A, B and C show concentrations of As, Pd and Cu against total Fe extracted by aqua regia digest from individually dated samples (analysed by ICP OES, Smith, 2001 and McQueen, 2005). D shows the major mineral compositions of bulk samples collected from the two main dated zones (quantitative XRD by SIROQUANT). Open symbols are for the 12 Ma (lower) site and closed symbols for the 60 Ma (upper) site. There is no detectable goethite in any of the samples. Gold content of the bulk samples is MCK15 (30 ppb), MCK16 (10 ppb), MCK4 (20 ppb) MCK9A-B (10 ppb). Fresh sulfide mineralisation contains 20 ppm As, 104 ppm Pb, 60 ppm Cu and 0.5-2.5 ppm Au.

New Cobar copper-gold deposit

The New Cobar deposit is a structurally controlled, vein-style polymetallic sulfide deposit with exploitable gold. It crops out as a small hill in an erosional terrain and shows weathering to approximately 130 m depth and is strongly oxidised to 75 m. Samples collected down the top 40 m of the weathering profile have yielded consistent Jurrassic palaeomagnetic dates. Within this zone there is strong depletion of Cu, Co, Ni, and Zn as well as depletion of Ag relative to Au. Gold is depleted in the top 10-15 m, but it is preserved or relatively enriched below this. Lead and to a lesser extent As are preserved in the upper part of the profile. Anomalous Pb levels, particularly developed with hematite/goethite in low-angle fractures, define a 70 m wide halo around the deposit. In the lower part of the oxidised zone (yet to be dated) lead and copper arsenates persist. Covellite and native copper occur in the upper part of the supergene zone above the present water table. Coronadite-cryptomelane and lithiophorite are common manganese oxides in the upper part of the profile, typically forming coatings on gossanous hematite and secondary silica. The cryptomelane has been dated as Miocene, indicating precipitation significantly latter than initial weathering and oxidation of the sulfide mineralisation in the Jurassic. This later stage precipitation of manganese oxides probably reflects more strongly oxidising and/or higher pH conditions in the Miocene, consistent with an arid climatic regime. REE carbonates are also a feature of the upper weathering zone. Textural evidence (including infillings in partially weathered pyrite) indicates that these have precipitated under very dry, high pH conditions at a late stage of the weathering and dispersion history. The REE were residually concentrated by early intense chemical weathering under acid conditions that effectively removed Ca. Later introduction of carbonate-enriched groundwater caused precipitation of REE carbonates (the best available cations) and also malachite in the upper part of the profile. This was probably coincident with calcite and dolomite precipitation to form calcrete in areas away from the deposit. There is more to learn about the history of element dispersion at this deposit but clearly there has been multistage dispersion under different chemical regimes over a 180 Ma time span.

Regional dispersion features

Geochemical investigation of the regolith across the Cobar-Girilambone region has identified a number of regolith-related element associations (McQueen and McRae, 2004). The important associations include:

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

The timing of these associations is not yet established. The 'evaporitic' association is related to the development of aridity but the timing of initiation and the duration of this episode are not known. The manganese oxide association reflects a period when Mn was able to escape deposition with Fe in the upper part of the oxidised weathering profile and precipitate separately and deeper by oxidation. Given sufficient Mn in solution this could occur if conditions became more oxidising after iron oxide precipitation. Alternatively, separation could occur if the ground water pH became more alkaline promoting Mn oxide precipitation at Eh conditions where Mn was still in solution but Fe oxides had already precipitated higher in the profile. Concentration of manganese oxides at a broadly similar depth, significantly above the present water table across the region suggests that it could represent a water table highstand formed in the Miocene. Iron oxides/oxyhydroxides show a wide distribution in the weathering profile, but a strong concentration in the top 20 m. There have been multiple stages of iron oxide/oxyhydroxide precipitation under a range of climatic conditions, but the details of associated element uptake from background under these different conditions is yet to be established.

CONCLUSIONS AND IMPLICATIONS FOR EXPLORATION

Initial studies utilising various regolith dating methods have confirmed that in regions subjected to prolonged weathering there are significant differences in element dispersion patterns formed at different times, reflecting different environmental conditions. Depending on the landscape history, different patterns are separately preserved or in some cases superimposed. It is planned to extend this line of investigation to fully characterise the different systems and to improve our understanding of anomaly formation in a range of regolith types and settings.

Geochemical exploration programs generally take a 'one size fits all' approach to setting thresholds and pathfinder associations for a particular style of mineralisation in known terrains with similar regolith and bedrock type. It is also important to know if element dispersion behaviour has changed with time and what episodes of dispersion may be represented at different sites and levels in the landscape. To understand geochemical anomalies properly we need to know what system we are in.
Different systems formed at different times can result in different anomaly patterns around similar deposits. Superimposed effects over prolonged periods may explain the effective removal of some anomalies. Particular temporal weathering regimes or systems may be more conducive to element dispersion and/or fixing or more favourable for supergene ore formation. Identifying these systems and understanding where they might be preserved in the landscape and regolith can help make geochemical exploration more predictive and successful.

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REGIONAL LATERITE GEOCHEMISTRY OF THE CENTRAL YILGARN

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Many areas of lateritic residuum in greenstone belts have probably been tested for Au, and potentially Ni, over the past 20-30 years; is laterite geochemistry therefore redundant? We think no!

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 Gossan Hill Deposit at Golden Grove, Western Australia, and the nearby Scuddles Prospect (Smith and Perdrix, 1983). Subsequent studies in the Greenbushes rare metal pegmatite district showed a multi-element anomaly of approximately 20 x 12 km (Smith et al., 1987). Over the period 1980-1993, a regional geochemical database (CSIRO-AGE) of several thousand laterite samples was generated (Grunsky, 1991; Grunsky et al., 1988; Grunsky et al., 1989), covering substantial parts of the Yilgarn Craton, mainly greenstone dominated areas. Between 1997 and 2000, through a collaborative research project between CRC LEME and Astro Mining NL, a regional laterite geochemical survey involving 3900 laterite samples was completed over approximately 100,000 km2 of the central Yilgarn Craton, mainly in granite-gneiss terrain. 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 preserved lateritic mantle at surface. On the other hand, it does not discount the possibility of another Boddington-size deposit or a VHMS base metal deposit under transported cover.
Could laterite geochemistry play a role in exploring areas of 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 host precious, base and rare metals, as well as many pathfinder elements. Geochemical dispersion halos in lateritic residuum due to mechanical transport and hydromorphic processes can be several times larger than the target itself. Lateritic materials mainly occur at surface as duricrust or sandplain. Following erosion, they form gravel beds within alluvial sequences or comprise parts of colluvial sequences, together with sand, clay and lithic materials. (Note: newly formed nodules and pisoliths within sediments (ferricrete) are not discussed further here). Conventional exploration commonly disregards these materials and where transported sequences have been falsely characterized as residual and yielded anomalous results; follow-up drilling commonly fails to detect the source of the anomaly as the material may have been transported over some distance. Such anomalies are considered 'false' anomalies.

Can the geochemistry of transported ferruginous gravels be compared and combined with that of lateritic residuum? Lateritic gravels derived from the erosion of nodular and/or pisolitic lateritic duricrust and incorporated into alluvial or colluvial sediments appear to retain their geochemical characteristics despite removal of their 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. On the other hand, mixing may be beneficial, particularly during a first pass regional geochemical survey, as the sample will represent a far greater area than lateritic residuum.

What does an anomaly or geochemical trend in transported gravel mean and can it be converted into a target, and can these be ranked and prioritized? Work is currently under way to establish this but indications are that it may be possible, particularly for mineralization with a distinct multi-element signature. Several case studies in the Yilgarn Craton have shown multi-element signatures of mineralization in nearby transported ferruginous gravels and at the residual regolith – colluvium interface (e.g., Harmony (Robertson, 2004) and Calista (Anand, 2001)). Current studies at the Jaguar and Teutonic Bore base metal deposits found geochemical signatures in transported gravels that appear to show the Teutonic Bore mineralization at least 4 km downstream from the deposit. Critical for the interpretation of such data are knowledge of:

- regional geochemical patterns of 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.

CSIRO/CRC LEME and GSWA have commenced a demonstrator project, a laterite geochemical map 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). The total number of sample locations will be approximately 4000 of which approximately 1000 samples are available from existing collections. This leaves approximately 3000 locations but it is estimated that due to difficult access and other problems, only about 2000-2500 will be sampled. To date, approximately 1200 samples have been collected in the southwest quadrant of the Yilgarn.

Representative geochemical signatures of various deposit types are currently being compiled. Much of this work has already been done as part of previous LEME or AMIRA projects and requires compilation. In some cases, samples will have to be reanalyzed to obtain analyses 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 in addition to the bulk geochemistry. At Golden Grove, Gossan Hill, textural information from lateritic nodules and clasts can be diagnostic (Smith, 2004)

Understanding the palaeotopography and dispersion direction 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 this is not the case, 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 this technique may hold additional potential for exploring areas of colluvium and alluvium.

By way of comparison, 15 years ago, Canada had no economic primary diamond deposit. Only the efforts of some determined companies, geologists and prospectors who unraveled the indicator mineral trails in glacial tills and glaciofluvial sediments led to the discovery of diamondiferous pipes and the start of what is now one of Canada's most important minerals industries. A new approach to diamond exploration in the Yilgarn Craton using geochemistry for approximately 4400 laterite samples (Cornelius *et al*., 2005), was tested by CSIRO/CRC LEME in collaboration with Astro Mining NL between 1997 and 2000. This work discovered an ultramafic lamprophyre in the Merredin region (Cornelius *et al*., in press) and demonstrated the validity of the approach as an alternative exploration method for alkaline ultramafic rocks such as kimberlites.

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MINERALISATION CLUES IN REGOLITH DETRITUS AT THE GOSSAN HILL CU-ZN-AU VHMS DEPOSIT, GOLDEN GROVE, WESTERN AUSTRALIA

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An investigation of basal lateritic conglomerate, which forms the cover about the golden Grove Gossan Hill VHMS deposit, has established some criteria to identify lateritic nodules, pisoliths and other clasts derived from the ore deposit or its immediate vicinity. These criteria include preserved tuffaceous textures with relict cassiterite (an associate of the ore zone sulfides), relict micron-scale Cu, Zn, As, or Pb sulfide inclusions in quartz grains of tuffs, micron-scale Au inclusions in nodules or clasts, ferruginous pseudomorphs after sulfides in nodules or clasts, and elevated indicators trace elements, Cu, As, Zn, or, more rarely, Sb or Bi, in the core matrix of nodules or clasts.

This study is located within the km-wide multi-element geochemical dispersion anomaly (Smith and Perdrix, 1983) in lateritic cover around the Golden Grove Gossan Hill deposit (Frater, 1983; Sharpe and Gemmell, 2002). Such broad and strongly-zoned geochemical anomalies in regolith are particularly important in mineral exploration for concealed ore deposits. It is well demonstrated that multi-element geochemistry can be very effective in *locating* and *delineating geochemical anomalies.* These two steps are obviously important in exploration yet are only the beginning. The purpose of this study is to develop methods for *anomaly identification*. In studying this pronounced multi-element geochemical anomaly at Gossan Hill, the study seeks to establish criteria that, firstly, are diagnostic of the VHMS ore system, and, secondly, can provide indications of proximity to it.

The Golden Grove district has been subjected to prolonged deep weathering resulting in thick saprolite formation, commonly 60-100 m deep, with oxidation of sulfides to similar depths. The top half metre of saprolite is commonly a mottled zone in which vermicular, nodular and concretionary iron enrichments occur in a clay matrix. Centimetre-sized lateritic pisoliths and nodules are present in the top 10 cm or so of the mottled zone with the pisoliths and nodules isolated by matrix. A concentration of lateritic nodules and pisoliths commonly overlies the mottled zone or the saprolite forming a widespread lateritic gravel unit reaching 1 m to 3 m thick, though not always present. Generally, the lateritic gravel is interpreted to have a variably residual to locally transported origin. In places, the lateritic gravel is cemented to form a lateritic duricrust. IN areas of low relief, the lateritic gravel is commonly overlain by half a metre or more of silty soil/Aeolian sands and in places by several metres of alluvium. Erosion of soil and the mantle of lateritic gravel or duricrust have resulted in local areas of outcrop of saprolite or saprock. The prospective felsic Archaean volcanic sequence (Gawlinsky, 2004) generally has low relief except where it rises some 80 m above the plains at Gossan Hill where an area of outcrop/subcrop, measuring some 500 m by 600 m forms the hill crest.

Diagnostic textural features are recognizable within clasts in the lateritic cover about Gossan Hill, despite intensive weathering. They are recognizable for at least 600 m off strike of the VHMS ore system in this continuing study. Implications in exploration are: (a) diagnostic textural features lead to better ranking of geochemical anomalies through identification of the likely source; (b) abundance of (weathered) mineralized clasts indicates proximity to source. Proximity indications can substantially improve interpretation when exploring areas of cover. Furthermore, (c) findings can provide models for exploration in areas of thick cover within the broad category of interface sampling (Robertson, 2001), where samples are provided by drilling.

The study also demonstrates that much can be learnt to aid exploration through thick cover by studying basal sediments where the cover is relatively thin. The findings can be applied in exploration in the Golden Grove district, in similar lateritic regions of the Yilgarn of wEstern Australia, and probably in comparable lateritic terrains elsewhere.

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Comments by Ian Robertson and Ravi Anand are appreciated.

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MINERAL MAPPING OF SEDIMENTS AT ST IVES AND WHIRLING DERVISH

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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 detect feldspars, quartz, sulphides and some other anhydrous minerals. The spectra 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. Two down-hole traverses over Au deposits are described: one in the Intrepide area, near Lake Lefroy, and the other at Whirling Dervish prospect, Carosue Dam, courtesy of Gold Fields and Sons of Gwalia, respectively. At the first site IR spectroscopy was used to map fresh rock alteration, regolith stratigraphy, in particular of shallow sediments over saprolite. The second site study demonstrates why the kaolinite crystallinity index (KCI), derived from the IR spectra, is less effective in defining the unconformity for deep channel sediments over saprolite. Spectra were measured using the ASD[1] FieldSpec Pro, with a wavelength range from 350 to 2500 nm, and analysed using "The Spectral Geologist"[2], with mineral compositions derived using the "Spectral Assistant" module.

Intrepide Traverse, St Ives

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

Mineral maps and mineral assemblages obtained from the spectral interpretation are consistent with visually logged geology, and also provide additional logging parameters. Intermediate rocks are distinguished by common muscovite and the Si- and Mg-rich muscovite, phengite. The phengitic zones, not recorded by visual logging, may be a useful alteration indicator. Ultramafic rocks have abundant chlorite; with an outer chlorite/talc zone, and carbonates at the contact with intermediate rocks. The rocks in some drill holes appear to have been logged incorrectly as intermediate rocks, as their chlorite-rich and mica-poor mineralogy indicate ultramafic character. The apparent deeper weathering on the western and eastern parts of the traverse may represent lithological contacts and faults.

Weathering of mafic rocks commonly produces Fe-rich kaolinite, which has a minor, though readily observed, peak at approximately 2240 nm. This is measured by KCh parameter derived from this spectral region. At Intrepide, this parameter successfully recognizes ultramafic rocks from analysis of saprolite. The high values of the KCh parameter on the eastern and western margins of the traverse indicate a contact with ultramafic rocks not identified by visual logging.

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[1] Analytical Spectral Device – Fieldspec Pro ©
[2] © Ausspec International Pty Ltd

Indices empirically derived from absorbances in the 500, 1950 and 2200 nm spectral regions are able to distinguish sediments, residual regolith down to the base of saprolite, saprock and fresh rock. These spectrally interpreted zones agree well with those determined by visual logging.

Spectral analysis can recognize rock types, regolith units and differentiate sediments from *in situ* regolith at this site. 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; whereas low crystallinity indicate 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 for rapid spectroscopic techniques to map mineralogical parameters in rock and regolith.

Whirling Dervish Traverse, Carosue Dam.

Transported and residual materials can be distinguished using infrared spectroscopy on the basis of the KCI parameter. The method provides a well-defined boundary between shallow sediments and saprolite but is less effective in defining the unconformity for deep channel sediments over saprolite. This latter issue is addressed in this study, with discussion of methods to overcome the difficulty. Regolith at Whirling Dervish consists of a 1-4 m thick calcareous and ferruginous hardpanized colluvium, red clayey alluvium, and saprolite. The alluvium mainly consists of red clays with lenses of magnetic nodules that provide a good colour and spectral contrast against the underlying light-coloured kaolinitic saprolite. At the SW end of the traverse, the unconformity between the transported and the residual materials is clearly marked by an abrupt change in colour and an increase in the KCI for the residual material. At the NE end of the traverse, a similar colour change from red to white is not accompanied by an abrupt increase in the KCI. Below the colour change, the material lacks saprolitic fabric and the KCI increases progressively over several metres until it reaches levels typical of saprolite. This transitional zone between red clays and unambiguous saprolite is difficult to classify on the basis of both macroscopic observations and the KCI, and was further investigated.

The particle size distribution (PSD) of the red clay alluvium contains a significant proportion of very fine clay (<0.2 µm). This fine fraction is also present in the transitional zone but absent in the saprolite. Transmission electron microscopy (TEM) investigations confirm that red clay consists of very fine (<0.2 µm), euhedral kaolinite crystals with well-developed faces. X-ray diffraction (XRD) and TEM of the transitional zone shows that kaolinite crystals are thicker and larger with depth. TEM also shows that both very fine kaolinite, similar to that of the red clay, and coarse kaolinite (>1 µm), considered to be neoformed, are present in the transition zone. Saprolite samples are devoid of very fine kaolinite, and are dominated by thicker and larger kaolinite crystals, some of which appear to pseudomorph mica.

The TEM, PSD and XRD analyses suggest that at the base of the deep sediments have been subject to a transformation process with destruction of iron-rich kaolinite and formation of more well-crystalline kaolinite, resulting in a gradual increase in the KCI with depth. Iron in the affected sediments, both as Fe oxides and structurally incorporated in kaolinite, is also removed, which leads to simultaneous bleaching. The vertical extent of the process is probably controlled by the groundwater table. Shallow sediments above the groundwater table are unaffected by the transformation and thus their colour and distinctive low KCI, compared to the underlying saprolite, is preserved. The study demonstrates that deep sediments cannot be logged solely on the basis of colour and that a KCI cut-off needs to be determined in view of the fact that the KCI may increase at the base.

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.

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 four spectrally derived parameters, a kaolinite crystallinity index, “brightness”, “colour” and the use of the 1900nm water feature. The result indicates that LogTrans can be used to make a reasonably stratigraphic interpretation on the basis of spectral indices, particularly where stratigraphic constraint is added. Further work is required is required to understand how reliably this can be used in other settings.

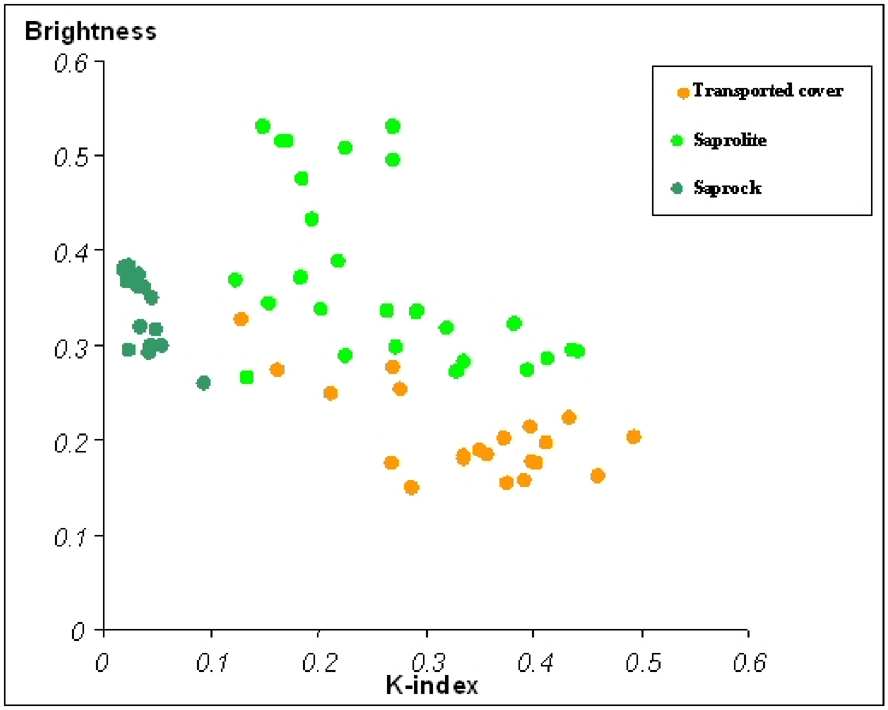

Figure 1: Spectral indices determined from the spectral measurement of drill chips, classified according to general regolith material type. Each material occupies a different "domain" in a "parameter space" as defined by these two spectral indices.

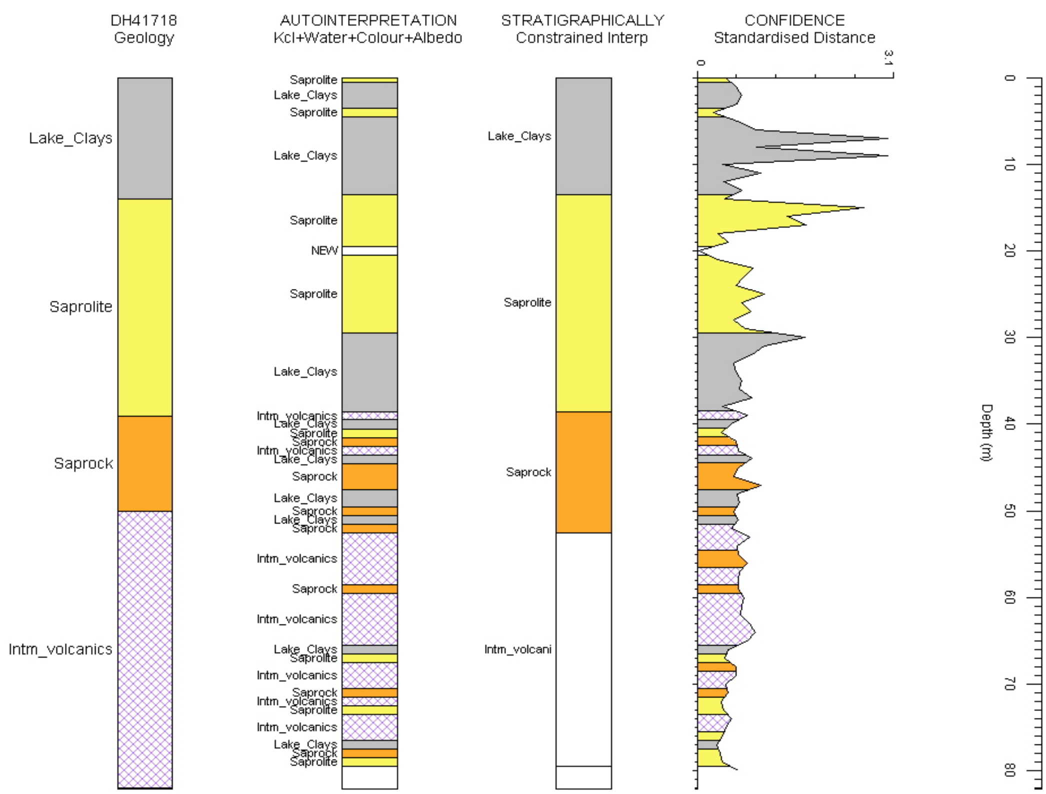

Figure 2: Actual (left) and LogTrans interpreted geological log (second left) for drillhole #1718, derived from the interpretation of spectral indices for "Colour" and Kaolinite Crystallinity, Water and Albedoe on which the automatic interpretation was based A measure of confidence for the derived interpretation is also plotted (right). Also shown is an interpreted log with stratigraphic constraint added.

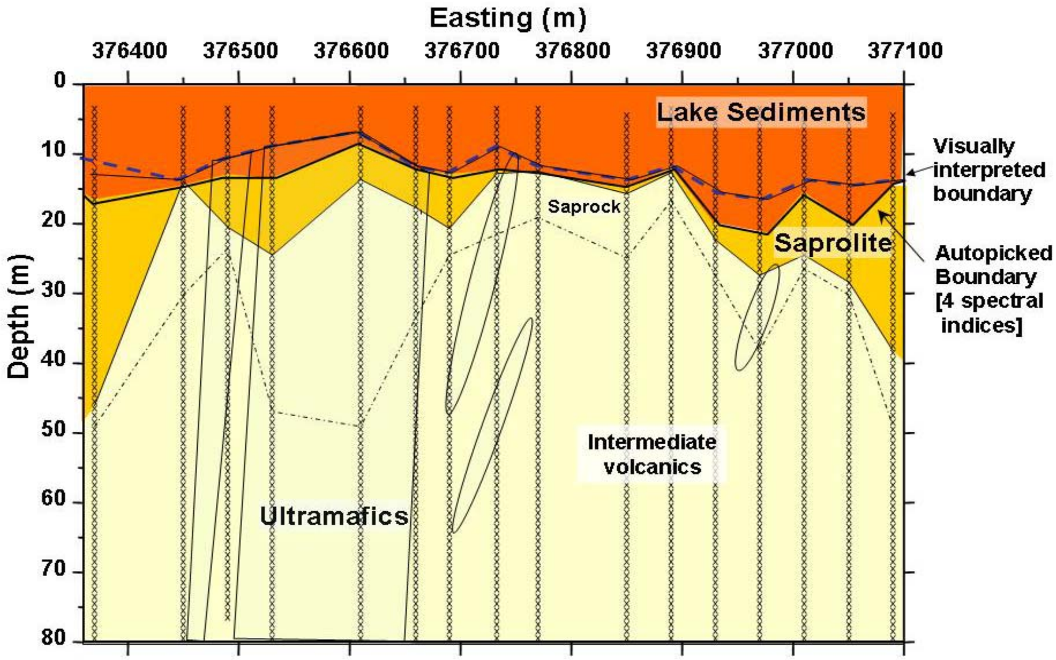

Figure 3: Geological section interpreted from a fence of drill holes. The boundaries between the main regolith units defined from a manual interpretation of drill chips are shown along with the interface between lake sediments and saprolite, detemined from the automatic interpretation of spectral indices.

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) (See Figure 2). This feature is similar to that employed in cluster analysis and provides a measure of how effectively 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. Figure 3 illustrates the potential of an automated interpretation of spectral indices as a means of discriminating between transported and in situ regolith materials. In this example, the boundary between transported sediments and saprolite defined from a LogTrans interpretation of 4 spectral indices is shown along with the visually defined boundary.

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.

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USING BIOGEOCHEMISTRY AND GEOBOTANY TO EXPLORE THROUGH TRANSPORTED COVER FOR MINERALISATION

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CRC LEME has been conducting research aimed at understanding and applying biogeochemistry for mineral exploration programs, particularly in areas of extensive transported cover. At the University of Adelaide a research group is emerging that is making significant breakthroughs in the application of biogeochemistry for mineral exploration, and includes examples of mineralisation discovery through transported cover.

Contributing factors important for facilitating this recent development of biogeochemistry for mineral exploration programs include:

- improved analytical techniques with better detection limits that can be conveniently obtained for a large range of elements;
- the development of rigorous and robust sampling and sample preparation procedures and techniques;
- the evolution of regolith-landform mapping approaches and its integration with vegetation mapping, providing important context for biogeochemical samples and used in data levelling and interpretation; and,
- increased knowledge of Australian plants.

This presentation provides an overview of recent research outcomes.

Background: pre-assay considerations

The research program here has been structured according to the flow chart in Figure 1. An important step in this has been the initial development of robust sampling and analytical procedures. These studies have basically employed the sampling and sample preparation procedure outlined in Hill (2003), with some studies, such as Hulme & Hill (2004) developing slight modifications, mainly to adapt to the research facilities available. Important attributes here have been the wearing of powder-free latex gloves, use of paper sampling bags, and the low temperature sample drying prior to milling. Samples generally have not been washed, mostly because of the variable effectiveness of this process, and the problems of sample leaching and contamination during the washing process. Orientation programs including test washing of selected samples, as well as the monitoring of elements typically associated with detrital contaminants, and in some cases microscopic investigations help to further test for detrital contaminants. As a general rule, eucalypts and acacias twigs, leaves and phyllodes have been mostly found to have insignificant detrital contaminants, whereas roots, rough bark, leaf litter and the leaves of some chenopod shrubs and forbs have been more problematic.

In an exploration or research program, orientation plants are usually sampled and tested before more extensive sampling programs. This includes sampling a variety of organs from trees in a variety of geological and landscape settings, and if possible conducting different seasonal sampling programs. Different organs from different plant species have significant differences in their biogeochemical characteristics. This means that an organ of a species that has been effectively employed in one area may not apply to the same organ from different species in other areas. As for the development of most other effective exploration techniques, time spent at the orientation stage of a program usually brings rewards in the long-term. In most of our studies, we have mostly used leaves or phyllodes as the preferred sampling media. This is not only based on biogeochemical characteristics where these organs can provide the strongest expression of underlying mineralisation, but also because leaves tend to be the most convenient, readily available and consistent sampling media.

Time and space are two other important variables to consider when planning a biogeochemical sampling program. Recent results convincingly show that seasonality (usually related to rainfall frequency in arid areas) can have a significant impact on plant chemistry (e.g. Hulme & Hill, 2004). The regolith-landform spatial context is also very important. For instance plants growing along drainage lines typically have different biogeochemical characteristics than the same species growing elsewhere (Brown & Hill, 2004). This partly relates to catenary differences in soil / regolith characteristics, but biological processes in these different settings are also very different. All of our biogeochemical sampling programs are integrated with regolith-landform maps that have proven important in the interpretation of biogeochemical results, in particular the relationships with chemical and physical dispersion processes (e.g. Brown & Hill, 2003).

Biogeochemistry and Geobotany

Two main aspects have been considered in this research:

1. geobotany, which examines the spatial associations of plant species and communities with substrate (typically regolith-landforms); and,
2. biogeochemistry, which examines the chemical associations between biological media and substrate.

Both of these approaches have been employed in the past, and in many cases linked to mineralisation discoveries.

Penetrators and amalgamators

A simple way to interpret many of the biogeochemical characteristics of biota is as either:

1. penetrators, which derive their chemical characteristics from deep in the regolith (such as buried bedrock interface) usually via deep root systems (e.g. well developed ‘sinker’ or ‘tap’ roots); or,
2. amalgamators, which derive their chemical characteristics from wider rather than deeper settings. This may be achieved branching root systems (extensive lateral roots) with biota providing a chemical signature that is a mixture of adjacent substrate chemical properties.

Chenopod Penetration of sheetflow and alluvial regolith, Curnamona Province, SA

Chenopod shrublands include low bushes of saltbush and bluebush, and are widespread across arid and semi-arid Australia. Although low in height, many of these shrubs may live for hundreds of years and can have extensive root systems extending for *over* 10 metres deep. The widespread distribution of these shrubs and their extensive, long-lived root systems make them ideal plants for biogeochemical surveys. One drawback with the use of species has been the abundance of halides within leaf tissues (typically including salt glands) significantly lowering the detection limits for Au. Recent research has been able to overcome halide interference problems in analysis by targeting twigs as the preferable sampling organ (Brown & Hill, 2004). The main species examined have been bladder saltbush (*Atriplex vesicaria*), black bluebush (*Maireana pyramidata*) and pearl bluebush (*Maireana sedifolia*).

Recent results obtained from the White Dam Cu-Au deposit (Brown & Hill, 2004) have shown the ability of bladder saltbush shrubs to reflect mineralisation buried beneath at least 5 metres of barren transported regolith. Equivalent success has also been achieved at the nearby Green & Gold, and Wilkins mineralisation sites using black bluebush.

Acacia Penetrators, Curnamona Province, SA

Australia hosts a wide range of acacia shrubs and low trees, that form major components of semi-arid and arid plant communities. As well as being widespread, some important characteristics to consider when using acacias for biogeochemical surveys include that some species (e.g. *Acacia victoriae*) have prominent tap-root systems (Hill *et al.,* 2005). Also, species and sub-species variation is a very important control on chemical characteristics (Hill, 2003; Hill, 2004). This is well shown by recent results obtained from mulgas growing over Au mineralisation near Tibooburra that do not contain detectable levels of Au, whereas many other adjacent shrubs do. Prickly wattle phyllodes have been effectively used to detection continuations of the Broken Hill Line of Lode beneath transported cover in the Northern Leases area (Thomas *et al*., 2002; Hill, 2004; Hill *et al.* 2005).

River Red Gum Penetrators and Amalgamators, SE Central Australia

River red gums are one of the most widespread large trees in Australia. Their use in biogeochemical sampling programs has demonstrated their ability to both penetrate and amalgamate transported regolith chemistry (Hulme & Hill, 2003; 2004; Hill & Hill, 2003; Hill, 2004). Recent results from the study of this sampling media are discussed in more detail in another presentation at this meeting (Hulme & Hill, this volume), in which the details of the recent discovery of Ag-Pg-Zn lodes extending under the transported cover of Pine Creek has been made near the Pinnacles Mine near Broken Hill.

Mallee Penetrators, Central Gawler Au Province, SA

Research is presently being undertaken to understand the biogeochemical characteristics, dispersion and residence and mechanisms within the mallee woodlands of the Central Gawler Au Province, SA. An ongoing Honours study by Anna Mayo has been sampling a variety of mallee eucalypts across different phases of aeolian deposits north of Wudinna. Geobotanical observations here indicate that different mallee species preferentially colonise different phases of the dune systems, and observations from excavations in the area are most encouraging in showing mallee roots penetrating not only calcareous hardpans but other regolith units beyond tens of metres in depth.

Tanami Geobotanical Associations Leading to Biogeochemical Penetration?

Research presently underway in the Tanami region is testing the ability of snappy gum (*Eucalyptus brevifolia*) and other eucalypt and acacia trees to provide biogeochemical expressions of bedrock through transported regolith cover. This is being tested at the Coyote Deposit, and Larranganni Prospect in WA, and is proposed for areas further east in NT. Preliminary results show some important geobotanical associations between regolith types and thickness of transported cover in these areas. Nathan Reid is conducting the biogeochemical study as a part of his PhD program, while Anna Petts is looking at geobotanical (plant distributions) and geozoological (especially termitaria) associations with known depths of transported cover within her PhD (Petts & Hill, 2004).

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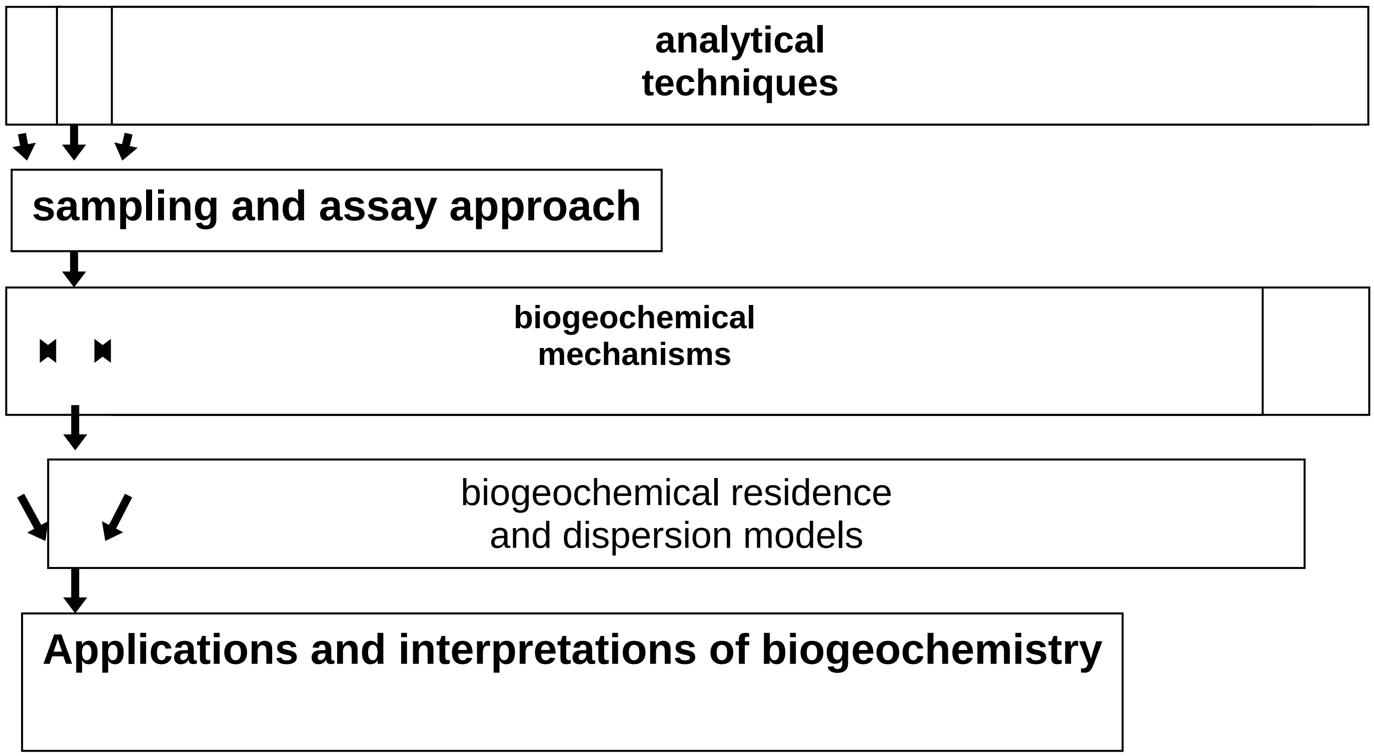

Figure 1: Biogeochemistry research flow chart representing this research program

MINERALISATION DISCOVERY THROUGH TRANSPORTED COVER USING RIVER RED GUMS (*EUCALYPTUS CAMALDULENSIS*)

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INTRODUCTION

River red gums (Eucalyptus camaldulensis) are one of the most widely distributed tree species within Australia and are particularly widespread across the Curnamona Craton and adjacent regions. They mostly occur along riparian zones of major drainage channel and alluvial outwash plains. Their prevalence in regolith-dominated terrains, in particular the basin margins flanking highly prospective bedrock-dominated uplands, provides mineral explorers with a new sampling media that can be employed along with more traditional sampling media, resulting in more effective mineral exploration through transported cover.

The river red gum biogeochemistry results from Pine Creek are discussed here. This area is within a regolith-dominated terrain that includes the Pinnacles Pb-Zn-Ag deposit and highly prospective Pinnacles-Thackaringa Shear Zone (Stevens, 1971; Ruggless & Govett, 1984; Parr, 1994).

BACKGROUND

The Pinnacles Mine is approximately 10 km southwest of Broken Hill. Pine Creek flows to the south from the Barrier Ranges, past the eastern margins of the Pinnacles Mine, and then into the Murray-Darling drainage basin, where it terminates within a series of ephemeral floodout fans and swamps.

The vegetation communities and dominant species are closely associated with the major landform settings for the region. River red gum riparian woodlands dominate major drainage channels and alluvial outwash plains, while smaller tributaries are colonised by prickly wattle (*Acacia victoriae)* shrubs and small trees.

To date, traditional methods of exploration are still mostly being employed at the Pinnacles Mine. Leyh (2003) recommends that the Pinnacles Mine has excellent potential for further upgrade and expansion given the systematic infill delineation drilling in the vicinity of the current mine.

RESULTS AND PRELIMINARY INTERPRETATIONS

Pine Creek River Red Gum Pilot Program

In December 2001, river red gum leaves were sampled from trees at approximately 250 m spacing along Pine Creek (Hill, 2004). Results revealed that Pb concentrations in river red gum leaves in close proximity to the Pinnacles Mine are up to 150 times background values (background is approximately 2 ppm Pb), Zn contents are 3 times that of background levels (background 33-57 ppm) and Ag contents 4.2 times that of background levels (background 0.84 ppm). In addition, pathfinder elements such as As and Sb also showed enrichment proximal to the Pinnacles Mine, while As contents are 28 times that of background values (background 0.05 ppm) and Sb contents are 7 times that of background values (background 0.2 ppm).

The encouraging results obtained from the pilot study, provided the basis for a more rigorous and detailed sampling program to be undertaken near the Pinnacles Mine. This involved the biogeochemical characterisation of different river red gum organs, ultrasonic washing to remove possible detrital contamination, and the sampling of every available river red gum to further constrain the geochemical footprint.

ORGAN CHARACTERISATION

The characterisation of individual river red gum organs was undertaken to determine the degree of heterogeneity within selected organs. Table 1, outlines the biogeochemical characterisation of river red gums organs.

Organs	Pb (ppm)	As (ppm)	Au (ppb)	Ag (ppm)	Zn (ppm)
Leaves	354	5.78	.910	.780	215
Fruit	28	.574	*	*	34

Table 1. Variations of metal concentrations within different oven dried tissues of an individual river red gum adjacent to the Pinnacles mine. * Signifies below detection limit.

The analysis revealed that Cd, Cs, Co, Eu, Hf, Ir, Lu, Mo, Rb, Se, Ta, Te, W, U, Zr, Be, Ga, In, Nb, Ti and V were in concentrations below detection limits within the selected organs. Many of the other elements displayed some detectable chemical heterogeneity between the two river red gum organs.

An assessment of the different media and element concentrations suggests that the leaves were a more convenient sampling medium. Leaves can be generally pulled straight from their branches. Fruit took a longer amount of time to collect an adequate sample weight, and they could only be picked in small clusters, and have a restricted sampling availability (spring and summer).

ASSESSMENT OF POSSIBLE DETRITAL CONTAMINATION

Results from washed and unwashed portions of three different *Eucalyptus camaldulensis* (river red gums) individuals sampled along Pine Creek adjacent to the Pinnacles Ag-Pb-Zn mineralisation are shown below.

Elements	Unwashed	Washed	Unwashed	Washed	Unwashed	Washed
	Pine Crk 5b		Pine Crk 6		Pine Crk 6a	
As ppm	7.400	8.040	4.360	5.490	5.780	5.990
Ag ppm	0.800	1.070	0.530	0.480	0.780	1.040
Pb ppm	539	464	207	266	354	383
Zn ppm	168	148	106	132	215	269

Comparison of unwashed and washed leaves of three Eucalyptus camaldulensis *(river red gums) displays the effects of sonic washing (one hour) in deionised water on the relative chemical composition of the samples.*

There were no significant decreases in the assay values for washed samples compared to the equivalent unwashed ones. Some elements (e.g. As, Ag, Pb, Zn) even appear in greater concentration in the washed samples. Possible explanations for this may be:

- elemental concentrations in the leaves are highly variable, then the difference between washed and unwashed samples could be within the range of the natural variation;
- element is concentrated in a part of the leaf that does not react with sonic washing (ie. if it is in the veins rather than the leaf tissue it may be concentrated due to relative accumulation);
- if any detrital components removed by sonic washing did not contain the elements in question and thus washing increases that elemental concentration by relative accumulation.

Following this finding, future samples were not washed during preparation. This is partly because the large, smooth, waxy leaves of river red gums were expected to be poor repositories for detritus and partly because the comparison of washed and unwashed sample assays in Table X did not suggest that washing had a significantly advantageous effect.

PINE CREEK SAMPLING

Following the results obtained from the pilot study, the characterisation of the river red gum organs, and the elimination of the possibility of detrital contamination significantly influencing chemical assays, all river red gums along Pine Creek were sampled. This resulted in the collection of 215 samples. The results have revealed that Ag, Al, Ba, Ca, Cd, Ce, Cl, Cs, Cu, Fe, K, La, Mg, Mn, Na, Nd, P, Pb, Pr, Rb, S, Sb, Si, Sm, Sr and Zn are detectable in the sampling media (leaves).

Assay results of river red gums adjacent to the Pinnacles Mine for the elements indicative of Pinnacles mineralisation revealed a Pb/Zn ratio of 3:2. The main lead lode is characterised by a Pb/Zn ratio between 2:1 and 4:1 and elevated Ag/Pb ratio of 45 g/t per 1% while mineralisation in the surrounding zone is generally characterised by a lower Pb/Zn and Ag/Pb ratios (Barnes, 1988). This possibly suggests that the Pb/Zn ratio of 3:2 and Ag/Pb 1:400 is indicative of the surrounding mineralisation.

These results lead to the excavation of a trench around a river red gum, which produced elevated metal contents. This resulted in the discovery of a previously unknown Zn-lode.

What is noteworthy is the location of a nearby river red gum, approximately 400m upstream that has a Pb/Zn ratio of 2:1 and Ag/Pb ratio 1:300, which is consistent with the suggested ratio for the main lead lode.

CONCLUSION

Through characterising river red organs, and eliminating the potential of detrital contamination, the application of river red gums as a means of exploration within a regolith-dominated terrain is very encouraging and has already lead to the discovery of previously unknown mineralisation under transported cover.

Acknowledgements

CRC LEME. NSW DMR, especially Barney Stevens. Craig Williams and all the guys at the Pinnacles Mine. Dallas and Helen Bright at Balaclava Station. David Garnett, formerly of Becquerel laboratories, for his patience and encouragement, as well as for arranging for the analyses. John Pike and Bill Pappas at Geoscience Australia. Anthony Senior and Simon Debenham for help with sampling during the initial pilot program.

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MULGA ANOMALIES OVER TRANSPORTED OVERBURDEN

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Biogeochemistry 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, bio geochemistry needs to be investigated. This paper presents findings of some recent LEME work on mulga trees 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 six sites. At these locations, transported cover ranges in thickness from 2 to 25 m. A variety of vegetation 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 vegetation and soil. In contrast to soil data, mulga 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 bio 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.

METAL MOBILITY IN MOONTA TRANSPORTED REGOLITHS

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INTRODUCTION

In arid to semi-arid environments, typical of much of the prospective mineral terrains in central and southwestern Australia, a thick unsaturated (vadose) zone is commonly developed above the water table. In this environment, understanding present and past hydrologic processes particularly with respect to flow through the vadose zone, is critical for modeling geochemical dispersion to surface of metal ions from a buried mineralised host. Northern Yorke Peninsula, South Australia is a semi-arid landscape with <400 mm annual rainfall. The flat to gently undulating topography reflects a thin sediment infill that blankets the Proterozoic basement and conceals the Moonta-Wallaroo copper deposits. The area includes examples of anomalous Cu in transported sediment that reflect the presence of mineralisation in weathered crystalline basement buried beneath. This was recognised and successfully exploited by miners when prospecting for new lodes in the district during the late 1800s to early 1900s (Jack, 1917), and later demonstrated convincingly in field studies reported by Sokoloff (1948) and Mazzucchelli, *et.al*. (1980). Recent investigation of trace element distribution in sediments sampled from sections at abandoned open pit mines at Poona and Wheal Hughes showed significant differences in Cu content in pedogenic calcrete at each mine (Hartley, 2000) (Figure 1). The observed differences provide a "real life" setting against which possible transport mechanisms for metal ions through the vadose zone can be considered and tested.

GEOLOGY AND MINERALISATION

The Moonta and Wallaroo districts, 120 km northwest of Adelaide, were important historic centres for copper mining and from 1860 to 1923 produced 330,000 tonnes Cu from narrow, shear-hosted sulphide vein deposits. Recent open pit and underground mining at Poona and Wheal Hughes (1986-92) produced a further 18,000 tonnes Cu from chalcopyrite-pyrite ore grading 4.5% Cu from lodes hosted by Moonta Porphyry of Palaeoproterozoic age. Wheal Hughes and Poona mines are 1.7 km apart in an interdrainage setting, 4.5 km from the coast. Water table is about 20 m below ground surface and is very saline (~42,000 mg/L). The porphyry is variably weathered for some 15 m; the top 4-6 m is highly weathered and mottled. Palaeomagnetic dating of iron-rich mottles at Poona gives Late Miocene to Pliocene ages of 8±4 Ma (Pillans pers com., 2004). The weathered profile and supergene Cu processes were therefore well developed before deposition of the 2-4 m-thick sandy clay equivalents of Hindmarsh Clay of Early Pleistocene age (~1 Ma). The clay is overlain by 1-2 m of calcareous aeolian sand and clayey silt with nodular and platy calcrete, and 0.6 m calcareous clay loam topsoil. At Wheal Hughes, the Pleistocene deposits overlie a 1-4 m-thick remnant of coarse-grained, arkosic sandstone, Winulta Formation of Cambrian age, which caps the weathered porphyry (Keeling et al., 2003).

Elevated Cu concentrations were measured throughout the Hindmarsh Clay in pit sections at Poona. Maximum values of 300 ppm were recorded 0.3-0.5 m below the contact with aeolian carbonate and were associated with thin, 20-70 mm wide, alunite seams developed in the clay. The results accord with anecdotal account of patches and nodules of radiating atacamite ($Cu_2Cl(OH)_3$) crystals encountered during overburden stripping of transported clay that overlay the back of the copper lode. This Cu-rich clay was stockpiled separately and subsequently picked over for mineral specimens. Specimens of atacamite lodged with the State Museum include one weighing 1.195 kg and estimated to contain over 600 gm Cu (Pring, SA Museum, pers com., 2004). In contrast, few high copper values in Hindmarsh Clay were recorded at Wheal Hughes and alunite seams were not observed in the clay (Hartley, 2000). The minimal dispersion of Cu into transported cover at Wheal Hughes is reflected in the less than background values for Cu in near-surface calcrete (Figure1).

At Moonta, inferred low rainfall infiltration rates, generally lower water tables and high evaporation during Pleistocene-Holocene times suggest that upward capillarity or metal ion diffusion could be significant mechanisms that have operated over time to transfer metal ions from the water table up through the vadose zone.

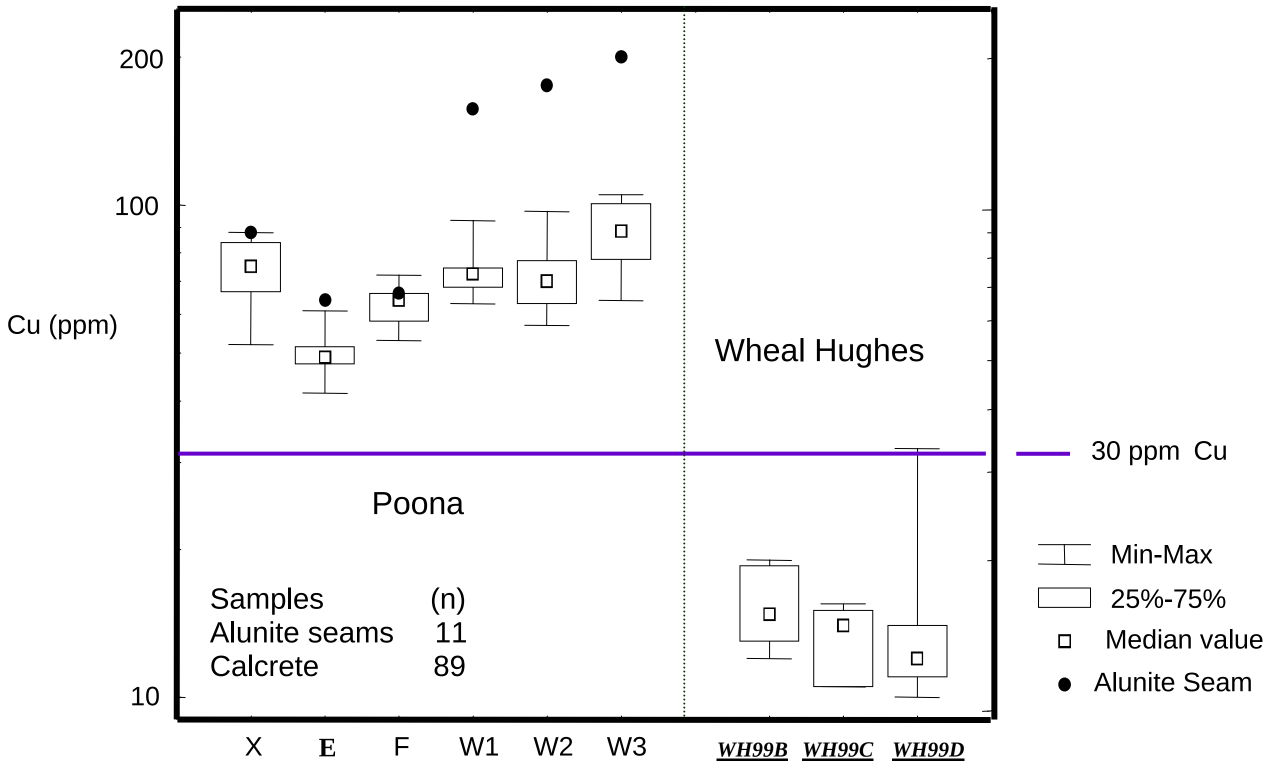

Fig.1. Box and whisker plots of Cu content in near surface calcrete and alunite samples from pit sections at Poona and Wheal Hughes mines highlighting the difference in Cu dispersion for the two deposits relative to the regional threshold of 30 ppm Cu (after Hartley, 2000).

CAPILLARITY

Fluid is present throughout weathered rock and sediment in the unsaturated zone above the water table. Fluid pressures in this zone are negative with respect to local atmospheric pressure and the water is held under tension and not free to flow as it does below the water table. Water molecules at the water table are subject to an upward attraction due to surface tension of the air-water interface and attraction of the liquid to “wet” mineral surfaces. This effect is known as capillarity. Where the capillary fringe extends into the zone of evapotranspiration, the loss of water results in effective pumping of water and contained solutes from the water table to the near surface.

The height of capillary rise is inversely related to effective pore diameter, which in turn is governed by grain size and grain size distribution (ie texture) in sediment or porous weathered bedrock. Theoretical values of capillary rise in sediments are given in table 1. These provide an order of magnitude estimate of capillary rise and are sufficient to demonstrate that advective transport of solutes in solution by this mechanism over significant distances is restricted to silt-sized particles or finer, with effective pore diameters <10 µm and preferably <4 µm (fine silt). Pore diameters observed by scanning electron microscopy of weathered moonta porphyry and clay sediments at poona and wheal hughes are certainly within the range 4 - <0.1 µm.

Table 1. Theoretical Height of Capillary Rise in Sediments

Sediment	**Grain diameter**	**Effective Pore**	**Capillary Rise (metres)**

	(mm)	diam (mm)	
Fine gravel	5	2	0.015
Coarse sand	0.5	0.2	0.15
Medium sand	0. 3	0.12	0.25
Fine sand	0.15	0.06	0.50
Very fine sand	0.075	0.03	1.0
Coarse Silt	0.025	0.01	3.0
Fine Silt	0.008	0.004	7.5
Coarse Clay	0.002	0.0008	37.5
Fine Clay	0.0002	0.00008	375.0???

The hydraulic and biological properties of soil pores, summarised in Table 2, highlight two related factors that limit hydraulic transport in very fine pores: low hydraulic conductivity and high negative pore pressure. At <0.2 µm effective diameter, hydraulic flow is negligible and water is held increasingly as hydroscopic water close to the surface of mineral grains. At high negative pore pressures of around pF 4.5 water approaches boiling point and boiling or the release of gases would disrupt the surface tension with continued water movement only in the vapour phase. Under semi-arid to arid conditions, high evaporation rates and increased osmotic suction due to high salt content in soils will contribute additional water potential or suction that may transport water in micropores over greater vertical distances than predicted by capillarity alone. This effect is observed in trees where evaporation from the leaves generates an atmospheric suction that can lift water to 110 m in xylem capillaries of diameter capable of capillary rise alone of <1 m (Koch *et.al*. 2004).

Table 2. Significance of pore size in physio-chemical and biological activity (modified from Blum, 2002) (pF is a measure of negative pressure or suction and is defined as the log of the height of an equivalent column of water measured in cms)

Pore Size (mm diam)	Hydraulic conductivity Water retention in pF	Biological Conditions
Macropores >0.05 mm	Excellent, gravity flow, free draining 0-1.8 pF	Large plant roots
Mesopores 0.03-0.05 mm	Good: some water retained after gravity draining 1.8-2.0 pF	Accommodates fungi and root hairs
Micropores 0.005-0.03 mm	Moderate capillarity flow 2.0-2.8 pF	Accommodates bacteria and other microbes
Ultra-micropores 0.0002-0.005 mm	Low capillarity flow 2.8-4.2 pF	Bacteria 0.5-3 µm, but space too small and not used by most microbes
Cryptopores or nanopores <0.0002 mm	Very low to negligible >4.2 pF Water retained against plant root extraction forces	Too small for bacteria, no space for plant roots or soil organisms. Reaction with organic chemical byproducts only

Preliminary calculations for poona indicate that a hydraulic flux of the order of 0.84 mm/year over a 100 ka would be required to generate a nodule of atacamite with around 600 gms cu, formed at 15 m above the water table; or 0.11 mm/year for a 750 ka period. These rates are above values modelled from field data for arid to semi-arid environments (scanlon, 2003) and suggest that capillarity alone may be insufficient to account for the accumulation of cu in hindmarsh clay, unless driven by high levels of evapotranspiration.

DIFFUSION

At very slow fluid flow rates, diffusion can be a more important mechanism than advection for dispersion of solutes. In the vadose zone, diffusion is confined to the water-filled fine pores and the film of water on grain surfaces. The rate of diffusion of a solute through water is described by Fick's law. Fick's Law needs to be modified for porous media where diffusion cannot proceed as fast as it can in water, simply because ions must travel around mineral grains, may diffuse into blocked pores, and may be absorbed onto mineral surfaces. In this case the effective diffusion coefficient D_e is used, where:

$$D_e = D_0 \tau$$

Where D_o is the diffusion coefficient in water and τ is an empirical coefficient for tortuosity.

For $CuSO_4$: Cu^{2+} is the rate limiting diffusing ion having a diffusion rate in pure water at 18°C of 5.88 x 10^{-6} cm^2 sec^{-1}. For assumptions of initial concentration of 200 ppm Cu, tortuosity = 0.1 and porosity = 30%, the diffusion flux can be recalculated at 4.86 mm/year; at best an order of magnitude estimate only. This rate is significantly faster than capillarity in fine pores, but diffusion operates in all directions and the effect is always to dilute the initial concentration. In order to accumulate sufficient Cu to form a nodule of atacamite with 600 gms Cu, a time period of the order of 9.0 Ma would be required, unless some means of focusing the diffusing ions was achieved. Even if this were possible, could the concentration gradient be maintained to drive the diffusion rate?

FURTHER INVESTIGATION

The Poona and Wheal Hughes mine sites provide a unique opportunity to explore potential mechanisms for Cu dispersion through the unsaturated zone that includes thin sediment cover. Marked differences in Cu dispersion recorded at the two sites are yet to be fully explained and offer the possibility of new insights into the principal driver of metal ion dispersion within the vadose zone over geological timeframes of several 100k years. Under a predominantly semi-arid to arid climatic regime, factors of regolith composition and texture, landscape position, Pleistocene climate and sea-level variation all modify vadose zone hydrology that could affect metal ion dispersion. The significance of identifying the main drivers is illustrated in the Moonta situation where surface geochemistry is apparently least effective in areas of sandstone cover. If sediment texture is a key factor that limits metal dispersion by capillarity, then the opportunity exists for new discoveries by mapping out the extent of sandstone and applying appropriate techniques to prospect these areas.

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EXPRESSION OF REGOLITH MINERALISATION IN ACID DRAINAGE WATERS - WA WHEATBELT

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Introduction

Installation of deep open drains (4m) to control dryland salinity through lowering of water tables, is currently a major initiative in the Western Australian Wheatbelt. 12,000Km of drains have been installed with regulatory approval, with an estimated 12,000Km of 'unapproved' drains also installed. Acid groundwater has been encountered across the state and in particular in drains in the eastern wheatbelt. Acid groundwater has the potential to release metals and trace elements potentially harmful to receiving areas and flora and fauna that inhabit these areas. Program three of CRC LEME 'Environmental Applications of Regolith Geoscience' is currently involved in a project that aims to quantify trace elements and minerals mobilised by acid drainage water, and determine their sources, sinks and transformation products in the WA regolith. The project is funded by the WA Engineering Evaluation Initiative (EEI), and commenced in July 2004.

A review of historical groundwater records in the WA Wheatbelt, and in particular, the Avon Basin, showed that acid groundwaters are prevalent in this region (fig 1.).

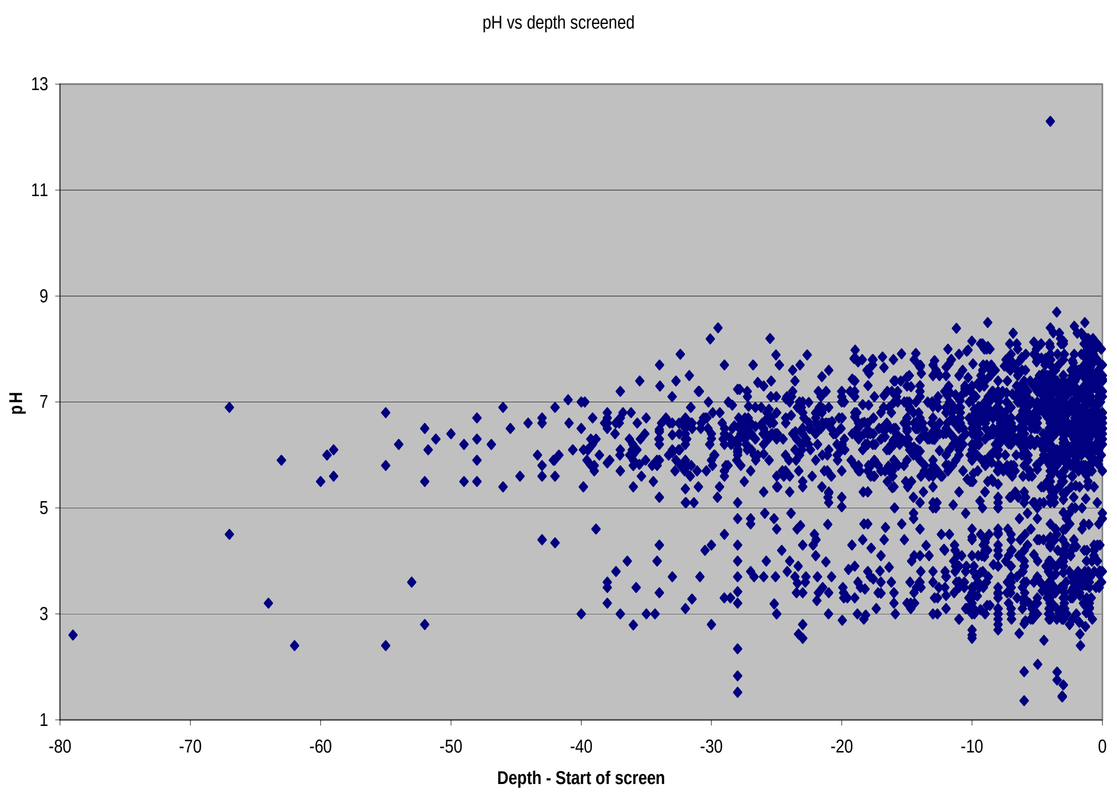

Figure 1 Summary of historical groundwater pH data

Methods

A geochemical survey designed to identify the potential risk of elevated toxic trace elements in drain waters and groundwater bores was conducted in October 2004, with a second sampling in January 2005. Most drains were sampled at only one or two locations. Over 200 samples were collected using standard hydrogeochemical techniques (0.45μm filtration and acid preservation on site) followed by ICP-OES and ICP-MS analysis, As and Se were determined by Hydride Generation ICP-MS. A full suite of major and minor cations, rare earths, actinides and lanthanides were determined in samples. Samples of drain sediments were collected in January for mineralogical analysis (XRF/XRD, SEM).

Results

Over 50% of drain waters sampled in October were acidic (pH 2.5-3.5), with a decline in pH (pH1.75-2.0) noted at many sites from the January sampling, acid drains were predominantly located in the eastern areas of the Avon catchment. Salinity of samples ranged from 6000mS/m to 20,000mS/m (seawater 5500mS/m), presenting significant challenges to ultra trace level element analysis.

Solution phase trace element, actinide and lanthanide concentrations were significantly elevated in acid drain waters, examples are summarised in Table 1. In alkaline drain waters most elements were below the limits of detection (with some notable exceptions including U and Zn).

Table 1. Examples of maximum concentrations of trace elements, actinides and lanthanides in solution in acid drainage waters

Element	***Maximum concentration (ppb)***
Co	650
Ni	380
Cu	9000
Zn	7000
Pb	1000
Au	10
U	900
Ce	2200

Mineralogical analysis of drain sediments showed the presence of elemental Cu and Zn/Pb sulphide minerals. In addition sediments contained As and Se in ppm concentrations.

Gold

Gold was detected in 10 of the 200 samples collected at concentrations ranging from 6-10 ppb. These initial results potentially indicate the presence of Au mineralisation in the surrounding regolith? These results are even more noteworthy as Au was not specifically being sampled for during this study (only small samples 100mL were collected and no pre-concentration of samples employing activated carbon was performed). The CRC proposes to follow up on these results with a more detailed drain, groundwater, regolith and vegetation reconnaissance survey.

Uranium

Highly elevated concentrations of U were detected in drain waters during this survey. Subsequent geochemical modelling of data (PHREEQ-C and Geochemists Workbench) along with spatial analysis of concentration trends has identified that all elevated levels of U are all located in a single drainage catchment, potentially indicating a localised U mineralisation in the regolith. As with Au we plan to follow up on these initial results with a more detailed reconnaissance survey.

Conclusions

Acid drainage waters in salinity mitigation drains in WA have highly elevated concentrations of trace elements and minerals. Solution phase mineral concentrations determined from a survey designed to assess environmental risk of toxic trace elements, (with no exploration or mineralisation reconnaissance goals), appear to indicate the presence of Au, U and possibly other mineralisation in this region. If further investigations prove that these initial observations do indicate mineralisation, then drainage waters may provide the exploration industry with a simple, accessible sampling medium.

This study also demonstrates the potential for regolith geoscience to deliver outcomes to both the environmental management and mineral exploration industries.

HYDROGEOCHEMICAL DISPERSION OF NICKEL AND OTHER ELEMENTS AT HARMONY NI DEPOSIT, WESTERN AUSTRALIA

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Harmony Ni deposit is situated 11 km NE of Leinster, Western Australia. Mineralization occurs over a thin 1.2 km north striking peridotite unit dipping to the west at approximately 80°. It is composed of pyritic massive Ni sulphides ranging from 1.0 to 5.5% Ni, overlying low-grade (< 1.0% Ni) disseminated sulphides in olivine peridotite. Oxidation occurs to 50 – 70 m depth. This study tested the potential of hydrogeochemistry for Ni exploration in the region, and investigated present-day groundwater dispersion processes.

The 73 groundwater samples collected at Harmony show low salinity and are commonly neutral (pH range 6.4 – 7.7). However, lower pH values (5.0, 5.9) were observed in two holes (Figure 2), possibly indicating sulphide oxidation. Such neutral and fresh groundwaters are observed throughout the northern Yilgarn, in contrast to the highly saline, acidic waters further south. Therefore, groundwater concentrations of metals at Harmony are expected to be strongly controlled by lithological factors, not predominantly by acidity and salinity as in groundwaters of the Kalgoorlie area. Thus, the high Eh and Fe values for Harmony groundwater may reflect ongoing sulphide oxidation.

Groundwaters are distinguished as mineralized where the drill holes intersected the mineralized vein. Ratios of mineralized/unmineralized medians for elements (less the two samples with [Ni] > 50 mg/L) are shown in Figure 1. Nickel and Co show a strong contrast between mineralized and unmineralized groundwaters. Dissolved Mo, As, Cr, V, Ge and Cu (and possibly Zn and Ca) are also enriched in the mineralized groundwaters. The U, Rb and Pb depletion may reflect lithological factors (*i.e.*, these elements tend to be low in ultramafic rocks), whereas the low HCO_3 may be a reflection of sulphide oxidation producing acidity and therefore removing dissolved HCO_3.

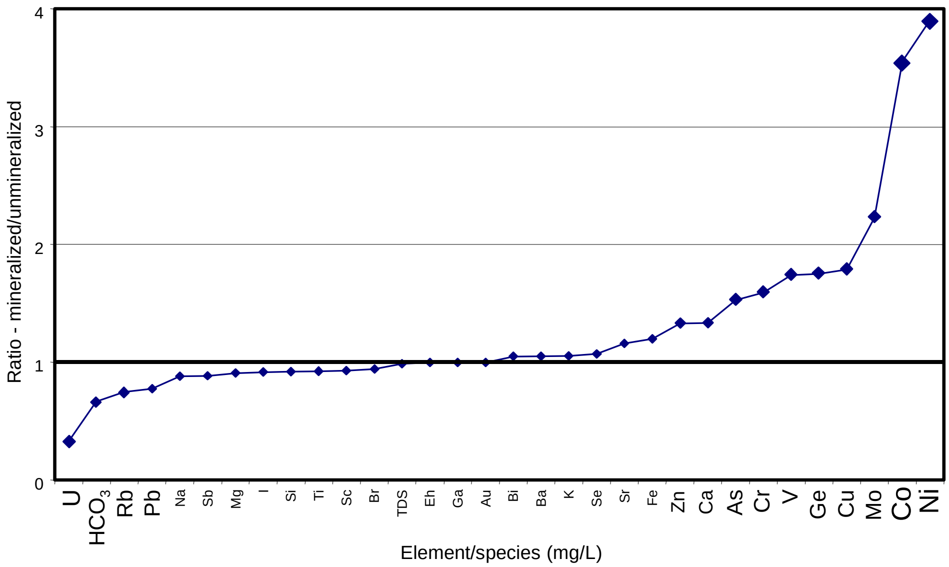

Figure 1: Ratios of mineralized/unmineralized medians for groundwaters at Harmony Ni deposit

Using element mapping, dissolved Ni (Figure 3) and Co are clearly enriched along the mineralized ultramafic unit, as are Mo, Cu, Ge and V. On the other hand, Cr (Figure 4) shows a broader anomaly reflecting the extent of ultramafic rocks, whereas As is only enriched along the northern part of the mineralized zone. Dissolved Pt, Pd (Figure 5), W and Re are, although low, also enriched along the mineralized zone.

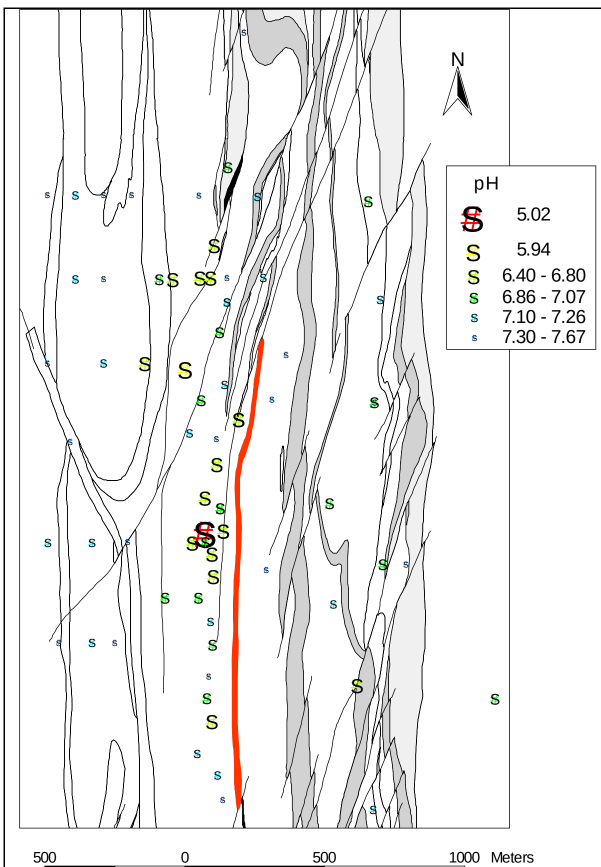

Figure 2: pH distribution at Harmony.

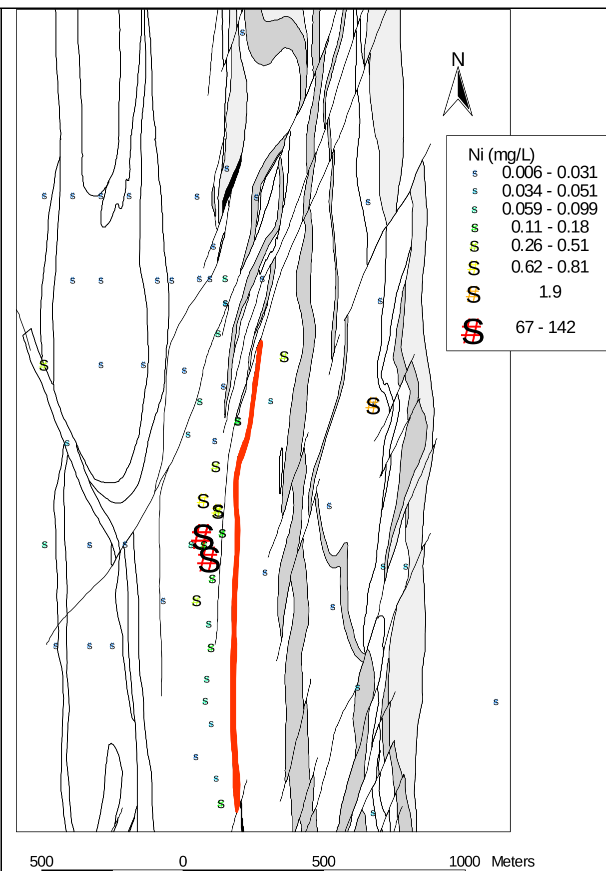

Figure 3: Dissolved Ni distribution at Harmony.

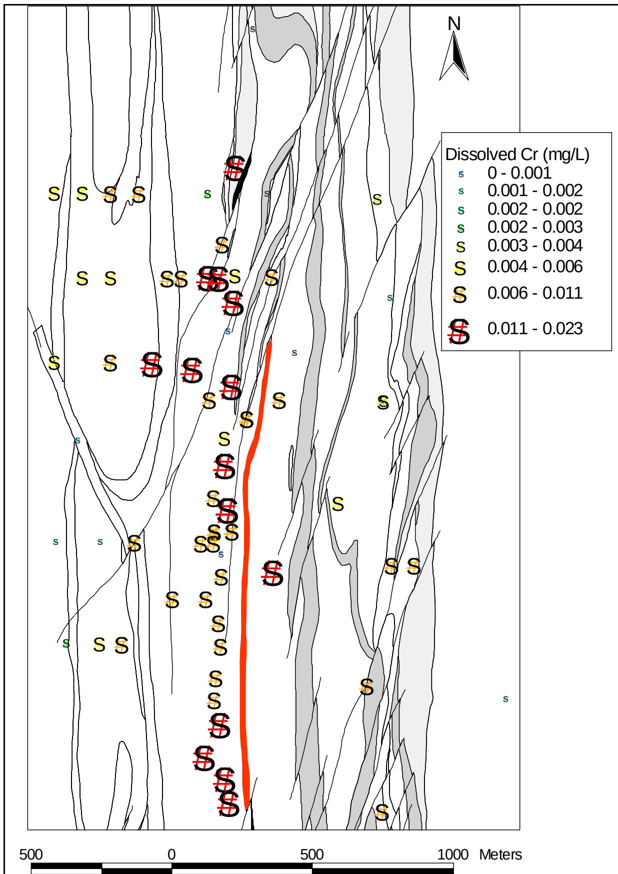

Figure 4: Dissolved Cr distribution at Harmony.

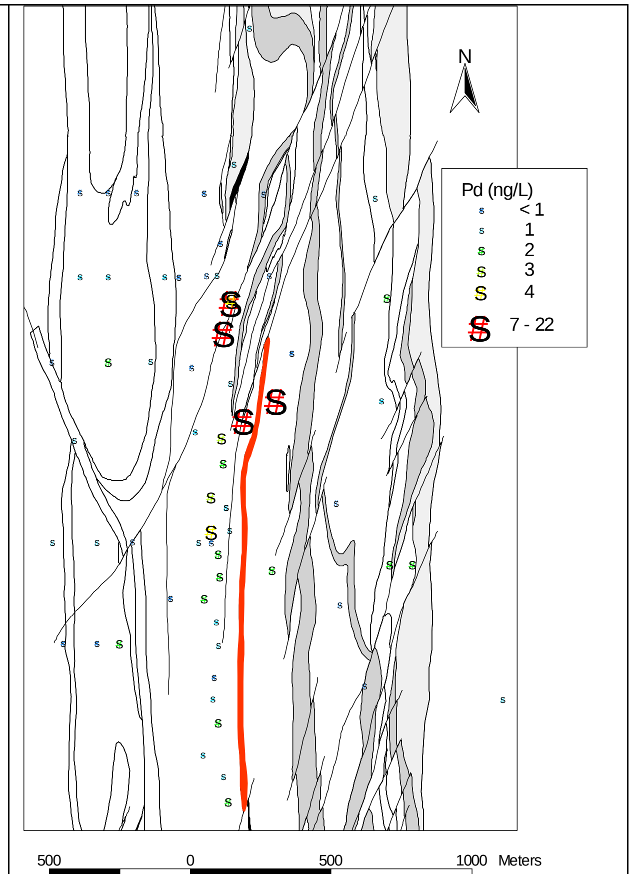

Figure 5: Dissolved Pd distribution at Harmony

Thus, hydrogeochemical sampling of groundwaters at Harmony was successful in locating the Ni sulphide mineralization and may be of use in the detection of further deposits in similar areas.

ACKNOWLEDGEMENTS

We would like to thank WMC Resources Ltd, and most particularly Dr Nigel Brand, who provided access to the Harmony site and to their exploration data base.

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 twelve months. 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. There are several current or recently completed CRC LEME research projects on calcrete that can be found on the CRC LEME website (LEME symposia).

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 are similar to those found for AMIRA-CSIRO Yilgarn studies undertaken last decade, but there have been some important additional knowledge gains:

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.
5. 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? To move forward on this problem, the research emphasis is now directed towards <u>understanding the process</u> and a number of projects have been completed, or are under way, that shed light on the way calcrete anomalies form.

This talk will highlight research on (i) the origin of the calcrete, (ii) the age of the calcrete, (iii) another process (apart from groundwater) that appears to be involved in the formation of Au anomalies, (iv) LA ICPMS studies that show the nature of distribution of invisible Au in a calcareous clay and (v) photomicrographs and SEM images of visible gold in calcareous materials associated with Au nuggets.

SOUTH AUSTRALIAN CALCRETE - GENESIS OF GOLD ANOMALIES IN CALCRETE BEARING REGOLITH

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Regolith carbonate accumulations such as calcrete and calcareous sands, which are widespread in semi-arid and arid regions in southern Australia, display a distinct covariance of Au with K and Mg and most prominently with Ca content and are commonly used as an effective sampling medium for Au exploration. However, the processes influencing the formation of Au anomalous calcrete in arid Australia are little understood. In this study we assess the geochemical properties of Au anomalous calcretes and a microbial process likely to facilitate its formation.
This study has investigated gold anomalous (2.5 to 50ppb) calcrete in aeolian sand dunes overlying gold mineralisation in Tunkillia suite granitoids on the Barns prospect, Gawler Craton, South Australia. Samples were taken from the aeolian cover on the Barns site, using a percussion soil corer. The geochemical analysis of these depth profiles of 2 to 4m clearly demonstrate the quantitative relationship between Au and carbonate forming elements (see for example Figure 1). The strongly systematic relationship of Au and Ca-Mg content to depth further shows the tight connection between the gold enrichment in calcrete and the underlying hydrothermal mineralisation. In addition to Ca and Mg the gold content also appears be linked to the K content. XRD and subsequent Rietfeld analysis showed that the K is contained in newly formed smectites. Thus the elevated gold content in the profiles is clearly linked to authigenic mineral forming processes. Intense calcrete formation and related gold enrichment also occurs in the close vicinity of roots penetrating the dune. Thin section petrography and cathodoluminescence shows that most of the calcrete in the regolith profiles is micritic and only rarely are sparic crystallites identified.

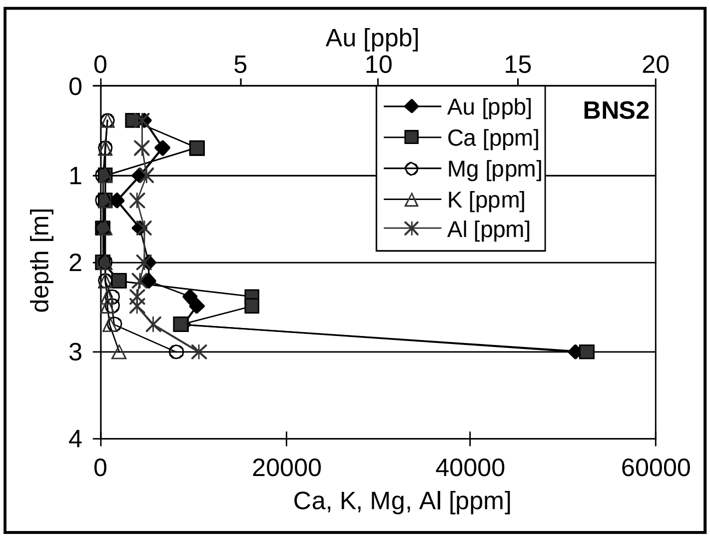

Figure 1: Relationship of Gold and major elements in

The formation of carbonate in regolith environments is controlled mainly by pH, p_{CO2} and concentration and availability of Ca^{2+} ions, which is readily available as free ions in the soil solution. pH and p_{CO2} in regolith and soil environments is controlled by either abiotic, inorganic or by biological processes. A possible microbiological process that is suitable to establish a chemical environment of high pH and elevated p_{CO2} concentrations is the ubiquitous enzymatic degradation of urea.

A set of samples from a depth profile in the dune was taken under sterile conditions. After impregnation with urea and incubation up to 24 hours samples from near surface contained 10 to 18 mg/l NH_4^+ decreasing to 1 mg/l at a depth of 2.3m over a background of 0.09 mg/l (see Figure 2). The genesis of the calcrete and pedogenic carbonate is thus suggested to be at least partly biomediated through biologically controlled reactions such as the urea breakdown, providing a favourable pH and pCO_2 environment throughout the depth profile. Gold, which appears systematically coupled to the carbonate content is scavenged from the soil solution in the calcrete precipitating reactions and finely distributed throughout the micritic carbonate in a non-particulate form.

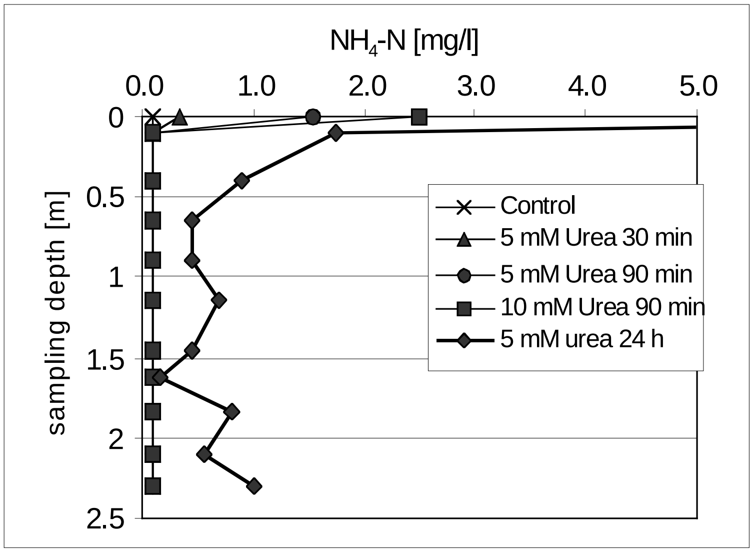

Figure 2:Ammonia production from the enzymatic