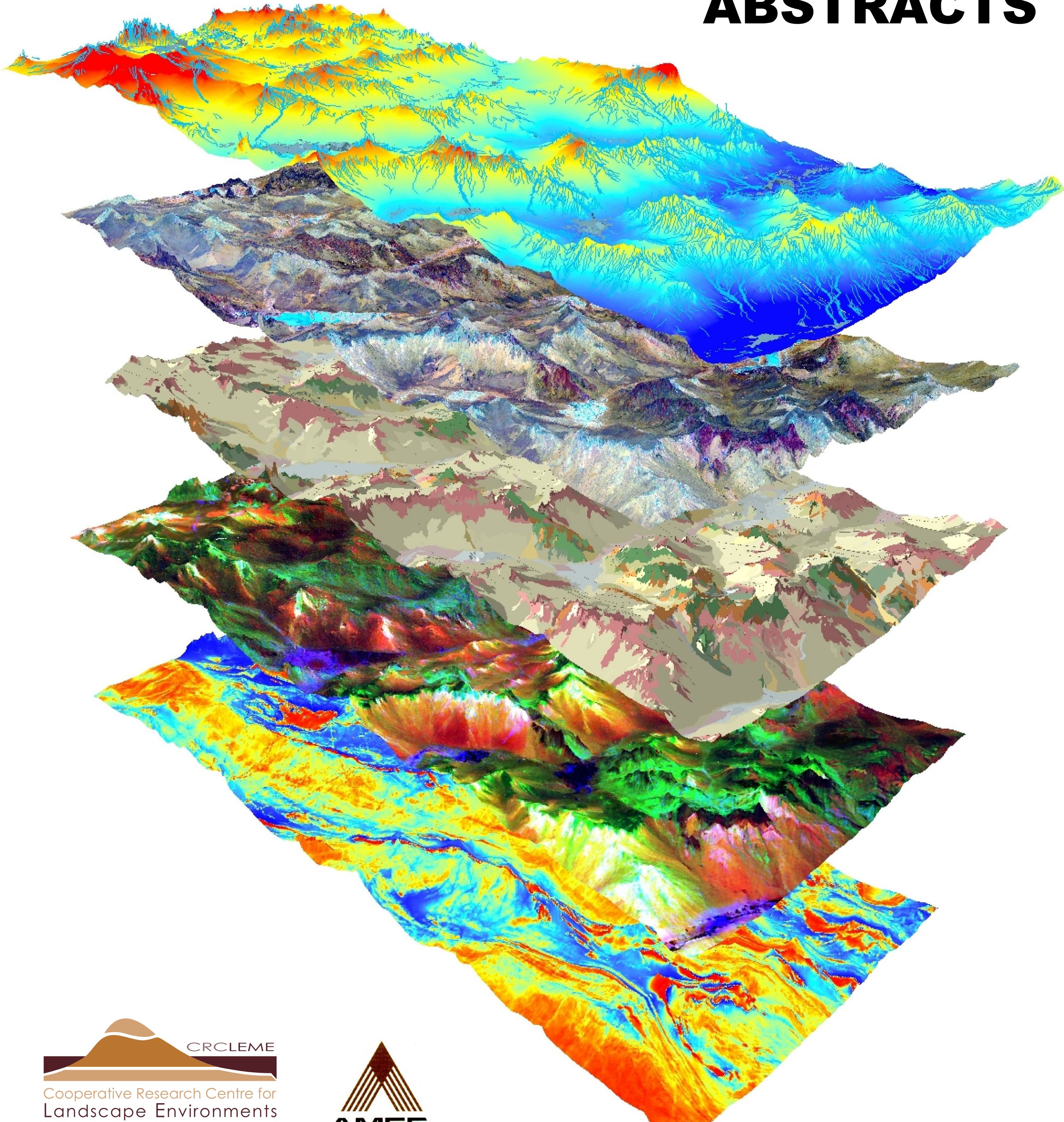
MINERALS EXPLORATION SEMINAR

18 June 2003

ABSTRACTS



CRCLEME

Cooperative Research Centre for Landscape Environments and Mineral Exploration

AMEC

CRC LEME is an unincorporated joint venture between CSIRO-Exploration & Mining, and Land & Water, The Australian National University, Curtin University of Technology, University of Adelaide, Geoscience Australia, Primary Industries and Resources SA, NSW Department of Mineral Resources and Minerals Council of Australia, established and supported under the Australian Government's Cooperative Research Centres Program.

CRC AUSTRALIA

MINERALS EXPLORATION SEMINAR

ABSTRACTS

Convenor

Dr Mehrooz Aspandiar
CRC LEME and Curtin University of Technology

18 June 2003

Australian Resources
Research Centre,
Perth

CRC LEME is an unincorporated joint venture between CSIRO-Exploration & Mining, and Land & Water, The Australian National University, Curtin University of Technology, University of Adelaide, Geoscience Australia, Primary Industries and Resources SA, NSW Department of Mineral Resources and Minerals Council of Australia.

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

CRC LEME Organising Committee
Dr Mehrooz Aspandiar Convenor)
Dr Ravi Anand
Dr Charles Butt
Mrs Sue Game

COOPERATIVE RESEARCH CENTRE FOR LANDSCAPE ENVIRONMENTS AND MINERAL EXPLORATION

CRC LEME Chief Executive Officer
Dr R Dennis Gee
CRC LEME
PO Box 1130
Bentley WA 6102
Tel: 08 6436 8695
Email: crcleme-hq@csiro.au

Seminar Convenor
Dr Mehrooz Aspandiar
Curtin University of Technology
Department of Applied Geology
PO Box U1987, Perth WA
Tel:08 9266 4373
Email: M.F.Aspandiar@curtin.edu.au

ASSOCIATION OF MINING AND EXPLORATION COMPANIES (INC) AMEC

AMEC Head Office
PO Box 545
West Perth WA 6005
Tel: 08 9321 3999
Email: amec@amec.asn.au
Web: http://www.amec.asn.au

Dr Peter Buck
Chairman, AMEC Mineral Exploration and Technical Committee
c/o LionOre Australia Pty Ltd
Level 2, 10 Ord Street
West Perth WA 6005
Tel: 08 9481 5656. Email: Peter.Buck@lionore.com.au

Web: http://crcleme.org.au

TABLE OF CONTENTS

LEME 2 RESEARCH PRIORITIES

R Dennis Gee
Cooperative Research Centre for Landscape Environments and Mineral Exploration

THE MISSION OF LEME 2

The mission of LEME in its second renewal is to apply regolith science to problems in the fields of mineral exploration and natural resource management. Core programs common to both streams will focus on methods of determining the 3-D architecture of the regolith, and the time-dependant physical, chemical, mineralogical and hydrological processes within it.

The Cooperative Research Centre (CRC) program is an Australian government initiative aimed to bring together research groups and industry to work on projects of national interest. The CRC for Landscape Evolution and Mineral Exploration (LEME 1) was set up in 1995 for a 7 year term. It produced outcomes that are universally regarded as outstanding, and successfully applicable in the exploration industry

LEME funding was renewed in early 2001 for a further seven years till June 2008, and it has a subtle name change to Landscape Environments and Mineral Exploration. It will build on the strong foundations of LEME 1, and contemporary technological developments (eg AEM). There will remain a strong focus on mineral exploration in the firm belief that many more discoveries are to be made beneath our extensive regions of transported regolith.

THE LEME BUSINESS MODEL

LEME is an unincorporated joint venture between Geoscience Australia, CSIRO (represented by divisions of Exploration and Mining, and Land and Water), Australian National University, Curtin University, Adelaide University, NSW Department of Mineral Resources, Primary Industries and Resources South Australia, and Minerals Council of Australia. It has access to about 117 (73 FTE) research scientists, drawn from both in-kind and cash-funded positions in participating organisations. This body of expertise is assembled into multi-disciplinary research teams to address strategic research objectives. Over the seven year life of LEME 2, the cash flows are likely to be:

Cash Income	$m	**Expenditures**	$m
CRC Grant	20.2	Cash funded salaries	15.5
Participants contributions	6.8	Scholarships	2.7
External income	6.2	Operating costs	16.5
Other	1.3		
Total	**34.8**	Total	**34.8**

Participant's cash contributions, plus the value of the in-kind salaries, together make the equity in the joint venture. In return, participants receive an annual apportionment of funds in the form of cash-funded salaries, project operating costs and scholarships, to a monetary value as near to practicably possible to their equity proportion.

When the value ($31.7m) of in-kind salaries over the life of LEME 2 is added to the total costs of $34.8, we have a research value of $65.5m. Of this, 25% is operational expenditure, a figure we would like to see increased by further industry support. LEME has the ability to deploy a considerable value of research capability for modest industry contributions, such that the leverage for industry is tenfold - $10 for every $1 contributed.

LEME is now drawing up its work program for next year, and will involve a range of technology development project, regional cluster projects, and generic process projects.

REGOLITH PROCESSES

Understanding chemical, mineralogical, physical, biological and hydromorphic processes at a range of scales, within a framework of regolith architecture, is essential for mineral exploration. Where transported regolith covers prospective basement, we will develop mapping techniques to model the palaeo-landscape, and analyse provenance, diagenesis and weathering history of sediments. To understand the dynamics of regolith processes, we will date materials (especially goethite-hematite) by innovative methods, so we may predict anomalies, identify sources, and prioritise their expressions. We will investigate the role of biota in the formation of regolith, and relate this to low-temperature chemical mobility and fluid dynamics. We will also determine what minerals host high elemental concentrations using modern micro-analytical techniques. Ultimately we will refine techniques to systematically and rapidly construct well-constrained 4D regolith models in key regions for direct application to mineral exploration. We are also developing objective, rapid logging techniques for the regolith.

MAKING GEOCHEMISTRY WORK THROUGH COVER

Exploration under transported regolith is the 'last frontier' of exploration geochemistry in Australia. In the Yilgarn there are some convincing examples of connected gold anomalies in transported regolith less than 25 metres thick, but only a few that may relate to hydromorphic processes. There are no convincing examples (at least in the public domain) of anomalies generated through regolith more than 25 metres thick, such as saline palaeodrainages. Yet gold is quite mobile in reduced chlorinated low-temperature aqueous environments. Experience in the Yilgarn, Tanami and Gawler is that sampling in transported overburden more than five metres has no predictive value in gold exploration. We cannot distinguish the negative result (nothing there) from the null case (not adequately tested). Similar challenges exist for nickel.

REGIONAL MINERAL EXPLORATION

Integrated regional studies in covered areas, incorporating regolith maps in GIS format are required, especially by the participating State geological surveys, to enhance mineral prospectivity and stimulate exploration. This will be achieved by detailed and regional scale studies that characterise the regolith, image its 3D architecture, date key regolith-forming events, place element mobility (metals and salts) into 4D models, and interpret geophysical and geochemical surveys in the context of these models. The regional focus will be on known mineral fields with further exploration potential. Projects done jointly with State geological surveys are coming to fruition in the Girilambone Belt in NSW, Harris Greenstone Belt in South Australia and Broken Hill.

INTEGRATED GEOPHYSICAL MAPPING AND MODELLING

Integration and modelling of semi-regional spatial datasets, built around interpretations of AEM TEMPEST data, has important applications equally in mineral exploration and land management. The full range of geophysical techniques (hyperspectral, magnetic, gradiometery, electromagnetic, ground penetrating radar, DEM laser scanners), will allow rapid 3-D mapping of areas selected for exploration and target generation. This allows a 'systems approach' which has recently been applied to the enigmatic Tunkillia area in South Australia. This showed surficial gold dispersion down a calcrete palaeodrainage. Exploration geochemistry has entered a phase where it must be integrated with all other investigative tools. The successful exploration practices of the 1990s of drilling structural targets (from high-resolution aeromagnetics) supported by geochemical anomalies, is largely exhausted.

REGOLITH GEOLOGY, FORMATIONAL PROCESSES AND IMPLICATIONS TO EXPLORATION

R. R. Anand
CRC LEME / CSIRO Exploration and Mining

This paper presents and reviews the processes responsible for the distribution and formation of regolith and associated landscapes of the Yilgarn Craton and highlights their implications for mineral exploration. The present, relatively flat, surface of the Yilgarn Craton indicates little of the complex regolith beneath. Recent mapping and the establishment of regolith relationships and distributions from drilling and mine exposures has revealed details of the sub-surface regolith and palaeolandscape, from which the landscape history can be deduced.

Much of the Yilgarn Craton is deeply weathered, locally to over 100 m. Weathering depths are generally greatest in the greenstone belts, though the intervening granites and much of the sedimentary cover, including Tertiary palaeochannel sediments, are also deeply weathered. An 'idealised' profile commonly comprises fresh bedrock, grading upwards into saprock and saprolite, commonly bleached towards the top, especially on felsic or sheared mafic rocks. This is overlain by a clay-rich and/or quartz-rich zone, a mottled zone and a ferruginous, bauxitic or siliceous upper zone. These horizons were formed by a combination of weathering and landscape processes. The upper, ferruginous duricrust and silcrete have developed in both residual and sedimentary materials of various ages. In many cases, alteration within the upper horizons of a weathering profile is so intense that it is difficult to identify the parent material. Consequently, unconformable contacts between Precambrian basement and Cenozoic sedimentary cover may escape detection. In other cases, weathering of sediments produces a sequence of horizons similar to those of a deeply weathered profile developed from Precambrian basement rocks. The ages of the deeply weathered profiles are difficult to determine because of the lack of suitable datable minerals. However, a number of estimates have been made based on the isotopic composition of certain secondary minerals and palaeomagnetic dating of hematitic mottles. Results of palaeomagnetic dating from *in situ* weathering profiles cluster into three range ages (Brad Pillans, ANU/CRC LEME, written communication 2001). The largest cluster of data at 60±10 Ma represents wet, cool temperate climate whereas the second cluster at late Tertiary (10±5 Ma) represents climates that were seasonally drier and warmer. A small cluster of palaeomagnetic ages also occurs during the Jurassic. (180 ±10 Ma). This suggests that the basement rocks were weathered by the early Tertiary.

Sedimentary cover is common on the Yilgarn Craton and ranges in age from Permian to Recent and in thickness from a few centimetres to many tens of metres. The nature, weathering and diagenetic features of sediments provide clues to climatic and landscape history. The sediments include glacial, glaciofluvial, colluvial, alluvial, lacustrine, estuarine, marine and aeolian types and several may occur in the sequence at a given site. They may overlie ferruginous duricrust, saprolite or bedrock. There are five principal sedimentary units:

- *Group A* (*Permian*)
  Boulder clays and sandstone
- *Group B* (*early to lid Tertiary*)
  Palaeochannel sediments:
  (a) Sand (Wollubar Sandstone-Middle Eocene)
  (b) Clay (Perkolilli Shale-Late Eocene)
- *Group C (interpreted mid Tertiary)*
  Clayey sand and sandy clays.
- *Group D* (*interpreted late Tertiary-Quaternary*)
  (a) Sandy, silty
  (b) Gravelly, sandy clay units

- *Groups E* (*interpreted late Tertiary-Quaternary*)
  Aeolian materials:
  (a) Dunes (sand dunes, gypsum dunes), lunettes
  (b) Aeolian materials in soils
  (c) Aeolian materials in ferruginous and bauxitic duricrusts

Regolith records a complex history including multiple weathering, truncation and burial and can be explained by progression from a moist, humid to possibly temperate climate with high water tables to the presently arid and semi-arid conditions. Four main stages of regolith and landscape evolution are postulated.

pre-Tertiary topography and weathering

The pre-Tertiary landscape comprised hills and broad, shallow valleys that were formed by the prolonged fluvial erosion of the evolving Bight rift basin between Australia and Antarctica. Broadly contemporaneous weathering of topographically higher parts and palaeovalleys formed saprolite, soils, lateritic residuum (residual nodules and pisoliths) and ferricrete (ferruginised sediments), with the valleys being prone to ferruginisation. Lateritic residuum and ferricrete were subsequently deposited into 'younger' palaeochannels within the palaeovalleys as detrital ferruginous gravel, some of which subsequently became ferruginised to form ferricretes.

early to mid Tertiary erosion and sedimentation

By the Eocene, drainage incision along palaeovalleys on the weathered land surface had resulted in development of 'younger' channels that are less than 1-3 km wide and many kilometers long. These palaeochannels are younger than the broad, shallow valleys in which they occur and were probably formed by stream rejuvenation following epirogenic uplift. Owing to an erodible mantle of deeply weathered bedrocks and a humid climate, incision probably progressed fairly rapidly. Formation of the palaeochannels involved stripping of the regolith removing much of the lateritic gravel. Stream rejuvenation reached an advanced stage of development, but before the streams were able to affect major valley widening by lateral planation, a change occurred in allogenic conditions (shift to strongly seasonal climate) which caused the stream beds to rapidly aggrade (Peter de Broekert, CRC LEME, personal communication, 2002). The coarse sandy and gravelly facies of Group B thus came into being and represent the fluvial basal units. Thereafter a major change in climate occurred led to the deposition of a thick clay probably in lacustrine and/or shallow swampy environments during Late Eocene-Oligocene. Lenses of ferruginous gravel reflect the episodic establishment of fluvial conditions.

Clayey sand (Group C) differs in distribution from palaeochannel sediments in that it is frequently exposed at or near the surface. It is generally overlain by gravelly sandy clay and silty sandy clay units of Group D. Presumably, this unit formed a sheet like deposit which extended for an appreciable distance beyond the palaeochannel margins (1-3 km). Except for crude horizontal bedding, no primary sedimentary structures are preserved within this unit. The landscape following deposition of these sediments probably comprised slightly elevated (but dissected) areas of pre-Tertiary terrain, surrounded by lower sediment-covered terrain.

mid to late Tertiary weathering

Sediments and the underlying bedrock were subjected to widespread weathering including the formation of ferruginous pisoliths, hematitic megamottles, Mn nodules, authigenic smectites, opal silica and dolomite. Sediments are heavily bioturbated as indicated by large columns and dense network of tubular structures. This suggest that biogenic processes have played significant role in the formation of secondary structures. Biogenic weathering has led to the destruction of the basal gravels of palaeochannel sediments and the formation of a new, second generations of ferruginous pisoliths. Megamottles in clay-rich sediments are formed by mobilisation and segregation of Fe by a combination of roots and reduced groundwaters.

The removal of Fe from around tree roots was probably effected by the microbial decay of organic matter, which generates reducing conditions under which Fe^{3+} oxides can be dissolved and redistributed. Younger hematite-goethite-rich residual lateritic gravel that may occur beneath the palaeochannel sediments is thought to have formed during this period.

Pisolitic ferricretes have formed at, and overprinted, the unconformity between the residual regolith on Archaean basement and overlying sediments (Group C). Within basement, the nodules preserve original textures and pisolitic structures are not common. Overlying clayey sands are modified by the *in situ* formation of hematite-rich pisoliths or the development of vermiform or cellular fabrics, the orientation of which is controlled by the original sediments. They are commonly overprinted by a later bleaching. The bleached areas are commonly cylindrical and are cored by tubes that may be filled with secondary silica or kaolinite. Widespread preservation of such tubes, presumably fossil root/solution cavity systems, attests to high permeability around the unconformity. Also forming a major part of Group C are very fine to medium sand sized 'kaolin spherites' which are commonly coated by Fe. These are interpreted to be detrital, resulting from erosion of kaolinitic clay derived from granitic bedrock.

late Tertiary to Quaternary erosion and sedimentation

During this period, another stage of instability and erosion, caused by tectonic uplift and change of climate to semi-arid to arid conditions led to the dissection of parts of the landsurface. A variety of sediments were deposited, mostly as the result of fluvial, colluvial and aeolian processes. Inland, in the absence of effective drainage system the resulting superficial deposits have been retained in the landscape. Increased erosion resulted in deposition of gravelly and silty clay sediments (Group D) in low-lying areas, the composition which broadly reflects that of the local lithology. Clasts are dominated by ferruginous gravels derived from erosion of duricrust whereas silty clays are derived from saprolite and mottled zone. In places, there is a stratigraphy in the sediments that is inverted in relation to the nearby ferruginous profile. Ferruginous nodules and pisoliths occur at the base of the colluvial-alluvial cover and are overlain by fine, clay-rich sediments.

Inland, these sediments are extensively overprinted by products generated by current soil forming and groundwater-related processes. During relatively wet periods, Fe and other elements leached from the higher parts of the landscape would have been flushed from the regolith by significant groundwater recharge and throughflow. The onset of more arid conditions resulted in reduced recharge and the precipitation of elements leached from the upper parts of the regolith profile in topographic lows. The topographically lower areas consequently become enriched in Fe, Si and Ca to form ferricrete, ferruginous saprolite, silcrete, red-brown hardpan and calcrete. In places, this process armoured the upper regolith against further erosion, and, it subsequently became topographically inverted.

With increased aridity, drainage became limited, and the groundwaters became saline, with geochemical effects as chloride came to dominate chemical reactions. The major valleys became the sites of chains of salt lakes. Aeolian processes become dominant, including the formation of gypsum-rich dunes, lunettes and lake parnas (Group E). There is a significant aeolian component in many soils. Aeolian deflation, on the other hand, has left vast areas covered by polished, ferruginous, siliceous, lithic, or polymictic lag, which, in some places, forms gibber plains. Lithosols are associated with fresh rock or saprock and areas of steeper slopes. Soils can contain abundant calcrete and smectite from recent weathering of mafic rocks.

Implications to exploration

Many of the regolith types have a distinctive distribution pattern, which could be potential sampling media. However, a combination of long weathering history and variable degree of erosion has resulted a landscape of highly variable and complex regolith. Thus, assessment of the nature and origin of the regolith, weathering history, geomorphological processes and regolith-landform relationships are essential in determining the optimum geochemical sampling medium applicable in a particular terrain. A regolith-landform framework and models of regolith evolution of the Yilgarn Craton provide a basis for exploration models and exploration strategy that with appropriate modification may be extended into similar terrain elsewhere.

FORM TO FUNCTION: GIVING MEANING TO OBSERVED AIRBORNE ELECTROMAGNETIC RESPONSES IN REGOLITH SETTINGS

Dr Tim Munday
CRC LEME/CSIRO Exploration and Mining

Airborne geophysical technologies have demonstrated application in exploring through regolith dominated settings. The routine application of airborne magnetics across Australia is testament to this. More recently, airborne electromagnetics (AEM) has been viewed as another technology with considerable potential for helping explore through the regolith. Collaborative studies conducted between CRCLEME and a range of state, commonwealth and industry partners through WA, South Australia and NSW have demonstrated the complementary nature of the information generated by geophysical systems that map the conductivity of the ground. However, these studies have also highlighted a need to consider the observed EM response (referred to as "form") as it relates to material, geographical setting (landscape), geology, water and process, if the full potential of these data in exploration are to be realised. By better understanding what and when the observed conductivity tells us something about structure, geology regolith and landscape allows us to make inference about weathering and hydrogeological process, with consequent benefit to the interpretation of geochemical data for example. Adding value to a relatively expensive mapping technology by these means is perhaps the only way EM data sets might be considered more routinely in the exploration for commodities such as Au and Ni in deeply weathered environments. This paper examines some of the issues involved by reference to an example taken from the Yilgarn Craton in WA, namely the Cawse Ni-laterite deposits, located some 80km NNW of Kalgoorlie in the Eastern Goldfields.

Until more recently regolith induced variations in conductivity have been regarded as a source of (geological) noise in AEM surveys; noise that obscured responses directly related to mineralisation. This is less of an issue today, with greater attention being given to the significance of this so called "noise", particularly as it can help explain why, how and where elements may be distributed within the regolith. In part, this trend can be attributed to the advances in system technology and to data processing which now allow us to image conductivity as a function depth, thereby enhancing information about the subsurface and rendering these data easier to interpret from a geological perspective. That said, a key challenge to better AEM data interpretation lies with an appreciation of factors that control conductivity in regolith settings. In the majority of regolith settings, electrical conductivity is controlled by the moisture quality (salinity) and quantity, along with textural characteristics of the regolith, most notably clay content.

Helicopter electromagnetic (HEM) and magnetic survey data were acquired over the Cawse district in the Eastern Goldfields of Western Australia, primarily to help define the structural controls that influence supergene mineralisation and delineate areas favourable for further exploration. The rationale for conducting the EM survey was that previous work in the area had demonstrated that local discontinuities, represented by stratigraphic and structural variations in the regolith, or related textural and/or mineralogical changes have influenced hydrogeological process and consequently the distribution mobile elements such as Ni, Co and Mn within the profile.

At Cawse, variations in regolith conductivity were attributed to contemporary hydrogeological process. More specifically, they are related to the distribution and abundance of soluble salts and moisture in the regolith. Clay type was not important in its own right, although textural variability was deemed important as it affects porosity and permeability and the ability of the weathered profile to store moisture and salt. Spatial variations in conductivity could be linked to hydromorphic barriers (structural, material), where salts and water accumulate. Whilst these zones did not always equate to zones of high Ni–Co–Mn grade, in places an association with Ni enrichment was apparent.

A complex interplay between material type, hydrogeology and regolith development determines observed response in the Cawse district, with similar controls expected elsewhere in the Yilgarn. A greater appreciation of contemporary hydrological /hydrogeological process helps explain the patterns in conductivity. The EM data also complements the available airborne magnetics helping define structural discontinuities which are not clear in those data.

By linking the mapped conductivity to an understanding of regolith material, landscape development, geology and processes involved in supergene Ni-mineralization, relevant information (from an exploration perspective) can be gained an EM dataset such as that acquired at Cawse.

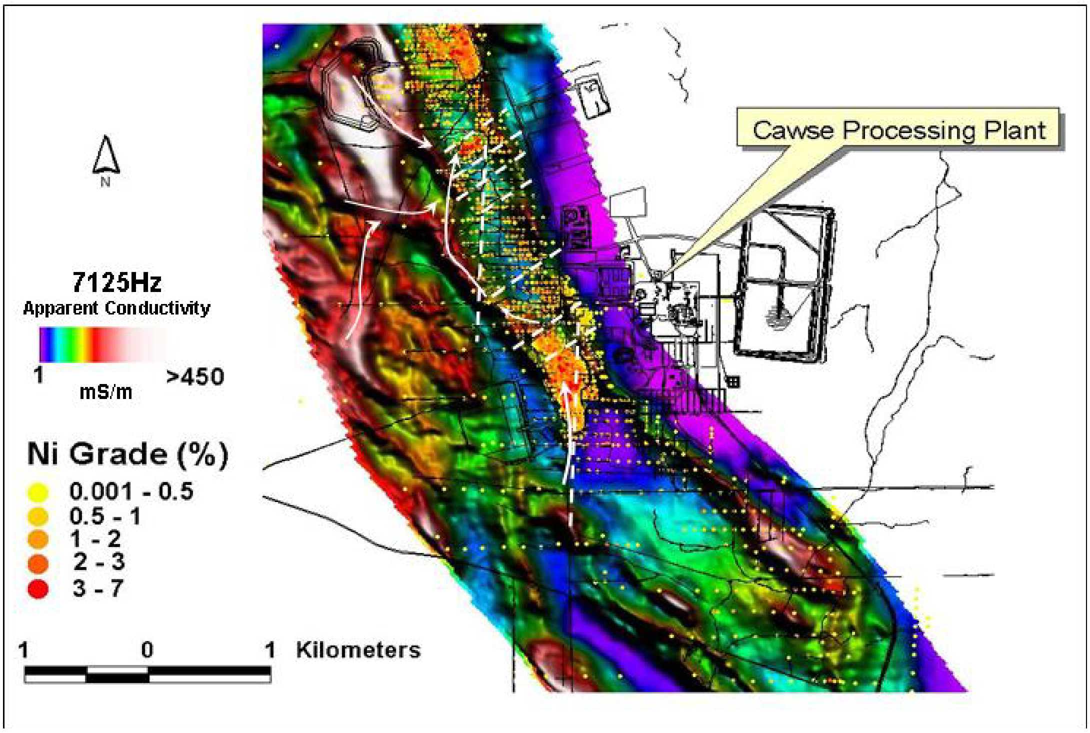


Figure 1: Sun shaded, pseudocoloured 7125Hz apparent conductivity image for the area in close proximity of the Cawse Lateritic Ni processing plant. Values for average hole Ni grade are overlain on the image. The observed conductivity patterns (form) are related to a combination of factors including regolith material type (specifically variations in the nature of the in-situ saprolite as it changes with lithology), groundwater quantity and quality. These patterns are also associated with valley-fill materials (palaeo-valleys – as defined by the white arrows)). Discontinuities in the conductivity structure can be linked to geological structures (white dashed lines) and changes in lithology which act as hydromorphic barriers. In summary, the spatial variations in conductivity describe a set of functional interactions between material and water which have value in helping interpret geochemical attributes of this landscape.

HYDROGEOCHEMISTRY AND SUPERGENE GOLD – RESULTS FROM AMIRA PROJECT 504

D J Gray, N B Sergeev, A F Britt and C G Porto
CRC LEME / CSIRO Exploration and Mining

Supergene Au depletion, especially documented in the Yilgarn Craton, are the product of modification under saline and acid conditions of a pre-existing, deeply weathered regolith. An understanding of the processes that form them are of major importance for effective mineral exploration. Typically, lateritic residuum appears to maintain any pre-existing Au enrichment, but the underlying saprolite may be severely leached. If the laterite has been eroded there may be little or no Au in the upper regolith, presenting a major exploration difficulty. Conversely, supergene enrichment zones may represent useful drilling targets and, in some circumstances, may even be economic Au targets in their own right. The three year CRC LEME/AMIRA Project P504 *"Supergene mobilization of gold and other elements in the Yilgarn Craton"* had, as its principal objective, "the determination of the mechanisms of supergene/secondary depletion, enrichment and dispersion of Au and other elements, so as to improve selection of drilling targets and further optimize interpretation of geochemical data".

As Au solubility is strongly enhanced in saline groundwaters, particularly when groundwaters are also acid and oxidizing, the marked variations in the chemistry of Yilgarn groundwaters (Figure 1) have major effects on supergene Au mobility. Thus, in northern regions of the Yilgarn, where the main valleys have significant flow slopes and there are small, restricted areas of high salinity, supergene Au mobility is limited. In the south and east, groundwater tends to pond and salinity is much higher and more extensive and observed Au mobility is strong.

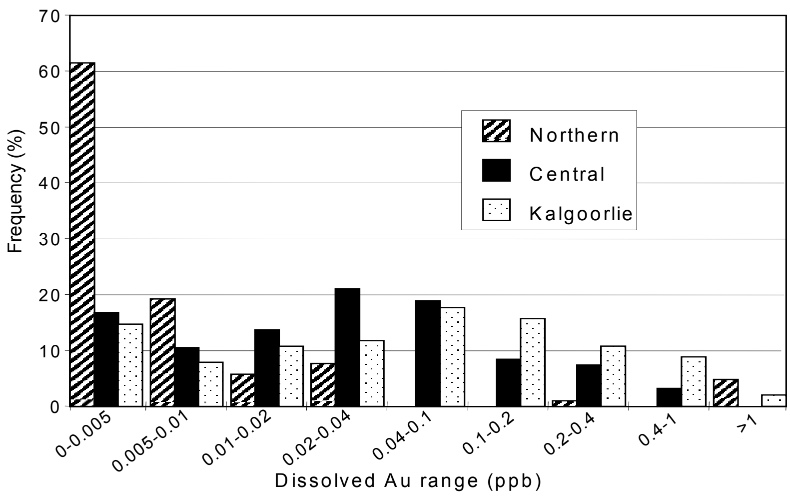


Figure 1: Distribution of dissolved Au concentrations for the Northern, Central and Kalgoorlie groundwater regions.

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

Supergene Au enrichment in the saprolite has a sharp upper contact with the overlying depleted zone (Figure 2). Typically, the highest Au concentrations occur in the top 1 to 5 m of the supergene Au enrichment zone, due to absolute chemogenic accumulation. Below this, enrichment appears to be almost exclusively residual. There appears to be no lateral dispersion (Figure 3) and hence no increase in size, though the absolute concentrations are greater than in the unweathered rock. In general, Au distribution delineated by the enrichment in saprolite roughly corresponds (at higher concentration) to that in the primary zone. Therefore, the saprolitic enrichment zone is not a result of lateral dispersion and does not increase the anomaly size, although absolute concentrations of Au are greater than in the unweathered rock.

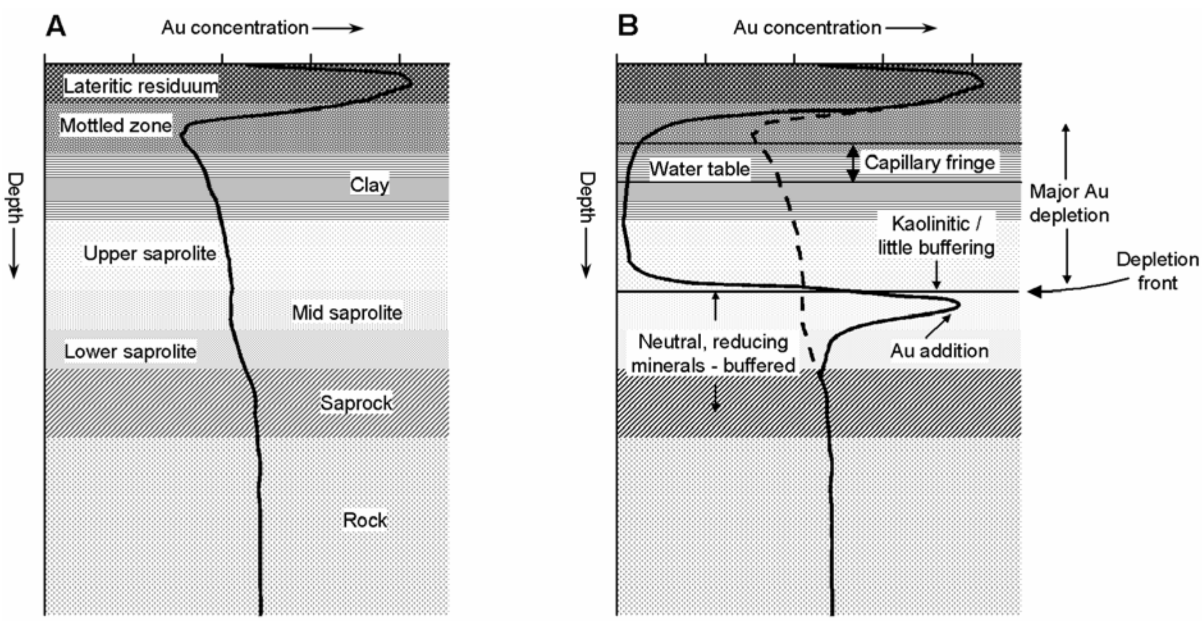


Figure 2: Diagrammatic representation of (A) supergene concentration (primarily residual) of Au during initial weathering , (B) supergene remobilization of Au due to saline groundwaters.

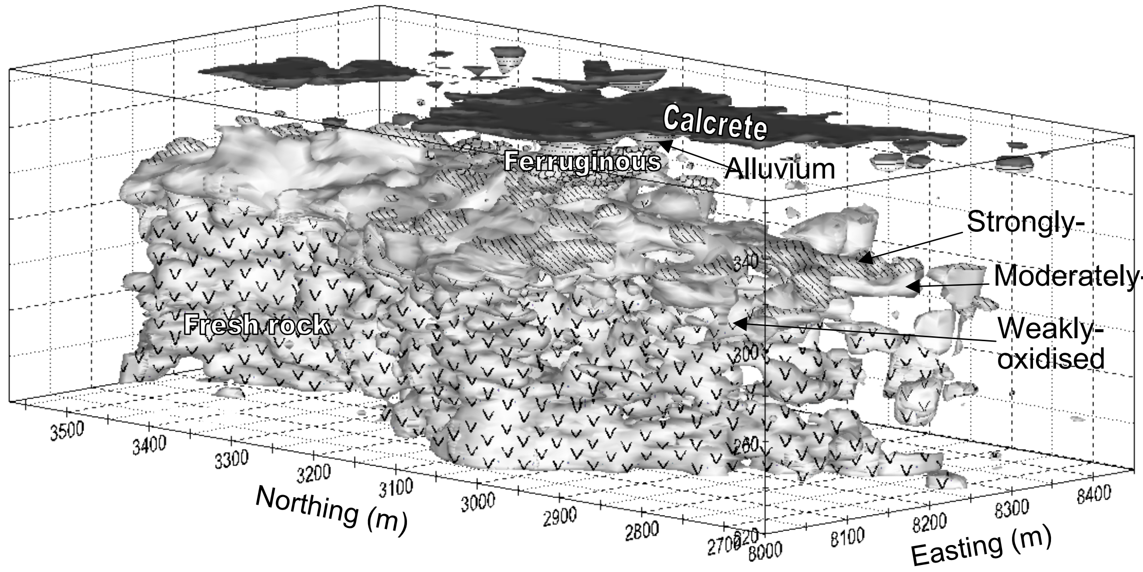


Figure 3: Gold distribution at Karari, using a 0.05 ppm cut-off and 2x vertical exaggeration.

The mean depth of the Au enrichment zone in saprolite is similar at most sites (30 to 40 m). However, there can be considerable local variation, depending on lithology, structure and regolith preservation. Horizon boundaries in the regolith normally have a major control on the depth of the Au depletion front (Figure 4), which commonly occurs at the clay saprolite to mid saprolite regolith boundary. This is generally related to the alteration front of primary aluminosilicates, ferromagnesian minerals and their intermediate weathering products (eg. smectites, vermiculites) to kaolinite and Fe oxides. This alteration front and the Fe^{3+}/Fe^{2+} redox front, tend to occur within a few metres of each other.

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

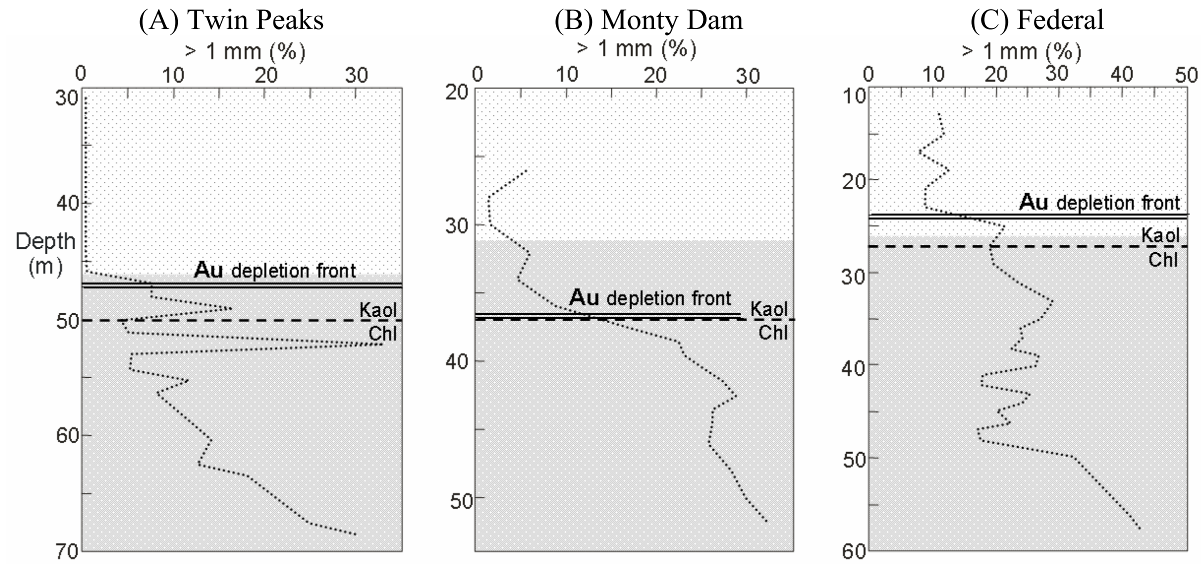


Figure 4: Variation with depth of the Au depletion front (double line), regolith colour change (thick shading = reduced, dots = oxidised), mineralogical transition from kaolinitic to chloritic (Kaol / Chl; dashed line) and the proportion of the > 1 mm fraction in drill spoil (dotted line) for representative drill holes from (A) Twin Peaks, (B) Monty Dam and (C) Federal.

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

ACKNOWLEDGEMENTS

The concepts discussed in this paper have been derived from many years of collaboration with the mineral industry. In particular, the sponsors of AMIRA Project 504 - "Supergene Mobilisation of Gold and other Elements in the Yilgarn Craton" are thanked for their support. CRC LEME is supported by the Australian Cooperative Research Centres Program.

ORA BANDA SILL PLATINUM PROSPECT

C.R.M. Butt and I.D.M Robertson

CRC LEME, CSIRO Exploration and Mining, PO Box 1130, Bentley, Western Australia 6102

LOCATION

The Ora Banda sill is centred about 55 km NNW of Kalgoorlie; this prospect is 1 km S of the Ora Banda town site, at 30º24’00”S, 121º03’30”E; Kalgoorlie map sheet SH 51-9 (Figure 1).

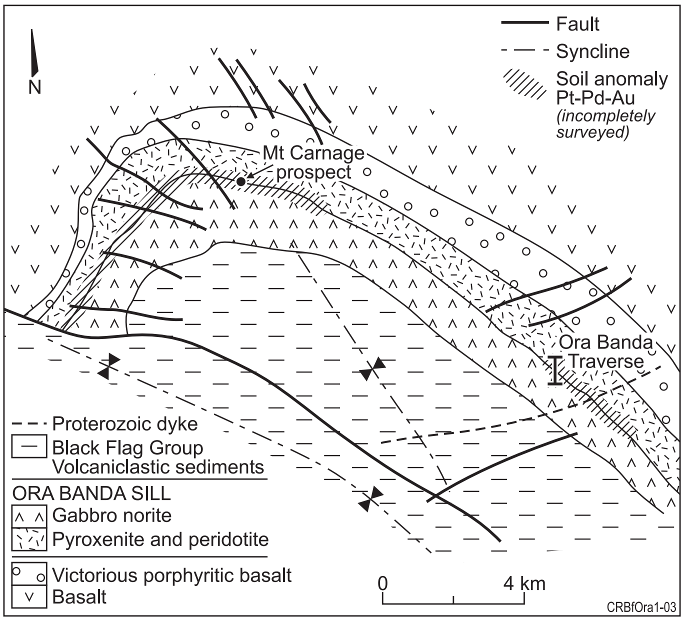


Figure 1. Regional geological setting of the Ora Banda Sill, showing locations of the Mt. Carnage and Ora Banda PGE prospects (after Menzies, 1988a).

DISCOVERY HISTORY

Much of the sill was explored by Carbine Gold N.L. during 1987-1990 at their Ora Banda and Mt. Carnage prospects, S and W of Ora Banda, respectively. Initial exploration was by soil surveys for Au, Pt and Pd, followed by rotary air-blast (RAB) drilling (Menzies, 1988a, 1988b). Overlapping angle holes (inclination 50-65°) were drilled to a downhole depth of 40 m on selected lines across strike. At Ora Banda, the principal drill section was on line 12500E (Figure 2), which intersects the strike of the inferred pyroxenite-peridotite contact at approximately 40°. This drilling confirmed concentrations of up to 2 ppm PGE in lateritic duricrust developed on pyroxenites, with some localized concentrations deeper in the regolith, but none in economic tonnages. Similar results were obtained by BHP Exploration on adjacent areas of the sill. Carbine Gold N.L. tested possible primary mineralization with two diamond drill holes, oriented approximately normal to the strike, drilled to intersect the pyroxenite-peridotite contact beneath 12500E. The drilling found general PGE enrichment in the pyroxenite, but no economic concentration. Much of this account is derived from detailed study undertaken as part of CSIRO-AMIRA project 252 (Butt *et al.,* 1992).

PHYSICAL ENVIRONMENT

The geomorphology of the Ora Banda site is controlled by the lithology of the sill. To the S, a prominent hill of unweathered norite rises above the duricrust-capped surface on the pyroxenites. There is an eroded zone along the pyroxenite-norite contact; in places, the contact forms a dip slope capped by an erosion scarp (breakaway). There is an undulating, locally dissected, lateritic surface on the pyroxenite, with a gentle slope across the peridotite to broad-floored drainages N of the site. The peridotite thus underlies slightly lower, less dissected ground. The area has a low acacia woodland, with scattered eucalypts; casuarinas are common on exposed duricrusts. The climate is semi-arid, with a mean annual rainfall of 250 mm and mean maximum and minimum temperatures of 35 to 20ºC (January) and 17 to 5ºC (July).

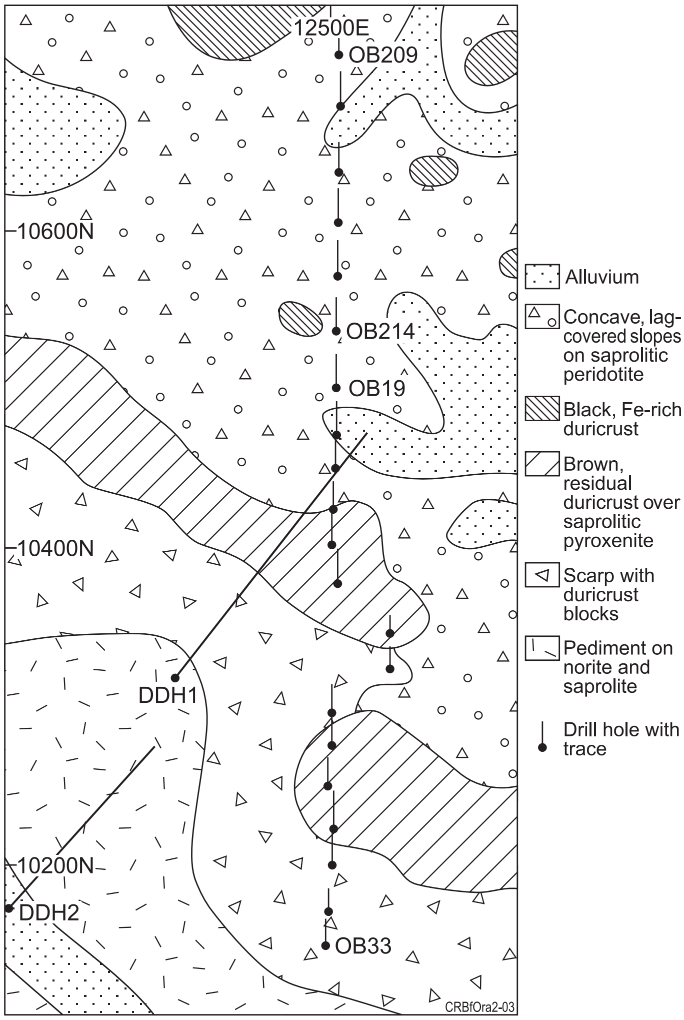


Figure 2. Regolith geology of part of the Ora Banda PGE prospect, indicating sites of lag sampling and drilling.

GEOLOGICAL SETTING

The Ora Banda sill is a 2 km thick high-Mg, mafic-utramafic intrusive body emplaced near the contact between tholeiitic volcanic rocks and the felsic to intermediate volcaniclastic rocks of the Black Flag Group (Witt and Barnes, 1991). The sill has six principal lithological units (Table 1); it is well exposed in its upper part, but the weathered basal peridotite and overlying pyroxenite rarely outcrop and are known principally from the two diamond drill cores. Low angle faults of small displacement have resulted in local repetitions of the peridotite-pyroxenite contact.

REGOLITH

Peridotitic and pyroxenitic rocks are generally weathered to 40-60 m depth. In contrast, the norite tends to be unweathered in outcrop. Essentially complete lateritic profiles are extensively preserved over

Table 1. Principal lithological units (after Witt and Barnes, 1991)

Zone	Thickness (m)	Lithology
Top		
6.	50-100	Pegmatoid gabbro, granophyre.
5.	540	Pigeonite-bearing gabbro-norite cumulate.
4.	315	Bronzite-bearing gabbro-norite cumulate. Some mm-scale layering; local lenses of anorthosite.
3.	90	Norite; massive equigranular plagioclase orthopyroxene adcumulate, grain size 1-2 mm.
2.	165	Orthopyroxenite; massive equigranular bronzitite adcumulate, grain size 1-2 mm.
1.	830	Peridotite. Olivine bronzite orthocumulate.
Base		

the pyroxenite, which is therefore characterized by tracts of lateritic duricrusts and derived soils. Duricrust is rare or absent over the peridotite, and soils are derived from saprolite. Massive, blocky duricrusts developed locally on the peridotite appear to lie directly on saprolite, and may be partly transported in origin. The top 1 to 4 m of the regolith contain pedogenic carbonate. Much of the lag is residual and shows excellent preservation of primary fabrics (Robertson, 1996). Typical profiles are:

Pyroxenite

Lag: coarse, brown, clay-rich granules, with dull, cellular surface, derived from duricrust.

0-2 m: Gravelly, calcarous soils; numerous lateritic nodules and pisoliths.

2-7 m: Massive, nodular and pisolitic duricrust, cemented near the surface; friable with depth.

7-13 m: Mottled clay zone; nodules and pisoliths in a ferruginous clay-rich matrix.

13-16 m: Clay saprolite, commonly ferruginous with some nodules; some green clays.

>16 m: Saprolite; yellow green, soft and clay-rich near the top, harder with depth.

Peridotite

Lag: dense, dark brown to black, ferruginous granules with a vitreous surface; some moss agate.

0-2 m: Calcareous, clay-rich red earths.

2-5 m: Non-calcareous red earths.

5-11 m: Clay saprolite; red clays becoming brown and green with depth.

>11 m: Clay saprolite; brown, khaki and yellow green saprolite; abundant silica and/or magnesite.

MINERALIZATION

Fresh pyroxenite has a broad zone of sulphide, PGE and associated Cu enrichment (as chalcopyrite), with mean concentrations of 130 ppb Pt (maximum 300 ppb), 80 ppb Pd (maximum 215 ppb) and 215 ppm Cu (maximum 3940 ppm) The distribution is rather uniform, with a possible antipathetic relationship between PGE and Cu contents indicating successive cycles of PGE-enriched sulphides. The base of the pyroxenite appears to correspond to the onset of sulphide saturation and the appearance of cumulate sulphides (Witt and Barnes, 1991). Peridotite has mean concentrations of 40 ppb Pt (maximum 235 ppb), 55 ppb Pd (420 ppb) and 30 ppm Cu (180 ppm). A peak value of 980 ppb Pd was not reproduced on re-analysis.

An apparently continuous PGE-enriched "stratigraphic unit" was intersected in saprolite, close to the top of the peridotite (Table 2). This unit has maxima of 3000 ppb Pt + Pd, 52 ppb Ru, 114 ppb Rh, 6 ppb Os, 20 ppb Ir over intervals of 1 to 3 m in three RAB holes. The high abundances of all PGE suggests that this represents a primary mineralized layer but, due to faulting or lack of continuity, the unit was not intersected by the diamond drilling.

REGOLITH EXPRESSION

The overall abundances of PGE and Cu in the regolith reflect the primary distribution, i.e., weathered pyroxenite is PGE- and Cu-rich compared to equivalent units in weathered peridotite. Distributions in the regolith are illustrated in Figure 3. High concentrations of PGE at Ora Banda occur particularly in lateritic residuum over the pyroxenites; this contains 300-400 ppb Pt and 110-190 ppb Pd i.e., 2 to 3 times that in fresh rock. At Mt. Carnage, PGE concentrations are greater, mostly 1000-1950 ppb Pt+Pd over thicknesses of 2-8 m, representing an enrichment of 4 to 7 times (wt/wt). The data also suggest that some enriched zones transgress regolith horizons; such zones dip gently S, sub-parallel to the presumed dip, and may therefore represent primary layering. There has been some apparent fractionation of Pt and Pd during weathering, with gradual depletion of Pd towards the surface. Thus, over the pyroxenites, the Pt/Pt+Pd ratio increases from a mean of 60-65% in the unweathered rock and saprolite to 70-75% in the lateritic horizons; the ratio increases to 90% in lag. There are no lateritic horizons preserved over the peridotites, but the data suggest

Table 2
PGM concentrations of enriched zones from RAB holes OB 19, 20 and 21, and possible source intervals in DDH1.

Hole/sample no.	Depth (m)	Lithology	Pt (ppb)	Pd (ppb)	Pt % (Pt+Pd)	Ru (ppb)	Rh (ppb)	Os (ppb)	Ir (ppb)
Detection Limit			2	2		2	1	2	2
OB 19	0- 4	Peridotite	260	475	35	21	11	2	4
OB 20	17-18	Peridotite	820	440	65	34	49	2	10
OB 21	26-27	Peridotite	1800	1200	60	52	114	6	20
DDH 1 00-5447	106.2-106.5	Pyroxenite	420	360	54	8	15	6	4
DDH 1 00-5448	106.5-106.7	Peridotite	170	118	59	6	11	4	2

Fire Assay NiS collection

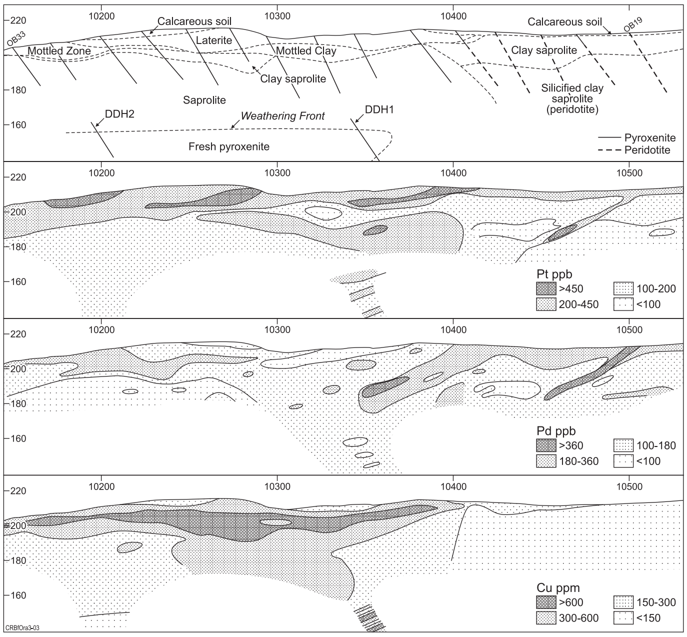


Figure 3. Drill section 12500E, Ora Banda, indicating regolith and bedrock geology, and distributions of Pt, Pd and Cu. Tracks of diamond drill holes show where they pass through the section (compare Figure 2).

Table 3
PGEs in complete laterite profile on pyroxenite (OB 27)

Depth (m)	Horizon	Pt (ppb)	Pd (ppb)	Pt % (Pt+Pd)	Ru (ppb)	Rh (ppb)	Os (ppb)	Ir (ppb)
Detection		2	2	-	2	1	2	2
1	Calcareous laterite	285	80	78	6	14	2	2
3	Laterite	440	124	78	8	26	4	4
5	Mottled clay	310	82	79	8	16	4	4
9	Mottled clay	170	52	77	8	17	4	6
14	Saprolite	145	64	69	4	7	2	2
20	Saprolite	215	82	72	4	10	2	2
25	Saprolite	300	98	75	4	10	<2	2
30	Saprolite	145	84	63	6	9	4	2
35	Saprolite	116	70	62	4	8	2	2
40	Saprolite	150	90	62	4	10	2	2

Analysis: Fire assay, NiS collection

that there may be some surface enrichment associated with calcareous soil and saprolite, perhaps equivalent to that known for Au in this region. However, selective leaching analyses have not confirmed such an association and the enrichment may be due to the residual accumulation of ferruginous lag.

The Cu content in the regolith developed on the peridotite is commonly <30 ppm. In comparison, all regolith units on pyroxenites have Cu contents >200 ppm and concentrations increase upwards through the saprock (mean 205 ppm) and saprolite (mean 315 ppm), to maxima of 700-1095 ppm in the saprolitic and mottled clays and the lower (nodular) horizon of the lateritic residuum. These high Cu concentrations form an approximately sub-horizontal zone of enrichment and are attributed to secondary accumulation with Fe oxides. The Cu distribution is accordingly similar to that of Fe, with which it is associated. Higher in the profile, in the upper lateritic horizons, the Cu and Fe contents decline (<600 ppm Cu); this corresponds to concentration of Al (20-28% Al_2O_3), as gibbsite and in aluminous goethite and hematite, during the further evolution of the lateritic duricrust and, ultimately, formation of the present soil. Copper is probably leached, rather than diluted, during the process of Al accumulation, and may contribute to the Cu enrichment of underlying regolith units. Equivalents of the narrow intervals in fresh pyroxenite having >3000 ppm Cu are not recognized in the regolith.

Ruthenium, Rh, Os, Ir also show upward increases in concentration through the regolith on pyroxenite, although abundances of Os and Ir are very low (Table 3). The highest contents are in the ferruginous horizons (mottled clay zone and lateritic residuum) and are probably due to residual accumulation as immobile elements. The enrichment is of the same order as that of Cu, Cr and Zr.

No separate, PGE-enriched, minerals were identified, despite detailed physical and chemical investigation (Gray et al., 1996). Most PGE are in the <2 m fraction, mainly in Fe oxides; Pt is hosted by hematite and some Pd by Al-rich goethite. This separation may reflect differences in primary host minerals, with Pt in an easily weathered phase, leading to early release and incorporation in hematite, and Pd in a more stable phase, to be incorporated in later formed minerals such as Al-goethite.

In lag, the Pt and Pd contents clearly reflect those of the parent pyroxenite and peridotite, and the regolith developed from them (Figure 4).

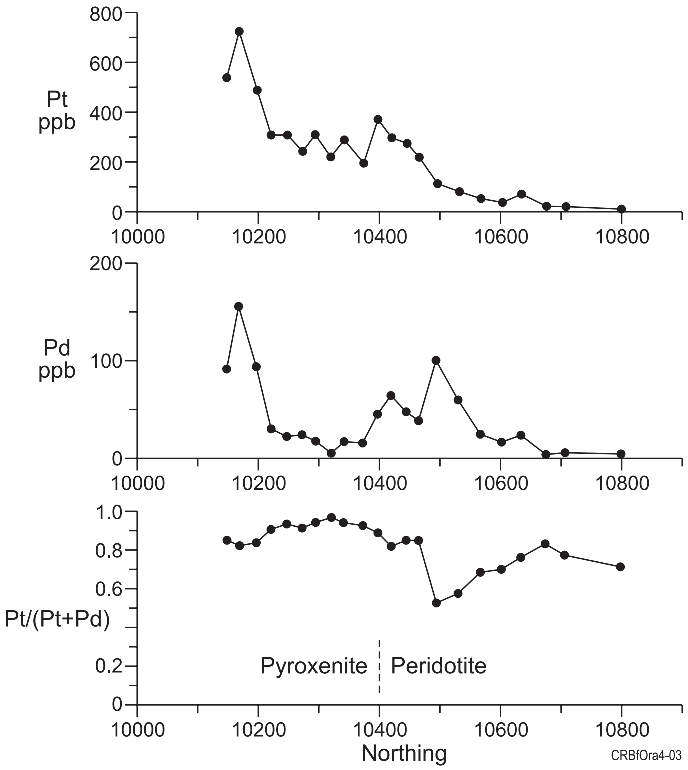


Figure 4. Platinum and palladium concentrations in lag, section 12500E, Ora Banda.

REFERENCES

Butt, C.R.M., Williams, P.A., Gray, D.J., Robertson, I.D.M., Schorin, K.H., Churchward, H.M. and Tenhaeff, M.F.J., 1992. Geochemical exploration for platinum group elements in lateritic terrain. Report No. 332R, CSIRO Australia, Division of Exploration Geoscience 3 Volumes. 413pp.

Gray, D.J., Schorin, K.H. and Butt, C.R.M., 1996. Mineral associations of platinum and palladium in lateritic regolith, Ora Banda Sill, Western Australia. Journal of Geochemical Exploration, 57: 245-255.

Menzies, J.C., 1988a. Second annual report, Ora Banda Prospect, Broad Arrow Mineral Field, Western Australia. Unpublished Report, WA Mines Department. 18 pp.

Menzies, J.C., 1988b. Second annual report, Mt. Carnage Prospect, Broad Arrow Mineral Field, Western Australia. Unpublished Report, WA Mines Department. 15 pp.

Robertson, I.D.M., 1996. Interpretation of fabrics in ferruginous lag. AGSO Journal of Australian Geology and Geophysics 16: 263-270.

Witt, W.K. and Barnes, S.J., 1991. The Ora Banda Sill. In: S.J. Barnes andR.E.T. Hill (Editors), Mafic-ultramafic complexes in Western Australia. Geological Society of Australia, WA Division Excursion Guidebook 3, pp. 31-35.

SAMPLE MEDIA - SUMMARY TABLE

Mean concentrations of selected elements in the regolith on peridotite and pyroxenite (from Butt *et al*., 1992).

Horizon	n*	Pt (ppb)	Pd (ppb)	Pt % (Pt+Pd)	Cu (ppm)	Ni (ppm	Cr (ppm)	Fe (%)	Al_2O_3 (%)	MgO (%)
Peridotite										
Ferruginous lag	18 (18)	53	11	78	50	745	32680	47.7	6.2	0.3
Calcareous soil	12 (2)	345	530	40	45	1420	6950	16.6	4.7	6.5
Clay saprolite	31 (44)	175	220	44	39	2175	4900	14.6	3.0	7.6
Silicified clay saprolite	22 (23)	200	165	36	24	1955	4310	12.4	3.0	9.9
Silicified saprolite	17 (52)	105	120	42	27	1840	4445	11.8	2.2	10.7
Saprolite	13 (47)	90	130	42	26	1760	4815	12.1	2.3	12.2
Fresh peridotite	8 (198)	42	55	45	33	1170	4570	12.2	1.8	32.4
Pyroxenite										
Ferruginous lag	26 (26)	400	50	90	485	745	12270	37.5	18.7	0.3
Calcareous laterite	7 (9)	315	110	74	300	405	5100	15.4	18.3	3.6
Laterite	13 (21)	360	120	75	495	535	7560	24.1	22.5	2.1
Nodular laterite	12 (24)	435	180	71	670	500	8380	28.8	19.8	0.85
Mottled clay	13 (34)	265	135	64	675	655	9085	24.6	18.7	2.0
Clay saprolite	13 (28)	265	170	60	660	1740	7110	17.8	8.4	4.8
Saprolite	62 (184)	215	145	62	325	1085	4520	10.3	4.1	15.7
Saprock	8 (72)	165	110	63	145	785	4342	9.9	2.5	27.34
Fresh pyroxenite	12 (160)	130	80	63	610#	1110	2965	11.1	3.3	26.55

Pt and Pd analyses by fire assay fusion, ICP MS. Detection limits 2 ppb

Al_2O_3 and MgO analyses by Li borate fusion and ICP-ES. Detection limits: 0.01%

Cu, Cr, Ni, Fe analyses by XRF pressed powders. Detection limits: Cu, Cr, Ni 10 ppm; Fe 0.01%.

* Numbers in parentheses refer to Pt and Pd analysis.

Data from Cu-rich section of core. Mixed acid ($HClO_4$-HF-HNO_3) analysis of 160 samples gives mean 215 ppm Cu.

3D REGOLITH MODELLING AS AN AID TO EXPLORATION IN DEEPLY WEATHERED TERRAINS - YANDAL BELT

R R Anand, A Cornelius and C Phang

CRC LEME / CSIRO Exploration and Mining

The Yandal greenstone belt is 250 km long and 40 km wide trending NNW in the northern and N in the southern part. Over much of the Yandal greenstone belt, there are considerable challenges to exploration created by a cover of weathered rocks and sediments produced by a long and complex history of landscape evolution. The regolith-landforms, regolith characteristics and geochemical dispersion in the Yandal greenstone belt were investigated for several deposits and prospects and their immediate environments. This established the regolith processes and the landscape evolution on both regional and local scales and was used to assess the use of a variety of residual and transported materials for geochemical exploration. Three dimensional (3D) visualisation models of regolith and Au geochemistry were used to identify major controls on Au dispersion and to assist with anomaly interpretation. The application of 3D mapping was restricted to areas with precise and accurate subsurface datasets which covered about 70 percent (about 50,000 drill holes) of the belt.

Deposits and prospects in the belt represent erosional and depositional landform regimes. In erosional regimes, the weathering profile is partially or wholly truncated. In depositional regimes, mining and drilling reveals Quaternary sediments concealing numerous older Tertiary paleochannels that are up to several hundreds of meters wide and many kilometers long. The extensive occurrence of maghemite-rich gravels in the palaeochannel sediments is coincident with dendritic aeromagnetic patterns. Sediments have all undergone post-depositional weathering and commonly overlie buried ferruginous lateritic residuum or an erosion surface cut into saprolite. In erosional regime, surface soil sampling detects mineralisation. However, where aeolian material occurs, it dilutes the geochemical signature of the residual soil. Sampling of soil has little value in depositional regime except where sediments are thin (<5 m). Six sites across the Yandal belt were selected to test the effectiveness of selective and partial extractions for exploration for buried mineralisation. At these sites, transported overburden ranges in thickness from 3 to 40 m. The extraction results for the soil traverses indicate that partial extraction analyses do not give any additional information that cannot be obtained using total analyses. Geochemical dispersion from primary mineralisation into the sediments is only minor, except where the latter immediately overlies the lateritic residuum or saprolite. The optimum sample medium is buried lateritic residuum where there has been less regolith truncation. However, because the nature of origin differs between the lower and upper ferruginous gravels, interpretation should be conducted separately for different regolith units. The hematite-maghemite-rich upper part has experienced more mechanical transport than the hematite-goethite-rich lower part and therefore may show displaced anomalies that have no underlying mineralisation. Understanding palaeotopography is essential for tracing the source of maghemite-rich gravels. Where lateritic residuum is absent, it is appropriate to sample the unconformity between the residual and transported materials (interface) or ferruginous saprolite.

There are significant differences in the distribution of Au in saprolite between the various deposits and prospects. In general, there are two situations: (a) Au restricted to quartz veins and structures, with limited or no dispersion within saprolite and (b) supergene enrichement of Au in saprolite. For example, at Mt Joel, quartz veining is abundant in saprolite and there is a spatial association between the Au and quartz veining. Supergene Au is a minor component of the Au in the regolith. At Cockburn, there is supergene enrichment, 5-10 m thick, in saprolite. It appears that, in addition to the groundwater regime, other factors such as mineralisation style and bedrock lithology play a role in determining depletion and enrichment zones. Primary Au, partly locked within quartz veins (e.g., Mt Joel, Jundee), is stable in the regolith and can be concentrated residually near the surface with only partial depletion from the upper regolith. By contrast, Au associated with sulphides (>15% S), is more mobile. Sub-micron particle size, easy access of supergene solutions and increased concentrations of various oxyanions favoring Au dissolution generate corrosive conditions. At the Cockburn deposit, these conditions have lead to strong Au remobilization in the regolith, independent of the surrounding groundwater regime.

Primary lithology may also influence the degree of supergene Au mobility. This was suggested by the two adjacent deposits at Gourdis which have contrasting lithologies and Au distributions in the regolith profile. The 81400 deposit, hosted by sheared quartz-feldspar porphyry and basalt, has strong Au depletion in the upper regolith. A few hundreds metres away, the 81800 deposit, hosted by sheared mafic, has Au enrichment in the upper regolith. Ultramafic and mafic rocks buffer groundwaters more than other lithologies, leading to less Au depletion (D. Gray, CSIRO, personal communication, 2002).

MURRIN MURRIN NI LATERITE: REGOLITH AND GEOCHEMISTRY

M A Wells
CSIRO Exploration and Mining

Weathering of serpentinized peridotites (*i.e.,* komatiitic olivine cumulates) within the Archaean Norseman-Wiluna greenstone belt at Murrin Murrin, located about 60 km W of Leonora, has produced a laterite-type regolith profile, which is expressed at the surface in two areas known as Murrin Murrin north, MM-North, and Murrin Murrin South, MM-south (Figure 1). The regolith profile at both sites can be broadly sub-divided into three zones: (1) A saprolite zone at the base of weathering, (2) A smectite zone with an upper ferruginous zone, and (3) A thin, ferruginous hardcap or duricrust, 'interbedded' with locally developed calcrete.

The saprolite zone is comprised mainly of Mg-rich clays (*e.g.,* saponite, Mg-chlorite) and cryptocrystalline silica. Magnesium-rich clay pseudomorphs of serpentinized olivine retain the cumulate or mesh-texture of the original peridotite. Locally, colloform magnesite ($MgCO_3$) boulders up to 1 m in diameter, occur in the lower part of the saprolite zone.

The mineralogy of the 'smectite' zone is characterized by a Fe-rich smectite (*i.e.,* nontronite-like), with chlorite, saponite and iron oxides, such as goethite and hematite. In the smectite zone at MM-south, 'nontronite' can comprise 30-50 wt% of the mineralogy, with chlorite about half as abundant. However, at MM-north, chlorite is typically twice as common as 'nontronite', with chlorite accounting for 10-20 % of the normative mineralogy in the smectite zone.

At both MM-north and MM-south the ferruginous zone consists mainly of kaolinite (30-50 wt%) and Fe oxides (goethite and hematite). The more intense weathering in the upper part of the profile has resulted in kaolinite replacing chlorite as the main Al-bearing phase. Iron oxide abundance markedly increases from 5 to 20 wt% in the saprolite and lower smectite zones, to about 50-70 wt% in the upper part of the smectite and ferruginous zones.

Variations in profile mineralogy can be related to variations in the underlying cumulate lithology. At MM-north the underlying lithology consists mainly of comparatively Al-rich ortho- and meso-cumulates. This may account for chlorite being the dominant phase within the saprolite and, in particular, the smectite zones, with chlorite being generally twice as abundant as either saponite or nontronite. At MM-south, the lithology mainly consists of an Al-poor adcumulate. Here, chlorite is less common than either saponite or nontronite in the saprolite and smectite zones, respectively. In addition, locally developed talc-carbonate alteration has produced profiles consisting almost entirely of talc and silicified magnesite.

At both MM-north and MM-south, Ni-Co mineralization is hosted mainly within the smectite and upper saprolite zones, with lesser amounts associated in their ferruginized equivalents. In these zones Ni is mainly associated with smectitic clays and chlorite, with lesser amounts associated with serpentine and Mn oxides. Cobalt mineralization is principally associated with Mn oxides, which occur at or near the contact of the smectite and ferruginous zones in the profile. The Mn oxides are identified as an asbolan-like phase, $(Co,Ni)Mn_2O_4(OH).xH_2O$, which can have a variable Co:Ni ratio but is typically 1:1 and a Co:Mn ratio of 0.33.

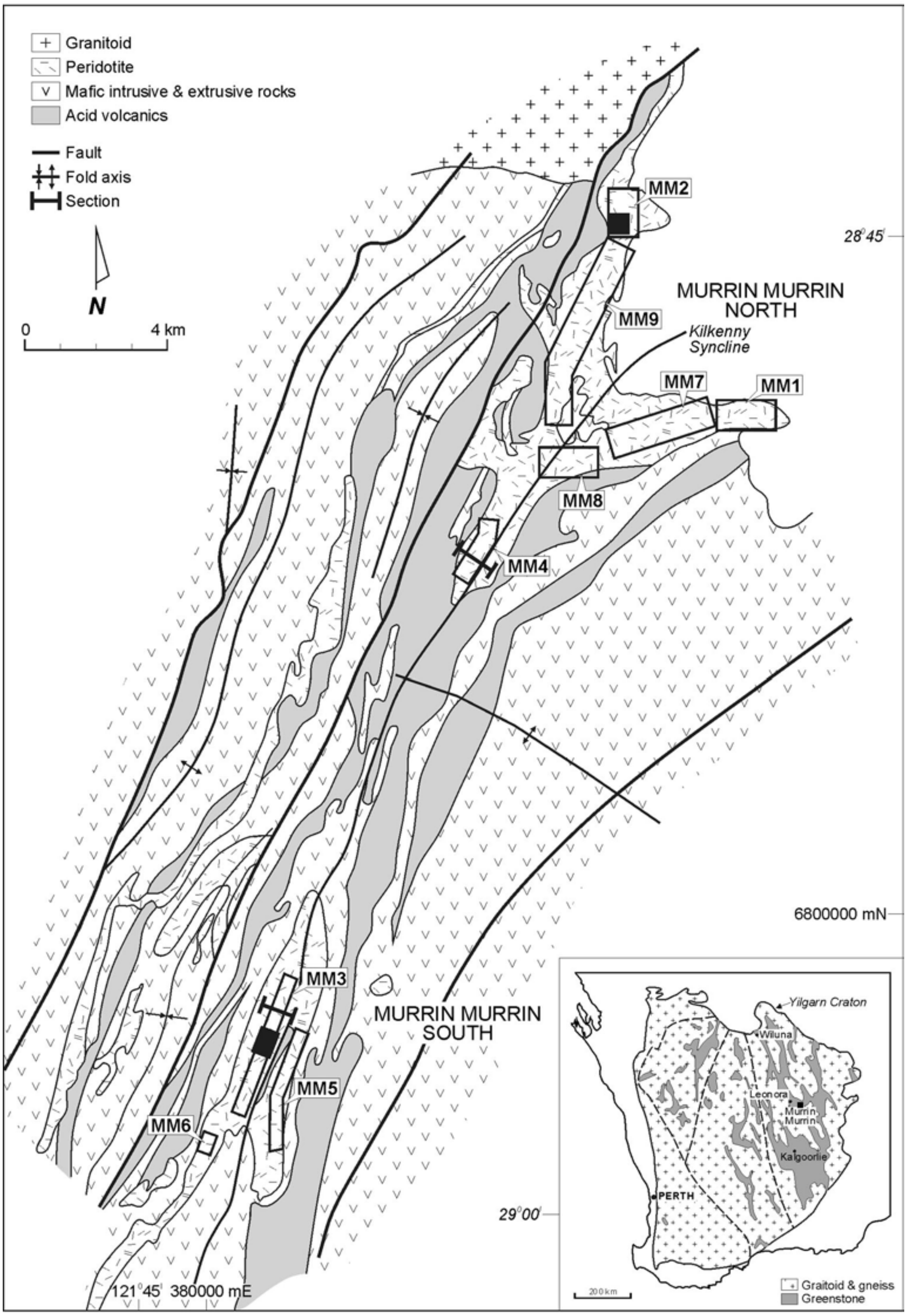


Figure 1. Location and generalized geology of the Murrin Murrin Ni Laterite deposits. The Ni laterite deposits are expressed at the surface in two areas referred to as Murrin Murrin north and Murrin Murrin south.

GOLD ANOMALIES IN TRANSPORTED REGOLITH

C.R.M. Butt
CRC LEME / CSIRO Exploration and Mining

The presence of a thick regolith is recognized as a major impediment to mineral exploration in the Yilgarn Craton and adjacent regions, as well as in many other parts of Australia. The processes of deep chemical weathering, erosion and sedimentation have served to conceal ore deposits in the underlying rocks, such that their geological, geochemical and geophysical expression in the regolith is greatly altered, weakened or buried. In general, surface geochemical techniques can be routinely and successfully applied to exploration in exposed areas, whether the surface materials are lateritic residuum, saprolite, fresh rock or soils derived from them. However, geochemistry has been much less successful where surface materials are transported. The initial problem is that of recognizing that the material is transported, and then establishing the circumstances (if any) under which it may be suitable as a sample medium.

The sedimentary cover ranges in age from Permian to Recent and in thickness from a few centimetres to many tens of metres. The sediments include marine, glacial, colluvial, alluvial, estuarine/deltaic, organic, evaporitic and aeolian types, and several may be present in the sequence at a given site. The various types of sedimentary overburden are commonly poorly characterized and are difficult to recognize. Consequently, they have not only been inadequately mapped, but their potential as geochemical sample media, or even as hosts to secondary mineralization, is poorly known. The overburden varies in character according to region, geomorphological setting and age, with each variant potentially presenting different problems and opportunities to mineral exploration. Upland areas are mantled by colluvium and, especially over sedimentary and granitic rocks, aeolian sands, that commonly overlie complete or partly truncated lateritic regoliths. Other areas are occupied by major drainages that form broadly dendritic systems on the Craton and adjacent sedimentary basins. The drainage systems may date from the early Mesozoic or earlier and are now represented by broad colluvial-alluvial plains, generally with deeper "palaeodrainage" channels within them. Some of these sediments may similarly overlie complete or truncated lateritic regoliths, whereas others may be contemporaneous with or pre-date lateritic weathering.

Transported overburden accordingly presents formidable problems and challenges to exploration. On the one hand, because of its exotic origin, it has commonly been considered unsuitable as a sample medium; on the other hand, because many of the sediments are ancient and have been subjected to diagenesis and post-depositional weathering, it has been thought that there is potential for their composition to be influenced by chemical dispersion from underlying mineralization. Exploration in depositional areas has proceeded according to both precepts, with some groups proceeding to drill through all transported and in some cases, residual regolith materials, and others continuing to collect and analyse shallow samples of clearly transported material in the belief that they will indicate the presence of concealed mineralization. This experience has shown that in many instances, transported materials yield anomalies in gold and other elements; relating these to their source, however, commonly remains problematic. Conversely, many concealed deposits appear completely blind, with no obvious expression in the transported cover; seeking procedures that can reliably ‘see’ through cover remains a challenge.

This talk will summarize some case histories from the Yilgarn, most of which were undertaken as part of CSIRO/CRCLEME/AMIRA Project 409 (Butt et al., 1997). The sites exemplify different regolith situations and different regions and the results yield a number of guidelines for the use of transported overburden as exploration sample medium.

The broad conclusion from these case studies is that there has been little significant geochemical dispersion of gold or associated pathfinder elements into or through transported overburden. Accordingly, it should not be expected that there will be a near-surface expression of concealed mineralization. In the Northern Yilgarn Craton, where soils are non-calcareous, there may be no response where the overburden thickness is greater than about three metres. In the southern Yilgarn, gold anomalies in pedogenic carbonate may give a response to mineralization concealed by up to 10 m of sedimentary cover, even where this directly overlies leached and depleted saprolite. Zones of supergene gold enrichment are present in the sediments of some palaeochannels, including basal sands (e.g., Lady Bountiful Extended, Steinway), lignite and organic sediments (e.g., Argo, Challenge-Swordsman (Higginsville); Swordfish) and clay (Kanowna QED). However, none of these is further expressed in the overlying colluvial sediments or soils.

There are some exceptions. A soil gold anomaly indicates mineralization at Penny West (Youanmi) through 10 m of gravel and sand resting on saprolite (Radford and Boddington, 2003). However, the dispersion mechanism is unknown and this unusual response cannot be relied upon as a general guide. At Fender, soil sampling is ineffective where sediment cover is less than 3 m thick (Radford and Burton, 1999.)

A geochemical response is commonly present in the sediments and /or upper residuum in the two or three metres across the unconformity. In the northern Yilgarn, these appear to be due largely to physical processes during or after deposition, possibly supplemented by chemical dispersion along the unconformity where this forms an aquifer or seepage zone. For example, the low grade anomalies in the top metre of shallow (1-3 m) sediments over lateritic residuum at Baxter/Harmony and Fender are probably due to bioturbation. In comparison, mixing during erosion and colluvial sedimentation has lead to the broadening of anomalies at the base of the deeper overburden, both where lateritic residuum is partly preserved (Calista, Bronzewing) and where it has been eroded and saprolite underlies the unconformity (Quasar, Golden Delicious, Fender). At Golden Delicious, chemical dispersion along the unconformity may also have contributed to the anomaly. Wide physical dispersion is a feature at Fender, where ore-associated elements, principally As and Sb, are hosted by detrital ferruginous nodules scattered through low energy silty clays. The nodules are derived from the erosion of lateritic residuum. In general, anomalies are very restricted in extent and tenor where sediments directly overlie saprolite. Sampling across the unconformity (interface sampling) can be an effective procedure for exploiting the zone of maximum dispersion, although recognition of the interval is critical and can be difficult. At Quasar, however, the high background (~50 ppb Au) in colluvium relates to distal mineralization and partly disguises the interface anomaly

Chemical dispersion of gold, both in groundwater and the regolith, is more prominent in the southern Yilgarn. Active chemical mobilization of a wide range of other elements under present conditions is also well established. For gold, this is demonstrated by high concentrations dissolved in acid, saline groundwaters, and by enrichment as highly soluble forms in pedogenic carbonates. However, this mobility does not appear to give rise to detectable dispersion haloes in transported overburden, except where this is thin. Thus, there are gold anomalies in calcareous soils where the cover over residual regolith is generally 5-8 m thick (Mt. Pleasant, Safari, Kanowna Belle, Carosue Dam), but not at Apollo, or any of the palaeochannel sites where thicknesses are 10->50 m. There is no response in any other element.

Anomalies in calcareous soil over palaeochannel mineralization at Steinway and Aphrodites (Higginsville) have particulate gold in immediately underlying ferruginous gravels as their immediate source, rather than the concealed mineralization. The gold-bearing gravels are in turn derived from outcropping mineralization upslope. It is concluded these soil anomalies are coincidental and cannot be regarded as successful exploration case histories. In comparison, there are no anomalies at Greenback, adjacent to Steinway, or Mitchell, near Aphrodites. There are numerous reports of anomalies without underlying sources and of mineralization with no surface expression; Steinway and Aphrodites represent sites where these situations coincide..

No additional response, compared to total analysis, was found by the use of partial extraction analyses of any type (Gray et al., 1999).

Geochemical response to concealed Au mineralization, Yilgarn Craton.

Sediment thickness	Characteristics	Depth to mineralization	Optimal response	Possible Au source
N. Yilgarn				
Harmony/Baxter 0.5-3 m; colluvium	Hardpan, overlying lateritic residuum	Lateritic residuum at ~3 m.	800 m at >30 ppb Au in lateritic residuum	Lateritic residuum
Calista 12-16 m; colluvium	Hardpan; sandy-gravelly alluvium and colluvium over lateritic residuum	Lateritic residuum at 12-16 m; massive sulphides at 80 m	>200 m at >100 ppb Au, 75 ppm As in lateritic residuum and gravelly colluvium	Lateritic residuum
Fender 2->8 m colluvium	Sandy hardpan on clay, overlying lateritic residuum or saprolite	Lateritic residuum or weathered mineralization at 3-5 m; locally some depletion	>250 m having >100 ppm Sb, W in gravels in basal clay/ interface and local outcrop	Eroded lateritic residuum
Quasar 5-8 m colluvium	Hardpan, colluvium on saprolite	Weathered mineralization at 5-8 m	50 ppb background in colluvium. >250 m at >60 ppb Au at interface.	Regional background from distal sources. Interface anomaly from weathered mineralization
Golden Delicious 6-16 m colluvium	Hardpan; calcareous silt and gravel; on saprolite	Weathered mineralization, 20 m	400 m at >40 ppb Au at interface	Weathered mineralization
S. Yilgarn				
Panglo Up to 0.5 m sheetwash	Thin calcareous soils on saprolite	Supergene mineralization at 30-40 m	25-115 ppb Au in top 10 cm. <20 ppb background.	Particulate Au in Fe saprolite and nodules
Safari 2-10 m; sheetwash, sand	Sandy sediments, on saprolite and saprock; calcareous 0.2-4.0 m.	Weathered mineralization at unconformity, 8 m	350 m at 7-25 ppb in top 0.5 m. Mean background 4 ppb.	Sub-cropping mineralization
Mt. Pleasant 6-8 m Alluvium	Calcareous soils on silty clay	Weathered mineralization at 8 m	>100 m wide at >10 ppb Au in soil; 20-25 m at >20 ppb at 2.5 m.	Weathered mineralization
Apollo 5-10 m alluvium, lacustrine clay	Sands, calcareous and non-calcareous red and grey clays, over saprolite	Weathered and ?supergene mineralization at 15-70 m	10-15 ppb Au in calcareous soil at 0-1.0 m (6-17 ppb background.)	Regional background
Steinway 30 m	Calcareous soil, mottled clay and	Supergene mineralization at	150x1000 m at >24 ppb Au in	Detrital gold in ferruginous

palaeochannel sediments	sand on saprolite	35 m	soil. False positive	nodules; from distal mineralization
Mitchell 40 m palaeochannel sediments	Calcareous soil, mottled clay and lignite on saprolite	Supergene mineralization in sand and lignite	<5-20 ppb Au in soil. No response to mineralization	Regional background

Acknowledgements

The data presented in this paper were summarized mainly from research by present and past colleagues in CSIRO and CRC LEME, working in collaboration with the Australian mining industry and AMIRA.

References

Butt, C.R.M., Gray, D.J., Robertson, I.D.M., Lintern, M.J., Anand, R.R., Britt, A.F., Bristow, A.P.J., Phang, C., Smith, R.E. and Wildman, J.E., 1997. Geochemical exploration in areas of transported overburden, Yilgarn Craton and environs, Western Australia. Final Report. Restricted Report 333R, CSIRO Australia, Division of Exploration and Mining, Perth. Restricted Report 36R, CRC LEME, Perth. 150 pp.

Gray, D.J., Wildman, J.E. and Longman, G.D., 1999. Selective and partial extraction analyses of transported overburden for gold exploration in the Yilgarn Craton, Western Australia. Journal of Geochemical Exploration 67: 51-66.

Radford, N. and Boddington, T., 2003. Penny West gold deposit, Youanmi, WA. In: Regolith Expression of Australian Ore Systems, CRC LEME. www.crcleme.org.au/casehist/PennyWest.pdf.

Radford, N.W. and Burton, P.E., 1999. The geochemistry of transported overburden: the time factor. An example from the Fender deposit, Big Bell, Western Australia. Journal of Geochemical Exploration 66: 71-83.

CALCRETE AS A SAMPLING MEDIUM - GAWLER CRATON

M J Lintern
CRC LEME / CSIRO Exploration and mining

Introduction

For almost a decade, South Australian exploration companies have used pedogenic calcrete as the preferred geochemical sample medium for gold exploration. Their experience, coupled with earlier (southern Western Australia) and on-going scientific research, is significant. Calcrete is secondary carbonate, principally consisting of calcite and dolomite, and typically forms in arid to semi-arid environments with average annual rainfall less than 600 mm. Calcrete is widespread in South Australia and commonly contains variable amounts of the substrate (e.g. soil, colluvium, laterite, saprolite and rock) on and within which they form. *Pedogenic* calcretes form in unsaturated (vadose) soil horizons, whereas *groundwater* calcretes form in saturated (phreatic) environments, typically in the axes of major drainages. The term "calcrete" here is used in its broadest sense and includes powdery accumulations and clay coatings of carbonate through to the massive indurated forms.

In 1995, CRC LEME and PIRSA initiated a cooperative agreement in which they recognised the importance of regolith in mineral exploration in South Australia. The South Australian Regolith (SAR) "umbrella" project was formed to provide a framework for exploration case histories covering (i) regolith-landform mapping, (ii) regolith geochemistry, (iii) soil geochemistry, (iv) biogeochemistry, (v) hydrogeochemistry and (vi) palaeochannel delineation. Calcrete was studied at 15 mainly Au prospects including Challenger, Birthday, Mt Gunson, Old Well, Adelaide Hills, Moonta, Jumbuck, the Olary area, Monsoon, South Hilga, ET, Golf Bore and Boomerang. Preliminary studies at Moonta and Olary indicate that calcrete is found to be of limited use in Cu exploration. The use of calcrete as a sampling medium will be exemplified by the Challenger case study.

Challenger

Introduction. The Challenger Gold Deposit is located in the Western Gawler Craton, 750 km NW of Adelaide and 140 km NW of Tarcoola, and was discovered in 1995 by calcrete sampling (maximum of 180 ppb Au), followed by drilling of the anomaly. Gold production commenced in 2002. The deposit is located beneath an expansive plain several tens of kilometres square with generally low relief (<50 m). The climate is arid with rainfall of about 150 mm per annum falling mostly in the winter.

Regolith landforms and regolith stratigraphy. The dominant regolith-landform is depositional; *in situ* erosional units comprise the remainder and mostly consist of highly weathered bedrock. There is very little outcrop and no lateritic duricrust; ferruginous materials (mostly granules) are locally abundant but generally scarce. Landform processes are mostly erosional but are probably limited to rare sheet flow events leading to local re-distribution of surficial materials, including colluvium and lag, and a general lowering and planation of the landscape. Aeolian processes are evident from the presence of sand spreads and carbonate dust. Intensive weathering has produced a regolith dominated by kaolinised saprolite and remnant quartz veining. The upper regolith has been variably silicified and, more recently, calcified.

Regolith expression. The geochemical expression of Challenger in the regolith was investigated at three levels:

1) Survey of elements in regolith materials (lag, calcrete and soil) over a 3 km x 3 km area;
2) Vertical distribution of elements in regolith materials along a 1.5 km orientation line that crossed three zones of mineralization (Zones 1, 2 and 3); the main Challenger I ore body mineralisation (Zone 1) sub-crops beneath a veneer of calcareous and

siliceous material and is continuous to depths in excess of 80 m; at Zone 2, mineralisation sub-crops but overlays a 14 m thick saprolite where Au is poorly concentrated; at Zone 3, mineralisation is concealed beneath about 20 m of principally barren transported overburden.

3) Detailed vertical distribution of elements in eight shallow (<3 m depth) soil pits along the orientation line.

The geochemical survey indicated that Au in calcrete and soil showed similar distributions but that the abundance of Au in soil is much lower; the soil is partly calcareous. The calcrete indicates mineralization better than soil but this may be an artefact of the sampling data density which was greater for calcrete. Gold in lag was anomalous over mineralization but not exclusively so.

Gold in surficial calcrete from the orientation line reaches a maximum of 2370 ppb over Zone 1. This particularly high concentration is due to coarse (clastic) Au, associated with quartz veining, incorporated in the calcrete. Anomalous values (~>10 ppb) extend for about 500 m over Zone 1 and about 200 m over Zone 2 (maximum of 52 ppb); no Au or other element anomaly was detected in surficial calcrete over the buried Zone 3 mineralization.

Gold concentrations in 2-3 m deep soil pits are extremely variable but there appears to be a general association between Au and Ca (Figure 1). The profiles highlight the non-clastic and clastic nature of Au that may occur in calcareous soils. The highest Au concentration (~100 ppm) was recorded at 2.0 m depth in pit GCP122, over Zone 1, although the Au concentration for the upper soil was only 250 ppb. For adjacent profiles from the same pit located within 5 m of each other, near surface sample concentrations of 35, 250, 380, and 900 ppb were recorded, indicating the extreme variability close to mineralization where clastic Au is present. The high Ca concentration (15%) at the base of pit GCP122 is unusual in that it is almost entirely due to the presence of gypsum; the Au concentration here is 760 ppb. Interestingly, Au concentrations in calcrete of the order of 20-30 ppb in GCP 106 (over Zone 3 mineralization located at ~20 m) are higher than in adjacent pits GCP110 and 100 (no mineralization) suggesting the possibility of Au enrichment related to mineralization. However, the Au-Ca association is not as strong in this profile indicating possible clastic Au from upslope.

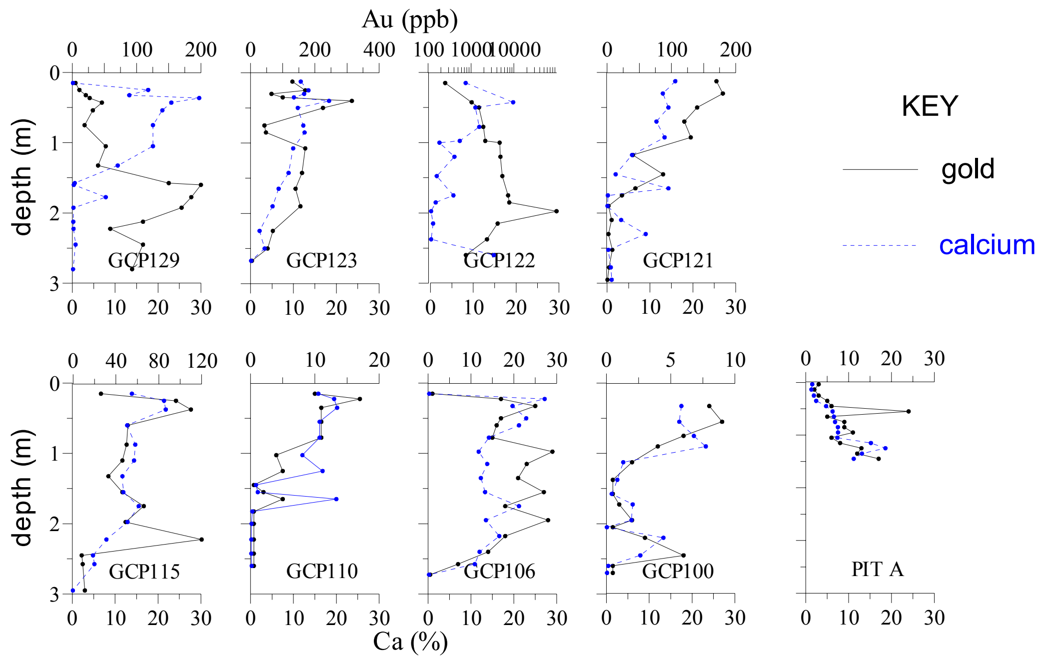


Figure 5: Concentration-depth profiles for Au and Ca in soil pits. All pits except pit A are located along the orientation line. GCP123-GCP121, GCP115 and GCP106 are located over Zones 1, 2 and 3 respectively.

The study confirms that calcrete is ubiquitous and is recommended as the best sample medium for detecting Au mineralization in the *in situ* regolith unit (Zone 1 and 2) providing broad, high-contrast anomalies for Au.

Conclusions: The presence of transported overburden has a profound effect on the expression of mineralization in the regolith. The case study highlights the importance of identifying transported units for geochemical sampling. Thus, whereas calcrete sampling is particularly effective in areas of *in situ* regolith (Zone 1), its use over transported overburden is less certain (Zone 3). Areas of low Au concentrations in calcrete (the null case) should be further investigated to see whether transported material forms the substrate, in which case, drilling into underlying saprolite may be more appropriate. It appears that the broad Au in calcrete anomaly over Challenger is related to chemical and mechanical dispersion of Au from *in situ* regolith. In areas of *in situ* regolith, alternative sample media such as shallow drill hole cuttings, soil, silcrete, vegetation, lag and, possibly, gypsum may be used, with caution, if calcrete is absent and the appropriate thresholds are applied.

Further reading

Case studies are described in individual site studies and available as CRC LEME Open File Reports. A report on the ET Regolith Project was released in May 2003 and describes exploration bordering sand dunes on the edge of the Great Victoria Desert. "Calcrete: characteristics, distribution and use in mineral exploration" is a CRC LEME publication (Chen, Lintern and Roach, 2002) and describes case studies from Australia and around the world.

Acknowledgements

South Australian Regolith team members are gratefully acknowledged for their contributions towards the project. Cooperation and support from companies is appreciated. CRC LEME is supported by the Australian Cooperative Research Centres Program. M. Cornelius and C.R.M. Butt are thanked for reviewing at short notice.

WOODIE WOODIE UNVEILED

J Meyers
CRC LEME / Curtin University of Technology - Mineral and Environmental Research Consortium, Department of Exploration Geophysics

The Woodie Woodie Manganese Mine is located in the east Pilbara region of Western Australia. Outcropping manganese (Mn) ore was first discovered at Woodie Woodie in 1950, and was mined at small scale until 1990 when Portman Mining began large scale production. Consolidated Minerals began operations in May 1999, reaching over half a million tonnes per annum since 2001. Mn ore is trucked from Woodie Woodie to Port Headland, where it is exported overseas and used in the refining and production of steel goods.

The Mn ore is hosted in the Archaean Carawine Dolomite (part of the Hamersley Group) and in the overlying Archaean Pinjian Chert Breccia. Published models for the deposition of Mn ore at Woodie Woodie are based on supergene enrichment in the regolith. However, new information from detailed geological mapping, such as the occurrence of discrete Mn veins in dolomite, suggests that primary Mn ore deposition may have been at least partly the result of hydrothermal processes. This has opened the way for exploration below surface, through either Permian glacial outwash sediments or the Proterozoic Waltha Woora Formation sandstones, which unconformably overlie the Carawine Dolomite, or beneath the dolomite itself. The geology is complicated by deep Tertiary weathering, which in places extends up to 100m below surface and has resulted in a typical lateritic profile in some areas. Permian glacial deposits fill broad to steep sided paleovalleys that form along bedrock units and cross structures. To the west, the Cainozoic Oakover Formation colluvial sediments overly all of the above geology to a depth of up to 40m.

Physical property measurements on Mn ore show that the contrast in density between high-grade ore and the surrounding dolomite is approximately +0.7g/cc, and the Mn ore tends to have inductive and galvanic conductivity in excess of 2 orders of magnitude above the surrounding rocks. High-resolution gravity surveying, using 50x50m station spacing, has played an important role in the discovery of Mn ore at Woodie Woodie. Discrete gravity anomalies, having amplitudes between 1.4-0.5mGal, have helped to discriminate zones of outcropping Mn that contain large tonnage at depth (Dentith *et al*., 1994). Magnetic Mn minerals braunite and pyrolusite, which have only weak magnetic susceptibility at about 0.002SI, sometimes occur in the high-grade ore zones, but there is generally no direct response detected in high-resolution aeromagnetic survey data. Magnetic anomalies are occasionally observed adjacent to Mn mineralisation, and this relationship is thought to be caused by iron oxide minerals associated with Mn ore forming processes.

Gravity surveying at 50x50m station spacing has recently been completed over the entire Woodie Woodie mine corridor (over 72 square kilometers with over 50,000 stations). This extensive gravity database has been useful for discovering Mn ore in areas of bedrock outcrop to subcrop. However, when a Mn ore body of 1 million tonnes sits more than 20m below less dense sediments, the amplitude of the gravity anomaly drops to below 0.1mGal, which is the local noise level in the area using modern exploration gravity meters and rapid DGPS survey methods. Reprocessing and editing of existing gravity survey data, along with careful analysis of the topography using orthophoto DEMs, has led to anomaly picking of subtle gravity features, and contributed to the recent, blind discovery of the Camp East deposit. Routine terrain correction methods applied to the gravity data did not remove subtle anomalies caused by local terrain variations, but experiments are ongoing to produce localised terrain corrections.

The complex patterns of subsurface density variations observed in filtered gravity images show that large, prospective areas overlain by Permian and Cainozoic sedimentary cover and weathered dolomite are too difficult for prospecting using gravity methods alone. Therefore, Consolidated Minerals funded a time domain helicopter electromagnetic survey over the mine corridor. The Hoistem system, under development by Newmont Mining and GPX Services, was chosen as the best method due to its wide band width, low flying height, and close sample spacing. Hoistem uses a square wave transmitter pulse of 5ms and a recording time of 15ms. The in-loop, coplanar transmitter-receiver frame of the Hoistem system was suspended below a turbo modified Bell 47 helicopter, and the frame had an average terrain clearance of 40m. A number of repeat lines were flown at 70m clearance for experimentation with height variations. Several repeat lines at the same flying height were also run to test for repeatability and system noise. The small footprint of the high-grade Mn deposits required a production flight line spacing of 80m, and a total of 1,280 survey line kilometers were flown.

Hoistem receiver data were stacked and noise filtered, binned into 140 channels, and windowed into 28 channels. Channel data were edited and processed to show shallow features associated with the regolith and identify features with decay constants that could represent conductive Mn ore. Many of the deep, Permian deposits were detected in the late time responses, and in places, it was difficult to separate the bottom of Permian deposits from Mn targets. Conductivity depth inversions (CDIs) using Newmont's software provided conductivity depth profiles and depth slices below the near surface regolith 'noise', but the conductive features were too broad for identifying discrete Mn targets. Therefore, experiments using EM Flow were carried out to test the ability of this software to produce more detailed CDIs. The preliminary CDIs using an adapted version of EM Flow produced CDIs that helped identify a number of high priority targets, and separated them from Permian sediments. Target drilling had a high success rate for greatly extending resources around a known resource and identifying a number of new Mn prospects below fresh outcrop and in covered areas. One of the Hoistem discoveries, Chris D, sits below 30m of Permian cover and contains a Mn resource in excess of 1.5 million tones (Figure 1). Some known Mn resources were not detected in the Hoistem data, and other, non-inductive geophysical methods are being tried across a number of prospects to test which methods are best suited to find these ore types.

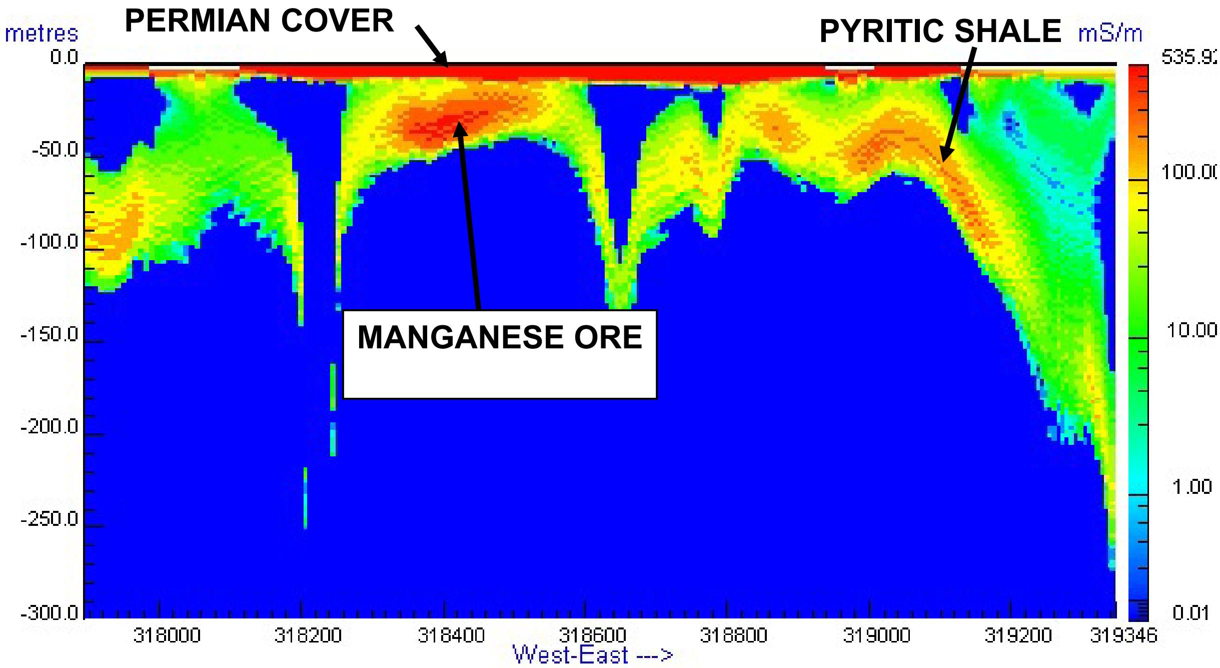


Figure 1. CDI profile along Hoistem Line 3270.

Sub-audio magnetic surveying (SAM) using a 4Hz transmitter was carried out over several prospects, and it was found that this technique works extremely well for mapping detailed conductivity variations above 30m depth. Shallow Mn mineralisation, pyritic shales, and regolith materials are mapped using SAM, but conductive Mn ore sitting below 30m depth was not detected.

Studies on the system and geometrical noise of Hoistem, along with survey design specifications, and calibration are continuing in order to refine the broadband signal and to produce more accurate CDIs. Future ground and downhole geophysical data will be processed using innovative methods, and these results will be integrated with other exploration data to produce a holistic approach for exploration under cover in the Woodie Woodie region.

Dentith, et al., 1994, Geophysical signatures of Western Australian mineral deposits: an overview. In: Geophysical Signatures of Western Australian Mineral Deposits, ASEG Publication 7, 29-84.

WEATHERING OF BASE METAL DEPOSITS, WESTERN LACHLAN FOLD BELT

K M Scott
CRC LEME / CSIRO Exploration and Mining

How weathering of base metal deposits occurs in the semi-arid environment of the Lachlan Fold Belt of western New South Wales affects their geochemistry in the regolith (outcrop and in derived soils) and hence interpretation of exploration geochemical results. Thus comparison of the weathering at Elura (43 km NNW of Cobar) and 200km SE at Mineral Hill (65km N of Condobolin) is instructive.

The Elura Zn-Pb-Ag orebody occurs in an area of low relief as 7 discrete zones in a sequence of Devonian siltstones and sandstones (*e.g.,* Webster and Lutherborrow, 1998). Massive pyrite, pyrrhotite, sphalerite and galena mineralization of the Main zone forms a vertical pipe-like body and is completely weathered to a depth of 80m, with partial weathering extending to 100 m. The orebody was probably blind and only strongly ferruginized wallrock, which has been slightly eroded, outcropped. However the ferruginous material is now covered by a thin red colluvial soil.

The Elura gossan profile displays an upward progression from primary to supergene sulfides through the supergene oxidate zone (sulfates, carbonates and arsenates) to the Fe-oxide dominated near surface material (ferruginous oxidate zone). The supergene sulfides are about 3 m thick and are dominated by the occurrence of pyrite, marcasite and galena and the absence of sphalerite. Anglesite and cerussite are also present in this zone. The interface with the overlying oxidate zones is marked by a 15 cm band of blue-black sooty chalcocite with some digenite and enargite. At the base of the 15 m supergene oxidate zone, native silver and cassiterite occur before giving way to beudantite-, mimetite- and hidalgoite-rich assemblages (Figure 1). 50 m of hematite- and goethite-rich material (ferruginous oxidate zone) then extends to the surface.

This complex sequence is considered to have formed as a 2-stage process. A period of initial oxidation resulted from the interaction of oxygenated water with the sulfides prior to the onset of aridity during the Middle Miocene (*cf*. Leah, 1996). During the more arid period to the present, the watertable fell and a Cl-overprint modified some of the earlier formed minerals to more Cl- rich ones (*e.g.,* some beudantite altered to mimetite and Pb oxychlorides formed). An effect of this complex weathering is the strong depletion of Zn and the local attainment of high concentrations of Ag, As, Ba, Cu, Hg, Pb, Sb and Sn in the profile.

Rich secondary Ag-Pb-Zn mineralization has been mined in the Mineral Hill Field since its discovery in 1908. From that time until the present, 2 700 t Pb, 10 890 kg Ag and 73 kg Au have been produced from 14 000 t ore (McClatchie, 1971). Such secondary ore extends to depths of 100m in some sections before giving way to primary galena and sphalerite associated with dolomite/siderite and chlorite in volcanic host rocks.

Weathering of the sulfides at Parkers Hill, in the Mineral Hill Field, shows a progression from carbonate-associated sphalerite-galena rich mineralization into about 15 m of partially weathered sulfides with anglesite (where the primary carbonates have been destroyed) and capped by a thin tetrahedrite-rich interval before passing into a 30-40 m thick zone dominated by cerussite (where chlorite has been weathered to kaolinite and Fe oxides and Pb-bearing alunite-jarosite minerals are developed from the weathered sulfides) and an upper (20 m thick) Fe oxide zone containing pyromorphite and plumbogummite. Within the cerussite zone, a bindheimite-rich, $Pb_2Sb_2O_6$ (O, OH), subzone (45-49 m) and a talc-rich interval can also be identified (Figure 2).

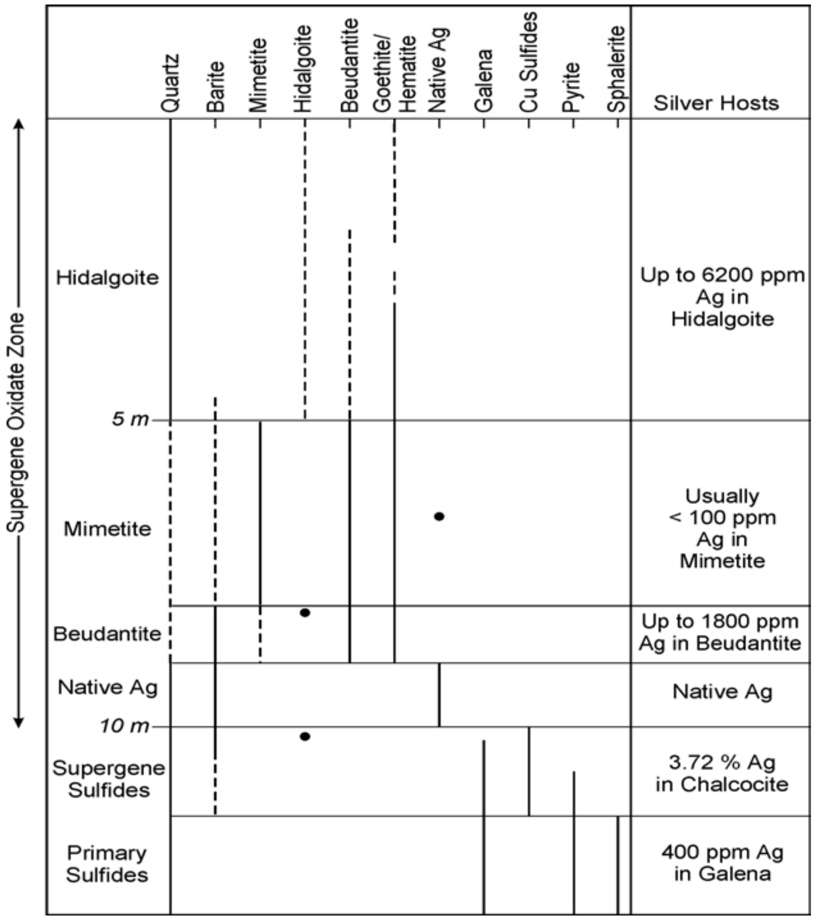


Figure 1: Mineralogical variation in the supergene oxidate zone at Elura, emphasising Ag distribution.

High abundances of Ag, As, Br, Cd, Cu, In, Mo, Pb and Sb in both the tetrahedrite-rich top of the sulfide zone and in the bindheimite subzone suggest that the two zones may be related *i.e.,* the bindheimite-rich material may be derived from tetrahedrite-rich intervals in the profile (as previously implied by McClatchie, 1971). The presence of Br in both these intervals is interesting considering the presence of Br (and presumably other halides) in gossanous material from the Iodide dump material. The occurrence of secondary Cu minerals in this zone (Figure 2) is similar to the Cu-enrichment that occurs at the sulfide/oxidate interface at Elura

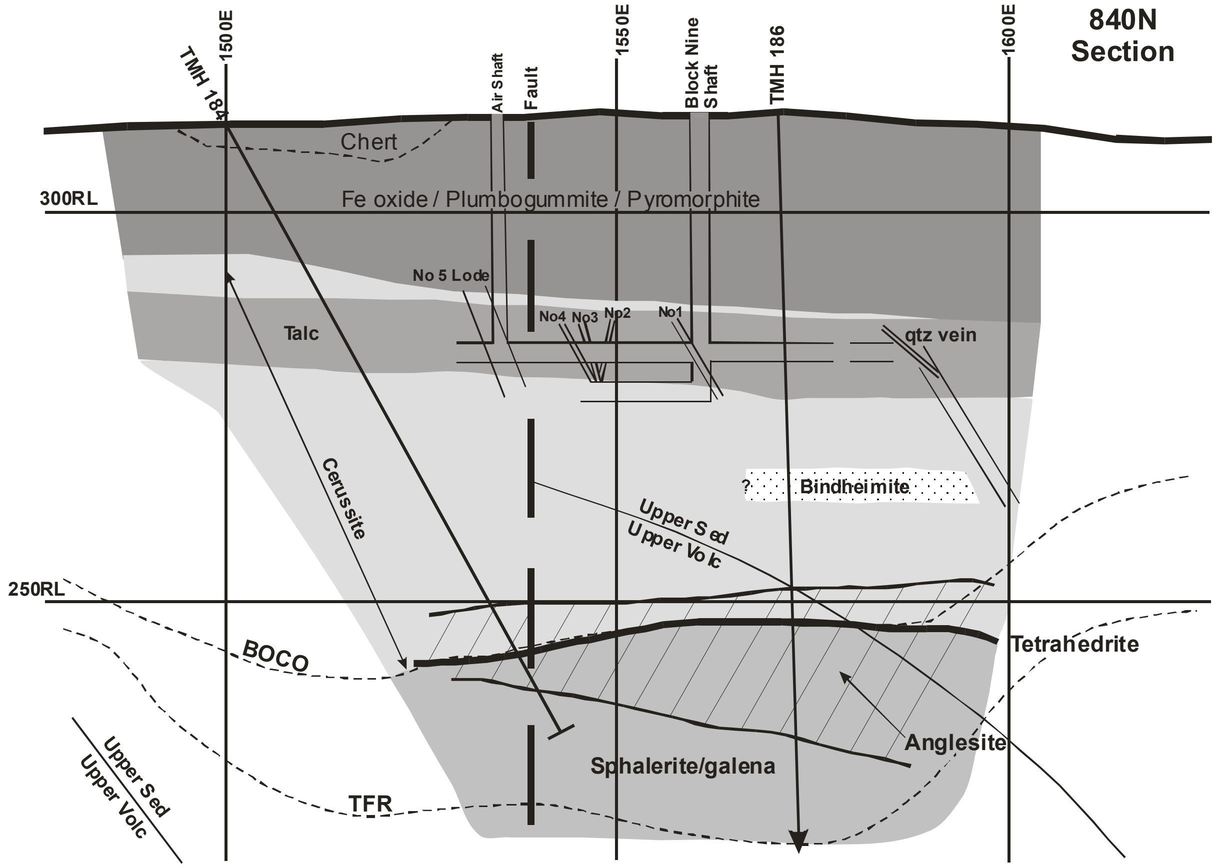


Figure 2: Mineralogical zoning at Parkers Hill

The weathering profile at Parkers Hill with its extensive zone of cerussite and retention of substantial amounts of normally mobile elements like Cu and Zn is different to that generally encountered in the weathering of base metal sulfides in the western Lachlan Fold Belt *e.g.,* Elura. There the original sulfides are pyrite-rich and very acid conditions are developed during the weathering so that only a thin zone of cerussite is developed with anglesite at the top of the supergene sulfide zone and a thick sequence of Pb-bearing alunite-jarosite minerals and mimetite is developed in the overlying oxidate zone (Taylor *et al.,* 1984; Scott, 2000). Under these acid weathering conditions elements like Ag and Cu may be strongly concentrated in supergene Cu sulfides immediately below the oxidate zone and then be strongly leached toward the surface. Zinc is strongly leached as soon as the host sphalerite starts to weather but Pb generally maintains similar abundance levels in fresh and surficial material although the actual Pb minerals present vary up the profile.

The retention of Cu and Zn, as well as Pb, in surficial samples in similar levels to those in fresh sulfides at Parkers Hill reflects the much more alkaline weathering conditions caused by the lack of pyrite at Parkers Hill and the strong buffering action of talc in the rocks. It also means that the base metal contents in the surficial gossan are a good indicator of the primary ore grades. Elements like Ag, Cd and Mo do appear to have suffered some depletion during weathering but As, Sb and W are enriched in the ferruginous gossan at Parkers Hill.

REFERENCES

Leah, P.A., 1996. Relict Lateritic Weathering Profiles in the Cobar District, NSW. *In* The Cobar Mineral Field – A 1996 Perspective, (Editors: W.G. Cook *et al.*), Australasian Institute of Mining and Metallurgy, Melbourne, pp. 157-177.

McClatchie, L., 1971. Base metal mineralization at Mineral Hill, central western New South Wales. Geological Survey of New South Wales Memoir 11 (118 pp + maps).

Scott, K.M., Elemental mobilities during the weathering of the Elura Zn-Pb-Ag orebody – the influence of mineralogy. *In* Extended Abstracts Central West Symposium 2000, (Editors: K.G. McQueeen and C. L. Stegman), CRC LEME, Perth , pp. 94-97.

Taylor, G.F., Wilmshurst, J.R., Togashi, Y. and Andrew, A.S., 1984. Geochemical and mineralogical haloes about the Elura Zn-Pb-Ag orebody, western New South Wales. Journal of Geochemical Exploration 22: 265-290.

Webster, A.E. and Lutherborrow, C., 1998. Elura zinc-lead-silver deposit, Cobar. *In* Geology of Australian and Papua New Guinean Mineral Deposits, (Editors: D.A. Berkman and D.H. Mackenzie), Australasian Institute of Mining and Metallurgy, Melbourne, pp. 587-592.

Acknowledgements: The support of Pasminco Exploration geologists at the Elura Mine over an extended time is acknowledged, particularly, the assistance of David Hall, Ian Kelso and Angela Lorrigan. Similarly the assistance of Triako Resources Ltd geologists, especially Ian Mackenzie and Angus Collins, is appreciated.

EXPLORATION GEOPHYSICS AT THE ADELAIDE UNIVERSITY

Dr. John Joseph
CRC LEME / The University of Adelaide

A team of four academics, post-graduate and honours students are involved in collaborative projects with a number of exploration and mining companies. Such collaborations were developed through national conferences and meetings; professional societies (Australian Society of Exploration Geophysicists), the Department's Industrial Liaison Committee as well as students' vacation employment. CRC-LEME promotes collaboration by providing students scholarships and project funds. Success of projects depends on various elements such as accurate problem definition, willingness to experiment and risk failure, a shared mission and vision; the retention of each organization's cultural strength; trust between the participants and mutually beneficial outcome. Students linked to projects are benefited by exposure to new technology, scientific publications, higher degrees and possibly a good job. The University benefits by receiving funding for creative research; applying new technologies, providing exposure to trends and current practices; developing opportunities to validate research results and finally introducing placements for students. Industries benefit by having access to high-quality students; advanced view of new technology and solutions to specific problems in the field of exploration and mining. CRC-LEME achieves its objectives in raising regolith awareness, students training, scientific publications and promoting industrial growth. A number of case studies on successful collaborative research projects at the University of Adelaide will be discussed in detail. Examples are briefly described below.

Example 1; Newmont Metal Ltd, a subsidiary of Newmont Australia owns and manages base metal deposits of Golden Grove Belt which is located about 230 km east of Geraldton, Western Australia. The ore bodies are accessed by drill holes (shafts and declines). Some of the drill holes did not intersect mineralisation but were very close. This "*Mise a la Masse*" (MALM) or near miss situation could be avoided by using some geophysical methods. Applied potentials are proved to be useful in delineating conductive base metal mineralisation.

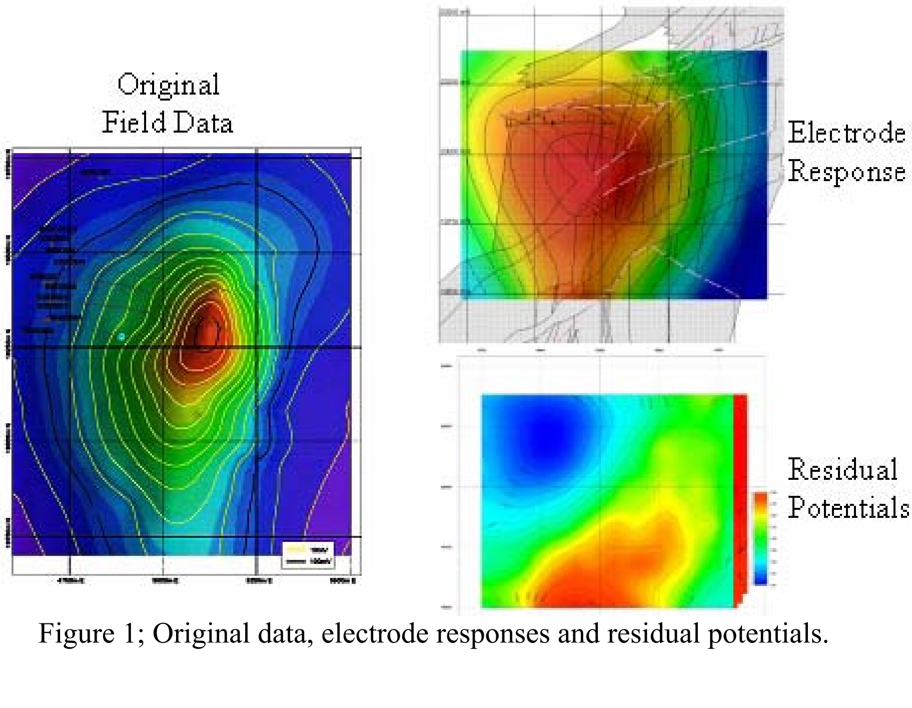


Figure 1; Original data, electrode responses and residual potentials.

In collaboration with Newmont Australia, one of the CRC-LEME Post Graduate students of the University of Adelaide is conducting studies on the feasibility of down-hole electrical potential to overcome such near miss situations. Figure 1 demonstrates the power of numerical modelling in resolving shallow and deep electrode effects, and producing residual potential, which reflects the underlying geology.

Example 2; 3-D full tensor gradiometery (FTG), or, high-resolution gravity gradiometry, is a multiple accelerometer system that records 5 independent tensor components of the gravity field. The result is an increased signal bandwidth that contains the full spectrum and allows identification and mapping of subtle density contrasts that arise from complex geological features. Individual tensor components allow mapping and identification of size, shape and thickness of target geology. FTG approach has greater resolution in the shallow section making it ideal for near surface mapping. Gradiometry essentially provides mass edge/lineament and axis definition, and is used to image both structural and lithological contacts generating density contrasts. Similarly, magnetic tensor measurements are also proved to be beneficial. One of the CRC-LEME funded PhD student is in the process of developing an inversion scheme for both gravity and magnetic gradient tensor data. Figure 2 shows the tensor responses (forward model as well as inversion) for a dyke. BHP Billington has provided FALCON^{TM} gravity tensor data testing this new inversion scheme.

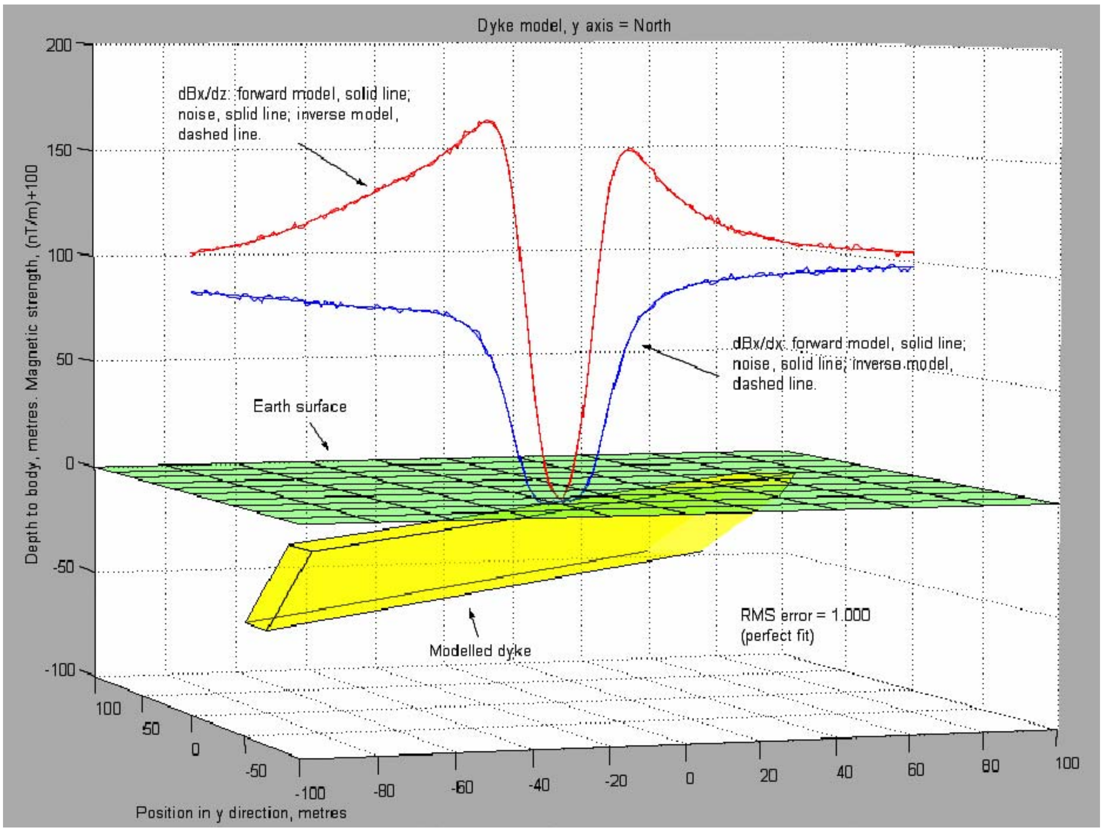


Figure 2, The magnetic tensor responses (both forward and inversion models) for a dyke. Depth to the top and bottom of the body are 10 m and 50 m respectively, width is 20 m, dip and strike are 45^{o}.

ATLASES, OPEN FILE REPORTS AND THEMATIC VOLUMES

I.D.M. Robertson
CRC LEME / CSIRO Exploration and Mining

Introduction
Research has little benefit unless it reaches those that use it. There has been considerable research on the Australian regolith by LEME and other organisations over the past two decades. Much has been provided, initially under confidentiality, as a large number of reports to sponsors. It forms a considerable resource that was largely untapped except by those that funded it, despite confidentiality having lapsed, apart from through published papers. CRC LEME strives to provide public domain access to this by releasing as much of the original material as possible (as Atlases and Open File Reports). These were made available as saleable items, advertised on the Web and at various conferences. LEME is also providing collections of case studies as three thematic volumes covering (a) the regolith expression of Australian ore systems, (b) regolith-landform evolution studies and (c) 3D regolith mapping in Australia. The case studies for these volumes are drawn not only from regolith researchers but also from their colleagues in industry.

Atlases
One of the chief difficulties in dealing with the regolith is recognising its components. There was a need for well-illustrated atlases of regolith materials and these were produced during early regolith research collaboration between CSIRO and AMIRA and since, under LEME. From their beginnings, they proved popular and many companies ordered extra copies for use in their district offices and in the field. This popularity continued with their release as Open File Reports; several hundred copies have been sold world wide.

The first atlases were products of major, multi-client Yilgarn Craton research projects and include: -

- Atlas of weathered rocks;
- Classification and atlas of regolith-landform mapping units;
- Genesis, classification and atlas of ferruginous materials, Yilgarn Craton.

The last of these has been completely restructured and updated very recently. Other atlases cover later research into transported overburden and into the regolith of NE Queensland: -

- Atlas of transported overburden,
- Atlas of ferruginous and siliceous materials, North Queensland.

Open File Reports
The first releases of the Open File Report Series covered the major regolith geochemistry collaborative research projects between CSIRO and AMIRA between 1987 and 1993. Reports generated by this were out of confidentiality by December 1994. They were released progressively from 1997 to 1999 and include: -

- Laterite geochemistry for detecting concealed mineral deposits (Project 240: 20 reports).
- Gold and associated elements in the regolith - dispersion processes and implications for exploration (Project 241: 40 reports)
- Geochemical exploration in complex lateritic environments of the Yilgarn Craton, Western Australia (Project 240A: 6 reports).

- Gold and associated elements in the regolith - dispersion processes and implications for exploration (Project 241A: 12 reports).

The first release comprised some 74 reports. Although each project had a project summary report, they contained a large volume of information that would be difficult to access by all but the most familiar with this work. Consequently, an index volume (Report 75) was produced in June 1999 that contained a searchable database (including abstracts) on CD. This CD also contains all digital data that had been provided on floppy discs with the various original reports, greatly extending the expected life of the data. Non-confidential but more recent LEME research was then released progressively. The next major release of previously confidential reports began in 2001 and covered: -

- Geochemical exploration for platinum group elements in weathered terrain (Project 252; 1 report),
- Geochemical exploration in areas of transported overburden, Yilgarn Craton and environs, Western Australia (Project 409; 26 reports).

These were also Yilgarn research. Again an index volume (Report 112) was prepared, capturing all new digital data but the searchable database covered these and all prior reports. The latest release brought out the last of the major projects that had come out of confidentiality: -

- Geochemical exploration in regolith dominated terrain, North Queensland (P417; 24 reports).

Another index report (Report 119) was provided for this research project but the accompanying database included all past reports. Other LEME reports continue to be released through the Open File System. Some of the most recent reports are available in .pdf format as web downloads. To date, 149 reports have been made available.

Thematic Volumes

Three thematic volumes are to be released as monographs. These are: -

- Regolith expression of Australian Ore Systems,
- Regolith-landscape evolution across Australia,
- 3D regolith mapping in Australia

Regolith expressions of Australian ore systems

This will be a systematic compilation of geochemical case histories and conceptual models covering the geological, geomorphological and environmental characteristics of individual deposits and occurrences and their expression in the regolith. These will be summmarized into a number of dispersion and exploration models to anticipate the surface expression of mineralization for a given area, 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 histories are from a wide range of published and unpublished sources, many from industry, and include hitherto unreleased exploration data.

It is intended that it will provide a substantially improved understanding of the effects of weathering and regolith cover on exploration methods, leading to reductions in the cost of exploration for concealed base metal, polymetallic and gold deposits in areas of residual and/or transported regolith. Case histories are being progressively released as .pdf files on the CRC LEME website until the final release of a hardcopy version.

Regolith-landscape evolution across Australia

This will be a compilation of regolith-landscape case studies and landscape evolution models. Generally, regions of outcropping bedrock and *in situ* regolith are well explored; the greatest potential lies beneath under-explored, substantial, largely transported cover. These 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 will also aid environmental research and management.

This volume will integrate the numerous 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 histories are being progressively released as .pdf files on the CRC LEME website.

3D regolith mapping in Australia

Regolith has a complex three-dimensional (3D) structure that results from geological setting and geomorphological evolution. This volume will discuss the 3D nature of regolith, and present data sources for mapping regolith in 3D. It will also discuss 3D regolith mapping methods and presentation. Case studies will be used as examples.