Advances in Regolith Research — A CRC LEME Perspective

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ABSTRACT

Recent research by CRC LEME from an Australian mineral exploration perspective, has focussed on regolith architecture and mechanisms of geochemical anomaly formation, within transported regolith. Methods have been developed for the rapid production of regolith-landform maps which is the starting point for understanding regolith architecture in the third dimension. Methods for development of 3D regolith models are less well advanced, and require integration of all available geological and geophysical datasets, but still with a heavy reliance on drill-hole information. The base of the transported regolith – the unconformity – remains the most important regolith boundary for geochemical sampling in transported regolith terrains. A new generation portable spectral logger, employing a broader spectrum can interpret important features from drill chips within the regolith. This allows internal architecture, redox fronts and the all-important interface to be objectively identified. Transported lateritic components can provide vectors to mineralisation in depositional regimes. Palaeomagnetic and new radiometric methods which date individual phases of the regolith provide evidence of different episodes, each characterised by different geochemical dispersion patterns in transported regolith. Along with lateritic residuum, calcrete is prime sampling medium. Calcrete is probably enriched in gold through physical and biological processes, rather than straight chemical processes. In South Australia, the lowermost calcrete layer buried within the depositional regime, especially where it lies directly over the silcrete layer at the buried interface, is the desired sampling medium. Certain gum trees, with deep roots in transported regolith have been shown to record anomalous values of gold and basemetals in leaves, twigs and bark. Anomalous metals in acid-sulfate soil seeps can also provide a window through sedimentary cover in respect of mineralisation in the basement. A number of Yilgarn occurrences of gold anomalies in transported cover, strongly infer hydromorphic and biological mobilisation of gold. This inference is supported by micro-analyses of regolith mineral hosts in hardpans and mottled sediments, which show gold and pathfinder elements prefer to reside in goethite and specific types of clay minerals. This creates anomalies in specific mineral phases. However the inference that that these are sites of mobile or labile metal ions remains enigmatic. Similarly there is inconclusive evidence that selective extractions will provide an anomaly not otherwise detected by conventional total dissolution methods. Hydrogeochemistry is a promising exploration tool for basemetal exploration. The importance of microbes in both the dissolution and precipitation of gold in the Australian regolith is demonstrated. We are on the verge of identifying the functional gene sequence of individual active microbes. A consideration of possible mechanisms for creating anomalies in soils above transported regolith, presents difficulties in facilitating upward movement of ions from the watertable to the surface. Perhaps the best avenues of research lies with surrogate soil gases, and biotic transfers.

THE IMPORTANCE OF REGOLITH

Regolith is the surficial blanket of material including weathered rock, sediments, soils and biota that forms by the natural processes of weathering, erosion, transport and deposition. It has complex architecture and may vary in thickness from a few centimetres to hundreds of metres. It hosts or hides valuable mineral deposits, we live on it, we grow our food in it, it is the foundation of many major engineering works, and much of our water supplies are stored in it. It underpins our economic, social and infrastructure systems.

Prolonged deep weathering over the last ten to 250 million years, on a predominantly stable continent of antiquity, has created a unique Australian regolith. An understanding of regolith architecture and the processes that act within it, are essential to address the challenges of sustainable economic development. Regolith science has important applications in the fields of mineral exploration and natural resource management. However the uniqueness of the Australian regolith means research has to be done here, and cannot be borrowed from anywhere else in the world.

EXPLORATION IN REGOLITH COVERED TERRAINS

Despite some impressive advances in exploration technology in the last two decades, geochemistry remains the prime direct sensor in the armoury of explorers. This is because many mineralisation styles have polar symmetry – that is pipe or sheet-like bodies of large vertical dimension. Inevitably they cut the Earth's surface and become disturbed in the regolith. However most surface expressions of mineralisation in residual regolith terrains have been identified and tested by explorers, many of them with considerable success. There remains now the subtle expression of near surface orebodies, and most importantly, the undiscovered mineralisation under sedimentary cover which presents a special challenge. Of even greater challenge, from the geochemical viewpoint, is the non-polar blind orebodies, that are encased in lithified rock.

Some of the exploration success of the last two decades, at least in Australia, relates to the work of LEME1. The Cooperative Research Centres (CRC) program is an Australian government initiative which aims to bring together separate research groups and industry to work on projects of national interest. The CRC for Landscape Evolution and Mineral Exploration (commonly known as LEME1) was set up in 1995 for a seven-year term. It produced outcomes that are universally regarded as truly outstanding, and their work is highly regarded in the exploration industry. Some of the achievements of LEME1 are:

- development of the new discipline of regolith geoscience;
- development of practical techniques for the identification and discrimination of geochemical anomalies in residual regolith material;
- development of regolith maps as an important dataset for mineral exploration; and
- an understanding of 3D geometry of metal distribution in the residual environment – particularly in regard to supergene gold.

LEME1 research concentrated on regolith descriptions, empirical geochemistry, and genetic models, in various geological regions. Perhaps the lasting legacy of LEME1, which incorporates earlier CSIRO work, is the lateritic-depletion-supergene model as shown in Figure 1. These achievements resulted in a paradigm shift in the use of regolith knowledge in mineral exploration. The second stage renewal is called Landscapes Environments and Mineral Exploration (LEME2). In the field of mineral exploration, LEME2 research has two priorities:

- understanding the dynamics of processes that determine the 3D architecture of transported regolith; and

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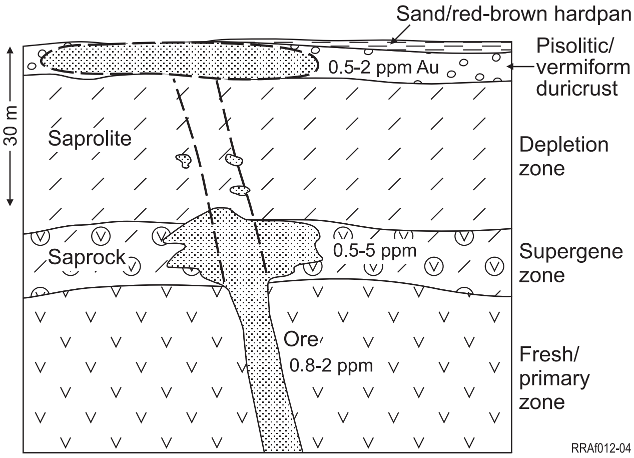


FIG 1 - Idealised profile of the lateritic-depletion-supergene model of gold distribution in typical Yilgarn regolith.

- understanding the processes of metal mobility so as to make geochemistry work through transported regolith.

This paper reviews some of the advances made by LEME in these two strategic areas.

REGOLITH-LANDFORM DATASETS

Regolith mapping is now widely practiced in Australia, and is increasingly being used as an aid to geochemical exploration. The mapping concepts have been developed by Colin Pain *et al* (Pain *et al*, 2001; Craig, 2001) of Geoscience Australia, and the methodology developed by Steve Hill of Adelaide University and Peter Buckley of New South Wales of Department of Mineral Resources. Regolith features are an integrated expression of geology, climate, landforms, geomorphic processes and landscape evolution, and generally have close empirical relationships with landforms. Thus, landforms become a surrogate for regolith and are the basis of mapping procedures.

Regolith-landform mapping units are shown on regolith maps as symbols depicted as alpha-numeric codes in the RTMAP system. The first two letters are capitalised and indicate the code for the regolith material type. The second two letters are lower case and indicate the landform associated with the regolith. Variation on the map symbol coding can be applied to thematic maps, such as the Kurnalpi-Kalgoorlie Special Regolith Landforms Map (Craig and Anand, 1993). Here the legend was customised according to interpreted regolith models (relict, erosional and depositional – the RED scheme). Despite conceptual limitations discussed by Anand and Paine (2002), the RED scheme provides a practical guide for geochemical sampling, and seems to work well for simple weathering cycles. Guidelines for regolith-landform mapping are documented by Pain *et al* (2001), Craig (2001) and Anand and Paine (2002).

Regolith-landform maps can be constructed by on-screen digitising using a number of datasets such as air photographs, digital terrain data, Landsat imagery, multi-channel radiometrics, hyperspectra, radar and aeromagnetics. These products are considered to be a proof-of-concept development, and it is now up to other mapping agencies and users to generate these products. In this respect it is important that they are produced in a rapid and systematic manner, so they can be treated as one of a number of spatial datasets within a GIS framework, of use to the mineral explorer.

Understanding the regolith setting is essential in planning geochemical surveys, and most importantly, in evaluating previous geochemical exploration surveys – an increasing amount of which is being released into pre-competitive information systems in digital format compatible with other GIS datasets. Regolith-landform maps are not intended to be end products in themselves, but they go some way to providing the two basic questions required by mineral explorers – is the near-surface material residual or transported, and how thick is the transported material? Regolith-landform maps are the starting point for understanding the third dimension.

THE THIRD DIMENSION

Existing models to date have been built around large drill-hole datasets. The Yandal project, one of the flagships of LEME1, included a 3D representation of residual and transported regolith over a major gold system in an Archaean greenstone belt (Anand, 2003). The model, shown in Figure 2, was based on a drill-hole database of over 70 000 holes, and high-resolution aeromagnetics which spectacularly identified the maghemite-defined palaeodrainages (Figure 3). These models which define the base of the transported regolith, weathering front, and the internal architecture, have genuine predictive value. Every important greenstone belt should have one. But they are difficult to construct even from good datasets for two reasons, inconsistencies of logging, and the difficulty in actually defining the interface.

A 3D model of the Harris Greenstone Belt has been constructed from a limited number of drill-holes and the magnetically modelled interface between mafic rocks and overlying lake sediments (Sheard and Robertson, 2004).

The low-frequency, broad-bandwidth, time-domain TEMPEST airborne EM system developed by Cooperative Research Centre for Australian Mineral Exploration Technologies (CRC AMET) has the promise to map regolith thickness and architecture, with a minimal amount of drill-hole calibration. Integration and modelling of semi-regional spatial datasets, built around interpretations of the AEM TEMPEST system, has important applications equally in mineral exploration and land management, as shown by the systems approach of the GILMORE project (Lawrie *et al*, 2000). In this project, subsurface regolith framework was mapped using a range of geophysical techniques – hyperspectral, magnetic, gradiometery, electromagnetic, ground penetrating radar, DEM laser scanning and electrical soundings.

In 2000, trial Tempest surveys at 150 m line spacing were conducted around Challenger and Tunkillia gold deposits in the Central Gawler Gold Province. These non-outcropping areas are characterised by sand dunes, calcrete, and complex patterns of transported and *in situ* regolith. Lane and Worrall (2002) successfully identified the regional long-wavelength conductors as palaeochannels, which were as much as 180 m deep, with basal sands saturated in saline water. However the CDI conductive units in the shallower regolith areas related to the saprolite-saprock interval, and therefore did not distinguish between transported and *in situ* regolith.

Anand (2003) developed maps showing thickness of transported cover for the Yandal belt, 30 per cent of which is covered by more than 5 m of sediments. This map provided a basis for the interpretation of regolith geochemistry. McQueen (2004) is developing prototype derivative maps in the Cobar-Girilambone area (Figure 4), showing residual areas, transported material less that 5 m thick, and areas deeper than 5 m. These 'go-maps' are created by fitting a form surface based on the extrapolation of the residual areas under major areas of transported regolith, guided by digital terrain and landform models, together with high-resolution aeromagnetics and drill-holes. Trials using nano-TEM (Davey *et al*, 2004) show significant contrasts between low resistive palaeochannel sediments and high resistive saprolite basement. This enables the production of depth-resistivity profiles that relate closely to the palaeochannel reconstructions from drill-hole sections. These

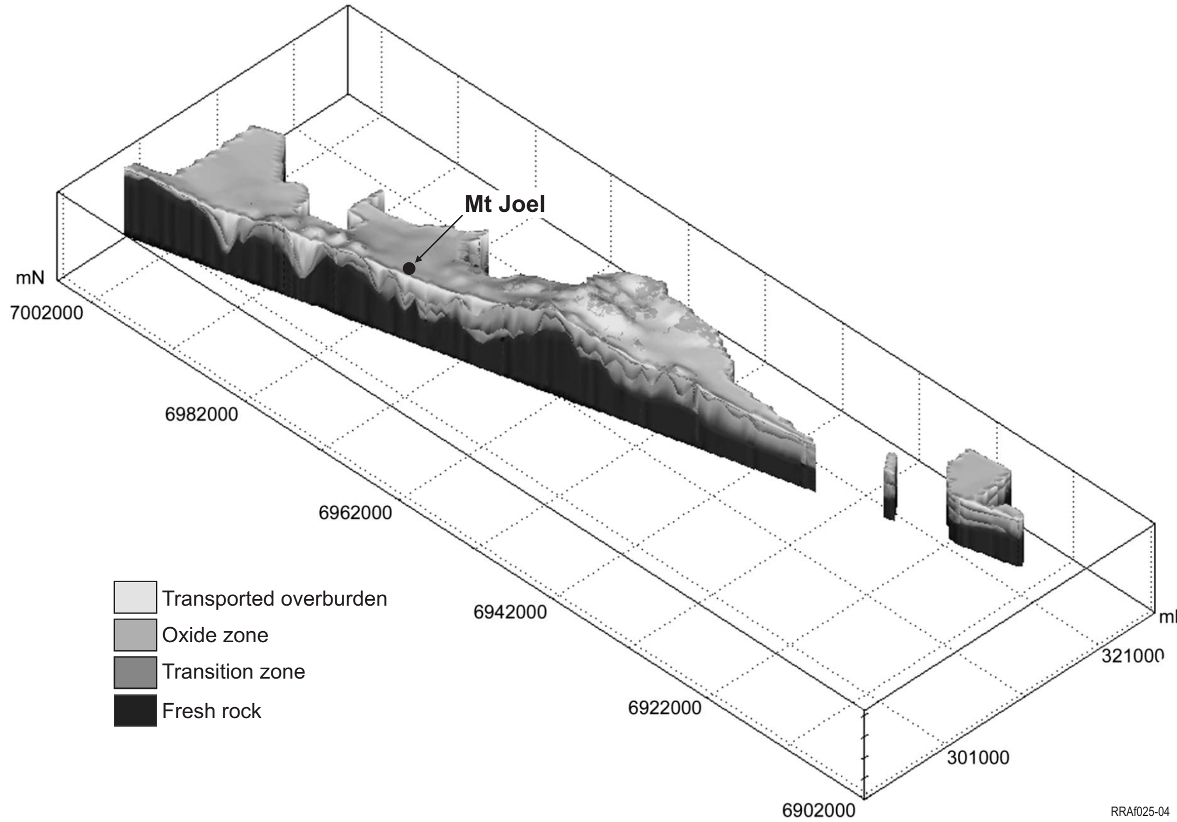


FIG 2 - 3D model of regolith over a 100 km strike length of the Yandal greenstone belt showing transported and oxide zones, based on a database of 70 000 drill-holes.

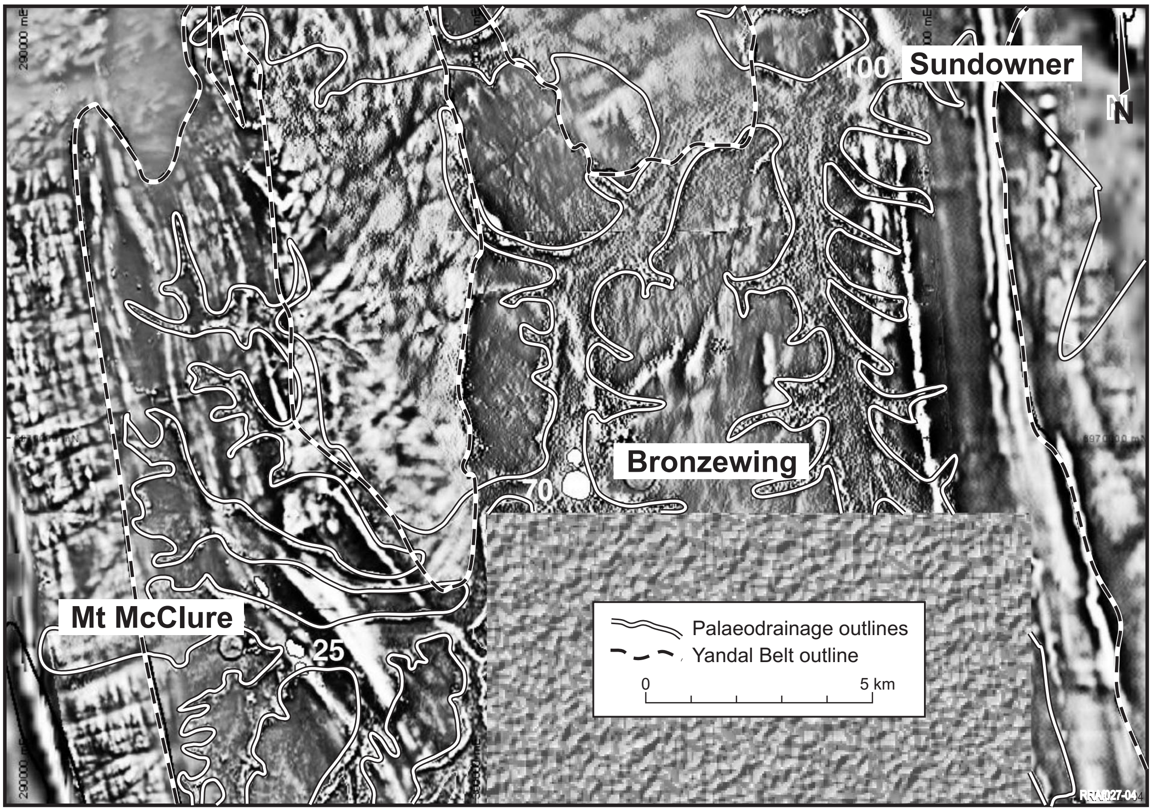


FIG 3 - Palaeodrainage lines interpreted from buried maghemite trails visible on first vertical derivative aeromagnetic imagery of the Mt McClure-Bronzwing-Sundower area of the Yandal greenstone belt.

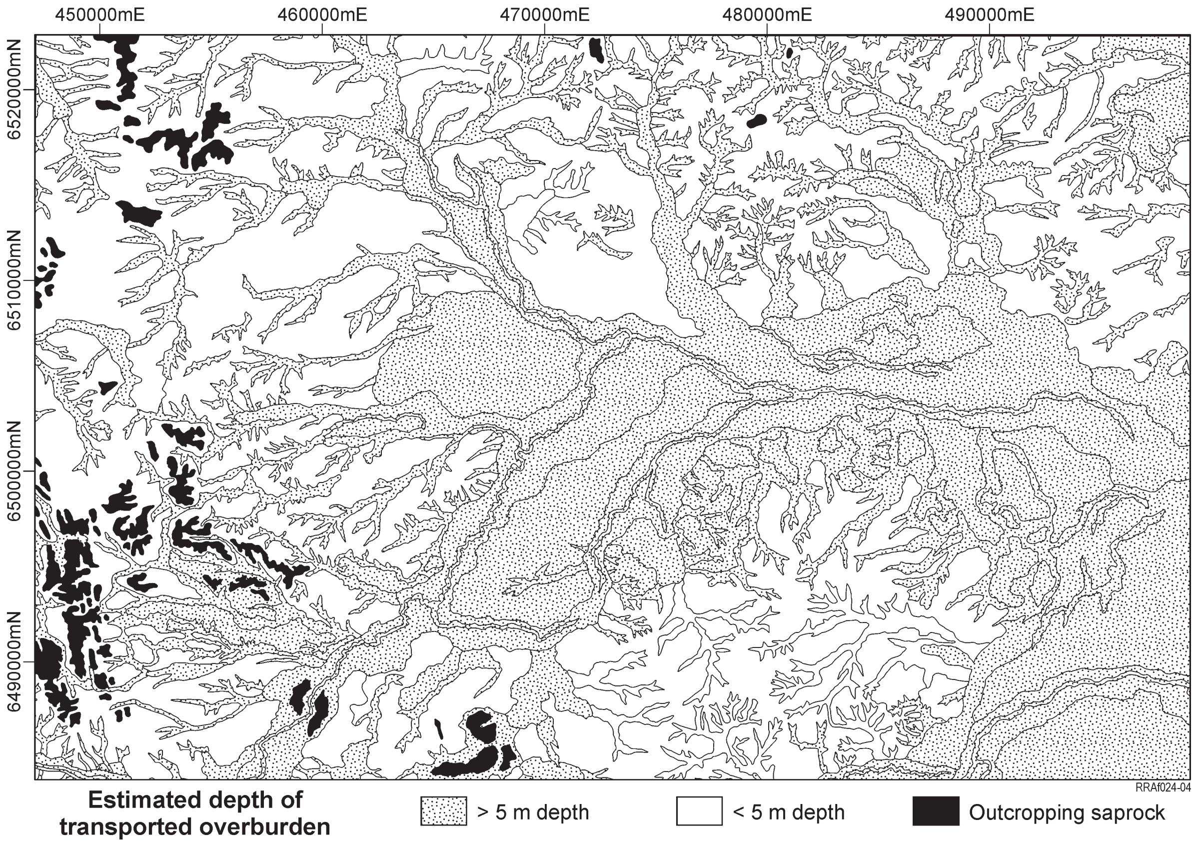


FIG 4 - Derivative depth-of-overburden map of the Cobar-Hermidale-Girilambone area showing areas of less than five and more than 5 m thickness of transported overburden, derived from regolith-landform maps, geophysical interpretation, and inverse-distance-weighting of drill-hole information; courtesy of Ken McQueen.

techniques require considerable more development before they can be considered accurate and rapidly produced tools for the mineral explorer.

A significant, but perhaps not surprising conclusion from these excursions into transported regolith models, is that despite the subdued landscapes across much of Australia, the palaeo-topography below the interface is quite rugged, and characterised by vigorous streams. It is this elusive form surface that will continue to host the best direct geochemical indicators of buried mineral systems.

OBJECTIVE AND AUTOMATIC REGOLITH LOGGING

During exploratory drilling programs, especially for gold, the challenge in regolith-covered terrains is to identify:

- the interface between transported and *in situ* regolith,
- the nature of the buried *in situ* regolith,
- the parent rock from which regolith has formed,
- potential depletion zones,
- the presence of ferruginous (redox) zones,
- alteration zones, and
- calcareous layers in the transported material.

The Yilgarn regolith is complex, with some indications of three-layered strato-regolith architecture (Anand and Paine, 2002), as shown in the generalised profile in Figure 5. But even when the general regional model has been elucidated, manual logging is slow, subjective, inconsistent, expensive, and fallible. In consequence, only a small proportion of potentially available information is obtained from many hundreds of kilometres of drilling undertaken annually by mineral explorers.

Portable spectroscopy is promising to be a reliable and rapid technique for identification of regolith and primary minerals. LEME is participating in the development of a new technology to make drill-chip logging more objective, efficient, and even automatic. It builds on the prototype spectral core logger (Hy-Logger), developed by CSIRO Mineral Mapping Technologies Group. Hy-Logger can scan as much as 1000 m of core per day, and the output is a mineralogical log coupled to a high-resolution digital image of the core. Spectra can be recorded at 1 cm intervals with mineralogy determined from spectral absorption features in the visible to shortwave infrared range (400 - 2300 nm).

In regard to regolith, it has long been known that the ubiquitous clay mineral *kaolinite,* has an inferior level of crystallinity in transported regolith than in the *in situ* regolith (Pontual and Merry, 1996). However, the transported – *in situ* interface may be less well defined where transported regolith directly overlies saprock or lower saprolite, because of low kaolinite crystallinity in saprock, and possible interference by smectite and muscovite/illite (Anand and Phang, unpublished data). Figure 6 shows a cross-section (A) based on lithological logging of a drill-hole section, compared to a grided image (B) of kaolinite crystallinity index, portrayed as a simulated cross-section. Lower crystallinity can be closely correlated with the unconformity at the base of the transported regolith. Similarly the water absorption peak of clays can also identify the transported *in situ* interface. Thus if Rotary Air Blast (RAB) chips are 'zapped' with a PIMA instrument, the important interface can be identified. PIMA records spectra in the limited range of 1300 - 2500 nm, and cannot always detect important mineral phases needed for understanding regolith framework.

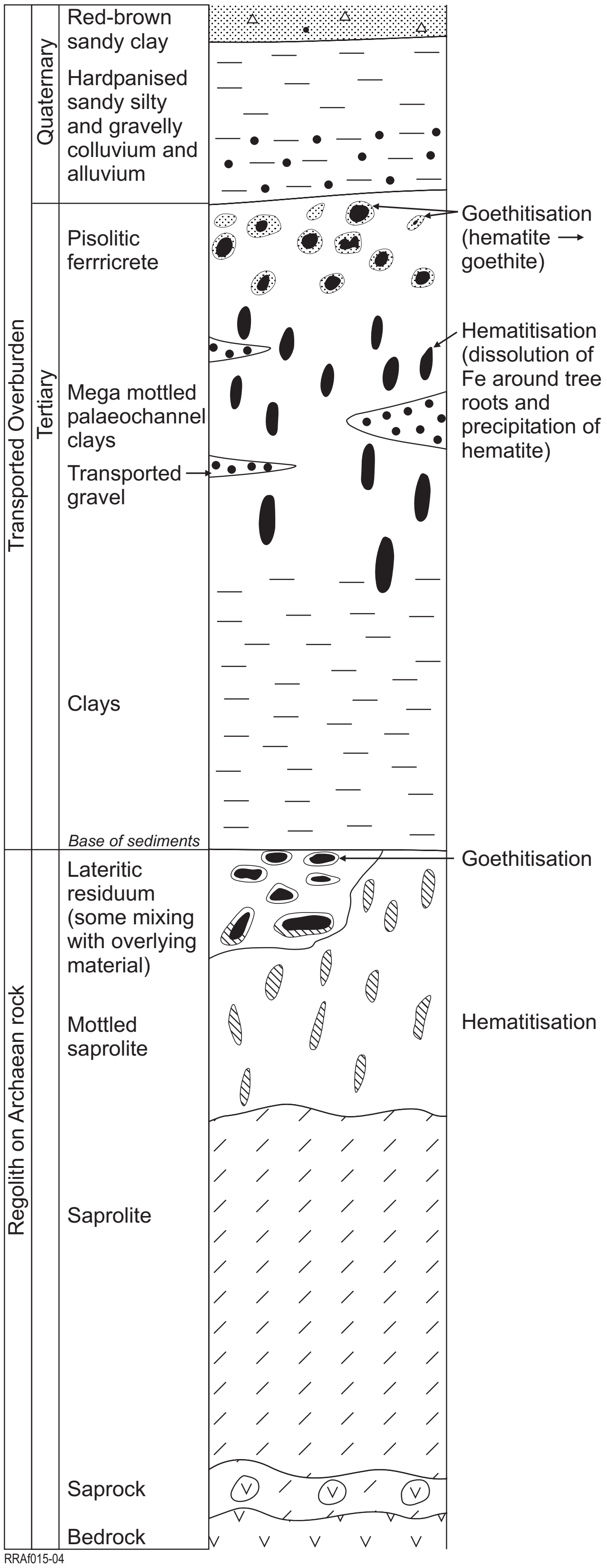


FIG 5 - Generalised regolith profile for the Yilgarn, showing a three-layered strato-regolith architecture, each with different degrees of ferruginisation, probably relating to episodic weathering events.

LEME has acquired a new spectral analytical device called the ASD FieldSpecPro Spectro-radiometer (Figure 7). This has a much wider spectral window covering the 350 - 2500 nm range, and is sensitive to clays, hydrous silicates, Fe oxides (eg goethite) and carbonates. Under certain environments these mineral phases are the preferred hosts for low-level metal signatures that disperse through the regolith from primary buried gold deposits. Goethite also defines redox fronts, which are prime sampling intervals. The technique does not recognise feldspars, quartz, sulfides and other non-hydrous minerals present in many rocks.

The ASD device is portable, and can be taken to the drill site, or the chip store. Depending on the feeding mechanism, it can read 600 - 700 samples per day. The current task is to write special software to convert spectral absorption data into semi-quantitative mineralogical interpretations. This information can then be imported into standard exploration data bases, along with other geochemical and drill-hole data where it can be plotted directly onto cross-sections. This is another theme in the rapid and automatic generation of 3D models.

LATERITIC RESIDUUM AND LAG SAMPLING

The ferruginous upper part of a weathering profile may be residuum, ferruginised sediment (ferricrete), ferruginised saprolite, or a mixture of these, to name some of the most common situations (Figure 5). Focus has been where the ferruginous upper part is a residuum. Lateritic residuum commonly evolves by partial collapse, involving some lateral movement, over say 10 - 50 m, following chemical wasting, as well as introduction and mixing of exotic material. It may be exposed or buried at depth.

The use of lateritic residuum geochemistry for mineral exploration in Western Australia was first recognised by Mazzuchelli and James (1966), and perfected in an operational sense by Smith and Perdrix (1983). The outstanding success of this method as applied to lateritic residuum is documented by Anand (2001) and Cornelius and other (2001). Residual accumulation, combined with hydromorphic and mechanical dispersion, results in widespread dispersion haloes related to concealed ore deposits. It provides an easily-collected sampling medium with the ability to scavenge and concentrate gold and pathfinder elements even where adjacent parts of the profile are depleted or transported. The haloes tend to be large, typically 100 to 400 times larger in area than the deposits from which they have been derived (Smith *et al*, 2000). Sampling of lateritic residuum can, thus, be useful for reconnaissance surveys through to early stages of prospect evaluation.

The recognition of buried lateritic residuum provides a useful sampling medium during exploration and was important in the discovery of Bronzewing (Wright *et al*, 1999). Studies around Mt McClure in the early 1990s (Anand *et al*, 1993) recognised buried lateritic residuum at some depth, and extrapolated the model further east in the depositional regime that is now Bronzewing (Anand, 2003). Buried residuum is now known from many other parts of the Yilgarn Craton, and criteria have been established to distinguish this from transported gravel and ferricrete (Anand, 2001). Stratigraphic drilling is necessary to establish whether the overburden overlies a buried lateritic residuum or an erosion surface cut into saprolite.

Cornelius (2004) is now looking at extending the application of ferruginous materials into transported and depositional terrains. Several case studies in the Yilgarn Craton have shown the continuity of multi-element mineralisation signatures of transported ferruginous gravels derived by degradation and dispersion from residual duricrusts. For example, at Jaguar Cu-Zn VMS deposit, lateritic gravels have signatures characteristic of both the Teutonic Cu-Zn deposit four kilometres up-drainage, and the underlying Jaguar deposit (Cornelius, 2004).

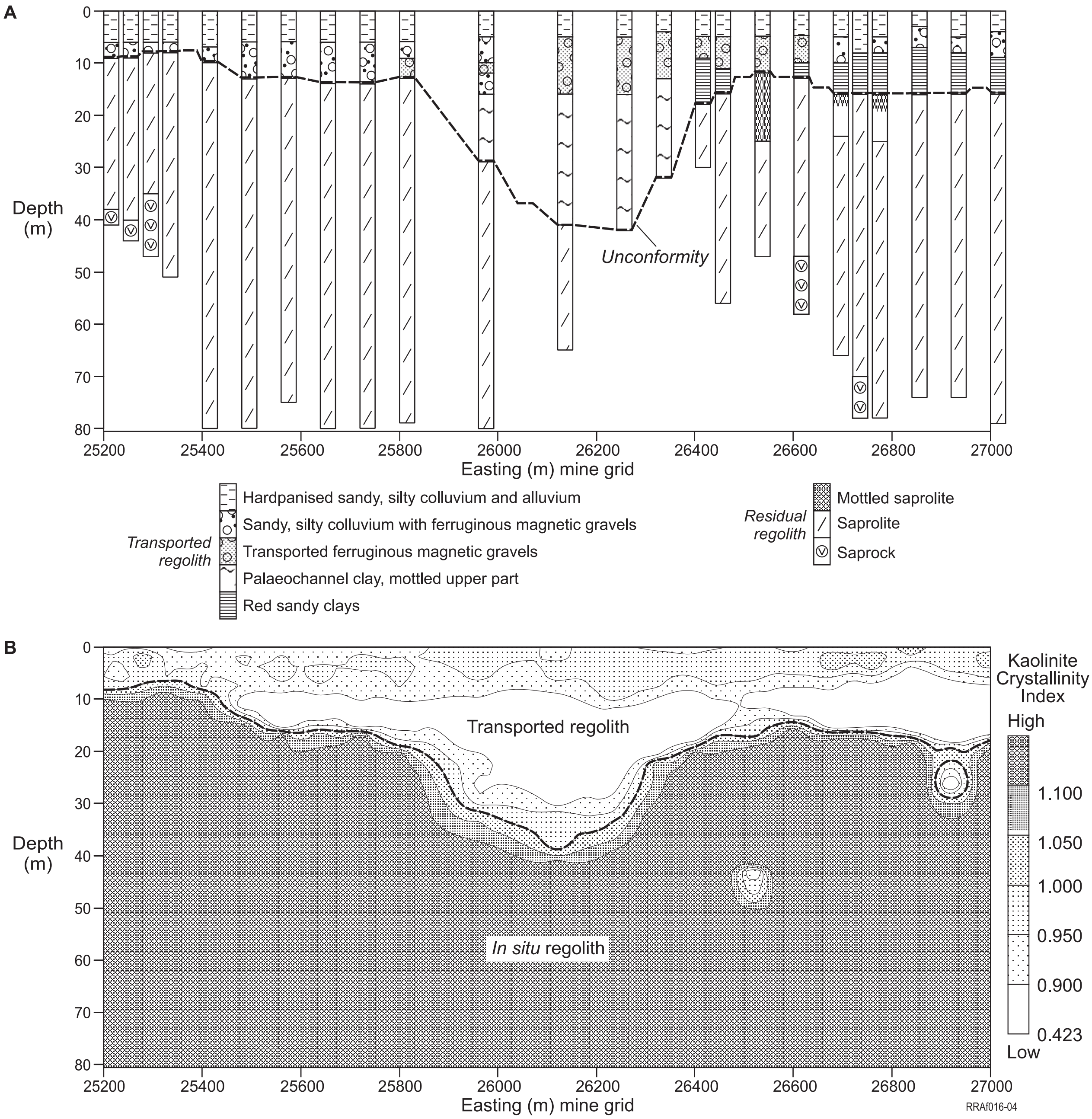


FIG 6 - Cross-section (**A**) based on lithological logging of drill-holes, compared to a grided image, (**B**) of kaolinite crystallinity index, portrayed as a simulated cross-section. Lower crystallinity can be closely correlated with the unconformity at the base of the transported regolith.

The interpretation of lateritic geochemical datasets using multi-variate discriminate analysis, in the context of current topography, palaeo-topography and dispersion directions can provide vectors to mineralisation under transported terrains. CSIRO/LEME and GSWA have commenced a program of regional lateritic residuum/lag sampling over the entire Yilgarn Craton, aiming for a 9 km triangular sampling pattern. The considerable number of samples already in the residual databases will be included in the new database. With the benefit of digital terrain and regolith models, the successful techniques of lateritic residuum/lag sampling can be of significant benefit for surface exploration. The chemical changes that residual ferruginous nodules undergo during redistribution into lags is not fully understood, but in the Yilgarn the original signatures seem to still be recognised using multivariate analysis, over distances of tens of kilometres.

McQueen (2004) has examined the partitioning of ore elements and pathfinder elements in residual and transported lags related to Cu-Au systems in the Cobar Mineral Field, In the *in situ* regolith, goethite is an important host for Zn, Cu, As and to a lesser extent Pb, Bi and Sb. Hematite is the predominant host for Cu. In goethite-dominant near-surface caps there is a strong correlation of As and Zn with Fe, whereas in hematite-dominant phases there is a strong correlation of Cu with Fe. However in the redistributed lags there is a progressive conversion of goethite-hematite phases to hematite-maghemite phases. At the same time there is an increasing correlation of Pb, As, Sb, Bi, Ba, Cr and Th with Fe, as these pathfinder elements increase in the mature lags. Significantly Zn, Cu and Au do not increase in the mature lags. Thus the actual ore elements fail to report, and the relatively immobile Pb once fixed into hematite can become widely dispersed by mechanical methods. These results indicate that pathfinder elements should be normalised against Fe for their correct interpretation.

ASD Field Spec Pro Spectroradiometer

FIG 7 - Portable ASD spectro-radiometer producing automatic mineralogical analysis from rapidly read VSWIR spectra.

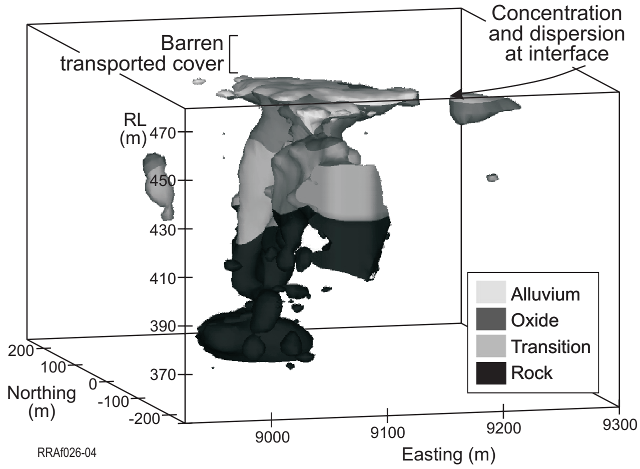


FIG 8 - 3D image of gold distribution above the 50 ppb level for the Mt Joel gold deposit, showing a spread of elevated gold values at the interface immediately below the transported regolith; courtesy of David Gray, CSIRO Exploration and Mining.

INTERFACE SAMPLING

A feature of all reconstructions of the palaeo-surfaces below transported regolith is its considerable relief and ruggedness. It is therefore not surprising that the interface between the 'basement' – collectively including saprock, saprolite and lateritic residuum – and the first overlying transported sediments, remains the prime sampling surface, of equal ranking with lateritic residuum and calcrete on the surface. The problem of course is that it may be buried below tens of metres of cover. The saprolite-transported interface may incorporate residual or partly transported palaeosols, with greater scope for mechanical and hydromorphic dispersion, during and after sedimentation. The material on the interface can include diverse materials from a variety of sources, depending on the degree of palaeo-exhumation of the palaeo-weathering profile. As well as containing metals in gossan particles, free particles (placer gold), and anomalous 'fossil' lags, the ferruginised material may act as sorption traps for hydromorphic gold and other metals. Experience has shown that, although the interface anomalies are of low contrast, their sizes are significantly greater than those in the top of the basement. Butt *et al* (2000), Gray *et al*, 2001, Anand (2001), Robertson (2001), Robertson *et al* (2001) and Anand (2003) summarises numerous examples of striking gold anomalies in the immediate basal sediment in many areas (eg Calista, Golden Delicious, Mt Joel, Bronzewing, Lawlers, Stellar, Quasar (Mt Magnet) and Harmony (Peak Hill) gold deposits). This is illustrated on a 3D image of the 50 ppb gold enveloping surface for the Mt Joel gold deposit (Figure 8). This shows a spread of elevated gold values on the interface, at the base of the first transported layer. In this case, the gold anomalies are at the base of the transported cover (itself composed of lateritic waste material) at the unconformity with the truncated saprolith, at depths of 40 - 60 m.

Modern micro-analytical techniques now allow the diagnosis of carefully selected individual grains from the interface. This can reveal not only the proximity but the style of mineralisation. For example Smith (2004) can recognise the textural and compositional characteristics of the Golden Grove Gossan Hill Cu-Zn-Au VMS deposit in clasts, lateritic nodules and other detrital grains in the basal conglomerate.

This reinforces the importance of precisely defining the palaeo-surface, and more importantly the loci of the buried thalwegs of the earliest palaeodrainages.

DATING EVENTS

Geological evidence indicated that most of the Australian continent has experienced extensive subaerial weathering over long periods with evidence of superimposition of effects. From a mineral exploration viewpoint, it is important to know if the weathering processes, and hence anomaly formation, is an expression of continuous or episodic weathering. The LEME geochronology project involves both technique development and dating of events.

The basic geochronological framework of the Australian regolith is provided by palaeomagnetic dating (Pillans, 2004). This is done (Figure 9) by plotting the pole of the chemical remnant magnetism (CRM) of secondary mineral phases on the trace of palaeomagnetic poles of known age – commonly known as the Australian apparent polar wander path (Schmidt and Clark, 2000). Most useful is the phase change from goethite – which has no CRM – to hematite which does. Pillans (2004) records palaeomagnetic determinations from some 30 sites (mostly mine sites) throughout Australia, with a focus on the Yilgarn Craton. There is a distinct bi-modality appearing in this data, pointing to events around 10 Ma and 50 - 60 Ma, with some evidence of Mesozoic or even earlier weathering, as shown in Figure 8. At around 60 Ma, the climate was wet, cool temperate and the vegetation was dominated by conifer forests and woodlands. The second cluster at late Tertiary (10 Ma) represents climates that were seasonally drier (though rainfall was still higher than present) and warmer, with consequent flora changes, as southern Australia drifted to lower latitudes. Thus, the two major episodes of hematite formation in the Tertiary occurred under differing bioclimatic regimes.

This spread of palaeomagnetic ages is revealed at Lancefield gold pit (WA), where saprolite (Archaean basement) is overlain by Permian fluvio-glacials, Tertiary palaeochannel clays, and Quaternary alluvium (Anand *et al*, 2004). The Permian and Tertiary sediments each show different suites of hydromorphic metal dispersion, particularly Au, As, Cu and Zn. It is likely that each suite represents a different weathering and hydromorphic event. If this is so, it emphasises the importance of dating the regolithic events so that the more favourable sampling media – either bulk sample or mineral phase – can be identified.

More precise isotopic techniques are being developed in LEME, notwithstanding the problems of finding suitable minerals, and the uncertainties regarding closed systems.

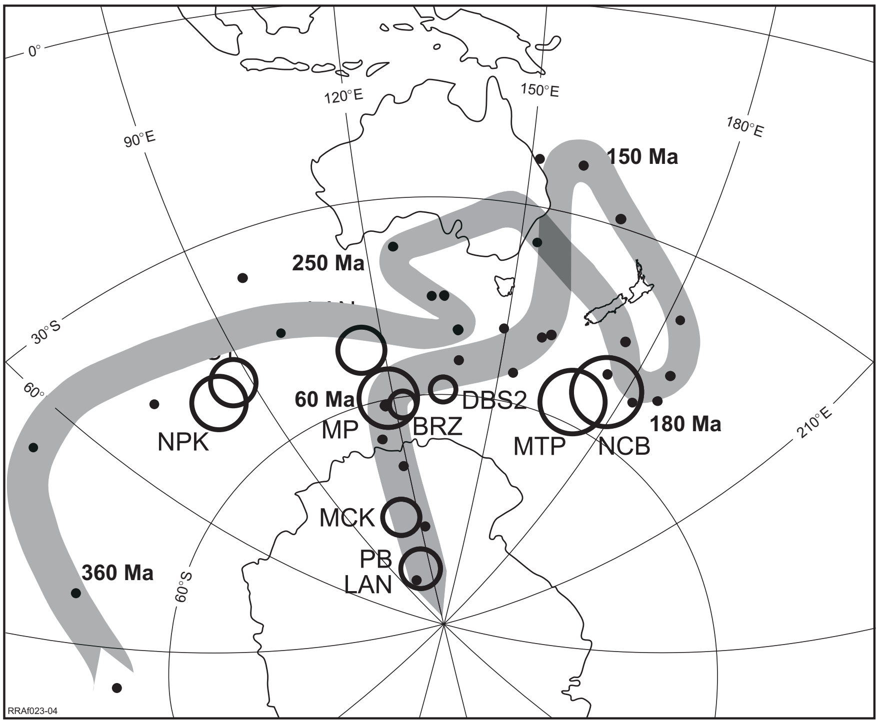


FIG 9 - Australian Apparent Polar Wander Curve from 360 Ma to present (Schmidt and Clark, 2000) with some representative palaeomagnetic poles (95 per cent confidence circles) from weathered regoliths from some Australian mineral deposits (Pillans, 2004). PB = Perth Basin (Schmidt and Embleton, 1976), MCK = MacKinnons (McQueen *et al*, 2002), MP = Morney Profile (Idnurm and Senior, 1978), BRZ = Bronzwing (Anand and Paine, 2002), DBS = Bead bullock soak (Pillans and Idnurm, unpublished), MTP = Mt Percy (Pillans and Bateman, 2000), NCB = New Cobar (McQueen *et al*, 2002), LAN = Lancefield (Pillans, unpublished) NPK = North Parkes (Pillans *et al*, 1999).

Pidgeon *et al* (in press) are developing the (U+Th)/^{4}He method on lateritic duricrust from the Darling Range, and have produced a date around 10 Ma, that is compatible with the youngest age of lateritic duricrust in the Yilgarn, recorded by palaeomagnetism. Other developments are U-Pb and U-series of goethite by Alex Nemchin (Curtin University), SHRIMP dating of opal by Susan Symons (PhD student, Curtin University), and U-Pb dating of anatase in silcrete by Martin Smith (PhD student, ANU). The challenge with these novel applications is the low levels of uranium in residual material.

Documenting the timing of regolith-forming events goes further that 'good-to-know' science. In Australia there is debate whether the 'lateritisation' process is episodic or continuous (Taylor and Shirtliff, 2003) on the continental scale. The answer to this has a bearing on modelling the distribution of gold in deeply weathered terrains. The work in the Yilgarn Craton (Anand and Paine, 2002) indicates the presence of possibly three extensive strato-regolithic units (Figure 5) – the lateritic duricrust (possibly 60 Ma), an intermediate ferruginous transported unit of red clay and grits, and the 'Wiluna Hardpan' (possibly 0.76 Ma). Each of these strato-regolith units has their own regolith gold signatures, which variously can record proximal, distal or spurious geochemical signatures.

CALCRETE (PEDOGENIC CARBONATES)

Calcrete geochemistry, along with lateritic residuum sampling, is one of the most effective techniques for gold exploration in deeply weathered terrains. A close correlation between calcium and gold was first demonstrated in 1989 from calcareous soils in a residual environment, over the Bounty gold deposit in the Yilgarn Craton by Lintern (1999). No other ore-related elements show this association; indeed most are diluted by the carbonates.

The presence of calcrete in both residual and transported regolith is a common feature in many semi-arid regions, whether these are juvenile terrains having soils developed from fresh rocks, or ancient landscapes with deep regolith. Calcrete forms by the cementation, displacive or replacive introduction of predominantly calcium carbonate, into the vadose zone (above the watertable), where it may occur as friable powders, nodules or massive layer-like accumulations. It forms by precipitation from near-saturated calcium carbonate solutions by processes that may include evaporation, evapotranspiration, degassing of CO_2, or bacterial consumption of CO_2. Gold content may be due to trapped detrital particles inherited from the host material, or it may be due to the stabilisation of hydromorphic gold, during or after the formation of calcrete. The mechanism is still uncertain.

Calcrete is the favoured medium for gold in South Australia, to the same extent as lateritic residuum in Western Australia. Whereas in the Yilgarn craton, calcrete sampling is generally used for in early prospect identification, in the Gawler Craton it is employed at all stages of exploration, including target definition. Calcrete geochemistry is credited with the discovery of Challenger and Barnes deposits in the Gawler Craton. However it is a fallible technique. There are examples of gold not reporting in calcrete above known mineralisation, and examples of large dispersed low-level anomalies that do not obviously pin point gold in the basement. To better understand the process of anomaly formation in calcrete, LEME is researching regolith relationships, micro-morphology of gold, and role of biota.

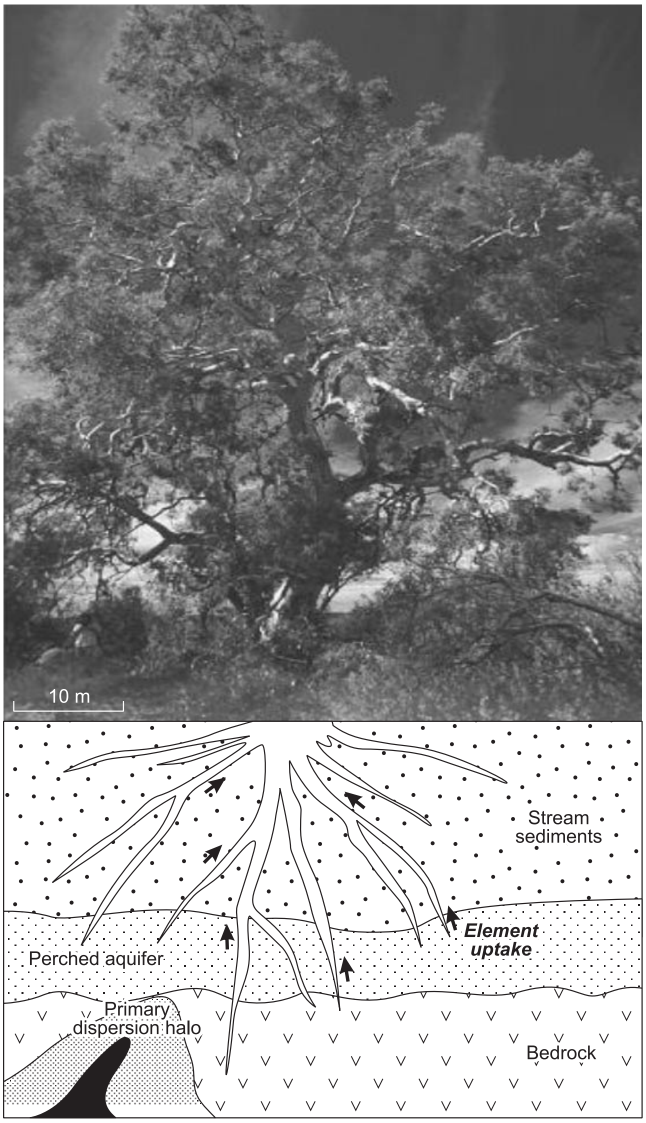
Lintern (2004) studied the regolith profiles and 3D distributions of gold at 19 mineralised sites in South Australia. These sites had different degrees of preservation of the residual profile, and different thicknesses of transported regolith. The model profile consists of saprolite capped by residual silcrete, commonly overlain by transported alluvial, colluvial and aeolian material. Calcrete has intergrown within these upper materials, generally within the top 5 m. But the most important is that layer developed just above the 'interface' silcrete, which forms a permeability barrier. Major conclusions are:

- anomalous gold in calcrete registers well with underlying gold mineralisation where calcrete is formed immediately above residual silcrete, irrespective of the extent of current exhumation or burial;
- where thickness of transported regolith is greater than 5 m, basement gold signatures are totally suppressed in near-surface calcrete;
- highly anomalous concentrations of gold (hundreds of ppb) may occur in calcrete at the interface; and
- in erosional and depositional regimes, gold may be dispersed laterally in both degraded silcrete and younger calcrete, thus providing false anomalies.

Current studies are underway to investigate the micro-morphology of non-detrital gold particles using x-ray photon microscopy, secondary ion mass spectrometery, and electron beam technologies. This should help to provide evidence on precipitation mechanisms. Experience with partial leach suggests that calcrete has a high proportion of weakly bound, easily soluble gold, indicative of a hydromorphic origin. For example, Gray *et al* (1990) note significant dissolution in iodide and deionised water, indicating a chemical origin. 'Chemical' gold may accumulate in calcrete because like Ca, it behaves like an evaporite. Microbes may play dual roles, firstly by providing ligands to dissolve and mobilise gold, and secondly to provide nucleation sites on their surfaces for gold precipitation.

BIOGEOCHEMISTRY

Research under the direction of Steve Hill (Adelaide University) and Ravi Anand is revisiting the vexed question of biogeochemical prospecting. Hulme (2003) at Adelaide University is focussing on river red gums (*E camaldulensis*) which present an ideal sampling medium because of their widespread occurrence in transported regolith in arid environments, their confinement to watercourses, and their extensive tap roots. Orientation sites have been set up in the Curnamona Craton, on the basis of proximity of various styles of mineralisation. Multi-element analyses have been done on leaves, twigs and bark, with repeat sampling to test for seasonal variation (Figure 10). Significantly, two sites over gold mineralisation had detectable gold with 0.6 - 1.4 ppb Au in twigs, and 0.2 - 0.4 ppb Au in leaves. Significant levels of As, Cu and Zn report in leaves and twigs. All other elements in the suite of 24 were below detection. These preliminary results offer promise of a rapid sampling medium in areas of transported arid regolith.



Tibooburra (highly prospective regolith-hosted Au)

	Au ppb (.3)	As ppm (.05)	Pb ppm (2)	Zn ppm (1)	Cu ppm (1)
Leaves	0.39	0.14	*	28.6	6.8
Twigs	1.4	0.04	*	15.4	5.2
bark	*	*	*	12.3	2

Flying Doctor (Ag-Pb-Zn mineralisation)

	Au ppb (.3)	As ppm (.05)	Pb ppm (2)	Zn ppm (1)	Cu ppm (1)
Leaves	*	0.051	*	28	7.6
Twigs	*	*	*	19.2	8.2
bark	*	*	*	22	2

Teilta Unknown (possible Cu-Au/Ag-Pb-Zn mineralisation)

	Au ppb (.3)	As ppm (.05)	Pb ppm (2)	Zn ppm (1)	Cu ppm (1)
Leaves	*	0.09	*	19.4	9
Twigs	0.62	0.04	*	19	12
bark	0.39	*	*	5	2

* = below detection limit

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FIG 10 - Element uptake through transported regolith via the roots of *E Camamdulensis* and reporting as anomalous values of Au, As, Pb, Zn and Cu in various parts of the tree, above some mineral prospects; courtesy of Karen Hulme, Adelaide University.

Similarly, Ravi Anand with assistance of Professor Pauline Grierson (University of WA) is conducting biogeochemical surveys over basemetal and gold mineralisation in the Yilgarn Craton. Phyllodes, branch wood, bark, litter and roots of several plant species are being analysed. Many pits were excavated to collect soil samples and plant roots for microbiological studies.

ANOMALIES FROM DEEP ACID-SULFATE SOIL SEEPS

Research on the environmental geochemistry of acid-sulfate soils (ASS) has spin-offs for mineral exploration. ASS seeps develop in advance of a rising watertable as a result of land clearing, which brings salt and other solutes to the surface. These seeps present a potential window on blind mineral deposits.

In the Mt Lofty area Skwarnecki *et al* (2002) developed a model to account for high metal discharges. In areas with sulfide-rich basement rocks, rising ground waters can be rich in sulfate, and have elevated As, Pb and Zn. These become further concentrated by evaporative transpiration. In soils of high organic carbon in waterlogged conditions, cyanobacteria reduce these sulfates, forming secondary framboidal pyrite and micro-filamentous authigenic sphalerite in soils near the surface (Figure 11). With further rise of the watertable these re-oxidise and produce scums and gels of Al and Fe hydroxy minerals (eg ferrihydrite) in discharge areas, with high element levels. This pilot study identified a multitude of anomalies, many of which correlate with known mineralisation, and some of which are new unexplained anomalies. This new sampling medium has potential to produce enhanced anomalies of large footprint, drawn from a wider basement substrate.

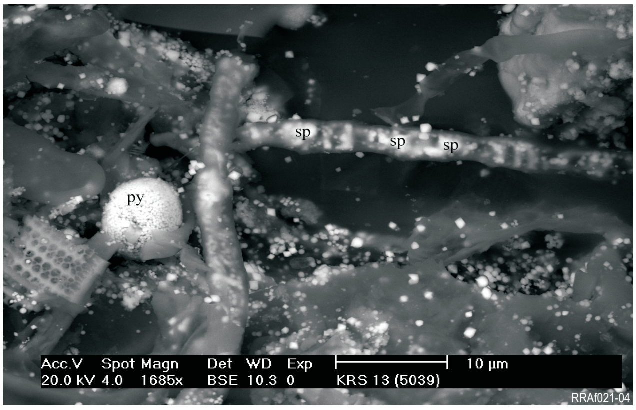

FIG 11 - Secondary framboidal pyrite and micro-filamentous authigenic sphalerite in soils near the surface above acid-sulfate seeps in the Lofty Ranges. Such occurrences can provide leads to buried mineralisation at depth; courtesy of Rob Fitzpatrick CSIRO Land and Water.

Baker and Fitzpatrick (2003) have used lead isotopes to model the interaction of groundwater with bedrock mineralisation, in the vicinity of ASS seeps. Lead isotope signatures from mineralised basement are shown to extend laterally for about one kilometre in groundwaters. The lessons for exploration are that soils in ASS seeps are good sampling points to detect blind mineralisation, but the bulls-eye anomalies are not necessarily point-source with respect to mineralisation.

GEOCHEMICAL ANOMALIES IN TRANSPORTED MEDIA

Experience in the Yilgarn, North Queensland and Gawler goldfields, suggests that sampling in transported overburden of more than five metres has little predictive value in gold exploration (Butt *et al*, 2000; Anand *et al*, 2002; Anand, 2003). Thus sampling cannot distinguish the negative result (nothing there) from the null case (not adequately tested). Yet there are many examples of strong near-surface gold anomalies in 5 - 25 m of transported material above known mineralisation – for example Matt Dam, Callista, Bronzwing, Deep South, Lawlers (Madden *et al*, 1998; Anand and Williamson, 2000; Anand, 2001), Quasar, Stellar (Robertson *et al*, 2001), Steinway, Safari Bore, Argo, Apollo, Higginsville (Lintern, 2001).

Some of these cases are best explained by mechanical redistribution of gold from residual environments. However there are a few instances (for example Deep South at Mt Gibson, Safari Bore near Lake Raeside, and Matt Dam prospect near Ora Banda) where physical mixing is not obvious, and hydromorphic or biogenic dispersion is suspected, with possible sorption of gold and pathfinder elements onto clays, goethite, manganese oxides and carbonates.

Tonui *et al* (2003) note elevated levels of As, Ni, Cu and Co in thick transported clays above the Tunderdome deposit in the Broken Hill region. Keeling *et al* (2003) describe evidence of upward capillary movement of copper-bearing solutions into transported clays 5 - 15 m thick, above the Poona (Moonta SA) Cu–Au deposit. Attacamite nodules developed in alunite-halloysite clays are interpreted to form by recent acid-sulfate weathering of depositional kaolinite/illite/smectite clays. This only happens where there is direct contact between transported clay and underlying weathered porphyry.

Many of these case histories remain inconclusive in terms of process, and require further detailed research. To evaluate the hypotheses of metal mobility in transported regolith we need to understand the nature of the sites of metals in regolith mineral phases.

MINERAL HOSTS FOR GOLD AND TRACE ELEMENTS

During weathering of mineral deposits, trace metals including gold, are displaced from their original host minerals, and after dispersion become fixed in newly formed secondary mineral hosts in the regolith. Of most interest are clay minerals, and iron and manganese hydroxides. Such mineral phases interact geochemically with weathering fluids, and so have the potential to trap trace elements, which creates an anomaly in a specific mineral phase. The new range of modern analytical instruments enables us to better understand the formation of geochemical anomalies in the regolith. Micro-mineral mapping combined with *in situ* geochemical analyses at the micron scale, points to new techniques of anomaly detection. The Mineral Hosts program at LEME employs electron microprobe, micro-RAMAN, electron back-scattered diffraction and now recently the laser ablation ICP-MS. The latter instrument uses a focused laser beam, allowing a full quantitative chemical analysis of virtually all elements, in an area of 20 - 30 microns diameter. The advent of LA-ICPMS and a new transmission electron microscope with full analytical facility is enabling high quality trace element analysis on much smaller solid samples than has hitherto been possible (Figure 12). Quantitative analysis is achieved either by normalising intensities of the observed peaks to the weight of the sample, or to an internal standard. Le Gleuher (2003) and references therein, provide a full description of the LA-ICPMS technique and the development of its application to regolith samples.

We will also be using the new Australian synchrotron for characterisation of the adsorption of elements on specific minerals. These will be the first *in situ* experiments to characterise the true situation of metals in weathering products above a mineral deposit, and crucially, identify whether they were incorporated as the weathering phases grew, or were

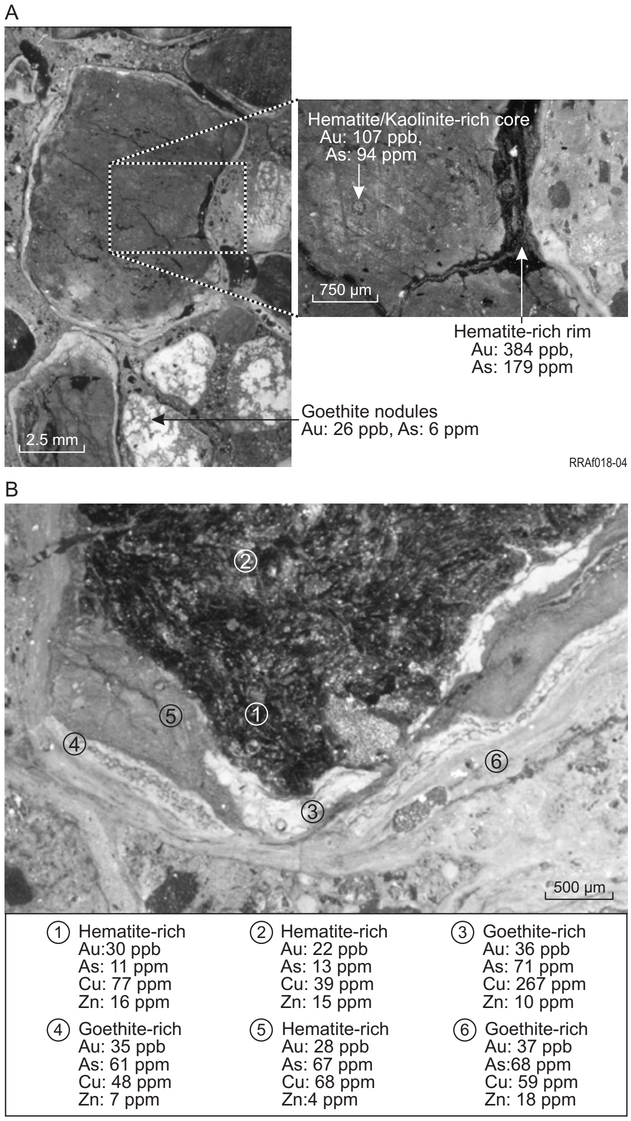

FIG 12 - Example of micro mineral mapping by LA-ICPMS. This technique is a powerful *in situ* method of identifying the sites of Au and other element distribution in regolith minerals; courtesy of Rob Hough CSIRO Exploration and Mining.

hydromorphically dispersed later. It will also indicate in what form the metals were transported – as ions, complexes or colloids. These fundamental issues need to be addressed to enable a bottom-up approach in elucidating how metal anomalies form in the regolith.

One important research project addresses the trace element content of the certain diagnostic clay minerals (kaolinite, interstratified clay minerals), iron oxides, phosphates, as well as amorphous materials. These investigations will establish the nature of geochemical dispersion patterns in various regolith units and the probable mechanisms involved. It will enable us to determine which selective leaches will, or will not, work. One significant finding to date is that trace metals of Cu, Zn and Au are preferentially absorbed and trapped in some specific types of clay minerals. If we could develop a cost effective way to beneficiate or selectively analyses these specific host phases, it would provide a new technique to regolith sampling, to enhance the otherwise swamped anomaly.

Recently Hough *et al* (2003) have shown that significant anomalous gold in hardpans and clastic ferricrete some 20 m above the primary/supergene gold deposit in the Enterprise Pit (Mt Gibson gold project), occurs within a variety of hosts, including kaolinite spherules, hematite overprints of hematite clasts, hematite cutans, and calcite matrix. All of this is consistent with late stage hydromorphic dispersion of gold in transported regolith.

Evidence of remobilised gold and pathfinder elements is most instructive at the Lancefield goldmine, where the oxidised orebody is overlain by sediments comprising 10 - 20 m of mottled Permian fluvio-glacial sediments, 3 - 8 m of mottled Tertiary palaeochannel clays, and 2 m of hardpanised colluvium (Anand *et al*, 2004). There is evidence (Pillans, 2004) from palaeomagnetic dating of multiple oxidising (weathering) events; for example, pre-Permian, post-Permian, post-palaeochannels and post-hardpan events. An early As-Cu-Au hydromorphic system seems to have been adsorbed on the goethite/hematite mottles in the Permian, and a later Cu-Zn(-Au) system been adsorbed onto goethite in mottles in the palaeochannels clays.

MOBILITY AND MICROBES

There is much evidence to show that microbial processes influence weathering processes in contemporary regolith environments. Welch and McPhail (2003) are looking at rates and phases of mineral dissolution reactions using soil, groundwater micro-organisms and microbial ligands, and comparing these with inorganic abiotic reactions. Laboratory experiments show that in granite samples, there is nearly a ten-fold increase in release of major ions like Fe and Al in organic solutions, compared to inorganic controls. Trace elements Ga, Ti, Li and REE show preferential mobilisation by organic acids. Presumably this is due to the formation of metal-organic complexes.

Frank Reith (Reith, 2003a, 2003b) at Australian National University (ANU) is looking at the role of heterotrophic bacteria in the dissolution, transport and stabilisation of gold in three sites around Australia – Tomakin in temperate southeast NSW, Peak Hill in semi-arid central NSW, and Palmer River in tropical north Queensland. On the dissolution side, selective sequential leaching shows that most gold in soil is associated with exchangeable clay-bound and carbonate-bound fractions, as well as organic fractions. Most of this gold can be extracted in the laboratory with mild organic leaches in the presence of living microflora, over a period of ten to 20 days. In contrast, sterilised samples released little or no gold to solution. The dissolution agent may be amino acids, organic acids or cyanide secreted from soil heterotrophic bacteria like *Chromobacterium violaceum*.

On the precipitation side, Reith notes that micronuggets (0.1 - 1.0 mm) have the form of budding cells (Figure 13), strikingly like *Pedomicrobium australiensis.* These are presumed to be bacterial colonies now fossilised by native gold. Reith demonstrates in the laboratory that microbes in the soil are active, and capable of precipitating amorphous ferrihydrite on planted gold flakes in a form identical to the micron-scale fossil buds. Some species of bacteria (and fungi) are able to accumulate gold in cell walls, replacing ferrihydrite (Figure 13). DNA staining on gold flakes shows the presence of biofilms on natural gold flakes. In conjunction with Rogers (2004), the functional 16s gene sequence of a bio-film from a single gold flake from Palmer River, has been amplified and identified by gel electrophoresis. This characterises the particular bacterium species.

Reith also noted an anomalously large count of *B cereus* spores in soils over the Tomakin deposit – in effect a biological anomaly. The role of bacteria in the precipitation of gold has been recognised for several years. However this new research has for the first time isolated the molecular gene structure of the mobilising agent.

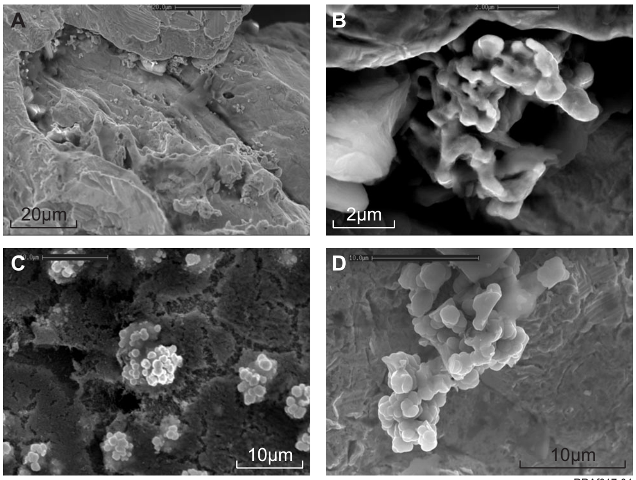

FIG 13 - (**A**) Fossilised colonies of *Pedomicrobium* in depressions of natural gold flake; (**B**) close-up of budding cells – Tomakin NSW; (**C**) *Baciliius cerus* in ferrihydrite, with striking analogy; (**D**) to form of gold globules precipitated on gold flakes incubated in Tomakin soils; courtesy of Frank Reith ANU.

SELECTIVE/PARTIAL EXTRACTIONS

Experimentation with partial extraction techniques started in the 1980s, in the pursuit of subtle less-obvious geochemical signatures that were swamped in non-diagnostic elements of the background 'noise'. This follows the advent of ultra-fine detection limits. The basis of this technique is the selective use of one or more leaches within a range of weak, moderate or strong dissolution agents. The leachate can include a spectrum from de-ionised water, enzyme leach, hydroxylamine hydrochloride, acetic acid, dilute HCl and complete dissolution with aqua regia. The weakest leaches dissolve mainly the most recently introduced metals that remain in water-soluble form. Other leaches dissolve specific secondary minerals. The basic presumption behind these techniques is that orebodies continuously but slowly release metal ions during weathering. These ions are presumed to rise more-or-less vertically to the surface where they are variously adsorbed by weathering phases such as clays, carbonates, amorphous or crystalline Fe and Mn oxides.

One example is the Mobile Metal Ion (MMI-proprietary leach) technique developed by the Geochemistry Research Centre in WA. This focuses on the more loosely bound metal ions in the soil, and employs as many as eight weak leaches to extract a range of elements diagnostic of specific ore deposit associations. The signals are a series of stacked response ratios (the ratio of element response to background). The values of this technique are that it:

- gives a vertical response,
- produces sharper anomalies,
- assists in reducing drilling costs,
- discriminates mechanical and detrital anomalies, and
- applies to a range of climatic and regolithic conditions.

Another proprietary line Regoleach© utilises a moderate leach, and samples the lower soil horizons. It focuses on amorphous iron and manganese oxides, as well as organic materials and carbonates.

These techniques clearly give positive responses in shallow regolith, and there are claims of responses from orebodies as deep as 700 m. Comparative studies (Gray *et al*, 1999) in different regolith environments, including transported regolith, show that weak, moderate and total dissolution methods give similar responses in areas where the transported cover is less than 10 m. Where the overburden was thicker, total analysis and both proprietary and conventional partial leaches all yielded some elevated concentrations of one or more elements unrelated to the ore composition. However, Carey and Dusci (1999) attribute anomalies in light rare earth elements detected by enzyme leach analysis to the presence of gold mineralisation buried beneath 10 - 15 m of saturated elements in saline playas. With gold, much depends on whether it is loosely bound or hard bound. Gold adsorbed onto clays is presumably hydromorphic in origin. But it also seems that hydromorphic gold can with time become hard bound into ferruginous nodules.

What is not universally agreed in the exploration industry is whether anomalies produced by labile metals can be shown to work where conventional total dissolution methods do not. This is one of the unresolved areas of gold exploration in Australia, which is not without it emotional protagonists and sceptics on either side.

Perhaps the greatest uncertainty with the partial leach techniques is that ion mobility is presumed to happen in nature, but we do not know by what mechanism this may happen.

PARTIAL LEACH ISOTOPE GEOCHEMISTRY

If labile elements really do exist in the regolith, one means of testing the connectivity between covered orebodies and surface geochemical expression, is to use the fingerprinting and tracing capability of Pb isotopes. This is being done under the industry-sponsored AMIRA Project 618 on six sites where partial leach techniques are reputed to have registered. This should throw light on whether such mechanisms as gas phase diffusion, electrochemical transport, biogenic factors or groundwater movement are responsible, and indeed if the partial leach techniques do in fact register mineralisation under cover. In theory partial extraction techniques will preferentially dissolve transported metal ion anomalies, which in turn should have isotopic signatures different to background rock lead. Results to date are encouraging in that the analytical technique for such ultra-low levels of lead is successfully developed, and connectivity is confirmed in some sites. However at these ultra-low levels of metal content, the anthropogenic effects from previous exploration, mining and processing operations may submerge the signature of genuine labile lead. This technique remains confidential to the industry sponsors.

SOIL GAS

Dating back to the mid 1950s in the Soviet Union, explorers have considered the gaseous products of sulfide oxidation as a suitable sample medium for targeting hidden deposits. Western geochemists and geologists made serious forays into soil gas geochemistry in the early 1980s. Klusman (1993) authored the definitive text on the subject, incorporating summaries of past work and numerous case studies from different sample media in many applications.

A new gas technique (www.sdpsoilgas.com.au), again largely an empirical method, seeks to identify the 'diagnostic' volatile compounds associated with different types of metalliferous deposits, rather than attempting to directly sense ore and pathfinder elements. Soil desorption pyrolysis (SDP) measures traces of a range of volatiles that presumably have moved into the soils as micro bubbles, and become adsorbed onto clays and organics in the ultra-fine 0.2 - 2.0 µm size range. As has been demonstrated above oil and gas deposits, hydrocarbons up to C_7 chain migrate upward as a flux through rock, regolith and water. However gases from ore deposits are different to those from enveloping rock sequences. Gases desorbed from their temporary hosts – clays and soil organics – are detached by pyrolysis and analysed. These include:

- aliphatic and aromatic hydrocarbons,
- halogenated hydrocarbons,
- organic sulfur gases,
- carbonyl sulfides,
- He and Ar, and
- SO_2, H_2S, CO_2.

The proof of concept for this technique will require building a large library of SDP analyses from about 7000 test cases to produce templates for various styles of mineralisation, for example, MVT, BHT, VMS, Carlin, IOCG, lode gold, kimberlite.

Processing and interpretation will involve use of ratios of various sulfur and hydrocarbon gases. The sum of all anomalies in a mineral-system template would define the existence of an anomaly, and the proportion of the total number of ratios that are anomalous would define the strength of the anomaly. LEME is a participant in this soil gas consortium.

HYDROGEOCHEMISTRY

Ground water should be an ideal sampling medium because it of its interaction with the materials through which it moves, and the apparent convenience and ease of sampling. However, it has not yet proven reliable for gold search in the Yilgarn Craton. Gray (2001) believes this is because gold in solution is liberally and extensively smeared in the saline groundwaters. Sampling to date shows no obvious local patterns that could pin-point gold deposits. He further argues that gold in solution relates more to regional patterns of salinity, pH and Eh, rather than local effects.

However indications to date are that hydrogeochemistry may well be applicable to basemetals. For example de Caritat and Kirste (2004) have collected 300 bore water samples from around Broken Hill, some in transported sediments 100 m thick. These have been analysed for major and trace elements, sulfur strontium and lead isotopes, and then subject to geochemical modelling. Some samples show an excess of sulfur (as sulfate) over what can be ascribed to evaporation or mixing with connate waters. All these have low $\delta^{34}S$ values indicative of derivation from primary sulfides. Moreover they also record $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}/Pb$ ratios comparable to known mineral deposits in the Broken Hill region. This technique is sensing nearby sulfide accumulations under as much as 100 m of sediments in the basins around Broken Hill. In terms of practical application, the diagnostic key to this technique is the ease and cost of analyses for sulfate and sulfur isotopes – the latter can be of the order of $25 per sample. This gives encouragement that a method for first-pass screening in greenfield areas can be developed.

There is also some evidence of striking and local anomalies related to nickel sulfide deposits (Figure 14). This is a fertile field for future research which LEME will pick address.

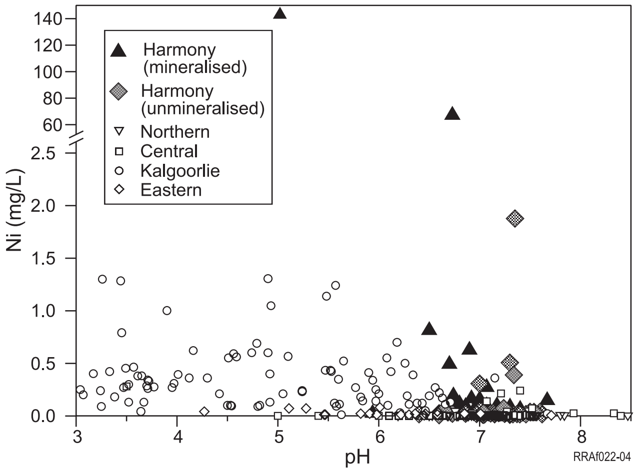

FIG 14 - Highly anomalous dissolved Ni content in groundwaters around Harmony nickel deposit, in comparison with various Yilgarn groundwaters; courtesy of David Gray CSIRO Exploration and Mining.

DISPERSION MECHANISM THROUGH TRANSPORTED REGOLITH

The selective, partial and mobile phase techniques have indeed passed the proof-of-concept stage, but at least in the Australian regolith, the relative advantages over total analyses is yet to be demonstrated. In general, partial extraction analyses may yield sharper anomalies, with higher contrast. Perhaps the most convincing examples of success of selective methods over total bulk approaches lie in the glacial tills of Canada (Cameron *et al*, 2004; Hamilton, 1998). Examples of partial-leach anomalies over base metal deposits, buried by 10 m-thick glacial tills about 10 000 years old, provide parameters and constraints on the processes that may be operating. For example, the most striking example of advective transport occurs at Spence Porphyry deposit in Chile where the earthquake-induced (seismic) pumping of mineralised groundwater to the surface through fracture zones is recognised. The assemblage of elements found in the soils above fracture zones is similar to that found in groundwaters at 60 m depth. Thus, it is necessary to understand the processes involved, so that the evaluation of the techniques for Australian conditions can be made.

A number of mechanisms have been proposed as summarised below.

- **Groundwater advection** is the lateral movement of water and its contained solutes as a result of piezometric potential. Variants of this, known as convection, can be due to thermal plumes related to exothermal oxidation, or density adjustment of hypersaline layers.
- **Ionic diffusion** can only take place in the water saturated zone. According to Cameron *et al* (2004) the diffusion coefficient in tills is too low to account for the generation of surface geochemical anomalies in glacial tills, in the available time.
- **Capillary** is the vertical migration of pore water due to surface tension of water films on grains. In porous sands it is likely to be totally counteracted by influx from rainfall. However capillary rise should be greater, albeit slower in clays where the grain size is smaller and the infiltration is less. John Keeling (pers comm) attributes the generation of Cu in the Moonta clays to this process.
- **Barometric pumping** refers to the process where cycles of high and low barometric pressure first force air into the earth and then withdraw a mixture of the air plus gases that were in the rock (Cameron *et al*, 2004). For all practical purposes, barometric pumping applies only to fractured rock. At the Mike gold deposit, Nevada, tests of metal content of soil air using collectors containing activated carbon failed to detect greater amounts of metals than blank collectors sealed in plastic bags (Cameron *et al*, 2004).
- **Electrochemical transport** involves the formation of electrochemical cells that are generated around sulfide bodies as a result of their oxidation. Such cells are often detectable by negative self-potential (SP) anomalies above the bodies. Cameron *et al* (2004) invoked transport along redox gradients rather than advection or diffusion process which are ineffective in moving waters over the last 10 000 years.

- **Gas transport** of metals can take place by attachment of metal ions or organometallic complexes to gas bubbles as they rise from bedrock through regolith.
- **Biochemical transformation** by vegetation is a potential mechanism of rapid metal transfer. Vegetation is known to take up Au, Ni, Cu, Pb, Zn and As with specific flora being adapted to substrates with high concentration of these elements. In drier climates, many pheratophyte plants have dimorphic root systems with laterals and sinker-tap roots. The latter roots acquire water from deeper groundwater source, especially during summer (as demonstrated by deuterium isotopes). The depth of rooting is critical to the ability of vegetation to transfer water and ore metals. A global rooting depth survey suggests that deep roots, especially sinkers, are ubiquitous with 10 m plus depths reached and confirmed in several climatic settings. Uptake of trace elements by plants is facilitated by production of ligands by plant roots (Romheld, 1991). Australian native plants are known for producing cyanide, oxalate and citrate. It is likely that other compounds are produced which have the ability to solubilise trace elements.
- **Bioturbation** by burrowing insects (termites, ants, earthworms) and other organism is a powerful mechanism to bring particles from depth to the surface. On the basis of optical luminescence in quartz, Pillans (ANU, pers comm) estimates that the soil to a depth of 20 m can be recycled over a period of about a million years or less.
- The role of **microbes** in transferring metals upwards is restricted, but they affect most of the processes responsible for metal transfer. Microbial metabolism affects the kinetics of many hydrochemical processes, especially redox and sulfide oxidation.

Considering all the above possible mechanism, it is difficult to see anything other than vegetation and mechanical bioturbation that will directly bring elements to any significant degree in semi-arid to arid areas where the watertable is deep. The limitations of all groundwater-transfer mechanisms is the upper limit to which groundwater rises, which is the watertable and the capillary fringe, except for the case of seismic pumping. In the Australian landscape, groundwater occurs commonly more than 5 m below surface except in lower landform sites. Therefore other mechanisms are necessary to transfer metals from the water table upwards into the soil. Surrogate organic volatiles with indirect signatures of mineral deposits have potential to bring elements up through the vadose zone. It is these areas that future research should be directed, in the thick and arid Australian regolith.

CONCLUDING COMMENTS

There have been some important developments over the years in exploration geochemistry which have become routine tools. However, many of the advances reported over the last few years are considered to be largely incremental. They relate to enhancing known techniques, and understanding regolith architecture. The focus for the future research is to develop an understanding of mechanisms that are responsible for dispersing ore and pathfinder indicator elements through transported cover in well controlled dynamic 3D regolith-landform frameworks. This will allow us to be more predictive and less empirical. The major challenge is to identify plausible mechanisms that will raise diagnostic labile elements through the vadose zone. Although there has been some important progress in understanding the physical/chemical processes in some environments, soil gas and biological processes that may in fact be the dominant contributing process.

ACKNOWLEDGEMENTS

This presentation is drawn from a selection of recent and current projects of LEME that relate to exploration through the regolith. Material comes from recent LEME monographs, and from individual colleagues, for which we are grateful for their help. Some of the source material relates to interim releases, and does not fully lend itself to referencing in the classical sense. Some interim releases are available on our website www.crcleme.org.au. We express thanks to Frank Reith, Bear McPhail, Brad Pillans, John Keeling, Cajetan Phang, Mel Lintern, Ray Smith, David Gray, Mat Cornelius, Rob Hough, Charles Butt, Graham Carr, Geoff Denton, Ken McQueen, Steve Hill, Patrice de Caritat, Dirke Kirste, Lisa Worrall, Richard Lane, Rob Fitzpatrick, Marian Skwarnecki, Merhooz Aspandair, and indeed many others.

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