Recent Practical Advances in Mineral Exploration Technologies

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Preface

In 2001 the committee that arranges SMEDG/AIG symposia broke from the tradition of having a conference theme based on a region or country and ran the “Exploration Strategies” symposium. The complement to “strategies” is “techniques” and a rough plan for a symposium based on techniques to match the 2001 symposium has remained in the background since then.

In the intervening years, SMEDG and AIG have joined with the NSW Geological Survey to run two “Mines and Wines” events, which have been stunningly successful. In 2008 the sad death of Terry Leach prompted a symposium dedicated to his work in the exploration industry.

At the start of 2009 it was intended that another “Mines and Wines” event be held but the only dates that were suitable for this clashed with a major AIG conference in Townsville. Instead, the M&W was postponed to 2010 and thus a space was left for a one day SMEDG/AIG symposium in the second half of the year. The original plan for an “exploration techniques” based conference was resurrected. This had been intended to concentrate on new geophysical and geochemical techniques but it quickly became apparent that the world of geological mapping had also been developing with GPS navigation and computerised 3D visualisation etc. A program that was divided into three to cover new technologies in geophysics, geochemistry and geological mapping plus drilling was devised. Since exploration for uranium has come back into vogue in recent years an effort was also made to also include one talk in this field. Thus this symposium, titled “Recent Practical Advances in Mineral Exploration technologies”, was born.

The aim of the symposium is to give the participants an overview of some of the exciting developments in exploration techniques that have been happening in recent years. The talks for this symposium are to be of a practical nature. Just as the “Exploration Strategies” symposium concentrated on “Which work, which don’t and why”, so the speakers at this “Technologies Symposium” were asked to concentrate on “How does this differ from previous practice, where does it work and where does it not work?”.

With all SMEDG/AIG conferences, there is a very strong bias towards case histories and where possible an avoidance of academic jargon. This symposium adheres to that tradition. The speakers were chosen because they are experts in their field and, particularly, experts with a keen understanding of the practical aspects of the technologies under discussion and a willingness to pass this expertise on to others in the field.

The committee for this symposium has worked like a well-oiled machine. The cooperation between SMEDG and AIG members of the committee has been seamless. Most of these people have been involved in previous conferences and symposia and are quick to volunteer their services wherever a need arises. I would like to thank each of these people for their efforts in making this symposium and the associated publication a success.

The speakers at this event put a huge amount of time and effort into their presentations and this publication. We all benefit not only from their expertise but also from their efforts in getting their knowledge into a form that can be presented in the short period allocated to each talk.

I would also like to thank our sponsors without whom this symposium could not take place. This year we have a number of enthusiastic sponsors and trade displayers and we remain indebted to them for this support.

All these come together to make an interesting and successful symposium.

Steve Collins

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ABSTRACT – NEW GENERATION HELICOPTER TIME DOMAIN SYSTEMS

Andrew Boyd

Helicopter time domain systems have evolved over the last ten years to become the most prevalent airborne electromagnetic configuration in use. Their general flexibility to task, higher spatial resolution, broader range of depth coverage and ability to use helicopters of convenience when required, has helped airborne EM reach significant new areas.

Helicopter TD systems have been operating commercially within Australia for over ten years and development of systems in North America and Europe has also occured. The systems designed have had a broad spectrum of use and application with system designs often reflecting their native geological environment and the applications they were originally developed for.

Applications range from within the mineral exploration sphere from deep basemetal exploration to shallow mapping of silicification, regolith characterization, water resource modeling and paleo-drainage mapping to engineering applications.

Improvements in processing, constrained inversions and an increased ability to use a priori information is enhancing the quality of interpreted information that is able to be obtained from surveys.

While not applicable to all EM problems, the robustness, flexibility and general ease of access to helicopter TD EM systems has allowed AEM to be considered as a baseline tool and dataset in many scenarios

GEOCHEMISTRY AND THE CHALLENGE POSED BY EXOTIC COVER

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Geochemical exploration continues to play a significant role in the discovery of new mineral resources in Australia and elsewhere, including terrains where mineralisation is buried or otherwise obscured by regolith cover of various types. Transported regolith cover commonly restricts the migration of trace elements to surface, especially in arid terrains, presenting a range of problems for traditional geochemical exploration methods that employ surface sampling methods. Regions dominated by transported cover include the northern parts of the Tasmanides in eastern Australia and the Yilgarn Craton which are variably covered by thick alluvium and Mesozoic to Cainozoic sedimentary rocks (Anand and Paine, 2002).

Numerous case studies have documented the development of secondary geochemical dispersion haloes and mineralogical changes within transported regolith above deeply buried mineral deposits in various regolith settings (Smee, 1998; Kelley et al., 2003, Hamilton et al., 2004). Recent studies in semi-arid to arid regions of Australia demonstrate that oxidising sulphide mineralisation can produce a range of direct or induced effects on the geochemistry and mineralogy of overlying transported regolith, including development of subtle metal dispersion haloes (Rutherford et al, 2005 and this volume).

Various mechanisms to explain geochemical dispersion through transported cover and alteration of regolith geochemistry and mineralogy have been proposed. These include combinations of advection, groundwater flow, capillary action, seismic pumping, diffusion of volatile compounds and biological action (Cameron et al, 2004; Cohen et al, 2007). One mechanism that has received significant attention over the last decade is electrochemical dispersion (Figure 1) whereby the development of self-potential currents associated with oxidizing sulphide deposits causes upward movement of electrons through the conductive sulphide body and formation of an electrochemical gradient between (underlying) reducing and (overlying) oxidizing environments (Govett, 1973; Smee, 1998). Migration of reduced species to the water table forms a reduced column over the mineralised zone and the development of geochemical anomalies in the overlying surficial overburden (Hamilton, 1998). The oxidation of Fe^{2+} and its precipitation causes acid production and subsequent dissolution of carbonate which precipitates at the edge of the reduced column where the pH is higher. The H^+ flux to surface may rearrange both the distribution and form of elements originally present in the transported regolith.

Detection of such dispersion haloes is facilitated by the use of selective geochemical extractions. These are designed to chemically separate trace elements contributed to overburden by secondary mechanisms, and associated with transient mineral phases in the regolith, derived from the trace element contents inherited from the transported cover itself. Selective extractions have dominated analytical methods developments over the last decade for use in geochemical exploration. A general relationship between some common extractions and the mineral components they theoretically attack is presented in Figure 2. Whereas most studies have tended to be empirical investigations of the response to selective extraction of regolith components derived from deeply buried underlying mineralisation, there has been limited work on the actual mechanisms of the extractions (Dalrymple *et al.*, 2005). Various commercial extraction methods have been developed with proprietary ingredients, but typically contain various combinations of acids, chelants, reductants and exchangeable ions.

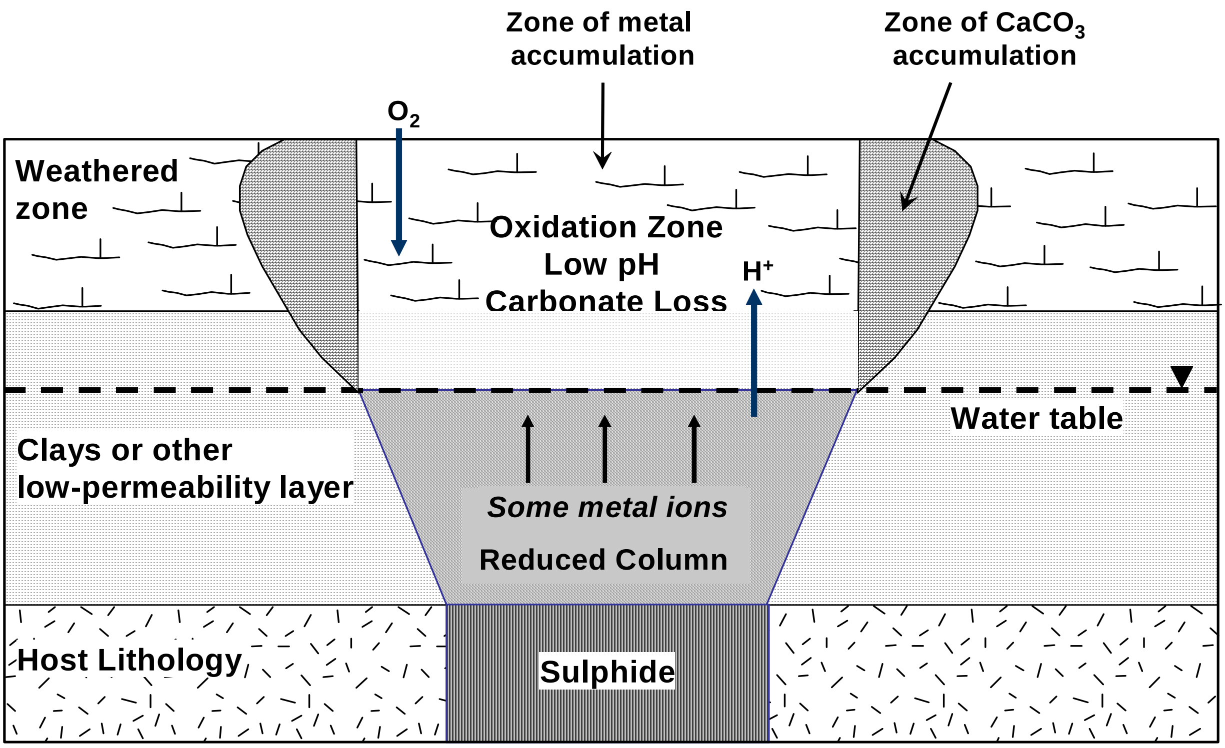

Figure 1. Redistribution of elements and minerals in a reduced chimney above an oxidising sulphide body. Metals mobile under reducing conditions migrate vertically along redox gradients and carbonates reprecipitates at the edge of the reduced column. Modified for arid zones after the models by Hamilton (1998) and Cameron et al. (2004).

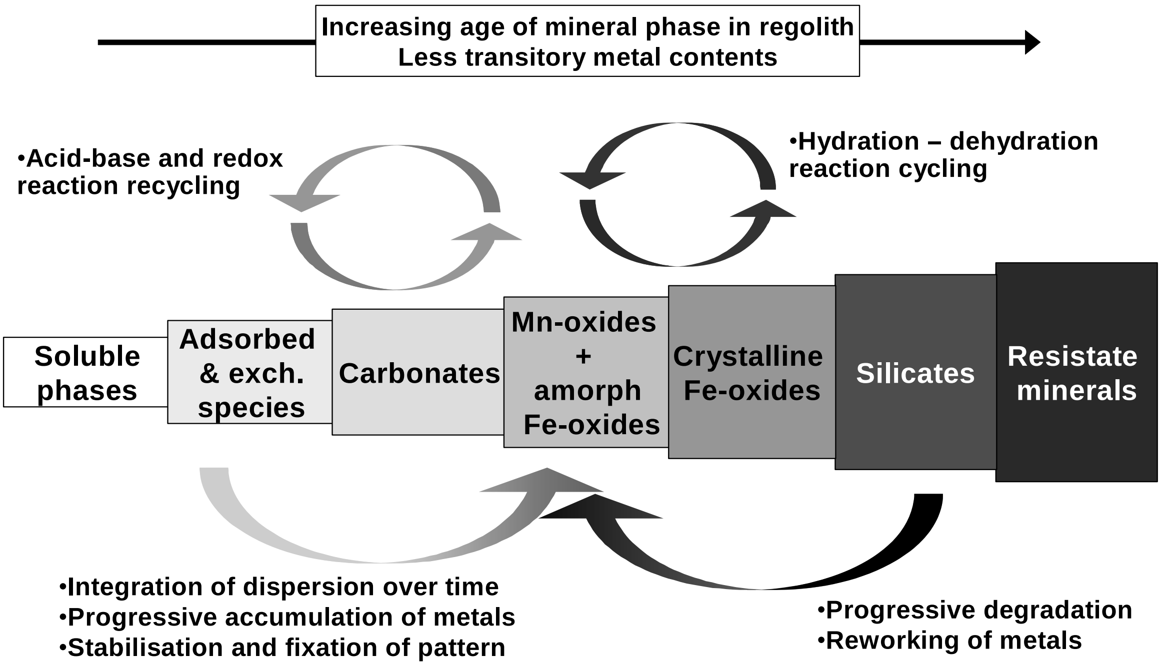

Figure 2. Relationship between various selective geochemical extractions and the extent of regolith mineral components attacked.

Coupled with the development of selective extractions is the old question of anomaly definition and detection. The traditional approach to the interpretation of exploration geochemical data has been to define a “background” population based at some distance to the centre of the dataset, or the characteristics of samples collected distal to known mineralisation. A number of problems have been identified in such an approach, especially for large areas where geology, regolith, and landscape vary substantially as they fail to recognise that background values vary on all scales (Riemann and Caritat, 1998). Recent experience with selective geochemical data would suggest that the notions of “background” and “anomalous” be abandoned in favour of recognising the multifaceted geochemical characteristics of a suite of samples, which reflect the influence of a large number of complex interacting processes (ancient and modern).

Most geochemical dispersion models for transported regolith cover have been developed for (and probably require maintenance of) a water saturated regolith profile, but there is uncertainty as to whether such processes can occur in more arid terrains typical of Australia, or the extent to which the effects of such processes can be preserved in transported regolith cover following a transition from wet to arid climatic conditions. Further evaluation of geochemical dispersion models for arid environments has been recently conducted, including that of the Mandamah deposit in central NSW (Mokhtari, 2007).

The Late Ordovician Mandamah Cu-Au deposit is covered by 35-40 m of saprolite and a further 50 m of alluvium. A distinct vertical pH zonation exists in the upper 2 m of the transported regolith cover across the site, with an upper layer of ~40 cm displaying near-neutral soil pH, an underlying 40-80 cm thick layer with variable amounts (up to 2%) of calcite+dolomite and 8.5–9.5 soil pH (not necessarily due to carbonate-induced alkalinity), and a lower layer extending below the high-pH zone which contains weak Fe mottling and soil pH below 5.7. This zonation has been derived from precipitation of salts due to evaporation, changes in redox potentials and accumulation of organic materials, in an otherwise relatively homogeneous quartz-clay alluvium. Whereas there is no indication of mass transfer of metals from mineralisation to surface (Dalrymple et al, 2005), ground conductivity measurements and variations in the amounts of selectively extracted metal contents display a strong spatial response to parts of the underlying mineralisation.

Over mineralization at Mandamah, surface samples display a strong “rabbit-ears” anomaly in acetate-extractable carbonate-related elements (Ca, Mg, Sr and REE), with a continuous central low over mineralisation and narrow zones of highly elevated concentrations of such elements at the margins of the mineralisation (Figure 3). There is no indication of any response from the mineralisation-related elements such as Cu, Mo or Au. Whereas Ca and Mg contents can vary over short distances in areas away from mineralisation, the zones of depleted REE are absent. The upper regolith over parts of the mineralisation displays low conductivities (directly measured and determined by shallow-penetration EM surveys), and elevated non-carbonate alkalinity (low acetate-extractable Ca but high Na) (Figure 4).

A model to account for these patterns at Mandamah involves modification of existing clay minerals and a redistribution of carbonates and various trace elements due to the development of an “acid chimney” above the oxidizing mineralisation during previous periods of elevated water tables. Subsequently some mobile elements have been redistributed back into the former acid chimney and resulted in the development of a zone of non-carbonate alkalinity following the onset of more arid conditions (Mokhtari et al., 2009).

The integration of the measurement of gross soil properties and selective extraction geochemical data provides a means for the detection of sulfide mineralisation buried under thick, transported regolith cover in arid terrains. Coupled with improvements in the understanding of the characteristics, evolution and geochemical processes that occur within the regolith, as well as methods for regolith mapping (Anand, 2000), the development of geochemical techniques offers new exploration approaches in previously explored terrains of high mineral potential.

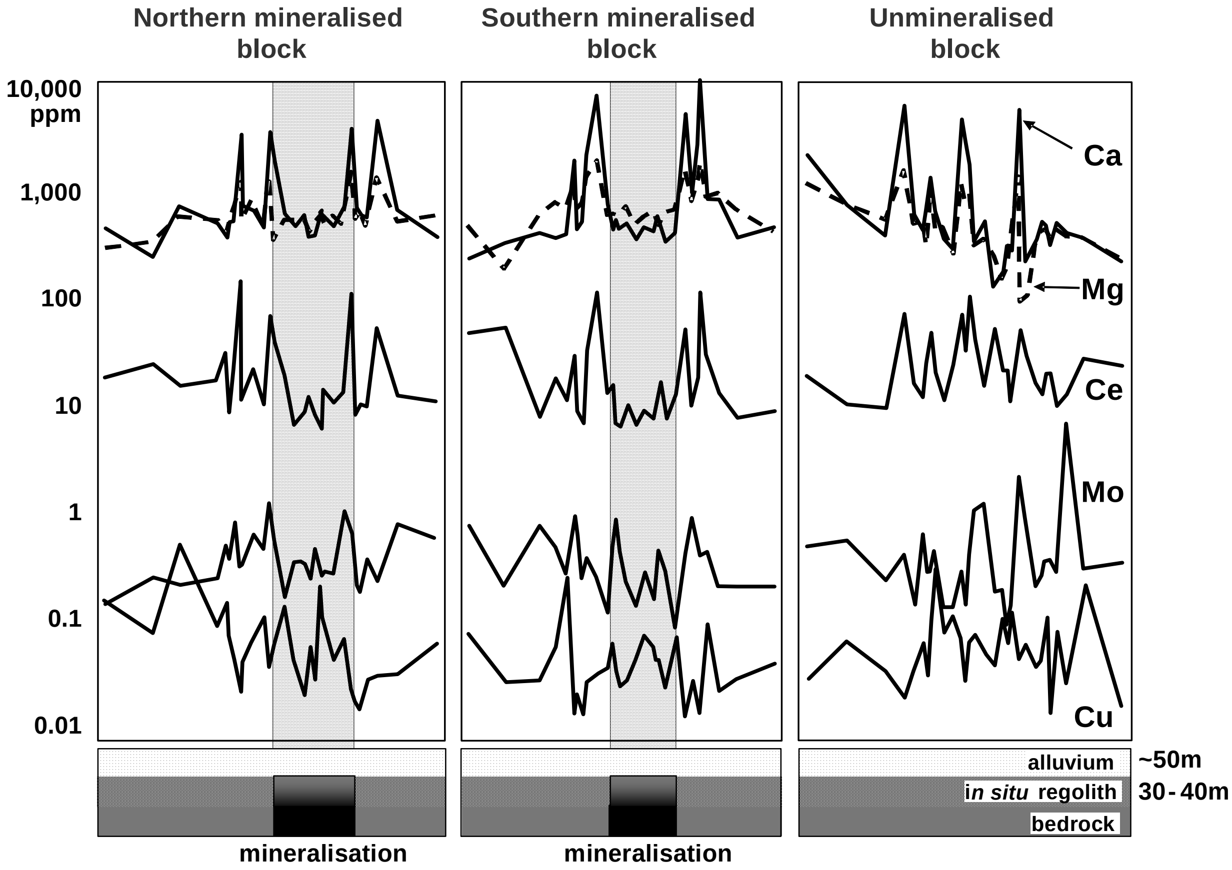

Figure 3. Development of “rabbit-ear” geochemical patterns in the K-acetate extractable components of transported regolith over Cu-Au mineralisation within unmineralised wall rock at Mandamah in central NSW (after Mokhtari *et al*., 2009).

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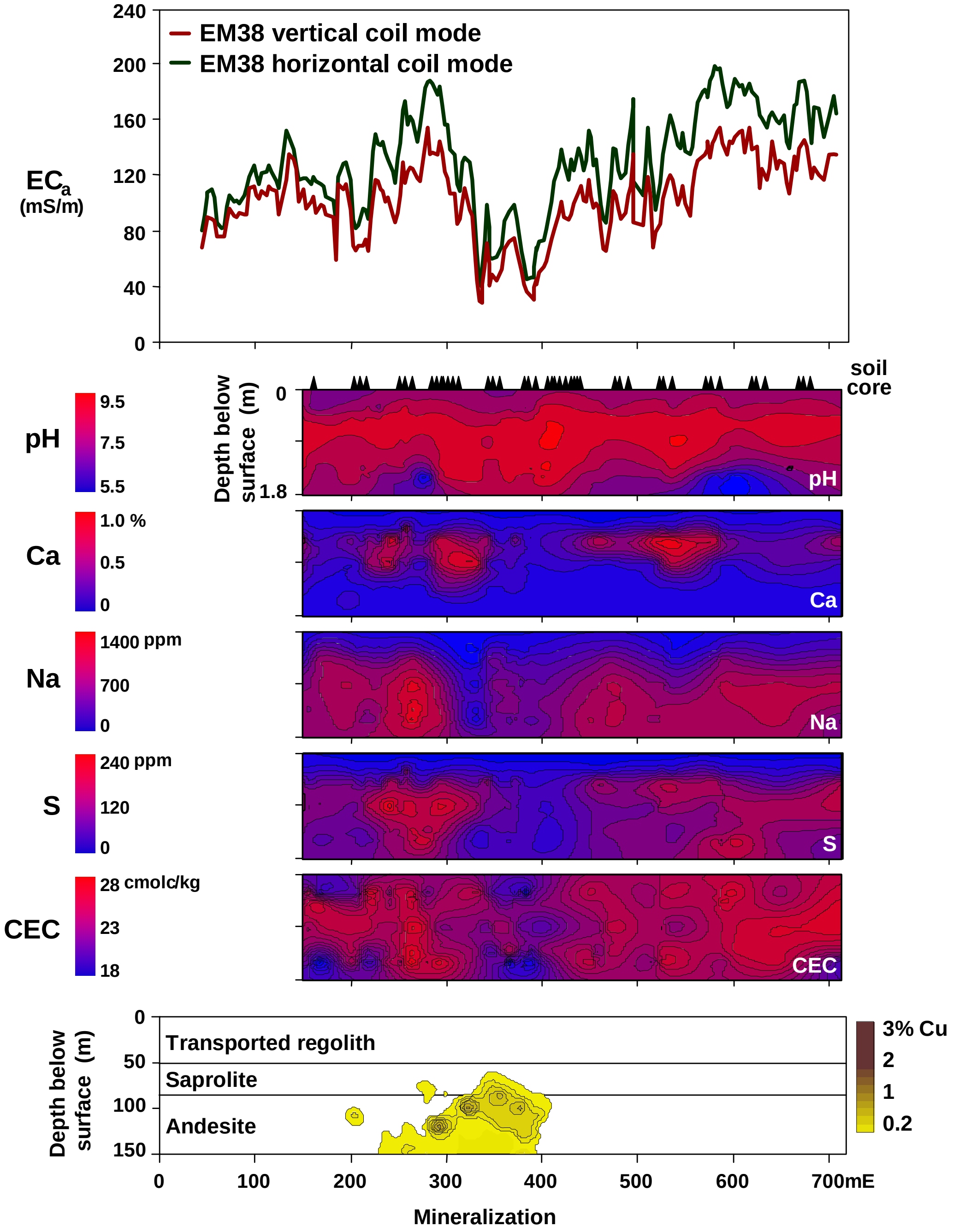

Figure 4. Comparison between surface EM response and profiles for pH, cation exchange capacity and aqua regia Ca, Na and S in the upper 2 m of a regolith profile across mineralization at Mandamah. (Mokhtari *et al.*, in press).

MODERN 3D IP SURVEYING.

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Introduction

The Induced Polarisation (IP) technique maps the bulk surface area of electrically conductive metallic grains in the earth. This measurement relates in a direct manner to the volume percentage of metallically conducting minerals and by association may be related to accumulations of economically significant minerals. It is sometimes said that “IP = Indicates Pyrite”. In many ways this is similar to the magnetic method, which is used in a mapping context where the mineral detected, magnetite, is not the actual target of the exploration effort but whose presence is used to infer geological conditions and mineralisation that would otherwise be unobserved. However, one major difference between magnetic and IP surveying is the cost per square kilometre. Many of the recent practical developments of the IP technique have been directed to making the technique more cost effective, through the application of modern electronics and processing technologies and by the optimisation of field techniques to fully utilise these technologies.

Brief History of the IP Survey Styles in Australia

The IP technique itself is not “New Technology”. Originally developed by Conrad Schlumbeger in France nearly a century ago, it started to become widespread for use in mineral exploration in the early 1950s (Siegel et. al., 2007). In its early development, numerous survey geometries were tried but by the time the technique became widely used in Australia in the mid to late 1960s the preferred geometry for surveying was either the “gradient” or “dipole-dipole” arrays. The gradient array has the advantage of cheapness and rapid coverage but is limited in penetration due to the horizontal current flow that is its main characteristic. The dipole-dipole geometry is more appropriate in areas of steeply dipping stratigraphy particularly where there is surface weathering or alluvial cover. Most other survey geometries were discarded because of either cumbersome field logistics or lack of data symmetry, which complicates the interpretation.

The advent of modern electronics has had a twofold effect on the method of IP surveying. Firstly, the cheapness and effectiveness of modern instrumentation has meant that field instruments can easily acquire large numbers of independent readings simultaneously. This has changed the emphasis in field logistics from one of how to move the recording instrument around to how to connect multiple measurement locations to a central point. The second influence of modern electronics is to do with the use of computer technology in interpretation of the data. The development of ‘inversion’ (non-linear optimisation) modelling software in the mid to late 1990s allowed the data from IP surveys to be presented as model sections and plans that have much more relevance to a practicing exploration geologist than the older forms of data presentation such as ‘pseudo-sections’ which can be quite misleading. The ability to generate computer models also freed the survey design from the restriction of needing to generate easily interpreted data.

The development of the MIMDAS IP system in the mid 1990s (Ritchie and Sheard, 1999) demonstrated both the field effectiveness of new technology and the benefit of the greater volume of data gathered for inversion modelling. The survey technique generally applied to MIMDAS surveying is the pole-dipole geometry, which has field advantages where deep penetration is desired but had previously been used only infrequently as it is difficult to interpret.

The early MIMDAS IP data was constrained to inline (2D) data due to the lack of true 3D inversion modelling software. As this software evolved, the differences between 2D models, 3D models from 2D data and 3D models from 3D data became apparent (Webb et. al., 2003). In particular, the greater resolution of the 3D data and inability of 2D surveys to define boundaries sub-parallel to the survey lines were noted.

While the MIMDAS system was highly effective and, a decade on, remains a ‘Rolls-Royce’ IP system, it was for many years proprietary technology and was not generally available. It is also relatively cumbersome, using complex low noise electrodes and requiring access for a computer truck within the survey area. For these reasons MIMDAS based IP surveys tend to be more expensive than can be achieved with other systems.

Recognising the advantages of 3D surveying and the need for most explorers to obtain good IP data over broad areas at reasonable costs, attempts were made to gain the advantages of the MIMDAS system using commercially available IP systems (White et. al., 2001). It quickly became apparent that a true 3D survey could be run efficiently with existing commercially available equipment if the IP transmitter and receiver were operated on adjacent rather than coincident lines (White et. al., 2003). The Offset Pole-dipole geometry was designed to balance the complexity of setting out and connecting multiple receiver locations with broad cover and true 3D data acquisition. This array geometry, or modifications of it, are commonly now run for 3D IP surveys.

Practical Survey Design

In order to achieve deep penetration there needs to be a large separation between the transmitter and receiver locations. A rule of thumb for the penetration of IP in good conditions is that the system will penetrate to a maximum of about one third of the maximum receiver-transmitter separation. Thus for a penetration of 500 metres the separations need to be at least 1.5 km. A major consequence of these large separations and the desire to make efficient use of the multi-channel capabilities of modern equipment is that there are severe logistical difficulties in keeping the whole system working over areas of more than a square kilometre at one time. This is particularly important in areas where curious wild or domestic animals are likely to interfere with cables.

Thus the design of 3D surveys becomes a balance between the production of as much independent data as possible and maintaining the survey infrastructure long enough to gather that data. There is little point in having a survey instrument that can take 100 readings at a time if by the time you have set out half the recording stations interfering wildlife (or curious locals) have started dismantling the system several kilometres back where you started.

Through field experience, a balance has been reached in the offset pole-dipole array geometry and variations of this. About 30 receiver locations are recorded at a time connected to a central receiver. The transmitter locations are on adjacent lines so as not to interfere with the receivers and to provide sufficient three-dimensionality to gain the benefits this provides. The geometry of the Offset Pole-dipole array, and a number of case histories are documented in geophysical literature (White et. al., 2003; Collins and White, 2003).

At current contractor prices, a well organised 3D IP survey costs approximately $7,000 per square kilometer in direct costs plus about $5,000 in other costs such as gridding, field expenses, modelling, interpretation and reporting. An equivalent inline (2D) dipole-dipole survey costs approximately $11,000 per square kilometre plus similar on-costs.

Figure 1 shows offset pole-dipole 3D IP model results over the Mineral Hill deposits in central NSW. This plan shows a horizontal slice through the 3D IP model at 100 metres below the surface compared with the projected location of mineralisation. Clearly there is a good correlation between modelled IP response and known mineralised horizons. The IP responses seen in this example at 100 metres depth are of the order of 100 metres across. These responses come from haloes of weakly disseminated sulphides surrounding the ore zones, not the ore veins themselves, which are only a few metres thick. Without the disseminated sulphide haloes, these ore zones would not have been detected at 100m depth. The IP technique is probably unique among exploration methods in that it detects surface area of metallic grains. For this reason it is common for disseminated material to respond more strongly than massive material.

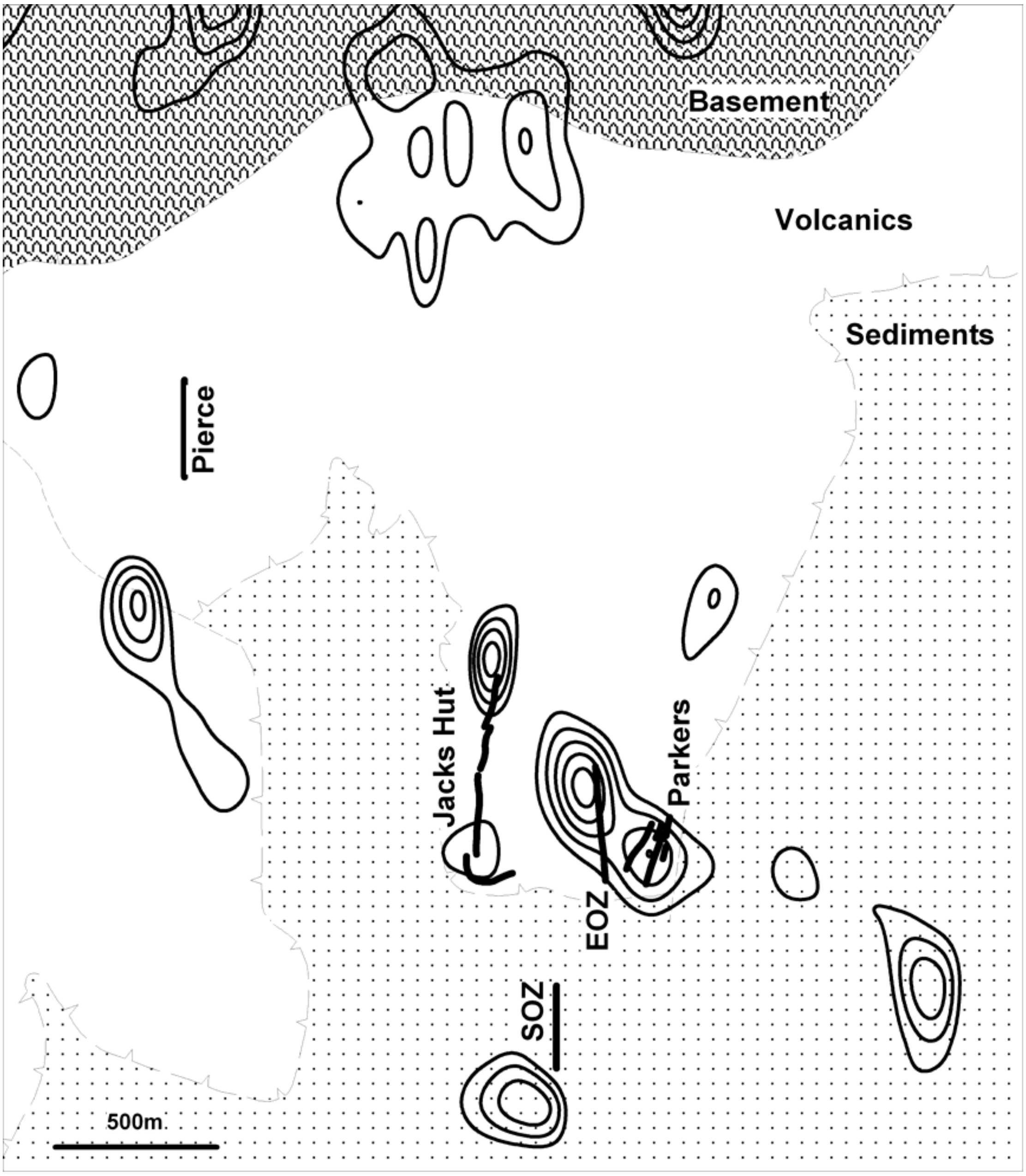

Figure 1. Mineral Hill NSW. Contours of IP response from a 3D model at 100 metres below the surface with the surface projection of known mineralised horizons.

Differences Between 2D and 3D IP Surveying

3D IP can be defined as any IP survey where the transmitter and receiver are not located on the same survey line. 3D inversion models can be used where multiple contiguous lines from a 2D survey are available or where true 3D data are available. 3D models have a definite advantage in 3D geology, which is the case in most mineral exploration environments. Edges and structures that run parallel to the survey lines are poorly defined using 2D models. A consequence of this is that 3D modelling is significantly better at resolving and eliminating the spurious effects of cultural interference such as responses from grounded fences.

3D data has an advantage over 2D data in that it has slightly higher resolution when interpreted using 3D modelling.

However, the biggest advantage of 3D over 2D data acquisition comes where broad areas (many square kilometres) of coverage are required is cost. In these cases properly run 3D surveys will be significantly cheaper than equivalent 2D surveys. Most of the cost advantage comes from the large number of readings that can be taken at the one time with 3D arrays.

The disadvantage that 3D surveying has relative to equivalent inline 2D surveys is in the complexity of the logistics. Setting up and maintaining an array of receivers over areas large enough to gain deep information requires careful planning and adequate manpower (8 men per crew). The efficient organisation of an 8 man crew is significantly more difficult than for a 3 man (inline survey) crew.

Limitations of the Method

Probably the main limitation of 3D IP is lack of resolution, particularly at depth. This is inherent in any electrical method where all of the equipment is on the surface of the ground, and is only slightly improved by using 3D data. For example, the instrument (transmitter-receiver combination) required to detect sulphides at a depth of 200m is at least 600 metres across. It is completely unrealistic to think that measurements over this distance can resolve fine detail, yet this is often what is expected when 3D IP surveys are commissioned. The resolution of the IP technique drops drastically with depth and no amount of extra data or sophisticated survey technique can overcome this.

In some situations, the presence of a conducting layer above a highly resistive bedrock target zone channels the electrical current in the conducting layer to the extent that almost no IP response is observed from the target zone. This is an inherent problem with IP that is not greatly improved by the use of 3D surveying.

The inversion models that are generated are ambiguous. Generally, the process places the source of the IP responses in roughly the right place, which is sufficient to define a drill target. However, the fine detail that may appear in the model is easy to over interpret, particularly at depth where the inherent resolution of the IP technique is poor. Inversion models of IP data should be considered to be ‘plausible solutions’ rather than real geology.

Present Trends in 3D IP Surveying

The offset pole-dipole survey geometry was initially designed to balance the number of meaningful simultaneous readings that can be collected against the logistical difficulties in setting out and maintaining large numbers of electrodes over a broad area. IP systems that can record hundreds of individual readings simultaneously are reasonably easy to build but these are not likely to be of significant use due to the field difficulties of employing this capacity. Some IP receivers can currently record up to about 60 but typically about 30 are used in a 3D survey.

Much of the present day development in IP instrumentation and survey design is directed towards the safety of the survey crew. Modern transmitters may send millisecond length high voltage pulses down the wires prior to switching to warn any operator who may still be in contact with these to let go quickly. These transmitters may also have earth leakage detection for the operator and will shut off instantly in the event that there is a significant change in the electrical characteristics of the system.

There is some development of higher power transmitters. However, this follows a law of diminishing returns, since the necessary transmitter power increases as the square of the signal to noise ratio. Thus a tenfold improvement in data quality requires a hundredfold increase in transmitter size and many times that again increase in logistical difficulty. It is likely that transmitters have already reached the limit in size as to what is really practical.

Systems currently in development use wireless network technology to reduce the need for complex and fragile cables that connect the receiver electrodes to a central recorder. This allows the replacement of fragile multi-core or network cabling with a single robust and easily substituted reference wire with the consequent streamlining of survey procedures. This development will not improve the data quality but should reduce survey costs through increases efficiency.

Future Developments

Little use has been made so far of improvements in signal processing of IP data. This is a badly neglected area of development. Most of the processing work in IP systems has been towards obtaining more information from the IP signal rather than obtaining normal IP signals for less effort. Several years ago major advances were made in the processing of radiometric data using noise reduction techniques. These techniques may also be applicable to IP data but are not in general use. Norvill and Kepic (2004) of Curtin University reported better than an order of magnitude improvement in signal to noise through the combined processing of 3D arrays of IP receivers but there has been little attempt to utilise this technology in the commercial environment. To put this into perspective, an order of magnitude improvement in signal to noise is equivalent to replacing a 50kVA transmitter, which needs to be towed in a trailer behind a truck, with a 500 watt back-packable device. Once sophisticated noise processing becomes commonplace in the exploration environment, there will be significant opportunities to greatly improve the efficiency and thus cost of 3D IP surveys.

There have been sporadic attempts over many years to utilise drillholes for IP electrode locations. This development is increasing in pace at the moment. This is a complex field and 3D borehole IP surveying has more difficulties than are practical to discuss here. However, significant progress is being made towards solving these problems. It is likely that it will soon be commonplace for readings involving borehole electrodes to be included in 3D IP surveys.

In the distant future, it is possible that magnetometers will become cheap enough for magnetic IP readings to be incorporated into 3D surveys. This would require a significant drop in the price of suitable magnetometers and major enhancements of inversion modelling software to allow the incorporation of these data.

Case History – Comparison of 3D IP Model with Kriged Ore Reserves

The Copper Hill Prospect near Molong NSW is somewhat unique in that it has been surveyed at various times with three different IP survey geometries including MIMDAS surveys in some areas. It has also has a full Kriged ore reserve block model generated from the extensive drilling of the prospect. The availability of these data sets allows a comparison of the ore reserve block model with the IP model on a level by level basis. This provides a rare check on the relevance of the IP model to exploration for this type of deposit. Figures 2, 3 and 4 show a direct comparison between Kriged copper grade block model and an equivalent block model generated from 3D IP data. These level plans are generated at approximately 50, 150 and 250 metres below the surface.

It should be noted that the IP results would not be expected to directly match the copper grades as the IP technique detects total metallic (sulphide) minerals and parts of the mineralised system at Copper Hill are relatively rich in pyrite rather than chalcopyrite. Nevertheless, the correlation between the IP and copper models is good, except in the northwest where there is limited drilling. The correlation remains reasonable at depth until the limited number of available drillholes prevents the generation of a realistic Kriged copper model.

Acknowledgements

The author wishes to thank Kimberley Metals Ltd. and Golden Cross
Resources Ltd. for permission to use their data.

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Figure 2. Copper Hill NSW. Contours of IP response from a 3D model at 50 metres below the surface with Kriged copper grades from drilling.

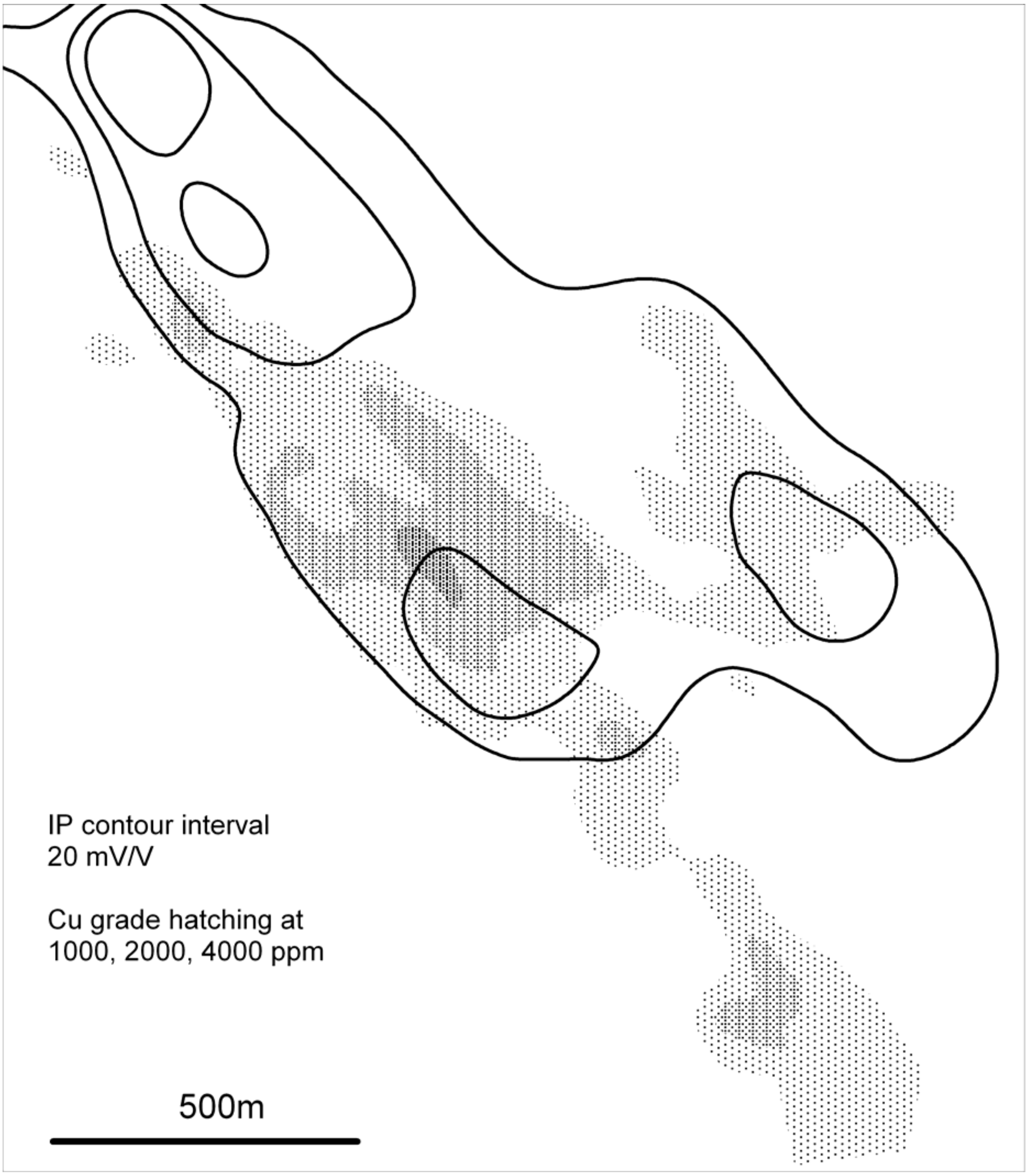


Figure 3. Copper Hill NSW. Contours of IP response from a 3D model at 150 metres below the surface with Kriged copper grades from drilling.

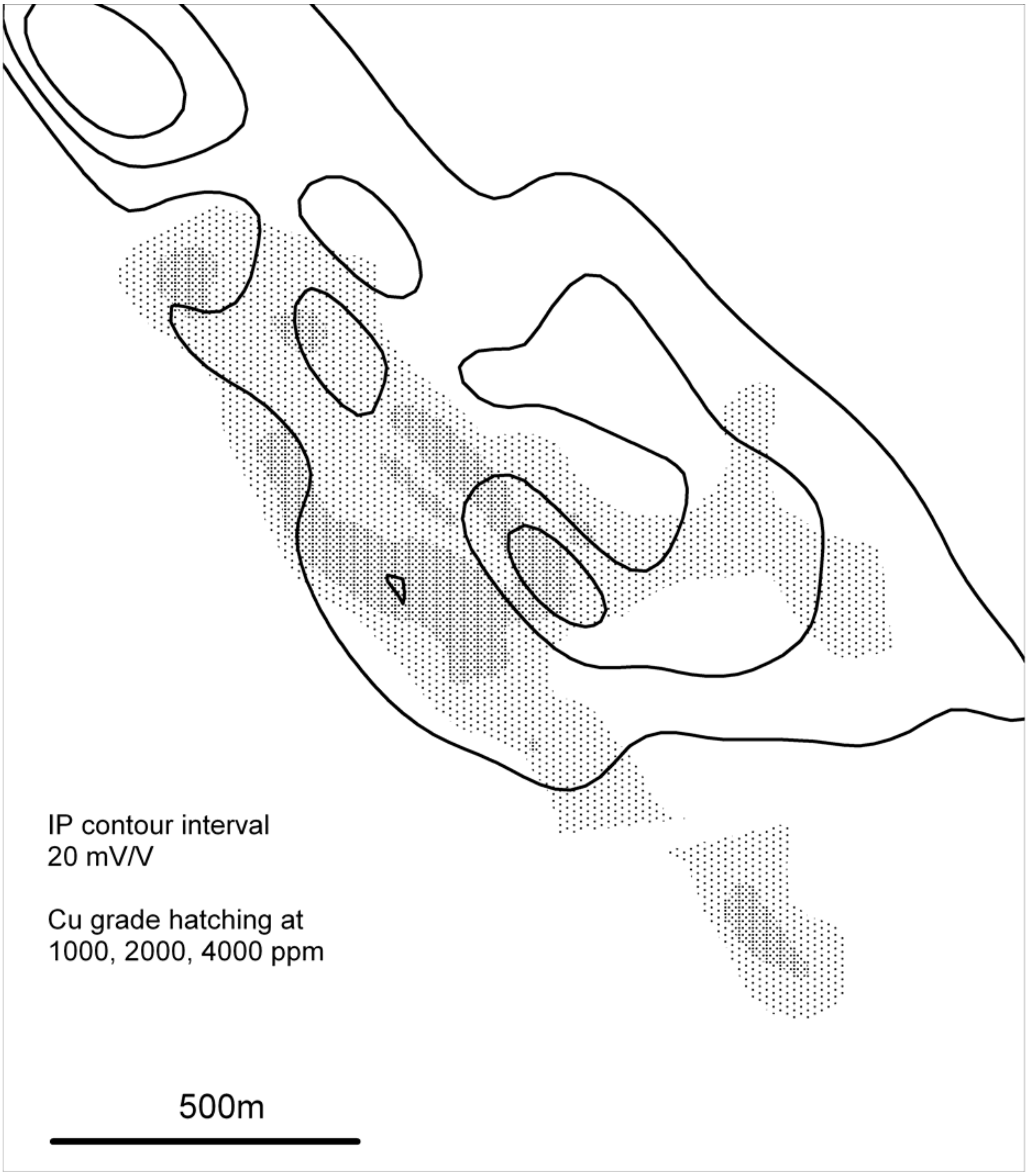


Figure 4. Copper Hill NSW. Contours of IP response from a 3D model at 250 metres below the surface with Kriged copper grades from drilling.

ADVANCES IN MINERAL EXPLORATION AND MINING DRILLING TECHNOLOGIES

Jock Cunningham
CSIRO

Significant funding and resources have recently been committed through the Cooperative Research Centre (CRC) programme to develop drilling and exploration technologies over the next eight years. The newly announced Deep Exploration Technologies CRC is planned to begin research in January 2010 with a total of $28M cash funding from the Australian government and in-kind contributions from participants/research organisations totalling approximately $100M over the eight year period.

The application for the new CRC was the culmination of several years of planning by the mining industry and especially the work co-ordinated by AMIRA. From the Industry sponsored AMIRA Drilling Roadmap, it was clear that while the oil industry had made significant advances in drilling technology through collaborative research. Over a 40 year period it had improved its drilling technology to enable access to deeper resources, resulting in an increased production from 80 BOE to 1,450 BOC.

Hard-rock mining and exploration drilling has not experienced an equivalent improvement and it now faces limitations in production similar to those faced by the oil industry 40 years ago. Neither mechanisms nor resources were in place to facilitate collaborative research in metalliferous mining and the lack of advanced drilling technology is now an impediment to exploration at depth.

AMIRA and a number of key companies and research organisations joined to submit a successful application for a new CRC to develop new technologies for deep exploration. A flyer for the DET CRC is attached. The application process took almost 2 years from conception. It evolved through a series of workshops across Australia to distil the R&D requirements from stakeholders. It culminated in a process to prepare the necessary documentation and to present the case to the CRC Committee. The consultation process was comprehensive and included the AMIRA Drilling Roadmap. The South Australian Government has committed significant cash towards the Programme.

The new DET CRC will have three research programmes: Drilling Technology, Data Fusion and Deep Targeting. The improvement of education, training and safety will be pervasive throughout each programme. Postgraduate studies and operator training will be integrated. The registered office will be based in Adelaide and a new drilling test site will be established nearby. This soon-to-be well equipped drilling site at a disused quarry will be a first in Australia to provide a dedicated testing facility that won't conflict with production environments. Experience shows that this should significantly reduce development time.

The **Drilling Technology Programme** will comprise three research components including the establishment of the test site:

1/ Fundamentals of Rock Fragmentation research will develop predictive models for the interaction between bit and rock under different conditions demonstrated in different bit designs and methods of bit excitation. The discoveries made in this programme will inform the developments in the remaining two projects.

2/ Drilling Optimisation will focus on optimisation (including automation) of current drilling systems. This research will develop sensors that can be used for measuring the performance of a drill bit and control systems that can then be used to automate the drilling process and enable it to adapt automatically to changing rock conditions.

3/ Next Generation Drilling Systems will develop new-concept composite/flexible drill strings with embedded sensors, long-life drill bits, steerable drill bits and instruments to allow bit localisation, control and data communication between a local or remote control station.

The **Data Fusion programme** will comprise four project areas:

1/ In-Front-of-Bit Imaging will develop down-hole tools/sensors and geo-imaging software to help the driller to respond quickly to changes in the nature of the ground being drilled.

2/ Sensors for Rapid Down-Hole Rock Characterisation will develop tools for generating on-site information about ore mineralogy characteristics.

3/ Integration of Geophysical and Petrophysical Data will establish a comprehensive database of mineralogical, geological, petrophysical data for mineral discrimination and lithological identification.

4/ Joint Inversion of 3D Seismic Data and Magnetotelluric (MT) Data will develop software to produce 3D representations combining geometrical and mineral information.

The **Deep Targeting programme** will comprise three areas of research:

1/ Lower Cost, More Effective 3D Seismic Exploration for Hard Rock Environments including optimised hardware and methods for hard rock seismic data acquisition and visualisation, combining data from surface and borehole techniques.

2/ Hypogene Alteration Associated with Mineral Deposits – atlas of hypogene alteration defining Australian onshore deep cover search space.

3/ Defining and Sampling the Cover – tools that utilise data generated from usage of outputs from Programs 1 and 2 in conjunction with alteration models to facilitate timely decision making in mineral exploration.

Further information including the participants and contacts for the DET CRC can be found in the attached flyer.

Acknowledgements

Much of the following text has been adapted from documentation prepared for the new CRC application for Deep Exploration Technologies CRC, Round 11. It has also been informed by the AMIRA Drilling Roadmap 2006, 2008. Many contributions (including the author's contributions) from different organizations were used to prepare those source documents. The DET CRC participants are grateful to the South Australian Government for their significant cash commitment towards the CRC.

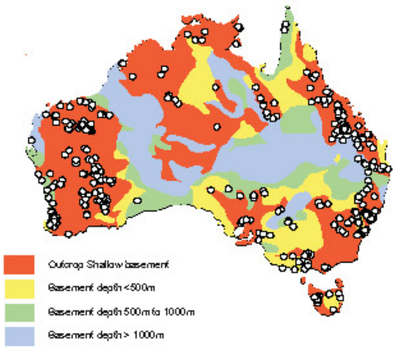
New CRC for Deep Exploration Technologies

to commence in January 2010

On the 7th August the Minister for Innovation, Industry Science and Research announced that the proposed Deep Exploration Technologies CRC for had been granted $28 M funding under the Cooperative Research Centres program.

The CRC has as its mission deep ore discovery by opening up both the Greenfields and Brownfield's Search Space, through quicker, more effective exploration at depth and through cover.

The Deep Exploration Technologies CRC has been established to address the most significant challenge to the future of the Australian minerals industry – the reduction in the mineral resources inventory due to high production and low mineral exploration success. The national response must be to develop new technologies to explore to greater depths and under cover in the vast areas of Australia that are known to be prospective for minerals.



The strategic objectives of the CRC are:

- Significant reduction in time and cost of drilling
- Significant improvement in drilling safety and environmental impacts
- Dramatically improve the quality and timeliness of down hole information
- Cost effective discovery by developing tools for deeper targeting
- Drive a change in the useful 3D knowledge obtained from copious amounts of data currently collected for project management & LOM planning purposes.

To achieve these objectives, the CRC will undertake research in three programs:

- **Drilling Program**
  - the development of radical, new hard rock drilling technologies.
- **Data Fusion Program**
  - down-hole and on-site surface technologies that enable data acquisition in real time.
- **Deep Targeting Program**
  - improving imagery of the rock volume at depth.

Cooperative Research Centre

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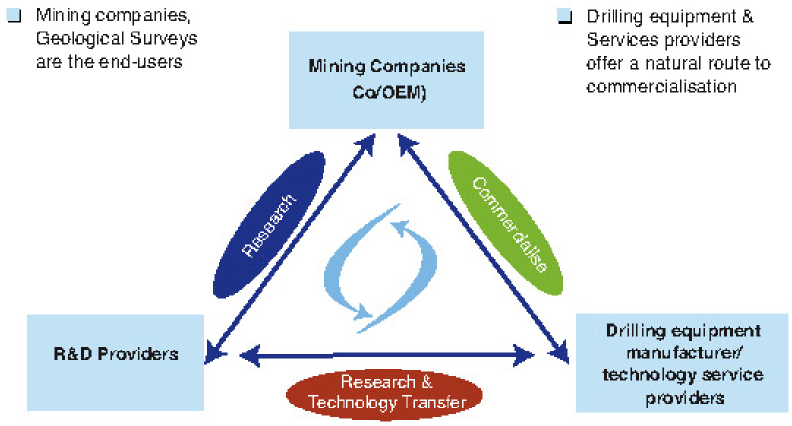
The consortium is keen to recruit more core and affiliate partners prior to start up in early 2010.

CRC
AUSTRALIA

Cooperative Research Centre

The CRC will be an Incorporated entity, driven by collaboration between mineral exploration end users, industry service providers and Australian and international R&D providers.



The CRC has been initiated by Industry through AMIRA International working with R&D providers. Over $100m in industry and government cash and R&D in-kind has been committed to the CRC.

The consortium is keen to recruit more core and affiliate partners prior to start up in early 2010.

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THE APPLICATION OF DHMMR AT BROKEN HILL

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Introduction

Down-hole Magnetometric Resistivity (DHMMR) is an electrical geophysical technique used primarily for locating mineralisation at a distance from the drillhole (Nabighian *et al.* 1984, Asten 1988, Bishop *et al.*, 1997). A grounded transmitter dipole channels electric current through more conductive units (i.e. the mineralisation), and the down-hole survey records the magnetic field generated by these galvanic currents. For narrow elongated mineralisation and/or relatively low conductivity targets, DHMMR has clear advantages over down-hole electromagnetics (DHEM). This is demonstrated here using data from a survey at the North Mine, Broken Hill, where DHMMR delineated mineralisation that (Down-hole Electromagnetic (DHEM) surveying failed to detect.

The aim of the survey was to detect the narrow discontinuous ribbons of low conductivity Zinc Lodes, located 20-50m above the highly conductive main North Mine orebody, and underneath or next to the North Mine infrastructure and development. One risk facing the survey was that the main orebody would act as a ‘short-circuit’, causing the impressed current to avoid the Zinc Lodes entirely. To mitigate this, one electrode of the transmitting dipole was placed down a deep drill hole in a Zinc Lodes intersection and the other was dug into a surface expression of the Zinc Lodes, ~1.5km south of the drill hole electrode. This layout very effectively isolated and energised the Zinc Lodes mineralisation. Despite these difficulties, the survey data were excellent.

DHMMR anomalies are modelled assuming bodies of infinite strike length (which is generally a reasonable assumption at Broken Hill) with a contrasting current density in a similar manner to gravity interpretation. Until recently the down-hole receiver was a standard DHEM probe measuring dB/dt, usually a single, axial component, although three component surveys have been carried out. Advances in technology presented the opportunity to use a 3-component B-field probe for the survey described here. This paper reviews the history and application of DHMMR at Broken Hill and presents results of the innovative application of down-hole magnetometric resistivity (DHMMR) on the North Mine Zinc Lodes mineralisation.

Background

Broken Hill is the largest known Pb-Zn-Ag massive sulphide deposit in the world and has been mined almost continuously since the 1880s. The long life and profitability of the mine have provided generations of geophysicists with the opportunity to develop and test new geophysical techniques. In the early 1960s, a new geophysical method called Induced Polarisation was introduced to explore for extensions to the Main Lodes and was responsible for the discovery of the Flying Doctor deposit. Since then, most geophysical methods have been either trialled on test sites such as Flying Doctor, or applied regionally in the search for Broken Hill-style mineralisation. Many thousands of line km of ground and airborne geophysics have been acquired over the region, with some notable successes and failures. One of the most valuable geophysical applications is borehole geophysics (DHEM, DHMMR and cross-hole applied potential), especially along the line of lode where geophysical data have reduced drilling requirements, focussed drilling programs, and illuminated off-hole mineralisation that may have otherwise been missed. On the Northern Leases alone, over 40,000m of DHEM and 50,000m of DHMMR were acquired in the period 1990-2008.

DHMMR at Broken Hill: DHMMR vs. DHEM

From a geophysical perspective, the Broken Hill mineralisation can be generalised into two categories: Massive Pb-Zn mineralisation that is invariably conductive enough (10-1000 S/m - Bishop and Emerson, 1999) to give good electromagnetic (EM) responses (Bishop *et al*., 1991); and Zn-rich Pb-poor mineralisation that is much less conductive and therefore less responsive to EM. The reported conductivity for this Zn-rich mineralisation (as taken from samples of the Zinc Lodes and Potosi mineralisation) is a few S/m or less (Emerson, D.W., Bishop, J.R., and Yang, Y.P, unpublished data, Godber, 2006). The effective 'invisibility' of this low conductivity Zn-rich mineralisation to EM methods led to the application of DHMMR at Broken Hill in the early 1990s (Bishop *et al*., 1990).

DHMMR is ideally suited for detecting narrow, ribbon-shaped and/or poorly conducting mineralisation (less than say 1 S/m), a target which is often invisible to EM methods. The physical reason for this is that DHMMR relies on current channelling rather than induced currents, and this channelling requires only a conductivity contrast between the host rock and the target rather than high absolute conductivities. As a rule of thumb, a conductivity contrast of 3 between host and target is sufficient to channel the current usefully and create a good DHMMR signal (Lewis, R.J.G, 1998).

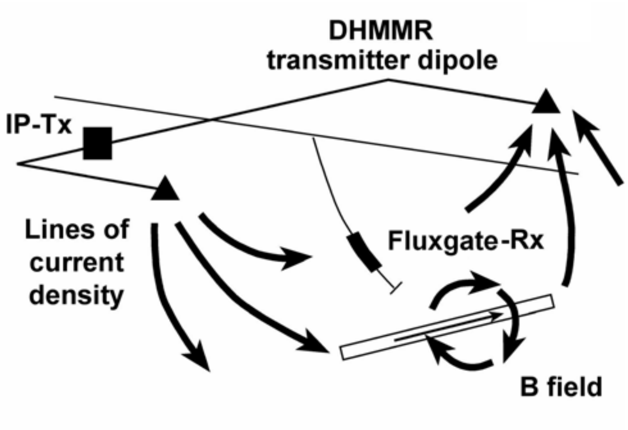

Figure 1: Survey layout for a standard DHMMR survey (modified after Asten, 1988).

DHMMR can also potentially detect extremely conductive targets, such as effectively perfect conductors (nickel deposits), where pulse type Transient Electromagnetic (TEM) equipment establishes essentially no changing currents within the body and no response can therefore be observed. A third and important reason is the increased target detection range – the magnetic field due to current channelling decays as r^{-1} to r^{-2} (depending on source geometry), whilst most TEM methods involve r^{-2} to r^{-3} factors. Detection distances of >150m have been recorded in Broken Hill surveys (Godber unpublished report, 2006; Bishop et al., 1997).

Disadvantages of DHMMR are considered to be as follows:

1. Lower signal to noise ratio.
2. Lack of readily available modelling software, and
3. Poorer resolution of target dip/distance from hole.

Whilst target resolution essentially is a limitation of using galvanic versus induced fields, the other perceived disadvantages of DHMMR are probably a result of inertia in the development of this technique. Simply put, the equipment and technology were available, but awareness and impetus were lacking. This survey described in this paper provided the opportunity to bring together the equipment, software and people to realise the potential of 3-component B-field probe DHMMR.

DHMMR at the North Mine: Geological Setting and Exploration Target

The North Mine orebody is hosted in a distinctive mine sequence comprising elements of the Broken Hill Group (Hores Gneiss and Freyers Metasediments) and the Thackaringa Group (Rasp Ridge Gneiss) of the Willyama Supergroup. There

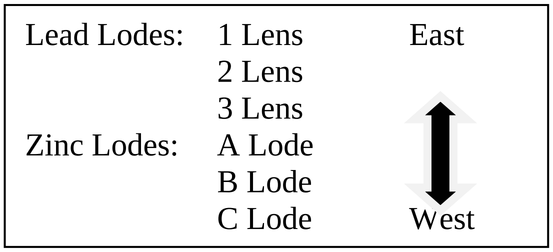

Figure 2: Horizontal position of the main North Mine mineralisation lodes.

are at least six stratiform economic mineral horizons, known as Lodes (Figure 2).

The main Lead Lodes (2-Lens and 3-Lens) are massive, conductive, isoclinally folded and plunge to the northeast at about 40-60°. The Zinc Lodes locally dip ~70° north-northwest, and lie about 20-50m northwest above the main lode with a parallel plunge. The steep plunge makes it difficult for a surface electrode to energise the mineralisation at depth in the northeast. This problem was solved by using an old drill hole with a Zinc Lodes intersection as the transmitter contact for the northeastern electrode (see Figure 3 and 4 for survey layout).

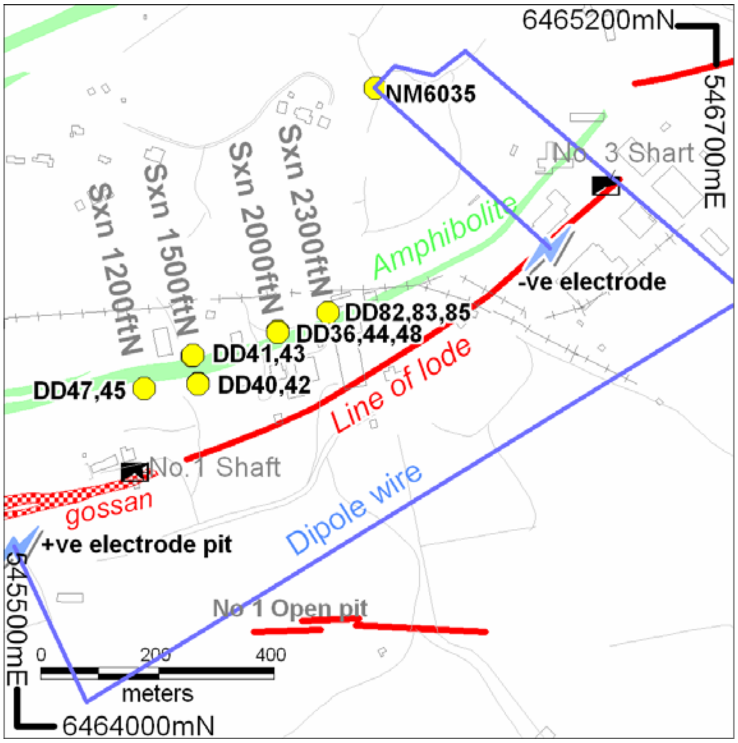

Figure 3 Location and survey set up for the North Mine DHMMR program. Yellow dots indicate drill hole locations (12 holes total), red is the surface expression of the Zinc Lodes mineralisation. The northeastern (negative) electrode is 550m down drillhole NM6035 in a Zinc Lodes intersection. The southwestern (positive) electrode is in the surface Zinc Lodes gossan.

The North Mine mostly mined the 2- and 3-Lens Pb-Zn lodes with a small portion of the Zinc Lodes. The major sulphides in the Zinc Lodes are marmatite (sphalerite containing up to 13% Fe) and galena. Petrophysical testing, DHEM, and DHMMR surveys have shown that the mineralisation may be only weakly conductive. The Zinc Lodes are considered stratigraphic correlates of the Potosi mineralisation, and as such difficult targets to define both geologically and geophysically. 'Zinc Lodes' is probably a misleading name for this mineralisation, which is rarely >2m thick @ 5-10% sphalerite ± 1-2% galena, discontinuous, and seems rather to be a series of narrow ribbons than continuous sheets. In addition, the mineralisation is poorly conductive, positioned only 20-50m above massive highly conductive Pb-Zn mineralisation, and lies directly below a working mine and railway track (Figure 3). DHEM has been tried on the Zinc Lodes but with little success (Bishop, 1991).

DHMMR at the North Mine: Method

The target zone was energised with a 1Hz square wave impressed into the earth via a grounded dipole which was laid out in a 'U' shape with the holes to be surveyed within the U (to reduce the effect of the magnetic field in the wire). The dipole length was 1000m along strike with the southwestern (positive) electrode in the surface expression of the Zinc Lodes (Figure 3 and 4). The positive electrode was a 2x2m pit pierced by several star pickets, lined with aluminium foil, and filled with water. The dipole wire was run east out and around the North Mine waste rock dumps and back west to drill hole NM6035 (on section 2900ftN). The negative electrode was lowered down NM6035 to ~550metres in a weak (5% Zn+Pb) Zinc Lodes mineralisation intersection (Figure 4). In this way, the current electrodes isolated and targeted the correct mineralisation, which may otherwise have been too deep for a surface electrode to energise. A standard IP transmitter was used to produce a 7 to 8 ampere current between the electrodes.

DHMMR at the North Mine: Results

The DHMMR data were modelled on a section-by-section basis. The 2D-polygons from this modelling were extended 50m up and down-plunge to create polygons with an arbitrary strike-length of 100m. These were incorporated into the mine resource modelling software to allow visualization of the relationship between the model results and the known mineralisation (Figure 4). The primary concern was that the current might be short circuited through the nearby highly conductive North Mine main lode. However plotting of the model results soon proved that the modelled conductors are consistently in the correct stratigraphic position.

The modelling indicated two types of mineralisation defined by different current densities. This variation was interpreted as primarily a function of the pyrrhotite composition of the two units, manifesting as current densities of 1 mA/m^2 (saturated) for pyrrhotite-rich to 0.1mA/m^2 pyrrhotite-poor mineralisation. This is supported by previous experience that pyrrhotite is generally very well electrically connected and highly conductive.

DHMMR at the North Mine: Discussion

This survey represents the first use of a 3-component fluxgate probe in a DHMMR survey at Broken Hill, and one of the first examples Australia-wide. The survey is considered very successful given the challenging target, location and environment (previously described). The data was very low noise with excellent repeatability, despite proximity to the underground mine workings, railway, and the North Mine infrastructure (see Figure 3), which are normally significant sources of EM noise and logistical challenges. The model DHMMR polygons correlated very well with the known geology and expected mineralisation, as well as indicating several new untested zones. The modelled polygons define nearly continuous ribbons west and above the main lode (Figure 4) with different current densities associated with different types of mineralisation.

The comparison between the modelling and the interpreted geology of the North Mine provides a very strong case for the use of DHMMR to delineate low conductivity (100S/m to <1 S/m) ore, even in difficult structural settings. In addition, the depth of investigation of DHMMR (when a down-hole source electrode is used) does not seem to be limited by any physical constraint other than drill hole depth. The success and accuracy of this survey using new equipment is expected to lead to a better appreciation of the potential of the DHMMR method.

Conclusion

The comparison between the modeling and the interpreted geology of the North Mine provides a very strong case for the use of DHMMR to delineate low conductivity ore in close proximity to other conductors in an electrically noisy environment. Surveys have been carried out well in excess of 1km and depth capabilities appear to be only constrained by the depth of the drill hole.

Clever and, most importantly, suitable applications of borehole geophysics has significantly improved drilling effectiveness on the Northern Leases and North Mine in three ways: 1) Improved confidence in drill targeting, 2) delineation of off-hole mineralisation that may have otherwise been missed, and 3) sterilisation of ground.

Acknowledgements

The computer program used for the interpretation was written by Roger Lewis (Lewis, 1998).
John Bishop and Steve Collins kindly read the manuscript.

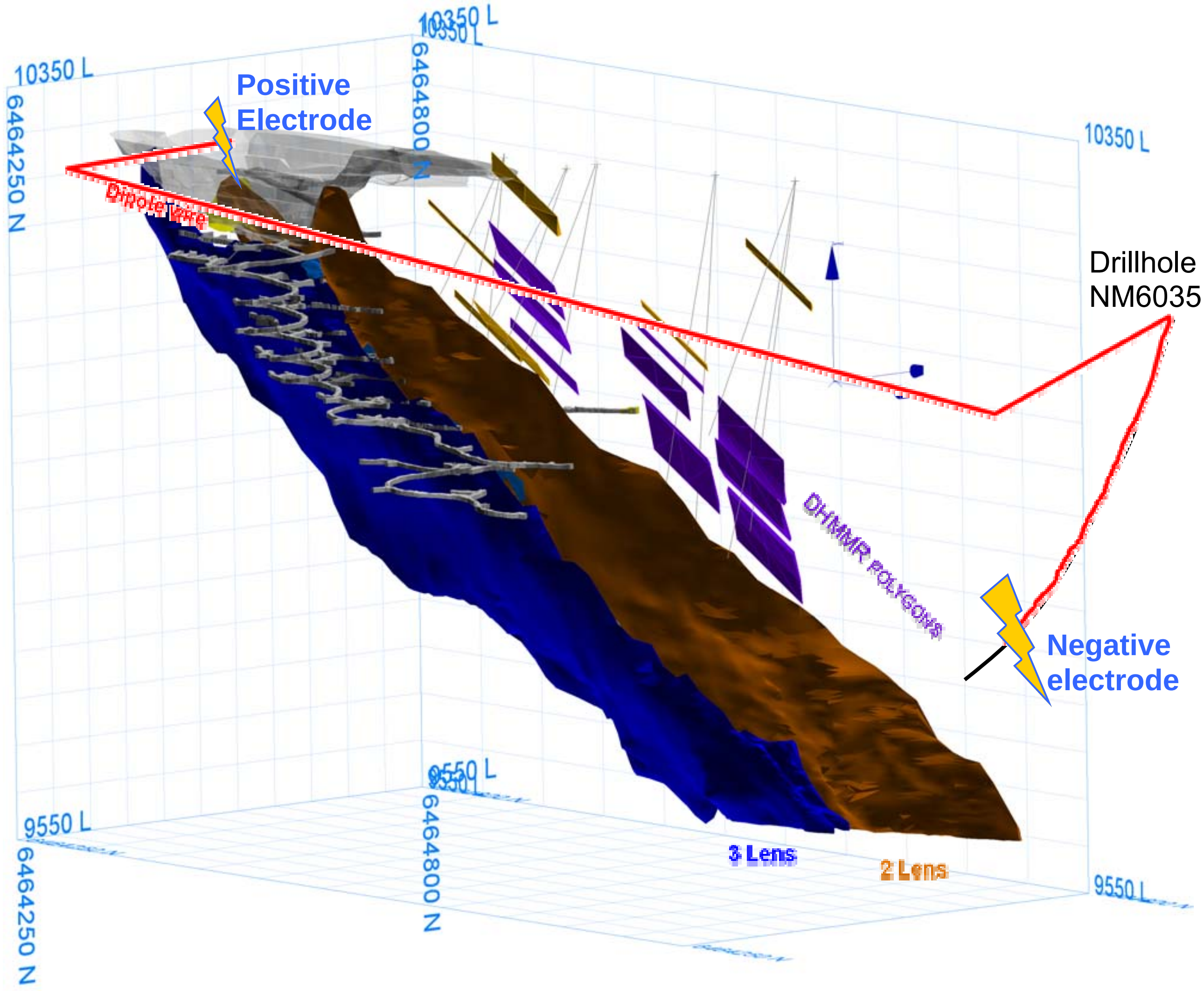

Figure 4: Perspective view looking northwest of 3D DHMMR model polygons and survey drill hole traces with 3-Lens and 2-Lens orebodies and the open pit (light grey). The DHMMR polygons are actually beyond and slightly above the main mineralisation. The negative electrode is 550m down drillhole NM6035 in a Zinc Lodes intersection.

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INVISIBLE GOLD REVEALED IN SUPERGENE AND HYPOGENE ENVIRONMENTS.

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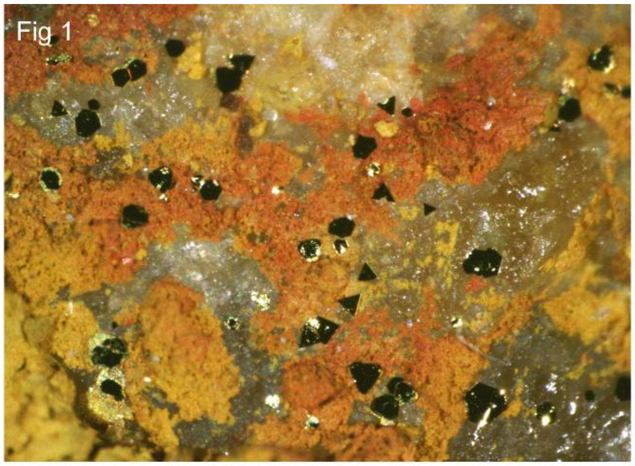
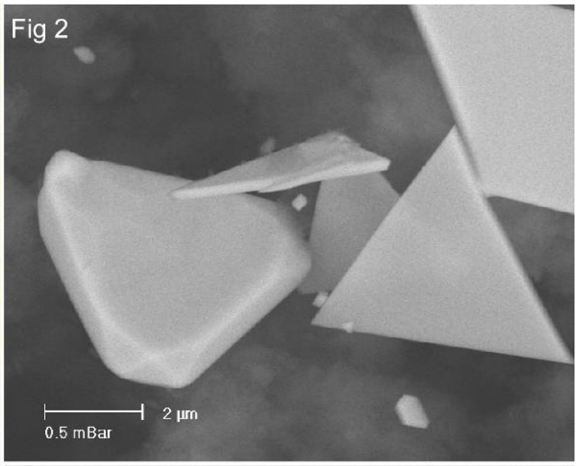
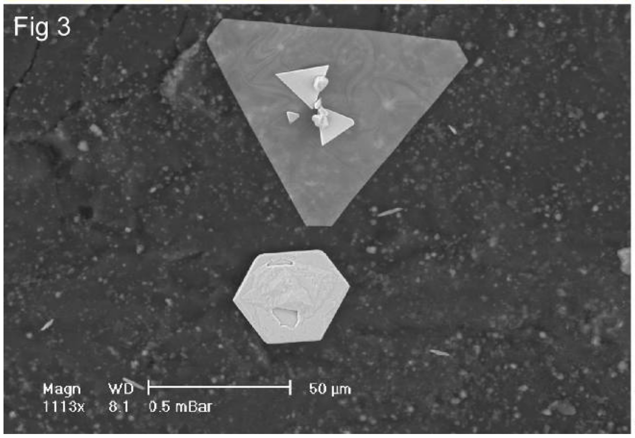
Natural supergene (secondary) gold deposition is a process whereby chemical weathering of gold deposits can lead to the dissolution of gold from the hypogene primary gold deposit (hosted by sulphides or quartz), transportation in solution and then precipitation elsewhere in the weathering profile. Whereas the primary gold present in the host fresh rock is commonly a Au-Ag alloy [1], the secondary gold is usually pure [2], although secondary Au-Ag alloys form in isolated cases [3]. In the southern region of Western Australia where groundwaters are highly saline (67,000 mg/L Cl) at up to 3x seawater salinity and acidic (pH from 3 to 7) gold presently occurs in solution as the gold chloride ion and will precipitate in its pure form. However, gold colloids may also form and provide a stable mechanism of transport in this environment.

The Golden Virgin pit, Parker Range, south of Southern Cross in Western Australia is a small gold deposit where primary mineralisation is covered by 30 m of regolith. Weathered fracture surfaces in the quartz vein blocks are lined with different generations of secondary iron oxides, clays and sulphates together with an exceptionally rich population of supergene Au crystals (Fig. 1). The gold is single crystalline Au particles with shapes such as hexagons, triangles and truncated triangles (Fig. 2).Gold is normally bright in BSE; however the supergene Au at Golden Virgin also included a population of grains that are darker grey (Fig. 3). Upon closer examination it was found that many of these crystals are transparent to the electron beam [4] with underlying materials visible through them. Some direct analysis of gold crystal edges indicate these nanoplates to be <17 nm thick. This indicates that gold, when thin, is not always bright in atomic number contrast (for SEM detection) and should be taken into account when searching for gold in samples using microscopy. SEM observations also reveal complex internal structures to the nanoplates where contouring of the lattice appears to produce these structures and small holes appear to act as seed points. These observations are similar to those made on gold crystals grown experimentally from gold chloride. On the surface of the gold plates we have found (using FEGSEM) a separate, nanoparticulate population of gold crystals that are 20-200 nm in crystallite size [4] (Fig. 4), in the form of heaxagons and triangles. This supergene gold occurs closely associated with salt crystals and sometimes intergrown with barite, supporting the premise that native gold (Au/Ag alloy) was dissolved locally into groundwater, the silver remained in solution, and pure gold was precipitated. The single crystal and ultra thin gold plates suggest rapid deposition of supergene gold in this environment, completed on the order of days rather than over prolonged timescales and driven by evaporation.

Gold colloids are of increasing importance in manufacturing because of their unique properties and experiments have shown that they can form rapidly when a gold chloride solution comes into contact with a reductant and once formed they are stable up to 400°C. The nanoparticulate fraction of gold would likely have occurred as a colloidal suspension prior to final deposition in the regolith; this represents the first direct observation of these nanoparticles in nature although it has long been postulated. Gold colloids are therefore, an interesting mechanism to transport gold in both spuergene and hypogene environments. Searches for such an *invisible* gold component in samples are now possible using novel microscopy and element mapping techniques







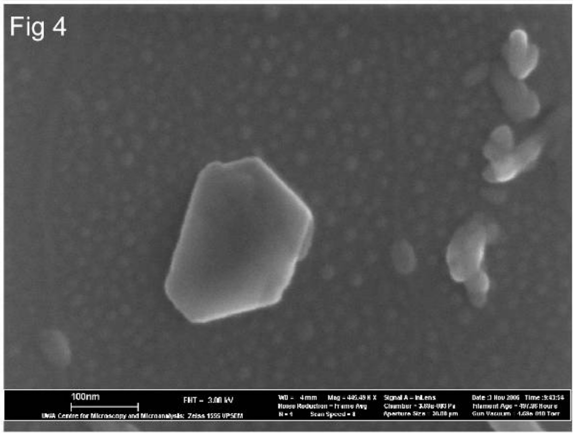


Figure 1. Optical micrograph of supergene gold nanoplates. **Figure 2.** SEM (BSE) of single crystal gold nanoplates. **Figure 3**. Atomic number contrast highlights effect of thickness variations in gold. **Figure 4.** High resolution SEM image of a gold nanoparticle on the surface of one of the nanoplates

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BOREHOLE RADAR FOR BROWN FIELDS EXPLORATION IN AUSTRALIA

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Keywords: Borehole radar, brown fields exploration, in-mine geophysics, drilling

Introduction

Exploration techniques have the challenge of not only finding new orebodies, but also of calculating the continuity of them. The reliable estimation of the continuity of a mineral resource and its subsequent ore reserve is critical to both the confidence in a feasibility study and also to the day to day operation of a mine (Dominy *et al.*, 2002). Specifically, underground mining requires a massive capital investment and mining engineers need to combine management strategy with a critical understanding and assessment of the technical and financial risks. A million dollar piece of machinery should not be used as a geological mapping tool. As mining costs increase and orebody discoveries become more complex, it is essential that mine planners have accurate maps of structures ahead of mining. It is no longer acceptable to mine blindly or with little knowledge of what lies ahead.

Geophysics has the ability to provide more detailed continuous information about an orebody than from drilling alone, both at the exploration and mine feasibility stage. Borehole radar is one such geophysical tool that can provide high detailed information about structure and lithology contacts associated with mineralisation (Turner et al 2001).

Orebody modeling

Geological risk in mining projects is well known and appreciated. Traditionally orebody modeling (David, 1977a and 1977b) is based on the interpolation of sparse drillhole data. Three dimensional (3D) orebody modeling and commercial mine planning software packages like VULCAN, GEMS Advanced Exploration, Surpac Vision or Datamine Studio aid the development of feasible models from these sparse drillhole datasets. These packages attempt to model and quantify the uncertainty and risk, traditionally by developing a deterministic block model that is assumed to be a fair representation of reality. (Menabde *et al.*, 2004, Dimitrakopoulos *et al.*, 2002) However, realistically there could be numerous block models that honour the sparse drillhole data. Authors are now recommending conditional simulation techniques that provide a means to quantify and assess the geological uncertainty of orebody attributes as well as to link this uncertainty to engineering processes, profitability criteria and decision-making (Dimitrakopoulos and Konstantinos, 2001).

It cannot be denied that ultimately additional mapping of the orebody will decrease the geological risk. However, additional drilling is often too expensive, when compared to the potential gain. Geophysical methods can provide substantial amounts of remotely sensed data about an orebody at a fraction of the cost of drilling for the same amount of information. The use of geophysical data to aid reserve modeling is well known in the petroleum industry (Journel and Alabert, 1990). Moreover geophysics is now not only recognized, but accepted as a means for more cost-effective metalliferous ore body delineation during not only resource definition but also mine development and production (Fullagar and Fallon, 1997).

Borehole Radar Then and Now

It is not a recent concept to use BHRs to identify and delineate structures of interest to miners. In 1910, the first reported BHRs were developed by Leimbach and Lowe (1911) and used to form a crude shadow image of an orebody. More recently, borehole-based radio frequency shadow imaging methods in higher frequencies have been used to map aquifers, coal insitu gasification tunnels, oil shale retort burnfronts and copper ore bodies (Holmes and Balanis, 1977; Annan and Davis, 1978; Rao and Rao, 1983).

More conventional surface based ground penetrating radar (GPR) methods have been used extensively in mining applications. GPR was used during the nineties in dry salt mines to map ground water, hazardous zones, roof cracks and stratigraphic variations. Nickel and Cerny (1989) reported 10-30 MHz GPR transmission ranges of 300 m in carbonate, 500 m in dry crystalline rock, 5000 m in Zechstein salt. Annan *et al.* (1988) report imaging in reflection to comparatively modest depths (of the order of 20 m) using a GSSI 100/300/600 MHz radar in damp Canadian potash mines in the late seventies. However, Scaife and Annan (1991) pointed out that GPR usage in mines is limited because environments are geometrically complex and often exhibit high radar attenuation. Roofbolts and wire meshes scatter 'clutter' back into the receiver. BHR operates from underground drillholes and, as a consequence, is able to escape radar signal reverberation in mining tunnels.

Today BHR's are being designed, built and sold throughout the world. The Slimline BHR probes used in this study were developed by Mason (*pers. com.*), Claassen (1995) and Hargreaves (1996). While the original radar has been copied quite widely, its specifications have changed very little. Its descendants continue to use ~20 kW pulsed transmitters. Radar probes are 25 to 35 mm diameter and up to 2 m long. They radiate in the 10 to 100 MHz band. Echoes received are amplified and then digitized to 12 bits stacking. Using carefully selected components gives the radar a well established capacity for operating in hot (70o C) hard rock mine boreholes.

BHR is now being used frequently in a number of different mining environments, from coal to metaliferous (Liu *et al*., 1998). Through parallel research on the hardware by Woods, Van de Merve, Van Brakel and Hargreaves (*pers. com.*) cableless downhole BHR tools have been developed. Although advances in antennas and hardware design are ongoing, radar probes are now sealed units that are light and easily deployable using the drillrig.

Borehole Radar interpretation and direction

One limitation of the current slimline BHR[1] system is that it is non-directional. A lot of work is being done on fat directional BHR antennas and the interpretation of their field data (Ebihara *et al.*, 1996, 1997 and 2000; Eisenburger and Gundelach, 2000; Sato and Tanimoto, 1992; Sato *et al.*, 1994) however, the diameters of these directional antennas are too large for applications in slimline mining boreholes. It is impossible with current technology to build efficient directional slimline BHR antennas at a frequency low enough for mining and mineral exploration applications.

Interpretation techniques have been developed to overcome the directionally problem. It is common knowledge that *a priori* information can assist with the identification of major reflectors in non-directional radar profiling (Osman, 2002; Osman *et al.*, 2003; Vogt, 2004; Du Pisani and Vogt, 2004). Current BHR interpretation techniques using synthesis and primitive forward modelling enable the interpretation of complex radar reflections in 3D.

Borehole Radar in Australia

Borehole radar applications in South African gold and platinum mines and Canadian diamond mines are well known where the stratigraphy simplifies the interpretation of BHR data. While there has been a lot of work in looking at the application of borehole radar to greenfields and brownfields mineral exploration in Australia (Turner, 1996), the complexity of Australian deposits initially stalled the application. This complexity now fuels the applications of the technology. BHR has been identified as a technique that can map complex geology at the resolution needed for in-mine and extensional exploration. For resistive hard rock mines BHR is the only mapping technique beyond drilling itself that can provide the resolution needed for accurate mine planning of these complex deposits.

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[1] A slimline borehole radar is less than 40mm in diameter.

Borehole radar is being used currently in both nickel and gold in-mine exploration in Australia to map structures and lithology that relate to mineralisation directly ahead of mining. For gold projects, BHR has the ability to map gold bearing quartz reefs and shears. For nickel projects BHR has the ability to map a prospective contact and the breaks and faulting of this contact. Recent work has also found that radar has the ability to use amplitude analysis to map out high massive sulphide content zones. This work is very recent and still ongoing.

A Nickel Example for BHR

BHR is being used to map out the basalt – ultramafic contact in Kambalda style nickel deposits. Figure 1 shows an exploration hole drilled from current development downdip to explore the contact at depth. The hole was wedged 4 times to explore this contact. A BHR survey was conducted in Wedge 4 (W4). The results of the BHR survey are shown as migrated section in Figure 2 and with the resource model overlain in Figure 3. By comparing figures 2 and 3 you can start to note the reflections from the contact are evident in the data. Interpretation is complex, but not impossible.

There are a number of things you can observe in the radar data. First note that the migrated image is symmetrical about the drillhole. The data is migrated in this way as we don't know the direction of reflections during processing and this enables the interpretation of data of both sides of the drillhole in this section. Secondly not the texture of the data, higher frequency data appears close the hole. The frequency of the data then gets lower as range increases from the hole. This is a function of the absorption of the radar signal in the rock.

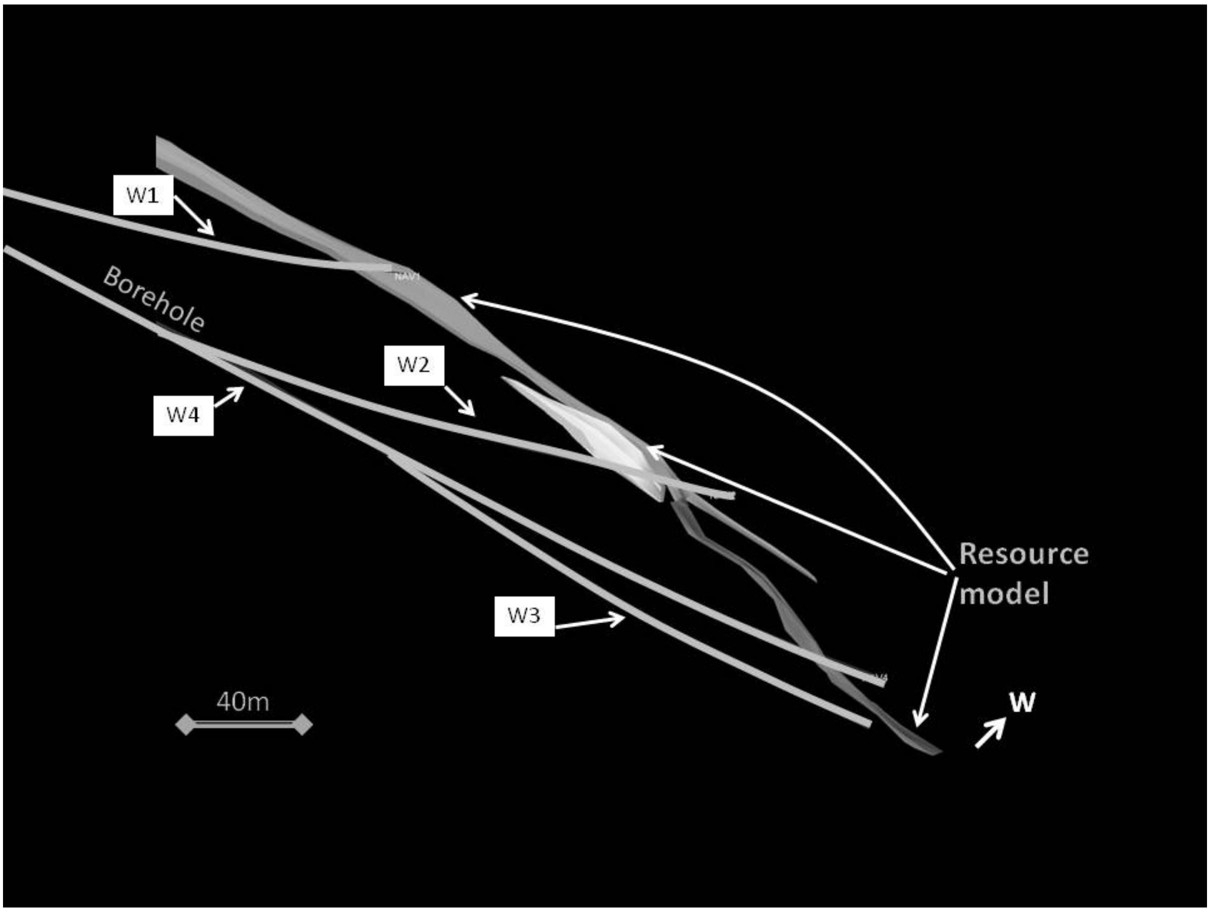

Figure 1: Layout of 4 wedge holes to explore the basalt-ultramafic contact at depth. A BHR survey was conducted in Wedge 4 (W4).

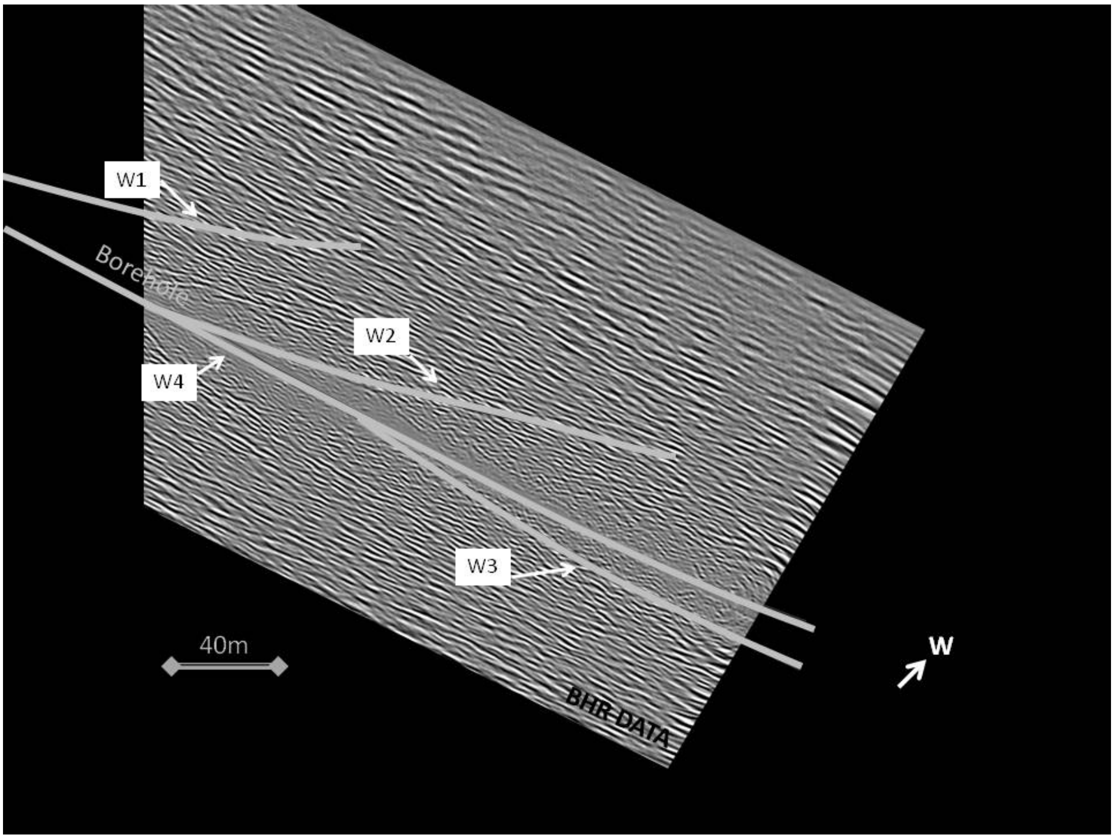

Figure 2: The BHR migrated data in section from Wedge 4.

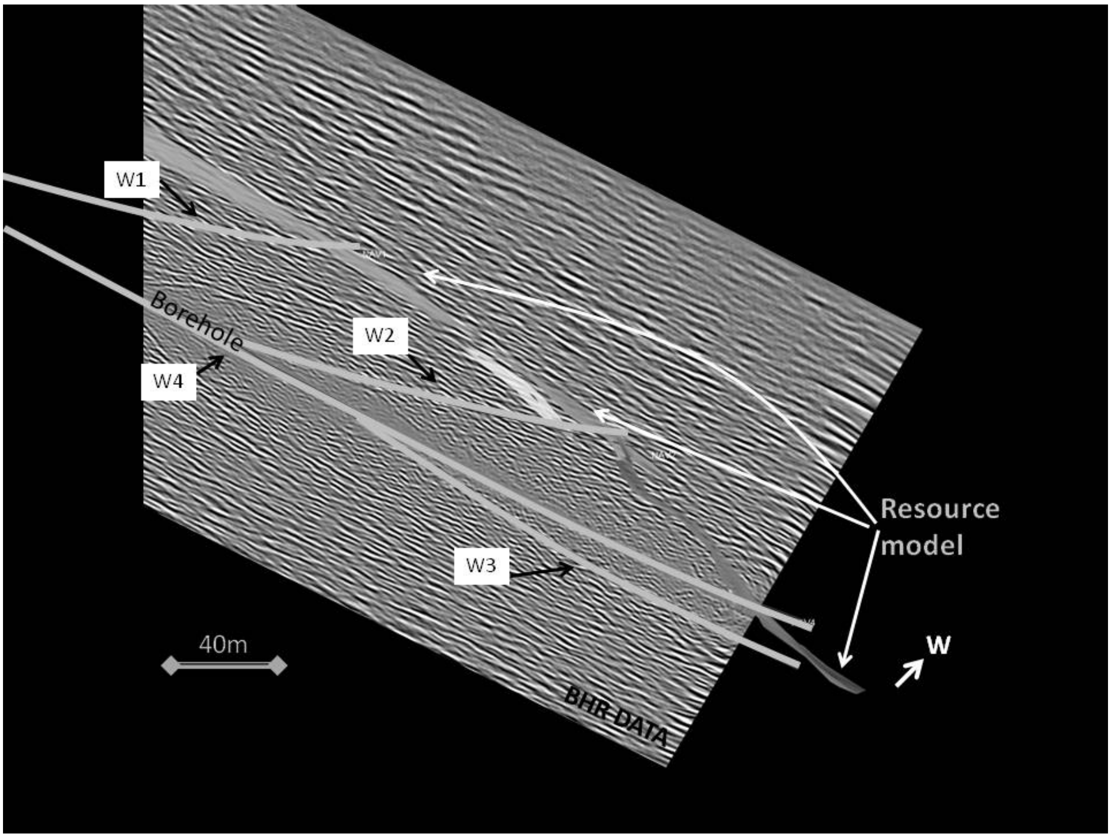

Figure 3: The BHR migrated data in section from Wedge 4 overlain with the resource model generated from drilling.

Conclusions

This paper has given a brief update on BHR technologies for exploration and mining. The data example for nickel exploration demonstrates the detail that BHR data has the ability to provide. Interpretation of radar data from Australian mineral deposits is complex as are the deposits, but BHR can provide the continuous information about the structure and lithological contacts from these deposits that is difficult to derive from drilling alone.

Acknowledgements

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NEW USES FOR OLD DATA; LITHOGEOCHEMISTRY FOR CLASSIFICATION, ALTERATION AND GEOMETALLURGY

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Introduction

Multi-element assaying of samples is common in exploration, resource and grade control work, especially in relation to commodities such as Ni and Fe. Further, some mining operations collect phase-specific data such as ‘extractable’ Cu, sulphide sulphur, silicate Ni and carbonate, and organic carbon among the many such measures available.

Using simple plots, projections of mineral compositions as points and lines onto diagrams, projections of assay data into a known mineralogy ‘space’ and deriving calculated mineralogy from assay data turns such data into valuable quantitative information. This can be applied directly to logging, mapping, stratigraphic correlation and the identification and quantification of hydrothermal alteration. It is also possible to derive more inferential estimates of key metallurgical performance parameters such as hardness, acid consumption, and the distribution of deleterious components, both as discrete phases, or as substitutions into specific minerals from such data.

These measures, when performed as formal metallurgical tests, are time consuming and expensive and are normally conducted on composites. Estimates derived at the sample scale are able to be modelled spatially, and therefore be used to classify materials in order to optimise plant feed. Examples of this approach are given below.

Classification

Many diagrams exist in the geological literature for classifying analytical data into, for example, rock type. Hallberg (1984) showed that based on the relatively immobile elements Ti, Zr and Cr (under both metamorphic and weathering conditions), it was possible to discriminate between volcanic rock types in the Yilgarn Block (Figure 1). The plot works because although mobile constituents are lost from the rock, immobile elements are conserved. The concentration of the immobile elements changes, but their ratio does not.

In Figure 1 (right) the same data are plotted on a TAS (total alkalis versus silica) diagram. The classification is not ‘one-to-one’ as the TAS diagram classification is based on relatively mobile elements. Even plots such as the ‘Hallberg’ plot still need to be applied with care. Under extreme conditions, and depending on the host for the immobile element in the primary rock, Cr and Ti may be mobilised to some extent. Robertson et al. (1998) report the plot is most useful for saprock, saprolite and the plasmic zone. The application of the plot to near surface materials (mottled zone and lateritic duricrust) is less successful because Ti is only partly stable.

Plots such as these are useful for a variety of purposes, are easy to apply, and may be developed for specific purposes and terrains.

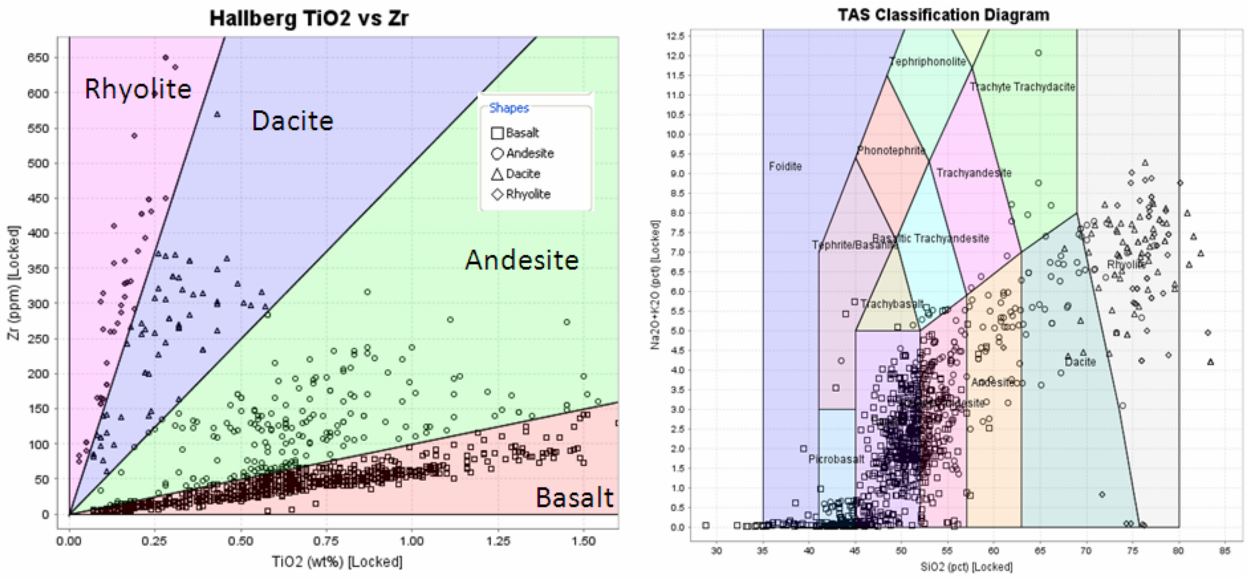


Figure1. Rock type identification in deeply weathered terrain, left, (after Hallberg, 1984) and with the same data plotted on a TAS diagram (right) for comparison.

Fertility & Mineral Chemistry

Figures 2, 3 and 4 provide an example of the application of diagrams to assessing mineral chemistry data for exploration fertility. Figure 2 (left) shows a Jensen cation plot. This plot is used to classify igneous whole rock data; however, the same triangular coordinates can be used to represent spinel compositional variations (see the nodes on Figure 2, right). To illustrate the use of the diagram, a subset of data from Barnes and Roeder (2001) has been plotted (Figure 3). Spinel data from ophiolites, kimberlites and amphibolites are shown. The data form discrete clusters in the compositional space on the diagram. If these classifications were deemed to be significant, contoured regions may be set up to classify newly acquired data into these pre-defined groups. Figure 4 shows derived regions that may be used to classify data into these groups. Note, these contours have been generated from point density regions, and as such, represent an automated yet empirical classification procedure. Figure 7 shows an example of a point density image.

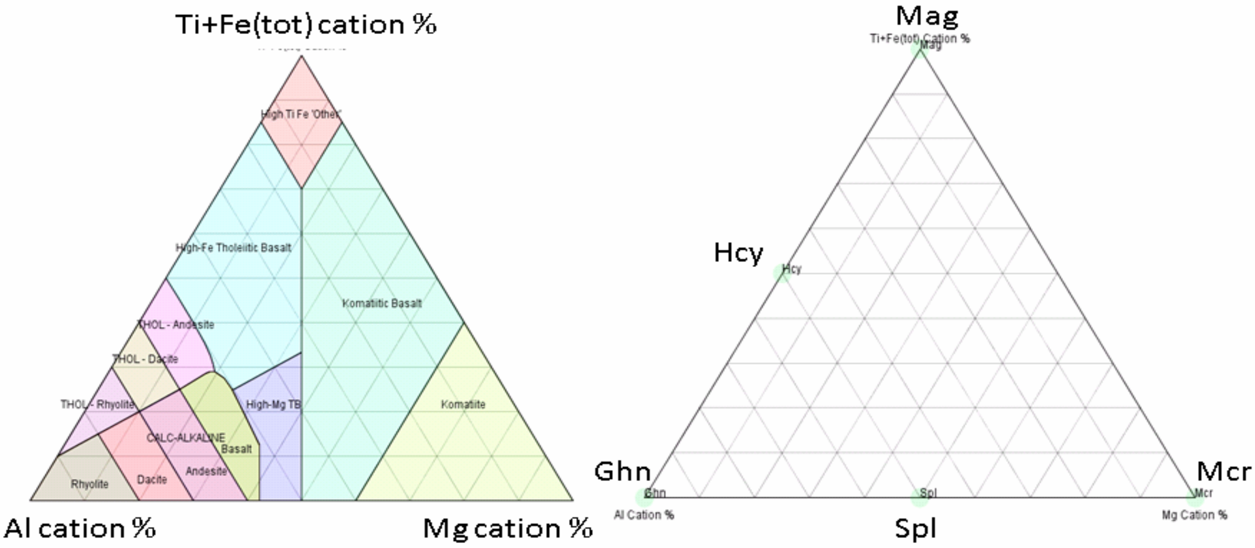


Figure 2. Jensen cation plot (left) and modified version (right) with spinel nodes shown. Spinel names abbreviated Mcr=magnesiochromite, Spl=spinel, Hcy=hercynite, Ghn=gehlenite, Mag=magnetite**.**

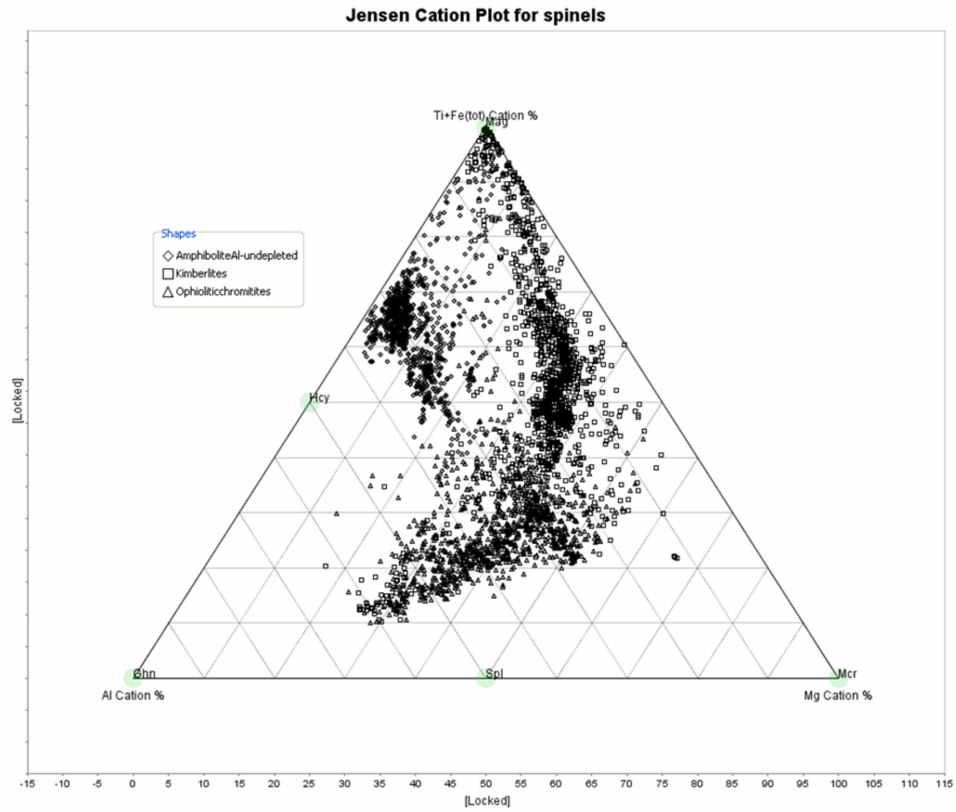


Figure 3. Spinel data from Barnes and Roeder (2001) plotted on the modified Jensen cation plot.

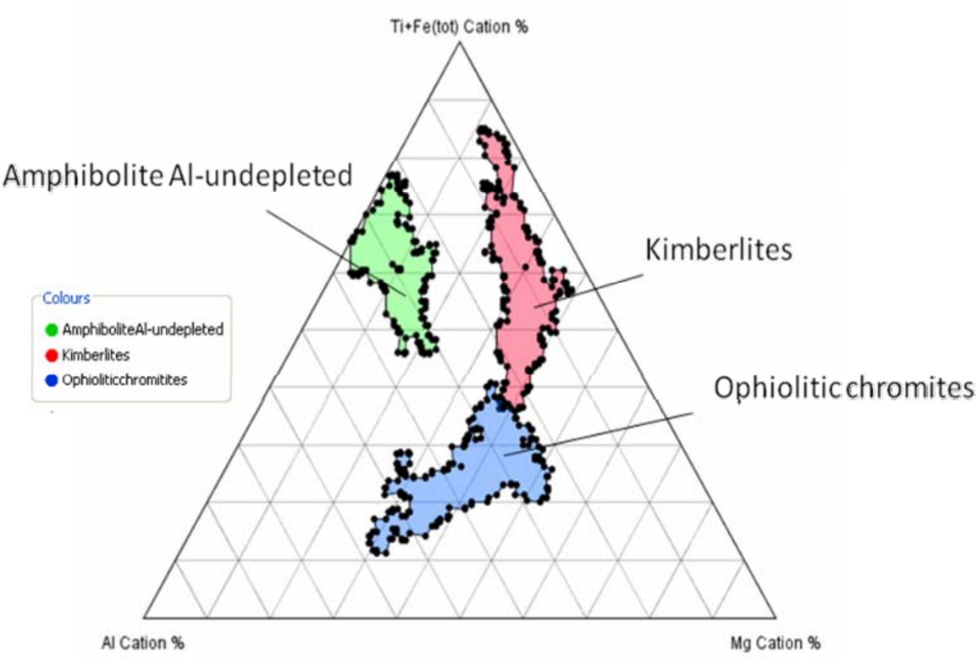


Figure 4. Classification regions derived from the data plotted in Figure 3 derived from the plotted data point density.

Alteration

Figure 5 shows a PER (Pearce Element Ratio) diagram that is designed to plot rocks with a basaltic composition on a line with a slope of one regardless of their relative abundances of olivine, plagioclase, orthopyroxene or clinopyroxene. This is achieved via the indices shown on both axes. The implication is that samples that are logged as being basaltic, yet plot off the control line, may have been hydrothermally altered. The data shown plot predominantly on the line with a slope of one, yet there are distinct samples that do not fit the basalt model, and may be altered and worthy of follow-up investigation if these data were being used in an exploration context. The angular displacement from the basalt control line down to the altered samples provides a quantitative measure of the degree of alteration. Figure 6 shows a GER (General Element Ratio) diagram adapted from Gemmel (2007) and Large et al. (2001) that is designed to represent important alteration mineral assemblages associated with VMS deposits. In this case lithogeochemical data from a VMS deposit have been plotted onto the diagram framework, and the point size varied by copper content. The diagram shows that the most mineralised samples are associated with dolomite, ankerite, chlorite and pyrite. The diagram allows assay data to be interpreted within a mineralogical framework, and at the same time a quantitative measure of the degree of alteration may be obtained for exploration vectoring purposes.

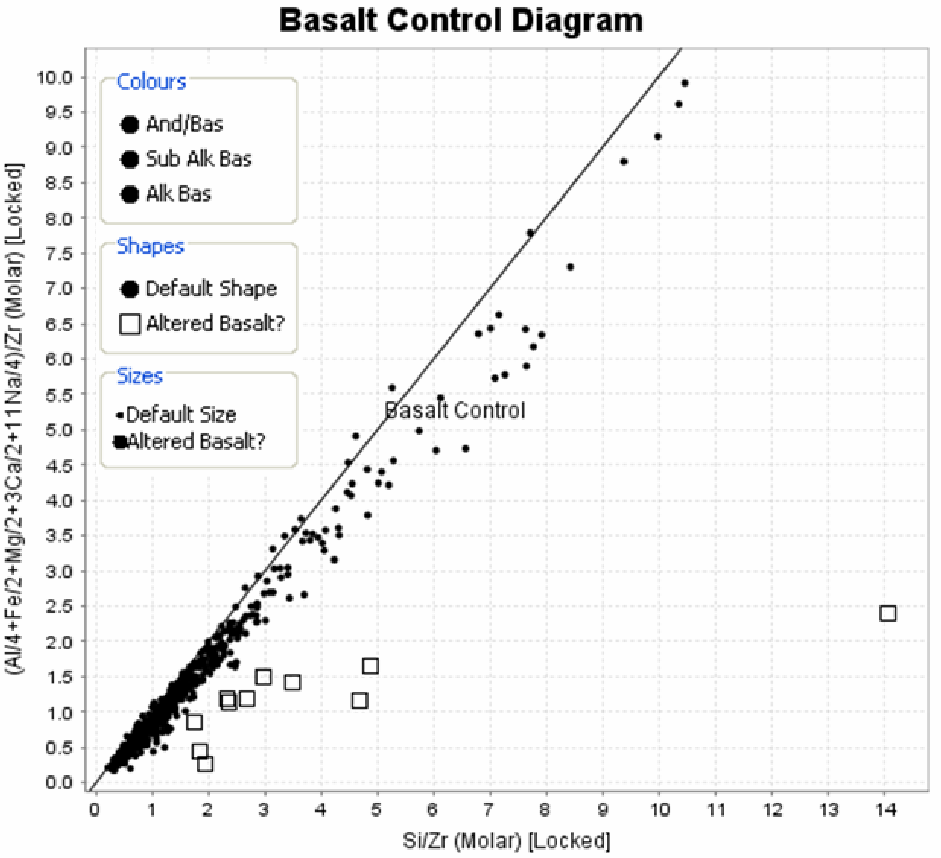


Figure 5. Basaltic samples plotted on a basalt PER control diagram. See text for discussion. Large squares indicate potentially hydrothermally altered samples worthy of follow-up.

Mineralogy and Metallurgical Properties

Copper and sulphur assay data have been plotted in Figure 7. To allow for a mineralogical based interpretation (and therefore, in a Cu processing context, potentially an important sample based metallurgical classification) control lines have been added for various copper mineral species. To facilitate interpretation, the Cu and S data have been expressed in molar quantities so that the slopes of the mineral control lines represent the minerals stoichiometry. For example, chalcocite would plot on a line with a slope of two. The diagram quickly reveals that the predominant copper minerals present are bornite, chalcopyrite, pyrite and perhaps cuprite (a non-sulphur bearing copper phase). Diagrams such as these do need to be used with care as other mineral species may interfere with the classification. For example, barite would cause a displacement parallel to the x axis, however, the barium content could be used to adjust the plotted sulphur value by subtracting ‘sulphur in barite’. Figure 8 shows another application of a mineral control diagram. In this instance, the diagram is designed to re-cast ultra-mafic rock assay data in terms of the dominant mineralogy, which includes talc. Such a diagram would be useful for classifying sample scale data in order to model the distribution of talc, and therefore potentially assist with the scheduling and stockpiling of talc-bearing material.

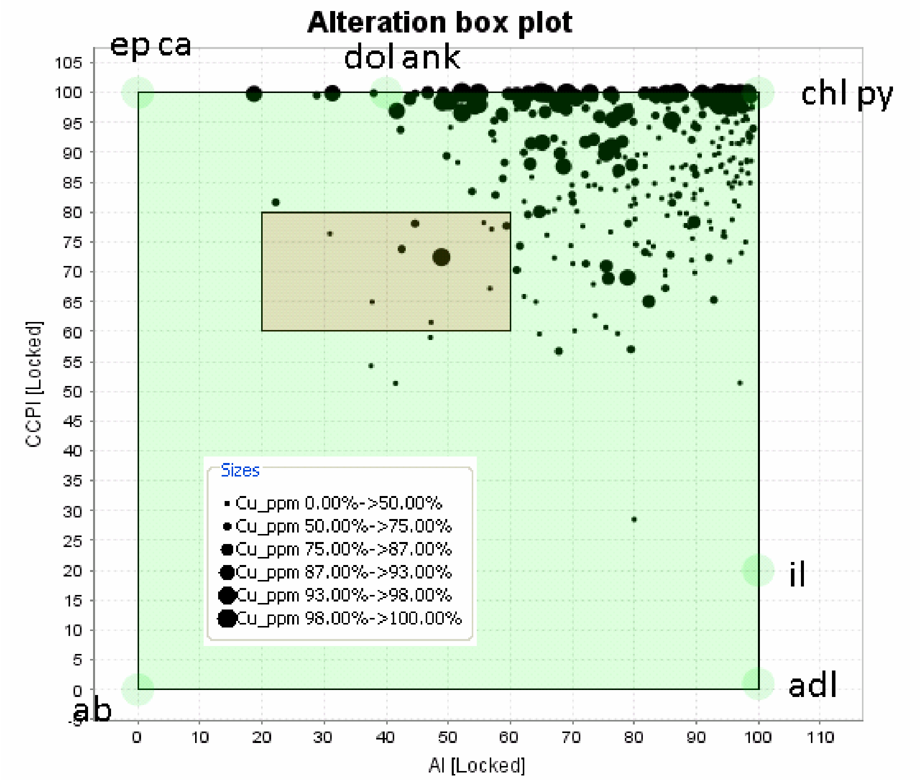
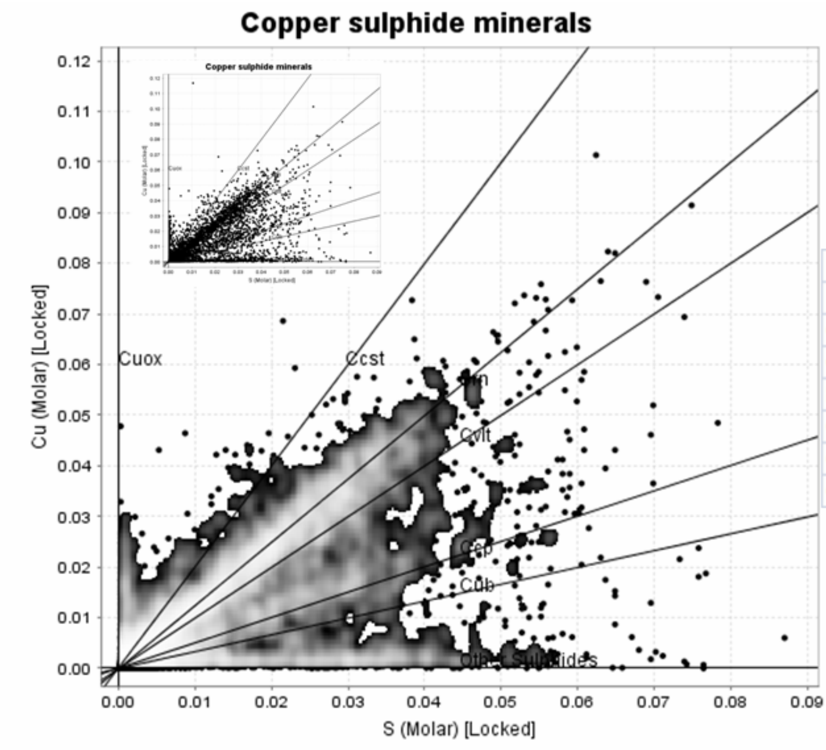
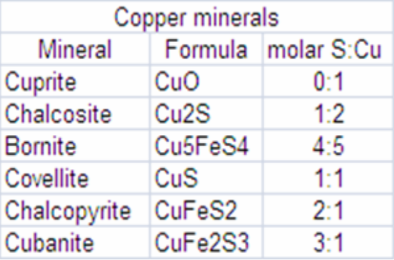


Figure 6. CCPI (chlorite-carbonate-pyrite index) vs AI (alteration index). Mineral names; ep-epidote, ca-calcite, chl-chlorite, py-pyrite, il-illite, ab-albite, adl-adularia. Diagram after Gemmel 2007 and Large et al. 2001. Point size proportional to Cu content.

Conclusion

The application of relatively simple interpretive tools to assay data is able to provide valuable quantitative information for geological mapping, alteration modelling, fertility assessment and metallurgical classification. In many cases the assay data are already available, and therefore the information is ‘cheap’. In cases where the data do not already exist, the value of such information should encourage systematic operation-specific assaying on a routine basis.





Copper minerals		
Mineral	Formula	molar S:Cu
Cuprite	CuO	0:1
Chalcosite	Cu2S	1:2
Bornite	Cu5FeS4	4:5
Covellite	CuS	1:1
Chalcopyrite	CuFeS2	2:1
Cubanite	CuFe2S3	3:1

Figure 7. Copper deposit assay data plotted on a molar Cu vs S diagram. Molar ratios of Cu to S and their 'slopes' for the diagram are provided in the table. The plotted data are shown as grey-scale point density regions.

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THE SPALDING COPPER PROJECT A CASE STUDY IN THE USE OF FIELD PORTABLE X-RAY FLUORESCENCE ANALYSIS IN COPPER EXPLORATION

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Abstract

The performance of three different Field Portable X-Ray Fluorescence (FPXRF) analysers was evaluated in:

- Terms of accuracy against a laboratory assay taken of sieved soil sample at same spot.
- Determining base and precious metal contents in dry vs damp soils.
- Determining base and precious metal contents in dry soils for 30sec vs 60sec readings.

When exploring for minerals, geologists are hampered by the fact that the potentially mineralised rocks are often covered with soil, sediment and or a deep weathering profile. A number of geological, geochemical and geophysical techniques have been developed to find indications of the nature of the underlying rocks. One of these techniques is soil sampling.

Traditionally this inexpensive procedure entails digging holes at specified intervals to collect samples from identified soil horizons. The samples are dried, screened to reject coarser material (that may bias a sample) and sent to a laboratory for analysis for the elements sought.

Drawbacks of the conventional soil sampling method include:

- The time between taking the soil sample, and receiving analysis from the laboratory.
- The cost of collection of those samples.
- The recording of an accurate location for those samples.
- The cost of analysis of those samples.

Phoenix Copper has been working with Innov-X and Thermo Fisher Niton to develop improved techniques for rapid quantitative analysis for base and precious metals including copper, lead, zinc, nickel and gold in soil and drill chip samples. Phoenix Copper has become the first company in the world to use the innovative Innov-X Omega Explore Package, a data assimilation combination incorporating the Innov-X Omega 6000 FPXRF analyser integrated with a Trimble Nomad global positioning system and a hand held computer using MapInfo and Encom Discover Mobile to take soil analyses in the field.

Phoenix Copper is using this package and a second comprised of a Niton XL3T linked via Bluetooth to a Garmin GPS to investigate the possibilities of:

1. Increasing sampling rates by reducing analysis times
2. Sampling damp media i.e. reducing down time
3. Proving the accuracy of analysis of FPXRF instruments.

Results indicate that

1. Analysis times can be reduced if the geologist is prepared to accept a decrease in accuracy.
2. Damp soils can be usefully analysed.
3. Accurate analysis can be achieved.

Introduction

Phoenix Copper Ltd (“Phoenix Copper”) is an Adelaide based company which listed on the Australian Securities Exchange on the 12th February 2008. Phoenix Copper is focused on copper and gold exploration in the Burra (Burra, Kapunda and Spalding projects) and Yorke Peninsula (Minalton project) regions of South Australia where it has eight tenements covering an area of more than 2,400 sq. km.

The company has been working with Innov-X and Thermo Scientific Niton to develop new and improved techniques for rapid quantitative analysis for base and precious metals in soil and in drill chip samples of the underlying rocks in the field throughout the year. The aim is to use the FPXRF analysers to immediately assess samples in the field, thereby reducing the number of conventional assays required, enabling immediate decision making during field investigations and saving considerable time and expense.

Historically handheld analysers have been considered inaccurate, expensive and fragile, and many exploration companies still take conventional soil samples by hand and submit them to commercial laboratories for analysis.

Geology

The Spalding inlier is a lens shaped area of tightly folded and faulted Upper Precambrian Willouran rocks, situated directly west of Spalding, and about 150km north of Adelaide. The inlier forms the core of an overturned anticline with an axial surface dipping about 700 to the west. The sequence is dominated by carbonaceous siltstone, silty and calcareous fine sandstone, limestone and dolomite. The Willouran sediments are intruded by small, intermediate to basic plugs and sills. The rim of the inlier is in most places faulted or thrusted against the younger Rhynie Sandstone of the Burra Group. Structurally the inlier consists of a series of northerly and north-easterly trending tight folds, with axial surfaces dipping west, parallel with the east - vergent thrust faults on the margins of the inlier.

Spatially igneous intrusives are clustered along the strongly deformed western fault boundary of the inlier, and some of the intrusives appear to have been controlled by the faulting. Locally the intrusives have converted calcareous lithologies into skarn and hornfels, e.g. South of the Gulnare-Spalding road near the northern boundary of the tenement a coarse grained skarn consists of quartz and calcite containing andradite garnet, with minor amounts of chlorite, tremolite - actinolite, and iron oxide, and trace amounts of chrysocolla and possibly malachite.

The main historical copper workings situated within the inlier include the Wheal Sarah mine, the Broughton Mine, the Broughton River prospect and the Ardincaple mine. Copper mineralisation occurs as veins, breccias and shear zones; as coatings on joints or fracture planes, and as disseminations and contact metasomatic replacement deposits in skarn. Most of the visible copper is in the form of the carbonates malachite and azurite. Gangue minerals include quartz, calcite and siderite, and at the Broughton mine irregular patches, veins and impregnations of micaceous hematite are associated with sulphides, limonite, and blebs of malachite in a breccia zone.

Issues to be Resolved Regarding FPXRF Analysers

Phoenix Copper's test work aimed to discover if:

- FPXRF analysers could provide results similar to those obtained from a laboratory in damp soils?
- FPXRF analysers could provide results similar to those obtained from a laboratory in short time readings.

As discussed by Scott et al 1999, and Laiho et al 2005, correlations of FPXRF and lab assay results were excellent for homogenous samples sieved to <125 micrometers however in these experiments sample sites simply had surface rocks and vegetation removed and the soil flattened to allow smooth contact with the face of the instrument.

Discussion of Test Work Undertaken

Experiment 1: *Determine if FPXRF Analysers provide Accurate Results in Damp Soil*

An experiment on the accuracy of XRF analysis in damp versus dry soils was undertaken on the 6,288,000N (AGD94) line of samples in the Spalding area. The soils are thin layers of calcareous silty clays overlying and surrounding subcropping Neoproterozoic siltstones, shales and dolomites.

Method: The following five analyses were taken on the same ground at <u>*about*</u> the same point:

- Sieved dry soil sample analysed in a laboratory via Aqua Regia with mass or optical spectrometer finish.
- Niton XL3T XRF analysis 60 second reading in damp soil after a rainfall and 60 second reading dry soil.
- Omega 6000 XRF analysis 60 second reading damp soil after a rainfall and 60 second reading dry soil.

Aim: Phoenix Copper aimed to determine if reliable assays can be achieved with analyses of damp ground.

Comments: If readings taken in damp soils are similar to those taken in dry soil and are also similar to sieved soil sample assays from the Laboratory then there is no need to wait for soils to dry after rain and therefore productivity increases can be achieved.

Results: The analyses for Cu, Pb and Zn were graphed as these elements are the primary indicators of the copper mineralisation we are looking for. On the Omega 6000, 60 second wet and dry readings for Cu, Pb and Zn showed very good similarity to the Lab assay of the sieved soil sample from the same point. On the Niton XL3t 60 second wet and dry readings for Cu, Pb and Zn showed similarity to the Lab assay of the sieved soil sample from the same point. Damp readings on both FPXRF units defined the anomalies quite well (Figures 1, 2 & 3).

***Figure 1*: Cu Lab Assay**

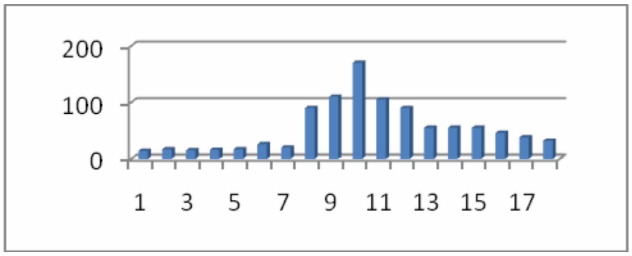


Figure 2: **Cu Omega 60sec Dry**

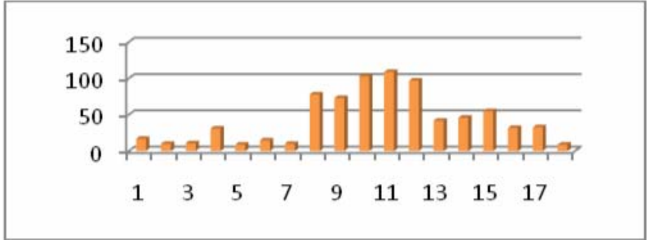
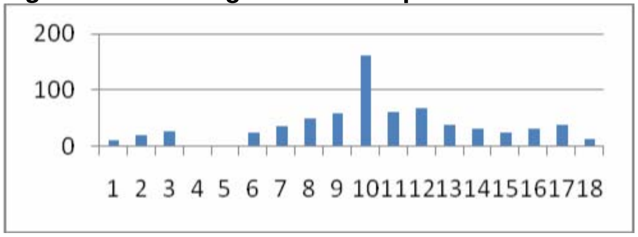


Figure 3: **Cu Omega 60sec Damp**



Conclusions: Reliable accurate readings can be taken and meaningful anomalies can be generated from analyses of damp soils with both instruments.

Experiment 2: Determine if accurate XRF analysis can be obtained in 30 seconds.

An experiment on the accuracy of XRF analysis taken in 30 seconds versus 60 seconds was undertaken on a line of samples in the Spalding area. The soils are thin layers of calcareous silty clays overlying and surrounding subcropping Neoproterozoic siltstones, shales and dolomites.

Method: The following five analyses were taken on the same ground at *about* the same point:

- Sieved dry soil sample analysed in a laboratory via Aqua Regia with mass or optical spectrometer finish.
- Niton XL3T XRF analysis 30 second reading and Niton XL3T analysis 60 second reading
- Omega 6000 XRF analysis 30 second reading and Omega 6000 XRF analysis 60 second reading

Aim: Phoenix Copper aimed to determine if reliable assays can be achieved with 30 second readings.

Comments: If readings taken in damp soils are similar to those taken in dry soil and are also similar to sieved soil sample assays from the Laboratory then there is no need to wait for soils to dry after rain and therefore productivity increases can be achieved.

Results: The analyses for Cu, Pb, and Zn were graphed as these elements are the primary indicators of the copper mineralisation we are looking for. Subject to detection limits, both the 30 second and 60 second readings for Cu on both the Omega 6000, and Niton XL3t showed excellent similarity to the Lab assay of the sieved soil sample from the same point (see figures 4, 5 and 6). Pb and Zn analyses for 30 second readings showed similar trends to the Lab sample assays but much better similarity in the 60 second readings.

Figure 4: **Cu Lab Assay**

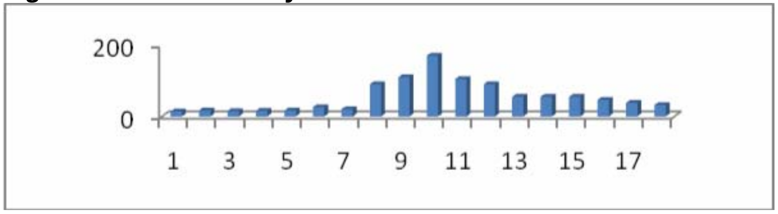


Figure 5: **Cu Omega 30sec**

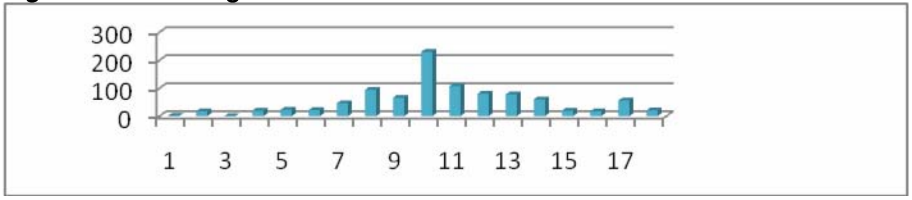
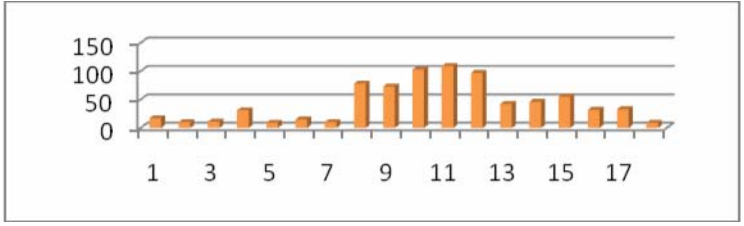


Figure 6: **Cu Omega 60sec**



Conclusions: Initial XRF readings should be taken at 60 seconds as the improved accuracy of the analysis overweighs time taken to collect the analyses. Accurate copper analyses were obtained in 30 second readings however the other element analyses are improved if 60 second readings are taken. Thus for first pass lines in an area 60 second readings should be taken and 30 second readings could be used effectively for infill lines.

Calibration and Control

The quality and precision of FPXRF results are strongly dependent on site preparation and calibration of instruments (Laiho and Perämäki 2005). All three experiments were conducted after calibrating the analysers and analysing standards and blanks and checking that the analyses of these were within acceptable tolerance ranges. The analyses for the standards and blanks were within range. Several approaches can be used for calibrating XRF analysers (Kalnicky and Singhvi, 2001). One method is based on the fundamental parameter method, another method is to perform an empirical calibration based on site-specific calibration standards analysed by an appropriate reference method. Phoenix Copper applied the latter method using standards of similar concentrations of elements as expected in the soils.

Conclusions

Note; given the different ages, specifications, power and limits of detection of the instruments it is not appropriate to make comparisons between the different FPXRF analysers however general observations can be made:

1. Analyses from these instruments cannot be considered absolute, however very accurate similar results to lab assays were obtained and contours of the element concentrations give similar shapes.
2. Reliable accurate readings can be taken in damp conditions and meaningful anomalies can generated from analyses of damp soils.
3. In a new area XRF readings should be taken at 60 seconds as the improved accuracy of the analysis overweighs any advantage in time taken to collect the analyses.
4. Accurate copper analyses were obtained in 30 second readings however the other element analyses are improved if 60 second readings are taken.
5. Thus for first pass lines in an area 60 second readings should be taken and 30 second readings could be used effectively for infill on copper projects in the Adelaide Geosyncline or similar terrain.

Acknowledgements

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References

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Kalnicky D.J., & Singhvi R., 2001, Field portable XRF Analysis of Environmental Samples, J. of Hazardous Materials 83 (2001) 93–122.

Detection Limits

Data from Portable Analytical Solutions Pty Ltd distributor for Thermo Scientific Niton

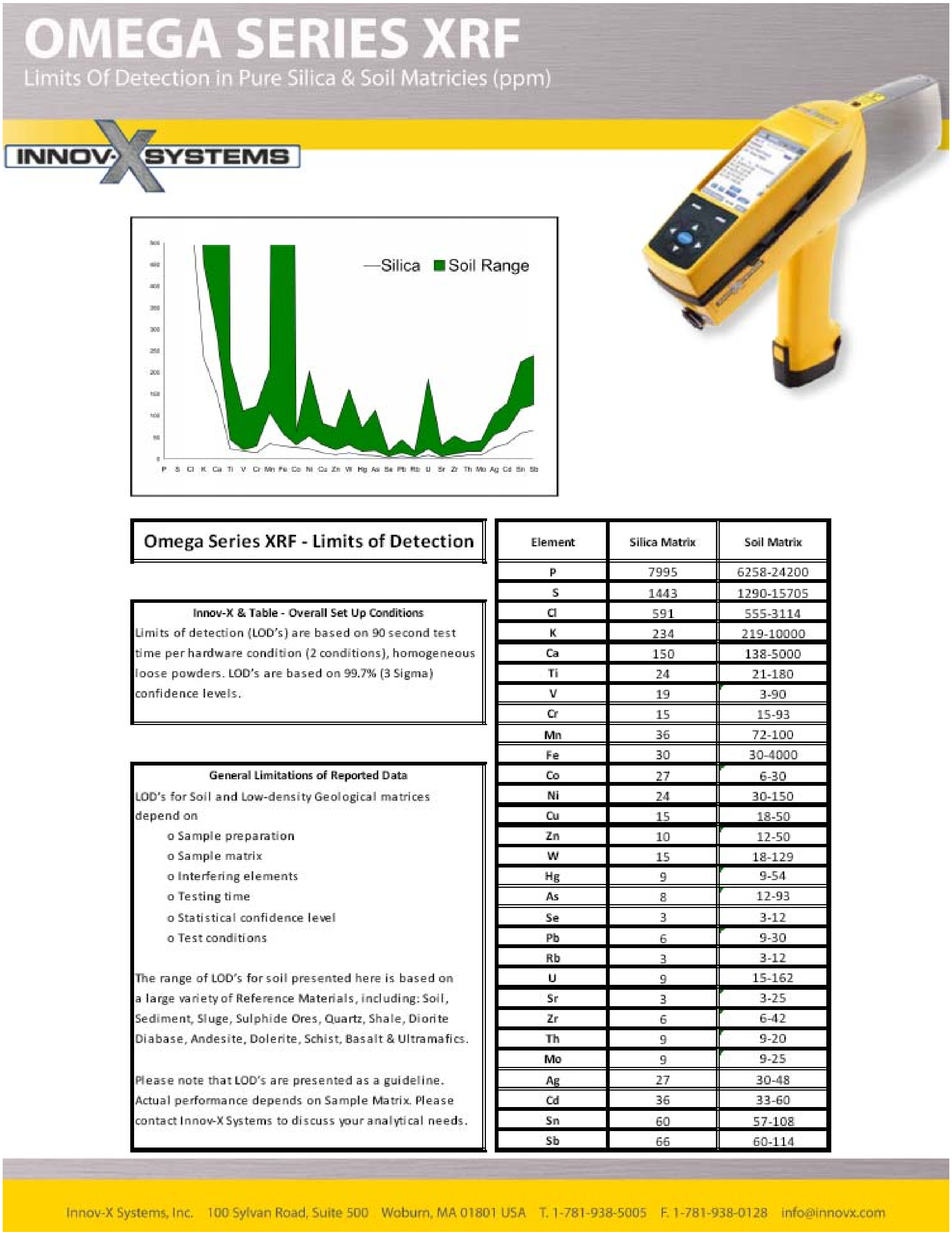
	Soil Matrix	
	Niton	**Niton**
	60 Sec for filter, 2 filters total 120 sec Standard Si Pin	**60 Sec for filter, 3 filters total 180 sec Standard Si Pin**
	Guaranteed MAX LODS	
Model	**XLt592**	**XL3t 500**
Element	**Soil Matrix**	**Soil Matrix**
P	2.50%	A/S
S	1.50%	A/S
Cl	1.50%	
K	500	A/S
Ca	400	500
Ti	200	160
V	175	70
Cr	100	85
Mn	300	85
Fe	500	100
Co	500	260
Ni	160	65
Cu	80	35
Zn	48	25
W		
Hg	20	10
As	19	11
Se	10	20
Pb	18	13
Rb	10	10
U		20
Sr	10	11
Zr		15
Th		20
Mo		15
Ag	50	10
Cd	40	12
Sn	70	30
Sb	72	30
Ba	1000	100
Nb		
Bi		
Au		
Sc	200	400

*** Note Niton LODS are guarantied to be no greater then listed above**

New NITON GOLDD SDD Detector			
	60 Sec for filter, 3 filters total 180 sec **SDD detector**		
	500	900	900He
	Guaranteed		
	Matrix		
Element	**Silica**	**Silica**	**Silica**
Mg		2.50%	0.25%
Al		2000	750
Si			
P		600	450
S	100	150	90
Cl	100	150	75
K	100	250	200
Ca	110	70	65
Ti	8	6	6
V	12	12	12
Cr	25	25	25
Mn	45	30	30
Fe	30	25	25
Co	25	15	15
Ni	25	22	22
Cu	15	12	12
Zn	6	6	6
W	50	50	50
Hg			
As	5	5	5
Se	4	4	4
Pb	4	4	4
Rb	6	6	6
U			
Sr	8	8	8
Zr	3	3	3
Th			
Mo	3	3	3
Ag			
Cd	7	8	8
Sn	10	16	16
Sb	10	15	15
Ba	20	50	50
Nb	3	3	3
Bi	3	3	3
Au	15	15	15
Sc	3	3	3

*** Note Niton LODS are guarratied to be no greater then listed about**

Detection Limits - Data from Innov-X



OMEGA SERIES XRF

Limits Of Detection in Pure Silica & Soil Matricies (ppm)

INNOV-X SYSTEMS

Omega Series XRF - Limits of Detection

Innov-X & Table - Overall Set Up Conditions

Limits of detection (LOD's) are based on 90 second test time per hardware condition (2 conditions), homogeneous loose powders. LOD's are based on 99.7% (3 Sigma) confidence levels.

General Limitations of Reported Data

LOD's for Soil and Low-density Geological matrices depend on

- o Sample preparation
- o Sample matrix
- o Interfering elements
- o Testing time
- o Statistical confidence level
- o Test conditions

The range of LOD's for soil presented here is based on a large variety of Reference Materials, including: Soil, Sediment, Sluge, Sulphide Ores, Quartz, Shale, Diorite Diabase, Andesite, Dolerite, Schist, Basalt & Ultramafics.

Please note that LOD's are presented as a guideline. Actual performance depends on Sample Matrix. Please contact Innov-X Systems to discuss your analytical needs.

Element	Silica Matrix	Soil Matrix
P	7995	6258-24200
S	1443	1290-15705
Cl	591	555-3114
K	234	219-10000
Ca	150	138-5000
Ti	24	21-180
V	19	3-90
Cr	15	15-93
Mn	36	72-100
Fe	30	30-4000
Co	27	6-30
Ni	24	30-150
Cu	15	18-50
Zn	10	12-50
W	15	18-129
Hg	9	9-54
As	8	12-93
Se	3	3-12
Pb	6	9-30
Rb	3	3-12
U	9	15-162
Sr	3	3-25
Zr	6	6-42
Th	9	9-20
Mo	9	9-25
Ag	27	30-48
Cd	36	33-60
Sn	60	57-108
Sb	66	60-114

Innov-X Systems, Inc. 100 Sylvan Road, Suite 500 Woburn, MA 01801 USA T. 1-781-938-5005 F. 1-781-938-0128 info@innovx.com

Data

Comparison of XRF Results Against Laboratory Samples Spalding 6288000N

Easting	Lab Assay	Niton 30sec	Niton 60sec	Wet Niton 60 Sec	Omega 30sec	Omega 60sec	Wet Omega 60sec
Copper Assays ppm							
275820	14	0	0	0	1	17	12
275840	17	0	0	0	17	10	20
275860	15	0	0	0	0	11	27
275880	16	0	0	0	20	31	2
275900	17	0	0	0	23	9	3
275920	26	0	0	0	22	15	26
275940	20	0	0	0	46	10	35
275960	90	75	0	50	94	78	49
275980	110	73	79	0	66	73	59
276000	170	195	0	103	230	103	161
276020	105	112	97	33	108	109	62
276040	90	112	53	65	81	97	67
276060	55	11	40	0	78	42	37
276080	55	0	0	44	60	46	32
276100	55	0	30	0	20	55	24
276120	46	0	35	0	18	32	31
276140	38	0	0	0	56	33	37
276160	32	0	0	0	21	9	14
Lead Assays ppm							
275820	5	0	0	0	7	2	5
275840	10	0	0	12	4	4	12
275860	5	0	0	11	0	3	5
275880	15	0	15	12	8	7	7
275900	10	0	0	21	5	16	8
275920	15	0	12	22	7	21	10
275940	10	0	0	0	0	3	8
275960	15	0	32	18	2	14	11
275980	15	29	15	23	2	8	10
276000	20	0	21	21	5	15	10
276020	20	21	0	0	1	13	13
276040	25	20	27	21	17	21	16
276060	30	30	17	30	13	21	27
276080	25	30	14	17	9	18	19
276100	25	0	15	20	14	15	23
276120	25	0	24	22	19	13	14
276140	20	25	15	16	17	11	15
276160	15	0	0	0	5	10	12
Zinc Assays ppm							
275800	24	0	28	28	40	21	0
275820	19	0	26	33	15	13	13
275840	20	0	0	23	32	24	22
275860	22	0	0	24	31	21	25
275880	21	0	42	18	21	14	27
275900	16	0	32	0	22	25	21
275920	23	0	0	0	41	30	18
275940	22	0	0	0	41	14	14
275960	25	0	24	0	36	26	23
275980	28	0	24	0	28	21	24
276000	24	0	23	22	21	28	19
276020	29	0	0	18	13	31	20

276040	24	0	25	0	39	29	19
276060	40	0	0	21	32	34	25
276080	29	0	0	32	27	27	30
276100	31	0	31	0	24	19	19
276120	40	0	2	21	38	24	31
276140	43	0	26	31	32	41	26
276160	47	0	24	41	55	38	30
276180	48	0	24	27	35	41	32
276200	48	0	31	0	59	36	38
276220	50	48	37	0	61	35	28
276240	145	54	58	60	69	57	72
276260	150	160	97	71	60	108	95
276280	80	0	34	0	45	100	33

Specifications of the FPXRF Analysers used for the Investigations

MODEL:	INNOV-X	NITON XLt 592 W	NITON XL3t 500
Manufacturer	Innov-X-Systems, USA	Thermo Scientific Niton Analysers	Niton Corp., USA
Operation principle	EDXRF	EDXRF	EDXRF
X-ray source	X-ray tube, Tantalum anode	X-ray tube, gold anode	X-ray tube, silver anode
Detector	High resolution Si-PIN	High Performance Si-PIN	High Performance Si-PIN
Cooling system	Thermo electrical	Thermo electrical	Thermo electrical
Main components	Single unit with integrated PC	Single unit with VGA touch screen	Single unit with VGA touch screen
Weight	1.6 kg with battery	1.2 kg	1.4 kg

HOW DEEP DO YOU WANT TO LOOK? TILT FILTERS, LAYER FILTERS, AND OTHER NEW WAYS OF EXTRACTING DEPTH STRUCTURE FROM GEOPHYSICAL DATA

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Key words: Potential fields, geophysical imagery, tilt filter, vertical derivatives, fractional derivatives, layer filtering, wavelet edge detection.

Potential field —gravity and magnetic—anomalies carry inherent information about the depth of their source. In essence, inferences about the depth of source rely on the observation that the “sharpness” of an anomaly, defined by the proportion of the amplitude made up of short wavelength/high wavenumber components, decreases with increasing source–detector separation. In the past, geophysical approaches to this problem emphasised direct numerical inversion of depth information. Geologists and explorationists, however, frequently pose the question in a different way: “How deep does this image see?”, or words to that effect. Their desire is to take the qualitative, geological-style interpretation of geophysical datasets used to support geological mapping or to make direct inferences of geological structure (e.g., Boyd & Isles, 2007), and imbue this with some indication of the depth of the structures resolved, or even into a discrimination of competing shallow and deep structural trends. What is needed is a visualisation method whereby the anomaly wavelength information related to source depth can be extracted in a form that preserves its map position and trends. The Geological Survey of New South Wales (GSNSW) has been investigating and developing a number of these approaches, and applying the results in support of recent mapping and interpretation.

Direct numerical inversion methods all consider local solutions to a wavelength–depth relationship. Simple half-width methods assume a simple source—a sphere, for example—and relate depth to the dominant wavelength of the anomaly. Euler deconvolution is a more sophisticated approach, applicable to gridded data, which also relates the lateral rate of decline of the anomalous field to the depth of source, but generalises to a wider range of source geometries by including a “structural index” which quantifies the power law relating source depth to anomaly amplitude. Incorporation of the structural index goes some way towards incorporating a geological understanding of the source, but goes no further than a broad categorisation of point, pipe (e.g., diatreme), cylinder or vertical slab (dykes, folds), and step (fault) type structures. Substantial ambiguity, and debatable estimates of source depths, arises in the Euler deconvolution of anomalies over areas of complex and variable geology, and much effort has gone into improving the discrimination of results (e.g., Fitzgerald et al., 2004).

Geological interpretation is better served by imagery that emphasises depth information. The simplest and most familiar images of this type show vertical derivatives. Simply put, the higher the degree of a vertical derivative, the more its response will be biased towards short wavelengths, and hence towards shallow sources (Ravat et al., 2002). In this sense, a vertical derivative is a form of high-pass separation filter, passing the signal of shallower sources and rejecting the signal of deeper sources. First vertical derivatives are stock-in-trade of geological mapping, because their responsiveness to short wavelengths means that they highlight features close to the Earth’s surface. Ideally, images of higher derivatives should correspond even more closely to the map surface, but in practice the rapid decrease in the signal-to-noise ratio with increasing differentiation order limits the approach to no higher than the second vertical derivative.

It is possible to exploit the relationship between vertical differential order and depth of source through the production of a series of fractional vertical derivatives over the range of orders from, say, ½ to 2. Differences between higher and lower orders constitute a qualititative layer filter, highlighting features over some intermediate depth range (Cowan & Cooper, 2005). Choosing three fractional vertical derivatives of different order, and applying one to each of the red, green and blue channels in a ternary image, produces an image that conveys some sense of contrasting deeper and shallower geology.

Other properties of derivatives are exploited by wavelet edge detection, the method commonly referred to as “worming” (Hornby et al., 1999). Maxima (or minima) in the first horizontal derivative occur over edges of source bodies. Increasing source–detector separation, usually achieved synthetically by upward continuation of the field, decreases the relative significance of short-wavelength components of the anomaly, and hence has the effect of a layer filter. Where a source edge—that is to say, a geological boundary—dips, the downward progression of the filtered layer with increasing upward continuation causes the maximum (minimum) of the horizontal derivative to migrate in the direction of dip. Presentation of a suite of wavelet edges coloured according to increasing upward continuation yields an image that the geologist can interpret as a map showing the dip of major faults and contacts.

While the mathematical treatment of magnetic and gravity fields is similar, they differ in some important respects. Most notably, the sources of magnetic fields are dipolar, while gravity sources are monopolar, with the result that magnetic anomalies decline more quickly with increasing source–detector separation ($\text{amplitude}^{-1} \propto r^3$ or a higher power) than do gravity anomalies ($\text{amplitude}^{-1} \propto r^2$). One expression of this behaviour is the structural index (S) of Euler’s equation; for equivalent bodies, $S_{\text{gravity}} = S_{\text{magnetic}} - 1$ (Stavrev, 1997; FitzGerald et al., 2004). The practical consequence for the interpretation of geophysical images is that, *ceteris parabis*, gravity images resolve deeper features than do equivalent magnetic images. Applied to wavelet edge images, a set of magnetic edges will, in general, resolve shallower features than an equivalent set of gravity edges. Comparison of magnetic and gravity edge sets can be particularly helpful in resolving contrasting deep and shallow structural trends, as might be encountered in fold-and-thrust belts characterised by thin-skinned tectonics.

Potential field edges have also been exploited in the GSNSW as a guide in inversion modelling. Not only do gravity and magnetic edges help constrain the location and trends of buried bodies that lack surface geological expression, they provide a powerful test of the admissibility of the final model, by comparison with synthetic edges calculated directly from the model anomaly (Musgrave et al., 2007).

Alternatives to conventional derivative methods are the phase filters, which combine aspects of edge detection and separation filtering. Recently, GSNSW introduced the use of the tilt filter applied to gridded TMI data, to generate imagery in which structural elements down to a depth of a few kilometres can be clearly discerned (Miller and Singh, 1994; Cooper and Cowan, 2006). The output of the tilt filter, applied to gridded TMI data after reduction to the pole, takes the form

$$\theta = \tan^{-1}\left(\frac{\partial T/\partial z}{\sqrt{\left((\partial T/\partial x)^2 + (\partial T/\partial y)^2\right)}}\right)$$

where θ is the tilt angle, over the domain $-\pi/2 < \theta < \pi/2$, and T is the intensity of the field. The tilt angle has the advantages of a wide dynamic range and a reduced sensitivity to source depth. Structures within the Stawell Zone in NSW have been interpreted from tilt-filter imagery despite sedimentary cover exceeding 5 km (Musgrave et al., 2008).

Imaging structure in the middle to lower crust, below the useful range of the magnetic tilt-filter imagery, is more problematic. Layer filtering methods involve attenuation of wavenumbers corresponding to sources above or below the depth range of interest (Cowan and Cowan, 1993). In the case of gridded aeromagnetic data, where sub-crustal sources are removed as part of the geomagnetic reference field, this reduces to some form of low-pass filter. Isostatic reduction of Bouguer gravity removes the contribution from isostatically-controlled variations in crustal thickness (e.g., Spencer & Musgrave, 2006), and the use of the ellipsoid as the elevation datum reduces the influence of geoid responses to mantle mass excesses and deficits. Similarly to layer filtering in magnetic data, the combination of isostatic reduction and the use of the ellipsoid datum effectively sets the base of the crust as the maximum limit to the depth of imaged sources. Both these approaches have been used in a GSNSW study to bridge the gap between near-surface methods (vertical derivatives and the tilt-filter) and sub-crustal (mantle lithosphere) mapping inferred from teleseismic tomography (Musgrave & Rawlinson, 2009).

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NEW TECHNIQUES IN REGIONAL 3D GEOLOGICAL MAPPING, SIMULATION AND VISUALISATION AND THEIR APPLICATION IN PREDICTIVE MINERAL EXPLORATION

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Keywords: 3D geology modelling, numerical simulation, data delivery, visualisation

Abstract. 3D Geological modelling of the Bendigo and western Victorian structural regions has lead to the development of robust modelling and data storage workflows within GeoScience Victoria. The products of this work has then been used as a basis for a number of "*value-add*" projects that, using numerical simulation and geophysical inversion technologies, aim to: (1) provide tools to companies exploring under cover, (2) assist in the development of prospectivity models for various commodities and new technologies in the energy sphere, and (3) improve our understanding of the tectonic development of the southern Tasmanides with particular respect to the minerals systems it contains.

Introduction

Geology is a three dimensional science. For decades exploration geologists in the coal, oil and gas industries, and more recently in the minerals industry, have been using sophisticated 3D modelling software to allow them to collate, visualise and analyse their datasets in three dimensions. Often however, this effort has been focussed at the reservoir/field or deposit/camp scale and few regional, full-crustal 3D geological models have been developed.

Several years ago the Victorian Government committed to providing to industry, the next generation of tools to explore Victoria. After consulting exploration geologists, researchers and government geologists it was recognised that 3D geological models would provide a critical tool to explorers interested in understanding, not just the distribution and history of mineral deposits, but the entire mineral system that was responsible for their development. To that end, GeoScience Victoria established the $2.5M 3D Victoria project which was designed to develop a sophisticated, fully attributed 1:250 000 scale 3D model of the whole crust incorporating the onshore and offshore geology of the state. It was envisaged that this project would:

- ☐ Provide a robust geometric framework for analysing controls on the formation and accumulation of resource systems
- ☐ Provide critical 3D data for existing minerals and energy exploration programs as well as next-generation exploration targets, including potential geothermal sources and geosequestration sites
- ☐ Highlight the controls exerted by basement structures on basin evolution
- ☐ Allow integrated studies of complex systems such as the pressure regime
- ☐ Within a basin undergoing simultaneous irrigation from onshore freshwater aquifers, drawdown of offshore oil and gas reservoirs and injection of captured CO2
- ☐ Make available valuable 3D constraints for future "value-add" projects such as numerical deformation, fluid flow, maturity and heatflow simulations, as well as 3D GIS analysis and prospectivity assessment.

This final point is critical to the success of regional 3D modelling programs. Regional models are valuable analysis tools in their own right, however, it is not until you start asking questions of your model such as "what are the regional structural controls on this belt of mineralisation and where else will I find them repeated?" using numerical simulation and other techniques, that the true value of 3D modelling becomes apparent.

Bendigo Zone Modelling

The first phase of regional modelling in the 3D Victoria project was concentrated on the Bendigo Zone due in part to the prospectivity of the belt, the high quality mapping and biostratigraphic control and the location of recently acquired deep seismic data.

This model covers the geology of the basement rocks from the Murray River, beneath the Murray Basin sediments, through the exposed Ordovician rocks of the outcropping Bendigo Zone, the Permian of the Ballan Basin, and beneath Otway Basin cover to the south. The zone is bound by the Avoca and Mt William fault zones to the west and east respectively (Figure 1).

The models themselves are available as volumes and surfaces at 1:250000 scale and contain surface and volumetric representations of the topography, stratigraphy (Cambrian, Ordovician, Silurian and Permian), fault geometries, cover thickness and the distribution of known ore deposits.

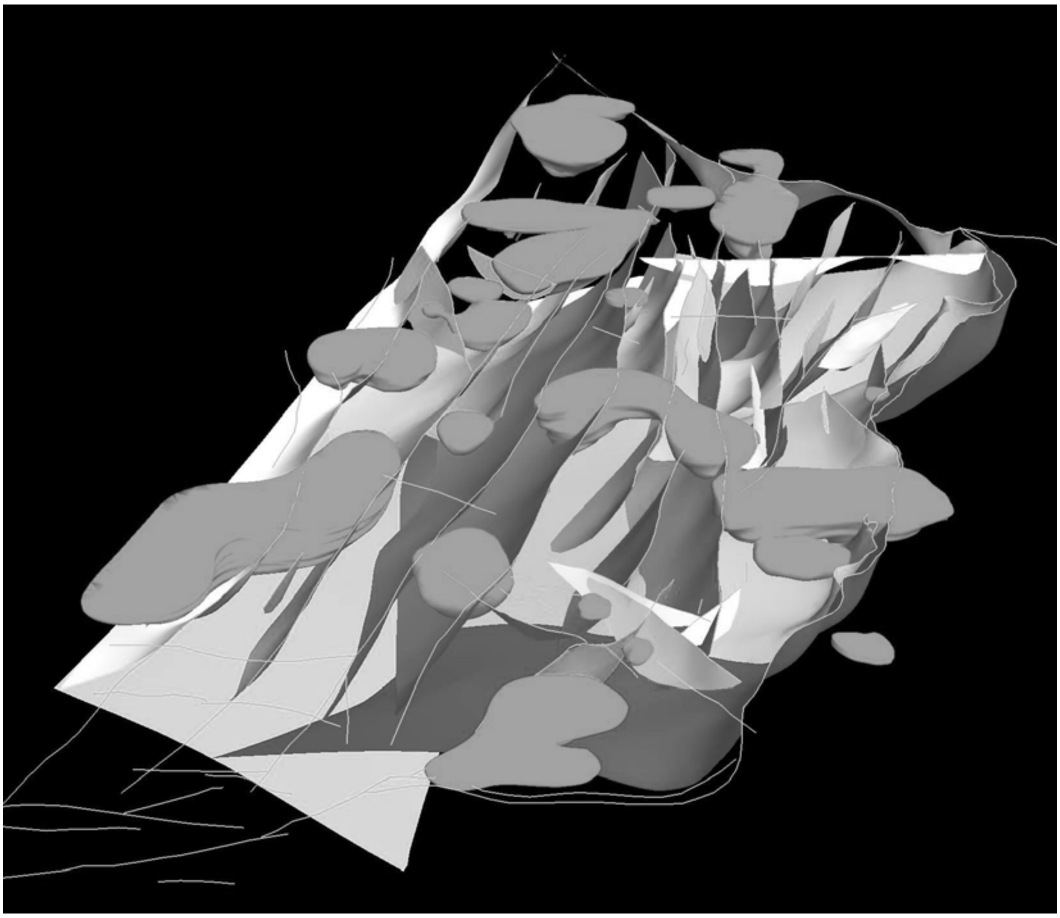


Figure 1. Perspective image of Bendigo Zone fault and intrusive model looking to the NW. Model is about 150km across.

3D Modelling Workflow

Geoscience Victoria's 3D modelling team have developed a model building workflow that is applicable to both onshore and offshore model building as well as integration modelling between basement and basin blocks, based on the flowing steps:

- Integrate all available surface mapping, drilling constraints, potential field datasets, 3D inversion models, seismic data, and other 2D and 3D datasets into a 3D storage and visualisation environment
- Define an agreed stratigraphy for the model region
- Construct serial cross sections based on surface geology and geophysical constraints perpendicular to major structural trend with some tie sections parallel to trend if there is sufficient structure to constrain the geometry in this direction.
- Serial sections were then digitised into a 2¾D potential field forward modelling package. Application of common rock property attributes (density and magnetic susceptibility) to the units in the sections and forward modelling of the interpreted geometries then allows a first order assessment of the validity of the starting geometry.
- Modelling was undertaken using the GeoModeller program where a potential field is derived that is constrained by all available structural measurements, stratigraphic information, mapping, cross sections and drilling and the 3D model is then calculated from that mathematical description.
- Visualisation of the modelling was primarily done using Gocad where the model, constraining serial sections and any other appropriate datasets and surfaces could be visualised and analysed.

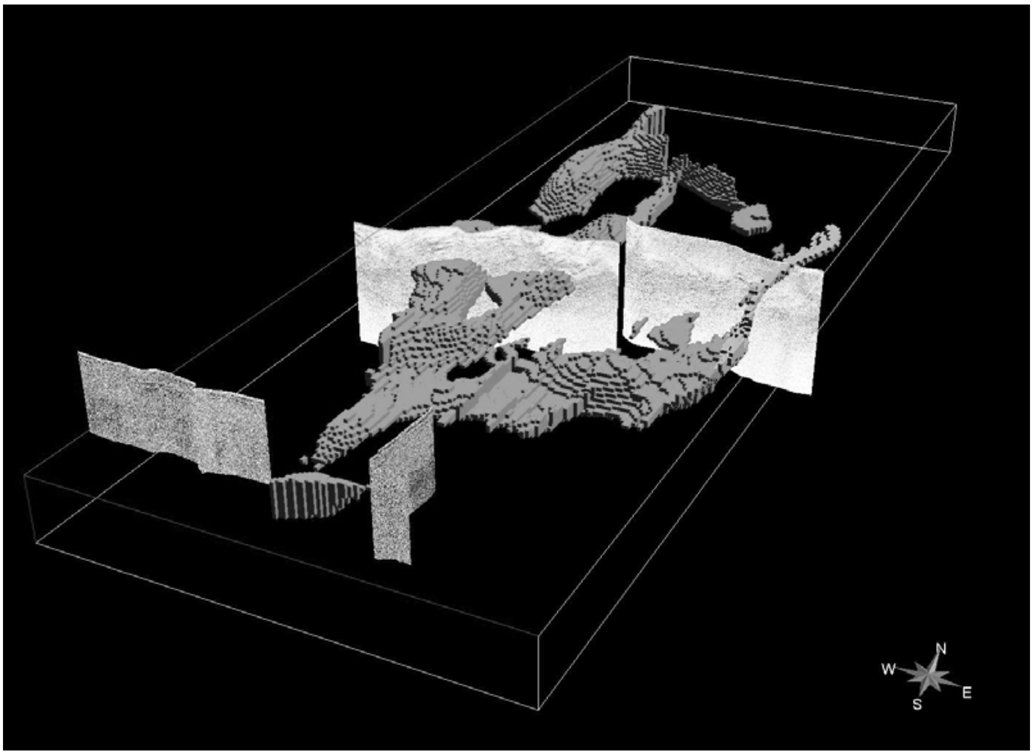
Model Storage and Distribution

Model outputs are stored in GeoScience Victoria's 3D Model Management System (3DMMS) which is a geospatially aware database developed for the GSV by Runge Ltd. This system allows models to be stored with associated metadata and searched or queried accordingly. Importantly, the 3DMMS also provides a visualisation and delivery mechanism where an explorationist can visit our office, upload their own 3D data into a secure and confidential part of the database and then visualise their data with whichever of our model objects they choose (in stereo in our 3D visualisation room if they wish). It does not matter what format the company data is in (Vulcan, Surpac, Minesight, etc) or what projection or coordinate system they use (AMG, MGA, local) as all of these conversions are handled on the fly by the 3DMMS and the user is able to look at any of the stored (open file) data, select useful objects and then download them in whatever format and projection they choose (again the conversion from our native Gocad format is handled on the fly).

Value-add Projects

As mentioned above it is clear to us that it will be the successful application of these 3D datasets to real exploration questions that will be the true test of their value to the explorer. As a result, as part of the 3D Victoria project, we are also initiating a number of "pilot" value-add projects utilising the 3D model outputs to constrain numerical simulations and 3D inversions (Figure 2). Models have been developed that investigate things such as the distribution stress and the nature of fluid flow during deformation, geometrically constrained heat flow (particularly beneath the Latrobe Valley coal measures), strain partitioning during the closure of an asymmetrical basin closure and collision. These simulation models have all been developed to help us better understand the geologic systems that we are dealing with, whether they be related to minerals or energy related commodities. Modelling is typically done at the crustal-scale as this allows us to better understand the the entire system and in particular the regional controls on mineralisation. It is our hope that explorers will be able to asses the value of the different simulation techniques and methods based on these results and then they will be able to run simulations related to their own exploration problems at smaller scales. The preliminary results of a number of these simulation studies will be presented.

Figure 2. 3D gravity inversion of the Bendigo Zone region to investigate the 3D distribution of Cambrian basalts. These are a potential gold source and are well constrained by the 2006 seismic line in the central part of the zone but are less well understood to the north and south.



PARTIAL LEACHES, SULPHUR ISOTOPES AND REGOLITH CONTROLS.
A CASE STUDY FROM THE OSBORNE CU-AU MINES
FAR NORTH QUEENSLAND

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Introduction

Geochemistry, like geophysics, has made the occasional major leap in its development or application over the last century that has widely impact on the exploration industry. As with new developments in geophysics the big leaps in geochemistry have to a large extent hinged on a very limited number of truly innovative changes, largely in technology, which have permitted a new level of resolution or better visualization of information which has in turn resulted in a new ways of understanding the information collected. In modern geochemistry this has been the development of ICP instrumentation, in particular ICP-Mass Spectrometry, which has permitted reliable rapid low cost analysis of a wide range of elements at very low detection limits. Today is truly the age of multi-element geochemistry.

Unfortunately many innovative methods in both fields have also languished due the inability of the users to truly comprehend or resolve the detail in the data. Much of this generally comes back to a poor understanding of the characteristics of the field setting from within which samples or data have been collected and to poor field descriptive records relating to the nature of the superficial regolith that controls the outcomes of many surveys. Despite the quality of analytical information available the inability to use it can curtail the real potential embedded in many methods. There is a tendency to ignore the complex, the subtlety and only look at the simple solutions (the big numbers, brightest colours issue), something that we can less afford to do if we wish to chase mineralisation in more difficult terrains.

It is this general theme that I wish to present from a geological and geochemical perspective using the results from a brief visit to the Osborne Cu-Au mine in 2002 to resolve a number of geochemical problems. This illustrates the inter-relationship of geochemistry with the natural environment and how easy it is to come to wrong conclusions using exploration geochemistry without coming to grips with the geological setting of the local environment. It also illustrates the value of modern low level geochemistry in resolving the subtlety present in the environment if we can only recognize it, document it and use it.

Partial and Selective Leaches

The success of ICP technology has opened the way to develop new analytical strategies to exploit the subtlety in field geochemistry. The ability to measure to detection limits often significantly below the natural background levels of most elements, particularly those of economic interest, enables us to achieve alternative ways of measuring anomalism derived from remote mineralisation, separating it to various degrees from often highly variably weathered background variation, resolving multi-element geochemical “signals” that are the true reflection of mineralisation and the pathways by which these signals reach the surface. It enables us to understand the very nature of geochemical signals and gives a new meaning to the concept of anomalism.

Prominent amongst these methods are the class of analyses which we “interchangeably” refer to as partial and selective leaches. There has been criticism of the use of these methods and they are often referred as “black box” geochemical methods due to the large number of secret variants that were developed to exploit the market “fashion” for the methods over the past few years by commercial analytical laboratories. These “secret” digestion formulations parallel the secret technology hidden in the circuit boards or software manipulations of various geophysical promoters.

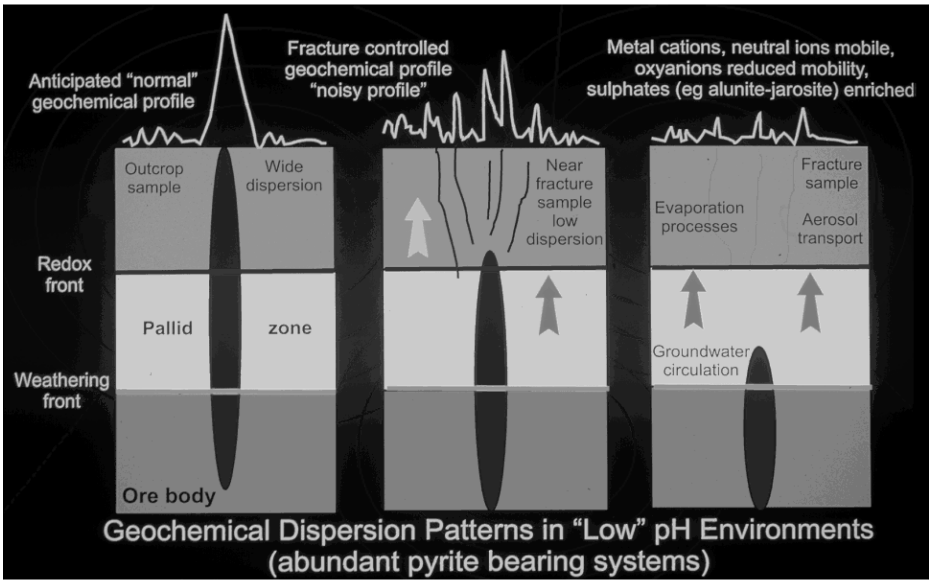
Many of the partial/selective leach methods do similar things and operate on similar components in a sample and if people understood what their results were telling them they would realize the benefits of the alternative analytical strategies now available. The reality is that most analytical methods are partial analyses so what we are talking about are variations on a theme. Some methods are more partial or selective than others, analytical method is a variable and one of the most common partial digestions used is aqua regia. In many circumstances this is unable to extract significant amounts of many elements into solution. Even so called total methods (four acid digests) are not truly total so why do we worry about going the other way and extracting even less signal with more subtle extractants that target the more soluble or specific species that capture anomalism from solution derived from some blind source.

To a large extent it comes down to the definition of what an anomaly should look like. Traditionally an anomaly has had to have a distribution that looks a bit like a Gaussian curve or have a near log normal distribution with the bulk of the values distributed in some way about a mean and is able to be manipulated by simple statistics. Anomalies are the tail on the high side, thresholds are often some arbitrary number below which we do not bother following up (big number, bright colour issue). Now, what if this is wrong, or at least wrong in far more cases than we realize.

What ICP-MS analysis and partial or selective leach geochemistry demonstrates to us is that in many cases where mineralisation is deep or occurs in deeply weathered terrains that classical anomalism is uncommon. The classic anomaly is really an end member of a much wider spectrum of possible anomaly expressions. It works really well in the case of outcropping or shallowly weathered mineralisation where geochemical signal from the source completely “floods” or overpowers other signal expression. Where this case does not exist the anomalous signal character can take on quite a different form and its expression can be either positive or negative, is often erratic in distribution and controlled by joint and fracture patterns (ground water pathways), local pH and Eh changes, salinity and weathering variation and differential erosion. This is where most people come unstuck in recognising anomalism. It has certainly moved out of the realm of big numbers, bright colours.

Some examples of anomaly expression patterns from geochemically difficult terrains are shown below. The signal character varies with depth to source and dispersion characteristics change depending upon groundwater acidity. This in turn affects which ore related species remain soluble or precipitate within fractures. Acid ground water can leach fracture zones producing low signatures in some instances.

Figures 1 and 2, Patterns of dispersion – the change in character of geochemical anomalism with depth.



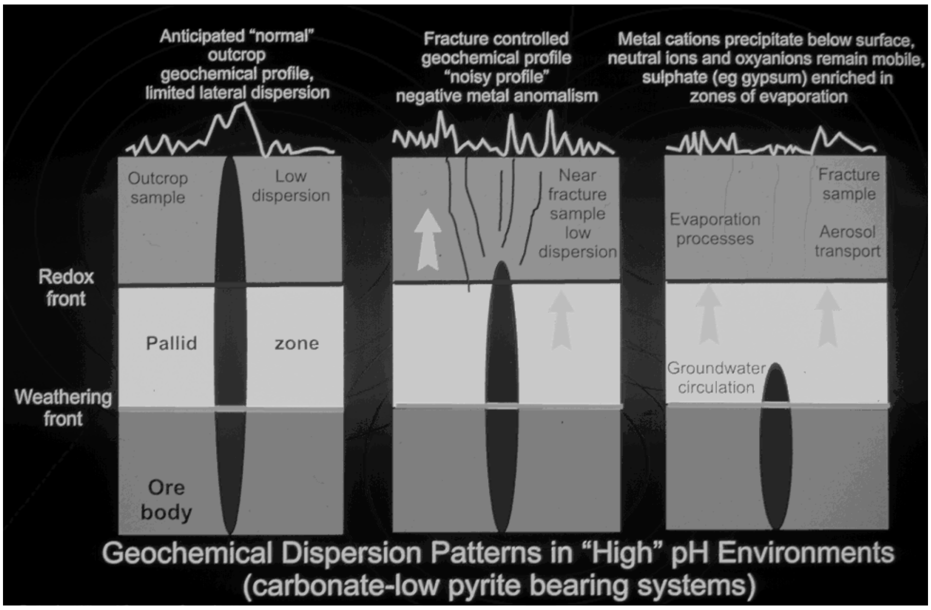
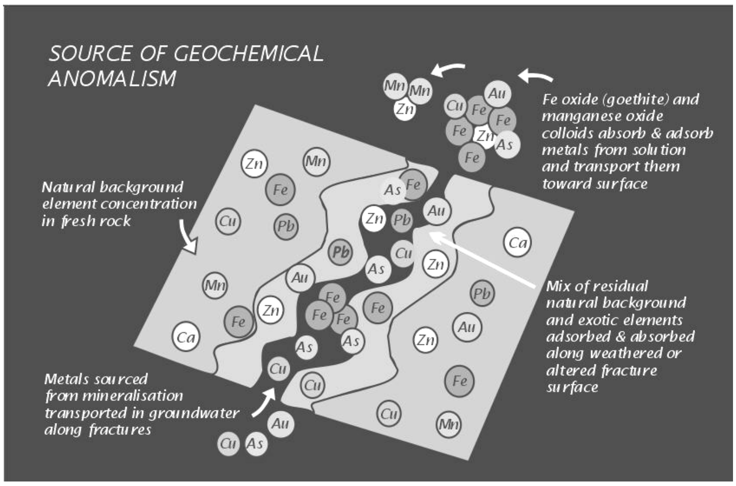


Figure 3, Sources and pathways for geochemical signals in weathered terrains and from depth.



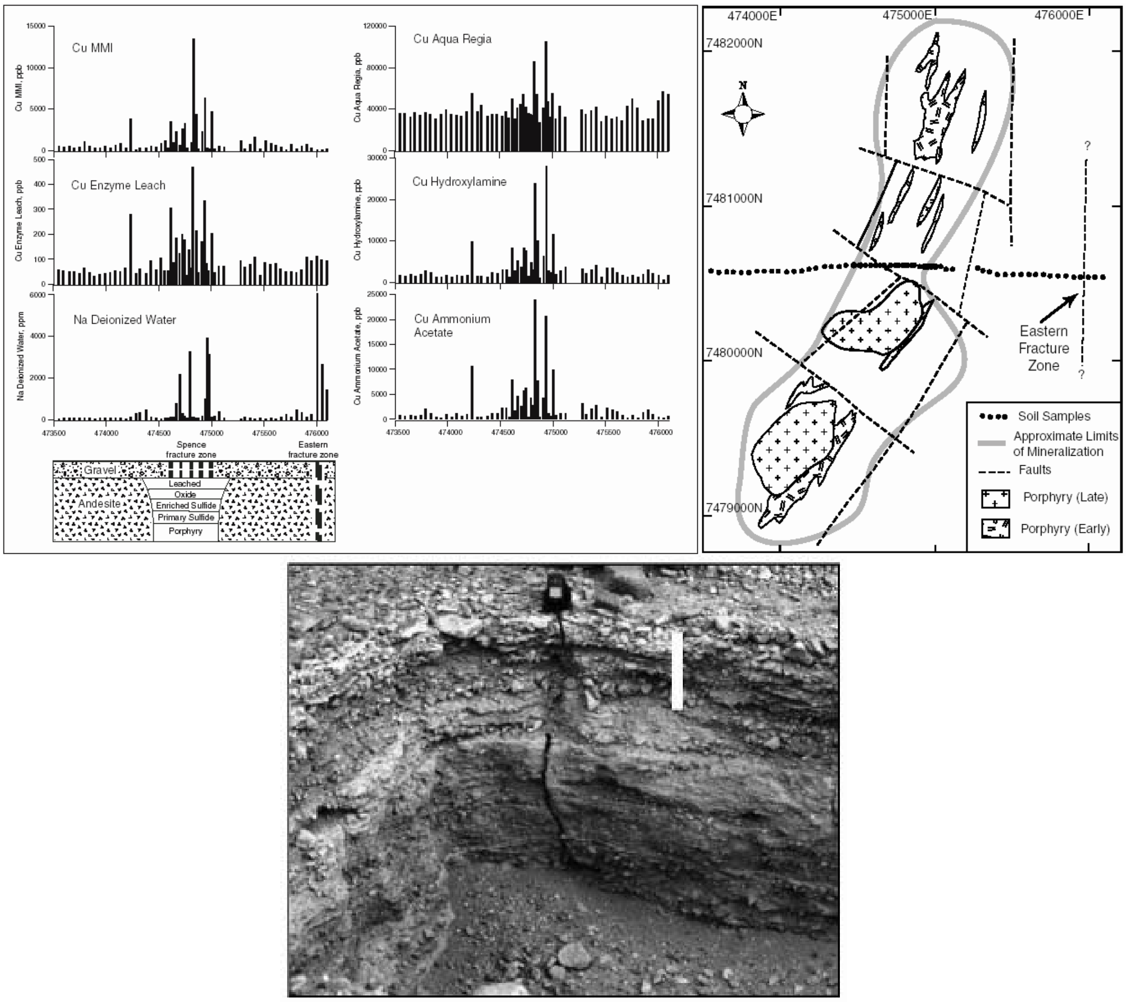


Figure 4, Geochemical anomalism at Spence Porphyry Cu deposit Chile (80 metres of cover). Controls are fractures created by earthquake activity that permit water egress (after Cameron, Camiro Project).

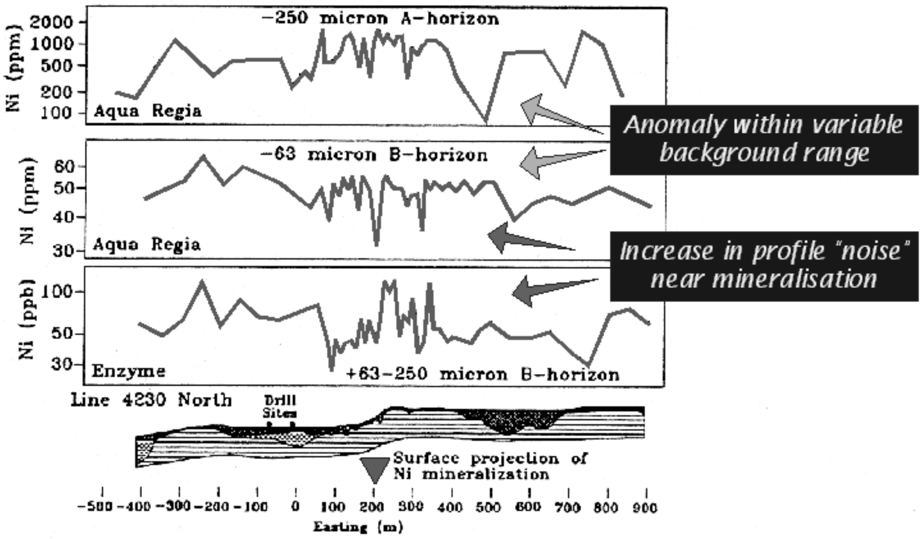


Figure 5, Increase in profile "noise" near and over mineralisation. This often relates to increased local fracture density and joints about ore bodies and pH-Eh variation related to differences in ground water geochemistry over ore zones compared to background areas.

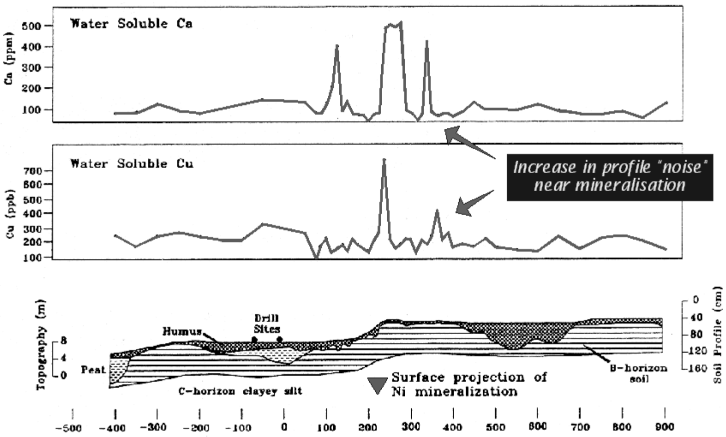


Figure 6, Often the subtle leaches are the most definitive, water in this case, although signal is very low it is easily determined by ICP-MS.

Sulphur Isotopes

Sometimes in geochemistry we focus too closely on the metals we seek. While this is logical and important often the metal component reaching the surface is very low and difficult to determine or to discriminate from within the general background variation in geochemical signals we measure. Sometimes the elements of interest are relatively immobile. Volumetrically it is often the rock alteration that is much more abundant and that can produce higher levels of anomalism than the ores. Common is the association of carbonate and pyrite as minerals within alteration zones about ore. Oxidation of the pyrite even at very subtle levels releases sulphate and calcium ions into the ground water. Sulphate in particular is to a large degree unaffected by pH and Eh barriers and can be readily transported in ground water well way from its point of origin. It inherits a sulphur isotope signature characteristic of the mineralisation which in many instances is likely to be distinctly different from that of the surrounding and surface rocks. Sampling and determining the sulphur isotopes of gypsiferous precipitates from the B-soil horizon or from drill core can be an effective determinant of mineralisation at depth and provide supporting evidence for deep mineralisation.

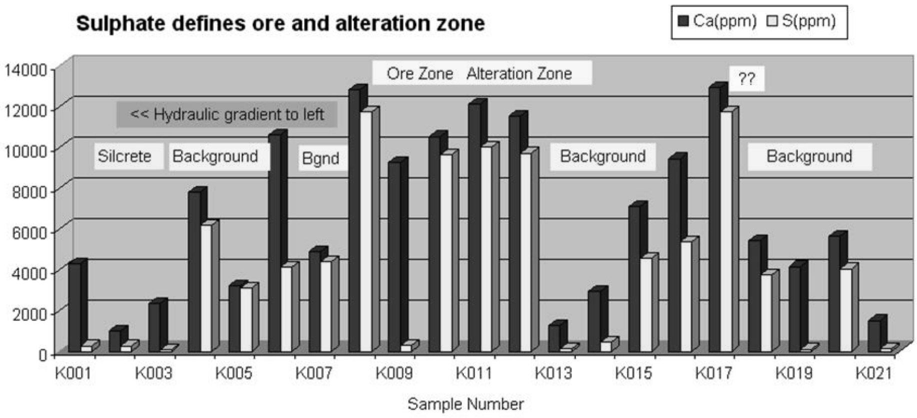
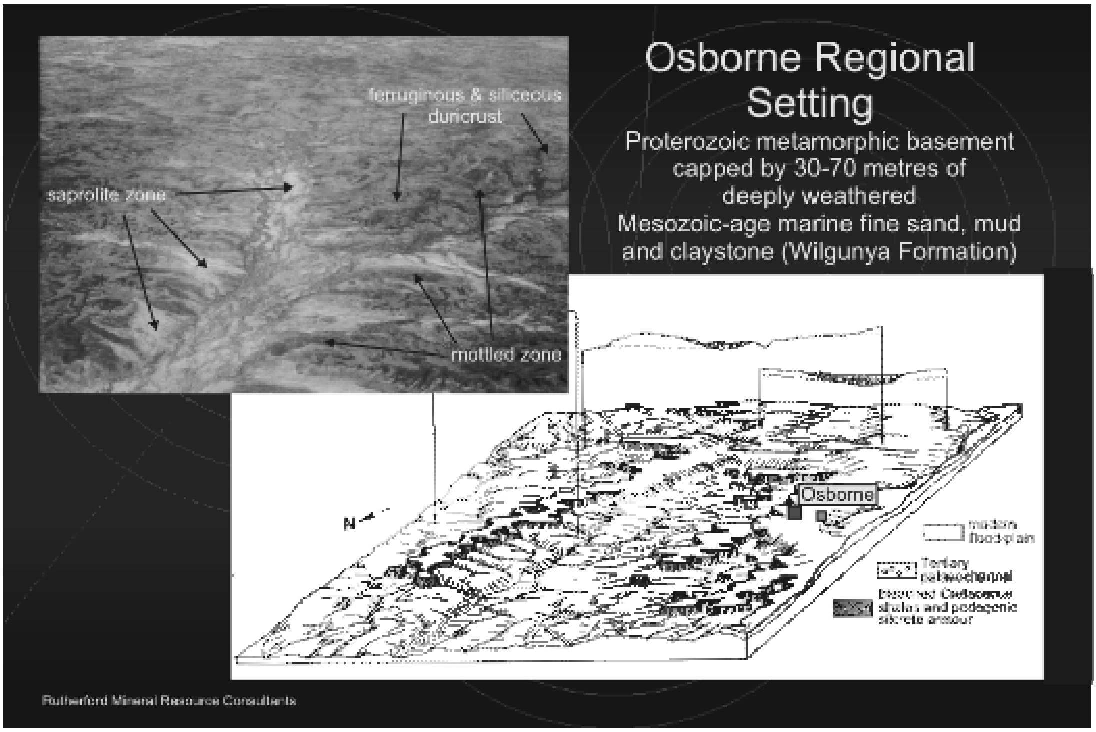


Figure 7

At Osborne this method provided direct proof of an extensive alteration zone disposed about high grade mineralisation Cu-Au mineralisation at some 350 metres depth. Strong vertical fracture control on groundwater movement focussed the alteration sourced sulphate to the surface.

Osborne Geological Setting

Osborne sits in a zone of rapidly eroding and re-forming silcrete, ferricrete and saprolite developed on a deeply weathered marine sedimentary sequence some 50 to 70 metres thick that caps eroded and weathered Proterozoic basement amphibolites and banded iron formations that host the mineralisation. It was discovered by drilling the BIF sequences. In reality the association of BIF and the Cu-Au mineralisation is fortuitous as the mineralisation is developed with a major fault system that intersects the BIFs and the alteration is dominated by magnetite and silica. Details of the geology and regolith setting of Osborne can be found in the cited paper. A second significant body of mineralisation at Kulthor is “blind” to geophysics as it does not occur in association with a BIF and does not contain magnetite as an alteration mineral.



Osborne Regional Setting

Proterozoic metamorphic basement capped by 30-70 metres of deeply weathered Mesozoic-age marine fine sand, mud and claystone (Wilgunya Formation)

Rutherford Mineral Resource Consultants

Figure 8

The Geochemical Issue at Osborne

Two distinctly different geochemical circumstances occur at Osborne:

- Strong surface partial leach multi-element geochemistry over the main Osborne ore body associated with the vertical projection of the ore body where it pitches to some 1100 metres depth. Drilling the strike continuation of the surface anomalism did not intersect any mineralisation.
- A complete lack of any surface geochemical signature from the Kulthor mineralisation located some 1.8 km from the Osborne open pit despite applying the same soil sampling procedures as at Osborne.

How do you get a “good” signal in one case and none in the other case using the same geochemical method and strategy? In reality you don’t get a good vertical signal from the ore over the projection of the deep ore body at Osborne you only think you do (it is not a contamination issue), it is coincidental and related to impact of the local regolith and you do at Kulthor if you sample the site properly taking the impact of the regolith into account.

The differences illustrate the impact of superficial geology, erosion dispersion, regolith formation and destruction and their impact on geochemical dispersion. The discrimination of regolith type can be done using radiometrics with limited field traversing to confirm interpretation. At Osborne the presence of silcrete outcropping at the surface trapped groundwater sourced from the more elevated Osborne open pit beneath it directing it down slope for about 1-2 kilometres from the open pit area before it escaped at the edge of the silcrete sheet coincident with the upward projection of the ore body at depth.

Down slope erosional scree from the more elevated Osborne site formed a 1 metre thick cover over the true bedrock at the Kulthor site. By recognising this and using an excavator to sample the true bedrock a very low order base metal anomaly was apparent. A very high gypsum signature was also present that had a sulphur isotope signature identical to that for the Kulthor sulphides and distinctly different to that for the general country back ground indicating its source was from alteration at some depth (ore at 350 metres depth.

Pathways for evolution of geochemically anomalous ground water are clear in the open pit walls and accounts for the spiky and erratic nature of geochemical signatures across the area.

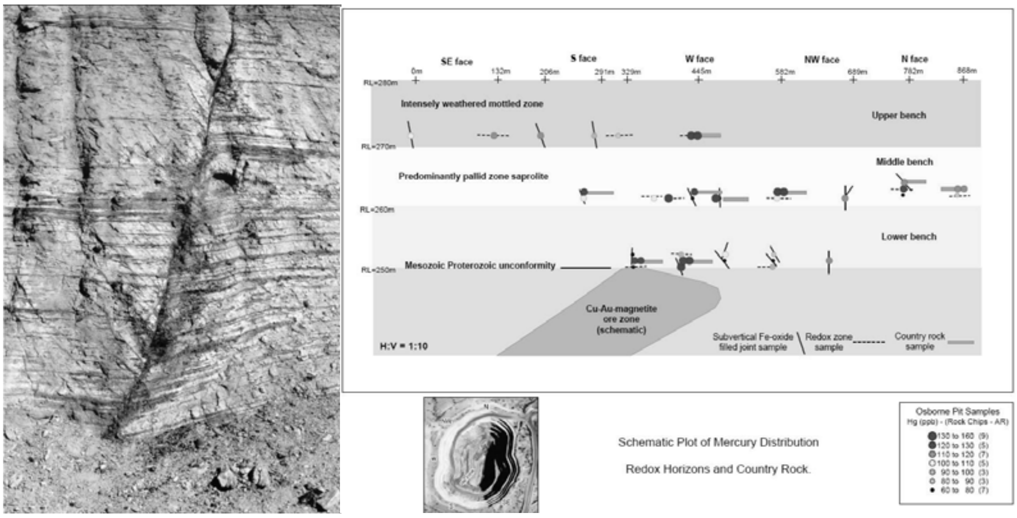


Figure 9

Acknowledgements:

Greg Hall (formerly with Placer Dome) and Gary Sparks from Osborne Mines Limited for funding, technical information and field support. Chris Johnston for his initiation of the original AMIRA pSIROGAS project. Anita Andrew for isotope analyses, Angela Giblin, Simon Gatehouse & Leslie Dotter, for ICP analyses, laboratory space and discussions (All formerly of CSIRO, North Ryde). Louisa Lawrance for discussions on her geochemical and regolith work on the Osborne Cu-Au deposit and supply of figures from that work. David Cohen and Ian Dalrymple, UNSW, for additional collaborative work on soil geochemistry at Osborne.

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A REVIEW OF RESULTS FROM THE FALCON® AIRBORNE GRAVITY GRADIOMETER FOR MINERAL EXPLORATION

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Abstract

A collaborative project between BHP (now BHP Billiton) and Lockheed Martin led to the development of the Falcon gravity gradiometer. In October 1999, BHP flew the first airborne gravity gradiometer survey over the Bathurst Camp, New Brunswick. Since that first survey, the number of operating gravity gradiometer systems has grown. Fugro Airborne Surveys (FAS) under and agreement with BHPB now operates four systems worldwide. To date application of the systems by FAS has been limited under the licence conditions to petroleum exploration. In April 2010 the Falcon system will become available to the mineral exploration industry introducing offering explorers a new technology as a tool in search for mineral deposits.

Introduction

Airborne gravity gradiometry has been in use for ten years (Dransfield 2007). The rotating, gravity, gradiometer instrument developed by Lockheed Martin is used in the FALCON AGG flown by Fugro Airborne Surveys (FAS).

Falcon delivers measurements of the gravity field from the air at a sensitivity and spatial resolution dramatically better than airborne gravimetry. At 3 km wavelength and a survey speed of 120 knots, the FALCON airborne gravity gradiometer (AGG) has a gravity error along a single survey line of about 0.2 mGal (Boggs and Dransfield 2004); an airborne gravimeter in these circumstances cannot do better than 1.4 mGal (van Kann 2004).

The total noise on a LaCoste and Romberg ground gravity meter is around 1 μGal (Andre et al. 1999). Cook and Carter 1978 measured errors for a 4 LaCoste gravity meters in a survey of Roosevelt Hot Springs and found an RMS error of between 0.004 and 0.024 mGal with an average RMS error close to 0.01 mGal. However, this is for a detailed ground survey with careful handling of the meter. Typical regional ground gravity surveys have a standard deviation of around 0.05 mGal. Errors in elevation measurements can also introduce considerable errors into calculation of ground gravity anomalies.

The noise characteristics of the Falcon gravity gradiometer therefore make it an ideal system for mineral exploration.

Most of the early airborne gravity gradiometer surveys were for mineral exploration. Airborne gravity gradiometers have been of considerable value in both direct detection and in geological mapping for a large variety of mineral commodities and deposit styles. Diamonds have been the biggest single target with numerous kimberlites directly including the diamondiferous Impala and Abner pipes and the Daniel diamond-bearing palaeochannel draining the Finsch mine. These were all airborne gravity gradiometer discoveries. Airborne gravity gradiometry has also proved useful in the search for base metals in iron-oxide copper- gold deposits, porphyries, Broken-Hill type deposits and volcanogenic massive sulphides, iron in massive haematite, nickel sulphides and gold. The Santo Domingo Sur copper deposit in Chile is the most advanced project that is a gravity gradiometer discovery.

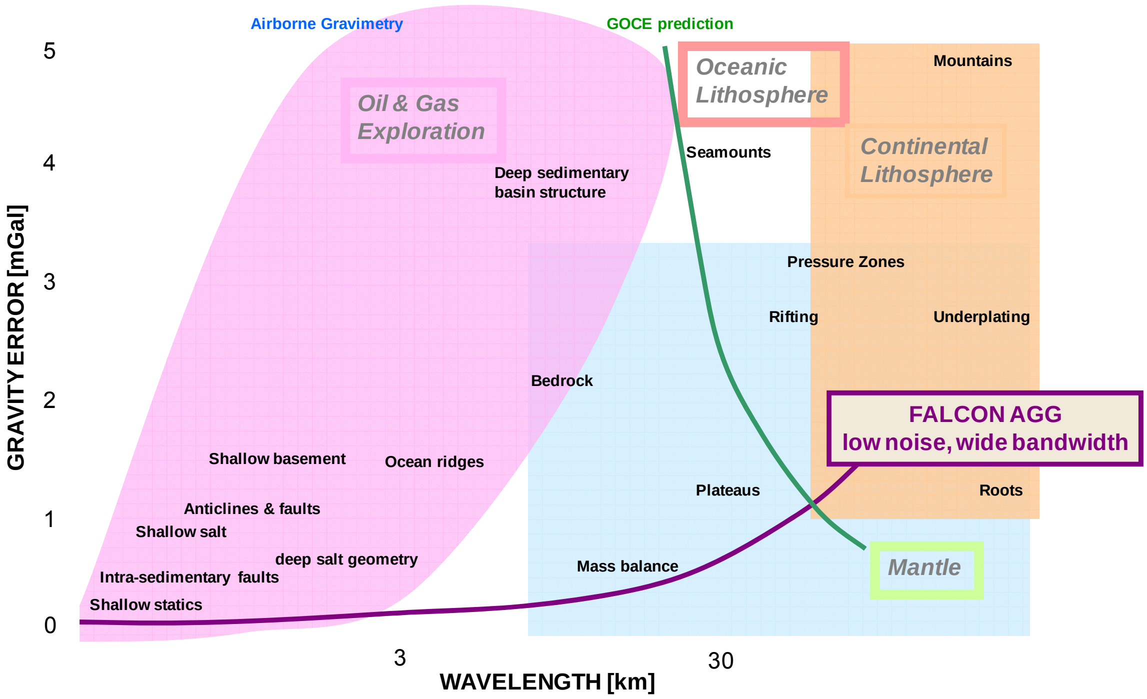


Figure 5. Schematic of noise levels for airborne gravity systems applied to various oil exploration scenarios.

Ekati Diamond Pipes – NW Canada

Rajagopalan et al., 2007, reported the use of Falcon to detect kimberlite pipes in the Ekati Diamond Field in the Northwest Territories of Canada.

Figure 2 shows the vertical gravity gradient. Almost all the known pipes are associated with gravity gradient anomalies. The nature of weathering in this environment has resulted in a deeper weathered zone over the pipe often filled with clay sediment that is both conductive and has a low gravity signature detectable with Falcon. Not all the pipes have a magnetic anomaly.

In May 2006 a helicopter-borne digital AGG system surveyed part of the Ekati areas that were previously flown with a fixed wing Falcon system (Dransfield, 2007). Survey specifications were for a 50 m line spacing flown at a nominal 50 m ground clearance and 30 ms-1 ground speed. Filtering is to a 0.3 Hz bandwidth.

Images of the resulting vertical gravity gradient data over the Central Ekati block are shown in a comparison with the original Ekati survey data after re-processing in 2004 (Figure 2).

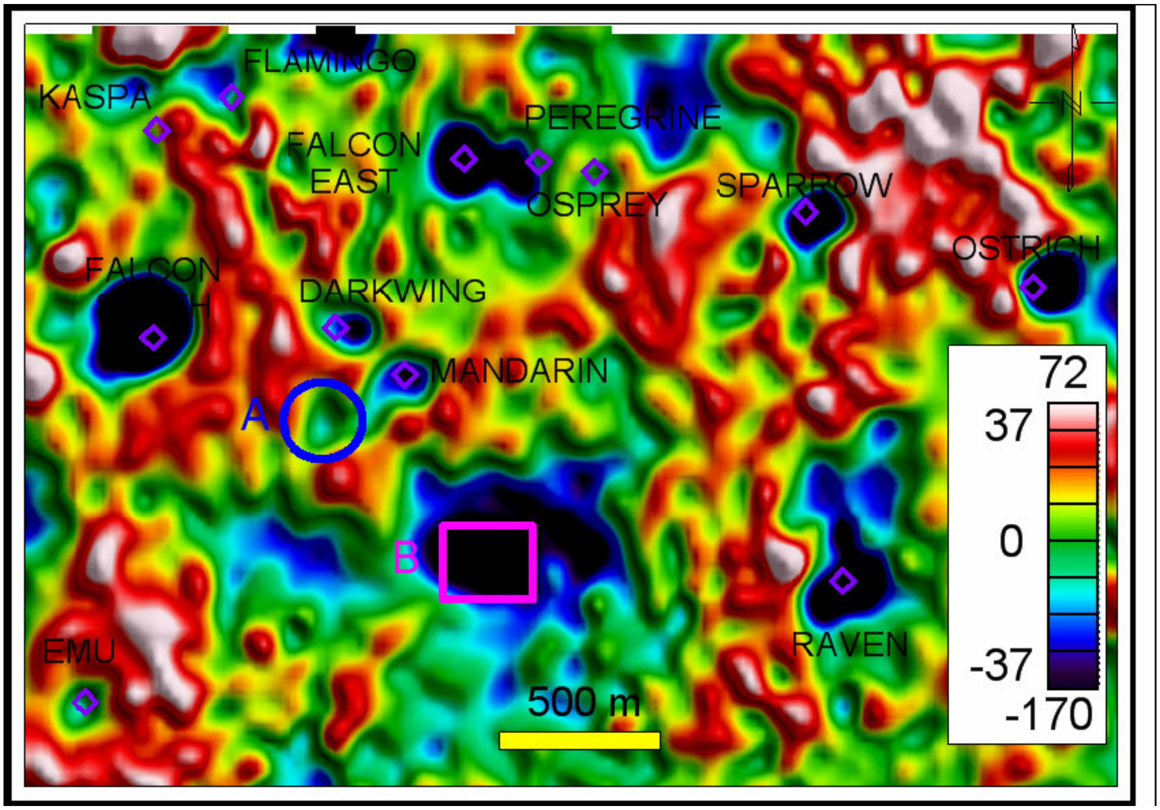


Figure 6. Vertical Gravity Gradient. All the pipes (diamond symbols) shown here, with the exception of Kaspa, are associated with gravity gradient anomalies. The anomaly due to the pipe is accentuated by the presence of lakes over most of the deposits (From Rajogapalan et al., 2007**).**

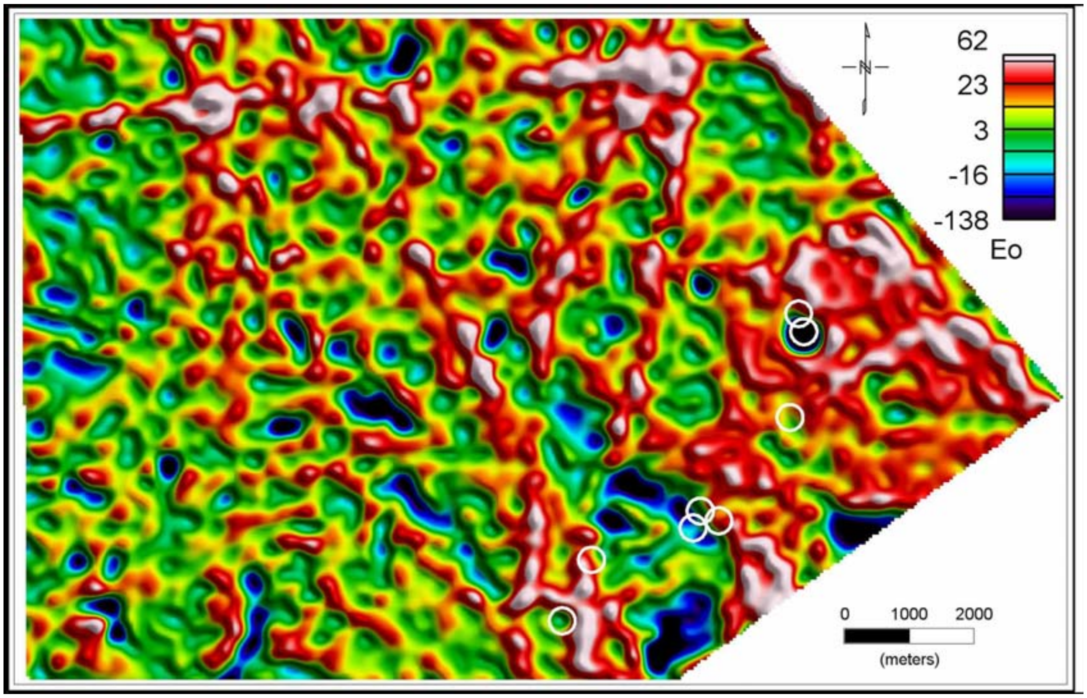


Figure 7 A portion of the data from the Falcon Ekati survey showing known kimberlites (white circles). These data were acquired by a fixed- wing aircraft in 2000 and re-processed in 2004. This area was re-flown as a heli-borne Falcon survey in 2006 - see below, (from Dransfield, 2007).

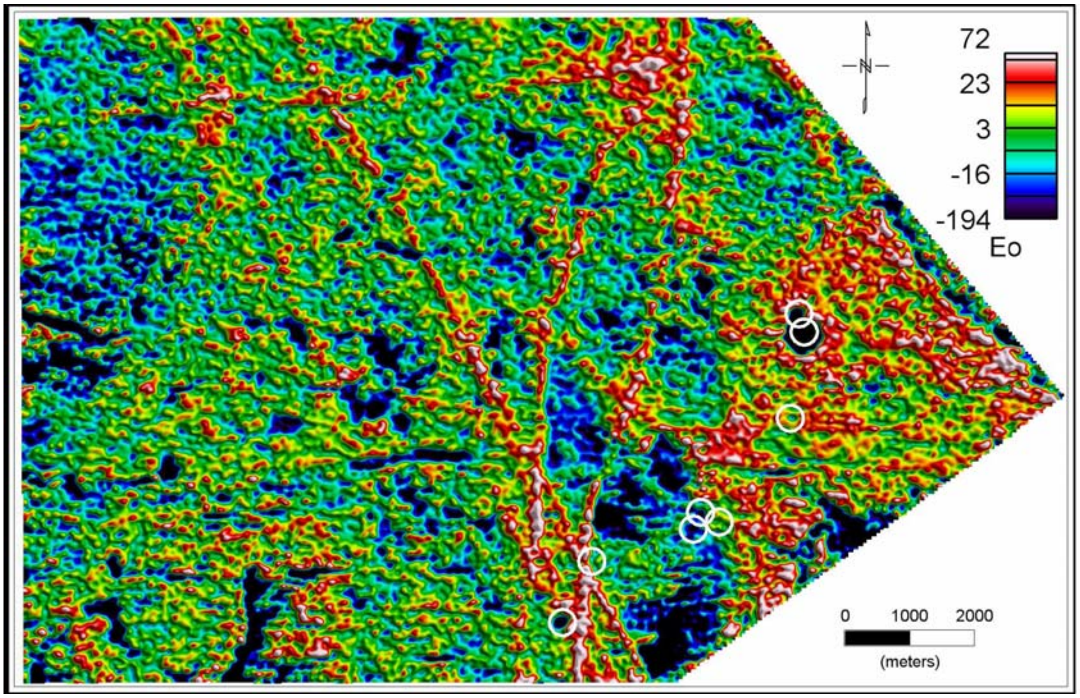
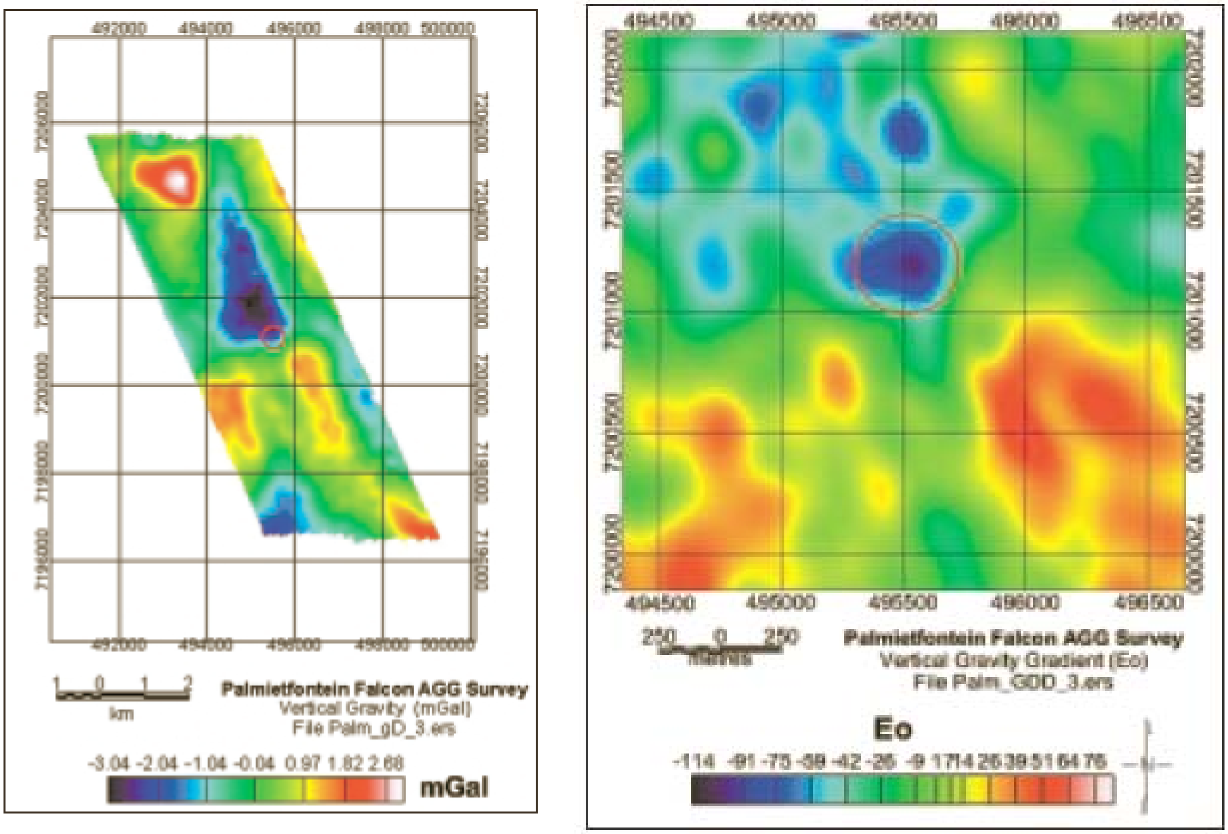


Figure 8: The Falcon Central Ekati survey vertical gravity gradient. Known kimberlites are indicated by white circles. The spatial resolution is dramatically improved in comparison to the fixed-wing survey (Figure 10) due to the slower flight speed and lower flight height (Dransfield, 2007).

Palmietfontein Kimberlite pipe

The Palmietfontein survey in South Africa was flown by the Falcon Einstein system in April 2001 as a test case study (Dyke, 2002). The Palmietfontein pipe is located approximately 150 km northwest of Johannesburg on the western edge of the Pilanesberg Intrusive Complex. It intrudes rocks of the Bushveld Complex at its contact with the Pilanesberg syenites and lies under shallow cover. The dominant northwest fabric of the area is well mapped in both the vertical gravity (gD) and a close up of the vertical gravity gradient (GDD) shown in figures 2 and 3 respectively.

The Palmietfontein pipe is expressed by a closed GDD anomaly of -50Eo and a possible gD anomaly.



A **B**

Figure 9 (A). Palmietfontein gD gravity data. (B) A close-up of the Palmietfontein GDD anomaly. The location of the pipe is indicated by the circle (from Dyke, 2002)

Cannington Ag-Pb-Zn Deposit

Christensen, et al, 2001 showed results from Falcon surveys of the Cannington Ag-Pb-Zn deposit in NW Queensland. In that study six test surveys were conducted to demonstrate the capabilities of the AGG instrument by comparison with ground gravity data. Various altitudes were flown and noise levels of the SGG system calculated. They found that the Falcon data compared favourably with upward continued ground data and clearly delineated the Cannington ore body. They found that a body such as Cannington was detectable from a flying height of 120m below 130m of regolith.

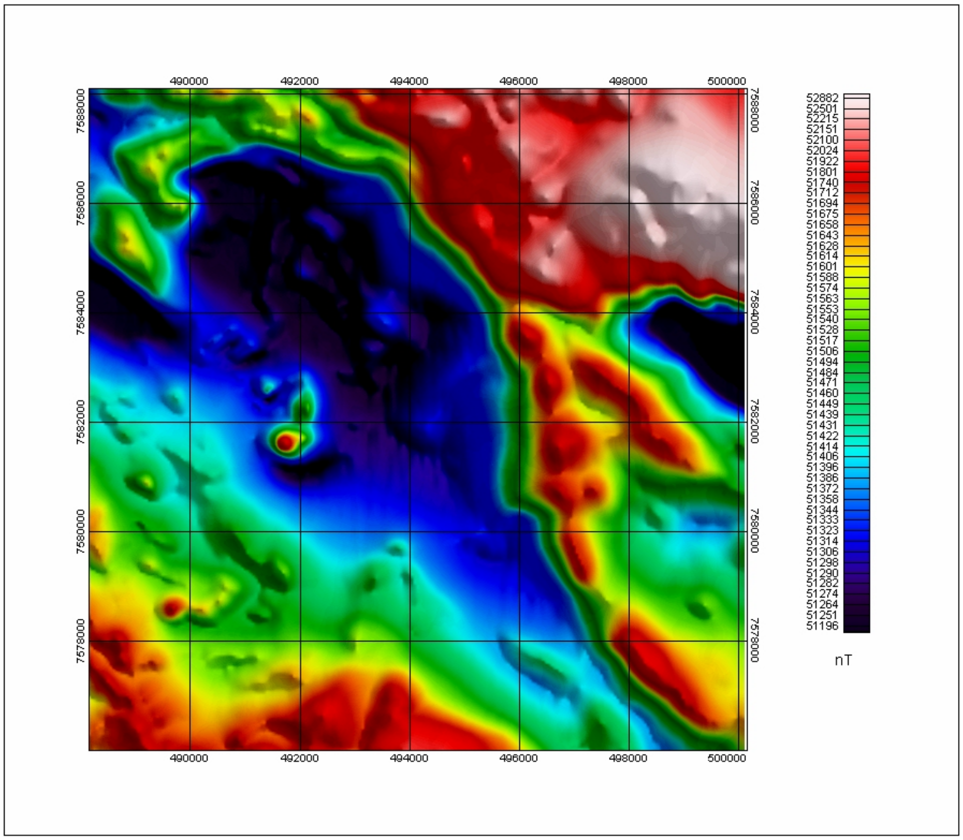
Error!

Error!

Survey	A	B	C	D	E	F
Clearance (m)	120	120	170	220	320	120
Bearing	NS	EW	NS	NS	NS	NS
Line spacing(m)	100	100	200	200	200	100
No. of lines	120	120	60	60	60	120
Line (km)	1750	1750	870	870	870	1750

Table 1. Survey parameters for the 6 AGG surveys over Cannington (from Christensen et al. 2001).

Figure 10 . TMI data from the Cannington survey area (from Christensen, et al. 2001)



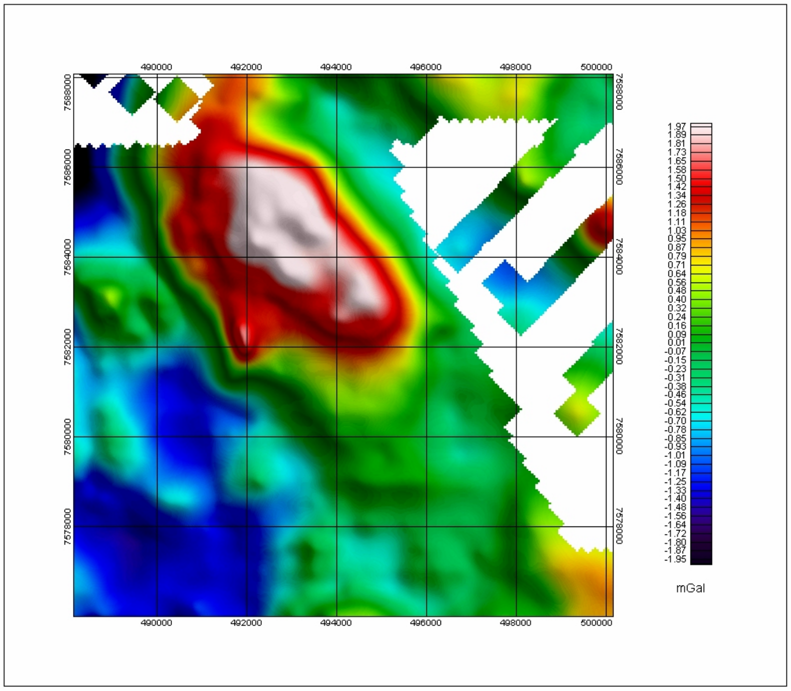


Figure 11 Residual Bouguer corrected ground gravity, gD, data after removal of 2nd order polynomial term and upward continuation to 120m above ground level (from Christensen et al., 2001).

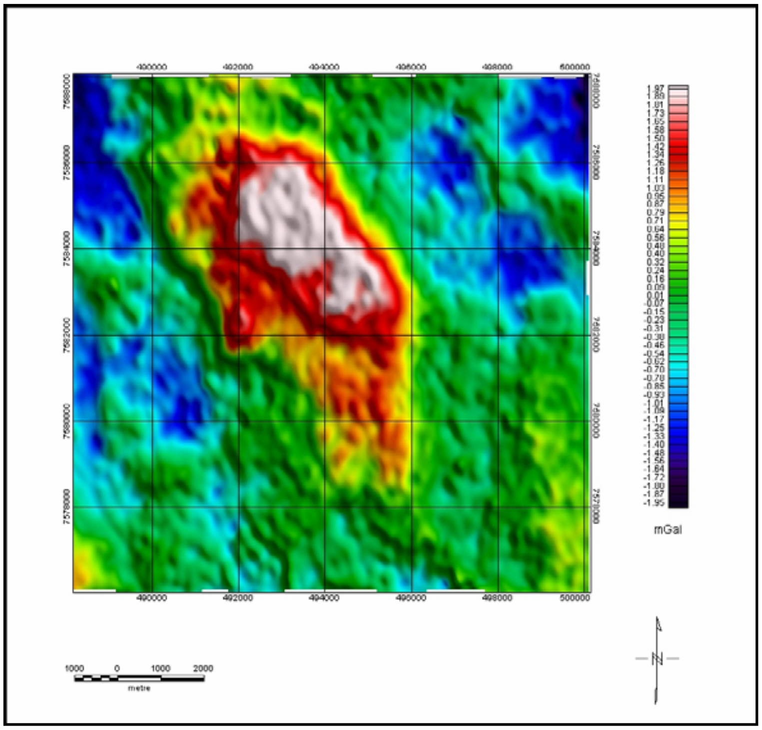


Figure 12 FALCON gD data from survey A flown at 120m above ground level. The Cannington ore bodies are associated with the discrete gravity and magnetic features to the left of the centre at (492000E, 7582000N) (from Christensen et al., 2001).

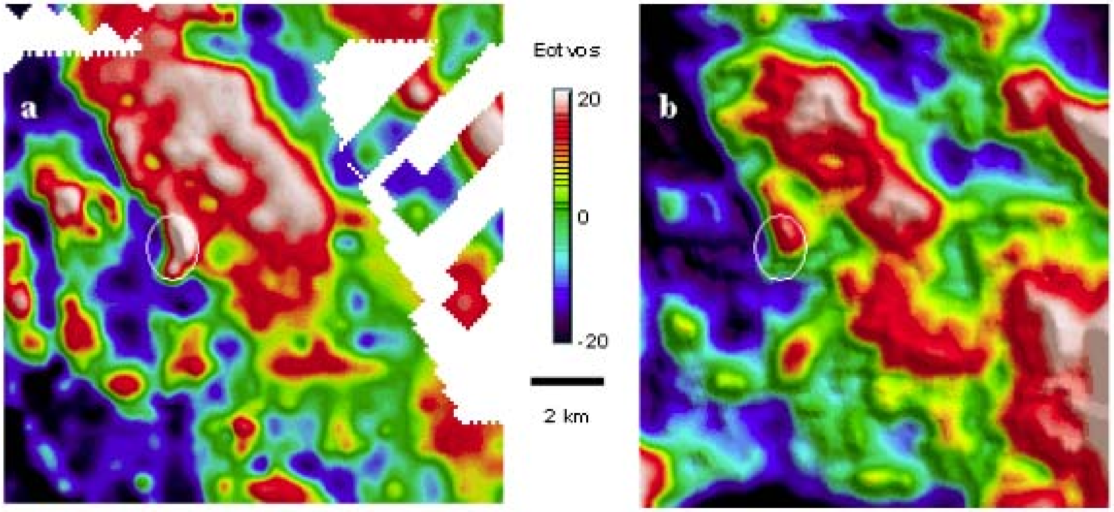


Figure 13. Vertical gradient of gravity for the Cannington region. a) From ground gravity measurements upward continued to the nominal altitude of the Falcon survey. b) Falcon survey data for the same altitude. The location of the Cannington deposit is circled.

Prominent Hill

The Falcon AGG system was flown over the Prominent Hill Iron Oxide-Copper-Gold Deposit in South Australia. Line spacing was 200m and flying height 100m mean terrain clearance. A comparison between ground gravity acquired over several years and the Falcon data acquired in two weeks is shown in Figure 14. The Falcon data shows better structural detail due to higher spatial sampling

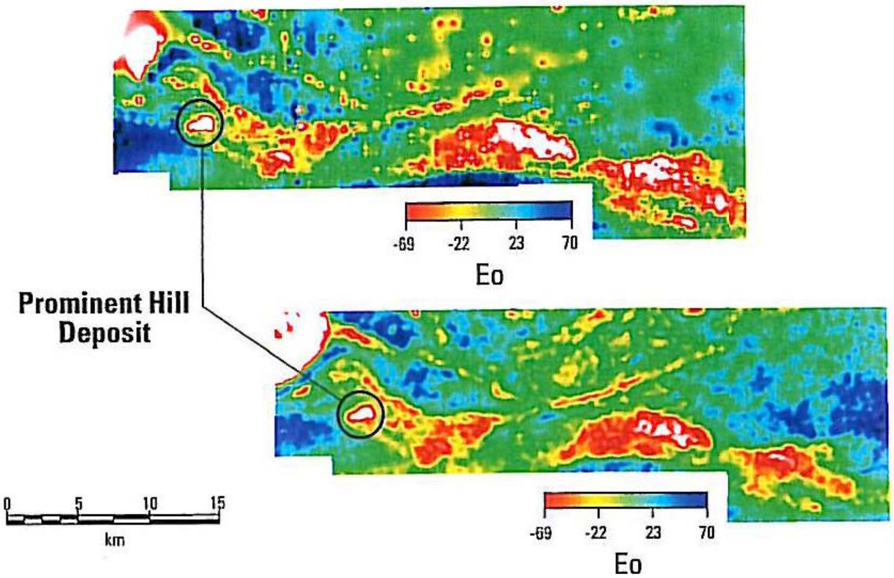


Figure 14. Prominent Hill IOGC deposit – top image is ground gravity data and lower image is Falcon GDD survey data.

The component measured by the Falcon system can be transformed to other components of the full gravity gradient tensor to aid interpretation. This can be carried out by three different methods to assist in validating the data. The main tensor component used for interpretation is G_{DD}, the vertical gravity gradient. A vertical gravity (g_D) image is derived by integrating the vertical gradient and this product is also used routinely for interpretation.

Figure 15 shows all the components of the gravity gradient tensor over Prominent Hill. The top row shows the two components measured by the Falcon AGG system (G_{NE} and G_{UV}), where $G_{UV} = (G_{NN}-G_{EE})/2$ and the vertical gradient (G_{DD}). The second and third rows show the vertical gravity (g_D) and the remaining independent gravity gradient tensor components.

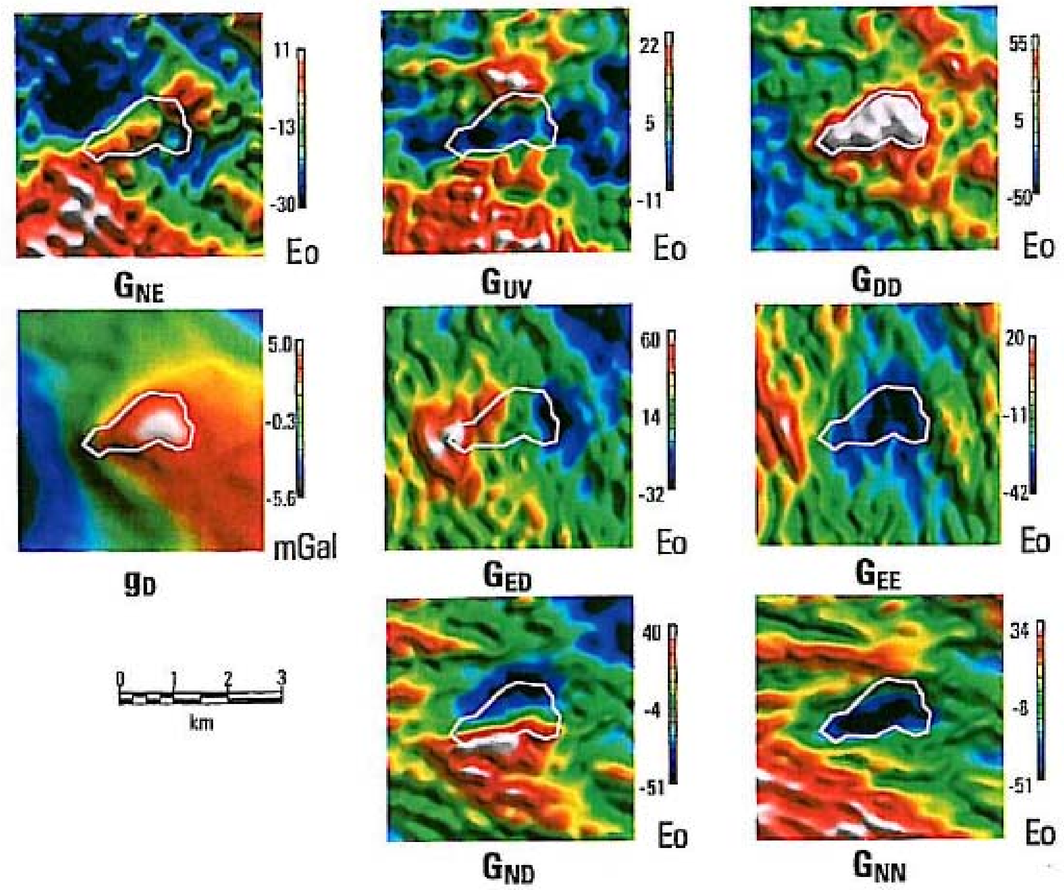


Figure 15 Full gravity gradient tensor components derived from Falcon data for the Prominent Hill deposit.

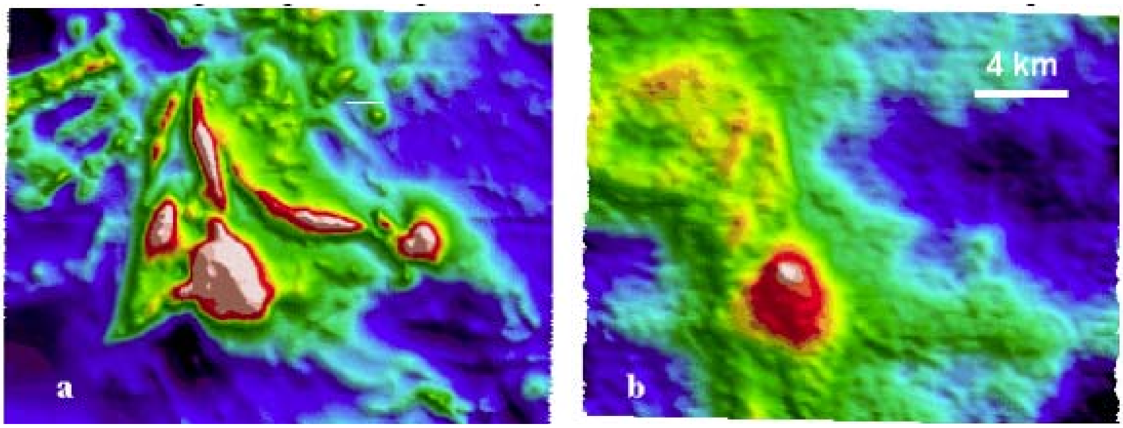
King George Gravity Anomaly

Mahanta et al. (2001) reported the survey of a possible IOCG target in shallow water of the coast of South Australia,

King George is a high priority magnetic anomaly that was identified within regional aeromagnetic data. The anomaly is located in 20-30m of water in the Spencer Gulf, South Australia, adjacent to the Moonta-Wallaroo mining field. Regional geology indicates that this area is highly prospective for Iron Oxide Copper-Gold (IOCG) style deposits.

IOCG deposits are expected to have a high gravity signature with possible association of magnetic anomalism, the latter being dependent on magnetite content. In March 2000, the Falcon airborne gravity gradiometer (AGG) system was flown over the King George anomaly, previously inaccessible to conventional gravity measurement techniques. The survey showed a 7 mGal gravity anomaly coincident with the 10,000nT magnetic anomaly, making the anomaly to a high-priority drill target.

Modelling of the airborne gravity and magnetic data indicated that two closely spaced bodies 200m below the surface produced the observed anomaly. Vertical gravity g_D was used during the modelling exercise. The Falcon AGG system measures the quantities G_{NE} and G_{UV} from which vertical gravity gradient G_{DD} and vertical gravity g_D are derived. To verify the gravity model, the G_{NE} and G_{UV} responses were also computed and compared with actual quantities measured by the Falcon AGG system. A good match between the measured and the modelled components was obtained.



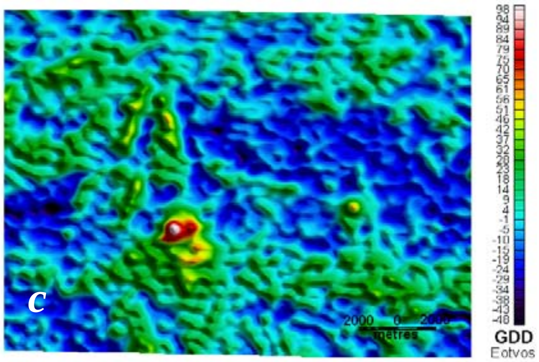


Figure 16 Falcon survey results for the King George anomaly, Spencer's Gulf, South Australia. a) Total magnetic intensity with the king George anomaly being approximately 8000 nT. b) Vertical component of gravity g_D at the flight surface, 120m above sea level, c) The vertical gradient or G_{DD} response. The King George anomaly is 5 mGal and 50 Eotvos (adapted from Lee et al. 2001 and Mahanta, 2001).

Latrobe Valley

The use of airborne gravity gradiometry in coal seam mapping in the Latrobe Valley, south-east Australia was described by Mahanta (2003). The coal seam, mapped as a vertical gravity gradient low in Figure 13 terminates where exposed along its southern edge and where the vertical gravity gradient reaches its lowest values. The seam then dips shallowly to the north-west under gravel cover, resulting in a gradual reduction in the amplitude of the gravity signal. Typical thicknesses of this seam are around 30-50 m at dips a little below 10□. The detectability of coal seams will generally be favoured by greater seam thickness and dip. Mahanta (2003) shows that the Falcon AGG can detect seams of greater than 10 m thickness at dips greater than 10°.

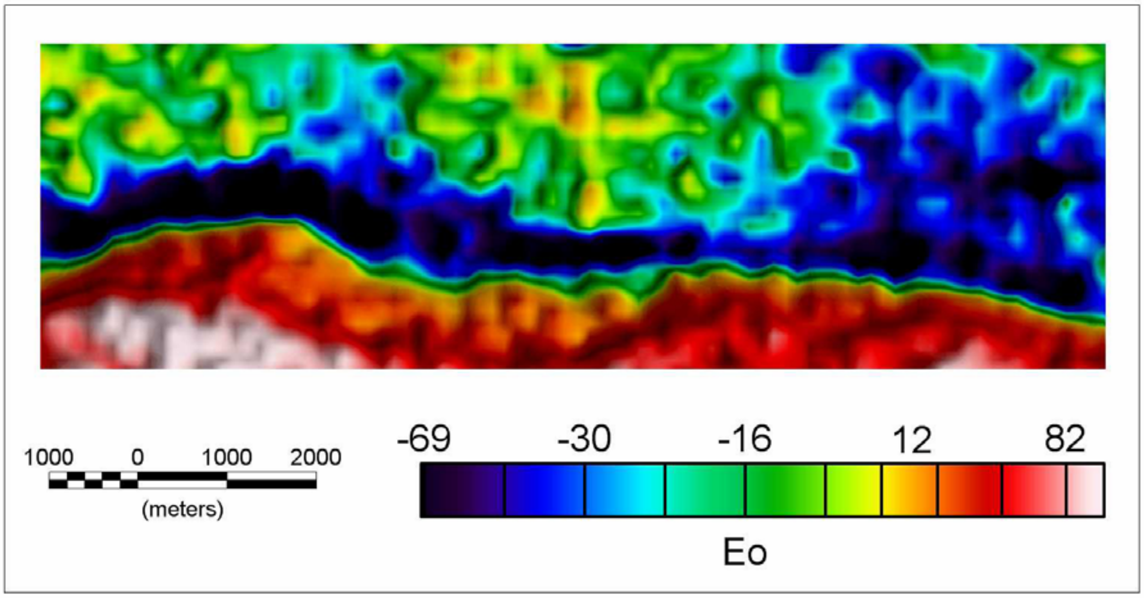


Figure 17 Mapping a coal seam in the Latrobe Valley with airborne gravity gradiometry. The data are from a survey flown in 2002 at 200 m line spacing and a ground clearance of 130 m. The low density of the coal produces a gravity low, truncated sharply at the Nosedale Monocline to the bottom of the image and dipping shallowly under gravel cover to the top left (Mahanta, 2003).

Middleback Range

The Middleback Ranges are the source of ore for the OneSteel steelworks at Whyalla, South Australia. The southern Middleback Ranges contain a number of hematite deposits which have been assessed as extensions to the reserves to supply the steelworks. The deposits are long, narrow and small tonnage with ground gravity anomalies of 0.5 to 2 mGal.

Fig. 3 (Lee et al., 2001) compares the results of the ground gravity survey collected at 50 m station spacing on 150 m spaced lines, with data from a Falcon survey at 200 m line spacing. The ground data are upward continued to the same surface as the Falcon data.

The Falcon data were collected in high turbulence and the survey area includes relief of over 300 m, both factors increasing the demands of the survey. A terrain correction was applied with an assumed density of 2.67.

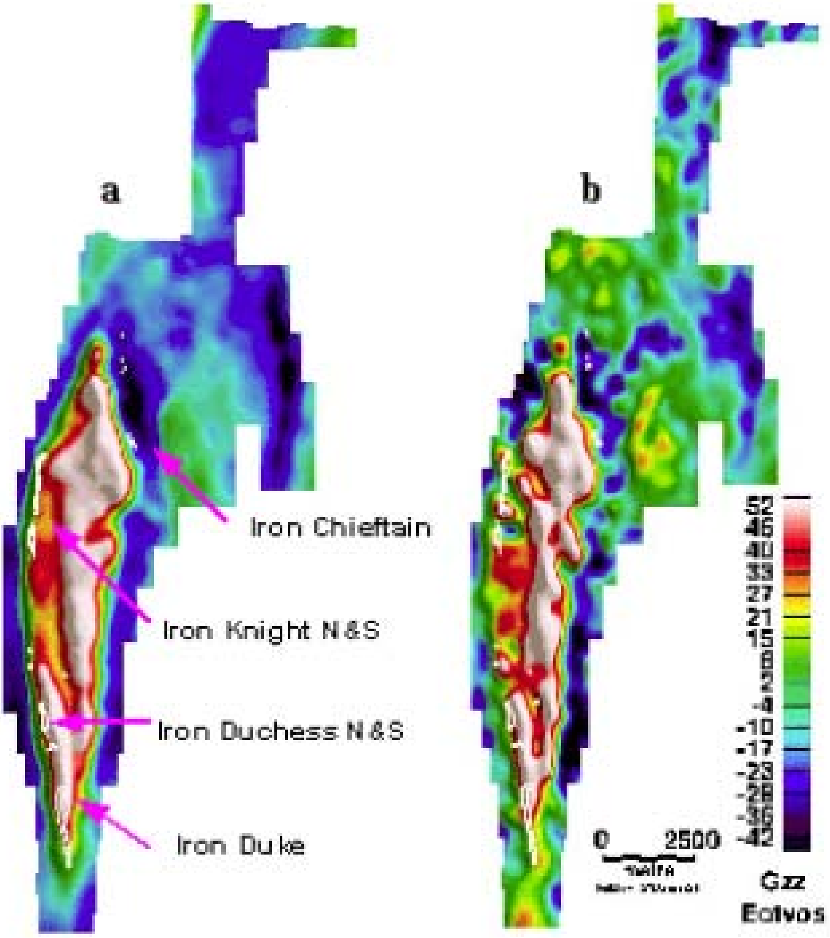


Figure 18 Vertical gradient of gravity for the southern Middleback Ranges, South Australia. Known hematite deposits are indicated by a white outline. The amplitude range is 100 Eotvos. a) Bouguer ground gravity measurements, upward continued to a level surface 500 m above sea level. b) FALCON survey results for the same surface (from Lee et al., 2001).

Discussion and Conclusion

Airborne gravity gradiometry has been shown to be an alternative to regional ground gravity and can cover large areas at a relatively low cost compared to ground crews.

Further developments of airborne gravity systems are underway but any decrease in instrument noise levels will be most likely offset by the noise from terrain corrections. Dransfield (2007) already suspects that terrain correction noise may be more significant than instrument noise in some surveys.

Further investment in systems also has to be justified by the market place. The release of FGG for mineral exploration in April 2010 will show whether the exploration industry sees a need for fast repeatable gravity over large areas at low costs.

Acknowledgements

The material for this paper has been drawn from various authors including Dransfield, Lee, Mahanta, Rajagopalan and others. A bibliography of references follows for those who wish to research this topic in more detail.

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